PROCEEDINGS

OF THE

INTERNATIONAL CONFERENCE ON TECHNICAL ASPECTS OF MARITIME BOUNDARY DELINEATION AND DELIMITATION (including UNCLOS Article 76 Issues)

International Hydrographic Bureau
Monaco
8-9 September 1999

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INTERNATIONAL CONFERENCE ON TECHNICAL ASPECTS OF MARITIME BOUNDARY DELINEATION AND DELIMITATION

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Organized by

International Hydrographic Bureau (IHB)
International Association of Geodesy (IAG)
International Board on Technical Aspects of the Law of the Sea (ABLOS)

Held at the

International Hydrographic Bureau
Monaco
8-9 September 1999

FORWARDS

WELCOME ADDRESS
by Rear Admiral Giuseppe ANGRISANO, President of the International Hydrographic Bureau (IHB)

It is a pleasure for me to welcome the Chairman of this Conference Peter Vanicek and you all, on behalf of the Directing Committee to this conference. The attendance has been far greater than our expectations and this demonstrate that the theme was really interesting and responding to the needs of various users of your expertise. It also demonstrate that the IHB staff led by the IHB Director, Rear Admiral Guy, made an excellent preparatory work and I would like to publicly thank them for this. Thanks should be also given to the past Chairmen (Rear Admiral Guy, Professor Peter Vanicek) and to the present Chairman (Ltcdr. Chris Carleton) and members of the Advisory Board on Law of the Sea (ABLOS) for their action and their contribution to the conference.

I am very glad also for having the possibility to make available to you the premises of the International Hydrographic Bureau for such a notable event. As you know the Government of the Principality of Monaco made these premises available, for free, to the IHB in 1996 for a duration of 99 years and in replacement of the old IHB Headquarter built for us in 1929. We are really grateful to the them for this generous offer.

Let me now very briefly introduce the International Hydrographic Organisation (IHO).
The IHO was created in 1919 by a group of 24 nations in London, took the name of the International Hydrographic Bureau (IHB) and its headquarter is hosted since 1921 in Monaco.

In 1970 the Organization became IHO and the acronym IHB only indicated its permanent headquarter; a Convention was approved and ratified by the governments of the Member States. At present the IHO MS are 67 while another 7 have requested to accede and another 3 are going to ask to accede. Practically almost all the most important maritime states are members of the IHO.

The objectives of the Organisation, as laid down in its Convention are:

- **a) The coordination of the activities of national hydrographic offices;**
- **b) The greatest possible uniformity in nautical charts and documents;**
- **c) The adoption of reliable and efficient methods for carrying out and exploiting hydrographic surveys;**
- **d) The development of the sciences in the field of hydrography and the techniques employed in descriptive oceanography.**

Very recently it was set up, be a special Working Group, a Strategic Plan, in which the main issues and goals of the IHO were identified and five programmes were established as follows:

1. **Co-operation between MS and with the International Organisations.**
2. **Capacity Building.**
3. **Techniques and Standards Co-ordination and Support.**
4. **Public Relations and General Management Support.**
5. **Corporate Affairs.**

Looking at the abstracts of your papers, I realised that they can be considered as a contribution to part of the main objectives of the IHO (in particular the objectives c and d) as well as to some of the programmes of the Strategic Plan (in particular programmes 1,2, and 3).

As far as the programme capacity building is concerned, I would like to recommend the attendees to this conference to make, through the IHB their expertise and studies available to those countries that are in need to define the maritime areas under their responsibility.

We are trying as far as we can to promote the awareness of he governments of the maritime nations that they have to know their seas. To know means to explore, to measure and to depict the aspects of the water mass and of the seabed in a systematic and comprehensive way. In 1998 we have obtained the adoption by the UN of a resolution in which the states are **invited to cooperate in carrying out hydrographic surveys and in providing nautical services.**

We expect that nations will ask us to be helped in defining *which is the area under their responsibility.* The answer to this question is exactly the theme of your conference. I am therefore sure that your contribution may help to respond in a scientific and accurate way to this requirement. But, again, this information should be made generally available and the access to it should be facilitated. A good example could be the recently completion by Rear Admiral Guy of a book that puts the accent on *The relevance of non-Legal, Technical and Scientific Concepts in the interpretation and application of the Law of the Sea.* This book is going to become an IHO publication that we are really glad to offer to the hydrographic services, to the scientific world and to the general public.

With this recommendation and with the auspice that you work be fruitful, I thank you again for your participation to the conference which I am sure will be successful.

Have a good stay in Monaco and a safe return to your homes.

OPENING REMARKS
by Petr VANICEK, ABLOS Chairman

Welcome everyone to this beautiful city and this wonderful place. Let me begin by thanking the International Hydrographic Bureau and Rear Admiral Giuseppe Angrisano (sitting on my left here) for making this place available to us for this Conference. This is the first International public conference organized by ABLOS. The occasion, for which the conference was conceived, is the "coming of age" of the UN Commission on the Limits of the Continental Shelf. And it is my special privilege to welcome among us members of the Commission, who had very kindly agreed to present to us some of the results of their two-year long deliberations. For the first time, we will see how the provisions of the UNCLOS Article 76 are to be put in practice.

As we all know, the deliberations of the Commission have now been embodied in their recently produced "Guidelines". Consequently, there seems to be a growing interest in Article 76 and this conference is one of the testimonies to it. We have here about 80 people from many walks of life, all interested in maritime boundaries, many focused on UNCLOS Article 76 in particular. In the next two days, we will be listening to 26 technical papers covering various different aspects of maritime boundaries. All this looks to me like a promissing mix for a successful conference.

Before opening the conference, I would like to take the opportunity to thank my fellow members of the organizing Committee, Prof. Rizos, Mr. Macnab, Cmdr. Carleton and RAdm. Guy, for all their work behind the scenes that made this venture possible. I wish to recognize as well the help given to ABLOS and to many of the participants by Mme Mollet and Capt. Rohde of IHB. My thanks go also to the convenors of the four sessions, whom you will all see ina ction in the next two days, for thie toiling on behalf of ABLOS.

With these introductory remarks out of the way, let me declare the Conference open.

MESSAGE
by Rear Admiral Neil R. GUY, Director of the IHB

The importance of data for the delimitation and delineation of maritime boundaries is assuming greater and greater importance. Those who are responsible for the acquisition of this data require clear guidance on the type and amount of data necessary. This Conference is dealing with specific aspect, of the UN Law of the Sea Convention related mainly to maritime boundaries and in particular to the establishment of the outer limits of continental shelf claims.

Article 76 is particularly difficult for everyone to understand and has been subject to widely varying interpretation. As the understanding of this article is vital to programmes that will have to be undertaken, probably at great expense, the consideration by this Conference of this article is both timeous and necessary.

The Convention is multi-disciplinary and conferences of this nature are vital to a better understanding by all. It is hoped that the papers that are to be presented by very eminent specialists in their field will provoke thoughtful and constructive discussions among the delegates.

The support for this Conference has indicated the need for similar conferences in the future and it is hoped that such conferences will address other issues of importance and that these initiatives of ABLOS will contribute to a better understanding of one of the most important UN conventions.

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ABLOS 99
Conference Program
9 and 10 September 1999
International Hydrographic Bureau
4 quai Antoine 1er
MONACO

REGISTRATION: (at the **International Hydrographic Bureau**, 4 quai Antoine 1er (4th Floor))

1400 - 1800	Wednesday 8 September
0830 - 1000	Thursday 9 September.

ADMINISTRATIVE ARRANGEMENTS AND WELCOME

Thursday 9 September 1999

0900	Opening Addresses: Committee	President of the IHB Directing and Chairman of ABLOS
0915	Administrative Arrangements:	IHB Director

0930 - 1300 **SESSION 1:** **Convenor:** **Mr. Galo CARRERA**

Issues concerning the UN Commission on the Limits of the Continental Shelf

0940	"The mandate and work of the Commission on the Limits of the Continental Shelf"	**Peter CROKER,** CLCS Member (Ireland)
10.00	"A review of continental margins of the world"	**Karl HINZ**, CLCS Member (Germany)
1020	*COFFEE BREAK*	
1040	"Formulating the New Zealand continental shelf claim: a first step"	**Iain LAMONT,** CLCS Member (New Zealand)

11.00	"Uncertainties and errors in sediment thickness"	**Harald BREKKE,** CLCS Member (Norway)
1120	"Wide continental margins of the world: a survey of marine scientific requirements and international regional cooperation needs posed by the implementation of article 76 of UNCLOS"	**Galo CARRERA**, CLCS Member (Mexico)
1140	"Information on the outer limits of the extended continental shelf"	**Alexandre ALBUQUERQUE**, and **Galo CARRERA**, CLCS Members (Brazil and Mexico)

1300 - 1400 LUNCH BREAK

1400 - 1700 **<u>SESSION 2:</u>** **Convenor: Mr. B.G. HARSSON**

<u>Geodetic issues, with emphasis on errors in maritime boundaries and how to reduce them</u>:

1400	"The impact of the seabed roughness on the location of the outer limits of the extended continental shelf"	**Galo CARRERA**, (Canada)
1420	"Coastal boundaries and vertical datums"	**Erwin GROTEN,** (Germany)
1440	"Propagation of errors from shore baselines seaward"	**Petr VANICEK**, (Canada)

1500 COFFEE BREAK

1520	"Accuracy of computed points on a median line, factors to be considered"	**Lars SJOBERG, M. FAN and M. HOREMUZ,** (Sweden)
1540	"Maritime zone boundary generation from straight baselines defined as geodesics"	**Brian MURPHY, P. COLLIER, D. MITCHELL and B. HIRST**, (Australia)
1600	"RTK/ DGPS service in maritime boundary delimitations"	**Stanislaw OSZCZAK, A. WASILEWSKI and Z. RZEPECKA, (Poland)**
1620	"The determination of boundaries at sea between Belgium and The Netherlands"	**I. ELEMA and Kees de JONG,** (The Netherlands)

1800 - 2000 SOCIAL EVENT – COCKTAIL PARTY (IHB)

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Friday 10 September 1999

0900 - 1200 **SESSION 3:** **Convenor:** **Mr. Ron MACNAB**

Tools needed for boundary delimitations:

0900	"GIS applications to maritime limit and boundary delimitation"	**Hal PALMER, l. PRUETT and k. CHRISTENSEN,** (USA)
0920	"A model for using publicly available data and methodologies to begin preparing a claim to an extended continental shelf under article 76 of the United Nations Convention on Law of the Sea (UNCLOS)"	**David MONAHAN, Michael S. LOUGHTRIDGE, Meirion T. JONES and Larry MAYER**, (Canada, USA, UK
0940	"An examination of publicly available bathy-metry data sets using digital mapping tools to determine their applicability to article 76 of UNCLOS"	**David MONAHAN, and Larry MAYER**, (Canada)
1000	"An overview of Australian Maritime Zone boundary definition"	**Bill HIRST, Brian MURPHY and Phil COLLIER**, (Australia)

1020 COFFEE BREAK

1040	"A set of integrated tools based on ArcView for defining the outer limit of Australia's continental shelf"	**Irina BORISSOVA, P.A. SYMONDS, R. GALLAGHER, B.C. COTTON and G. HILL,** (Australia)
1100	"Contrast of the 'Surface of Directed Gradients' with the 'Surface of Maximum Curvature' to compute the foot of the continental slope"	**John BENNETT**, (USA)
1120	"The HH code: facilitating the management, manipulation, and visualization of bathymetric data"	**Jennifer HARDING, H. VARMA, J. HART and Ron MACNAB,** (Canada)
1140	"Integrated procedures for determining the outer limit of the juridical continental shelf beyond 200 nautical miles"	**M. HALIM, M. D'ARCY, J. HARDING, Ron MACNAB and David MONAHAN**, (Canada)

1300 - 1400 ***LUNCH BREAK***

0900 - 1700 **SESSION 4:** **Convenor:** **Mr. Chris RIZOS**

Other issues and case studies (not necessarily related to Article 76):

1400	"Article 76 in the Arctic - a catalyst for international collaboration"	**Ron MACNAB,** (Canada)

1420	"Bathymetry and deep structure of the Arctic Continental Margin of Russia in the context of article 76 UN Convention on the Law of the Sea"	**Georgi CHERKASHOV, I.S. GRAMBERG, A.P. MAKORTA, V.D. KAMINSKY, G.D. NARYSHKIN, V.A. POSELOV and M. SOROKIN** (Russia)
1440	"Contribution of the SCICEX Project towards the implementation of article 76 of the UN Convention on the Law of the Sea in the Arctic Ocean"	**Bernard COAKLEY**, (USA)
1500	*COFFEE BREAK*	
1520	"Australia's approach to defining its extended continental shelf: progress and issues arising"	**Phil SYMONDS,** (Australia)
1540	"Achievable uncertainties in the depiction of the 2500m contour and their possible impact on continental shelf delimitation"	**David MONAHAN, and D. WELLS**, (Canada)

SUMMARY AND CLOSING DISCUSSIONS

SESSION 1 – Paper 1

SESSION 1 – Paper 2

A REVIEW OF CONTINENTAL MARGINS OF THE WORLD

by Karl Hinz, BGR, Hannover, Germany

Short biography

Date and place of birth:
12.04.1934, Klebow, Germany

Education:

1953 - 1958	Study of geology at the Humboldt University, Berlin, Germany
1962 - 1964	Advanced study of geophysics and geology at Bergakademie, Clausthal, Germany Ph.D. in Geophysics / Marine Geology

Professional career and experience:

1958 - 1974	Research scientist at VEB Erdöl & Erdgas, the Geological Survey of Lower Saxony, Germany, and at the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany.
1975 - 1985	Head of Sub-Division Exploration Geophysics at the BGR.
1985 - 1999	Appointment to Director and Professor at the BGR; Head of Sub-Division Marine Geophysics and Polar Research (1985 - 1992); Head of Division Geological and Geophysical Research at the BGR, Hannover, Germany. Participation in 48 marine expeditions designed to study aspects of geodynamics, plate tectonics, resources and methodical and technical development. Miscellaneous International Scientific and Advisory Functions.
1968 – 1999	Member of several Advisory Panels and Working Groups of the International Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP); Advisor of CCOP (1973 - 1998); Member of the Scientific Committee of IGCP (1987 - 1990); Member of the Editorial Board of Marine and Petroleum Geology.
1997	Member of the UN Commission on the Limits of the Continental Shelf
Publications	140 on different aspects of marine geosciences

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ABSTRACT

Over the last 20 years, geoscientific research has demonstrated the presence of a variety of continental margins, which can be grouped into three major categories:

(a) Convergent continental margins are formed along plate boundaries linked to active and inactive subduction zones, where energy and mass transfer between the Earth's lithosphere and interior occurs. At convergent plate boundaries part of the descending lithospheric plate is either scraped off, creating a wedge of deformed rocks in front of the upper continental plate (*Accretionary Convergent Continental Margin Type*), or is underplated beneath the upper plate and removed by the descending plate, respectively (*Poor- or Non-Accretionary Convergent Continental Margin Type*). At some plate boundaries, material from the upper plate is eroded and removed by the subduction process (*Destructive Convergent Continental Margin Type*).

(b) Rifted (extensional, passive, divergent) continental margins represent a transition zone between continental and oceanic lithosphere, which formed during continental breakup. Two most contrasting types have been demonstrated. Continental breakup resulted either in the formation of complex sedimentary rift basins, containing also economically important hydrocarbons, along some rifted margins (*Rifted Non-Volcanic Type*), or in a rapid emplacement of huge volcanic features, known as sequence of seaward-dipping reflectors, near the time of continental separation along other rifted continental margins (*Rifted Volcanic Type*). Along most volcanic margins, these huge volcanic constructions are buried by a thick pile of sediments.

(c) Sheared continental margins are found where major oceanic fault zones intersect continental margins.

1. Introduction

The formation of the present continental margins was begun with the breakup of a super-continent and the accompanying formation of mobile lithospheric plates. Continental margins are the World's principal locus for valuable resources; for earthquake, volcanic, landslide and climatic hazards, and for the greatest population density. The continental margins, consisting of the coastal area, the shelf, the slope and the rise - if developed - cover with about 77 million km² a larger area than the continental sedimentary basins altogether.

Although remarkable knowledge is available on the geological architecture of continental margins, many of the mechanical, fluid, chemical and biological processes that shape and destroy continental margins are poorly understood and are the challenge for future research.

2. Types of continental margins

Over the last 20 years, geoscientific research has demonstrated the presence of a variety of continental margins, which can be grouped into three major categories - Convergent continental margins, Rifted (extensional, passive, divergent) continental margins, and Sheared continental margins (Figure 1: A - F):

2.1 Convergent continental margins are formed along plate boundaries linked to active and inactive plate boundaries, but not always associated with a trench. At convergent plate boundaries, the lithosphere of one plate is subducted at depth under the lithosphere of another plate. This process is associated with high earthquake frequency; volcanism, crustal deformation, and the opening of backarc basins are the more superficial expressions of the subduction process. Igneous activity and metamorphism accompany the process at depth. The convergent continental margins with a total length of approximately 44,000 km comprise three different types:

2.1.1 *The accretionary convergent continental margin type* is widely distributed and consists in the normal case of the forearc region, the forearc basin and the island arc (Figures 1A and 2). The forearc region comprises the trench itself, the accretionary wedge and the forearc basin. The accretionary wedge is constructed of thrust slices of trench infill sediments and also possibly oceanic crust, which have been scraped off the downgoing slab by the leading edge of the overriding upper plate. The landward adjacent forearc basin is a region of mostly flat-bedded deposits between the accretionary prism and the volcanic island arc. Figure 3 shows a depth migrated seismic section across the accretionary wedge of the southern Chilean continental margin.

2.1.2 *The poor or non-accretionary convergent continental margin type* has been recently recognized at several plate boundaries and it appears that this type is widely distributed. Seismic reflection records have imaged a pronounced structural style from this convergent continental margin type consisting of three superimposed units overlying actively subducting oceanic crust. The basic structure is a crustal wedge consisting of high-velocity rocks and characterized by high-amplitude reflections at the top and the base, covered by a sedimentary apron, fronted often by a commonly small accretionary prism and underlain by a distinct sequence of high-amplitude - low-frequency reflections about 1 - 2 km thick (Figures 1B and 4). Although the crustal wedge has not been knowingly sampled in marine environment there is in few cases evidence that it is composed largely of accreted ophiolite. Although the nature of the wedge-shaped rock bodies known from e. g. Central America and Guatemala subduction zones, the SE Sulu Sea, the Celebes Sea, the Kuril subduction zone is uncertain it is permissible to speculate on its origin: one possibility is that it originates from thickened oceanic crust formed during accelerated melt production along a former spreading ridge and displayed by a notably thicker oceanic crust. One can assume that strongly thickened oceanic crust colliding with a continent is too buoyant to be subducted and is instead accreted to the continent causing a seaward jump of the subduction zone. Another possibility is that subduction erosion e.g. by hydrofracturing erodes material from the base of the upper plate resulting in slope retreat and removal of this material.

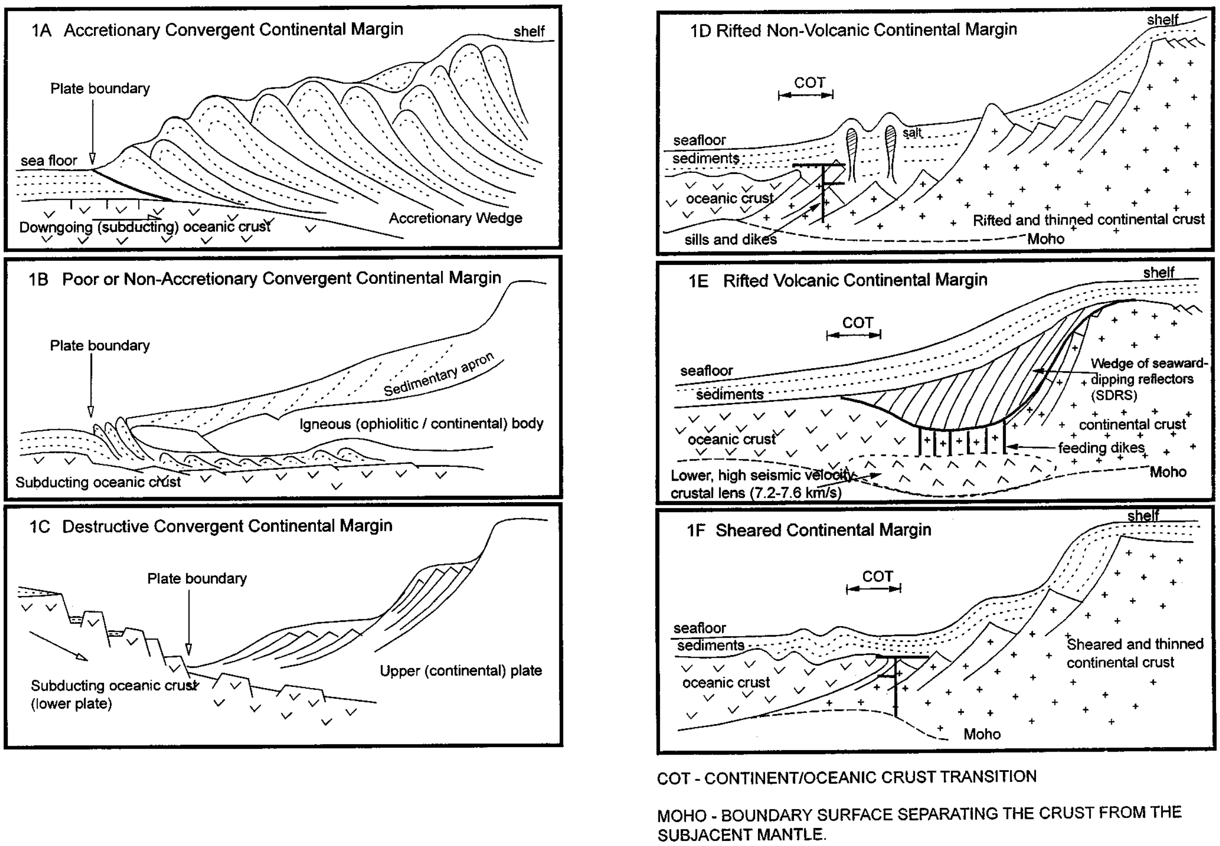

Figure 1: (A - F): Schematic illustration of different continental margin types.

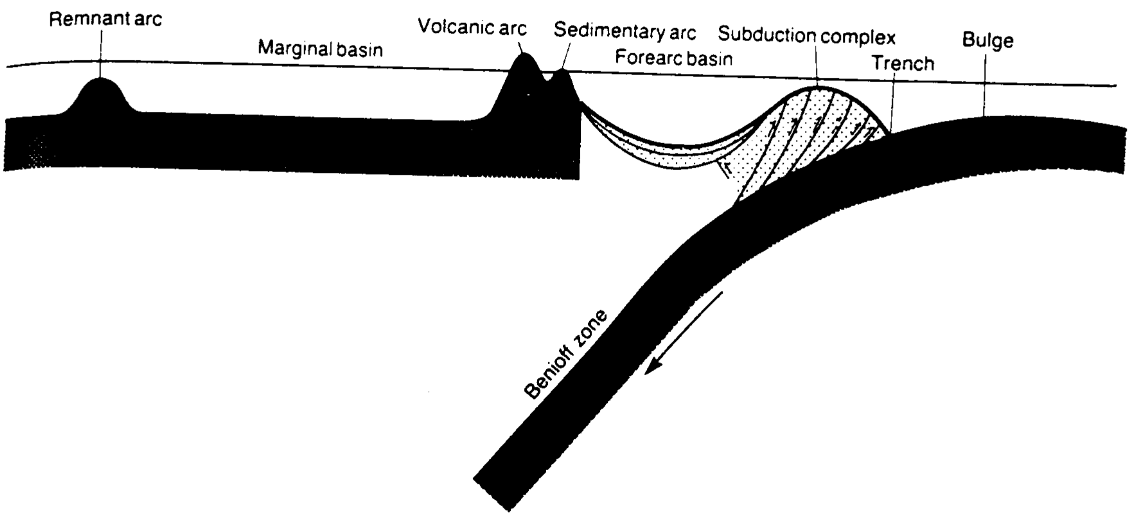

Figure 2: Generalized schematic morphology of an oceanic subduction zone.

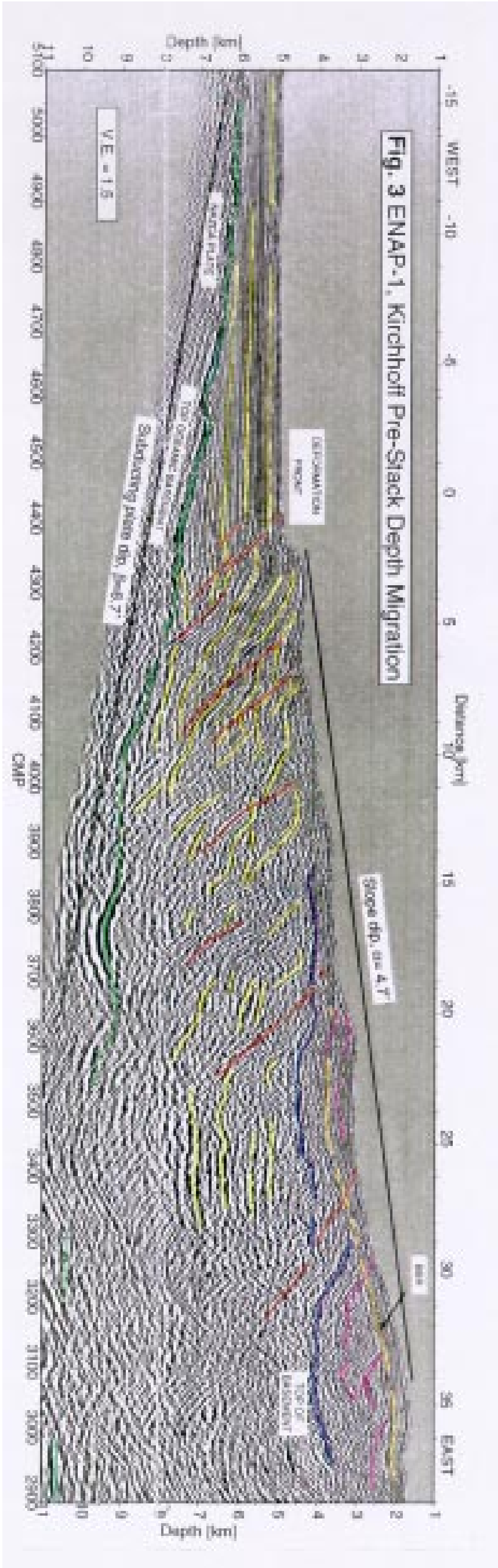

Figure 3: Depth migrated seismic section across the accretionary wedge of the active convergent margin of southern Chile.

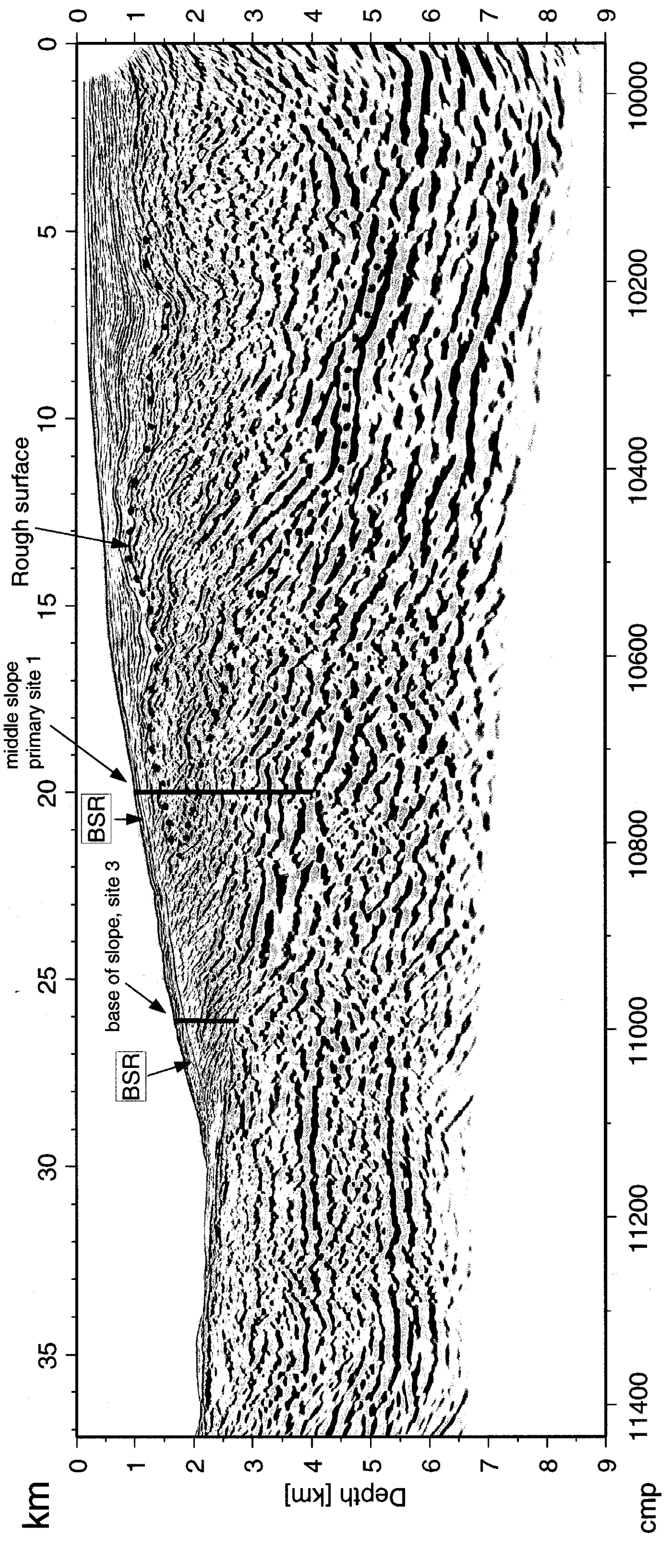

Figure 4: Depth-migrated section from the active convergent margin off Costa Rica. The section shows the basic configuration of the poor or non-accretionary continental margin type. The crustal wedge is indicated by dots. The low-frequency reflections along the plate boundary are interpreted to represent subducted and underplated material.

2.1.3 *The destructive convergent continental margin type*

One of the best-studied destructive convergent continental margins is the northern Chilean continental margin, located in front of the high Andean mountain chain which was generated by subduction of oceanic lithosphere since late Jurassic times. Subduction of the Nazca oceanic lithosphere currently takes place at velocities of about 9 cm/y to the east. The subduction angle is about 10° from the trench to 30 km depth, but at greater depth the angle steepens to 16° and 22° respectively.

Abundant active volcanism, particularly in the Central Andes, high seismicity, crustal thickening of some 60 to 80 km, and the presence of four volcanic arc systems are characteristic features of the Andean orogenic belt.
Especially the conclusive field observations for a landward shift of the volcanic arc and consequently of the subduction zone by 250 km since upper Jurassic times raises the fundamental questions on the tectonic erosion process and what happened with the 250 km wide continental crust formerly located to the west of the present shore line.

Bathymetric mapping and multichannel reflection seismic data show that the Eocene-aged and sediment-starved oceanic crust of the Nazca plate becomes blockfaulted when approaching the trench (Figure 5). The 50 km to 70 km wide outer trench slope is characterized by a complex system of horst and graben structures resulting from the strong down-bending of the lower plate. A common seismic feature of the slope is an up to 2,000 m thick apron (unit CM 1 in Figure 5) overlying a unit of high reflectivity characterized by seismic velocities ranging between 4 and 5 km/s, and affected by both large-scale and small-scale rotational blockfaulting. Deep-reaching, curved faults interpreted to represent major detachment planes, and small-scale faults forming boundaries of narrow rotational blocks mainly in upper crustal levels are recognizable in seismic sections suggesting that massive gravitational sliding and mass wasting are the dominant processes in shaping the northern Chilean continental margin. These processes affect successively deeper levels of the upper plate when approaching the trench, resulting in thinning of the upper plate and finally resulting in the production of debris masses imaged by the seismically transparent apron. The material removed by this mechanism from the upper plate infills the gaps of the subducting oceanic plate. The infilled debris becomes compressed, imbricated and is finally removed beneath the upper plate by the subducting Nazca plate.

A raw estimate of the volume of continental debris that is removed by infilling of the gaps of the subducting Nazca plate yielded values of approximately 40 - 50 km^3 per 1 Ma per 1 km trench length. These estimated values are roughly in accordance with the requested removal of some 250 km of the northern Chilean continental margin during the last 170 Ma.

In the case that the foot of the slope is difficult to define by bathymetric data, and evidence to the contrary (Article 76, paragraph 4(b)) is introduced by a coastal State, the Commission might consider the seaward edge of the accretionary wedge (Figure 1A and 1B), or in the case of a destructive margin by the foot of the upper plate (Figure 1C), as an equivalent of the foot of the slope in the context of paragraph 4.

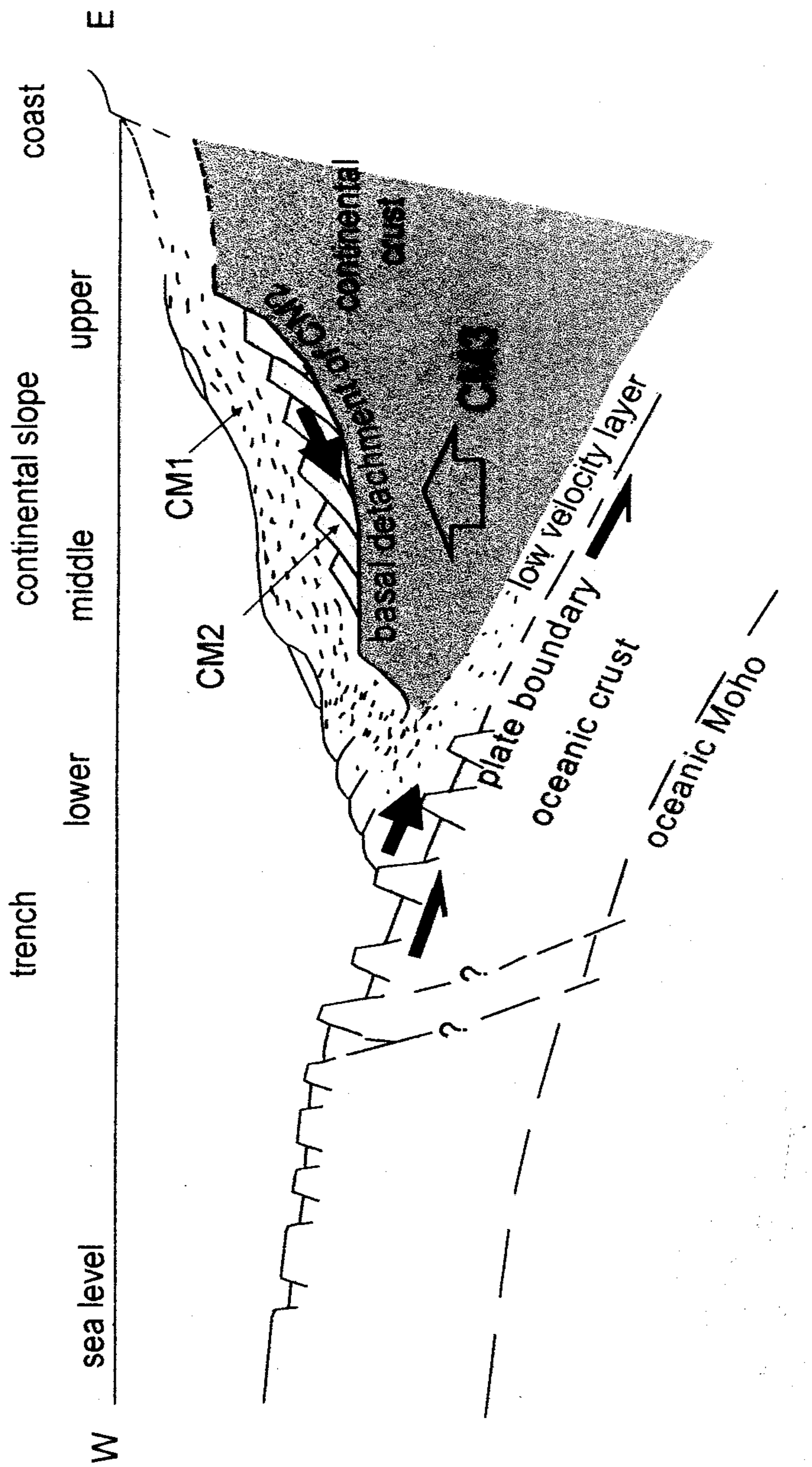

Figure 5: A model for tectonic erosion: Major erosion occurs at the top side of the continental wedge requiring continuous uplift of the wedge to enable erosion of deeper crustal levels. Dotted area: increased brecciation and trenchward transport of debris at the top side of the wedge along listric master detachments; melange formation with rocks of the oceanic crust at the frontal unit and removal by subduction along the plate boundary.

2.2 *Rifted (extensional, passive) continental margins*

Most modern rifted continental margins originated as divergent plate margins formed during the breakup of the supercontinent Pangea in the early Mesozoic. The most reasonable model for continental splitting seems to require a regional tension to exist affecting the whole plate, possibly caused by trench subduction force acting on opposite edges of the plate. The category of rifted continental margins can be subdivided into two types:

2.2.1 *The wide, thin-crusted continental margin type (rifted non-volcanic margin, Figure 1D)* contains evidence for two phases in their evolution: a rift phase, which occurs before breakup of the continent, and a drift phase, which occurs after the onset of seafloor spreading. The rift phase is a tectonically active one, with normal faulting, thinning of the crust, locally high rates of basin subsidence and sediment accumulation. The drift phase is one of lithospheric cooling, thermal subsidence, and development of broad depocenters. Crustal extension is spatially highly variable and can be symmetric (pure-shear rifting) as well as asymmetric (simple-shear rifting). The old Moroccan continental margin (Figures 6 and 7) has been chosen to demonstrate the complex architecture of rifted non-volcanic margins.

2.2.2 *Rifted volcanic continental margins* are characterized by a buried, approximately 100 km wide and 5 - 10 km thick wedge of seaward-dipping reflectors, comprising extruded lavas emplaced near or above sealevel, and by a lower crustal lense with seismic velocities of 7.2 - 7.6 km/s (Figures 1E and 8). Geophysical studies have demonstrated that approximately 70 % of the Atlantic rifted margins are volcanic margins (Figure 9). Voluminous igneous activity has accompanied the initial opening of major Atlantic Ocean segments. The transient events occurred during four episodes: A middle Jurassic episode during which the United States East Coast volcanic margin was formed, extending over a length of 2,500 km. The next volcanic episode was during the early Cretaceous between about 125 and 135 Ma. Extensive volcanism accompanied the opening of the South Atlantic and resulted in the formation of a volcanic construction extending continuously over a length of 3,500 km from near the Falkland Plateau to Southern Brazil. A similar wedge is present along the South African - Namibian continental margin. Intensive volcanism accompanied the final separation of Greenland from North America, and the final separation of Greenland from Eurasia. Huge wedges of seaward-dipping reflectors were emplaced along the conjugate continental margin pairs from Southeast Greenland - Rockall Plateau in the south to Northeast Greenland - Barents Sea. The available data suggest that the formation of volcanic rifted margins follows a more or less common evolutionary model:

a.) Lithospheric extension along a relatively narrow rift zone prior to breakup
b.) Regional syn-rift uplift caused by magmatic activity.
c.) Widespread volcanism with voluminous outpourings of basaltic lavas mostly in a subaerial environment.
d.) Subsidence of the volcanic margin after abatement of the transient excess of volcanism.

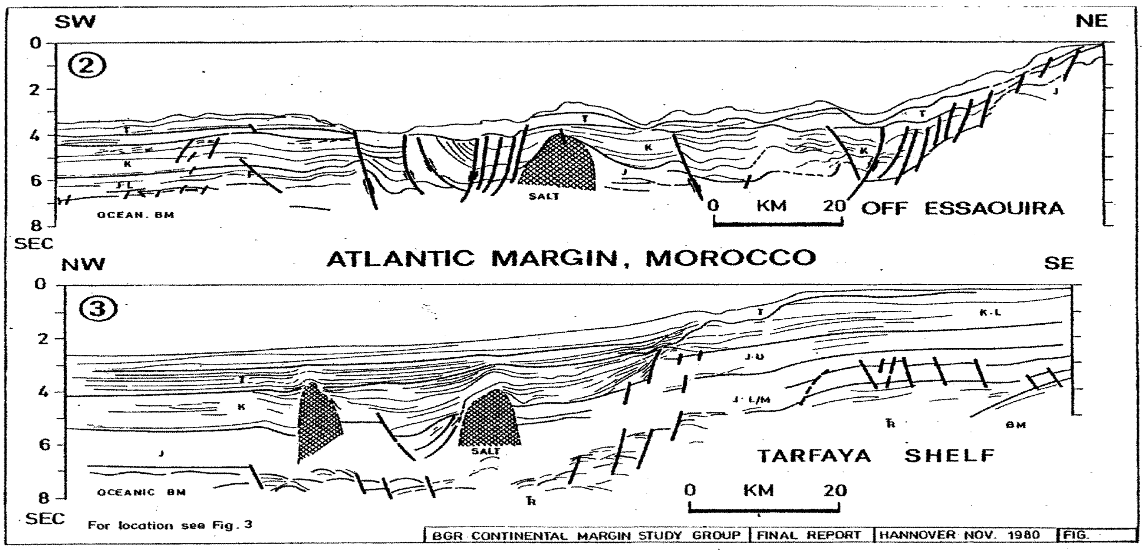

Figure 6: Geoseismic sections from the Moroccan continental margin. Most of the depositional sequences J/J·L/M and salt were deposited during the rift phase. Deposition of sequences K and T occurred during the drift phase. Intensive salt diapirism affected the depositional units of the margin since Early Cretaceous.

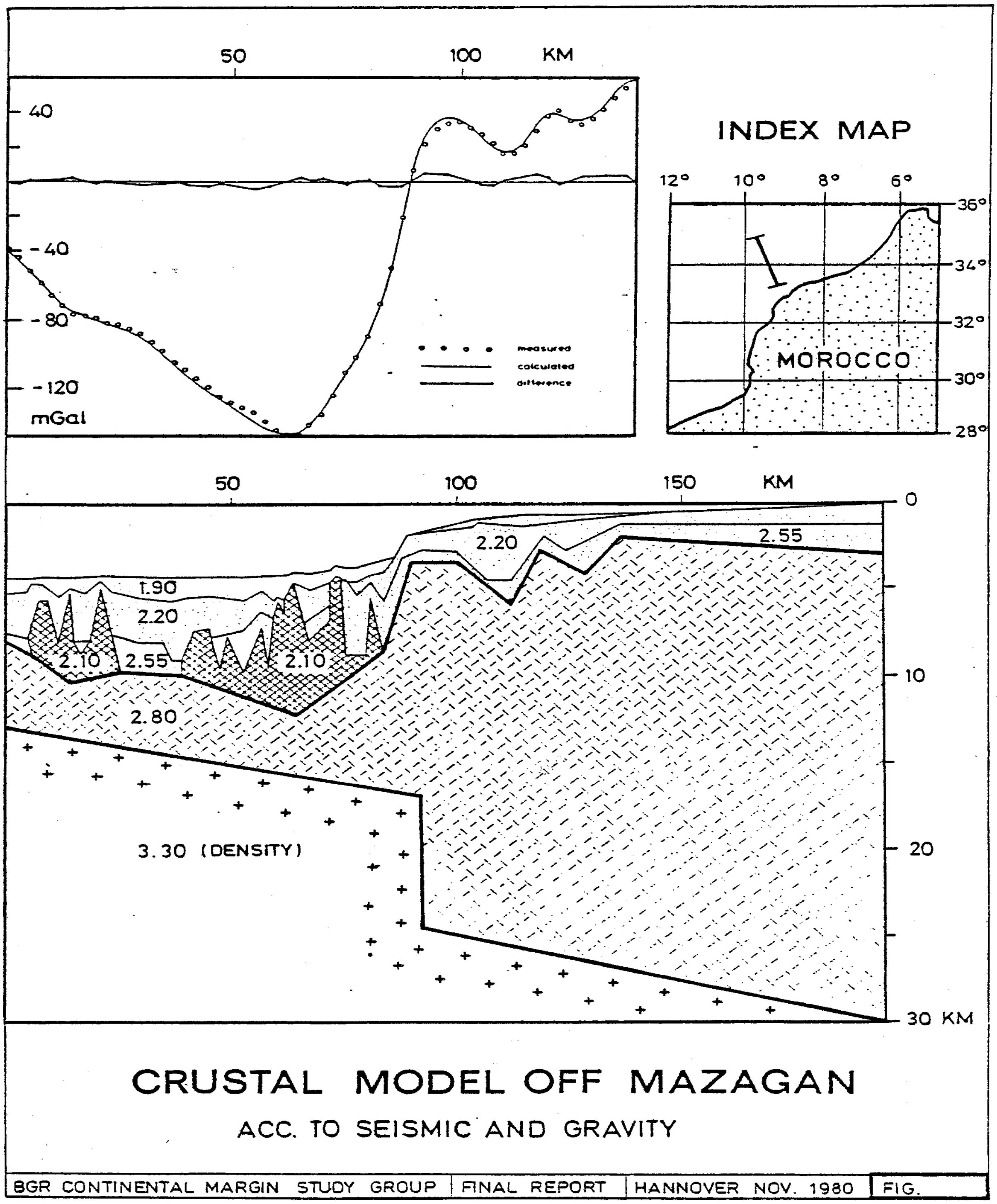

Figure 7: Schematic crustal section across the rifted non-volcanic continental margin of Morocco/Mazagan segment derived mainly from gravity modeling. Thick sedimentary units and large salt diapirs overlie strongly thinned continental crust.

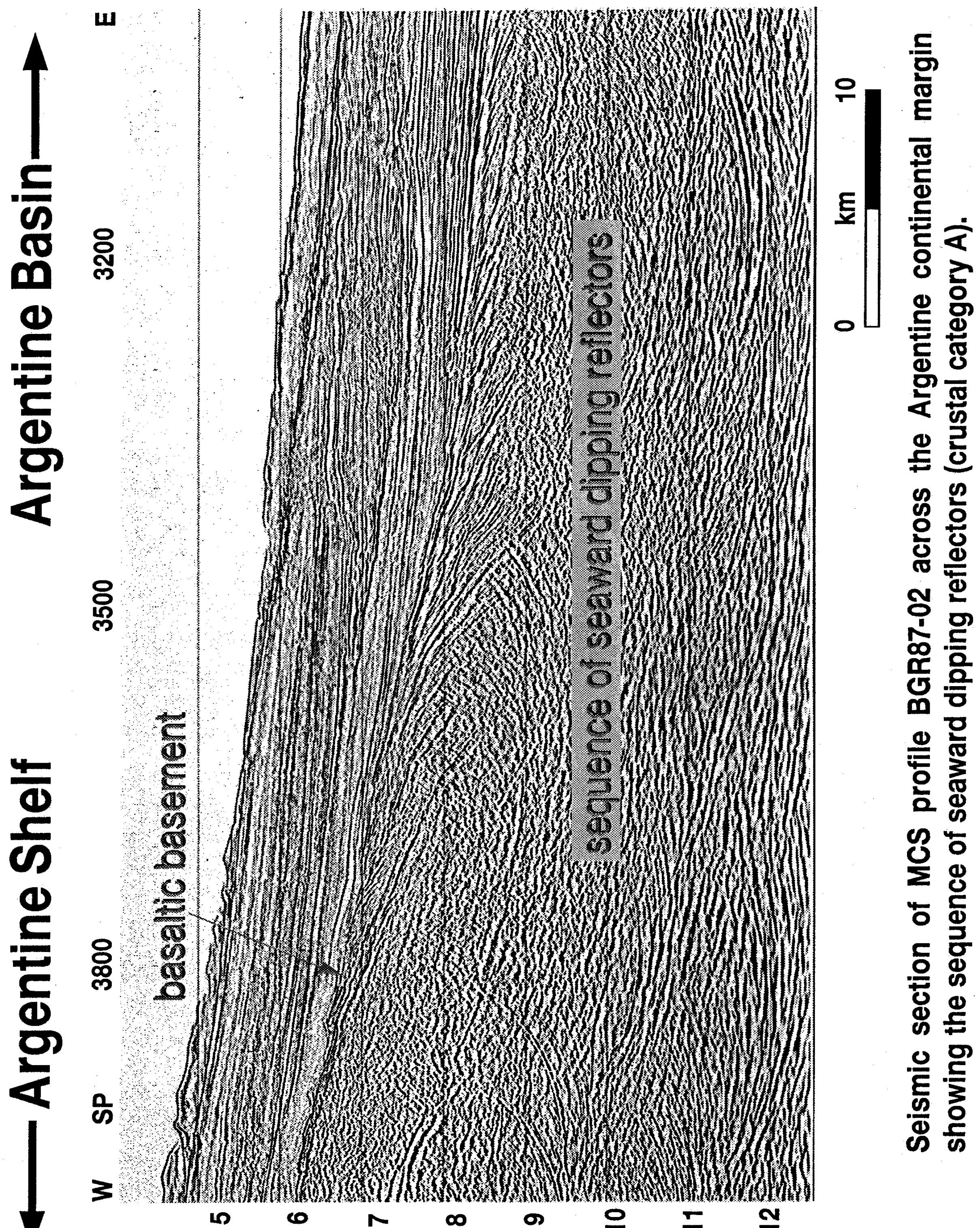

Figure 8: Seismic section of MCS profile BGR 87-02 across the Argentine rifted volcanic continental margin showing a sequence of seaward-dipping reflectors beneath thick drift sediments.

BGR

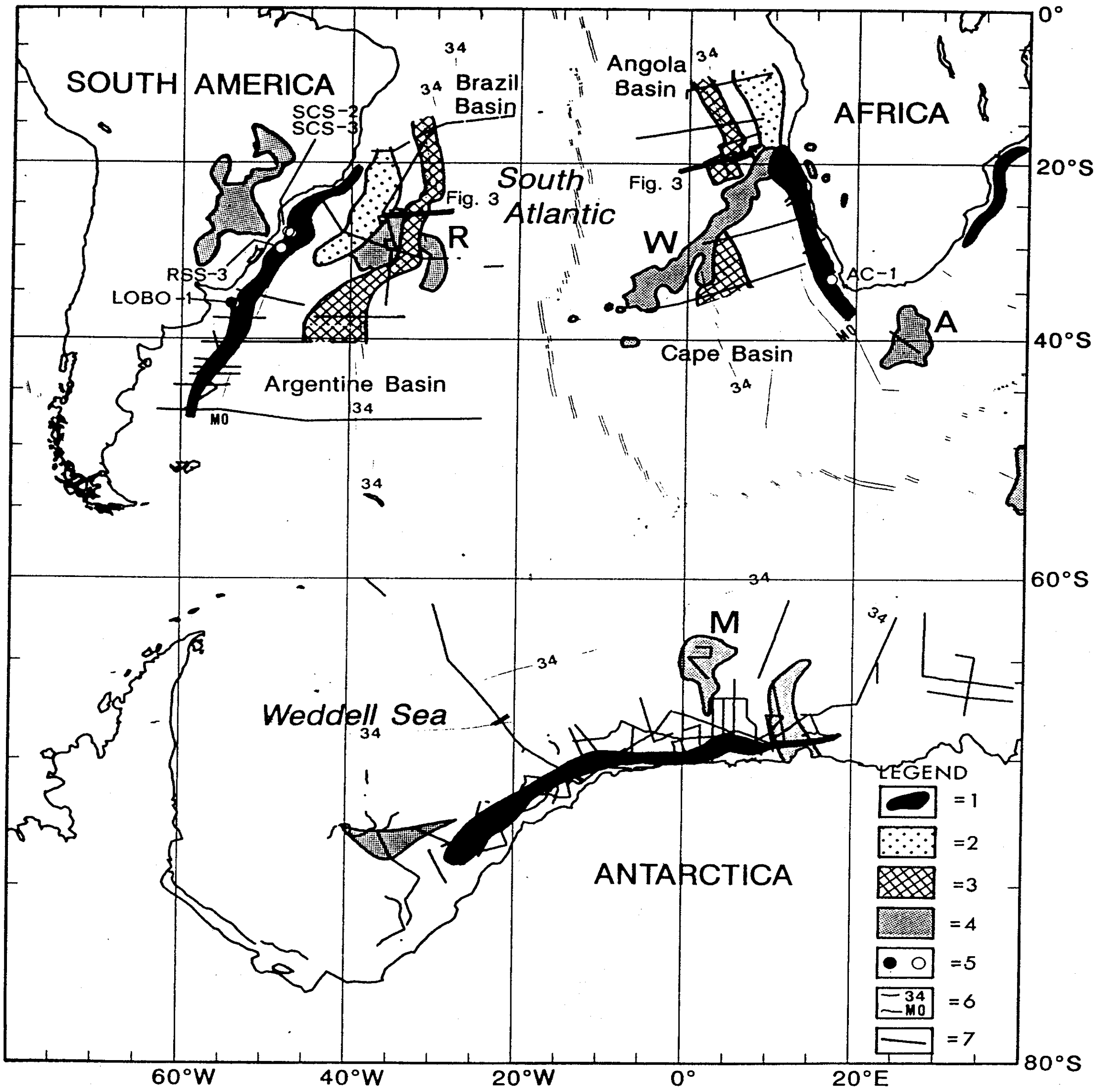

Figure 9: South Atlantic Volcanic Provinces
1 = Volcanic continental margin with seaward-dipping reflector sequences. 2 and 3 = Oceanic crustal segments characterized by a highly reflective lower-crustal unit and notably thicker crust, interpreted to represent episodes of excess melt production at the pre-existing spreading axis. 4 = Continental flood basalt and Large Igneous Provinces. 5 = Location of selected DSDP/ODP/commercial bore holes. 6 = Magnetic chrons 34 and M0. 7 = Location of selected deep seismic reflection lines of the BGR.
A = Agulhas Plateau, M = Maud Rise, R = Rio Grande Plateau, W = Walvis Ridge.

The major volcanic phases resulting in the formation of the wedges of seaward-dipping reflectors were brief and are in the order of 1 to less than 5 Ma. The average basaltic extrusion rate during the formation of the huge volcanic construction are in the range of 4 km³ per 10,000 years per 1 km rift length. Considering this large volume of igneous material that was generated, it follows that the emplacement of the wide-spread volcanic continental margins is manifested by particularly intense and brief periods of material and energy flux from the Earth's interior to the surface by processes not well understood yet.

2.2.3 *Sheared continental margins* created along zones of translational continental rupturing during continental breakup starting with strike-slip motion probably resulting in brittle deformation of the upper crust and ductile deformation at depth. The former can give rise to pull-apart basins and folding and faulting of the sedimentary infill by the transform motion. Finally the sheared margin passes adjacent to oceanic crust of the spreading center and later becomes in contact with cooling oceanic lithosphere.

3. *Determination of the foot of the continental slope of rifted continental margins with respect to evidence to the contrary*

The seaward limit of both the rifted non-volcanic continental margin and the sheared margin continental margin is defined as the transition between continental crust and oceanic (Figure 1D). The boundary between the two crustal types is mostly transitional extending over several tens of kilometers. If the foot of the slope is very difficult to define on the basis of bathymetric data the Commission might consider the landward limit of the transitional zone as an equivalent of the foot of the continental margin in the context of paragraph 4, provided that the submitted geoscientific data conclusively demonstrate that the submerged land mass of the coastal State extends to this point.

The volcanic continental margins (Figures 1E and 9) mostly merge seaward without a sharp boundary into oceanic crust created at a pre-existing spreading center. The seaward extent of rifted volcanic continental margins can be defined as an area in which most of the sequence of seaward-dipping reflectors terminate seaward and where the igneous continental crust decreases to values typical of oceanic crust, i.e. less than 15 kilometers.

Wide-angle reflection/refraction data and magnetic and multichannel seismic reflection data are needed for determining the landward limit of the transitional zone (COT in Figure 1E - 1F) of the rifted and sheared continental margins, which might be considered by the Commission as an equivalent of the foot of the continental slope in context of paragraph 4.

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SESSION 1 – Paper 3

FORMULATING THE NEW ZEALAND CONTINENTAL SHELF CLAIM: A FIRST STEP

by Iain LAMONT, New Zealand

Biography

Iain Lamont is the manager of the Nautical Information Services, Hydrographic Office , Royal New Zealand Navy . He is also a United Nations Commissioner on the limits of the Continental Shelf . Formerly a navigating officer , he has spent the past 30 years supplying expert advice on maritime boundaries and Law of the Sea aspects to the New Zealand Government and South Pacific Island States. In addition he is also a navigational tutor and examiner.

ABSTRACT

New Zealand ratified the United Nations Convention on the Law of the Sea in July 1996 and has until 2006 to lodge its claim. The New Zealand Government has commissioned a desktop study as a first step towards the development of a continental shelf claim. The principle objectives of the Desktop Study were; firstly, to evaluate existing information for its usefulness as evidence to support a continental shelf claim and secondly, to identify survey requirements in areas where existing information is insufficient to support a claim. This paper will give a sketch of the New Zealand Government's approach to developing technical and scientific evidence to support a claim.

INTRODUCTION

New Zealand ratified the United Nations Convention on the Law of the Sea **(UNCLOS)** in July 1996 and under the terms of the Convention has until 2006 to lodge its claim for a legal continental shelf extending beyond a distance of 200 nautical miles (M) from the baselines of the territorial sea. The New Zealand Government has commissioned a Desktop Study as a first step towards the development of a legal continental shelf claim submission to the United Nations.

The New Zealand continental shelf has a complex geomorphology. New Zealand straddles the Pacific and Australian tectonic plate boundary *(running North-east/South-west).*

The extent of a potential legal continental shelf encompassed by a New Zealand claim beyond 200M is very large, from a minimum of three times to nine times the area of the New Zealand land mass *(268,738 km^2***).**

The cost and time commitment required to carry out marine surveys of New Zealand's large continental shelf area and explore its geological complexity fully was a source of considerable concern to the New Zealand Government. Accordingly it was decided as a first step to undertake a desktop study to explore the data requirements necessary to support a claim submission under **UNCLOS.**

A main objective of the Desktop Study was to evaluate the minimum survey requirement to substantiate a claim submission to a reduced continental shelf area under Article 76 and also to identify an optimum survey requirement which would substantiate New Zealand's claim to its full continental shelf entitlement without carrying out unnecessary (*and costly*) marine surveys. This evaluation of alternative survey requirements would indicate to the Government the range of survey cost options and could allow an estimation of benefits against costs. The benefits of the optimum survey programme included increased confidence of the quality and robustness of the final claim submission. In May 1999, Ministers agreed that the strategic nature of a continental shelf submission was of paramount importance and the optimum survey programme was elected as the preferred survey option. This paper will give a sketch of the New Zealand Government's approach to developing technical and scientific evidence to support a claim submission to the Commission on the Limits of the Continental Shelf.

OBJECTIVES

The principle objectives of the Desktop Study were; firstly, to evaluate existing information for its usefulness as evidence to support a continental shelf claim submission. This included making an assessment of any areas which may potentially be claimed through a submission under Article 76 and also areas where existing data is sufficient to substantiate a claim. The study also set out to identify survey requirements in areas where existing information is insufficient to support a claim submission.

BACKGROUND

Data available to New Zealand is sparse in many areas of the Continental shelf so evaluations of the existing data required careful consideration of the age and quality and also the locations of the existing data. No systematic survey has ever been made of the greater continental shelf so the task of the technical team working on this study was to evaluate all data available and determine which data (*of the highest quality*) should be used for a submission and where data is inadequate, to devise a survey programme to gather data which is appropriate for the formulation of a submission under Article 76.

The distribution and quality of bathymetric data vary throughout the region, with data density generally reducing away from New Zealand. Much of the analogue GEBCO data are unreliable, predating modern navigational positioning. Transit satellite data are of variable quality depending on the frequency of satellite passes at the time of surveying. Existing seismic reflection data include both single-channel and multi-channel profiles of various vintages and qualities. As part of this study modern satellite gravity data were utilised to assist in the interpretation of existing bathymetry and seismic reflection profiles.

The definition of the legal continental shelf in terms of Article 76 appear simple in concept, but when considered in detail there are a number of ambiguities, which have a major impact on New Zealand's potential claim. New Zealand and its continental shelf are situated on evolving boundaries of highly active, merging tectonic plates. This has resulted in complex deep marine geological and morphological structures, which will have a strong influence on the delimitation activities required.

For New Zealand the fundamental uncertainty arises from determining what can be included in natural prolongation of the continental margin.

- This gives rise to questions such as ridges what is the precise definition of the terms "**oceanic ridge**" and "**submarine ridges**" .

- How does one identify the foot of the continental slope along complicated margins?

- Where does the continental slope become continental rise and do all margins have a rise?

- Will these terms be interpreted geological or morphological grounds, or both?

- Where does the base of the slope lie on margins with complex basement structure and little sediment cover?

The nature of the rocks beneath the sediments on the slope may be important, as Article 76 provides that subsurface structural information may be used to determine the foot of the slope and the natural prolongation of the landmass. In such areas of uncertainty it may be necessary to use geologic evidence to distinguish which region should be considered part of the of the deep ocean and which are inherently part of the continent.

- Is a shallow crustal body of continental shelf origin which lies beyond the foot of the slope but within the legal continental shelf (*i.e.; foot of slope + 60M*) or the 1% sediment line) part of the natural prolongation of the land mass?

- Is the outer limit of the claim to be measured from a continuous 2,500metre isobath on the flank of the margin or will isolated closures of 2,500m lying further oceanward but within the continental margin be considered valid?

- What quality standards will be accepted by UNCLOS from identifying the position of the 2,500m isobath and the foot of the slope?

Data Types and Quality Requirement

Bathymetric data are required to define the 2,500 metres (m) isobath, a line connecting points at a depth of 2,500m. The isobath may be derived from single-traverse narrow beam soundings or multi–beam swath data. The level of accuracy is not specifically stated in Article 76, but with appropriate knowledge of the density structure of the water column depths can be determined to + or - 1% (+ or - 25m at 2,500m water depth). In practice the level of bathymetry accuracy is largely a function of navigational positioning, the slope of the seabed, knowledge of spatial and vertical variation in the velocity of sound in water and type of echo-sounder. In addition the quality of existing data is partly dependent on the historical methods of data reduction and presentation.

For the purpose of the Desktop Study it has been assumed that only bathymetric data derived from high-frequency echo-soundings and positioning by Transits Satellite or Global Positioning System will be of sufficient quality for a Legal Continental Shelf claim submission. Therefore bathymetric data obtained prior to satellite positioning systems may not be of acceptable standards. However, data of this nature may assist in supporting a submission, particularly in areas of complex margins.

Profiles of the seabed morphology are required to determine the base of the foot of the slope from which the 60M and the outermost line of 1% sediment thickness are measured. Depth accuracy is not critical to define the foot of the slope as it is only the shape of the bottom profile and the geological substrate that is important. Therefore the profiles may be derived from bathymetric echo-soundings or seismic reflection data. It is assumed here that satellite navigational positioning of the profiles may be required by the Commission.

Because of the uncertainties in how Article 76 will be interpreted by the Commission, guidelines published by the United Nations Legal Office **(UNCLOS**, *1996)* were used to identify areas where bathymetric or geophysical data need to be collected. For areas considered in the desktop study, targeted bathymetry together with both deep-penetration and shallow, high resolution seismic reflection profiles are required to substantiate New Zealand's claim. To determine sediment thickness seismic refraction data obtained using expendable sonobuoys are required. On all proposed seismic lines single-beam bathymetry data would also be acquired. Gravity and magnetic data would strongly support specific arguments for natural prolongation of the margin.

Seismic reflection profiles are the most efficient method to determine the thickness and distribution of sediment away from the foot of the slope and for identifying the outermost line of 1% sediment thickness with an accuracy sufficient to support a claim. Although no specific levels of accuracy of the velocity estimates are defined in Article 76, it is noted that sediment thickness calculated from multi-channel seismic stacking velocities are likely to be inaccurate by at least + or - 10%.

Existing Data Bases

For the purpose of the desktop study all existing bathymetric data and seismic reflection profiles available in the New Zealand area of potential legal continental shelf have been compiled and interpreted.

The Desktop Study has drawn on both national and international sources of marine survey data. Key data-sets utilised included those collected by the National Institute of Water and Atmospheric Research Ltd. **(NIWA**) and the Institute of Geological and Nuclear Sciences Ltd. **(IGNS**), the archives of the Hydrographic Office of the Royal New Zealand Navy **(RNZN**) and databases managed by the Crown Minerals Group of the Ministry of Commerce, the **GEBCO** and the **GEODAS** databases. Data from overseas sources such as the Australian Geological Survey Organisation, Hydrographic Office of the Royal Australian Navy, World Data Center, Boulder, Colorado, the **IHO's** Ocean Sounding Sheets and other existing paper charts were also investigated and were relevant.

Peer Review Panel

It was decided at the outset to have the desktop study reviewed by a Peer Review Panel of national and international experts in the fields of geology, geophysics, hydrography and maritime boundaries to ensure the study was robust and give added confidence to the conclusions and recommendations of the report. Specifically the Peer Review Panel were charged with providing:

- A critique of the assumptions of the Desktop Study team and its interpretation of **UNCLOS,** Article 76 .
- Recommendations on improvements or remedial actions to interpretations made by the study team
- A report assessing the findings and evaluations of the study team and,
- Liaison as necessary with other experts.

The comments of the Peer Review Panel were to be based on their understanding of the requirements for a successful claim submission to the **UNCLOS** Commission on the Limits of the Continental Shelf.

RESULTS

> The results of the study provided a series of reports on the existing data and implications for a claim submission. In addition to the reports, a database was developed which listed the details of survey information and a suite of charts was worked up showing the existing survey information and potential claim areas of a claim submission. Survey options were developed to provide the additional data required and from these options the cost of surveys could be estimated.

UNCLOS Database

A Microsoft Access database was developed to record the co-ordinates of foot of slope, 2,500m depth, or 1% sediment positions and details of the surveys these points or picks were gathered on.

(*Note: fields are listed as bold below. This list is the main one, there are other fields which are of an administrative nature e.g.* ***interpretation*** *by who and* ***date).***

Each point or pick is given a **unique identifier** and designated a **type** *(FOS, 1% sediment, 2,500m*). A record is made of whether the pick is **real or interpolated.** If the pick is interpolated the **error interval** is recorded. Position details of **latitude** and **longitude** are recorded as two fields in the database and the data source is recorded (i.e. descriptions of the **digital single beam echo sounder** or **digital swath** or **paper chart** or **raw paper profiles** or **seismics** are recorded as **five** fields with the appropriate accompanying information). A field of the **cruise or survey identity** is included along with fields for **ship, year, date of the data pick, time of data point used for the pick, line number** from the original survey, **shotpoint number** from data point used for pick, and **organisation** that collected the data. Fields are allocated for the recording **of navigation type, navigation instrument, bathymetry instrument, bathymetry beam width, bathymetry error;** yes/no codes are recorded for the following **bathymetry velocity correction** and **bathymetry motion correction.** For seismic data the following information is collected: **seismic sound source, seismic gun size, seismic array** and one field to indicate whether a **seismic sonobuoy** was deployed. In accordance with IHO classification of surveys (SP 44) the following fields were created for the recording of IHO survey classification codes: **IHO position, IHO sounding IHO fidelity, IHO data.**

Charts

A suite of four charts was developed for each of the GEBCO sheet areas over the New Zealand region. These charts were primarily designed to satisfy the following objectives:

Chart 1: Maximum Limiting Lines on the Outer Limits of the Legal Continental Shelf (*Ref: UNCLOS Article 76, para 5).*

This chart is essentially a collector sheet which shows 200M and 350M limits from the basepoints of the territorial sea for New Zealand and its neighbouring states along with the ship tracks and bathymetry for the 2,500m depth data.

Chart 2: The Outer edge of the Legal Continental Margin
(*Ref: UNCLOS Article 76, para 4)*

This chart is essentially a collector sheet which shows 200M and 350M limits from the basepoints of the territorial sea for New Zealand and its neighbouring states along with the ship tracks and foot of the slope points plus 60M buffers on ship tracks. Where there is uncertainty in the data quality or data gaps, both innermost FOS and outermost FOS positions are recorded.

Chart 3: Maximum claim of the New Zealand Legal Continental Shelf
(Ref: UNCLOS Article 76)

This chart attempts to identify the outermost and innermost positions of the 2,500m depth, the 100M buffer and the innermost and outermost limits of the 1% sediment thickness envelope and the innermost and outermost recorded foot of slope plus 60M buffer where this is known.

Chart 4: Survey options to delimit the New Zealand's UNCLOS claim.

The final chart in the series illustrates the New Zealand minimum and maximum potential claim of Legal Continental Shelf where delimited by:

- 200M distance
- 350M maximum limit.

- Maximum and minimum 2,500m depth points plus 100M buffered
- Maximum and minimum envelope of base of slope plus 1% sediment
- Maximum and minimum base(s) of slope plus 60M buffer
- identification of required additional survey areas for optimum surveys
- identification of required additional survey areas for minimum surveys
- identification of required tracks and recommended technique(s) on each track for optimum surveys
- identification of required tracks and recommended technique(s) on each track for minimum surveys

This chart depicts the envelope for possible maximum claim areas (*determined by outermost identified FOS, 1% sediment and 2,500m isobath*) and minimum claim areas (*determined by innermost limits of FOS, 1% sediment and 2,500m isobath).* Minimum survey requirements to substantiate the innermost limits of the claim area as above, were illustrated here along with optimum survey requirements to substantiate the outermost limits of the claim area.

Historic Data Compilation

Under the current desktop study all relevant historic information have been retrieved and evaluated for the purpose of identification of the additional marine surveys, for cruise planning and costing purposes However, this information as currently presented in the charts is insufficiently detailed to support New Zealand’s future Legal Continental Shelf claim submission.

REPORTS

The reports of the study were initially broken down into four regions of New Zealand’s continental shelf to help facilitate the review process.

Reviewers commented on each "*chapte*r" as it was completed, then a final review was carried out which included extensive questioning between the review panel and the technical project team at the end of the reporting process. These question sessions were invaluable to all concerned and provided a forum for discussion of interpretations and difficulties encountered during the study.

Final reports included discussion of the interpretation of Article 76 and assumptions made in formulating a survey programme along with general philosophy behind the interpretation of **UNCLOS.** Discussion of the historical data, its collection, density and distribution was included along with discussion of data compilation and synthesis for each of nine geologically distinct regions. Final reports also included an assessment of risks, benefits and priorities associated with the proposed survey programme.

MARINE SURVEYS

Having considered carefully identified data requirements, the various logistical options and the achievable cost effective efficiencies, a two-staged strategy for the marine surveys to obtain the needed information has been identified.

Marine Surveys Stage I: Deep Seismic Surveys

Stage 1 of the marine surveys would involve the acquisition of deep penetration seismic reflection data using a purpose built, industry standard seismic survey vessel. The seismic equipment would comprise a digital data acquisition system. Gravity and magnetic equipment should be available and positioning of the vessel would be by Global Positioning. The vessel should also be equipped with a deep sea single beam sounding system to IHO standards and have allowance for data collection along continuous profiles. It is envisaged that this survey will also obtain part of the additional required bathymetric, gravity and magnetic data, where this is cost effective. To collect the deep seismic information various options were considered including the use of a vessel on a commercial contract and a cost effective joint venture arrangement with a neighbouring coastal State.

Marine Surveys Stage 2: Bathymetric Surveys

The marine surveys of Stage 2 would involve the acquisition of further bathymetric data, shallow penetration seismic reflection profiles and gravity and magnetic information. For the single-beam surveys two New Zealand vessels and a foreign vessel were evaluated. Equipment requirements for the bathymetric surveys would, as a minimum, comprise one deep sea, continuous recording single-beam hydrographic sounder to IHO standards, a seismic system capable of imaging basement to a depth of at least two seconds two-way time, gravity and magnetic equipment and global positioning navigation. For optional swath equipment a minimum depth precision of + or - 1% over the full swath width will be required, in addition to the vessel specifications for the single-beam surveys.

Data Synthesis and Documentation of a Claim Submission

To finalise the delimitation work in the studied regions considerable data processing, compilation and presentation will be required concurrent with, and subsequent to, the proposed marine surveys.

1501

1502 CONCLUSIONS

The New Zealand Desktop Study was carried out prior to the finalisation of the *Technical and Scientific Guidelines* of the Commission on the limits of the Continental Shelf. Although there remain questions about valid interpretations of Article 76 the approach taken by New Zealand in the Desktop Study has resulted in the production of a database, reports and a suite of charts which, when combined with the additional new survey data, may satisfy the CLCS requirements for information in support of a claim submission.

The survey programme determined by the Desktop Study is a stand-alone programme, however, as progress is made, checks of the remaining programming requirements will be made against new data gathered for scientific and other marine exploration projects. This will ensure best use is made of all new marine survey data as it comes to hand. In this way it will be possible to ensure the UNCLOS survey programme is a lean one and selectively targets data requirements to satisfy UNCLOS criteria and formulae.

The only method for any country to truly delimit its maximum Legal Continental Shelf claim is a very expensive, complete data saturation approach, mapping the entire region with both swath imagery and a suite of high quality geophysical data **(seismic, gravity and magnetic**), acquired on closely spaced transects to support the sediment thickness or continental prolongation aspects of Article 76. However, it is believed that for most countries, including New Zealand, this saturation approach cannot be economically justified. The additional increase in claim area, over what can be achieved by carefully planned cost effective surveys targeted to meet the requirements of Article 76, is small and the increased expense is not warranted.

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SESSION 1 – Paper 4

RANGE OF SYSTEMATIC ERROR IN THE POSITIONING OF THE OUTER LIMIT OF THE CONTINENTAL SHELF AS DETERMINED FROM SEDIMENT THICKNESS

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ABSTRACT

In several places around the world the outer limit of the continental shelf may be established by geodetic points at which the sediment thickness below the seabed is at least 1% of the distance from such a point to the foot of the continental slope. In most of these cases 2D multi-channel seismic reflection data will be the only suitable data for the estimation and documentation of the sediment thickness. This involves the acquisition of such seismic data at the appropriate locations, careful processing, geological interpretation, and depth conversion of the seismic profiles. The geological interpretation and the depth conversion procedure will be the basis for the estimate of the thickness of the sediments. The two most critical factors are the definition of the base of the sediments (interpretation of the top of the basement) and the quality of the velocity model for the conversion of two-way travel time to depth in meters. In areas lacking well data the depth conversion will depend on stacking velocities for the determination of root mean square velocities and Dix interval velocities in the velocity model. In such cases the velocity model will always deviate from the real propagation velocities of the subsurface, leading to an error in the estimated thickness. From an analysis of geometric relationships it is possible to show that the range of error in estimated sediment thickness translates into a systematic range of error in the horizontal positioning of the corresponding fixed boundary point. This horizontal position error, $\pm \Delta X$, is a function of the range of error of the estimated sediment thickness, $\pm \Delta Y$, the dip of the basement, and the dip of the seabed.

The United Nations Convention on the Law of the Sea of 10 December 1982 (UNCLOS) entered into force on the 16 November 1994 following the ratification of the Convention by Guyana a year before, as the sixtieth state to ratify. After the adoption of Agreement Relating to the Implementation of Part XI of UNCLOS on 28 July 1994 the number of ratifications greatly increased, and UNCLOS is now de facto becoming part of international law. Article 76 in Part VI of UNCLOS defines the term Continental Shelf and lays down the regulations for how to determine the outer limit of that shelf (United Nations 1997). According to one of these regulations, the outer limit of the Continental Shelf may be placed along fixed points where the sediment thickness below the seabed is 1% of the shortest distance from each of those points to the foot of the continental slope (“the sediment thickness rule”). Alternatively, the outer limit may be placed along fixed points at a maximum of 60 nautical miles (M) from the foot of the continental slope (“the 60 M rule”). In those areas of the world oceans where the sediment thickness at 60 M from the foot of the slope is more than 1111 meters (i.e more than 1% of 60 M), “the sediment thickness rule” is more favourable for the coastal state than “the 60 M rule”. Sediment thicknesses of this order in this setting are mainly found outside the mouth of major rivers and around the locations of major Late Tertiary to recent glaciations. In the classical morphological model of a continental margin, these sediments constitute the continental rise. However, the classical rise is missing in many parts of the world oceans, even in places of substantial sediment thickness adjacent to the foot of the continental slope.

In most parts of the world, the seabed seaward of the foot of the continental slope is at water depths of more than 2500 – 3000 meters. In this setting 2D multi-channel seismic reflection data will be the most practical (and least expensive) data for the estimation and documentation of the sediment thickness. This involves the acquisition of such seismic data at the appropriate locations, careful processing, geological interpretation, and depth conversion of the seismic profiles. The geological interpretation and the depth conversion procedure will be the basis for the estimate of the thickness of the sediments. The two most critical factors in this process are the definition of the base of the sediments and the quality of the velocity model for the conversion of two-way travel time to depth in meters.

The sediment thickness is defined as the vertical distance from the top surface of the sediments (i.e. the seabed) to the basal surface of the sedimentary succession (i.e. the top of the crystalline basement rocks) (United Nations 1999). In general, in most of the relevant cases, the sediments rest on a basement of crystalline magmatic rocks formed by the sea-floor spreading process (Fig. 1). The velocity contrast between these hard and dense crystalline rocks and the overlying soft and less dense sediments usually give rise to a very prominent seismic reflector. This reflector is further easy to identify as it separates the well defined succession of sub-horizontal reflectors of the bedded sedimentary succession from the non-bedded, noisy, and chaotic seismic signature of the basement. Hence, interpreting the top of the basement, though commonly being uneven and rugged, usually presents no problem to an experienced interpreter.

When the interpretation of the top of the basement in the seismic profiles is completed, the problem is to determine realistic velocities to convert the recorded normal incidence two-way travel time between the seabed reflector and the basement reflector into depth in meters. This is usually done by subdividing the sedimentary succession into a suitable sequence of intervals (representing sedimentary beds) bounded by the main bedding reflectors, and then assigning an interval velocity to each interval (Fig. 2). Multiplying the travel time in each interval with the corresponding interval velocity then converts the two-way travel time section (Fig.2) into a depth section (Fig. 3). For the purpose of the “sediment thickness rule” it suffices to concentrate on the area around the spot where the thickness is 1% of the distance to the foot of the slope.

Determining the best interval velocities is the heart of the game of depth conversion, which since the 1950-ies has become a professional discipline all by itself. In-depth treatment of this discipline is far beyond the scope of the present paper, and the reader is referred to more specialised literature (e.g. Dix 1955, Hubral and Krey 1980, Cordier 1985, and Al-Chalabi 1974, 1979, 1997). The fundamental basis for the discipline is the multi-channel technique that enables the recording of a set of multiple reflection signals from each reflector in the subsurface. The basic principle is that, in processing the data, summing up (“stacking”) the energy of each of the individual reflection signals from the same reflector suppresses the random noise, thus enhancing the “real” signal. Since there is a time lag between each successive recorder channel in the recording of the signals from the same reflector, the signals have to be “time corrected” prior to being summed. The correction is done by a common factor found by iteration. This factor has the dimensions of a velocity and is termed “the stacking velocity”. The only case in which the stacking velocity equals the real, physical sound propagation velocity, is the case of one single reflector at the base of one layer of constant velocity. In all other cases the stacking velocities deviate from the real velocities. None the less, the stacking velocities are the sole basis for all depth conversion of seismic signals in the absence of velocity logs from drill holes. In short, the best way to do this is to calculate the root mean square Dix interval velocity from the stacking velocities, and to substitute the interval velocities in the model with these Dix interval velocities (Fig. 2). How close the stacking velocities approximate the root mean square velocities vary greatly with the physical conditions at the location of the survey. The stacking velocities approximate the root mean square velocities at its best when (Al-Chalabi 1979, Hajnal and Sereda 1981, Cordier 1985):

1. The bedding in the section of interest is sub-horizontal
2. The depth to offset ratio is large
3. The interval thickness to depth ratio is large
4. The velocity contrast between major layers is small
5. The average velocity in the section of interest does not change significantly with depth
6. The stacking velocities are calculated from the near traces
7. Multiples are excluded

All these conditions, except 3 and 6, are normally fulfilled in the relevant areas at the outer edge of continental margins because of the great water depths and stable conditions for sediment accumulation. Conditions 3 and 6 is a matter of subjective judgement and choice.

This means that, in the areas of interest, all conditions are in favour of fairly accurate velocity models. One should therefore expect that the error in these cases to be much less than the usually loosely quoted error bar of ±10 – 15 % on substituting stacking velocities for root mean square velocities. If possible this should be checked against the velocity log from nearest drill hole penetrating the equivalent sediment section.

The best approximation of the interval velocities is, however, achieved by determining the root mean square velocities at zero offset from the stacking velocities by calculation and extrapolation (Al-Chalabi 1974, Cordier 1985). This involves new stacking velocity analysis and may be a very time consuming exercise, if at all feasible.

The velocity model of Fig. 2 was made by calculating the Dix interval velocities directly from the corresponding stacking velocities, and then substituting these Dix interval velocities for the real interval velocities. There are no nearby well data available for calibration at present. However, a comparison of stacking velocities from different seismic surveys against log data of a well through the time equivalent sediment section 650 km to the south (but still in the same regional setting of the continental margin), indicate that the error in average velocity and calculated depth may be less than ±1% (Fig. 4). For the sake of illustration, the velocity model in Fig. 2 is then assigned a range of error of ±1%. This is later compared with the effects of the general, loosely quoted range of error of ±10%.

In the present case the position where the sediment thickness is 1% of the distance back to the foot of the slope is found to be located in the outermost half-graben (Fig. 1) at the distance of 214.214 km, corresponding to a sediment thickness of 2142 meters (Fig.3). To calculate the translation of the ±1 % error in vertical thickness, corresponding to ±21 meters, into a range of systematic error in the horizontal position of the 1% thickness location (i.e. the final boundary point in map view), a geometric function is needed. In the following, the formula of such a function is developed.

The starting point is the simple case where the top of the basement is horizontal and the seabed dips away from the foot of the slope by the angle α (Fig.5). From the horizontal top basement line at the position of the foot of the slope a line of 1 % slope is constructed. This is the line defining the vertical sediment thickness of 1 % of the distance from the foot of the slope, and has an angle β with the top of the basement. The location of the point where the sediment thickness, Y, is 1 % of the distance, X, from the foot of the slope is at the crossing between the 1 % line and the seabed (Fig. 5). A close-up of the area around this crossing point is needed to illustrate the relationship between the range of error of the vertical sediment thickness, $\pm\Delta Y$, and the corresponding horizontal location error, $\pm\Delta X$ (Fig. 6). Graphically, the error bar, $\pm\Delta Y$, is equivalent to moving the line of the seabed (i.e. the top of the sediment succession) up and down the amount $\pm\Delta Y$. By this hypothetical action, the crossing point will move obliquely up and down the 1 % line, and thus generating the horizontal error bar, $\pm\Delta X$ (Fig.6). It can be demonstrated that the horizontal error, $\pm\Delta X$, can be expressed in terms of the sediment thickness error, $\pm\Delta Y$, and the slopes of the seabed and the 1 % line ($\tan\alpha$ and $\tan\beta$, respectively) (Fig. 6):

1) $$\pm \Delta X = \frac{\pm \Delta Y}{\tan \beta + \tan \alpha}$$

Now consider the more common case where the top of the basement has an angle of dip, θ, with the horizontal. It is assumed that in the general case the basement dips towards the foot of the slope (Fig. 7). The proposed graphical solution to this is to keep the distance X, the vertical sediment thickness Y, and the position of the crossing between the seabed and the 1 % line, all fixed. This implies drawing a circle with the radius X and with centre at the distance X along the horizontal from the foot of the slope (Fig. 7).

It can be seen that, as the angle θ increases, the angle β diminishes until it becomes zero as θ becomes 90 (Fig. 7).

Again, a close-up of the area around the crossing points is needed to illustrate the details of the relationship between the different surface dips and the vertical and horizontal error bars (Fig. 8). It is evident that the only difference from the simple case (Fig. 6) is that the dip angle of the basement, θ, is added in the slope of the 1 % line (Fig. 8):

2) $$\pm \Delta X = \frac{\pm \Delta Y}{\tan(\beta + \theta) + \tan \alpha}$$

To be a practical formula, the angle β must be expressed in terms of the angle of dip of the basement, θ (the "rotation angle"). This is achieved by finding expressions for all the angles in the essential triangles of the relationship construction (Fig. 9). It is seen that β is a simple function of the dip of the basement, θ :

3) $$\beta = \operatorname{Arctan}\left[\frac{\tan\beta_0 \cos\theta}{1 + \tan\beta_0 \sin\theta}\right]$$

Where β_0 is the angle of slope of the 1 % line at the "starting position" of a horizontal basement (i.e. θ equals zero). In this position the slope of this line, $\tan\beta_0$, is of course 0.01, which corresponds to the vertical sediment thickness cut-off of 1 % of the distance from the foot of the slope, which is the requirement stated in UNCLOS (see Fig. 5).

Substituting equation 3) into equation 2) gives the final formula:

4) $$\pm \Delta X = \frac{\pm \Delta Y}{\tan\left[\operatorname{Arctan}\left[\frac{\tan\beta_0 \cos\theta}{1 + \tan\beta_0 \sin\theta}\right] + \theta\right] + \tan\alpha}$$

From 4) it is evident that the horizontal position error, $\pm \Delta X$, is a function of the range of error of the sediment thickness determination, $\pm \Delta Y$, the sediment thickness cut-off criteria, $\tan\beta_0$, the dip of the basement *towards* the foot of the slope, θ, and the dip of the seabed *away* from the foot of the slope, α:

5) $$\pm \Delta X = f(\pm \Delta Y, \beta_0, \theta, \alpha)$$

Now consider a case where the sediment thickness at 60 M from the foot of the slope is estimated to be 1111 meters, and the range of error of that estimate is set to be the "usual" ±10%. It is evident that for small values of α and/or θ (gentle dips of seabed and/or basement) the horizontal position error becomes very large (Figs. 10 and 11). At gentle dips of the seabed and basement dips of less than 5°, small changes in the dip angle of the basement has dramatic effects on the range of error in the horizontal boundary position (Fig. 10). Likewise, small changes in the dip of the seabed has great effects at seabed dips of less than 0.1°, and gets increasingly critical with an increasing dip towards the foot of the slope (i.e. turning to a negative dip angle). The error reaches infinity at the asymptotic dip, i.e. when the seabed becomes parallel to the 1% line. For a horizontal basement this asymptotic seabed dip angle corresponds to a slope of - 0.01 (β_0 in Fig. 5).

In order to implement 4) one has to determine both the dip of the seabed and the dip of the basement in the area around the location where the sediment thickness is estimated to be 1 % of the distance to the foot of the slope. The range of error of that thickness estimate is also required. In our example the thickness estimate is assigned a range of error of ±1%, corresponding to ±21 meters (Fig. 3). The depth-converted section (Fig. 3) is also used to calculate the dip of the seabed and the dip of the basement in the same area. The seabed was found to have a very gentle dip of 0.104° towards the foot of the slope, which corresponds to a negative dip angle of α = - 0.104°. The dip of the basement within a reasonable "window" around the exact location of the calculated thickness of 1 % of the distance, was calculated to be 5.87° towards the foot of the slope (i.e. a positive angle). By implementing equation 4), this gives a range of error in the horizontal position, ΔX, of ±189 meters. It may be noted that the error, ΔX, is very moderate because the magnitude of the positive dip angle of the basement by far outweighs the negative dip angle of the seabed. Fortunately, the dip of both the seabed and the basement may be regarded as constant within such a short-range window (see Fig. 3). In cases where the range of error is considerably larger, the basement dips may vary significantly within that "error window". In some cases this may have to be taken into consideration in the estimation of the final error bar. How this may be done, will depend on the actual case.

It is also evident that there is a range of error inherent in the calculation of the dip of the seabed and the dip of the top of the basement. This stems both from the depth conversion and minor irregularities in the relevant surfaces. This error is expected to very small in absolute values, but at small angles even minute error bars may translate into very large values of ΔX (see Figs. 10 and 11).

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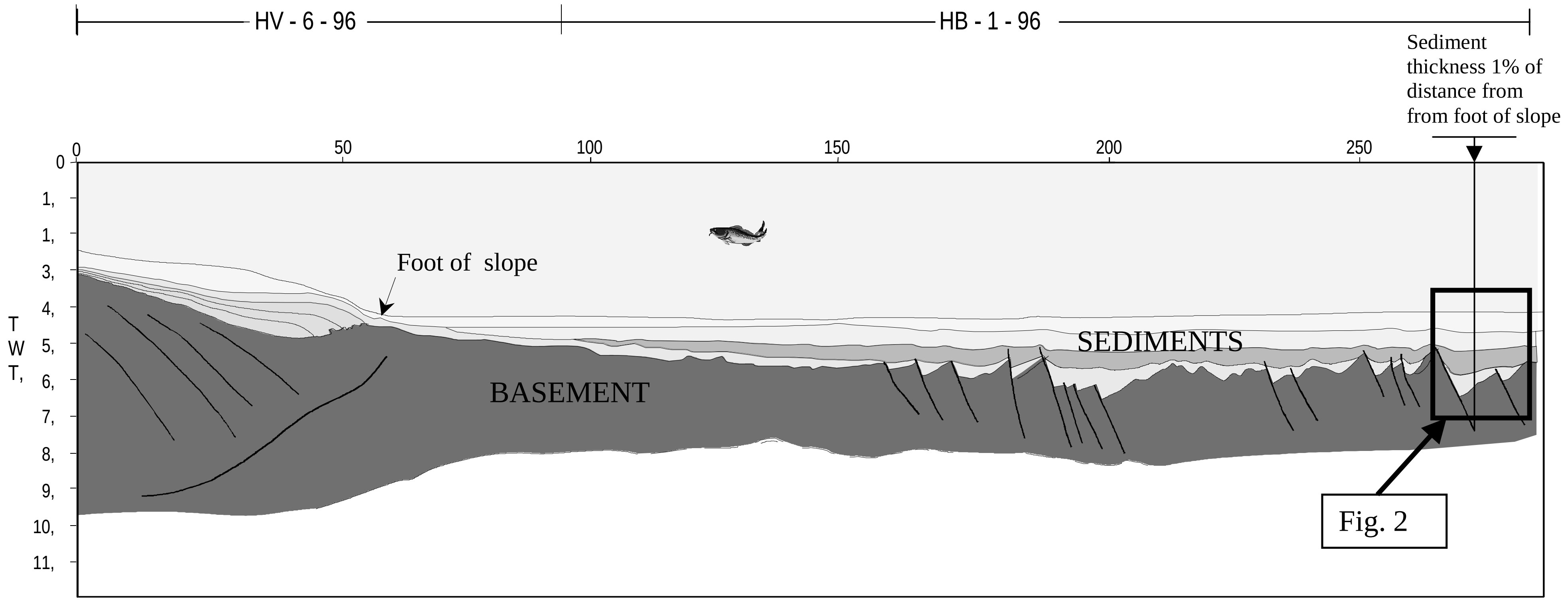


Fig. 1. Interpretation of seismic profiles HV-6-96 and HB-1-96 from the Norwegian Sea Continental Margin. The profile lies entirely within the 200 nautical miles zone of Norway and is chosen for illustration purposes only. It has consequently no bearing on the delimitation of the Norwegian continental shelf beyond 200 nautical miles.

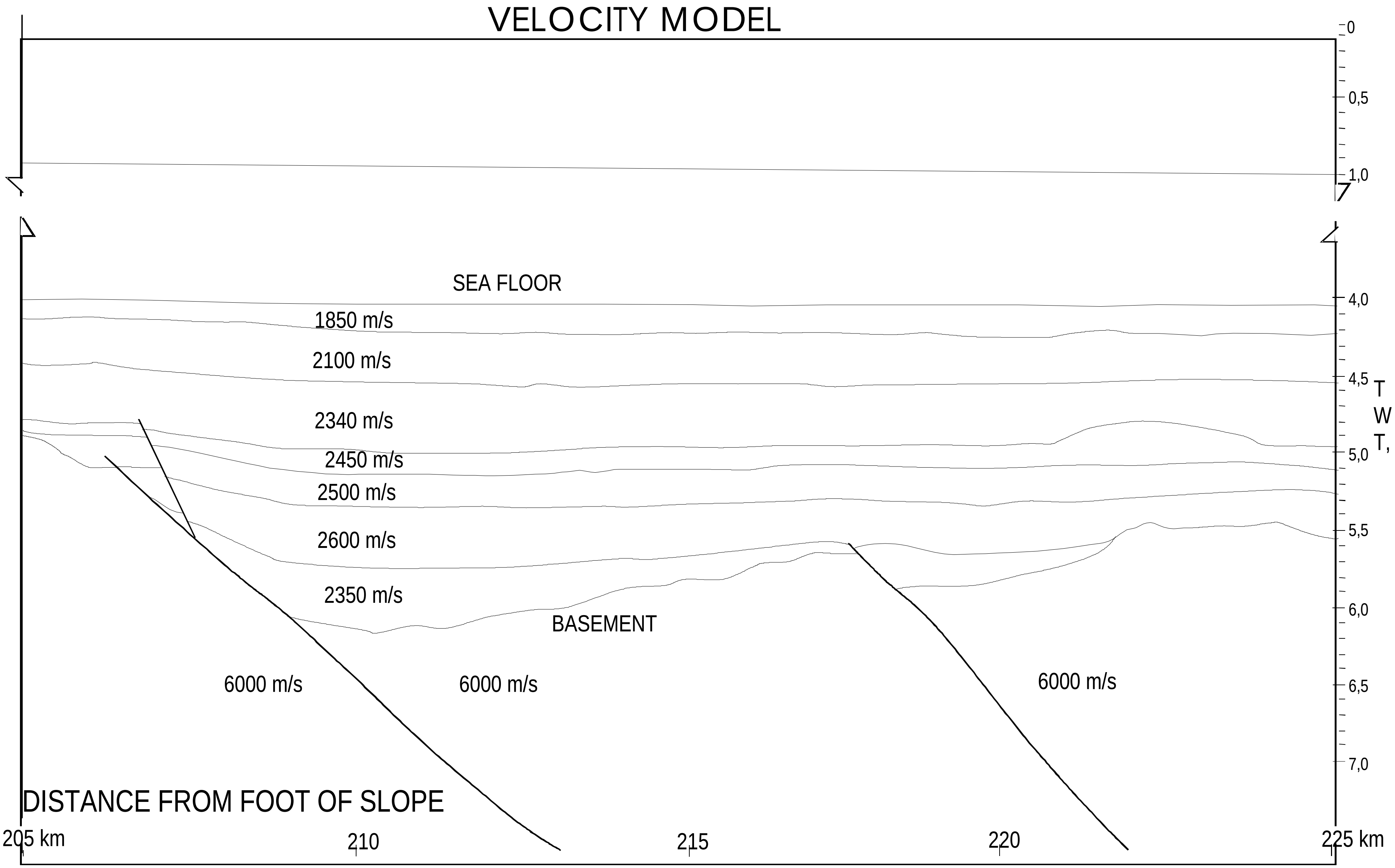


Fig. 2. Detailed interpretation of outermost half-graben of profile in Fig.1. Interval velocities are Dix interval velocities calculated from stacking velocities substituted for root mean square velocities. See Fig. 1 for location.

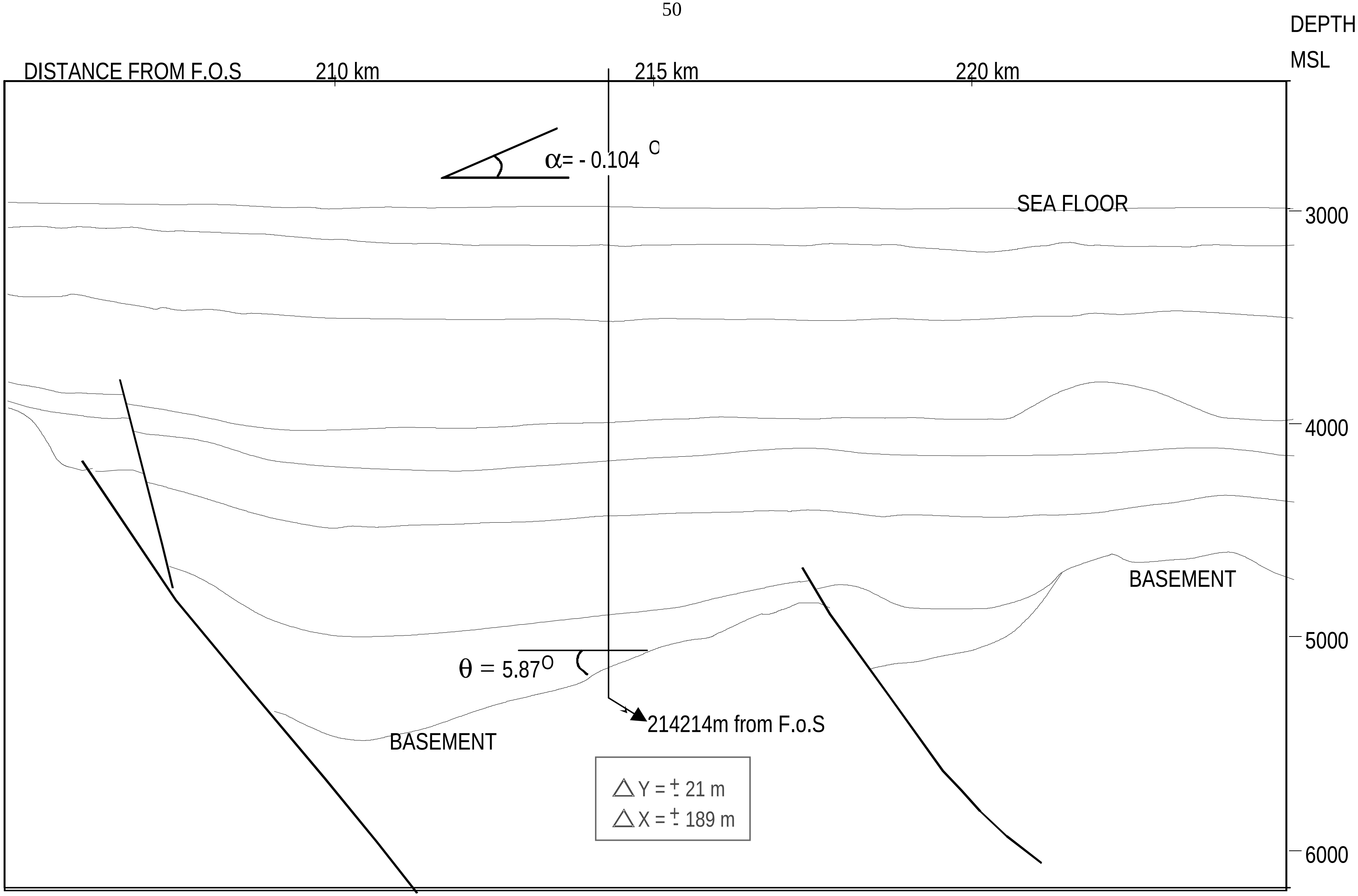


Fig. 3. Interpreted profile of Fig. 2 converted to depth. Sediment thickness 1 % of distance to foot of slope found at distance 214.214 km. α and θ are angle of dip of seabed and top of basement, respectively. See text for discussion.

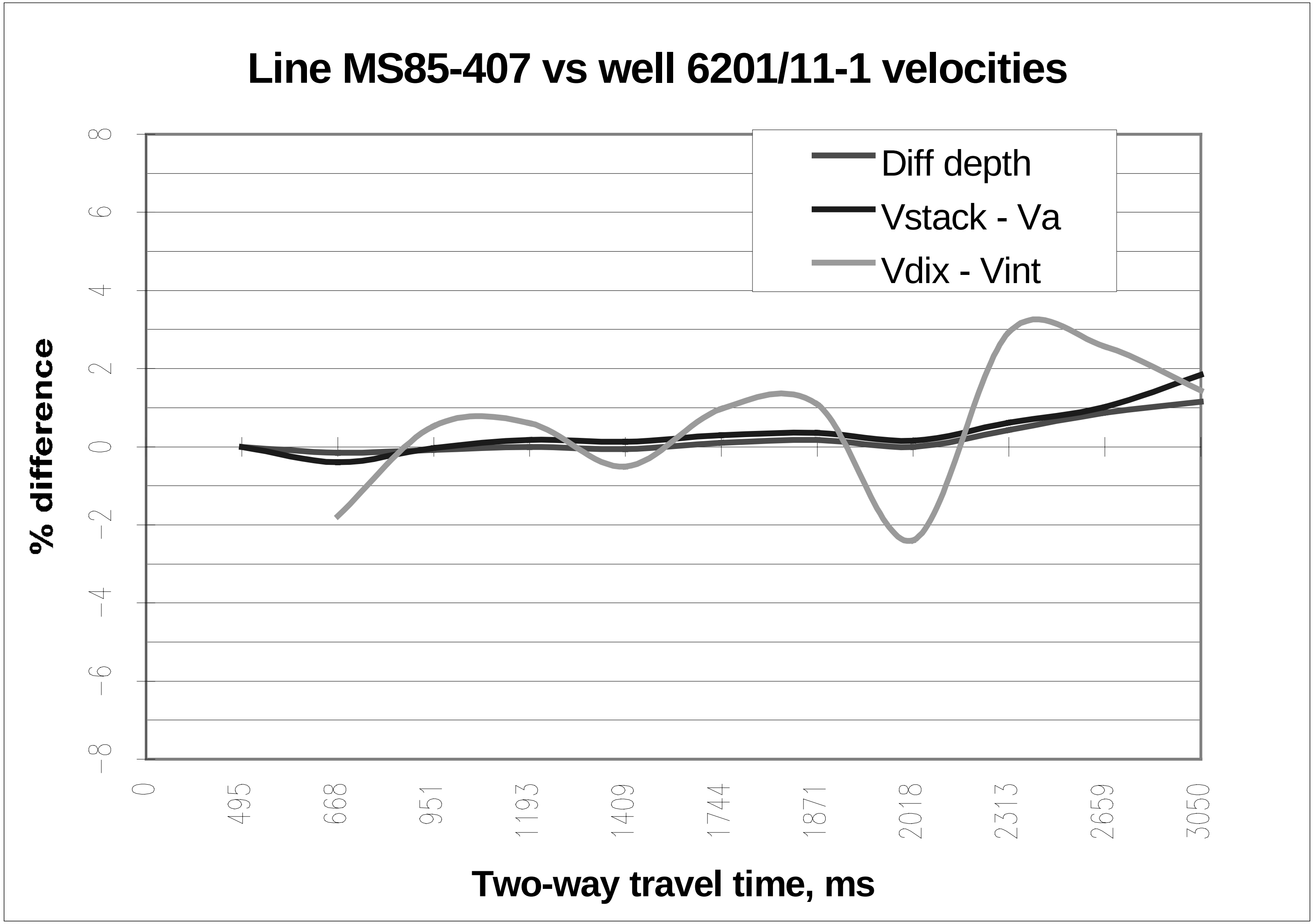
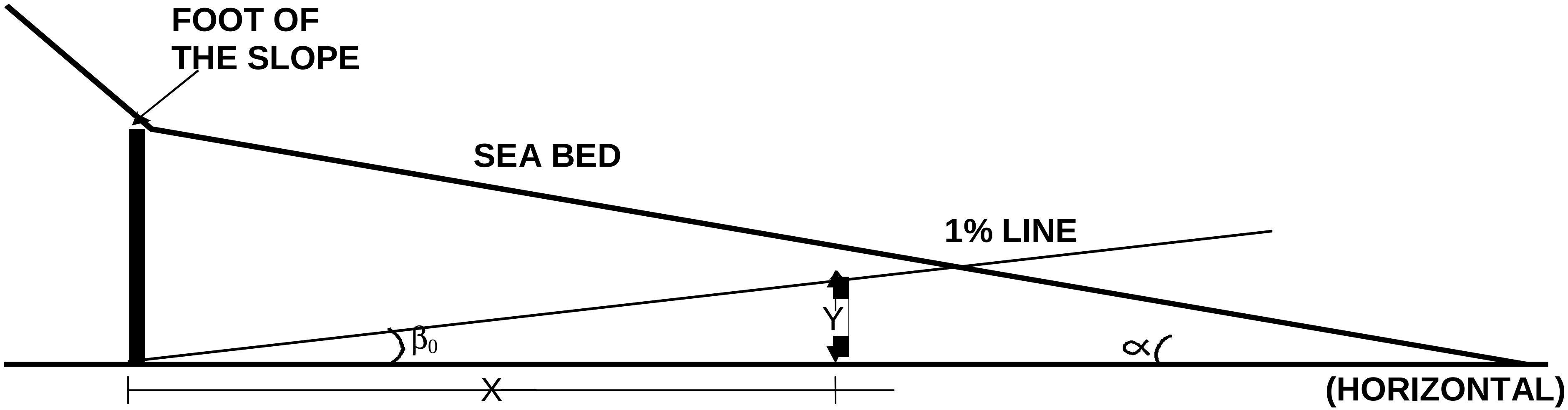


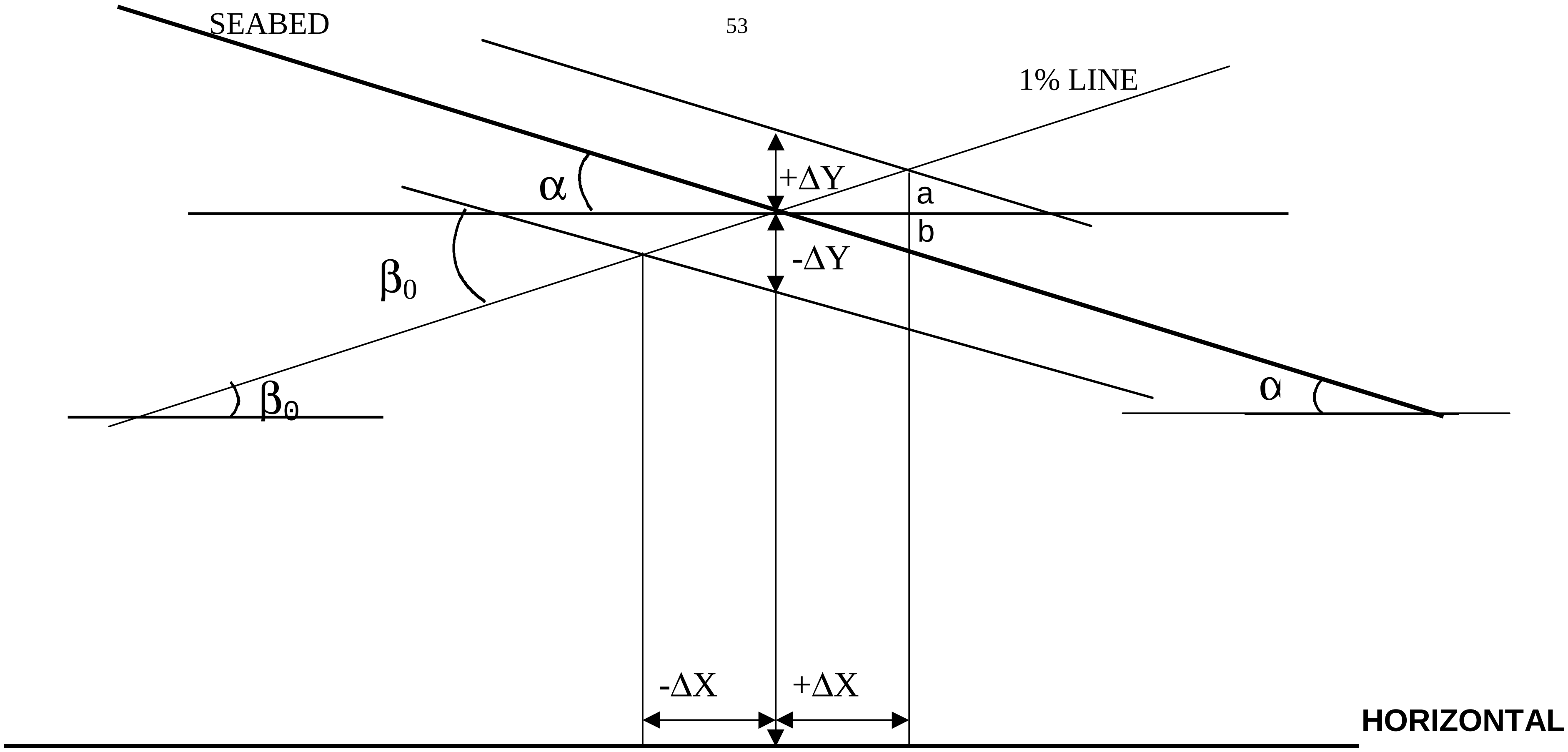
Fig.4. Comparison of velocity log data from Norwegian well 6201/11and stacking velocities of the crossing seismic line MS85-407. “Diff depth” is the difference between the depth calculated from Dix interval velocities based on stacking velocities, and the depth as measured in the well. Vstack - Va is the difference between the stacking velocities and the average velocities as measured in the well. Vdix - Vint is the difference between the Dix interval velocities based on stacking velocities, and the corresponding interval velocities as measured in the well.



$$Y = 0.01X$$

$$\tan \beta_0 = \frac{Y}{X} = \frac{0.01X}{X} = 0.01$$

Fig.5. The determination of the location of the point where the sediment thickness, Y, is 1 % of the distance, X, to the foot of the slope. α is the dip of the seabed away from the foot of the slope. β_0 is the angle between the horizontal basement surface and the line defining the vertical height being 1 % of the distance back to the starting point at the foot of the slope.



$\Delta Y = a + b$

$\tan\beta_0 = \dfrac{a}{\Delta} \longrightarrow a = \Delta X \tan \beta_0$

$\tan\alpha = \dfrac{b}{\Delta} \longrightarrow b = \Delta X$

$\Delta Y = a+b = \Delta X \tan \beta_0 + \Delta X \tan\alpha$

$\Delta Y = \Delta X(\tan \beta_0 + \tan\alpha)$

$$\boxed{\Delta X = \dfrac{\Delta}{\tan \beta_0 + \tan\alpha}}$$

Fig.6. Relationship between vertical sediment thickness error, ΔY, and horizontal position error, ΔX, in the case of a horizontal basement surface.

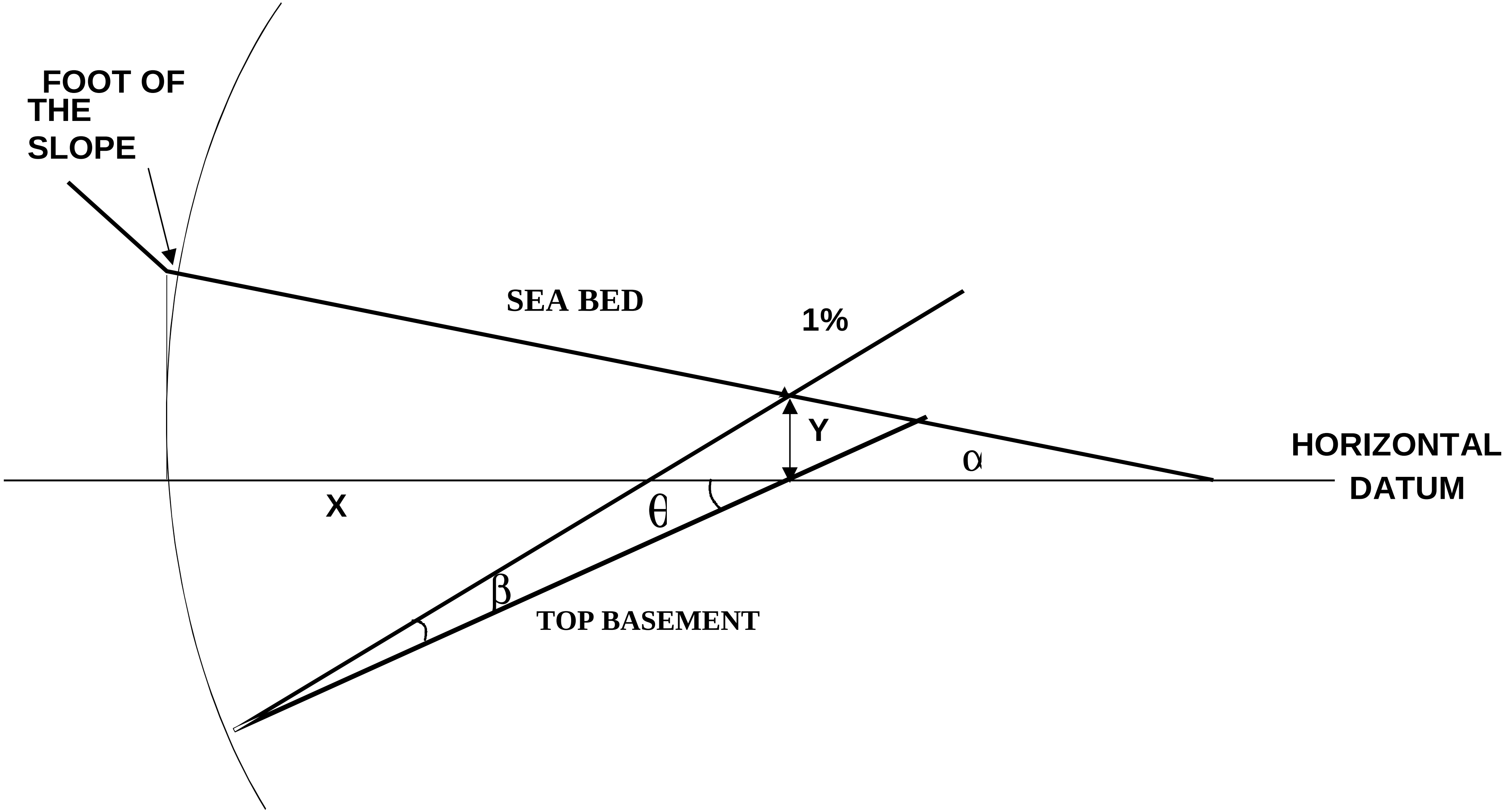
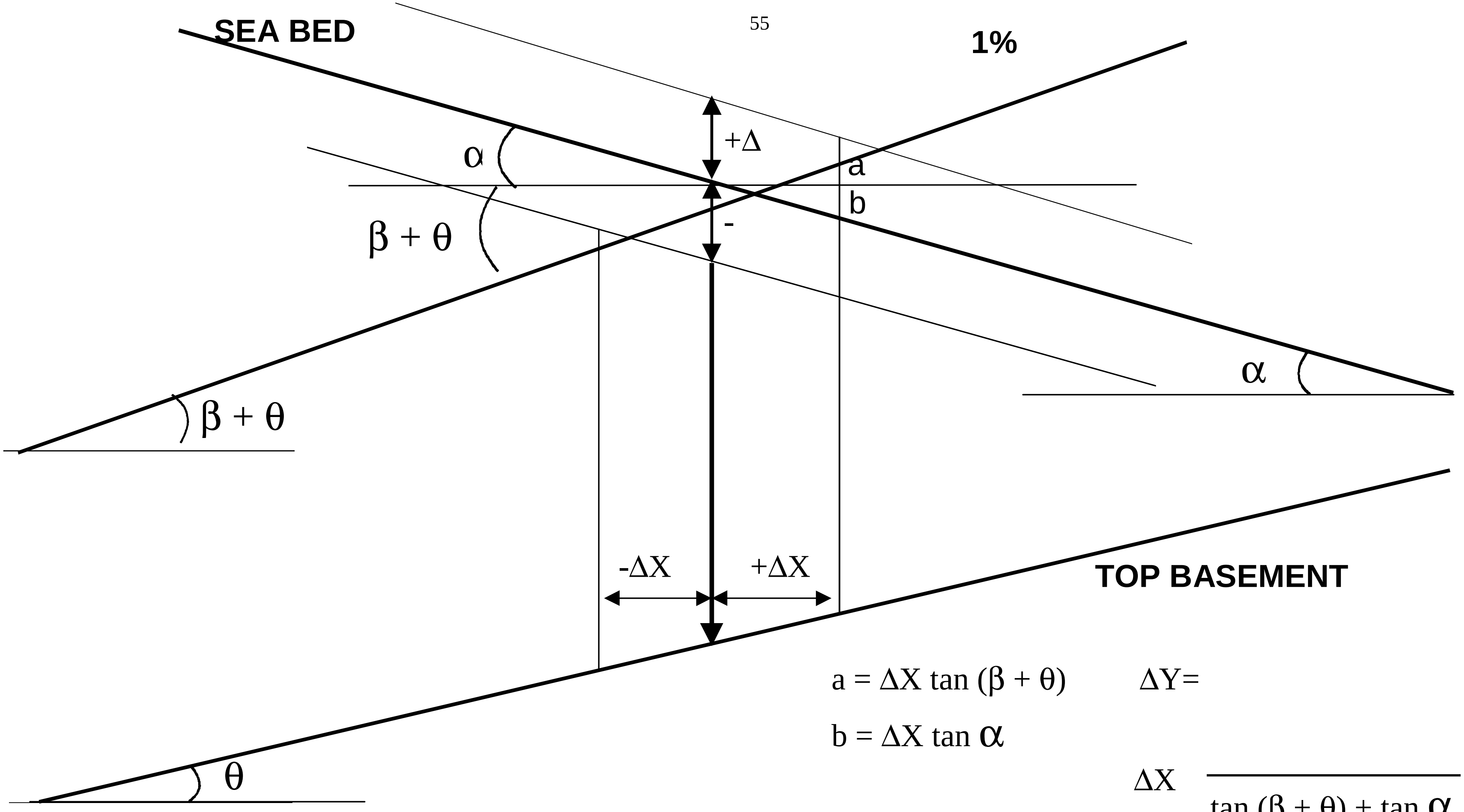


Fig. 7. The general situation where top of the basement dips towards the foot of the slope by the angle θ, and the seabed dips away from the foot of the slope by the angle α. In the construction the distance X back to the foot of the slope and the corresponding 1 % sediment thickness, Y, is kept constant in magnitude and position . The crossing point between the 1% line and the top basement line hence lie on a circle with the radius X and the centre at the the distance X from the foot of the slope as measured along the horizontal.

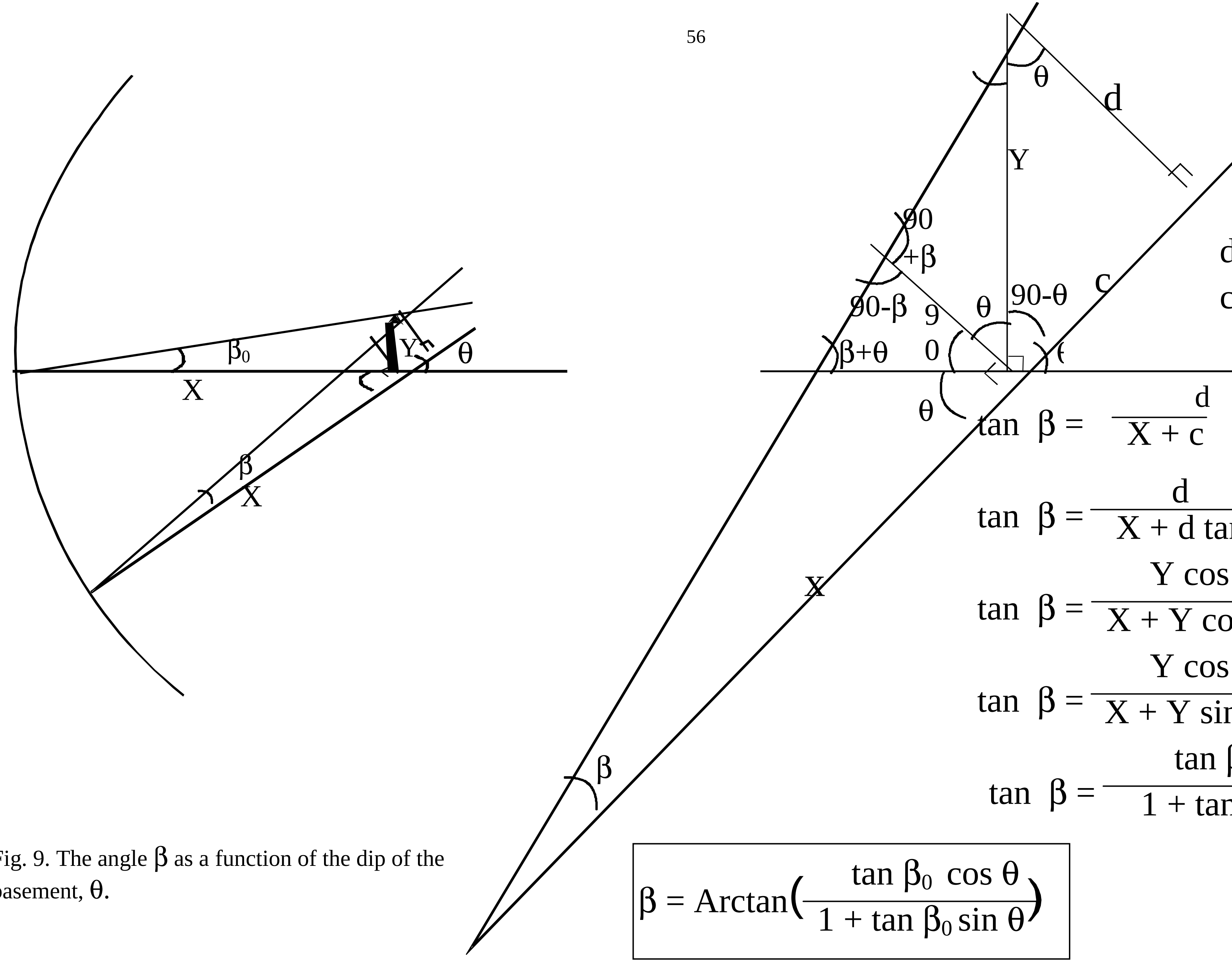


$$a = \Delta X \tan(\beta + \theta)$$

$$b = \Delta X \tan \alpha$$

$$\Delta Y = \frac{\Delta X}{\tan(\beta + \theta) + \tan \alpha}$$

Fig.8. Relationship between vertical sediment thickness error, ΔY, and horizontal position error, ΔX, in the case of a dipping basement surface.



$$d = Y \cos \theta$$

$$c = d \tan \theta$$

$$\tan \beta = \frac{d}{X + c}$$

$$\tan \beta = \frac{d}{X + d \tan \theta}$$

$$\tan \beta = \frac{Y \cos \theta}{X + Y \cos \theta \tan \theta}$$

$$\tan \beta = \frac{Y \cos \theta}{X + Y \sin \theta}$$

$$\tan \beta = \frac{\tan \beta_0 \cos \theta}{1 + \tan \beta_0 \sin \theta}$$

Fig. 9. The angle β as a function of the dip of the basement, θ.

$$\boxed{\beta = \text{Arctan}\left(\frac{\tan \beta_0 \cos \theta}{1 + \tan \beta_0 \sin \theta}\right)}$$

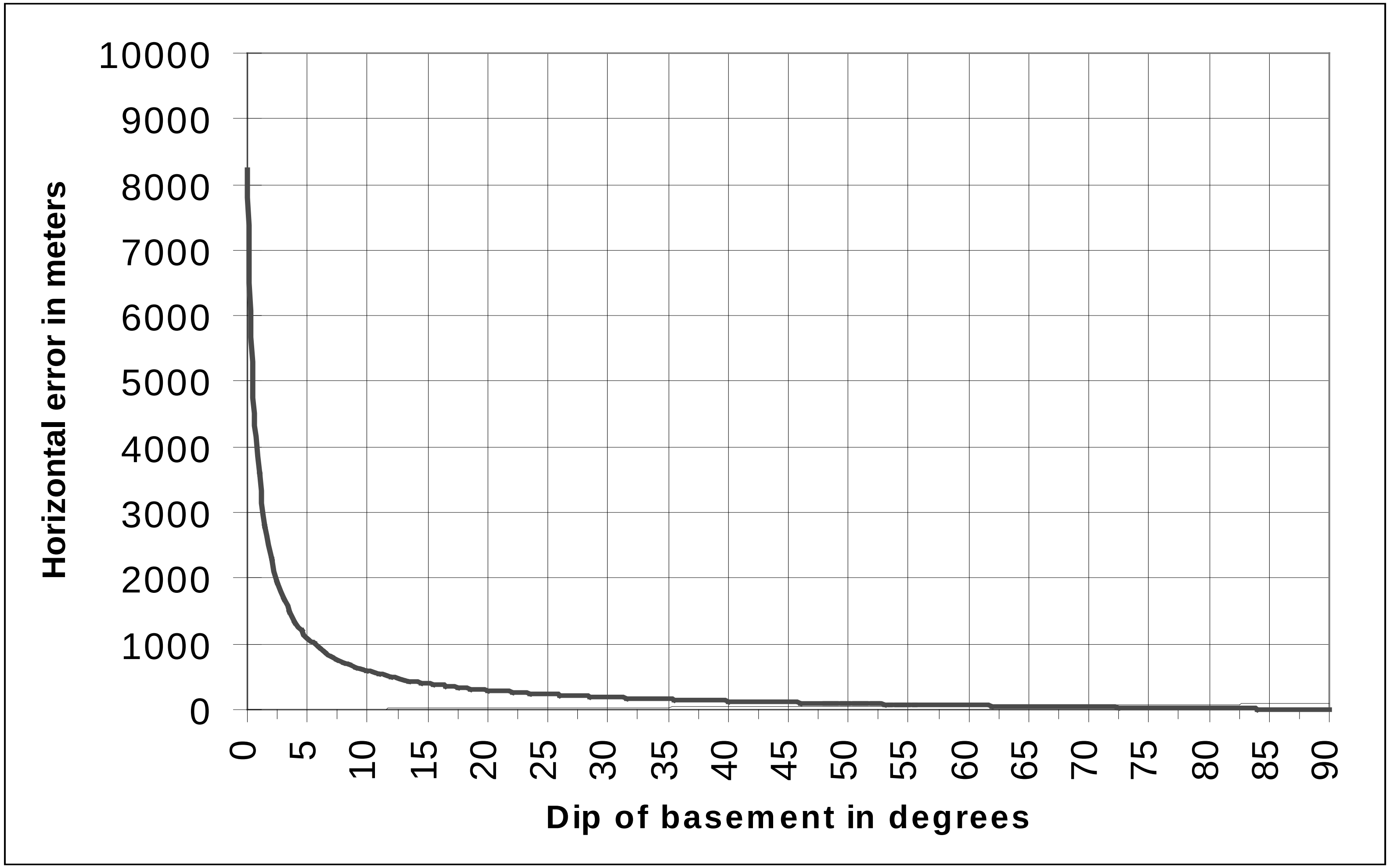


Fig. 10. Error in position of boundary for varying dip of basement at 0.2 degrees dip of seabed away from foot of the slope and 111 meters error in sediment thickness.

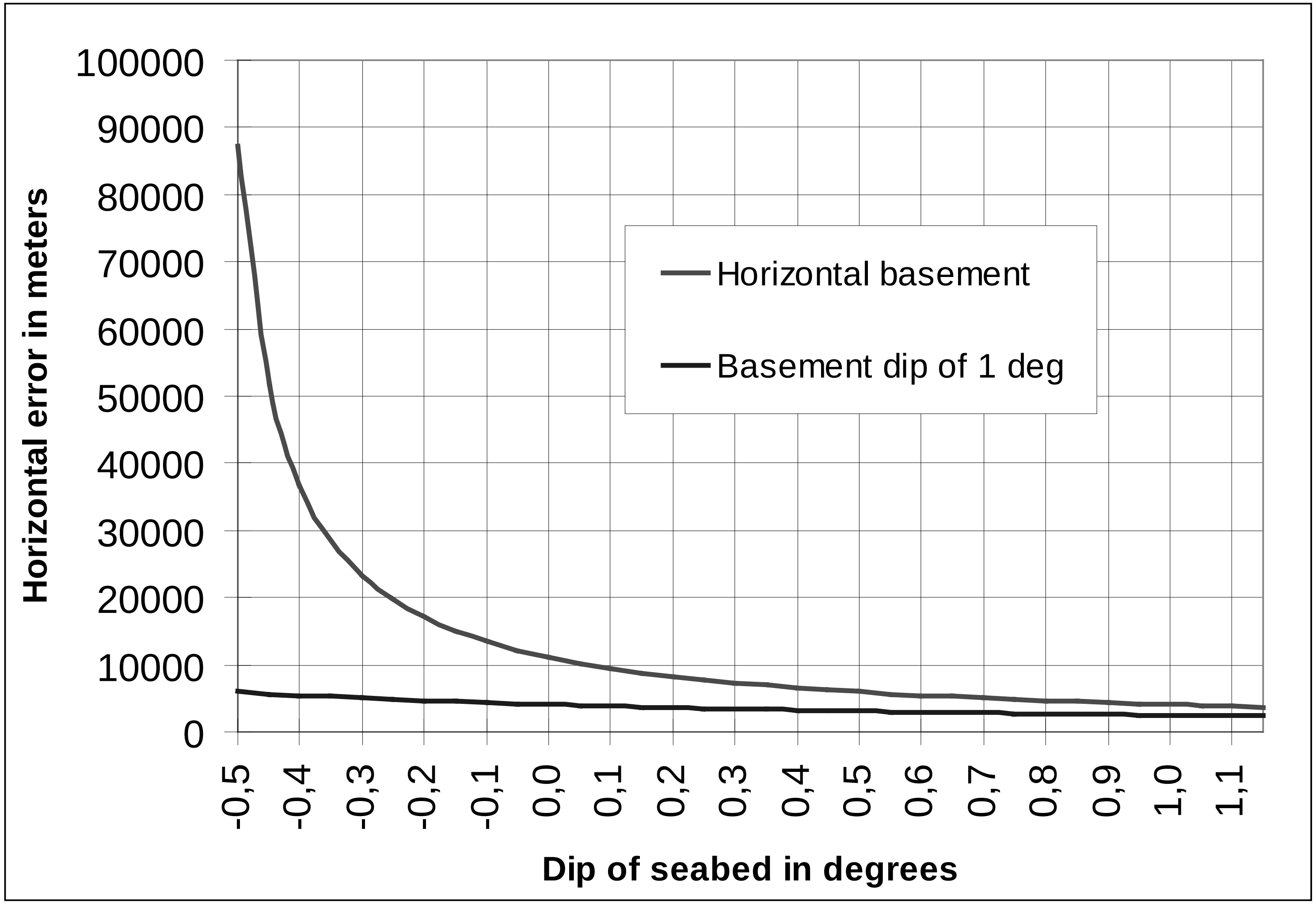


Fig. 11. Error in position of boundary for varying dip of seabed following from 111 meters error in sediment thickness

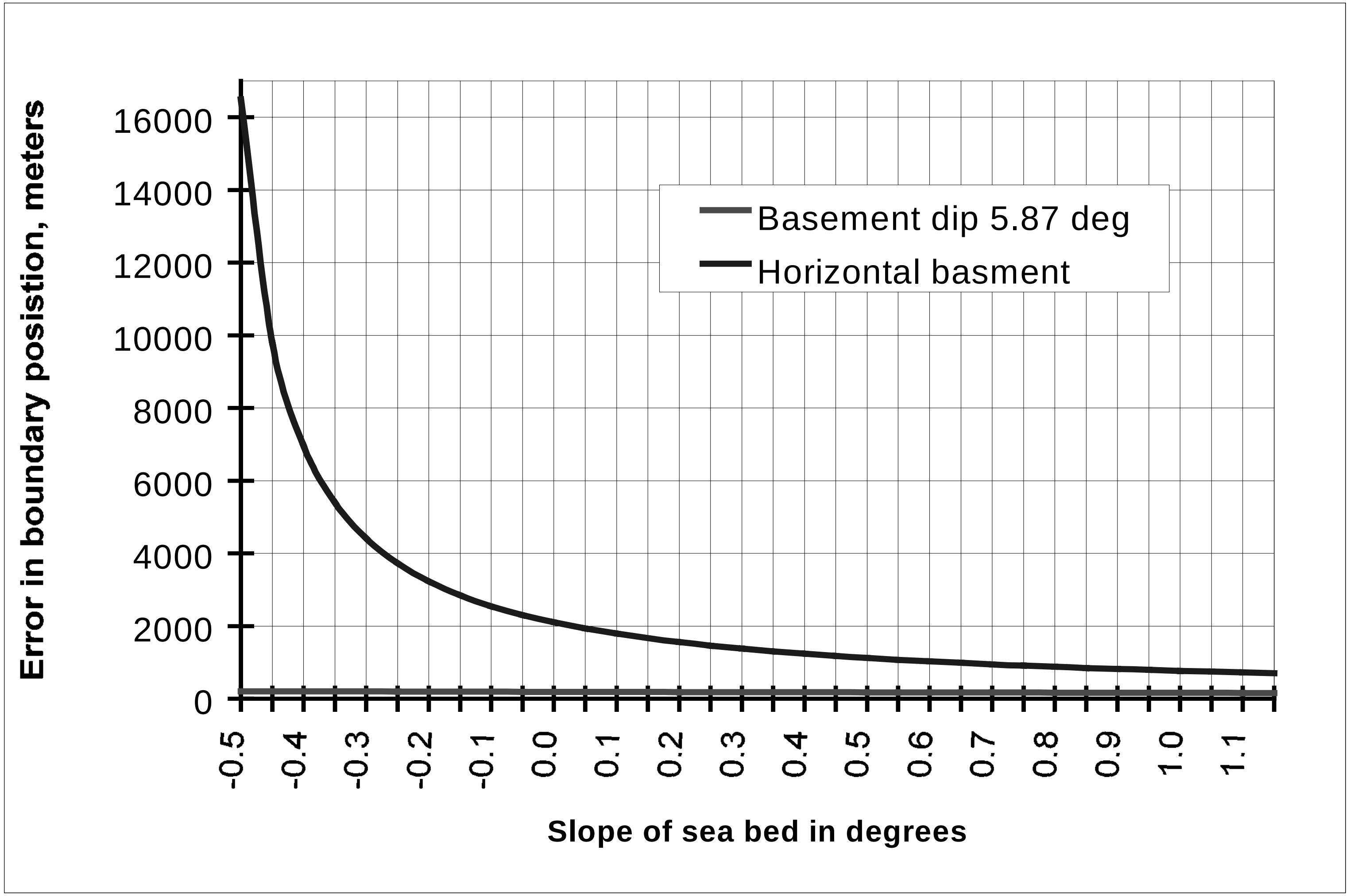


Fig. 12. Error in position of boundary following 21 m error in thickness in the model of Fig. 3.

SESSION 1 – Paper 5

WIDE CONTINENTAL MARGINS OF THE WORLD:

A SURVEY OF MARINE SCIENTIFIC REQUIREMENTS POSED BY THE IMPLEMENTATION OF ARTICLE 76 OF THE UNITED NATIONS CONVENTION ON THE LAW OF THE SEA

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ABSTRACT

The full implementation of article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) poses one of the most significant scientific challenges in the fields of geodesy, geology, geophysics and hydrography during the next decade. These challenges stem from the collection, compilation, and processing of vast amounts of marine data to be presented to the Commission on the Limits of the Continental Shelf as evidence in support of continental shelf claims to national jurisdiction extended beyond 200 M.

This paper outlines the scientific challenges confronted by coastal States to implement the provisions contained in article 76 and their geographic scope. These tasks are compounded by the needs to develop the most accurate and economic scientific methodologies, and to ensure their rapid technology transfer to developing countries.

INTRODUCTION

The full implementation of article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) poses one of the most significant scientific challenges in the fields of geodesy, geology, geophysics and hydrography during the next decade. These challenges stem from the collection, compilation, and processing of vast amounts of marine data to be presented to the Commission on the Limits of the Continental Shelf as evidence in support of continental shelf claims to national jurisdiction extended beyond 200 M.

This paper outlines the scientific challenges confronted by coastal States to implement the provisions contained in article 76 and their geographic scope. These tasks are compounded by the needs to develop the most accurate and economic scientific methodologies, and to ensure their rapid technology transfer to developing countries.

1. The continental shelf

The use of the term *continental shelf* as a designator of a marine geomorphologic feature appears to have been first made by H.R. Hill in his work *Realm of Nature* as early as 1887. However, it was until the International Committee on the Nomenclature of Ocean Bottom Features was created during the VIII Assembly of the International Union of Geodesy and Geophysics (IUGG) held at Oslo in 1948, that standardisation efforts were undertaken to define a brief, simple and unambiguous scientific nomenclature for marine geomorphologic features. Agreement on final definitions was reached by the Committee at Monaco in 1952 (Wiseman and Ovey, 1953).

The definition and our scientific knowledge about continental margins has advanced and evolved in the context of plate tectonics over the last three decades (e.g., NRC, 1979; COSOD II, 1987; ODP, 1996). Similarly, the concept of the continental shelf in law has also undergone considerable but separate development. The legal status of the continental shelf is defined in international codified law by the 1958 Convention on the Continental Shelf and the United Nations Convention on the Law of the Sea (UNCLOS).

The 1958 Convention defines the outer limit of the legal continental shelf by reference to the 200 metre isobath and a criteria of exploitability. The outer limit of the legal continental shelf in UNCLOS, on the other hand, is determined by reference to a distance of 200 nautical miles (M); or to the outer edge of the geological continental margin wherever the margin extends beyond 200 M. There are States that currently use one or the other definition in their national legislation. There is, however, a general trend among coastal States to replace the provisions of the 1958 Convention by those contained in article 76 of UNCLOS. Figure 1 shows the distribution of continental shelf claims made by States to date.

2. Article 76 of UNCLOS

Figure 2 shows the outer limit of the continental shelf at a distance of 200 M as established in one of the provisions of article 76. When the continental margin extends beyond 200 M States must apply a complex formula where the outer limit must be located up to:

- a distance of 60 M from the foot of the continental slope (Figure 3); or
- a line where the ratio of sediment depth to its distance from the foot of the continental slope is 1/100 (Figure 4);

but no further than:

- a distance of 350 M from the baselines from which the territorial sea is measured (Figure 5); or
- 100 M from the 2,500 m isobath (Figure 6).

The implementation of the above rules presents scientific challenges in a number of marine disciplines: the determination of the foot of the continental slope falls in the realm of geomorphology; the determination of sediment thickness is a geophysical assignment; the determination of all distance rules, as well as positioning and geometric elements fall within the realm of geodesy; the determination of isobaths and all other ocean mapping tasks are routine in hydrography; and marine geology plays an essential role in the identification of many features.

3. Propositional formulation of Article 76 of UNCLOS

The provisions contained in article 76 can be expressed in symbolic form by means of a propositional formulation:

G	gradient rule	foot of the slope + 60 M
T	thickness rule	1% sediment thickness
D	distance rule	350 M
B	bathymetry rule	100 M from the 2,500 m isobath

g the limit given by **G** is larger than 200 M
t the limit given by **T** is larger than 200 M
d the limit given by **G** or **T** is lower than **D**
b the limit given by **G** or **T** is lower than **B**

Normal continental shelf claims: $(-g \wedge -t) \supset \mathbf{N}$
Extended claims: $(g \vee t) \wedge (d \vee b) \equiv \mathbf{E}$

where

- $-$ negation
- $\wedge$ conjunction
- $\vee$ nonexclusive alternation or inclusive disjunction
- $\supset$ material conditional
- $\equiv$ material biconditional

4. The Commission on the Limits of the Continental Shelf

UNCLOS establishes a process for the registration of continental shelf claims beyond 200 M. This process involves an organisation created by the same Convention and named the Commission on the Limits of the Continental Shelf. Information on limits beyond 200 M shall be submitted by the coastal State to the Commission. The Commission, in turn, shall make recommendations on matters related to the establishment of the outer limits. The limits of the shelf established by a coastal State on the basis of these recommendations are final and binding.

The election of the Commission was held at UN Headquarters in April 1997. Candidates were nominated by States Parties to UNCLOS, and 21 members were elected for a period of five years. This election was carried out with a regional allocation of members: Africa (5); Asia (5); Latin America and the Caribbean (4); Eastern Europe (2); and Western Europe and others (5).

The Commission has produced three documents to date:

- *Rules of Procedure* which describe its organisation, structure and procedure.

- *Annexes I* and *II* to the Rules which describe its agreement with respect to matters of delimitation and confidentiality;

- *Modus Operandi* which describes its operational aspects interaction with submitting States and third parties; and

- *Scientific and Technical Guidelines* which describe the scientific and technical aspects of a submission on limits prepared by coastal States.

5. Regions for Potential Research

This study identifies a sample of potential research regions for continental shelf claims. Its purpose is to assess the geographic scope of the research that might be conducted to determine with certainty whether an extended continental shelf claim is feasible or not. Its objective is to highlight the need for international and regional scientific co-operation during the execution of feasibility and implementation studies carried out by States. Figure 7 shows a preliminary, ongoing, and non-exhaustive inventory of wide continental margin regions.

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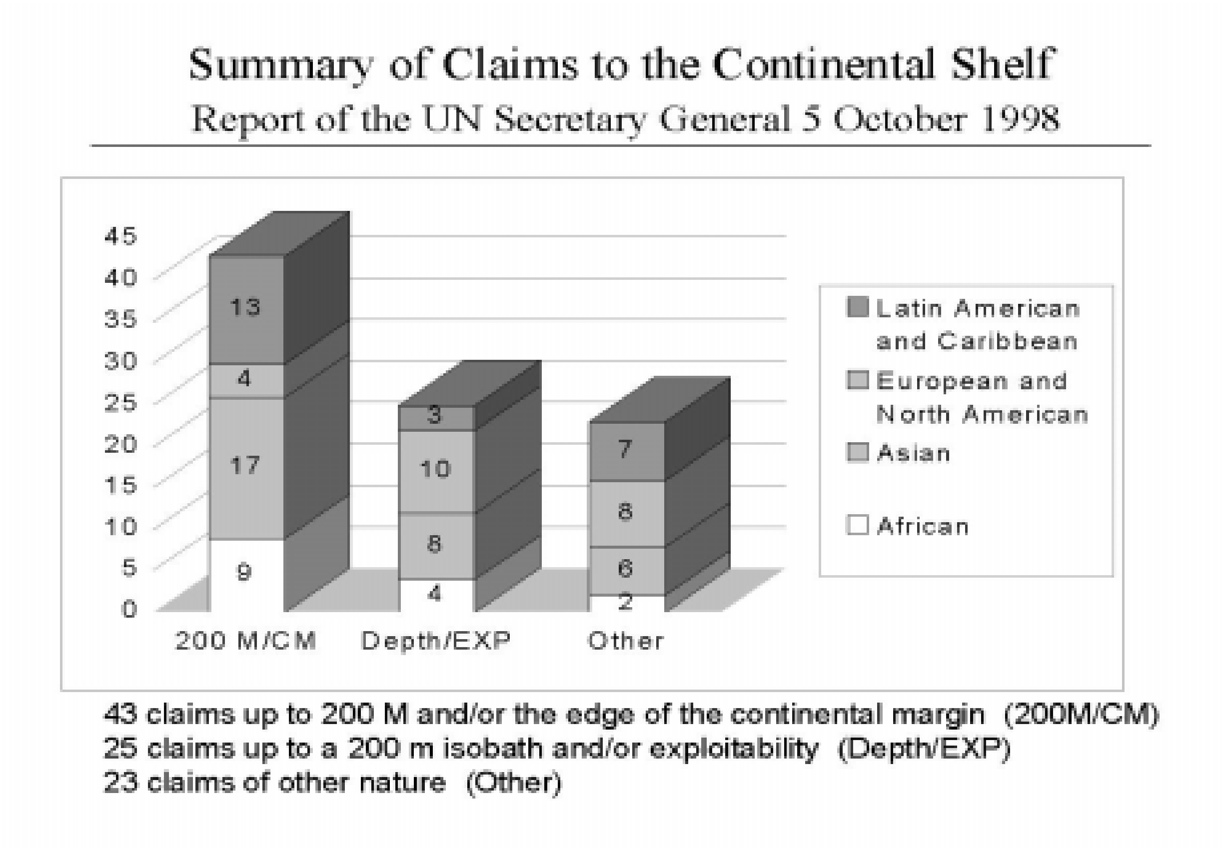

SESSION 1 – Paper 6

SESSION 2 – Paper 1

SESSION 2 – Paper 2

COASTAL BOUNDARIES AND VERTICAL DATUMS

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Biography

Prof. Erwin Groten is Director of the Institute of Physical Geodesy and a professor at Darmstadt (Germany) Institute of Technology since 1970. He is an author of about 200 scientific publications and of several text books. He is president of the Special Commission on "Fundamental Constants" of the Intern. Assoc. of Geodesy. Moreover he is a member of a large number of scientific and professional international organizations. He is affiliated with several other universities world-wide.

ABSTRACT

There are basically two approaches for unified baseline coordinate determination, using the "low-tide" principle, in order to implement continental borderlines beyond individual national borders. (1) Using GPS (and other satellite techniques) a purely "geometrical" approach, related to WGS 84, would yield baseline coordinates in a global reference frame so that such coordinates are related to one and the same reference ellipsoid. (2) Using repeat GPS in combination with tide-gauge systems and satellite altimetry the MSL (mean sea level) and the associated global geoid, with constant geopotential W^o could serve as (physical) reference. Such a Vertical Datum Approach is not yet implemented and, with decimetric accuracy, could combine borderline implementation with other oceanographic purposes. At present, the first approach is favored. The second approach is under way.

A number of presently ongoing projects are described on which the implementation of a world-wide global vertical geodetic datum could be based. The components of a vertical datum are discussed. Also time-dependent phenomena are taken into account. Besides local relative vertical datums, which may have relatively high internal accuracy, the global vertical datum, based on an exact definition, may be soon implemented with accuracy of about one decimeter or even better. A key constituent is the geopotential at the geoid, W°.

1. Introduction

In general, coastal boundaries are defined and implemented in ellipsoidal “low-tide” systems. This means that the differences between ellipsoid, geoid and mean sea level (MSL) were basically ignored. For most practical purposes this approach is sufficient. With the advent of three-dimensional satellite techniques in navigation, with more emphasis on secular mean sea level changes in connection with global climatic considerations and by taking into account tectonic continental vertical motion the third, i.e. vertical, coordinate besides ellipsoidal longitude and latitude gained significance. These effects became of interest to coastal boundaries, mainly in areas of shallow coastal zones. Subsidence and uplift, such as in Scandinavia, associated with post-glacial rise, is only one such case.

Moreover, GPS and similar satellite systems gave the opportunity to take account of the vertical component in global systems such as the International GPS Service (IGS). Tide gauge systems were globally interrelated as in case of the International "World Ocean Circulation Experiment (WOCE)" so that the intercontinental boundaries could be implemented globally in contrast to locally defined coastal systems related to national reference frames.

2. A review of geodetic reference systems

In definitions, delimitations and implementations of ocean borderlines usually three or even more different concepts are combined in a not quite consistent way; such procedures are mainly justified by insignificant numerical uncertainties as consequences of such inconsistencies. This is true and correct in many cases but, in view of legal consequences, one should avoid, whenever possible, inconsequent procedures leading to legal difficulties. One self-explanatory example is the combination of “low astronomical tide” baseline or coastal points with 2,500 m isobath-lines, which, today, are mostly implemented using GPS-positioning. Along shallow or only slightly inclined coastlines even small uncertainties in vertical coordinates may translate into horizontal uncertainties of several hundred meters or even kilometers. The transformation from “low”- to “mean”- or “zero”-tide, defining mean sea level (MSL) involves oceanic tidal models in the transition from “low-tide” benchmarks to isobath-lines related to MSL which is implemented by tide-gauge or altimetric measurements of the ocean surface. If positions are then determined by GPS or other satellite techniques we mainly use ITRF-(ITRS) in terms of IGS-coordinates, which have no direct vertical component, or WGS 84 coordinates as part of the NIMA ellipsoidal system. Thus a mixture of “low-tide” benchmarking with “mean”- or “zero”-tide dynamical heights together with purely geometric ellipsoidal heights is applied.

In geodesy, we clearly distinguish between the "tide-free"-situation where all tides have been removed, the "zero-tide"-situation where the indirect permanent tide is preserved and the "mean-tide"-situation where all direct tides are preserved; for details see (Groten, 1999).

In horizontal positioning meanwhile IFRF(S) and/or WGS 84 (in the form updated by NIMA in 1997) have been adopted for hydrographic purposes. However, when borderlines are derived from baselines along the shore, geodesics are mainly used to interconnect discrete baseline points. In those cases not only the WGS 84 related ellipsoid has been applied, but rather different ellipsoids associated with national or regional geodetic datums are used. Such ellipsoids have mostly non-geocentric origins differing from the geocenter by up to 0.5 km. For the main local or regional geodetic datums the distances from the geocenter have been derived with accuracy of a few meters. However, the sea surface is closer to a geoid than to an ellipsoid (with separation geoid-ellipsoid up to 150 m). Consequently, the determination of geodesics between baseline stations depends on the deviation of this specific ellipsoid from the mean sea surface in that area approximated by a geoid section if we want to get a solution for the boundary as close to reality as possible. It is difficult to describe the consequent errors in geodesics associated with both error sources. Nevertheless, it would be desirable to derive geodesics in the future only on the geocentric WGS 84 ellipsoid in order to reduce uncertainties in legal interpretation to a minimum. This would go along with the rule to derive positions only, in the future, with respect to ITRF. It should, however, be noted that ITRF includes the determination of temporal changes of time-dependent terrestrial coordinates; as far as horizontal coordinates are concerned, it makes, consequently, sense to associate an epoch with such coordinates in terms of geographic latitude and longitude.

The transition from geocentric ellipsoidal heights to heights or depths related to MSL is more intricate. Whenever differential satellite positioning, such as DGPS, is applied to achieve higher accuracy than in case of single-point positioning (± 100 m because of “selective availability” (SA) etc.) we might switch from ellipsoidal to orthometric height differences between the reference and the rover station. This is not always necessary or desired so that the pure ellipsoidal concept may be applied instead of a vertical geodetic Datum concept.

The vertical geodetic Datum makes use of the fact that local Datums are referred to tide-gauge (s) where MSL may significantly (± 1.5 m) deviate from the (local) tide gauge datum. The geocentric location of the tide-gauge may be verified or monitored by (temporary or permanent) GPS-control.

However, in case of border lines related to 2,500 m isobath or 200 nautical miles etc., accuracies are not as demanding as in case of median in narrow border situations between neighboring coastal countries. In the latter situation accuracies of one meter or similar may play a role. Thus, in those situations more detailed consideration of geodetic systems, particularly of vertical geodetic systems, should be taken into account.

The transition between modern regional geodetic reference systems, such as ERTS, EUREF and global systems, such as WGS 84 (updated version), ITRF, IGS etc. is, of course much more precisely defined by rather precise transformation parameters, than in the aforementioned case of traditional or classical geodetic systems. In principle, the same is true for UELN (= Unified European Levelling System). But the interrelation of vertical datums deserves a special consideration in view of recent progress in global ocean tide models, global interrelation of world-wide geocentric tide gauge systems by projects like WOCE as well as by global gravity and geopotential modeling in terms of geodetic reference systems such as GRS 80 (ellipsoidal Geodetic Reference System 1980) which differs only slightly from the updated version of WGS 84 but contains an ellipsoidal gravity model for the space around the earth's surface. The update of this model in terms of a GRS 2000 is presently under consideration in the International Association of Geodesy.

Let us assume that we can associate coastal boundaries with the ”low-tide” situation of sea level. If we take into account significant secular variations of global climate which may be associated with significant secular changes of mean sea level (MSL) then the interrelation between definition and implementation of coastal boundaries with Vertical Datums is obvious. Part of these effects may also be changes in ocean circulation. In this way, the interrelations of conventional local (or national) Vertical Datums with the global Vertical Datum which is related to the potential $W°$ at global geoid (and its temporal changes) gain interest. Moreover, the long-period part of ocean tides which is represented by the zonal spherical harmonics part of tidal potential (with wave-lengths up to 18.6 years) gains significance. As this part disappears at certain geographic latitudes (and is relatively small close to them) such areas were considered in the past as appropriate area of first investigations for such purposes if we can assume that static tides prevail at such long periods.

Conventional national Vertical Datums define the zero-points of national height systems, mainly with $h = 0$. If the associated tide gauges are controlled by permanent GPS-stations within a global reference system, such as IGS, the world-wide geometric interrelation of such regional and local Vertical Datums in terms of ellipsoidal or rectangular geocentric coordinates can be established.

On the other hand, satellite altimetry can globally be used to survey and supervise, more or less, permanently and continuously MSL after appropriate tidal reductions. If we use a global reference ellipsoid and its associated reference system, such as WGS 84, as a base for the GPS-elevations or heights and the global geoid as a reference for temporal variations of MSL then the separation of the geoid (with constant potential $W°$) from the ellipsoid may be denoted by geoid height N. In principle, we could avoid N by directly relating MSL and geocentric locations to the ellipsoid.

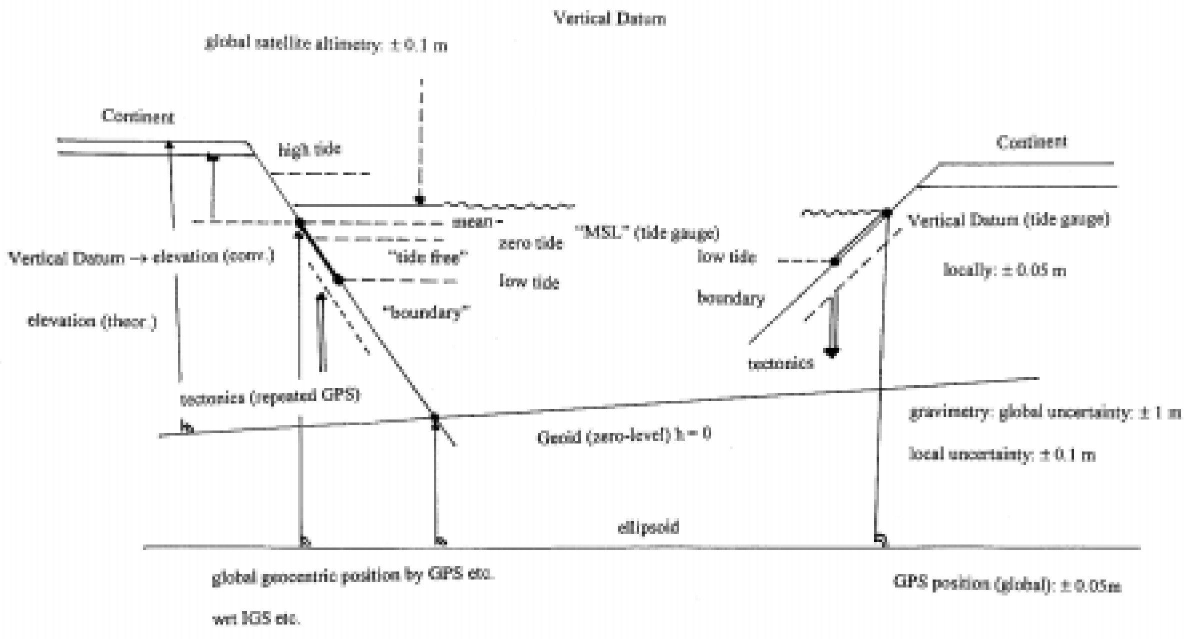


Fig. 1
Vertical Datum interrelations in coastal areas including subsidence, uplift and MSL-variations as recorded by gravimetry (geoid undulations), GPS and satellite altimetry above the ocean.

However, if besides secular MSL-changes, due to thermic expansion of the ocean and similar effects, also tectonic motion in continental areas, leading to systematic variations of heights at tide gauge stations, are presumed then dynamical aspects gain increasing interest. One should realize that tide gauges are relative instruments which cannot separate MSL-variations from height changes at the installation sites of the gauges.

It is, consequently, common practice to define a global geodetic Vertical Datum by a geocentric location at a certain epoch of time (t_o) with a potential W° for h=0, where W° basically depends on the mass M of the Earth and the volume v of the geoid where v, of course, is depending on the secular variations of MSL; if v equals the volume of the chosen ellipsoid, as in case of WGS 84 (at least approximately) and the Mass M (of the ellipsoid used in WGS 84) equals the mass of the Earth, there is no constant offset N_o inherent in N and the global average of N disappears.

There is a variety of approaches to use gravimetric, altimetric and other (global) data sets together with repeat GPS-tide gauge positioning in order to determine the offsets of principal Vertical Datums used at different continents with respect to a unified global Vertical Datum: The Amsterdam, Kronstadt, Finnish, North American, Australian, Adriatic and other Vertical Datums have thus been interrelated, to cite only a few of them. However, these are only first attempts by Rapp, Bursa and others. We are only at the beginning of such global studies.

The main error sources in such studies do not affect significantly the present interrelation of definition and implementation of coastal boundaries. They are anyway only of practical interest in special regions such as Fennoscandia with its (partly) shallow coast lines and postglacial rebound. But Vertical Datums are a primary tool for interconnecting precisely national height systems with centimeter accuracy. So the uncertainties in present models of long-period ocean tides, variations of volume of the geoid due to MSL-changes (caused by the greenhouse and related effects), global solid earth deformations (associated with global geotectonics), deficient modeling of ocean-atmosphere interaction such as in case of El Nino or La Nina should only be briefly mentioned in this context.

As ellipsoidal heights, their temporal changes and related systems are purely abstract quantities without any connection to physical reality it is appropriate to use (dynamic, normal or orthometric) heights h and elevations with respect to level surface, such as the geoid (W°), which are physically defined and can thus be implemented and related to the actual world and nature.

3. More detailed considerations of Global Vertical Datum Concepts

The definition and implementation of a global vertical geodetic datum is one of the ultimate goals of modern geodesy which has not yet been achieved until now with sufficient accuracy. There is a series of attempts by Bursa et al. (1998, 1999), Rapp and associates and others (Groten, 1999) which has led to decimeter accuracy recently. Nevertheless, still higher accuracy, of the order of a few centimeters, is desired. Yet some prerequisites are not fulfilled so that a number of quite different approaches need to be accomplished beforehand.

Why do we need a global vertical datum? If for any point on earth we want to give globally precise coordinates above "mean sea level" such a Datum is needed.

If we dismiss, at first, more or less unproved and/or insignificant global variations due to time-variable gravitational constant, due to various relativistic implications as well as those following from expanding earth theories we may have to take into account periodic changes of the surface of the fluid-solid earth surface due to thermic expansion, vertical motion associated with global plate tectonics etc. There is a variety of geodynamic processes which actually implies temporal variations of the volume of the earth. This makes it difficult to define a global precise vertical datum.

Historically, regional or national vertical datums have been based on long-time averages recorded at tide gauges such as the Amsterdam or Kronstadt gauge leading to a local mean sea level (MSL) as an approximation of the geoid. Assuming that pole tide as well as earth-tide (as combination of solid earth and ocean including loading tides) were eliminated in this way, the deviation of such a purely conventional "Normal Null" (N.N) datum from the geoid would be basically due to wind, salinity, very-long period tides (up to 18.6 years) etc. which are essentially the deviations of the ocean from an ideal (frictionless) fluid. Such deviations were found to be up to 1.5 m in Australia, 0.5 m at Amsterdam etc. In Finland the local vertical datum is almost identical with the geoid. This leads to the fact that Grafarend and Ardalan's (Groten, 1999) recent discussion of a global vertical datum is valid because it is incidentally based on the Finnish Datum.

Most gravimetric geoids until now deviate from the actual global geoid which coincides with the MSL globally in a minimum-norm (least squares) way by specific N_0-terms because they do not fulfill the conditions

$$\text{volume (geoid)} \qquad = \text{volume (ellipsoid)} \tag{1}$$
$$\text{mass (earth)} \qquad = \text{mass (ellipsoid)} \tag{2}$$

where the ellipsoid is the global minimum-norm (best fitting) ellipsoid which us usually chosen as the base of the geoid computation in the sense that the geoid height, N, is the separation of the geoid from this "earth ellipsoid". As (1) and (2) are never perfectly (defect of about 0.1 m, at present, resulting from deficits in (1) and (2)) fulfilled, resulting errors lead to a constant N_0.

As tide gauges are relative instruments their temporal variations of vertical coordinates must be continuously supervised by GPS or similar geocentric satellite approaches in order to interpret correctly tide gauge records in terms of MSL-variations. Such observational series exist only at a few stations (selected stations in the Baltic Sea, as part of the Baltic Sea level Project, in Japan and of the WOCE program are typical examples) so that we are still at the beginning of such data with the desired quality and accuracy.

When, in addition, satellite altimetry yields sea level data in a unified global reference system (ERS-1/2, Topex-Poseidon, tracked, e.g., in WGS 84) we obtain redundant information for ocean and (from global tracking systems such as IGS, ITRS, ETRS, EUREF and its subsystems) land areas so that in combination with global or regional vertical networks (UELN etc.) we can determine the volume of the earth, leading to the volume of the geoid by leveling, and thus to (1); (2) is derived from the application of Kepler's third law to satellite orbits including the atmosphere.

It is important to note that most of the global networks of IERS on which horizontal coordinate systems are based, as mentioned before, still lack exact vertical coordinates.

To interrelate or connect regional datums we do not only need to tie together by GPS, Glonass or similar relative those fundamental tide gauges globally but also their associated potential values which deviate from the potential W° at the global absolute geoid, fulfilling the conditions (1) and (2).

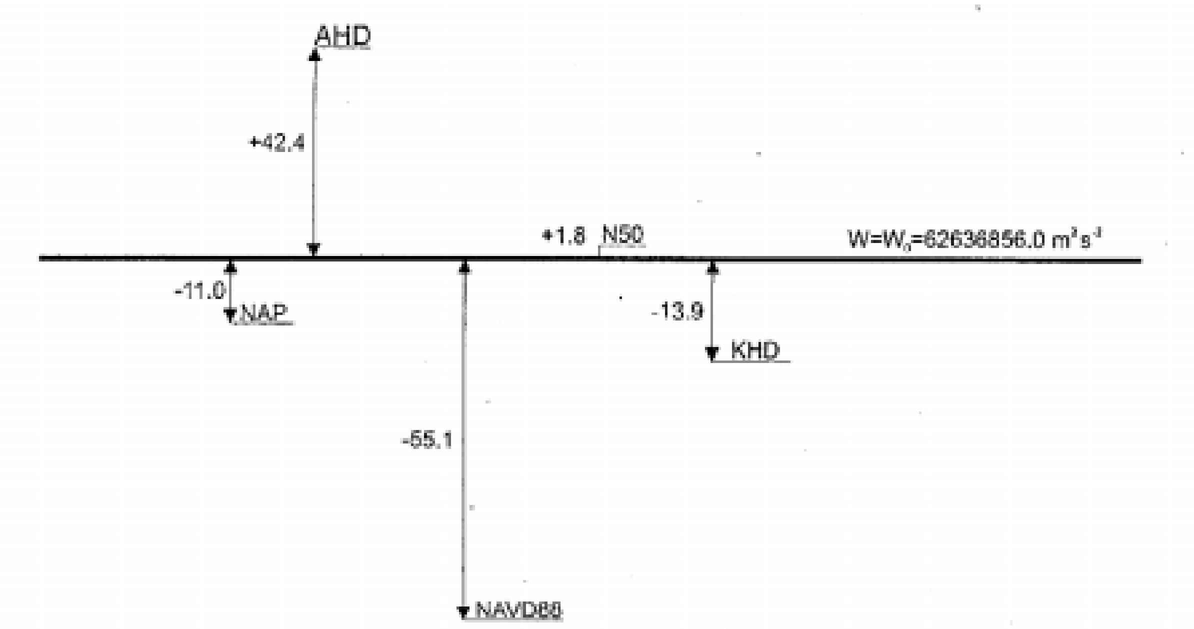
Absolute gravimetry is one of the tools to globally interrelate the stations, in terms of gravity $\nabla W = -\vec{g}$.

If relative gravimetry in terms of shipborne gravimetry and dense gravity meter networks is supplementing sparsely distributed absolute gravity stations we thus have discussed all components of a precise vertical datum:

a) GPS etc. is a well defined geocentric frame
b) satellite altimetry
c) regional geoids
d) tide-gauge dates
e) extended "global" networks such as ITRF
f) tidal observations of high accuracy.

4. Implementations of Vertical Datums

The best presently available results are derived by J. Ries, M. Bursa and R.H. Rapp and associates (Groten, 1999). The latest global Vertical Datum is based on the data discussed above and was published



last year (Bursa at al., 1998, 1999); see Fig. 2.

Fig. 2
Vertical shifts (in cm) of the origins defining several local Vertical Datums with respect to the reference equipotential surface $W^0 = 62\ 636\ 856.0\ m^2\ s^{-2}$

The best presently available geopotential units for the global geoid as base of a unified global height system at zero elevation h = 0 are (Groten, 1999)

$$W^{o} = (626\ 36856.4 \pm 0.5)\ m^{2}\ s^{-2} \quad \text{by J. Ries}$$

$$\text{and } W^{o} = 626\ 36856.0 \pm 0.5)\ m^{2}\ s^{-2} \quad \text{by Bursa et al.}$$

The secular variations were found to be negligible globally by Bursa et al. (1999) so that globally W^o may be considered to be a constant if we omit seasonal and yearly period variations which are well known to be quite strong locally. For instance, in the Mediterranean Sea yearly variations of the order of 0.2 m are well known in some areas.

Ardalan and Grafarend, in a series of papers (results are collected in (Groten, 1999)) investigated W^o for the Fennoscandian area where special postglacial aspects exist. As expected, in view of the uplift, they found in relation to the Finnish Vertical Datum NH 60 a significant secular change of W^o. In general, we may however assume that the geoid and the related geopotential field is quite stable in relation to mean sea level variations. With respect to land uplift the geoid is well known to be affected in its position by about ten percent.

Ekman (1999) found detailed results for temporal and regional mean sea surface variation which agree quite well with temporal change derived elsewhere. All the temporal variations within one century are of the order of a few centimeter (mainly uplift); in detail Ekman reported on 0.2 m per century for the Baltic Sea and deviations from mean sea level (MSL) for the same area of about the same size.

5. Conclusions

As in legal cases the demands on consistency are higher than numerically demanded, a discussion of geodetic aspects appears appropriate even if, for formal reasons, the discussion in this paper goes beyond the accuracy presently applied for hydrographic purposes.

In view of ongoing progress in geodesy we should look into future applications and consider future demands and needs. In so far the consideration of what geodesy can provide for hydrography is worthwhile.

Hydrographic and geodetic reference systems, when incorrectly interrelated, cause systematic errors which should be kept ten times smaller than random errors, in general. Therefore, the detailed discussion of inconsistencies well below the error limit, as done here, makes sense.

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SESSION 2 – Paper 3

PROPAGATION OF ERRORS FROM SHORE BASELINES SEAWARD

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ABSTRACT

All maritime boundaries are defined by turning points and by straight lines or curves connecting these points. The points can be positioned only to a limited accuracy. That accuracy is normally shown by two-dimensional confidence limits, also known as error ellipses. These confidence limits can be thought of as portraying the areas of positional uncertainty. The main problem we investigate in this paper is: What is the uncertainty in the line (baseline) connecting two such uncertain positions? The corollary problem of probabilities associated with the uncertainties as well as the role of statistical dependence between baseline end-points are discussed. Then the impact of uncertainties in baselines on the maritime boundary is addressed. Some thought is given to the impact of boundary uncertainty on encroachment litigation.

Introduction

While positional uncertainties have always been considered in geodesy (in terms of covariance matrices and confidence regions), uncertainties in lines that connect two uncertain positions have received little attention. In this contribution, the latter problem is addressed with the goal of deriving a rigorous (as rigorous as statistics allows us to get) expression for the line uncertainty when the two end positions are burdened with random errors. The problem of systematic errors is considered beyond the scope of this presentation.

It is shown that the line uncertainty (confidence region) should be depicted by an 'uncertainty belt'. The shape of the uncertainty belt is dictated by the positional uncertainties of the end points and the cross-covariance between the two positions. All this is shown by means of elementary mathematics and statistics, which should be easy to follow.

Further, the probability (statistical confidence level) associated with uncertainty belts of different width is discussed. It is demonstrated that this probability is a function of the multiple of standard deviations used in the construction of the uncertainty belt and of how the covariance matrices of the end points have been estimated.

Once the boundary uncertainty is known, it makes an eminent sense to ask about its impact on encroachment issues. It is shown that the encroachment can be viewed as strictly probabilistic problem.

Positional uncertainty

No position on the surface of the earth can be determined with an absolute accuracy and every (point) position contains errors. These errors belong to two broad families: systematic and random. Systematic errors are those that can be evaluated through analysing all the circumstances. For a discussion of systematic errors in positions and their effect on maritime boundary uncertainties the reader is referred to [Vaníček, 1998]. Here we shall concentrate on the random errors. Random errors are unpredictable; they

can be described only statistically by means of standard deviations (σ_x , σ_y) of coordinates x, y, and by the covariance σ_{xy} between them [Mikhail, 1976], for a specific probability level "p".
The usual way of describing the random error in a position (x,y) is by the <u>covariance matrix</u> **C**, assembled as

$$C = \begin{bmatrix} \sigma_x{}^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_x{}^2 \end{bmatrix}. \tag{1}$$

This matrix is a standard by-product of geodetic position estimation (computation) and should be routinely available for all desired positions. A covariance matrix (1) can be interpreted geometrically as describing a one-sigma error ellipse, known in statistics as the one-sigma <u>confidence region</u> [Mikhail, 1976] – see Fig.1.

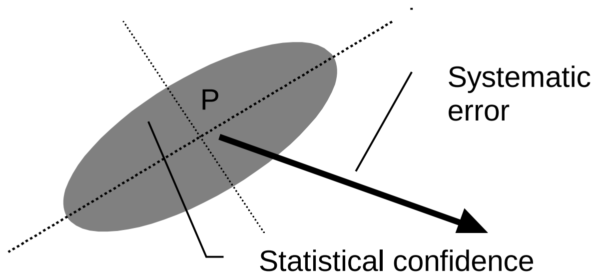

Figure 1- Positional uncertainty

We shall be using, for the moment, the map coordinates (two-dimensional Cartesian coordinates x and y) to derive the uncertainties in the baselines. We shall show later how the results are applied to geodesics on the reference ellipsoid.

Uncertainty belt of a straight baseline

The question now arises: What will the <u>uncertainty belt</u> of a straight baseline that connects two points burdened with random errors look like? The situation is shown on Fig. 2. What we have to

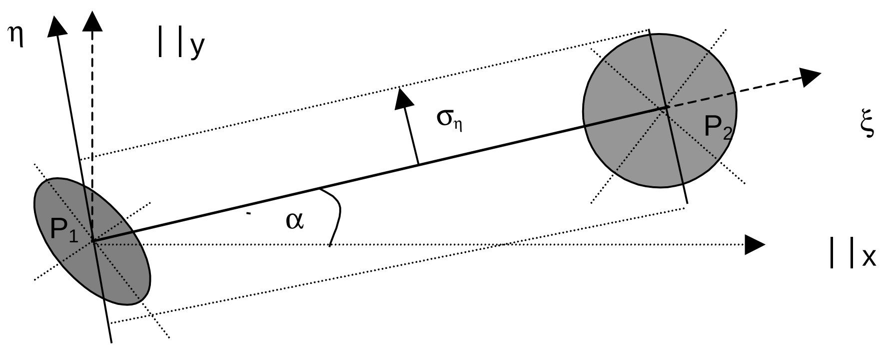

Figure 2 – Uncertainty belt of a straight baseline

investigate is the shape of the uncertainty (error) belt, which we shall also call the confidence region of the straight baseline.

In the local coordinate system ξ,η at point P_1, the equation of the straight baseline is

$$\eta(\xi) = 0 \quad . \tag{2}$$

The shape of the uncertainty belt can be described by the standard deviation of the coordinate η as a function of ξ, i.e., by $\sigma_\eta(\xi)$, which, in turn, will be a function of positional uncertainties in points P_1 and P_2, and their cross-covariances. Thus, to derive the expression for $\sigma_\eta(\xi)$, we have to have not only the covariance matrices $\mathbf{C}_1$ and $\mathbf{C}_2$ of points P_1 and P_2, but also their cross-covariance matrix $\mathbf{C}_{1,2}$ assembled as:

$$\mathbf{C}_{1,2} = \begin{bmatrix} \boldsymbol{\sigma}_{x1,x2} & \boldsymbol{\sigma}_{x1,y2} \\ \boldsymbol{\sigma}_{y1,x2} & \boldsymbol{\sigma}_{y1,y2} \end{bmatrix} \tag{3}$$

The three matrices we need make up the (four by four) complete covariance matrix of the pair of points P_1 and P_2

$$\mathbf{C}^* = \begin{bmatrix} \mathbf{C}_1 & \mathbf{C}_{1,2} \\ \mathbf{C}_{2,1} & \mathbf{C}_2 \end{bmatrix} \tag{4}$$

Such complete covariance matrix (of the vector $[x_1, y_1, x_2, y_2]^T$) is obtained as a by-product of the simultaneous estimation (computation) of the two positions and is, once more, routinely available for selected pairs of points. What we have to do now is to derive the expression for $\sigma_\eta(\xi)$ as a function of $\mathbf{C}^*$.

Let us begin by writing the equation for the baseline (eqn. (2)) in the x,y coordinate system. We get

$$y = a + b\,x = y_1 + \tan\alpha\ (x - x_1)\,, \tag{5}$$

where

$$a = y_1 - b\,x_1\,,\ \ b = \tan\alpha = (y_2 - y_1)/(x_2 - x_1)\,. \tag{6}$$

Next, we differentiate eqn. (5) to linearize the relation between x and y on the one hand and the four 'variables' $\mathbf{x} = [x_1, y_1, x_2, y_2]^T$, the errors in which we know (in terms of the covariance matrix $\mathbf{C}^*$):

$$dy = (\partial a/\partial\mathbf{x} + \partial b/\partial\mathbf{x}\ x)\ d\mathbf{x}\,, \tag{7}$$

where $\partial a/\partial\mathbf{x}$ and $\partial b/\partial\mathbf{x}$ are Jacobi's matrices composed of partial derivatives of scalars a and b with respect to the vector $\mathbf{x}$, and $d\mathbf{x}$ is the differential vector

$$d\mathbf{x} = [dx_1, dy_1, dx_2, dy_2]^T \tag{8}$$

The Jacobi matrices can now be evaluated. We get

$$\partial b/\partial\mathbf{x} = \mathbf{B} = \partial/\partial\mathbf{x}[(y_2 - y_1)/(x_2 - x_1)]\ , \tag{9}$$

$$\begin{aligned} \partial a/\partial\mathbf{x} = \mathbf{A} &= \partial y_1/\partial\mathbf{x} - b\,\partial x_1/\partial\mathbf{x} - \partial b/\partial\mathbf{x}\ x_1 \\ &= \partial y_1/\partial\mathbf{x} - b\,\partial x_1/\partial\mathbf{x} - \mathbf{B}\,x_1 \end{aligned} \tag{10}$$

and further

$$\mathbf{B} = [\tan\alpha, -1, \tan\alpha, -1]/(x_2 - x_1) = [\mathbf{D} \,|\, \mathbf{-D}]\, /(x_2 - x_1)\ , \tag{11}$$

$$\begin{aligned}\mathbf{A} &= [0,1,0,0] - b\,[1,0,0,0) - \mathbf{B}\, x_1 = [-b,1,0,0] - \mathbf{B}\, x_1 \\ &= [-\tan\alpha, 1,0,0] - \mathbf{B}\, x_1 = [\mathbf{-D} \,|\, \mathbf{0}] - [\mathbf{D} \,|\, \mathbf{-D}]\, x_1 /(x_2 - x_1) \quad ,\end{aligned} \tag{12}$$

where the symbol **D** stands for $[\tan\alpha, -1]$ and $|$ denotes matrix partitioning [Thompson, 1969]. Back substitution into eqn.(7) then yields

$$dy = \{[\mathbf{-D} \,|\, \mathbf{0}] + [\mathbf{D} \,|\, \mathbf{-D}]\,(x - x_1)/(x_2 - x_1)\}\, d\mathbf{x} \tag{13}$$

or, more simply,

$$dy = \{\mathbf{A}^* + \mathbf{B}^*\,(x - x_1)/(x_2 - x_1)\}\, d\mathbf{x} \quad . \tag{14}$$

We may now realize that the argument $(x - x_1)/(x_2 - x_1) \in < 0,1 >$ can be also interpreted as running along the ξ-axis and we may thus replace it by

$$\xi^* = \xi / S_{1,2}\ , \tag{15}$$

where $S_{1,2}$ is the length of the baseline. Equation (14) then becomes

$$dy = (\mathbf{A}^* + \mathbf{B}^*\,\xi^*)\, d\mathbf{x}\ , \tag{16}$$

which is the equation that can be used for evaluating the systematic error in y from known systematic errors in **x**.

As we are here interested in random errors, we have to use the <u>law of variance propagation</u> [Vaníček and Krakiwsky, 1986] to see how the variances (squares of standard deviations) and covariances in the two end positions affect the variance of y. We get

$$\sigma_y^2(\xi^*) = (\mathbf{A}^* + \mathbf{B}^*\,\xi^*)\, \mathbf{C}^*\, (\mathbf{A}^* + \mathbf{B}^*\,\xi^*)^T \tag{17}$$

and, after carrying out the algebraic operations,

$$\sigma_y^2(\xi^*) = \mathbf{A}^*\mathbf{C}^*\mathbf{A}^{*T} + 2\,\mathbf{A}^*\mathbf{C}^*\mathbf{B}^{*T}\,\xi^* + \mathbf{B}^*\mathbf{C}^*\mathbf{B}^{*T}\,\xi^{*2} \quad . \tag{18}$$

We now substitute for **A*, B*** and **C*** to get

$$\begin{aligned}\sigma_y^2(\xi^*) &= \mathbf{D}\,\mathbf{C}_1\,\mathbf{D}^T - 2(\mathbf{D}\,\mathbf{C}_1\,\mathbf{D}^T - \mathbf{D}\,\mathbf{C}_{1,2}\,\mathbf{D}^T)\,\xi^* + (\mathbf{D}\,\mathbf{C}_1\,\mathbf{D}^T - 2\,\mathbf{D}\,\mathbf{C}_{1,2}\,\mathbf{D}^T + \mathbf{D}\,\mathbf{C}_2\,\mathbf{D}^T)\,\xi^{*2} \\ &= \mathbf{D}\,[\mathbf{C}_1 - 2(\mathbf{C}_1 - \mathbf{C}_{1,2})\,\xi^* + (\mathbf{C}_1 - 2\,\mathbf{C}_{1,2} + \mathbf{C}_2)\,\xi^{*2}\,]\,\mathbf{D}^T \quad .\end{aligned} \tag{19}$$

Let us write the **D** matrix in a slightly different form:

$$\mathbf{D} = [\tan\alpha, -1] = [\sin\alpha, -\cos\alpha] / \cos\alpha = \mathbf{S} / \cos\alpha\ . \tag{20}$$

Substitution into eqn.(19) then yields

$$\sigma_y^2(\xi^*) = \mathbf{S}\,[\mathbf{C}_1 - 2(\mathbf{C}_1 - \mathbf{C}_{1,2})\,\xi^* + (\mathbf{C}_1 - 2\,\mathbf{C}_{1,2} + \mathbf{C}^2)\,\xi^{*2}\,]\,\mathbf{S}^T / \cos\alpha \quad . \tag{21}$$

We have derived the equation for $\sigma_y^2(\xi^*)$; what remains to be done is to transform it into $\sigma_\eta^2(\xi^*)$ and we are done. As the angle between the (x,y) and the (ξ,η) coordinate system is α, the transformation between differential vectors $d\mathbf{r}_x$ and $d\mathbf{r}_\xi$ is given by

$$d\mathbf{r}_\xi = \mathbf{R}(\alpha)\, d\mathbf{r}_x\ , \tag{22}$$

where $\mathbf{R}(\alpha)$ is the rotation matrix [Vaníček and Krakiwsky, 1986] which rotates one coordinate system into the other. An application of the variance propagation law then gives

$$\mathbf{C}_\xi = \mathbf{R}(\alpha)\, \mathbf{C}_x\, \mathbf{R}^T(\alpha) = \mathbf{R}(\alpha)\, \mathbf{C}\, \mathbf{R}^T(\alpha) \;, \tag{23}$$

and we get for the variance in the η-direction

$$\sigma_\eta^{\,2} = \sigma_x^{\,2} \sin^2\alpha - 2\, \sigma_{x,y} \sin\alpha \cos\alpha + \sigma_y^{\,2} \cos^2\alpha \;. \tag{24}$$

We note that the locus of distances σ_η (or equivalently, the locus of σ_ξ) around a point is known in geodesy as the pedal curve [Vaníček and Krakiwsky, 1986]. In our application $\sigma_x^{\,2} = \sigma_{x,y} = 0$, as x is the independent variable, and we get

$$\sigma_\eta^{\,2} = \sigma_y^{\,2} \cos^2\alpha \;. \tag{25}$$

Substitution back in eqn.(21) yields the final expression we have been seeking

$$\sigma_\eta^{\,2}(\xi^*) = \mathbf{S}\, [\mathbf{C}_1 \; - 2(\mathbf{C}_1 - \mathbf{C}_{1,2})\, \xi^* + (\mathbf{C}_1 - 2\, \mathbf{C}_{1,2} + \mathbf{C}^2)\; \xi^{*2}\,]\, \mathbf{S}^T \;. \tag{26}$$

Note that the variance $\sigma_\eta^{\,2}$, i.e., the square of the uncertainty belt width, is a quadratic function of ξ. It is easy to see that for $\xi^* = 0$ (point P_1) and $\xi^* = 1$ (point P_2), we obtain the correct values of $\sigma_\eta^{\,2}$ that we would get directly from $\mathbf{C}_1$ and $\mathbf{C}_2$.

To close this section, let us have another look at eqn.(16). It can be easily transformed into the following form

$$d\eta = \mathbf{S}[(1 - \xi^*)\, d\mathbf{x_1} + \xi^*\, d\mathbf{x_2}\,] \,, \tag{27}$$

and, replacing the differentials with systematic errors denoted by ε, we get

$$\varepsilon_\eta = \mathbf{S}[(1 - \xi^*)\, \varepsilon_\mathbf{1} + \xi^*\, \varepsilon_\mathbf{2}\,] \,, \tag{28}$$

the equation that describes the effect of systematic errors $\varepsilon_\mathbf{1}$ **,** $\varepsilon_\mathbf{2}$ in the end-point positions on the width of the uncertainty belt. We note that the effect is a linear function of ξ.

A closer look at the uncertainty belt

Let us now have a closer look at eqn.(26). Not surprisingly, we discover that the shape of the uncertainty belt is controlled by the cross-covariance matrix $\mathbf{C}_{1,2}$ for the two end points. We can identify the following three extreme cases:

1. For the total statistical independence of the two positions (this situation occurs when the two end points had been positioned completely independently), which is characterised by $\mathbf{C}_{1,2} = \mathbf{0}$, eqn.(26) reduces to

$$\sigma_\eta^{\,2}(\xi^*) = \mathbf{S}\, [\mathbf{C}_1 \; - 2\mathbf{C}_1\, \xi^* + (\mathbf{C}_1 + \mathbf{C}_2)\; \xi^{*2}\,]\, \mathbf{S}^T \;, \tag{29}$$

which can be further simplified to

$$\sigma_\eta^{\,2}(\xi^*) = \sigma_{\eta 1}^{\,2} - 2\, \sigma_{\eta 1}^{\,2}\, \xi^* + (\sigma_{\eta 1}^{\,2} + \sigma_{\eta 2}^{\,2})\, \xi^{*2} \;. \tag{30}$$

Take, for simplicity, the same variance $\sigma_{\eta 1}^{\,2}$ at both ends of the baseline. We get

$$\sigma_\eta(\xi^*) = \sigma_{\eta 1} \sqrt{(1 - 2\, \xi^* + 2\, \xi^{*2})} = \sigma_{\eta 1}\, Q(\xi^*) \tag{31}$$

and the shape $Q(\xi^*)$ is a square root of a quadratic function of ξ^*. The ordinate at the mid-point is equal to 0.707.

2. For two <u>totally positively statistically dependent</u> positions (this situation occurs, for example, when one position is determined relative to the other position with very high relative accuracy), typified by $\mathbf{C}_{1,2} = \mathbf{C}_1^{1/2}\,\mathbf{C}_2^{1/2}$, considering again the same accuracy at both ends ($\mathbf{C}_{1,2} = \mathbf{C}_1 = \mathbf{C}_2$), eqn.(26) reduces to

$$\sigma_\eta(\xi^*) = \sigma_{\eta 1} \ . \tag{32}$$

The standard deviation in η is then a constant function of ξ^*. Generally, for two totally positively statistically dependent positions, the uncertainty belt is delimited by straight lines.

3. For two <u>totally negatively statistically dependent</u> positions (this situation is only of an academic interest as it cannot occur in practice) and considering again the same accuracy at both ends, eqn.(26) becomes

$$\sigma_\eta(\xi^*) = \sigma_{\eta 1} \sqrt{(1 - 4\,\xi^* + 4\,\xi^{*2})} = \qquad \sigma_{\eta 1}\,Q'(\xi^*) \ . \tag{33}$$

The shape of the belt, $Q'(\xi^*)$, is again a square root of a quadratic function. This time, however, the ordinate at the mid point goes to 0.

The three extreme cases are shown in Fig.3. We note that any real case will fall probably

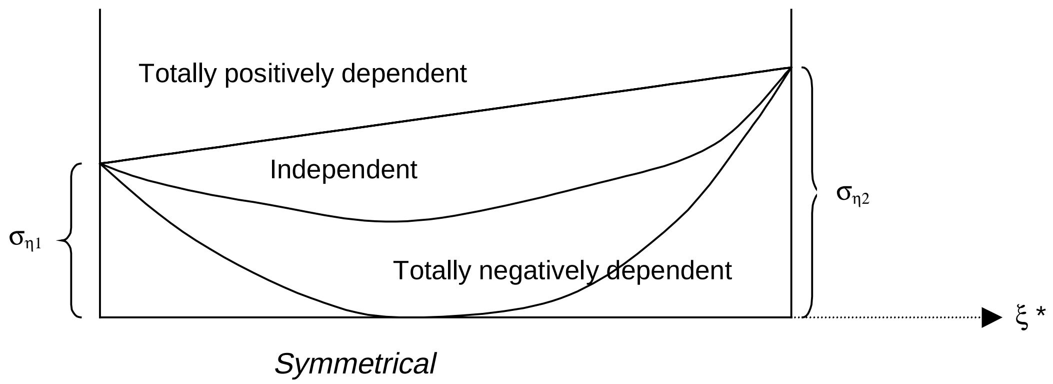

Figure 3 – The shape of uncertainty belt

somewhere between the total positive dependence and the total independence. An example of a real uncertainty belt for a straight baseline is shown in Fig. 4.

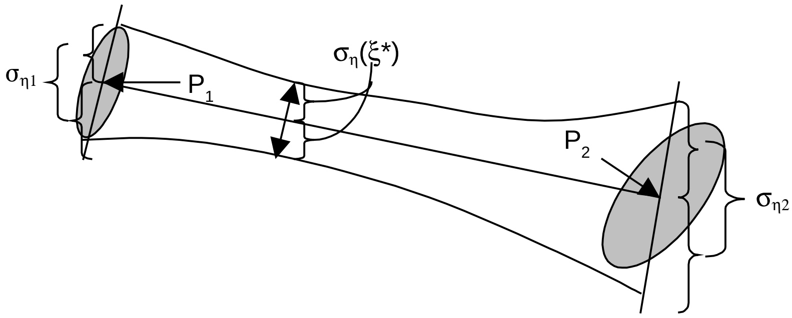

Figure 4 – Complete uncertainty belt

Probabilistic issues

What is the probability of the actual straight baseline being within the uncertainty belt computed according to eqn. (26)? The one-standard-deviation uncertainty belt we have constructed above is associated with the same probability p as the two standard deviations at the ends of the baseline imply. This probability, in turn, depends on how the scale σ_0 of the covariance matrix **C*** [Vaníček and Krakiwsky, 1986] had been determined. The way the scale, known as the variance factor, had been determined dictates the probability density function (PDF) which governs the whole probabilistic consideration.

We can be dealing with any one of the following three PDFs:
1. Normal PDF (n), which is applicable when the variance factor σ_0 isknown independently;
2. Pope's τ PDF, applicable when σ_0 had been estimated during the computation of the end positions;
3. Student's t PDF, applicable when σ_0 had been estimated from a different experiment (from different measurements).
4. The three probabilities, associated with the three PDFs, obey the following inequalities:

$$p_n > p_t > p_\tau \quad . \tag{34}$$

If an uncertainty belt of a specified probability, also called confidence level in statistic, is desired then an appropriate multiple of $\sigma_\eta(\xi^*)$ is used. Fig. 5 shows how this idea works for the

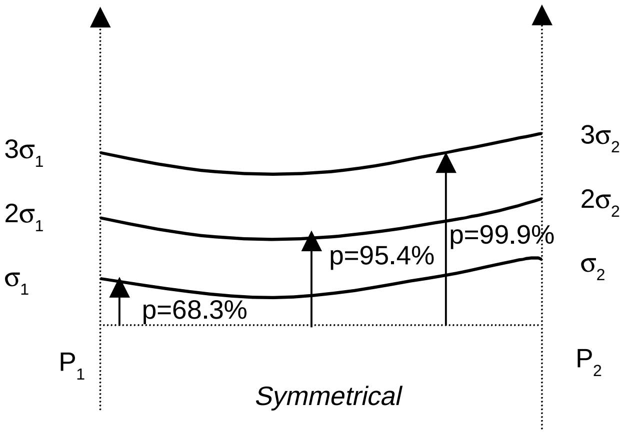

Figure 5 – Probabilities associated with multiples of standard deviations

known σ_0 , i.e., for the normal PDF (and for $\mathbf{C}_{1,2}$ = **0**). Naturally, different '$k\sigma_\eta$ - belts' will have different confidence levels for different PDFs.

Geodesic curve as a straight baseline

Generally, a geodesic curve on the reference ellipsoid appears on the map as a curve and not as a straight line. We speak of the projected geodesic. A typical situation is shown on Fig.6. Since most of the time, the 'straight baselines' are defined as geodesics on the reference

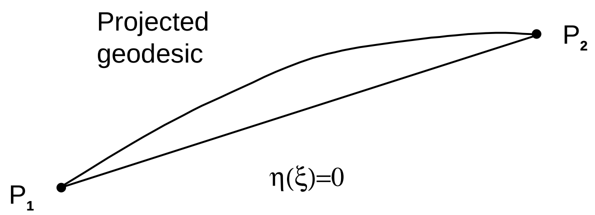

Figure 6 – Geodesic curve on the reference ellipsoid projected on the mapping plane

ellipsoid, this is the situation we will face. Let us just note that while the curved line is an image of the geodesic connecting points P_1 and P_2 on the reference ellipsoid, the straight line $\eta(\xi) = 0$ is the geodesic connecting points P_1 and P_2 on the mapping plane.

To get the uncertainty belt on the reference ellipsoid we simply calculate two curves on either side of the geodesic with +/- $k\sigma_\eta(\xi)$ offset. The result is illustrated in Fig. 7. We note,

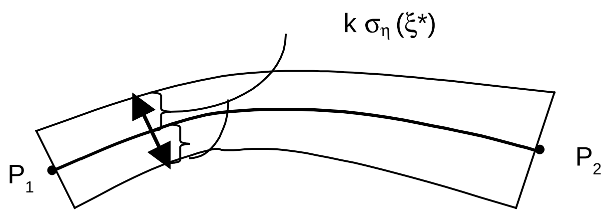

Figure 7 – Geodesic curve as a baseline

that the borders of the uncertainty belt on the ellipsoid are no longer geodesic curves.

Seaward extension

When straight baselines are extended seaward by a specific number (m) of nautical miles, the +/- $k\sigma_\eta(\xi)$-belts remain the same. For the circular portions of the sea boundary, the uncertainty belt must be calculated from the positional uncertainty (i.e., the covariance matrix **C)** of the point around which the circle is drawn. The expression for the uncertainty σ_ξ is computed again from eqn.(23). We obtain (cf. eqn.(24))

$$\sigma_\xi^2 = \sigma_x^2 \cos^2\alpha + 2\ \sigma_{x,y} \sin\alpha \cos\alpha + \sigma_y^2 \sin^2\alpha \ . \qquad (35)$$

The situation is shown on Fig.8.

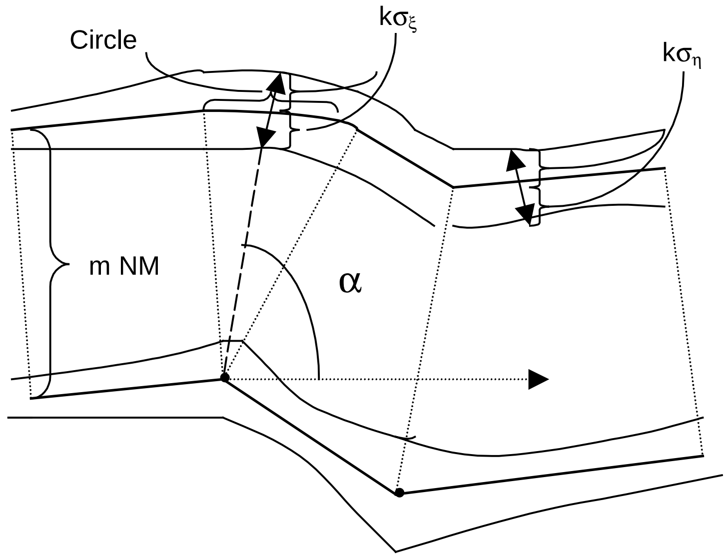

Figure 8 – Extension Seaward

Clearly, the uncertainty belt constructed around a boundary extended from land straight baselines is likely to be quite narrow. As the baselines are connecting land-based points, which are apt to have been determined to a fairly high accuracy, we may expect the width of the +/- $k\sigma_\eta(\xi)$-belt to be typically in metres, after an appropriate care has been taken to eliminate the existing systematic errors [Vaníček, 1998]. However, a similar +/- $k\sigma_\eta(\xi)$-belt should be constructed also around a boundary extended from base points located either on the 2,500-metre isobath, or at the foot of the continental slope. The positional accuracy of these submersed base points will be much worse, perhaps by up to three orders of magnitude, and, consequently, the width of the uncertainty belt may be up to several kilometres wide.

Encroachment issues

The most important consequence of the boundary uncertainty is in the realm of encroachment. How does the uncertainty impact the act of encroachment? Put quite simply, an <u>encroachment becomes a probabilistic issue</u>! It should be possible to attach a probability to a statement "Party A is encroaching on state's X territory". This concept is illustrated in Fig.9. The

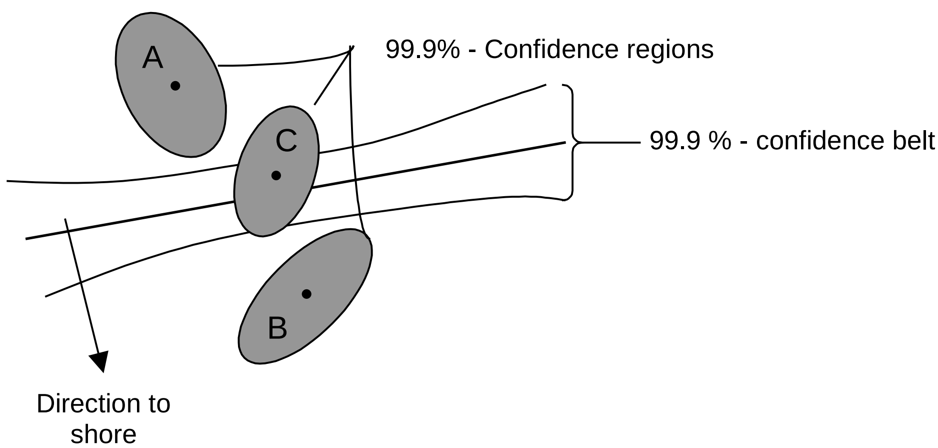

Figure 9 - Encroachment

figure shows a boundary with its uncertainty belt, the positions of the potential encroachers and the positional uncertainties of these positions. It is easy to see that in this illustration, the probability of party A encroaching on X's territory is practically nil. Conversely, the probability of B encroaching is practically equal to 1, i.e., party B is certainly encroaching. The answer is not clear cut in the case of party C.

In reality, the situation is even more complicated. In addition to the position determined by the potential encroacher there is the position (of the potential encroacher) as determined by the potentially injured country. In Fig.10, A is the position determined by encroacher and A' is the

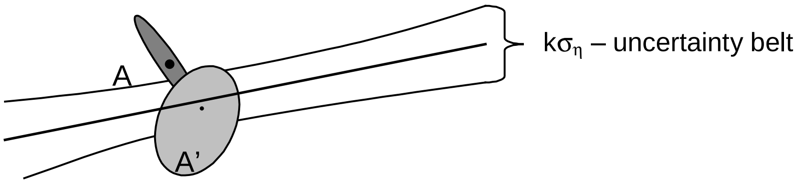

Figure 10 – Real situation

position determined by the injured country. The two positions as shown are statistically compatible on a probability level that can be evaluated from the overlap of the confidence regions. What is now the probability that party A is encroaching?

Conclusions

We have derived the rigorous expressions for the uncertainty in a maritime boundary caused by random errors in position determination and suggested how this uncertainty can be quantified, and shown on the reference ellipsoid or on a map, for a desired level of probability. We have also pointed out that, once the uncertainty is quantified, it is possible to determine the specific probability with which an encroachment occurs. Finally, we have pointed out that in practice the situation is more complicated by the fact that there would be two 'competing' position determinations, one by the potential encroacher and one by the potentially injured country. Working out the involved probabilistic estimates was, however, considered to be outside the scope of this contribution.

It is recommended that the probabilistic estimates be investigated in detail and the legal connotations be tested in court.

Acknowledgment

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SESSION 2 – Paper 4

ACCURACY OF COMPUTED POINTS ON A MEDIAN LINE, FACTORS TO BE CONSIDERED

by Milan HOREMUŽ, Lars E. SJÖBERG and Huaan FAN, Sweden

The Precision of the Median Line Turning Points for Various Reference Surfaces and Computing Algorithms

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Biographies

Milan Horemuž received the master degree in Geodesy and cartography in 1987 and the doctoral degree (1996) in geodesy, both from the Slovak Technical University (STU) in Bratislava.

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His research interests include problems in applications of GPS in surveying engineering, like ambiguity resolution, systematic error reduction, deformation monitoring and analysis and recently precise navigation of a moving platform by means of sensor integration.

Lars E. Sjöberg graduated from the School of Surveying, Royal Institute of Technology (KTH), Stockholm, in 1971, and four years later he achieved a PhD in Geodesy at KTH. He worked as a research associate at the Ohio State University for 15 months during 1977 and 1978, and after a short return to KTH he worked with the National Land Survey of Sweden to 1984, when he returned to KTH as a full professor in geodesy.

Through the years he has been a member of several IAG special study groups and commissions, and he has chaired three such study groups. He is a Fellow of the Alexander-von-Humboldt Foundation since 1983, Fellow of the IAG since 1991, a presidium member of the Nordic Geodetic Commission since 1982 and corresponding member of the German Geodetic Commission since 1989.

His research interests are in the fields of geodetic theory of errors, physical geodesy, GPS positioning and deformation analysis. He has served in the editorial boards of Manuscripta Geodaetica and Bulletine Geodesique from 1989 to 1995 and he has published more than 180 articles and reports.

Huaan Fan received his BSc in engineering surveying in 1983 from Wuhan Technical University of Surveying and Mapping, Wuhan, China. He obtained his PhD in 1989 from Royal Institute of Technology, Stockholm, Sweden. He is now a senior lecturer in geodesy and Director of Studies at the Department of Geodesy and Photogrammetry, the Royal Institute of Technology. His major research interests are in the fields of physical geodesy, ellipsoidal geodesy and adjustment theory.

ABSTRACT

The median line between states separated by sea and its turning points are computed based on known coordinates of basepoints on the shorelines. Here we study the precision of computed coordinates on three reference surfaces: plane, sphere and ellipsoid. Four different algorithms for turning points computation are investigated. Sample calculations show significant propagation of errors in the basepoint coordinates into computed coordinates of median line turning points.

INTRODUCTION

The sea boundary between two opposite countries is conventionally defined by the median line. The median line should be in ”the middle” of the sea separating the two countries, or, by definition, each point of the median line must be equidistant to the nearest points on the baselines from which the breadth of the territorial seas of each of the two States is measured. To be able to apply this definition, one has to define the baselines on both shores. Each baseline is in reality a continuous curve, except in some special cases, named in the UNCLOS (1982), when straight baselines are used instead. But for practical calculations, the continuous curve must be broken down into a finite set of points, which sufficiently well approximates the curve. Then these points can be treated as a set of baselines (direct connectors of neighbouring points) or simply as a set of individual points, depending on the chosen algorithm for median line computation. Hence, the median line is formed by a string of straight lines. It may have as many turning points as is the number of basepoints, i.e. the surveyed and marked points on the shorelines (being the end points of the baselines). In other words, each basepoint can cause a turning point on the median line, depending on the particular situation.

We do not attempt to suggest an algorithm for median line computation in this work. The purpose is rather to investigate the precision of calculated coordinates of median line turning points using four different algorithms. Neither of the algorithms produces a solution in perfect accordance with the definition under any geometrical situation. According to the definition, the median line should be computed from baselines, rather than from individual points. Since there have been applied algorithms using individual points (i.e. Carrera 1987), we have also included two such algorithms in our study. We understand these four algorithms as the basic model situations for the turning point calculations. The rigorous solution of the median line could be a combination of these approaches.

It is obvious that the coordinates of the basepoints in both countries must be given (or transformed) into the same reference frame, for example ITRF92. The calculations can be performed on any reference surface, like plane, sphere, or preferably on an ellipsoid. We will study the random error propagation on the plane and the sphere, and in the case of the three-point algorithm also on the ellipsoid.

Four algorithms for the turning point calculations are thus investigated:

Algorithm 1 A turning point is calculated as an intersection of a median line and a line perpendicular to one of the baselines and passing through the basepoint (Figure 1).

Algorithm 2 A turning point is calculated as an intersection of two median lines (Figure 2).

Algorithm 3 A turning point is calculated as a midpoint between two opposite basepoints (Figure 3).

Algorithm 4 A turning point is a point equidistant from three basepoints (Figure 4).

The first two approaches use baselines for the definition of the median line, while approaches 3 and 4 use basepoints.

This paper is mainly based on the studies by Sjöberg (1996), Horemuž (1999) and Fan (1999), and more details can be found there.

Solution in the plane
Algorithm 1

Let us consider the simplest situation: there are two baselines formed by four basepoints B_1, B_2 and B_3, B_4, respectively (Figure 1). The median line will be formed by the axis of the angle between baselines B_1-B_2 and B_3-B_4. The turning points are constructed as the intersections between the median line and the perpendicular lines to B_1-B_2 or B_3-B_4 passing through points B_1, B_2, B_3 and B_4, respectively. Here we study the precision of turning points P_1 and P_2 defined as shown in Figure 1. The lines p_1, p_2 pass through a pair of basepoints, which depend on a particular situation. In this work we did not investigate which pair should be chosen, but we always use points B_1 and B_2.

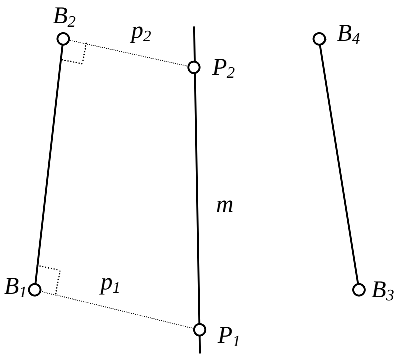

Figure 1: Construction of median line turning points, approach 1: B_1...B_4 are basepoints; P_1, P_2 are turning points of the median line *m*, i.e. intersection of the median line m and a line p perpendicular to baseline B_1-B_2 passing points B_1 and B_2, respectively.

The coordinates of points P_1 and P_2 can be expressed analytically as follows (Horemuž 1999):

$$n_{pi} = \frac{C.\alpha - A.\gamma_i}{-A.\beta + B.\alpha} \qquad e_{pi} = \frac{\beta.C - \lambda_i.B}{-A.\beta + B.\alpha} \tag{1}$$

where

$$\left.\begin{aligned} A &= \pm a_1.\sqrt{a_2^2 + b_2^2} - a_2.\sqrt{a_1^2 + b_1^2} \\ B &= \pm b_1.\sqrt{a_2^2 + b_2^2} - b_2.\sqrt{a_1^2 + b_1^2} \\ C &= \pm c_1.\sqrt{a_2^2 + b_2^2} - c_2.\sqrt{a_1^2 + b_1^2} \end{aligned}\right\} \tag{2}$$

$$\left.\begin{aligned} &\alpha = (e_2 - e_1), \beta = (n_2 - n_1) \\ &\lambda = (e_2 - e_1).e_i - (n_2 - n_1).n_i,\ i = 1,2 \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} a_1 = n_2 - n_1, \quad b_1 = e_1 - e_2, \quad c_1 = n_1.e_2 - e_1.n_2 \\ a_2 = n_4 - n_3, \quad b_2 = e_3 - e_4, \quad c_2 = n_3.e_4 - e_3.n_4 \end{aligned}\right\} \tag{4}$$

and n_i, e_i, $i=1...4$, denote planar coordinates (northing, easting) of points B_1...B_4. The solution is not unique (± in Eqs. (2)) because there are 2 possible median lines between baselines B_1-B_2 and B_3-B_4. One of them is displayed in Figure 1 and the second one is perpendicular to the first one and is passing through the intersection of the baselines B_1-B_2 and B_3-B_4. The suitable solution must be chosen, depending on the particular situation.

The covariance matrix of coordinates is derived by applying the law of variance propagation to Eqn. (1). If Σ_{bas} is a covariance matrix of the basepoints, then the covariance matrix of coordinates of point P (Σ_p) will be:

$$\Sigma_p = J_p . \Sigma_{bas} . J_P^T \qquad (5)$$

where

$$J_P = \begin{bmatrix} \dfrac{\partial e_p}{\partial e_1} & \dfrac{\partial e_p}{\partial n_1} & \cdots & \cdots & \dfrac{\partial e_p}{\partial e_4} & \dfrac{\partial e_p}{\partial n_4} \\ \dfrac{\partial n_p}{\partial e_1} & \dfrac{\partial n_p}{\partial n_1} & \cdots & \cdots & \dfrac{\partial n_p}{\partial n_4} & \dfrac{\partial n_p}{\partial n_4} \end{bmatrix} \qquad (6)$$

Algorithm 2

In this approach, the coordinates of turning points are calculated by the intersection of two median lines. Figure 2 shows an example.

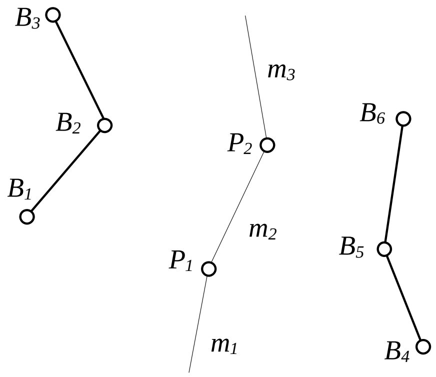

Figure 2: Construction of median line turning points; algorithm 2.

The turning point P_1 is the intersection of median lines m_1 and m_2, with the coordinates:

$$e_{p1} = \frac{B_1.C_2 - C_1.B_2}{A_1.B_2 - A_2.B_1}, \quad n_{p1} = \frac{C_1.A_2 - A_1.C_2}{A_1.B_2 - A_2.B_1} \qquad (7)$$

and turning point P_2 is the intersection of median lines m_2 and m_3, with the coordinates:

$$e_{p2} = \frac{B_2.C_3 - C_2.B_3}{A_2.B_3 - A_3.B_2}, \quad n_{p2} = \frac{C_2.A_3 - A_2.C_3}{A_2.B_3 - A_3.B_2} \qquad (8)$$

where A_i, B_i, C_i, $i=1...3$, are functions of planar coordinates (n_i, e_i) of basepoints B_1,...,B_6. For further details see Horemuž (1999). The covariance matrix of coordinates (n_{P1}, e_{P1}, n_{P2}, e_{P2}) can be derived by applying the law of variance propagation to Eqs. (7) and (8).

Algorithm 3

A turning point of a maritime limit can be simply defined as a midpoint of two opposite basepoints (Figure 3). This algorithm is also described in Carrera (1987).

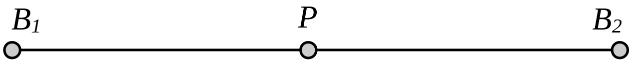

Figure 3: Construction of a turning point, algorithm 3. Distance B_1 - P = Distance B_2 - P.

The coordinates of P are simply calculated as the average of coordinates of points B_1 and B_2:

$$e_p = (e_1 + e_2)/2, \quad n_p = (n_1 + n_2)/2 \tag{9}$$

and their variances are given by:

$$\sigma_{ep}^2 = (\sigma_{e1}^2 + \sigma_{e2}^2)/4, \quad \sigma_{np}^2 = (\sigma_{n1}^2 + \sigma_{n2}^2)/4 \tag{10}$$

From Eqn. (10) we can see that the precision of the calculated position of P depends only on the precision of basepoints, not on their geometry.

Algorithm 4

In the following approach, the turning point is determined as the equidistant point from three basepoints (Figure 4). Two of them lie on one coast and one on the other. This algorithm is also known as a three-point algorithm (Carrera 1987).

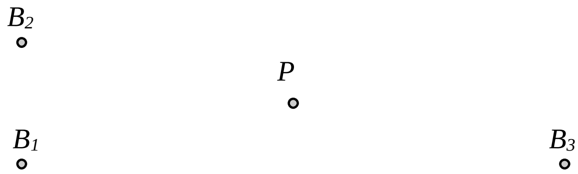

Figure 4: Construction of a turning point P; algorithm 4. Distance B_1-P = B_2-P = B_3-P.

Analytically, the coordinates of P can be calculated by the intersection of the normals of the lines B_1-B_2 and B_1-B_3. The normals pass through the midpoint of B_1-B_2 and B_1-B_3, respectively. The resulting coordinates become (Horemuž 1999):

$$n_p = \frac{1}{2} \cdot \frac{(e_3^2 + n_3^2) \cdot (e_2 - e_1) + (e_2^2 + n_2^2) \cdot (e_1 - e_3) + (e_1^2 + n_1^2) \cdot (e_3 - e_2)}{n_3 \cdot (e_1 - e_2) + n_2 \cdot (e_3 - e_1) + n_1 \cdot (e_2 - e_3)} \tag{11}$$

and

$$e_p = \frac{1}{2} \cdot \frac{(e_3^2 + n_3^2) \cdot (n_2 - n_1) + (e_2^2 + n_2^2) \cdot (n_1 - n_3) + (e_1^2 + n_1^2) \cdot (n_3 - n_2)}{n_3 \cdot (e_1 - e_2) + n_2 \cdot (e_3 - e_1) + n_1 \cdot (e_2 - e_3)} \tag{12}$$

and the law of variance propagation can be applied.

Solution on the sphere
Algorithm 1

Let us now consider an analogous situation, as shown in the Figure 1, on a spherical surface. Now, all lines in the figure can be considered as great circles on a sphere of radius r. We decided to solve this problem in a three-dimensional Cartesian coordinate system with the origin in the centre of the sphere. The coordinates of points P_i, i=1,2, can be computed using the following equations (Horemuž 1999):

$$X_P = \pm \frac{r \cdot (C \cdot \beta_i - B \cdot \gamma_i)}{AUX}, \quad Y_P = \mp \frac{r \cdot (C \cdot \alpha_i - A \cdot \gamma_i)}{AUX}, \quad Z_p = \pm \frac{r \cdot (B \cdot \alpha_i - A \cdot \beta_i)}{AUX}, \tag{13}$$

where

$$AUX = \sqrt{\left(B\cdot\gamma_i - \beta_i \cdot C\right)^2 + \left(\alpha_i \cdot C - A\cdot\gamma_i\right)^2 + \left(\alpha_i \cdot B - A\cdot\beta_i\right)^2} \tag{14}$$

and all terms in Eqs. (13) and (14) are functions of the Cartesian coordinates of the basepoints.

Let us consider the analogous situation as in the planar case. That is: each basepoint B_1, B_2, B_3, B_4 has the same standard error of coordinates. These standard errors are expressed in a coordinate system of local geodetic horizon - LGH (see Figure 6) in the east and north direction, and they are assumed not correlated. Then the covariance matrix of a basepoint will be as follows:

$$\Sigma_{LGH} = \begin{bmatrix} \sigma_n^2 & 0 & 0 \\ 0 & \sigma_e^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{15}$$

where we assume that all points lie on a spherical surface with zero standard error of the height coordinate. The covariance matrix can be rotated to the Cartesian system as follows:

$$\Sigma_{XYZ} = R^T \cdot \Sigma_{LGH} \cdot R \tag{16}$$

where

$$R = \begin{bmatrix} -\sin\varphi\cdot\cos\lambda & -\sin\varphi\cdot\sin\lambda & \cos\varphi \\ -\sin\lambda & \cos\lambda & 0 \\ \cos\varphi\cdot\cos\lambda & \cos\varphi\cdot\sin\lambda & \sin\varphi \end{bmatrix} \tag{17}$$

is the rotation matrix from Cartesian to LGH coordinate system.

The covariance matrix of the Cartesian coordinates of point P, Σ_{PC}, follows from the equation:

$$\Sigma_{PC} = J_p \cdot \Sigma_{XYZ} \cdot J_P^T \tag{18}$$

where

$$J_P = \begin{bmatrix} \frac{\partial X_P}{\partial X_1} & \frac{\partial X_P}{\partial Y_1} & \frac{\partial X_P}{\partial Z_1} & \cdots & \cdots & \frac{\partial X_P}{\partial X_4} & \frac{\partial X_P}{\partial Y_4} & \frac{\partial X_P}{\partial Z_4} \\ \frac{\partial Y_P}{\partial X_1} & \frac{\partial Y_P}{\partial Y_1} & \frac{\partial Y_P}{\partial Z_1} & \cdots & \cdots & \frac{\partial Y_P}{\partial X_4} & \frac{\partial Y_P}{\partial Y_4} & \frac{\partial Y_P}{\partial Z_4} \\ \frac{\partial Z_P}{\partial X_1} & \frac{\partial Z_P}{\partial Y_1} & \frac{\partial Z_P}{\partial Z_1} & \cdots & \cdots & \frac{\partial Z_P}{\partial X_4} & \frac{\partial Z_P}{\partial Y_4} & \frac{\partial Z_P}{\partial Z_4} \end{bmatrix} \tag{19}$$

The covariance matrix Σ_{PC} can be rotated back to the coordinate system of LGH (Σ_{PLGH}) by the transformation:

$$\Sigma_{PLGH} = R\cdot \Sigma_{PC} \cdot R^T \tag{20}$$

Algorithm 2

Let us consider the same situation as in the Figure 2, but on a spherical surface. Lines are now defined as intersections of planes and sphere. The formulae for computing Cartesian coordinates of the turning point P_1 are as follows (Horemuž 1999):

$$X_{P1} = \pm \frac{r \cdot (C_1 \cdot B_2 - B_1 \cdot C_2)}{AUX}, \quad Y_{P1} = \mp \frac{r \cdot (C_1 \cdot A_2 - A_1 \cdot C_2)}{AUX}, \quad Z_{P1} = \pm \frac{r \cdot (B_1 \cdot A_2 - A_1 \cdot B_2)}{AUX} \tag{21}$$

where

$$AUX = \sqrt{(C_2 \cdot B_1 - C_1 \cdot B_2)^2 + (A_2 \cdot C_1 - A_1 \cdot C_2)^2 + (A_2 \cdot B_1 - A_1 \cdot B_2)^2} \tag{22}$$

and all terms in Eqs. (21) and (22) are functions of the Cartesian coordinates of the basepoints. The error calculation is similar to that of algorithm 1.

Algorithm 3

The spherical case in this approach is similar to the planar one (Figure 3). The coordinates of the space midpoint *P’* can be calculated as the average of the basepoints coordinates
$P’[(x_1 + x_2)/2, (y_1 + y_2)/2, (z_1 + z_2)/2]$.
The midpoint *P* on the sphere can be computed as an intersection of the line *OP’* (*O* is the origin of the coordinate system) and the sphere as follows:

$$\left.\begin{aligned} X_p &= \pm \frac{r.(x_1 + x_2)}{\sqrt{(x_1+x_2)^2 + (y_1+y_2)^2 + (z_1+z_2)^2}} \\ Y_p &= \pm \frac{r.(y_1 + y_2)}{\sqrt{(x_1+x_2)^2 + (y_1+y_2)^2 + (z_1+z_2)^2}} \\ Z_p &= \pm \frac{r.(z_1 + z_2)}{\sqrt{(x_1+x_2)^2 + (y_1+y_2)^2 + (z_1+z_2)^2}} \end{aligned}\right\} \tag{23}$$

Please note, that if the point B_1 lies exactly on the opposite side of the sphere as the point B_2, i.e. the line B_1B_2 passes the centre of the sphere *O*, then there are an infinite number of solutions to this problem. In all other cases there are two solutions (± in the Eqn. (23)). The error calculation is identical with that of algorithm 1.

Algorithm 4

The geometry of this approach is shown in Figure 5. Symbol Q_1 denotes the plane which is perpendicular to the plane defined by points B_1, B_2 and *O* (centre of the sphere) and passing through the midpoint of points B_1 and B_2. The plane Q_2 is defined analogously. The turning point *P* is then formed by the intersection of the planes Q_1, Q_2 and the sphere.

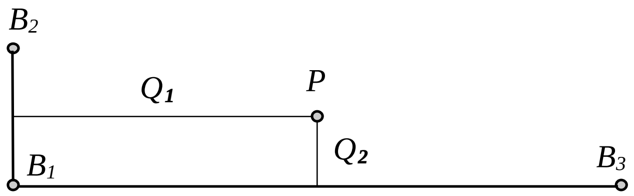

Figure 5: Construction of a median line turning point on the sphere; algorithm 4.

The derivation of the formulae is similar to the derivation of the algorithm 1. The coordinates of point P become: ,

$$X_P = \pm r \cdot \frac{b_4 \,.\, c_3 - c_4 \,.\, b_3}{AUX}, \quad Y_P = \pm r \cdot \frac{a_4 \,.\, c_3 - c_4 \,.\, a_3}{AUX}, \quad Z_P = \pm r \cdot \frac{b_4 \,.\, c_3 - c_4 \,.\, b_3}{AUX}$$

(24)

with

$$AUX = \sqrt{(c_3 \cdot b_4 - b_3 \cdot c_4)^2 + (c_4 \cdot a_3 - c_3 \cdot a_4)^2 + (a_3 \cdot b_4 - b_3 \cdot a_4)^2} \tag{25}$$

and all terms in Eqs. (24) and (25) are functions of the Cartesian coordinates of the basepoints. The law of variance propagation can be applied to Eqs. (24) to calculate the variance-covariance matrix of P.

Solution on the ellipsoid

We now present an ellipsoidal solution of the algorithm 4. Let P_1, P_2 and P_3 be three points on the reference ellipsoid and let (ϕ_1, λ_1), (ϕ_2, λ_2) and (ϕ_3, λ_3) denote the geodetic latitude and longitude of these three points, respectively. Let P_m (ϕ_m, λ_m) be the point on the reference ellipsoid which is at equal distance $s_1 = s_2 = s_3 = s$ to P_1, P_2, P_3, respectively (Fan 1999). Furthermore, we assume that (ϕ_m^0, λ_m^0) denotes the approximate coordinates of P_m and $(\delta\phi_m^0, \delta\lambda_m^0)$ denotes the corresponding corrections of coordinates:

$$\phi_m = \phi_m^0 + \delta\phi_m, \quad \lambda_m = \lambda_m^0 + \delta\lambda_m \tag{26}$$

Generally, the geodesic line s_i is a function of ϕ_m, λ_m and ϕ_i, λ_i ($i=1,2,3$):

$$s = s_i = f(\phi_m, \lambda_m, \phi_i, \lambda_i) = f\left(\phi_m^0 + \delta\phi_m, \lambda_m^0 + \delta\lambda_m, \phi_i, \lambda_i\right) \tag{27}$$

which can be expanded into a Taylor series around the approximate coordinates (ϕ_m^0, λ_m^0) :

$$s = s_i = f\left(\phi_m^0, \lambda_m^0, \phi_i, \lambda_i\right) + \frac{\partial f}{\partial \phi_m} \cdot \delta\phi_m + \frac{\partial f}{\partial \lambda_m} \cdot \delta\lambda_m + \frac{1}{2!}\frac{\partial^2 f}{\partial \phi^2} \cdot (\delta\phi_m)^2 + \cdots \tag{28}$$

Knowing the approximate coordinates of P_m, the approximate geodesic line $s_i^0 = f\left(\phi_m^0, \lambda_m^0, \lambda_i\right)$ is the solution to the so called inverse geodetic problem on the ellipsoid. Neglecting all non-linear terms, we have:

$$s \approx s_i^0 + a_i \cdot \delta\phi_m + b_i \cdot \delta\lambda_m, \; i = 1,2,3 \tag{29}$$

where a_i, and b_i are defined as follows (Fan 1997b):

$$a_i = -M_m^0 \cdot cos\,\alpha_{mi}^0, \;\; b_i = N_i \cdot cos\,\phi_i \cdot sin\,\alpha_{im}^0 \tag{30}$$

In Eqn. (30), α_{mi}^0, α_{im}^0 denote azimuths from P_m to P_i, and from P_i to P_m, respectively, computed using (ϕ_i, λ_i) and (ϕ_m^0, λ_m^0). M_m^0 is the radius of curvature of the meridian at latitude ϕ_m^0 and N_i is the radius of curvature in the prime vertical at latitude ϕ_i:

$$M_m^0 = \frac{a \cdot (1 - e^2)}{\left(1 - e^2 \cdot sin^2\,\phi_m^0\right)^{\frac{3}{2}}}, \quad N_i = \frac{a}{\sqrt{1 - e^2 \cdot sin^2\,\phi_i}} \tag{31}$$

Subtracting the first equation in (29) from the second and third one, respectively, we obtain:

$$\begin{bmatrix} a_2 - a_1 & b_2 - b_1 \\ a_3 - a_1 & b_3 - b_1 \end{bmatrix} \cdot \begin{bmatrix} \delta\phi_m \\ \delta\lambda_m \end{bmatrix} = \begin{bmatrix} s_1^0 - s_2^0 \\ s_1^0 - s_3^0 \end{bmatrix} \tag{32}$$

Denoting the first matrix in Eqn. (32) as $\boldsymbol{A}$, $(\delta\phi_m, \delta\lambda_m)$ can be directly solved as:

$$\begin{bmatrix} \delta\phi_m & \delta\lambda_m \end{bmatrix}^T = \boldsymbol{A}^{-1} \cdot \begin{bmatrix} s_1^0 - s_2^0 & s_1^0 - s_3^0 \end{bmatrix} \tag{33}$$

After $(\delta\phi_m, \delta\lambda_m)$ has been computed, the final coordinates (ϕ_m, λ_m) of P_m can then be obtained from Eqs. (26).

If the coordinates of the coastal points P_1, P_2, P_3 contain errors, these errors will automatically propagate into the coordinates (ϕ_m, λ_m) of the mid-point P_m derived from Eqs. (26) and (33). The relations between the coordinate correction $(\delta\phi_m, \delta\lambda_m)$ for the mid-point P_m and the coordinate correction $(\delta\phi_i, \delta\lambda_i)$ for a coastal point P_i ($i=1,2,3$) can be found through linearization of the distance s_i from P_m to P_i :

$$s_i = f\left(\phi_m^0 + \delta\phi_m, \lambda_m^0 + \delta\lambda_m, \phi_i + \delta\phi_i, \lambda_i + \delta\lambda_i\right) \approx s_i^0 + a_i \cdot \delta\phi_m + b_i \cdot \delta\lambda_m + c_i \cdot \delta\phi_i + d_i \cdot \delta\lambda_i, \tag{34}$$

where s_i^0, a_i and b_i have been already introduced and c_i, d_i are defined as follows:

$$c_i = -M_i \cdot \cos\alpha_{im}^0, \quad d_i = -b_i = -N_i \cdot \cos\phi_i \cdot \sin\alpha_{im}^0 \tag{35}$$

By subtracting the second and third equations in (34) from the first one, respectively, we obtain:

$$\begin{bmatrix} \delta\phi_m & \delta\lambda_m \end{bmatrix}^T = \boldsymbol{A}^{-1} \cdot \begin{bmatrix} s_1^0 - s_2^0 & s_1^0 - s_3^0 \end{bmatrix}^T + \boldsymbol{B} \cdot \begin{bmatrix} \delta\phi_1 & \delta\lambda_1 & \delta\phi_2 & \delta\lambda_2 & \delta\phi_3 & \delta\lambda_2 \end{bmatrix}^T \tag{36}$$

where $\boldsymbol{A}$ has the same meaning as in Eqn. (33) and $\boldsymbol{B}$ is defined by:

$$\boldsymbol{B} = \boldsymbol{A}^{-1} \cdot \begin{bmatrix} c_1 & d_1 & -c_2 & -d_2 & 0 & 0 \\ c_1 & d_1 & 0 & 0 & -c_3 & -d_3 \end{bmatrix} \tag{37}$$

Applying the error propagation law (Fan, 1997, p.12) on Eqn. (36), the variance-covariance matrix $\boldsymbol{\Sigma}_m$ of the coordinates (ϕ_m, λ_m) of P_m can be obtained:

$$\Sigma_m = \boldsymbol{B} \cdot \Sigma \cdot \boldsymbol{B}^T \tag{38}$$

where $\boldsymbol{\Sigma}$ denotes the variance-covariance matrix of the coordinate vector $\boldsymbol{X}_c$ for the three coastal points P_1, P_2, P_3 :

$$\boldsymbol{X}_c = \begin{bmatrix} \phi_1 & \lambda_1 & \phi_2 & \lambda_2 & \phi_3 & \lambda_2 \end{bmatrix}^T \tag{39}$$

Sample calculations

For all the following numerical calculations let us assume that the coordinate standard errors of basepoints expressed in a plane are uncorrelated and the same with $\sigma_e = \sigma_n = 0.05\ m$. The sample cases were generated by the following scheme: Coordinates of basepoints were calculated in the LGH plane of the point B_1 (Figure 6), based on chosen azimuth of baselines and distances between points. The origin of the LGH system is thus point B_1, e-axis points to the east and n-axis points to the north. The coordinates calculated in this way were used for calculations in the plane.

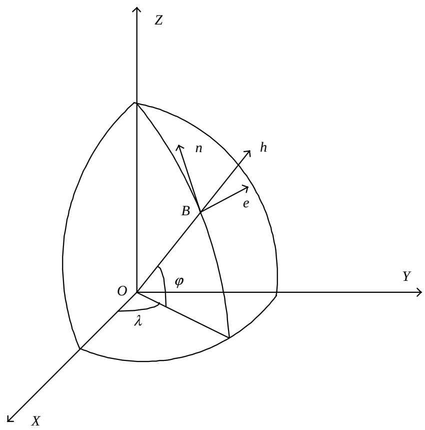

Figure 6: The coordinate system of Local Geodetic Horizon (LGH).

The spherical coordinates of point B_1 were chosen as, $\varphi = 59°$, $\lambda = 59°$ and transformed to Cartesian coordinates XYZ, by the relation:

$$X = r \cdot \ cos\ \phi \cdot cos\ \lambda, \quad Y = r \cdot cos\ \phi \cdot sin\ \lambda, \quad Z = r \cdot sin\ \phi \tag{40}$$

where the radius of the sphere r was set to 6378 km. Then the LGH coordinates were rotated to Cartesian using the rotation matrix (Eqn. (17)):

$$[\Delta X \quad \Delta Y \quad \Delta Z]^T = \boldsymbol{R}^T \cdot [n \quad e \quad h]^T \tag{41}$$

where ΔX, ΔY and ΔZ are the coordinates relative to the point B_1.
Having the Cartesian coordinates, it is then possible to perform calculations of coordinate errors of points P on a spherical, or an ellipsoidal surface.

Algorithm 1 – example

The geometry of this example is shown in Figure . The baselines are 10 km long and separated by 1000 km. In Table 1 we can see almost identical standard errors in the n coordinate, but rather big difference in e coordinate between the planar and spherical solutions. The big difference between σ_n and σ_e is reasonable, because the median line has a north-south direction and thus σ_n is bigger. It is worth to point out that a 5 cm error in the basepoints causes almost 4 m error in the calculated turning point of the median line.

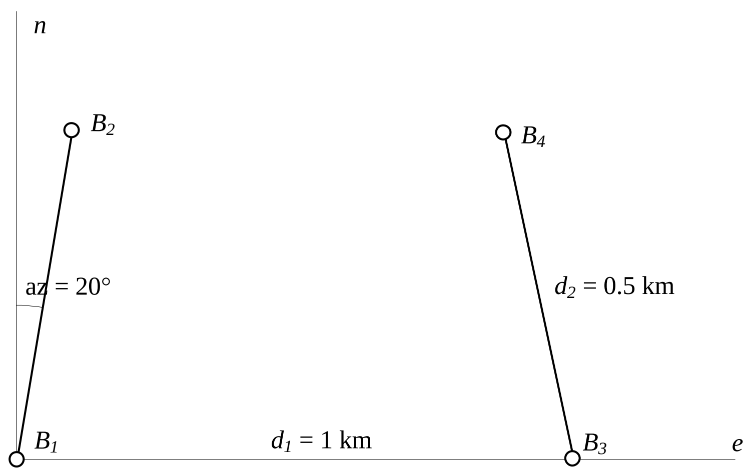

Figure 7: Configuration of baselines in the example of algorithm 1.

Table 1: Standard errors of the median line turning point coordinates; algorithm 1.

Point	Spherical solution		Planar solution	
	σ_n [m]	σ_e [m]	σ_n [m]	σ_e [m]
P_1	3.922	0.512	3.997	0.038
P_2	3.913	0.474	3.983	0.038

Algorithm 2 – example

The turning point P_1 (P_2) is calculated as an intersection of the median lines formed by baselines B_1-B_2, B_4-B_5 and B_1 -B_2, B_5-B_6 (B_1-B_2, B_5-B_6 and B_2- B_3, B_5-B_6) - Figure 8. This example can be compared to the previous one, where roughly the same ratio between the length and separation of baselines is used. Table 2 shows the coordinate errors calculated on the sphere and in the plane. They are approximately at the same level as in the previous example. We notice also that in this case the differences between the spherical and planar solutions are small.

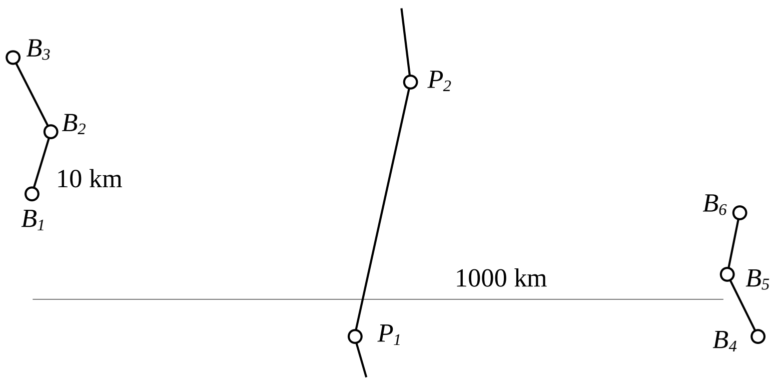

Figure 8: Configuration of baselines in example of algorithm 2

Table 2: Standard errors of the median line turning point coordinates; algorithm 2.

Point	Spherical solution		Planar solution	
	σ_n [m]	σ_e [m]	σ_n [m]	σ_e [m]
P_1	2.103	0.659	2.124	0.579
P_2	2.087	0.681	2.133	0.600

Algorithm 3 – example

The propagated errors depend exclusively on errors in basepoint coordinates on the planar surface and almost exclusively on the sphere. The error propagation on the sphere is almost identical to the planar case. The propagated errors in the case, when the distance between basepoints is 1000 km, is the same for both surfaces: $\sigma_e = \sigma_n = 0.035\,m$.

Algorithm 4 – example

To be able to compare the results of algorithm 4 with previous examples, we choose the distance between points B_1 and B_2 (Figure 5) as 10 km and the distance between points B_2 and B_3 to 1000 km. Table 3 shows the results for this case. The points B_1 and B_2 lie on one shoreline. Unlike algorithm 3, here propagated errors depend on both geometry and errors in the basepoints. There are only small differences between spherical and ellipsoidal solutions - only 6 mm in σ_n and 0 mm in σ_e. This result is expected due to little eccentricity of the reference ellipsoid.

The large standard error in the north direction is due to the fact, that the baseline B_1-B_3 has a north - south direction and is 100 times shorter than the length of baseline B_1-B_2.

Table 3: Standard errors of the median line turning point coordinates; algorithm 4.

Point	Spherical solution		Planar solution		Ellipsoidal solution	
	σn [m]	σe [m]	σn [m]	σe [m]	σn [m]	σe [m]
P	3.472	0.468	3.535	0.035	3.478	0.468

Concluding remarks

We have studied how the errors in basepoint position propagate into the calculated coordinates of the median line turning points. The error propagation is different for each algorithm and is different for the calculations in the plane and on the sphere and ellipsoid. It is worth to point out here, that, although the difference between calculated coordinates on different surfaces is several kilometres, the difference in calculated errors is only several decimetres. Certainly we would get even smaller differences, if we choose the best fitting plane for the given region, or chart plane. In our calculations we used tangential plane in point 1. In Fan (1999), the Gauss-Krüger map projection has been used to obtain the planar solution. The error propagation depends on both the configuration of the basepoints (except for algorithm 3) and on the errors in basepoints. Based on the numerical investigation, we conclude:

1. The larger the separation between basepoints and of shorelines, the bigger is the difference between planar and spherical solution. The difference between calculated standard errors can be as large as 0.5 m for the 1000 km coastal separation for the given examples.

2. The random error propagation is insensitive to the scale. That is, if we change the distance between baselines and the length of baselines by the same factor, we will get the same errors in calculated coordinates. This holds exactly only for calculations in the plane.

3. The propagated errors are proportional to the ratio between coast separation and baseline length. It is therefore preferable to form long baselines on coasts. However, increased baseline length might lead to worse approximation of the real coastal lines.

All numerical examples were evaluated using standard error of the basepoint coordinates $\sigma_e = \sigma_n = 0.05\,m.$ m, which is a reasonable value, if the points were determined by geodetic measurements. If we multiply this value by some factor, then we magnify the calculated turning point errors by the same factor. The numerical examples were intended to give an idea of the magnitudes of the propagated errors.

It is generally accepted that all coordinate computations concerning maritime delimitation are to be performed on the reference ellipsoid. Based on the differences between error propagation in the plane and on the sphere we can conclude that differences between the error propagation on sphere and ellipsoid will be reasonably small or negligible. This assumption is confirmed by the example of algorithm 4, where the ellipsoidal solution is also derived. The sphere approximates the ellipsoid better than the plane approximates the sphere. For example, if we approximate the sphere by a tangent plane, we commit more than 8 km error at 1000 km distance. But if we approximate the ellipsoid by a sphere, the error becomes only 35 m at 1000 km distance. These errors are calculated for the case where the plane, (sphere) is tangential to the sphere, (ellipsoid) in one point. For a given region it is possible to find an optimum approximation when the plane, (sphere) intersects the sphere, (ellipsoid). By doing so we minimise the differences between planar and spherical, or spherical and ellipsoidal solutions, respectively. This approximation is not sufficient for coordinate calculations, but it may be suitable for error propagation calculations.

This work does not deal with the choice of method of coordinate calculations of the median line, but it must be noted that none of the presented approaches provide a rigorous solution. However, each approach can be a part of such a solution, depending on a particular situation. The rigorous solution is a subject to future research.

After all, is the error calculation needed at all for median line determination? Yes, because if we deal with a position of a point, it is vitally important to know its accuracy. In the case of the maritime boundary, the computed median line represents the most probable position of the boundary. When it comes to a potential dispute about its validity, or about an exploitation near the border, it may be requested to re-measure the basepoints and re-determine the border. If the new measurement changes the position of a basepoint by 5 cm, the border can be shifted in some cases one or more metres. Consequently, it is important to associate the computed border with an uncertainty region, i.e. with error information.

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SESSION 2 – Paper 5

MARITIME ZONE BOUNDARY GENERATION FROM STRAIGHT BASELINES DEFINED AS GEODESICS

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Biographies

Brian Murphy, a registered surveyor, is a maritime boundary delimitation consultant. At the time of his retirement from the Australian Surveying and Land Information Group (AUSLIG) in 1998, he was managing the Maritime Boundaries Program and was responsible for the implementation and development of the Australian Maritime Boundaries Information System (AMBIS), which encompasses information of interest to all levels of Australian government. Brian has very wide experience in many facets of surveying and mapping, including geodesy and topographic and bathymetric mapping.

Philip Collier, a registered surveyor, obtained his Bachelor of Surveying and PhD at the University of Melbourne where he is now a Senior Research Fellow in the Department of Geomatics. He has wide interests in geodesy and high-precision satellite positioning. Currently, Phil is working as part of a research group to develop algorithms and software for the automated delimitation of maritime zone boundaries under the relevant provisions of UNCLOS, in addition to the geodetic definition of the limit of the legal continental shelf in keeping with Article 76.

David Mitchell completed his Bachelor of Surveying with Honors and Bachelor of Science (Computer Science) at the University of Melbourne in 1993. In 1994 he commenced full time employment with the Department of Geomatics and has since been involved in a number of research projects, primarily as a computer programmer.

ABSTRACT

Articles 7, 9, 10 and 47 of the United Nations Convention on the Law of the Sea define the circumstances under which coastal States can construct straight, closing and archipelagic baselines. However, the subject Articles do not specify, or require coastal States to specify, the geometric or technical properties of these lines. As a consequence, coastal States are free to apply any interpretation they choose in the technical definition of straight baselines, whether these are loxodromes, arcs of great circles, arcs of small circles, grid lines, normal sections from either terminal of a segment or geodesics. Coastal States have occasionally defined the technical properties of straight baselines through promulgation in national

maritime legislation or in international maritime boundary delimitation treaties, but this has been very much the exception rather than the rule.

This paper provides a general overview of some of the technical problems that can arise when maritime zone boundaries are generated from straight baselines legally defined as geodesics, as is the case with Australian national maritime legislation. It also outlines a practical application of the method of *tracés parallèles*, which is the essence of the *Anglo-Norwegian Fisheries Case* judgment handed down by the International Court of Justice in 1951. Lastly, the paper briefly overviews the implications of the requirements set out in the recently published "*Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf*" in relation to the geometric properties and use of straight baselines.

1. Introduction

Straight lines are an integral part of any boundary system, whether onshore or offshore. The geometric properties of straight lines are usually defined in terms of a rectangular grid system or a map or chart projection system.

Under the provisions of the United Nations Convention on the Law of the Sea (UNCLOS), coastal States are permitted to use straight lines as components of the baseline from which specific maritime zone boundaries are measured. Articles 7, 9, 10 and 47 define the circumstances under which straight lines can be drawn, respectively:

- across the mouth of a river (Article 7)
- across the mouth of a juridical or historical bay (Article 9)
- as part of a system of straight baselines (Article 10)
- as part of an archipelagic straight baseline system (Article 47)

The subject Articles do not specify, or require coastal States to specify, the geometric or technical properties of the straight lines. Coastal States are, therefore, free to define these lines as loxodromes, arcs of great circles, arcs of small circles, grid lines, normal sections from either terminal of a segment, geodesics or any combination thereof.

An examination of straight, closing and archipelagic baseline legislation promulgated by various coastal States will reveal that the definition of the geometric properties of straight lines is very much the exception rather than the rule. In the great majority of cases, the legislation simply refers to straight lines joining named coastal features defined by geographical coordinates, or by lines joining points on the normal baseline defined by geographical coordinates, or by a combination of both of these methods. In some cases, the legislation refers to large or small-scale charts or maps, officially recognised by the coastal State, that are appended to the legislation and upon which the straight lines have been drawn. However, the cartographic depiction of such lines on paper charts, or their digital equivalents, raises a number of technical questions relating to their legal status. This is especially the case where straight baselines legally promulgated and defined as geodesics are plotted on hydrographic charts. However, these issues are beyond the scope of this paper.

The absence of definition of the geometric properties of straight, closing or archipelagic baselines from national maritime legislation is undoubtedly due to the non-explicit nature of the wording of UNCLOS Articles 7, 9, 10 and 47. It could be argued that this situation has not been improved by some coastal States simply following the precedent set by others in the wording of their own legislation. However, coastal States can take advantage of this situation as it enables the choice of a particular line type that can be used to gain a territorial advantage. For example, under certain circumstances, the use of loxodromes rather than geodesics can sometimes lead to a significant maritime territorial gain, especially where long lines are involved. The converse case can also occur, with a geodesic offering an advantage over the use of a loxodrome.

2. The Accuracy of Straight Baseline Determination

As the terminal points of straight, closing or archipelagic baselines are normally chosen so that they are coincident with points on the normal baseline, any error in the location of the latter will be translated directly into the maritime zone boundary. In general terms, the legal view is that once the baseline terminal point coordinates have been promulgated in national maritime legislation, the location of the line joining the points defined by those coordinates is absolutely defined. This view is based on the assumption that the location of the normal baseline, as depicted on charts officially recognised by the coastal State, is accurately defined.

However, in many cases, the location of the normal baseline has not been accurately known and the locations of straight baseline terminal points have been determined purely by inspection and scaling of coordinates from the best available charting or mapping information. The scaled coordinates have then been promulgated in national maritime legislation. In the case of the Australian legislation, the lines joining terminal point locations are explicitly defined as geodesics.

Recognising the errors that may be inherent in the mapping and charting information used to define the location of the normal baseline, the maritime legislation of some coastal States, including Australia, allows the *scaled* locations of baseline terminal points to be shifted. The shift enables the points to be located in positions which are consistent with the situation on the ground, such as would arise where the location of the normal baseline has been determined by hydrographic survey. However, the Australian legislation permits only the shift to a point on the normal baseline that is *closest to* the scaled location and experience has shown that the implementation of this legal mechanism can sometimes lead to ambiguous situations. Additionally, distances of up to three nautical miles between the originally scaled and shifted locations of baseline terminal points have been encountered which has made straight baseline and associated zone boundary definition extremely complex.

Some coastal States, notably the Republic of Indonesia and Norway, have undertaken detailed surveys to determine the location and coordinates of straight baseline terminal points. Invariably, these points have been connected to permanent onshore reference monuments that have been coordinated in a geocentric reference system, such as the International Terrestrial Reference System (ITRS) or WGS84. These surveys have been undertaken for different purposes. In the case of Norway, the surveys were related to international maritime boundary delimitation negotiations with the United Kingdom in the North Sea, where a difference of one metre in the agreed boundary location equated to $US3 million (1984) in terms of the underlying oil reserves (Harsson, 1996).

There is a clearly demonstrated need for an unambiguous and technically sound definition of straight baselines. Modern positioning technologies such as the Global Positioning System (GPS) now make it possible to achieve relative positioning accuracies at the sub-metre level in mid-oceanic regions. The Norway-UK negotiation is but one example of this need and the positioning capabilities of GPS demonstrate that this need is more than just a theoretical or legal nicety; it is an achievable and practical necessity.

3. The Geodesic Defined

As mentioned above, coastal States are entitled to use any one or a combination of several geometric line definitions, including the geodesic, when defining straight, closing and archipelagic baselines. Although the properties of the geodesic can be found in many standard reference textbooks on geodesy, it will be useful, in the context of this paper, to summarise the more commonly known features:

- a geodesic is the line of shortest distance that can be drawn on the surface of the reference ellipsoid between any two points;
- where both terminal points lie on the same side of the equator, the geodesic is a line of double curvature;
- the geodesic generally lies between the plane curves drawn between the terminal points;

- when both terminal points lie on a meridian, the geodesic and both plane curves coincide with the meridian;
- if both terminal points are in nearly the same latitude, the geodesic may cross one of the plane curves; and
- at every point along it, the geodesic satisfies the following equation (Clark, 1963):

$$R_p \sin \varphi = \nu \cos \varphi \sin \alpha = \text{constant}$$

Where:

R_p = radius of a parallel of latitude
α = geodetic azimuth
ν = radius of curvature of the prime vertical section
φ = geodetic latitude

As the geodesic is a complex line, the task of offsetting a maritime zone boundary from such a line is no less complex. A recommended method by which this process can be undertaken is known as the method of *tracés parallèles* and is defined in a judgment handed down by the International Court of Justice (ICJ) on 18 December 1951.

4. The Method of *Tracés Parallèles*

The ICJ, in the judgement relating to what is now known as the *Anglo-Norwegian Fisheries Case* of 1951, originally prescribed the method of *tracés parallèles* for the delimitation of maritime zone boundaries from straight baselines. Article 4 of the 1958 Convention on the Territorial Sea and the Contiguous Zone embodied the essence of the ICJ judgment. Essentially, the method is a generalisation of the method of envelopes of arcs that is applied to points on the normal baseline. Many sets of national maritime legislation now reflect the application of this method of delimiting zone boundaries from straight baselines through inclusion of the following, or similar, phraseology:

"…by a line every point of which is at a distance of … miles from the respective baseline"

A number of technical issues arise when the *"the respective baseline"* is legally defined as a geodesic, as is the case with Australian national maritime legislation. By far the most significant of these is the fact that, on the surface of the reference ellipsoid, it is geometrically impossible to define a geodesic that is offset from and at all points parallel to a given geodesic which has been legally defined as a straight, closing or archipelagic baseline.

When delimiting maritime zone boundaries from straight, closing and archipelagic baselines defined as geodesics, it is computationally invalid to simply offset by the maritime zone width along the normals constructed from each of the baseline terminal points and to then join the constructed points with another geodesic (as illustrated in Figure 1). This approach can lead to significant errors, as can be seen from Table 1. The table shows the mid-point separation between a geodesic baseline and an offset geodesic using various maritime zone widths applied to the maximum permissible archipelagic straight baseline length of 125 nautical miles (M), as specified in UNCLOS Article 47 (2).

The above construction is even less valid, and can lead to significantly greater errors, when undertaken on nautical charts that use a variety of map projections.

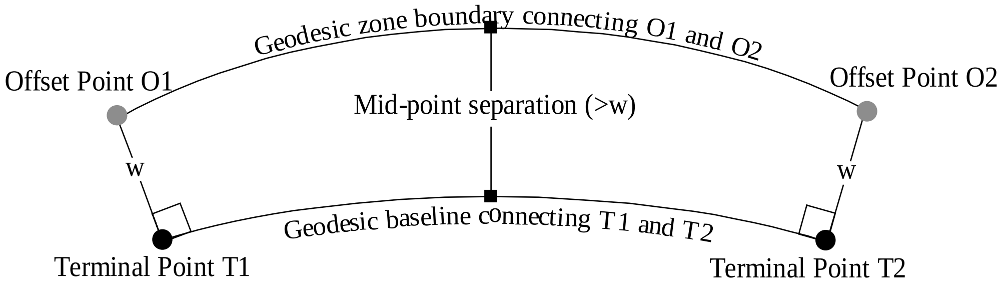

Figure 1 – The variation in zone width (w) caused by offsetting a maritime zone boundary from the terminal points of a geodesic straight baseline

Maximum Archipelagic Baseline Length 125 M **Baseline Origin: 45° North or South Latitude** **Baseline Azimuth: 45°, 135°, 225°, 315°** **Ellipsoid: GRS80**		
Maritime Zone Width (M/m)	Separation Between Mid-points of Baseline and Zone Boundary Geodesics (m)	**Difference (= Error) (m)**
12/22224	22227.66	+3.66
24/44448	44455.32	+7.32
200/370400	370460.86	+60.86

Table 1 – The error in zone width at the mid-point of a geodesic 125 M in length for zone widths of 12 M, 24 M and 200 M

In theory, the rigorous application of the method of *tracés parallèles* - when applied to a geodesic straight, closing or archipelagic baseline - requires the interpolation of an infinite number of points along that baseline. A normal (which is also a geodesic) is then constructed at each terminal and interpolated point and extended by the required maritime zone width (w), as illustrated in Figure 2. This process can be computationally intensive and will produce as many points defining the required maritime zone boundary as the number of points the user chooses to interpolate along the baseline.

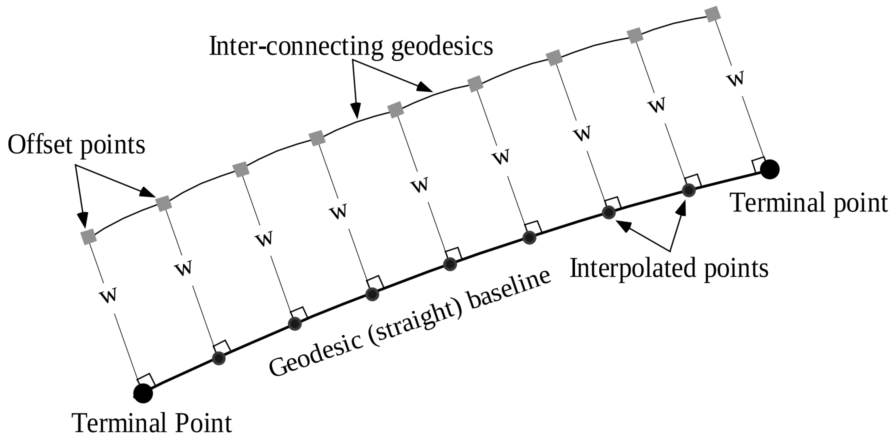

Figure 2 – Implementing the method of *tracés parallèles* to delimit a zone boundary from a geodesic straight baseline

As the offset points defining the required maritime zone boundary are computed on the surface of the reference ellipsoid, the lines of shortest distance inter-connecting adjacent offset points will become, by definition, geodesics. These geodesics will have a different orientation, or azimuth, to the corresponding segments of the baseline geodesics. Furthermore, the required maritime zone width (w) will only be true when measured directly between the interpolated and offset points. All points on the geodesics inter-connecting adjacent offset points will lie at a distance that exceeds the maritime zone width as measured from the corresponding segments of the baseline geodesic, irrespective of how short these segments are.

A practical approach is required in the determination of zone boundaries offset from geodesic straight baselines. This approach, which would never replace the rigorous method of *tracés parallèles* where that was required to be applied, must be related to the maximum tolerable error in the location of the boundaries. This error will always bear a direct relationship to the relative accuracy with which points defining the zone boundary can be defined in relation to the straight baseline terminal points and the stated precision of the coordinates used to define points on the boundary.

5. A Practical Application of the Method of *Tracés Parallèles*

A practical solution for the implementation of the method of *tracés parallèles* is suggested here. This solution will give results that closely approximate those obtainable from a rigorous implementation (if that were computationally possible). The proposal enables the use of geodesics to define maritime zone boundaries offset from straight baselines also defined as geodesics. It will also reduce the computational intensity and the large amounts of data produced by the use of a rigorous method of *tracés parallèles*. Application of the method results in the mid-points of the offset geodesics being located at a distance from the mid-points of the corresponding baseline geodesic segments *that does not exceed the subject maritime zone width by more than a user-defined distance, typically by not more than a few tens of centimetres*. For example, a user may require that the maximum offset error in the maritime zone width not exceed 10 centimetres. The application of this method will prove useful in a number of practical situations, such as where the offset geodesics are to be cartographically represented. A brief description of the method follows.

When implemented on the surface of the reference ellipsoid, the method of *tracés parallèles* can be rationalised so that the baseline geodesics are divided into a finite number of segments of equal length, as illustrated in Figure 2. The segmentation length is determined from, and is directly related to, a user-defined maximum tolerable error in the maritime zone width (δw) between the mid-point of the baseline segment and the mid-point of the corresponding geodesic defining the subject maritime zone boundary (see Figure 3).

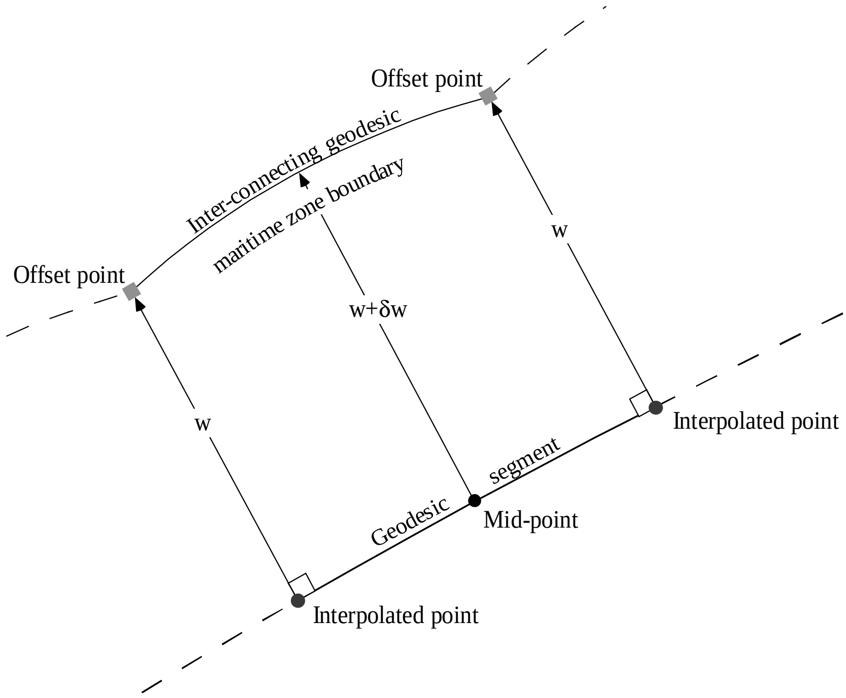

Figure 3 – The error (δw) in the maritime zone width at the mid-point of a geodesic segment

A computer algorithm has been developed to implement the proposed baseline segmentation procedure on the surface of the reference ellipsoid.

Table 2 shows, for maritime zone widths of 12, 24, 200 and 350 M, the approximate baseline segmentation length corresponding with a user-defined maximum offset error of δw = 0.25 metre.

Baseline Origin: 45° North or South Latitude Baseline Azimuth: 360°, 45°, 90° Ellipsoid: GRS80		
Maritime Zone Width (M/m)	Maximum Separation Between Mid-points of Baseline Geodesic Segments and Zone Boundary Geodesics (m)	Baseline Segmentation Length (approx.) M/m
12/22224	22224.25	32.40/60000
24/44448	44448.25	23.06/42710
200/370400	370400.25	8.10/15000
350/648200	648200.25	6.04/11195

Table 2 – Baseline segmentation lengths that give a mid-point separation of δw = 0.25 m for various maritime zone widths

6. A Note on Precision

A potential criticism of the approach proposed above for the practical implementation of the method of *tracés parallèles* is that it does not rigorously satisfy the criterion that every point on the zone boundary should be exactly the zone width from the straight baseline. It has been pointed out that the variation in the offset distance can be minimised by choosing a very small segment length for the computation of interpolated points on the baseline geodesic, however, reducing the segment length imposes a greater computational load.

When choosing the maximum tolerable variation in the zone width, realistic precision limits need to be considered. Generally, terminal point coordinates will be quoted to no better than ±0.1", equating to approximately 3 m at the equator on the surface of the reference ellipsoid. Because of the one-to-one correspondence between the precision of the terminal point coordinates and the precision of the generated zone boundary, it is meaningless to require that the maximum tolerable mid-point separation error should be significantly smaller than the precision of the generating coordinates. It is suggested that if the mid-point separation error is set to be an order of magnitude smaller than the intended precision of the coordinates, the algorithm described above will provide a rigorous implementation of the method of *tracés parallèles* within the precision limits of the data supplied. For coordinates quoted to ±0.1", the maximum allowable error would therefore be approximately 0.3 m.

7. Straight Baselines, Article 76 and the Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf

Where coastal States are able to claim an extended continental shelf, UNCLOS Article 76 (5) provides that:

> "The fixed points comprising the line of the outer limits of the continental shelf on the seabed, drawn in accordance with paragraph 4 (a)(i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the territorial sea is measured…"

Furthermore, Article 76 (6) provides that:

> "Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from which the territorial sea is measured."

However, Article 76 (7) states that:

"The coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length ”

Coastal States that have proclaimed straight, closing and archipelagic baselines and intend to claim an extended continental shelf may *be able to define the outer limits at a distance of 350 M from those baselines. The constraint imposed by Article 76 (7), whereby* "straight lines not more than 60 nautical miles in length*" must be used to define the outer limits, raises the problems associated with the delimitation of boundary lines offset from straight, closing or archipelagic baselines which have already been discussed.*

At this point, it is important to note that the recently published "Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf", *Section 3.3, Geodetic Definition of Baselines, stipulates that* "…the Commission shall accept the definition of straight, closing and archipelagic baselines as either geodesics or loxodromes." *Furthermore, in relation to the use of straight lines not exceeding 60 M in length as specified in Article 76 (7),* "… the Commission will employ geodesics on the surface of the official geodetic reference ellipsoid used by a State in each submission to define the path and distances of these specific straight lines." *(Section 2.3, Delineation of the Outer Limits of the Continental Shelf).*

Where a coastal State, in its submission to the Commission on the Limits of the Continental Shelf, chooses to use the maximum constraint line length of 60 M in the definition of the outer limits in accordance with the provisions of Article 76 (7), it may need to define some or all of those lines as geodesics offset 350 M from geodesic straight, closing and archipelagic baselines. In this case, the separation between the midpoints of the offset geodesics and the midpoints of the corresponding segments of the baseline geodesics will exceed the zone width by approximately 24.4 metres (computed on the GRS80 ellipsoid using baseline azimuths of 360^o, 45^o and 90^o, with starting coordinates at 45^o north or south latitude).

Finally, the requirement to define straight, closing and archipelagic baselines as either geodesics or loxodromes as set out in Section 3.3, Geodetic Definition of Baselines, of the "Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf" *applies only to those coastal States intending to proceed with the submission of a claim for extended continental shelf under the provisions of Article 76. Coastal States unable or unwilling to claim an extended continental shelf can continue to define the geometric properties of straight baselines by whatever method they choose.*

8. Summary

The promulgation of straight, closing or archipelagic baselines in national maritime legislation without an explicit definition of the technical properties of these lines continues to pose problems for all disciplines associated with maritime boundary delimitation. These problems are only exacerbated when such lines need to be used in international maritime delimitation.

The offsetting of maritime zone boundaries from straight, closing and archipelagic baselines defined as geodesics presents geodesists and cartographers with a number of complex technical issues. Unless these are fully understood, significant errors will arise in the definition of those boundaries.

This paper has proposed a method for implementing a practical and workable solution to the method of *tracés parallèles* when offsetting maritime zone boundaries from a geodesic straight baseline. Whilst the solution is approximate, specifying the allowable discrepancy between the nominal zone width and the actual zone width can control the degree of approximation. This error limit is then used to determine an appropriate segment length for the subdivision of the baseline geodesic prior to computing the offset zone boundary. The terminals of the zone boundary segments, as offset from the corresponding terminals of the baseline geodesic segments, are rigorously located at the nominal zone width. The method proposed also has application in the computational definition of the legal limit of the extended continental shelf boundary under the provisions of UNCLOS Article 76 (7), where that boundary may need to be offset from straight, closing and archipelagic baselines which have been defined as geodesics.

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SESSION 2 – Paper 6

RTK/DGPS SERVICE IN MARITIME BOUNDARY DELIMITATIONS

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ABSTRACT

The paper addresses projects on establishing of DGPS and DGPS/RTK service on Baltic Sea Polish coast. In 1995 two permanent DGPS reference stations in Rozewie and Dziwnow were put into operation mainly for marine navigation.

In 1998 started a joint project of the Polish Committee of Scientific Research, Gdansk Voievodship and Olsztyn Institute of Geodesy on establishment of a network of three reference stations for DGPS and RTK purposes, which are currently under development, in the cities of Gdansk, Gdynia and Sopot. The three cities are located on the Baltic coast line, forming a large aglommeration. There is an urgent need to take advantages of DGPS and RTK positioning service in this area.

RTK messages will be used for precise positioning and surveying applications. This will make it possible to perform precise surveys for planning, stakeout and as-built, and other LIS surveying measurements in real time on land and sea having only one GPS receiver.

DGPS RTCM 104 corrections will be mainly used by emergency services (police, fire and ambulance services, etc.) for positioning and navigation. The network could contribute to the more efficient management of fleets for emergency vehicles in Integrated Safety and Rescue System, currently under development for the Three-city area.

Moreover, the reference stations would be used for GIS/LIS data collection, maritime boundary delimitations, near-shore marine navigation and marine engineering purposes.
The paper presents a concise report of on-going works, field experiments, status of the project and schedule of main implementation stages.

INTRODUCTION

For maritime delineation and delimitation the modern satellite GPS positioning methods are used taking advantage of Local Area Differential GPS Service (DGPS) and Real Time Kinematic (RTK) method. The paper addresses projects on establishing of DGPS and DGPS/RTK service on Baltic Sea Polish coast. In 1995 two permanent DGPS reference stations in Rozewie and Dziwnow were put into operation mainly for marine navigation. In 1998 started a joint project of the Polish Committee of Scientific Research, Gdansk Voievodship and Olsztyn Institute of Geodesy on establishment of three reference stations for DGPS and RTK purposes, which are currently under development, in the cities of Gdansk, Gdynia and Sopot. The three cities are located on the Baltic coastline, forming a large agglomeration. There is an urgent need to take advantages of DGPS and RTK positioning service in the area.

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The paper presents a concise report of on-going works, field experiments, status of the project and schedule of main implementation stages.

PUBLIC MARITIME DGPS STATIONS IN POLAND

The European Maritime Area assignments in the radiobeacon band were decided in 1985 then modified in 1991 to provide for the DGPS transmissions. General plan of rearrangements for navigation services proposed by Maritime Administration started in Poland with two years delay.

The intention of service provider (Maritime Office Gdynia) was to cover the Polish coast line and responsibility zone with only two reference stations located in Dziwnów and Rozewie (Fig.1) started working „on air" in 1995.

Currently, in the region of Polish coasts of the Baltic Sea, DGPS overlapping signals from the following foreign reference stations are available: Hammerodde (Denmark), Hoburg (Sweden), Wustrow (Germany) and only sometimes Almagrundet (Swedish).

Each reference DGPS station should fulfill the international requirements that determine the operational usefulness of the system. These include technical functions of an equipment and coordinates of antenna which must be tied to the WGS'84 system, e.g. to the ETRF'89 system (European Terrestrial Reference Frame at the epoch 1989) that constitutes a geodetic realization of the WGS'84 system in Europe (thus also in Poland). The localization of the two new Polish reference stations in Rozewie and Dziwnów (Tab.1) ensures the best geometric configuration of coverage of this region of the Baltic Sea, especially the biggest ports (Fig. 1).

An important feature of the region Gdansk Bay is very intensive sea traffic resulting from location of two big ports in this zone. The positioning accuracy requirements are determined on the basis of navigation and hydrographic conditions and recommendations of IMO and they range from 1 m (for hydrographic and sea engineering purposes) to about 50 m (to ensure safety navigation of small sea units). For maritime boundary delineation and delimitation the positioning accuracy can vary from 1 meter to some centimeters in the case of cadastral surveys.

To enable such a positioning accuracy, the coordinates of the stations in the ETRF'89 system have been determined with centimeter level accuracy.

To fulfill the accuracy requirements and to avoid introducing of systematic errors resulting from determination of ETRF'89 coordinates of the reference station, the first step during creation of a new reference DGPS station must be tying it to a global reference system WGS'84 with required accuracy. In the case of the two Polish stations the team from Institute of Geodesy of the Olsztyn University and the Polish Naval Academy performed this task. In both the cases, Dziwnów and Rozewie, at the very beginning a project of a reference network were elaborated. Such a project should enable:

- determination of ETRF'89 coordinates of adjacent baseline marks that would be convenient for carrying out classical measurements to DGPS antennas
- independent checks of these determinations.

1503 Architecture of Polish Maritime DGPS Service

Both Polish reference stations have the same system concept and similar equipment. Their operation conforms to the common international standards. System architecture consists of three general segments:

- Reference Sites
- Local and/or Remote Monitors
- Central Control Station

1504 Reference Site Arrangements

Both reference stations are located close to beacon transmitters. The 12-channel GPS reference receivers track all satellites in view and generate pseudorange corrections, which are broadcast by the beacon under control of local computer. To ensure compatibility across a wide variety of DGPS user equipment, the corrections are provided in the RTCM format. Reference antennas, reference receivers, modulators and transmitters are doubled and supplied from buffer via separate stabilizers. Redundancy of the equipment controlled by PC is provided in order to maintain high total hardware reliability and to ensure continuity of broadcasting. Local Integrity Monitor for faults and automatic change for hot stand-by blocks continuously monitor proper functioning of equipment. Data is accessible via telephone line modems for remote monitoring, controlling and alarm reporting purposes.

Radio Broadcast Characteristics

The transmission is broadcast with MSK modulation in the band allocated for marine radionavigation Region A1 (283.5-315 kHz). Both stations include second carrier emission spaced by 500 Hz to maintain RDF service until it is necessary (probably until 2000). Assigned frequencies, nominal ranges for signal strength 34 dB (50μV/m) are shown in Table 1.
Technical characteristics conform to standard adopted by ITU-R in Recommendation M.823 including data and message format based on RTCM SC 104 Version 2.0 standard. Data transmission is continuos with 100-baud rate; class of emission is G1D (digital with phase modulation). Maximum occupied bandwidth is less than 130 Hz. Transmitters coupled to omnidirectional antennas share the nominal 100W output power for direction finding signal and DGPS data transmission.

Static Accuracy, Coverage/Range, Availability of DGPS Service

Static accuracy is of order of 1.5–3 m, (95%), depending on the distance and propagation conditions (Fig. 2 and Fig.3). Practical coverage radius of sea area for Rozewie station is about 120 km, while for Dziwnow it is estimated to be about 80 km.

Coverage range may also be estimated according to availability at a certain levels of noise and emitted power. For example, if assumed SS=38dBμV and SNR>=10 than coverage area of Rozewie station would be about 100 km with the availability 99% and for Dziwnów these figures would be only 47 km at 99%.

DGPS/RTK REFERENCE STATION LOCAL NETWORK OF THREE-CITY AREA GDANSK, SOPOT, GDYNIA

1. This is a joint project of:

- the Polish Committee of Scientific Research,
- Gdansk Voivodeship and
- Olsztyn Institute of Geodesy

2. There are also other centers, which cooperate in realization of the project, as follows:

- Maritime Office in Gdynia,
- Maritime Academy in Gdynia,
- Navy Academy in Gdynia,
- Gdansk, Gdynia, Sopot Municipalities,
- Gdansk University of Technology,
- Planetary Geodesy Department of Space Research Center of the Polish Academy of Sciences, Warsaw,
- Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology,
- Institute of Geodesy and Cartography in Warsaw.

The system will consist of 3 reference stations, located in the three towns (Fig.4). Each reference station will be equipped in a dual frequency GPS receiver having an access to the P-code, DGPS and RTK options. Also, a computer, radio system for transmission of correction data, modems and transmission system to provide mutual connection between stations will create an infrastructure of each reference station. The performance objectives of the reference stations (RS) may be listed as follows:

- carrying out permanent GPS observations,
- raw data handling (archivization)
- broadcasting DGPS and RTK messages in RTCM 104 v. 2.1 standard
- post-processing of user's data, re-sending of solutions

One of these 3 RS will also work as a Master Station, its tasks will be:

- to monitor all RS,
- to gather raw data from all RS,
- post-processing of users observations,
- Integrity Monitoring.
-

The link between reference stations and user receivers will be held using radio waves of frequency of about 438 MHz, power of transmission will be of 1 W (perhaps 2 W). It is planned that the system should be fully operational in 2001.

3. Performance objectives

The system will be widely used in the field of navigation as well as geodesy. In the field of navigation it will fulfill the following tasks:

- augmentation of emergency and civil town services (Police, fire brigades, first aid and ambulance services, transportation etc.)
- real-time positioning and navigation (land, maritime),
- bathymetric measurements, maritime navigation signs, etc.

On the other hand, in the field of geodesy it will enable:

- data acquisition for GIS/LIS,
- geodetic primary and detailed networks establishment and modernization, augmentation of Total Station instruments in land details surveying for digital mapping purposes, engineering surveying, etc.
- maritime boundary delineation and delimitation,
- cadastral surveys with centimeter level of accuracy.

4. GPS equipment and software

At thy reference stations, Ashtech Z-FX receivers, one at each station, will be used. To perform preliminary experiments and checking of the system performance we will use as rover receivers 2 Ashtech Z-Surveyors. This receiver was designed for high-accuracy, real-time, carrier phase differential (RTK) surveying/mapping, it incorporates hardware and firmware enhancements, rendering it the good tool for a variety of surveying applications, including control surveys, topographic surveys, land/boundary/cadastral surveys, route surveys, construction surveys, etc.
Both types of receivers belong to the so-called Ashtech Z-Family GPS receivers. They can be characterized with the following features:

- they are 12-channel receivers,
- they take advantage of Ashtech Z-Tracking™ technology,
- recorded observables: C/A and P-code pseudoranges, L1 and L2 (full wavelength) carrier phases, Doppler shifts on L1, L2,
- removable data storage via plug-in PCMCIA memory cards (or via cabled I/O ports),
- satellite acquisition and reacquisition improvements,
- improvements in ambiguity-fixing,
- faster update rates etc.

The above hardware will be completed with proper software to enable optimum work of the system. The main program we will use is the Ashtech Geodetic Base Station Software (GBSS). It is designed to control a wide range of GPS reference station operations, including land surveys, mapping and GIS, engineering and scientific applications. Designed to operate in 32-bit multitasking environment, the base station software logs GPS data to a PC hard drive and runs on the Microsoft Windows 95 or Windows NT platforms. The Geodetic Base Station Software currently supports the receivers we chose. This software allows the user to:

- create simultaneously a wide variety of different files types (Ashtech, Rinex, NMEA formats, ionospheric model file, compressed files, etc.),
- create automatically different epoch intervals for the same time period,
- use many file management tools,
- open up an FTP connection at the end of each session and send the data to any remote FTP site in the world,
- make the data files possible to be available to other users.

5. Preliminary estimation of accuracy of the RTK/DGPS service

In order to determine the practical accuracy of RTK/DGPS service in the Three City area a number of tests and field trials were performed. In Fig. 5 the results of analysis of positioning accuracy for various type of observation data are shown. The values of Root Mean Square (RMS) error are of order of 0.40 – 0.65 meter for code type of observations used in DGPS service while for code and phase observations used in RTK service the achievable accuracy can be of order of centimeter.

Fig. 6 shows the results of analysis of positioning accuracy for different baseline length using the RTK method in real-time and post-processing mode. The RMS values for RTK real time positioning are of order of 6-8 cm while for RTK method in post-processing mode the RMS values are of order of 1-3 cm.

FUTURE OF SATELLITE NAVIGATION SYSTEMS IN CENTRAL AND EAST EUROPEAN COUNTRIES

To promote international cooperation in satellite navigation, within the Central European Initiative (CEI), the Working Group on Science and Technology (WGST), Section C “Geodesy”, the CEI Working Group on Satellite Navigation Systems was established on 5th May 1997 in Budapest.

The activity in the region is promoted also by the Commission of European Union (CEU) due to the some important aspects.

First of all, the ETG - European Tripartite Group (CEU + ESA + EUROCONTROL) and EGS - European GNSS Secretariat consider the extension of GNSS EGNOS project to the Central and East European countries a priority in their external relations activities.

Another important aspect is that the EGNOS project has been designed to include Central and East Europe in its core service area. Furthermore, GNSS is an integral part of TEN (Trans-European Network) project for international transport corridors and the extension of this network to the CEI region would be greatly facilitated by satellite navigation and positioning system.

GNSS is also the driving force behind the creation of European Radionavigation Plan and should facilitate the smooth integration of local/ national DGPS navigational aids (LADGPS networks) into the unified European satellite navigation and positioning GNSS network.

The CEI Working Group on Satellite Navigation Systems activity will serve as a significant opportunity to raise EGNOS awareness and to promote European cooperation and coordination for satellite navigation in the region. In this way, it may be possible to afford early operational benefits from the EGNOS service for both the CEI countries and the European Union for a multitude of transport and other positioning and navigation applications. It will also ensure the integration of local area DGPS systems with the EGNOS wide area system and facilitate a coherent approach to infrastructure planning.

The main stages of integration of Polish local area networks with the European GNSS-1 EGNOS service are as follows:

- Integration of DGPS with DGLONASS
- Development of national RTK/DGPS/DGLONASS networks (e.g. Austria, Sweden)
- AOS status of the European Geostationary Overlay System (EGNOS) ~2002
- Development of interfaces between Local Area DGPS/DGLONASS Networks and EGNOS.

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Baran L.W., S. Oszczak – GPS/DGPS Permanent Stations in Poland, Reports on Geodesy (in print).

Tab.1. PUBLIC MARITIME DGPS STATIONS IN POLAND

Broadcast Station Name	Function	Geogr. Position	Nominal Range (50μV/m)	Frequency kHz	Bit rate Bit/s	Emission	RTCM Message Type	ID. code ID. no	Antenna
DZIWNÓW	**RDF DGPS**	**N 54°01' E 014°44'**	**90 90**	**287.5 288.0**	**- 100**	**100HA1ABN 100HG1DCN**	**- 1,2,3,7,16**	**DZ 481**	**vertical mast**
ROZEWIE	**RDF DGPS**	**N 54°49' E 018°20'**	**90 90**	**310.5 311.0**	**- 100**	**100HA1ABN 100HG1DCN**	**- 1,2,3,7,16**	**RO 482**	**horizontal 2T**

Fig.1. OPERATION ZONES OF THE POLISH DGPS REFERENCE STATIONS IN ROZEWIE AND DZIWNÓW

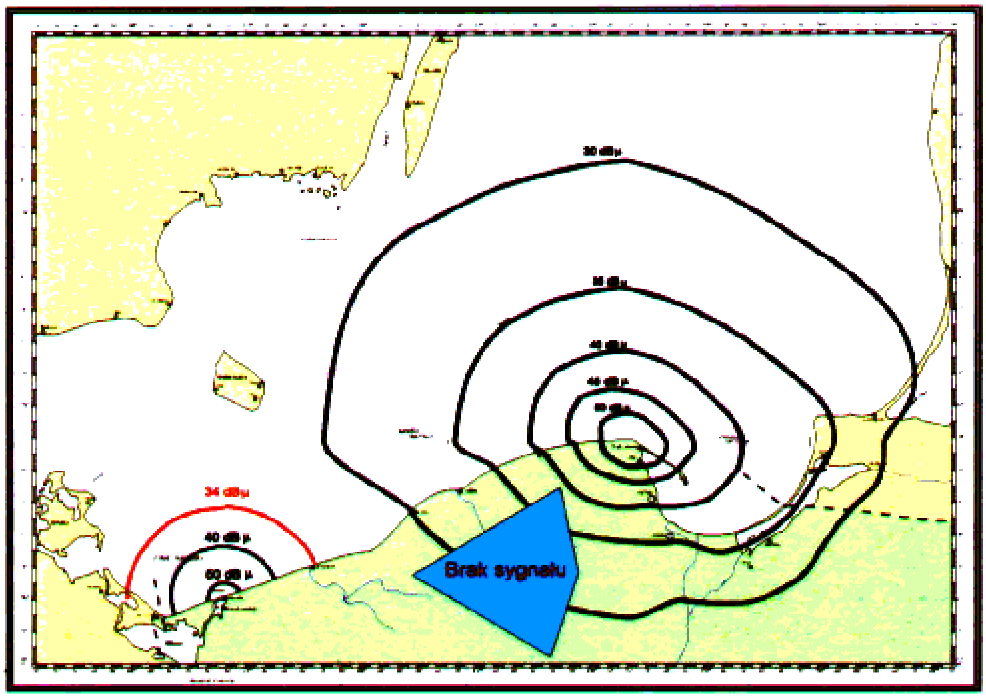
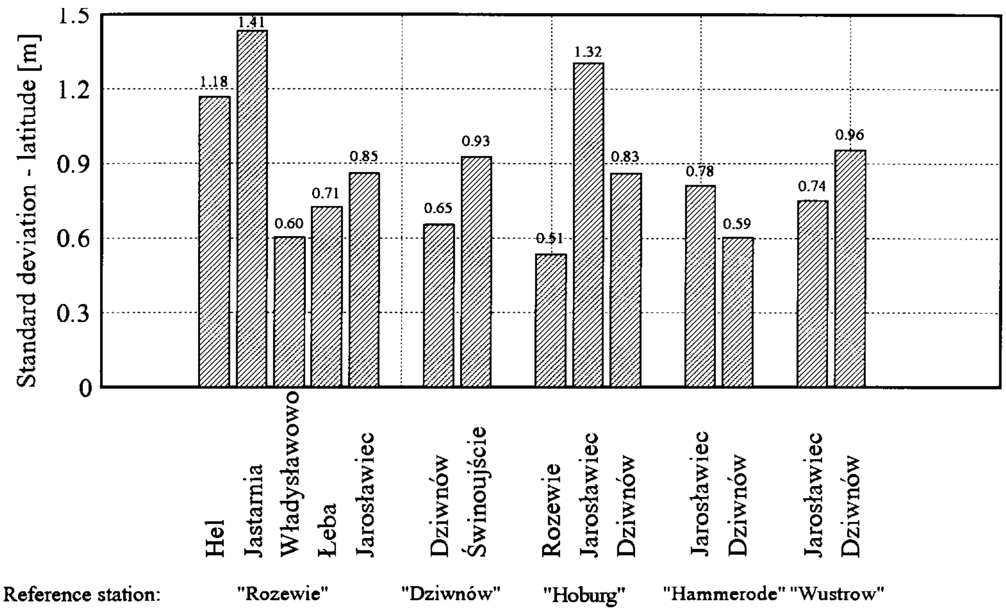
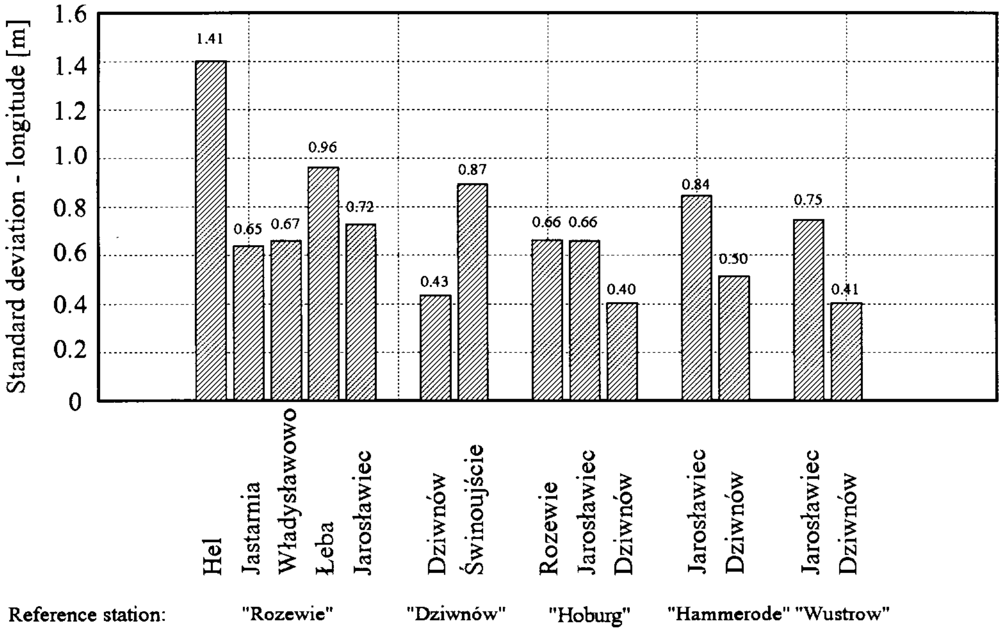


Fig.2. LATITUDE ERRORS MEASURED FOR DIFFERENT REFERENCE STATIONS



Reference stations: PL PL S DK G

Fig.3. LONGITUDE ERRORS MEASURED FOR DIFFERENT REFERENCE STATIONS



Reference stations: PL PL S DK G

Fig.4. DGPS/RTK REFERENCE STATION LOCAL NETWORK OF THREE-CITY AREA: GDANSK, SOPOT, GDYNIA IN POLAND

SESSION 2 – Paper 7

THE LAW OF THE SEA AT THE NORTH SEA
Datums and error sources in co-ordinates
A technical review with example

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ABSTRACT

In this contribution an overview is given of the geodetic factors which should be taken into account when defining boundaries at sea. Particular attention is given to the North Sea area, a small sea, which is surrounded by a relatively large number of countries. First, geodetic and vertical (chart) datums are considered. Next, precision and reliability aspects of median lines are discussed. In the last part of the paper a recent example of boundary delimitation is given, followed by some conclusions and recommendations to preclude future ambiguities in boundaries.

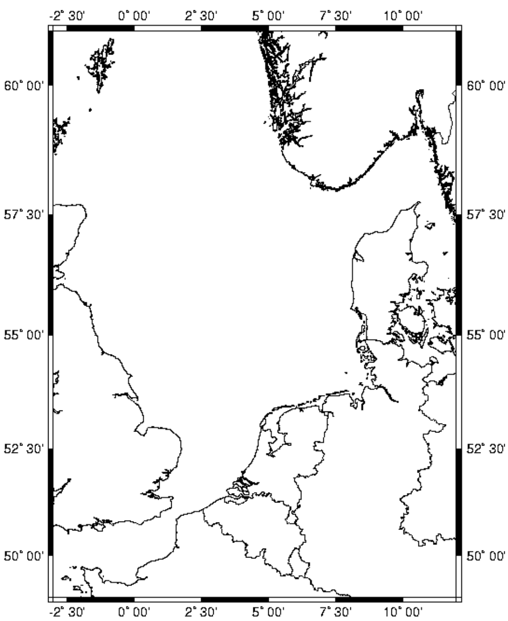

Figure 9: The North Sea and the countries surrounding it.

Introduction

Despite its relatively small size, the North Sea is surrounded by a large number of countries, as is shown in Figure 1. For exploration and exploitation of e.g. gas and oil and fishery, delimitation is important. The delimitation of the continental shelf in the North Sea started in the mid-1960's, after the entry into force of the Convention of the Continental Shelf (1964). The first boundaries were established by bi- or trilateral negotiations, following the method of equidistance. At the end of the sixties the treaties of the boundaries were affected by a decision of the international Court of Justice in the *North Sea Continental Shelf Cases*, which stated that equitable principles had to be taken into account as well [Charney et al, 1993].

When delimiting boundaries, one should be aware of geodetic subtleties and pitfalls of the applied techniques, [ABLOS, 1996]. In the next sections we will focus on differences in geodetic and vertical datum definitions between states establishing a boundary, error propagation and the precision and reliability of the median lines by which the boundaries at sea are often defined. Finally, an example is given regarding the delimitation of boundaries between Belgium and The Netherlands.

Geodetic datums

At the end of the 19th and the beginning of the 20th century, many European countries developed their own national co-ordinate systems. These regional and national geodetic datums were based on an ellipsoid, which best fitted the area of interest. After selecting a proper reference ellipsoid, a map

Country	Ellipsoid	Semi-major axis (m)	Flattening	Map projection
Belgium	Hayford	6378388	1/297	Lambert
Denmark	Hayford	6378388	1/297	TM
England	Airy	6377563.396	1/299.325	TM
France	Clarke 1880	6378249.145	1/293.465	Lambert
Germany	Bessel	6377397.155	1/299.153	Gauss-Krüger
Netherlands	Bessel	6377397.155	1/299.153	Stereographic
Norway	Bessel (modified)	6377492.018	1/299.153	TM
Europe	Hayford	6378388	1/297	UTM

Table 1: Ellipsoids and map projections used around the North Sea and for Europe.

projection has to be chosen, to project the ellipsoid directly or indirectly, e.g., using a conformal sphere, on a horizontal plane. Consequently, a wide variety of ellipsoids, with different location and orientation in space, and many different map projections exist, see e.g., [DMA, 1991] and [Strang van Hees, 1994]. For offshore positioning, these local datums were in general extended towards the sea. In Table 1 some of the reference ellipsoids and map projections for the countries surrounding the North Sea are given. These local datums were traditionally adjusted with astronomical observations.

The European datum ED50

After World War II the USA initiated the work on a European first order trigonometric network. The adjustment was completed around 1950 and became known as European Datum 1950 or ED50. ED50 was established using existing terrestrial and astronomic measurements. It is based on the International Ellipsoid and the Universal Transverse Mercator (UTM) projection. ED50 is often used at sea. It is for instance (still) the datum used for most of the Netherlands nautical charts. On land, the local datums of Table 1 are nevertheless still used. Due to the inhomogeneity of the national networks, ED50 is inhomogeneous as well. This inhomogeneity can be felt especially around the North Sea, see Figure 1. The width of this sea and the absence of islands made it impossible to establish a geometrically strong geodetic network covering this area. For example, the definition of ED50 in the UK was based on only one tie across the English Channel, [Bakkelid & Rekkedal, 1983].

In the North Sea area positions of continental shelf boundaries and concession boundaries have to be defined in ED50. This is a historically grown situation: the first median line boundaries in the North Sea were established graphically on charts, [Bakkelid & Rekkedal, 1983]. This technique is not too precise – additional errors were introduced by the conversion from grid lines from local datum to ED50. A consequence of the regulation to use ED50 is that all positioning systems used at the North Sea for official purposes should provide positions in ED50 as well. The present situation is that most modern positioning systems output positions in a geodetic datum, differing from ED50 and usually more homogeneous, but that eventually these positions have to be transformed to that datum.

The advent of satellite systems in the second half of the 20th century, in particular of the NNSS/Transit system and its successor GPS, made it possible for the first time to establish truly global geocentric datums. The World Geodetic System 1960 (WGS60) was defined by the USA in 1960; the most recent version, WGS84, is used by the GPS community since 1987. The introduction of satellite systems for precise positioning painfully revealed the inhomogeneity of ED50. Inhomogeneities appeared in the discontinuities at land-water boundaries, inconsistencies in the positioning of off-shore platforms and a lack of consistency when reconstructing boundary lines. Replacing ED50 by the satellite datum could have solved these problems, but due to legal regulations this was not achievable.

The above discontinuities could have been reduced to a great extent by applying a pseudo least squares connection in the North Sea area, a technique well known in geodesy for connecting lower- to higher-order networks. In this approach, the satellite-derived positions are transformed to ED50 using a least squares adjustment. In the second step, the new satellite-derived positions at sea are in ED50 and should get an additional correction, based on the correlation with the shore-based points. This second step was not performed, only the transformation parameters were determined.

Datum transformations

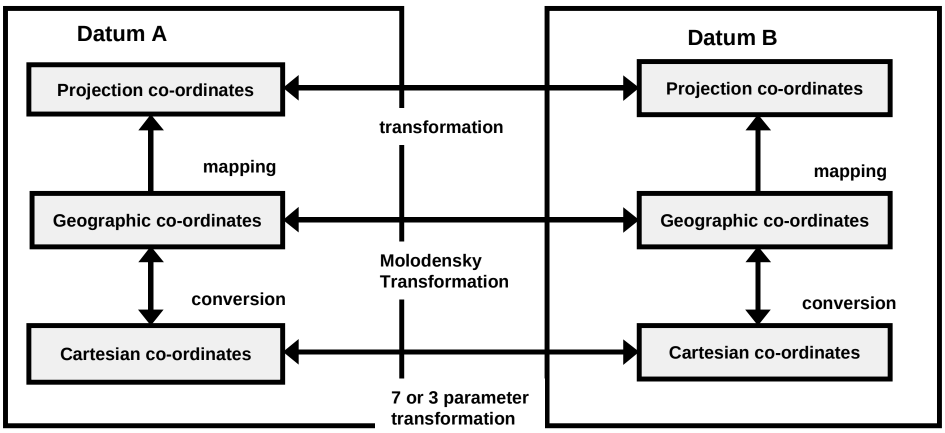

Figure 2: Datum transformations

Due to the variety of datum definitions, transforming co-ordinates from one datum into another is often required, e.g., when in a maritime delimitation case different geodetic datums are used by the states involved. In general, nations agree to use one datum during negotiations on maritime delimitation. The process of transforming co-ordinates from one datum into another, see Figure 2, generally introduces errors into the transformed co-ordinates. These errors are in addition to any existing errors in the original co-ordinates. For transforming co-ordinates from one datum to another, several methods are available. The transformation can be performed in geodetic co-ordinates or in Cartesian co-ordinates. When performing the transformation directly on geodetic co-ordinates, the method of Molodensky is most commonly used. For many applications, use of the Molodensky Datum Transformation Formulas produces results that are of sufficient accuracy only when local, rather than mean, datum shifts are used [DMA, 1991]. However, in general only mean datum shifts are available. When transforming Cartesian co-ordinates, the 7-parameter Helmert transformation is most common. The 7-parameter transformation takes into account three translations, three rotations and one scale factor. Often the rotations and scale factor are zero, resulting in a 3-parameter transformation, which consists of just three translations. The 7- and 3-parameter transformations assume the geodetic system has a consistent scale and orientation throughout the network. In practice this is not always the case. A minimum number of three stations with precisely known co-ordinates in both systems is required to determine the 7 parameters. A 7-parameter transformation produces co-ordinates that are in almost all cases equal or superior in accuracy to those obtained from a 3-parameter datum transformation. The DMA (now part of NIMA) has published 3-parameter sets for many datums all over the world. The 7- and 3-parameter transformations are the most commonly used and are often programmed, together with several sets, internally in GPS receivers.

Many sets of transformation parameters are determined by several organisations and used in the North Sea area. Among them are those of STANAG (NATO), UKOOA and DMA. To make things more confusing, the datum for the GNSS/Transit system depended on whether broadcast or precise ephemeris parameters were used in the data reduction. In 1981 a working group of six nations around the North Sea recommended two sets of parameters for the transformation between WGS72 (the predecessor of WGS84) and ED50, [Ordnance Survey, 1981]. With the introduction of WGS84 and the establishment of ED87 (an extension of ED50, not only covering a wider area, but also including satellite data) this working group met again to define new, so called North Sea formulas, [Harsson, 1990]. For the transformation between WGS84 and ED87 seven parameters were defined, whereas for the transformation between ED87 and ED50 fourth degree polynomials as function of latitude and longitude were chosen to compensate for inhomogeneneities. However, these transformation sets are hardly used, probably due to the complexity of the polynomial expressions. In 1989 a start was made to establish a new European Reference frame (EUREF) based entirely on GPS observations. The realisation of EUREF, known as the European Terrestrial Reference System 1989 (ETRS89), is attached to the Eurasian plate and can be considered equal to WGS84 at the decimetre level. Two sets of transformation parameters between ED50 and ETRS89 have been determined: one consisting of three translations only, the other consisting of three translations, three rotations and a scale factor, [van Buren et al, 1999]. According to [*ibid.*] the different parameter sets currently available show levels of agreement that can be expected for ED50. This means that each of the parameter sets is equally valid. It should be noted that the area of applicability of the transformation parameters for the North Sea includes only those parts of the continental shelf, which belong to the participating countries, i.e., Denmark, Germany, Great Britain, Norway and The Netherlands. The Belgian part of the continental shelf is not covered, but the transformation parameters are valid for this part of the continental shelf as well due to its proximity to the area of applicability and due to its small size.

Strictly speaking a set of transformation parameters is only valid for a small area. When using a transformation set for larger areas, a generalisation is made. The larger the area, the larger the error which is introduced. The size of the errors depends on a number of factors. They are the type of equations used, the quantity and quality of geodetic control data from which the parameters were derived, the size of the area covered by the transformation parameters, and the distance from the control data, [Philip, 1988]. For some sets of transformation parameters, an estimation of the precision is known and given together with the transformation sets. For example, DMA (NIMA) in the second edition of its report on WGS84, [DMA, 1991], included an estimate of the precision of their sets. However, any precision statement will only apply to the geographical area covered by the data used to derive a set of transformation parameters. Extrapolation outside the stated area carries a risk of larger errors.

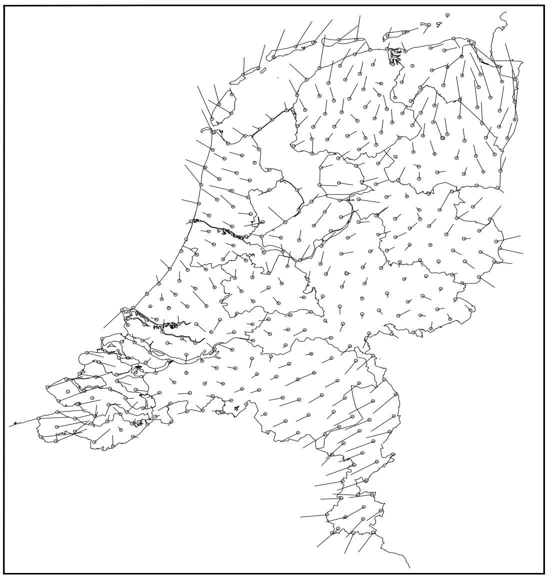

Figure 3: Discrepancies between the current and future reference systems of The Netherlands. The maximum difference of almost 25 cm appears at the border with Belgium

Different organisations recommend using different transformation sets. Offshore operators, for example, are often advised by their clients to use the UKOOA set. The IHO, on the other hand, advises the use of parameter sets provided by the DMA when no other transformation sets are defined by a particular country [IHO, 1994]. For example, when an offshore company has surveyed a pipeline, ED50 co-ordinates must be passed to the hydrographic services of the states involved. Co-ordinates, which are generally obtained using DGPS, are transformed to ED50 using the UKOOA set by the offshore operator. When submitted to the Netherlands Hydrographic Service, this organisation transforms the co-ordinates back again to WGS84 using the inverse UKOOA transformation, after which the final transformation to ED50 is performed using the DMA set EUR-M, since this is the standard set used by the Netherlands Hydrographic Service. The vertical differences between the two sets of ED50 co-ordinates are about 3 metres, the horizontal differences about 1.5 metres. These differences depend on the location in the North Sea.

When basepoints are taken from topographical maps instead of the commonly used nautical charts, transformation between the national co-ordinate system and ED50 becomes important. E.g., the Netherlands national system (RD-system) is based on a double projection to transform ellipsoidal latitude and longitude to Easting and Northing on a map. The ellipsoidal co-ordinates are first transformed to spherical co-ordinates, after which they are projected onto the plane using a stereographic projection. To transform these map co-ordinates into ED50 UTM, series expansions in differences in easting and northing with respect to a reference point, are required.

Before the satellite era, national geodetic systems were established using terrestrial methods. It appears that the precision of terrestrial networks tends to deteriorate with an increasing distance from the origin. Since the origin is often defined in the centre of the network, the worst precisions are obtained at the borders with other states. This should be kept in mind when boundaries have to be defined with high precision. In Figure 3 the differences are shown between points of the Netherlands national network, determined using terrestrial observations in the early 20th century, and a new realisation of it, determined by using GPS. The GPS network is homogeneous and the discrepancies between the two can almost entirely be attributed to errors in the terrestrial network. Figure 3 clearly shows how the precision of the co-ordinates of the current reference system deteriorates towards the borders.

Transition to WGS84

Nowadays, the IHO strongly supports any initiative of hydrographic services to reference charts to WGS84, [IHO, 1994]. In 1996, the NSHC (North Sea Hydrographic Committee) stated in Conclusion 73 of the North Sea Hydrographic Conference of that year: *"… to adopt WGS84 as the uniform horizontal reference system, for nautical charts within the NSHC area, as soon as practical."* This process started already in most member states. The first charts of The Netherlands produced in WGS84 were published in 1998. Also topographical maps show a transition to WGS84. Furthermore the input for official Electronic Nautical Charts (ENC's), to be used in an ECDIS (Electronic Chart Display and Information System), has to be in WGS84 [IHO, 1996]. In boundary definitions a transition to WGS84 or ETRS89 is also recognised, e.g., the maritime delimitation in the area between the Faeroe Islands and the United Kingdom. The Netherlands are also considering, and looking into the consequences of, a transition from ED50 to WGS84 in its "Mijnwet Continentaal Plat" (Mining law for the continental shelf).

Height systems

Country	Chart Datum	Remarks
Belgium	MLLWS	
Denmark	MLWS	
France	LAT	
Germany	MLWS	
Norway	LAT	
The Netherlands	MLLWS	Different from the Belgian datum, due to a different computation method
UK	Approximately LAT	

Table 2: Chart Datums used around the North Sea

According to [Rapp, 1994] there are about 100-200 different vertical datums in the world. Some are used solely at land, others only at sea. The vertical datum used as reference level in nautical charts, is called Chart Datum. Due to the many varied tidal characteristics a large number of definitions of Chart Datums exist. Nevertheless, the Chart Datum is always some kind of low water level. For countries around the North Sea an overview of the chart datums in use is given in Table 2.

Vertical chart datums are usually related to time-dependent mean ocean surfaces, such as Mean Lower Low Water (MLLW), Mean Low Water (MLW), Low Water (LW), Lowest Astronomical Tide (LAT), Mean-Low Water Spring (MLWS). These surfaces are related to Mean Sea Level (MSL), which, locally, is determined from long time series of tide gauge measurements along a country's coast. On a global scale it can be determined from satellite altimetry measurements. An impression of the different vertical chart datums is given in Figure 4.

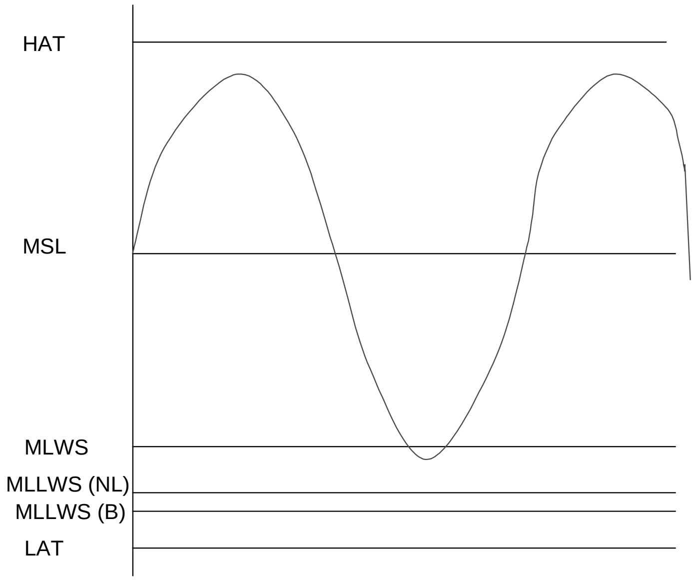

Figure 4: Vertical chart datum definitions; the curve depicts the actual tide (not to scale).

As stated in [IHO, 1993], the fact that there are different definitions of vertical datum means that adjacent or opposite states may use different levels at which to establish their baselines. A recent example of discrepancies arising due to different datum definitions is described in [Symmons, 1995]. France uses LAT, whereas Belgium uses MLLWS as its Chart Datum. The difference between both datums is approximately 0.3 m. As a result, sand banks close to the coast of the two countries were shown on French charts, but not on Belgian charts. Consequently, after applying the two datums, two dividing lines, both based on equidistance, were produced. Finally, the area between the two median lines was divided in agreed parts. Usually, a common Chart Datum is agreed upon and used in negotiations for the delimitation of a boundary.

Standardisation of vertical datums

Just as with horizontal datums, several organisations try to adopt one reference system to refer their heights (or depths) to. The IHO and IMO already stated in the early 1980's that states should consider adopting an astronomical Chart Datum as reference system. Since 1995 the Tidal Working Group of the NSHC has proposed to use LAT as chart datum in the North Sea. At the 1996 NSHC conference, the North Sea Hydrographic Commission accepted *"…to adopt LAT for Chart Datum in the NSHC region and to encourage its members to implement this adoption at the earliest practicable opportunity."* It was not possible to formally agree on a date of introduction. The NSHC order is now, under good co-ordinated bilateral and trilateral co-operation transition to LAT. Some countries, like Germany have made the transition to WGS84, but not yet to LAT. The Netherlands made an inventory of the practical problems that may arise while implementing the change to WGS84 and LAT. At this moment The Netherlands are working on a new reduction chart for the North Sea based on LAT. Frequently discussions take place between The Netherlands and neighbouring countries, to discuss the connection of the reduction chart to topographical datum. It is especially important to have junction to the Standard Ports. At the moment, data of ENC's is not required to be defined with respect to LAT. If digital data to be used in ECDIS is not in LAT, the used Chart Datum must be permanently displayed, [IHO, 1996].

Geoid

MSL is often assumed to coincide with the geoid, whereas it actually consists of the geoid, superimposed by the time-dependent Sea Surface Topography (SST) [Vanicek & Krakiwsky, 1982]. The Sea Surface Topography can be considered as a long wavelength feature.

Precise 3D positions can easily be obtained using GPS relative positioning techniques like RTK-OTF (Real Time Kinematic – On The Fly). Heights obtained using GPS are related to the WGS84 ellipsoid and have only a geometrical meaning. Since one is mainly interested in heights related to reference surfaces like MSL, the difference between WGS84 ellipsoid and reference surface becomes important to know. For such purposes, a precise geoid-model should be determined. In 1997, a preliminary North Sea geoid-model has been computed [de Bruijne et al, 1997]. Firstly, a gravimetric geoid based on the global EGM96 geopotential model and available gravity measurements was computed. Secondly, a correction model to this gravimetric geoid was determined, based on all external data from GPS, levelling and altimetry, combined in an optimal way. These two models form a geoid-model to compute the MSL with respect to a reference ellipsoid. The resulting preliminary North Sea geoid, shown in Figure 5, is assumed to have a precision better than 4 cm at sea and better than 6 cm along the coast. Currently, plans are being developed to determine a new, second-generation precise geoid for the North Sea area, [de Min et al, 1999]. For this new computation, data from other countries surrounding the North Sea should be obtained and included, so one geoid can be computed and connected to the different existing land geoids. The proposed plan not only foresees in the computation of one common geoid-model but also in its acceptance, implementation and use in practice. When all the countries surrounding the North Sea will provide the available data and accept this geoid, a leap forward will be made. This geoid, in conjunction with the use of precise GPS positioning, may help solving the ambiguities, which arise due to using the present different vertical chart datums.

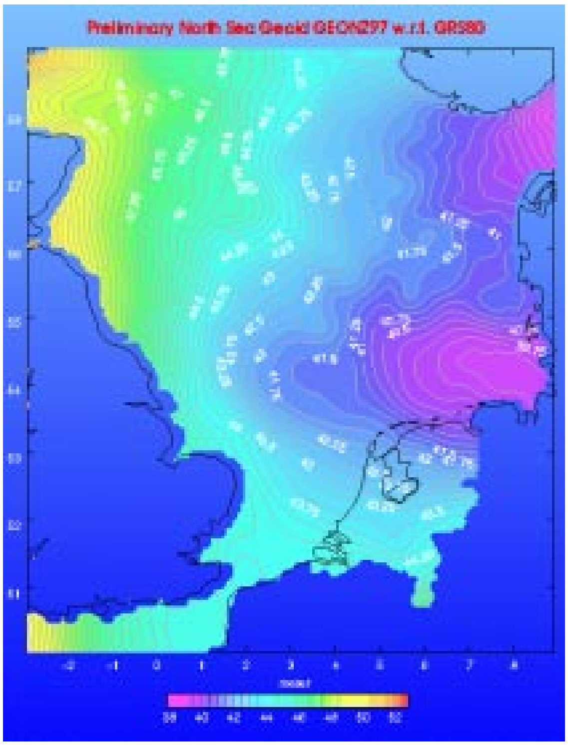

Figure 5: Preliminary North Sea Geoid (from [de Bruijne et al, 1997]).

In [Kumar, 1994] a new concept is proposed for using a time-invariant global height system, based on a high-accuracy geoid as the reference system, and heights derived from GPS. Before 2010 a new, high-precision global geoid model should be available, [Kenyon, 1998].

Precision and reliability of boundaries

Maritime boundaries are often defined by median lines, having equal distances to the respective basepoints of nations. These normal basepoints are taken from the low water line. The median line consists of a number of sections, the start and end points, generally known as turning points, which are determined using the basepoints. As a result the precision of the turning points defining the median line depends on the precision of the basepoints from which they are derived. Once the linear(-ized) relationships between median line and basepoints are known, the precision of the former can be obtained from the latter using the propagation law of covariances. This propagated covariance should be part of the definition of a median line point (besides its co-ordinates), as it gives a description of the quality of the point.

As stated in [IHO, 1993], geographical co-ordinates of basepoints are usually given to the nearest second in latitude and longitude. As a result their precision is of the order of 30 metres in each component. Even today it is common practice to digitise normal basepoints from nautical charts. In order to be able to show any considerable length of coast, scales between 1:100,000 and 1:250,000 have to be used, [IHO, 1993]. The precision of basepoints taken from such small-scale charts is usually of the order of several tens of metres. Often some sort of artificial precision seems to be present in the given basepoints, created by the large number of digits in which they are given. The actual number of significant digits is often much smaller than the total number of digits given. This artificial precision also appears in published co-ordinates, digitised from a small-scale map, which are rounded to the nearest integer – their actual precision is worse.

The precision of basepoints taken from nautical charts depends on the accuracy of the surveys from which they were determined and the accuracy of the chart. Even some charts today are based on very old surveys. Therefore when such charts are used for a delimitation case, they are sometimes used in combination with aerial photography. Sometimes even the geodetic datum used in a chart is unknown. Additional errors will be introduced when transforming co-ordinates from one datum into another, as explained above.

Therefore the precision of the points defining a median line, and thus of the median line itself, can never be better than the precision of the basepoints. In fact, it may even be several orders of magnitude worse, [Horemuz, 1999]. This can be explained by the linear(-ized) relationship between the two types of points, in which the relative geometry is included. When this geometry is unfavourable, small errors in the basepoints may become very large in the median line points. Examples of bad geometries are lines intersecting at angles close to zero or 180 degrees.

The IHO recommends greater precision in the co-ordinates of basepoints if the technology permits, [IHO, 1993]. With the availability of GPS, this is indeed the case: precisions of several centimetres or better are routinely obtained nowadays. Especially for the North Sea area the highest possible precisions should be aimed for to derive the basepoints, due to the large economic interests of the oil and gas industry.
Apart from precision, one should also take into account reliability. Positions can have a very good precision, but at the same time can be very unreliable. Reliability in this context refers to the ability to detect possible gross errors in the given co-ordinates of basepoints and the observations used to derive the median line. Together with precision, reliability is said to constitute accuracy. For an overview of the concept of reliability, see [LGR, 1982].

To reduce the number of points defining the median line, this line may be simplified, see also the example below on the boundary delimitation between Belgium and The Netherlands. It is for instance possible to simplify the median line by exchanging specific areas between states. The resulting sum of areas lost and gained should be zero. To this end area computations on a reference ellipsoid are required, see e.g. [van Gein and Gillissen, 1993] and [Gillissen, 1993]. Using a different datum affects the size of an area, due to different sizes of the ellipsoid used, see Table 1. For example, the area covered by the Netherlands continental shelf will change from 56821 to 56826 km^2 when changing from ED50 to WGS84. This change to another datum would have an impact on e.g. the boundaries between states, of the continental shelf and concession areas, and traffic separation schemes.

Once the turning points of the median line have been determined, they have to be connected. This can be done in several ways. For the delineation of limits this is often a source of confusion [van Gein and Gillissen, 1993]. For instance, many boundaries in the North Sea are defined using parts of great circles on a sphere, even though the horizontal datum is defined on an ellipsoid of revolution. In addition, in the treaties between states, often no reference sphere (its size and location in space) is mentioned. It also happens that limits that should be the same, such as those of a continental shelf and an EEZ, are defined in a different way. Nowadays, with enough computing power available, it is no longer necessary to revert to a sphere to determine segments of a median line. All computations can be performed on a (well-defined) reference ellipsoid. This will also avoid discussions like those taking place in 1986/87 between the hydrographic and geodetic offices of Denmark, Germany, Norway and the United Kingdom, on whether to use great circles arcs connecting segments or ellipsoidal geodesics.

Nowadays we also encounter the problem of precise navigation equipment and not so precise boundaries. The co-ordinates of the turning points of most of the defined boundaries are given to the nearest full second, of arc; their precision is at best of the order of 30 metres. Differential GPS provides positions better than 5 metres. In earlier days very precise boundaries were not required, since the navigation systems were not precise either, but this situation has changed dramatically over the last 15 years.

The Hydrographic Service of the Royal Netherlands Navy

Established in 1874, the Hydrographic Service of the Royal Netherlands Navy is responsible for the publication of nautical charts, for which purpose they and other organisations perform surveys at the North Sea. In addition, the Hydrographic Service supports the Netherlands government, the Navy and a number of other organisations in the area of hydrography, maritime meteorology, oceanography and marine geodesy, [Elema, 1999].

Part of its supportive function is the technical assistance the Hydrographic Service provides to the Ministry of Foreign Affairs in cases of maritime delimitation with neighbouring states of The Netherlands and Netherlands Antilles.

To deliver quick assistance to the Ministry of Foreign affairs, software has been developed to perform various computations in the field of maritime delimitations. Among others, software has been developed for median (equidistant) computations, computation of zones of a particular number of nautical miles (e.g. 12 or 24) around basepoints, intersection of two lines, distance computations, area computations, and datum transformations. Most of the software (besides the two first mentioned items) has been integrated into one user friendly package, called PCTrans, see Figure 6. This software package can be obtained as freeware at www.hydro.nl. Development, translation and integration of the software is an ongoing task.

Figure 6: Screen snapshot of PCTrans

The datum transformations, which can be performed with PCTrans, are based on the 3- or 7- parameter method. Many sets are included. It is also possible for users to define and add new sets. Furthermore several projections are incorporated in PCTrans, like UTM, TM, Mercator, gnomic, stereographic and Lambert. It is also possible to transform co-ordinates from one projection into another. Other geodetic computations that can be performed include the direct and indirect problem on the ellipsoid, computation of point of intersection between several kinds of lines or circles, perpendicular line and area computations. These computations can be performed by either manual or file input. A number of file formats is supported. Help screens provide on-line assistance while running the program.

An example of a recent project, carried out by the Hydrographic Service, is the assistance provided to the Ministry of Foreign Affairs for the delimitation of the territorial sea and the continental shelf between The Netherlands and Belgium.

Boundary delimitation between Belgium and The Netherlands

For a long time the boundary between The Netherlands and Belgium was a matter of discussion. In 1965, an agreement about the boundary was reached at official level for the continental shelf from 3 nM onwards according to the method of equidistance. Letters reserving rights in the territorial sea belonged to this agreement. However, this agreement was never ratified. Furthermore a draft treaty existed for the territorial sea (which at that time extended to 3 nM) connecting the last point of the boundary at land with the first point mentioned in the agreement of the continental shelf. The Netherlands used this boundary in its “Mijnwet Continentaal Plat” (Mining law for the continental shelf), e.g., for the distribution of areas for the exploration and exploitation of gas and oil.

Since 1988 Belgium tried to open negotiations to obtain newly established, ratified and legal boundaries between Belgium and The Netherlands. Belgium stated that the agreement of 1965 had no legal meaning due to (at that time) the deficiency of a Belgian law concerning the continental shelf and because no ratification or treatment by the Belgian or Netherlands parliament had taken place. Since 1965 circumstances had changed in favour of Belgium. First of all there was an extension of the port of Zeebrugge towards the sea, which should shift the boundary northward. Secondly, in 1969 the International Court of Justice (ICJ) decided that, for the North Sea Continental Shelf Cases, the method of equidistance was not a rule of law. Equitable principles had to be taken into account in case of maritime delimitations as well. In the mentioned case Germany was assigned a larger continental shelf area than could be expected on the basis of its concaved formed coastline, to the detriment of The Netherlands and Denmark.

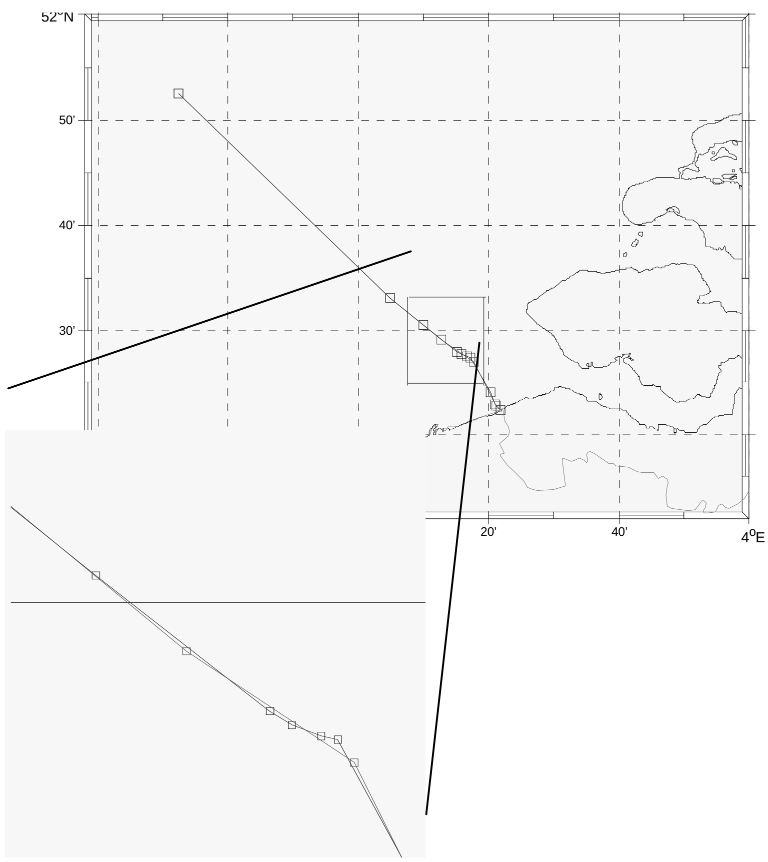

Figure 7: Equidistance and final boundary between Belgium and The Netherlands

Reference to equity by Belgium was based on the adverse coast of Belgium and the geographical conditions fore the Belgian coast. Furthermore, a lot of international shipping takes place over the continental shelf of Belgium. At first instance, The Netherlands did not stand in need for new negotiations, since the Netherlands stated that the treaty of 1965 could be considered as a final arrangement. The Netherlands based itself on this statement, because the boundary line was a technical result of the equidistance principle, recognised by Belgium, and by the fact that the boundary line had been used in practice for a long time and thus could be considered common law.

Finally, on good neighbourly terms, a compromise could be found. The Netherlands was willing to give up a small part of its continental shelf, although according to The Netherlands delimitation had already taken place. Belgium got to Belgian opinions on a basis of equity, in addition to its own continental shelf, a small part of the Netherlands continental shelf.

Technical considerations.
At the end of 1994, the negotiations between Belgium and The Netherlands started for the delimitation of the territorial sea and continental shelf between Belgium and The Netherlands. The department of Marine Geodesy of the Hydrographic Service assisted the Netherlands Ministry of Foreign Affairs in the computation of the delimitation of the new boundary.

For the territorial sea, the equidistance principle was applied, as described in article 15 of UNCLOS III.

For The Netherlands the following baselines were used:

- the low waterline along the coast (normal baseline according to article 5 UNCLOS);
- the low waterline of the low tide elevation Rassen (according to article 13.1 of UNCLOS)

For Belgium the following baselines were taken into account:

- the low waterline along the coast (normal baseline according to article 5 UNCLOS);
- the seaward extension of the harbour of Zeebrugge (according to article 11 UNCLOS)

In co-operation with Belgium, the equidistance line was approximated by a large number of points up to a maximum distance of 12 nautical miles off the harbour of Zeebrugge and the most western point of the high tide elevation Rassen. The computed equidistance line included several turning points, shown in Figure 7. An important turning point is where the low tide elevation Rassen was taken into account, instead of the normal baseline. As one can see, by strictly applying the method of equidistance, an irregular boundary is obtained, due to also irregular low water lines. Such a boundary is not easy to maintain. Taking this into consideration, a simplification of the boundary was made, without being detrimental to the equidistance rule.

Figure 8: New boundary between Belgium and The Netherlands

The areas which resulted from the intersection of the true equidistance line and the simplified and generalised boundary line were equally divided over the territorial zones of Belgium and The Netherlands. The results are shown in Figure 7 and sketched in the nautical chart in Figure 8.

For the continental shelf delimitation, the equity principle was taken into account. A connection had to be made between the end point of the territorial sea and a point at the continental shelf boundary between The Netherlands and the United Kingdom. For the construction of this point last mentioned, two auxiliary points on this line were computed:

a) a point, that, taking into account the equidistance principle, has the same distances to the port of Zeebrugge and the most western point of the high tide elevation Rassen

b) a point which has the same distances to the port of Zeebrugge and the most western point of the Walcheren peninsula in The Netherlands.

The final point of the delimitation of the continental shelf is the point, lying on ¼ of the distance between points a en b. This point is the new tri-point of Belgium, The Netherlands and the UK. The existing treaty between the UK and The Netherlands needs a small modification for this new tripoint.

The points are connected by parts of arcs of Great circles, even though ellipsoidal geodesics would be more appropriate. Compared to the boundary defined in 1965, The Netherlands lost in total about 386 km2 of its continental shelf and its territorial sea.

In December 1996, the treaties with Belgium with regard to the continental shelf and territorial sea were signed. They were ratified by both nations in 1998. Since 1 January 1999, the new boundary came into force.

Conclusion

A number of factors affect the precision by which boundary lines can be established. This contribution dealt with some of them, such as inhomogeneous datums, datum transformations, different definitions of chart datums and the precision of basepoints. All these factors should be taken into account when determining the precision of the turning points, which define the median line. This can be accomplished using the propagation law of covariances, which also takes into account the relative geometry between base- and turning points. In addition, reliability is an important measure, which, together with the precision, should be used to describe the quality of a point. The definition of the median line itself may be ambiguous since it is often not clear what type of "straight" lines were used to connect the turning points. It is recommended that these lines consist of geodesics, defined on the ellipsoid of revolution of the datum involved. However, even nowadays one often reverts to arcs of great circles, as for example in the case of boundary delimitation between Belgium and The Netherlands.

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SESSION 3 – Paper 1

GIS APPLICATIONS TO MARITIME BOUNDARY DELIMITATION

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Mr. Kurt Christensen, is a member of the technical staff with MRJ Technology Solutions, Farifax, VA, USA. He has been with that firm for over five years, and leads efforts in electro-optical systems, natural language understanding, geospatial database processing and scientific visualization. He has 15 years experience in artificial intelligence, computer systems development and consulting, and holds B.S. degrees in physics and mathematics, M.S. in electrical engineering and expects to receive an M.S. in engineering management in January 2000.

ABSTRACT

The construction of the Global Maritime Boundaries Database (GMBD) in a geographic information systems (GIS) incorporates both adjudicated and claimed maritime boundaries. The claims provide the basis for determining what marine activities are permissible under the UNCLOS Articles and the GMBD of such boundaries and limits, coupled with attribute tables containing pertinent parameters, qualifications and references, permits offshore operators to plan and conduct activities which will not be in violation of UNCLOS articles or the coastal states's claims. The GMBD will be commercially available this fall through Elsevier Science Ltd., Oxford, England.

With the increasing capability to exploit natural resources on and under the deep seabed at least 33 nations can, under Article 76, draw limits to their continental shelf which extend beyond their respective EEZ's (200 nautical miles from the baselines). In some cases, as with EEZ's, such claims overlap and bilateral agreements or median lines then become the basis for delimitation. MRJ has developed a program using Avenue scripts developed in ESRI's ArcView GIS software to create a global set of median lines on the

surface of a spheroid. The program does not require the user to preselect controlling points from the baselines: the program selects them directly from the shoreline (any scale source) and straight baseline data. The user can indicate the desired accuracy by adjusting the step size and tolerance.

Introduction

The establishment of a boundary on land is quite straightforward - build a fence, a wall, a road, or a ditch and declare that access to or occupation of the terrain on “your” side is subject to your discretion. This works well when distinct points on the ground may serve as markers from which your boundary lines originate. A “property owner” with the means to control access may thus regulate activities within that region. This owner hopes that another state acknowledges such claims and any question about their location and associated or implied rights can be settled amicably. There are other means of adjudication open to states who may dispute boundaries - one such body is the International Court of Justice which renders decisions affecting boundary delimitation.

The “straightforwardness” of delimitation based upon terrestrial features begins to fail when a body of water becomes part or all of the boundary. A river, lake, estuary , shoreline or other fluid body complicates delimitation. Such features are dynamic and may change within short periods of time, leading to revised interpretations of geographic location upon which boundaries are based. Beyond the sight of land, reasonably accurate positioning is achieved through satellite positioning systems such as the Global Positioning System (GPS) or similar geodetic locational methods In the sea the delimitation of maritime jurisdiction is further compounded by the selection of the datum from which boundaries are derived. There are at least six different vertical references (hydrographic datums) employed to define the basis for drawing maritime boundaries. While such issues are beyond the scope of this paper, we will examine the traditional maritime boundaries invoked by coastal states and the application of Geographic Information Systems (GIS) to facilitate display and interpretation of coastal state claims.

Maritime Boundaries

Coastal states draw maritime boundaries to delimit areas for juridical purposes. The declaration of a baseline is the basis for establishing the geographic reference from which other maritime limits are drawn. Specific protocols under the Articles of the United Nations Convention on the Law of the Sea (UNCLOS) describe the conditions under which a state may establish such baselines, using the shoreline (mean low water), a straight baseline established under UNCLOS Articles, or a combination of both. The traditional zones of a Territorial Sea (usually 12 nautical miles), the insertion of a Contiguous Zone (additional 12 nautical miles) and the claim of an Exclusive Economic Zone (EEZ, usually 200 nautical miles) are shown in Figure 1. Since the fundamental reference to such boundaries is the baseline, the UNCLOS has declared formulae to determine the length and direction of lines other than the curvilinear “shoreline” which is based upon various vertical datums.

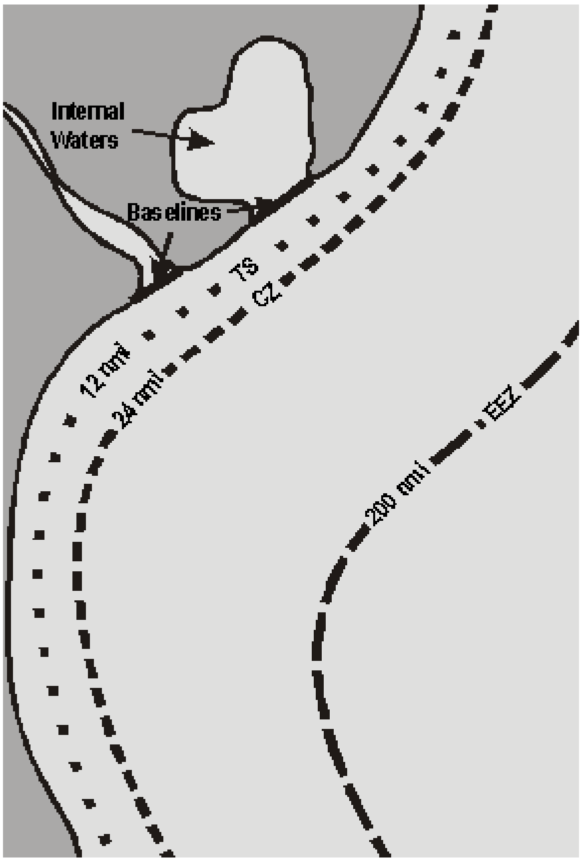

Figure 1: Primary maritime boundaries drawn from baselines. TS=Territorial Sea, CZ=Contiguous Zone, EEZ=Exclusive Economic Zone. Continental Shelf boundaries may extend seaward of the EEZ limit.

These constructs, termed “straight baselines,” enclose river mouths, irregular embayments of a specific size, and other features where “internal waters” may be claimed. Under Article 7 of the UNCLOS, straight baselines may be constructed only in a) localities where the coastline is deeply indented and cut into or, b) where a fringe of islands lies in the immediate vicinity of the coast. Two conditions regarding the width of embayments and permissible baselines appear in Figure 2.

Another maritime boundary of growing significance is derived from geographic references other than the baseline. Delimitation of the Continental Shelf Regime employs bathymetric, geomorphic and geologic datums which also require geospatial documentation. Whereas the EEZ is established to allow of control of activities on the sea’s surface and in the water column, the Continental Shelf claims are directed toward resources, mineral and living, which lie on and under the seafloor. These shelf claims can extend for significant distances beyond the 200 nautical mile EEZ and encompass enormous tracts of the seafloor. Finally, there are claims on the seafloor under high seas regions which lie beyond any coastal state’s claims. These are included under the United Nations “Sea Bed Authority” and convey rights to deep-sea mining in international waters.

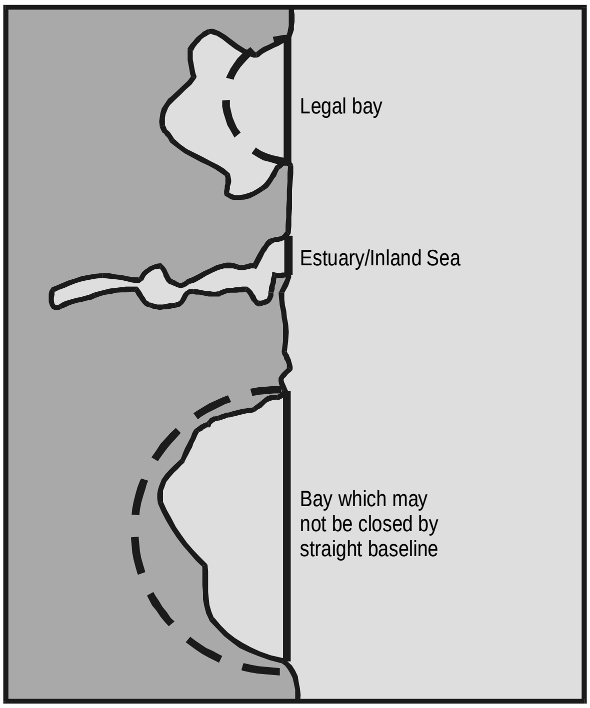

Figure 2: Straight baseline construction according to Article 10 of the UNCLOS. The depth of indentation of an embayment must be greater than one-half the length of the baseline closing the bay.

Maritime Boundaries as Spatial Data

Maritime boundaries established under either the UNCLOS protocols or unilateral coastal state claims are dependent upon some geospatial reference which (initially) provides a point on the earth's surface as the fixed basis for a claim. In the case of the low water datum or straightlines for baseline construction, such locations depend upon a variety of hydrographic determinations referenced to their vertical datum. For Continental Shelf boundary constructions (and for other boundaries far from shore), oceanographic and geophysical surveys and their attendant positioning capabilities under such systems as the GPS determine the accuracy of geospatial coordinates employed in establishing boundary claims.

The Management of Maritime Boundary Data in a GIS Approach

A Geographic Information System (GIS) is a computerized data management system for the capture, storage, retrieval, analysis and display of spatial data. The basic elements of a GIS are <u>points, lines, and polygons.</u> They permit the display of two-dimensional presentations of "attributes" - descriptions of features and data which characterize a particular data set.

To manipulate spatial data in a GIS mode, the computer needs three things:

- Where each feature is in some referenced geographic space (position)
  - What each feature is (attribute information)
  - The spatial relationship of each feature with respect to others ("neighborhood")

For maritime boundaries, these conditions are met by the declarations of the coastal state in applying for recognition of its jurisdiction. The basic features are the points: these may be shoreline low water (or other datum) points, geographic features serving as points (headlands, islands, etc.), "turning points" for straight baseline constructions, end-points for a line, or corners for a polygon. After these elements are entered in the GIS database, attributes are applied which "label" the feature and provide background information on the nature of that feature. Finally, the GIS relates the feature (point, line or polygon) to neighboring features (coastline, similar features, different features, etc.).

Applications of a Maritime Boundary Database

Maritime boundary information is available from a variety of sources, including the United Nations, various State Departments or their equivalents in coastal states, academic institutions and private databases. Yet nowhere are all the data, and especially their attributes providing essential background information, available in a GIS database. Marine enterprises benefit from, and depend upon, information regarding the juridical claims presented by coastal states. Under such claims, stipulations addressing constraints to various activities under UNCLOS protocols or coastal state declarations become integral elements in planning offshore developments which will both justify investor's support and assure unimpeded execution of proposed offshore endeavors.

MRJ Technology Solutions has developed, and will shortly offer, a Global Maritime Boundary Database (GMBD) which will contain information on current maritime delimitation and offer periodic updates to changes in coastal state's claims to jurisdiction over offshore regions. An example of such a database entry is provided in Figure 3. Here the claims of Pakistan have been displayed and the variety and nature of UNCLOS claims as well as indigenous claims and the location of a disputed area are presented in a database format.

At present the GMBD boundary data are derived from numerous sources. We have employed World Vector Shoreline (WVS) at the scale of 1:250,000 as the reference for boundaries. Due to the small scale of the WVS as compared to the larger scale of approach and harbor charts (1:100,000 to 1:25,000) from which listed boundary coordinates are derived, a review has been made of nautical charts and supplementary sources of hydrographic data to ensure islands, reefs, rocks and shoals were represented in WVS. Buffers constructed from such data provide the basis for graphic presentation of boundaries in the GMBD.

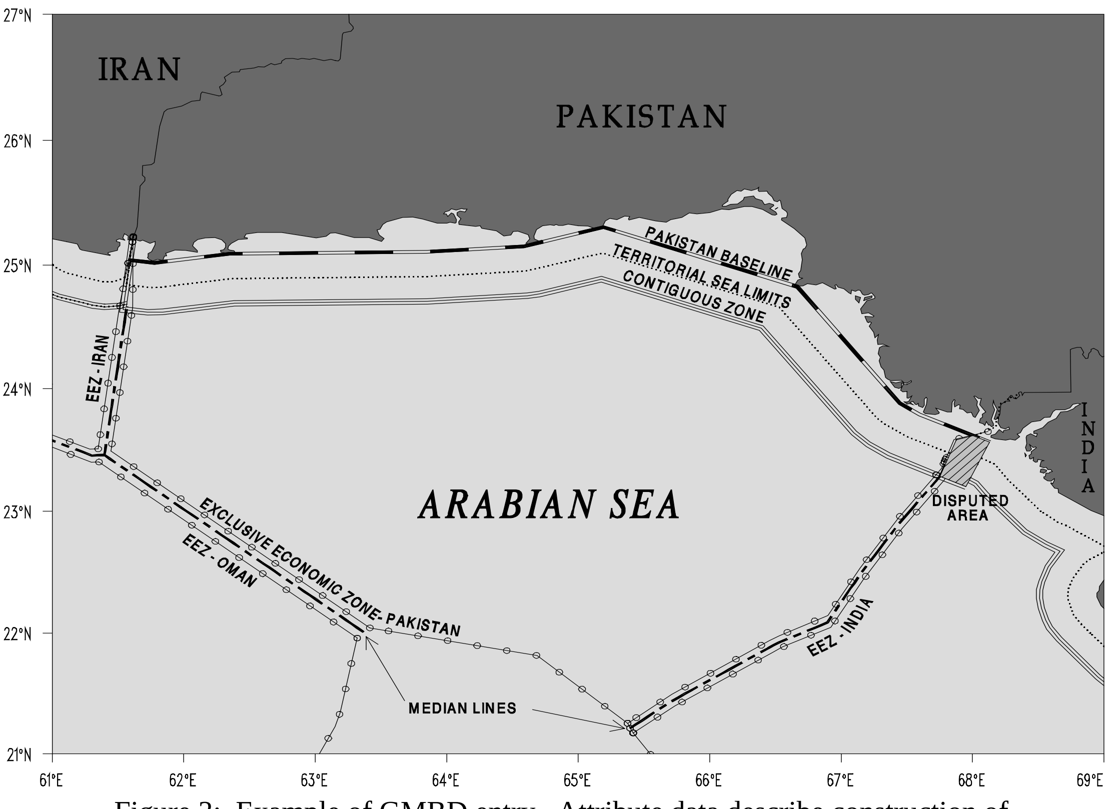

Figure 3: Example of GMBD entry. Attribute data describe construction of maritime limits and sources of information.

Maritime boundaries: India, Oman, Iran (median lines, not arbitrated).

Signed UNCLOS	12-10-82	
Ratified UNCLOS	02-26-97	
Baselines	08-29-96	
TSL Claimed	1996	12 nmi
CZ claimed	1996	24 nmi
Fisheries Zone(1)	1973	35 nmi
EEZ	1976	200 mi
Continental Shelf	1976	200 mi
(plus continental margin definition)		
MSR Jurisdiction	Yes	
MSR Regulations	Yes	

Baseline published in Gazette of Pakistan via Ministry of Foreign Affairs, 29 August 1996. (DOALOS, Law of the Sea Bulletin #34, p. 45, 1997). Straight baseline turning points:

(a)	25°02.20’N	61°35.50’E
(b)	25°00.95’N	61°46.80’E
(c)	25°05.30’N	62°21.00’E
(d)	25°06.30’N	63°51.01’E
(e)	25°09.00’N	64°35.20’E
(f)	25°18.20’N	65°11.60’E
(g)	24°49.45’N	66°40.00’E
(h)	23°52.80’N	67°26.80’E
(i)	23°47.30’N	67°35.90’E
(k)	23°33.90’N**	68°07.80’E**

**disputed by India

Comments:

Straight baselines from which TSL, CZ, EEZ and Continental Shelf shall be measured. From Pakistan's Territorial Waters and Maritime Zones Act of 1976 (sec. 2, par. 3). Internal Waters lie landward of these baselines.

(1) Current deep sea fishing policy reserves exploitation rights in Zone I, between 12 and 35 nmi from shore, for artisinal fishermen. Zone II, 36-200 nmi, open to larger trawlers and longliners, requires a license from Ministry of Food, Agriculture and Livestock. (World Fishing, January 1998, p. 2)

**Disputed zone with India results from overlap of TSL/CZ boundaries. (DOALOS, Law of the Sea Bulletin #35. p. 41, 1997)

Sources of Error

Questions of scale and projection enter into an assessment of accuracy in any GIS. In the case of maritime boundaries, this is especially true since data derived from nautical charts suffer from factors such as line width on the chart and variations in chart datum between countries (hence a discrepancy in buffering). Mercator projection is the common basis for mariners, and errors in line length and in true distances increase cumulatively as distance from the equator increases. The basis and assumptions for all data in the GMBD are carefully enumerated for the user and sources of error are identified as appropriate to each entry.

Users

Maritime boundaries affect all those engaged in offshore activities, from extractive industries such as fisheries and petroleum to the conduct of marine research. The latter is of special concern to the academic community since formal permissions for obtaining samples from the water column or the seafloor may require not only consent from the coastal state but participation on-board ship by coastal state scientists. The GMBD is designed to provide those engaged in maritime activities with a planning tool which presents the geographic extent of real or perceived jurisdictions of coastal states. It further identifies those regions in which boundaries are in dispute, overlap or are otherwise unresolved. For example, numerous boundary issues have been raised as a result of fisheries disputes, and in many cases the fisheries agreements and their limits and conditions (usually quotas, restrictions in gear and vessel size or seasonal constraints) are incorporated in the GMBD.

Conclusions

No maritime activity should be anticipated or undertaken without cognizance of boundaries claimed by coastal states. Coastal states are entitled to control and participate in marine activity occurring in waters which they may rightly claim under ratification of the UNCLOS. As the legal framework of maritime boundaries evolves, the GMDB will provide current status and locational information in a GIS context useful to a variety of users.

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SESSION 3 – Paper 2

A MODEL FOR USING PUBLICLY AVAILABLE DATA AND METHODOLOGIES TO BEGIN PREPARING A CLAIM TO AN EXTENDED CONTINENTAL SHELF UNDER ARTICLE 76 OF THE UNITED NATIONS CONVENTION ON LAW OF THE SEA (UNCLOS)

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ABSTRACT

Under the United Nations Convention on Law of the Sea (UNCLOS) some States will be able to claim jurisdiction over an extended continental shelf. Article 76 of UNCLOS regulates the extent of such a claim and establishes the United Nations Commission on the Limits of the Continental Shelf to examine claims and recommend their adoption. This paper presents an iterative model that can be followed by any Coastal State in preparing its claim.

The model includes the two types of action that a response to the Guidelines calls for, namely making judgmental decisions and providing scientific interpretations, both substantiated by data. Judgmental decisions include deciding when to invoke the "evidence to the contrary" clause, deciding which isolated sea floor elevations to include as part of the continental shelf, and when to use the ‘sediment thickness’ approach. Scientific interpretations include the tidal regime to be applied to Baselines, the location of the 2500m bathymetric contour, the various methods of determining sediment thickness, and in the case of "evidence to the contrary" the entire question of where the geological edge of a continent occurs. Applying the model presented here will be useful in planning the approach a Coastal State will take in seeking funding and approval to develop the claim, in demonstrating to the Commission how a claim has been prepared, in educating would-be claimants, and in developing software to be used in the process.
The first two iterations of the model can be carried out using readily available data. The global bathymetric contours of the General Bathymetric Chart of the Oceans (GEBCO) may be used for the first iteration while the global soundings database of the IHO Data Centre for Digital Bathymetry may be of use in the second.

1. INTRODUCTION

With the coming into force of the United Nations Convention on Law of the Sea (UNCLOS), (United Nations, 1983), Coastal States have an obligation to examine their continental shelves and decide whether they wish to claim extended jurisdiction over part of the seafloor beyond the 200 nautical mile-wide Exclusive Economic Zone (EEZ) which the Convention grants them automatically. The exact number of States which may be affected by this is not yet clear but, out of approximately 150 Coastal States, about 60 have neighbours closer than 200 nautical miles thereby preventing an extended claim, a further 30 or so have a shelf less than 200 nautical miles wide, leaving of the order of 50-60 potential claimants.
States wishing to claim are regulated primarily by Article 76 of UNCLOS. Article 76 defines a legal continental shelf and establishes the United Nations Commission on the Limits of the Continental Shelf to which States must submit their claims. This Commission has produced Guidelines (United Nations, 1999) which elaborate the types of evidence it will accept, as well as detailing how that evidence must be arranged, mapped and supported by data bases, and the accuracies and standards to which it should be reported. The evidence includes water depth, sea floor shape, sea floor composition, and potential fields over the sea floor, and the various methods of mapping and portraying these characteristics**.**

1.1 The situation a Coastal State faces

States deliberating on making a claim are faced with;

a) understanding Article 76 and the Guidelines within the context of their own geography,
b) deciding, within the judgmental elements of Article 76 and the Guidelines, which features they may wish to attempt to claim as part of their legal continental shelf
c) examining the existing data to determine whether it will support a claim
d) where necessary, planning for and collecting additional data,
e) assembling the data into a supported and defensible claim and
f) submitting a case,

all within ten years of ratifying the Convention.

This paper examines the first four steps in this process and develops a model that can be used as an overall guide to preparing a claim. A State intending to prepare a claim will probably wish to use the most economical and productive approach, one that uses the best elements of all possible methods in a synergistic manner. The iterative model developed here applies several approaches in a mutually supportive flow that will lead to an effective claim, supported by appropriate interpretations of the evidence available. It also addresses the questions of deciding where data are needed, and when to invoke the “evidence to the contrary” clause and move from morphology into developing the geological case.

1.2 An overview of Article 76

Article 76 establishes a zone within which the claimed Outer Limit of the continental shelf may lie. The inner edge of this zone is the outer limit of a Coastal State’s Exclusive Economic Zone, which is at a distance of 200 nautical miles from “the baselines from which the breadth of the territorial sea is measured” (referred to simply as “Baselines” in this paper. For a technical description of baselines, see Beazley, 1971). The remaining edges to this zone are either boundaries that will have to be resolved with another State, or a boundary with the United Nations-controlled region called “The Area”. In the latter case, Article 76 applies and can be used to the State’s advantage. The State can choose the most beneficial combination of either a line drawn 100 nautical miles seaward of the 2500m bathymetric contour or a line 350 nautical miles from the Baselines, to establish an outer “constraint line”. There is an exception to this rule; over “ridges”, only the 350 nautical miles line may be used.

Within the zone established as outlined in the preceding paragraph, the claimed Outer Limit must be derived. The point of departure is from a construct known as "the Foot of the Slope", a theoretical physiographic feature on the surface of the sea floor separating the Continental Slope from the Continental Rise. There are judgmental elements in deciding whether to include physiographic highs that are separate from the continuous margin, followed by the problem of establishing just where the line should fall. There is also an alternative path to mapping the Foot of the Slope, wherein the surface expression is ignored and "evidence to the contrary" is invoked to establish the continental – oceanic boundary on geological / geophysical grounds. In either case, the claiming State can then choose the most beneficial combination of a line drawn 60 nautical miles seaward from the Foot of the Slope or use the sediment thickness line,

> "a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope".

The lines claimed as outer limits need not be defined along their entire length but only at points separated by a maximum distance of 60 nautical miles. Other lines, for instance the Baselines and the 2500m contour, must be prepared as continuous lines.

Clearly, there are both judgmental and more strictly defined elements to the Article, and depending on it's geography and geology, a State may need to invest effort in deciding how best to apply the latitude given.

1.3 The steps in making a claim

Coastal States will begin the process of preparing a claim from different positions in terms of their expertise in the subject and the amounts of data available to them, to say nothing of the physical setting of their margin. All States will follow the steps shown in Table 1; they will probably step through this table again and again, at each step improving their knowledge of their continental shelf, until they are satisfied that they have sufficient evidence to support their claim.

Table 1 Overview of steps in preparing a claim

	STEPS in preparing claim
A	**PREPARE BASE MAP**
B	**ESTABLISH THE ZONE POSSIBLE**
C	**DEFINE BASIS FOR GOING BEYOND 200 NAUTICAL MILES**
D	**PREPARE OPTIONS BEYOND 200 NAUTICAL MILES**

The first two iterations through this model can be done using existing publicly available data, as this paper shows. Completing these first two iterations quickly and at low cost will permit identifying where more detailed work is required. An exposition of how these two iterations can be made is given in the following sections while a summary of the key elements of the iterative model is to be found in Table 2.

Table 2: Iterative model for preparing a claim

A	**PREPARE A BASE MAP**	
1	ON EXISTING MAP DRAW	SHORELINE BATHYMETRY

		BILATERAL BOUNDARIES
2	DO BASELINES EXIST?	IF YES, INCLUDE ON BASE MAP IF NO, USE SHORELINE AS INTERIM MEASURE
B	**ESTABLISH THE ZONE POSSIBLE**	
1	DRAW 200nm LIMIT	***DOES IT INFRINGE ANOTHER STATE'S 200nm LINE? IF YES, DRAWN MEDIAN LINE AND STOP (NO CLAIM CAN BE MADE INSIDE ANOTHER STATE'S 200nm LIMIT)
2	DRAW 350nm LINE	
3	DRAW 2500m + 100nm LINE	
4	DRAW OUTER CONSTRAINT LINE (MOST SEAWARD COMBINATION OF B2 AND B3)	***DOES IT INFRINGE ANOTHER STATE'S CONSTRAINT LINE? IF YES, DRAWN MEDIAN LINE. WHERE MEDIAN LINE IS NEEDED, IT BECOMES A CONSTRAINT LINE
5	SKETCH EXTENSIONS TO BILATERAL BOUNDARIES	
C	**DEFINE BASIS FOR GOING BEYOND 200 NAUTICAL MILES**	
1	MAP 'FOOT OF THE SLOPE' ALTERNATIVES USING BATHYMETRY	***IS IT SEAWARDS OF 200 MINUS 60nm? IF NO, CONSIDER 'EVIDENCE TO THE CONTRARY'
D	**PREPARE OPTIONS BEYOND 200 NAUTICAL MILES**	
1	DRAW 'FOOT OF THE SLOPE' + 60nm	***IS IT SEAWARDS OF OUTER CONSTRAINT LINE? IF YES, GO TO NEXT ITERATION
2	DRAW SEDIMENT THICKNESS LINE	USE SEDIMENT MAPS AS AN INTERIM MEASURE
3	COMBINE D1 AND D2	TAKE MOST SEAWARD COMBINATION TO CLAIM FOR FURTHEST EXTENT
4	RESULT	MAP SHOWING POSSIBLE CLAIM INCLUDING a) AREA WHERE 'FOOT OF THE SLOPE' + 60nm WILL SUFFICE b) AREA WHERE SEDIMENT THICKNESS DATA WILL BE NEEDED c) AREA WHERE 'EVIDENCE TO THE CONTRARY' WILL NEED TO BE CHECKED

***FOOTNOTE: IN CASES WHERE THE RESPONSES TO TESTS B1, B4, C1 AND D1 VARY ALONG THE LINE BEING TESTED, THE INSTRUCTIONS APPLY TO THAT PART OF THE LINE TO WHICH THE RESPONSE RELATES

2. FIRST ITERATION

2.1 Objective

The first objective is to decide whether an extended continental shelf may exist adjacent to a Coastal State and the approximate zone within which it might fall.

2.2 Prepare a base map

Sea floor physiography is shown on bathymetry maps, which are available in highly variable quality, scale and coverage depending on the area of the world being examined. Bathymetry of all the world ocean has been mapped to at least a "first look" stage through an international IHO/IOC collaborative exercise known as the General Bathymetric Chart of the Oceans (GEBCO). This is a good starting point for any preliminary investigation, although where more recent or better scale maps exist, they should be used. In paper form, any map series permits gaining an overall appreciation of the geography involved, and permit hand drawing and measuring. The paper chart version of GEBCO was published by the Canadian Hydrographic Service in the 1980s (IHO, IOC and CHS, 1984). It is now being updated in digital form through a product called the GEBCO Digital Atlas with new versions being published on CD-ROM at three yearly intervals by the British Oceanographic Data Centre (IOC, IHO and BODC, 1997 and Jones, 1997). The CD-ROM version allows for calling up only selected contours, say the 200m and 2500m, to help emphasize or clarify a point. It also includes a facility for making distance measurements directly on the screen to evaluate the feasibility of including a feature based solely on distance. As an example of how the GDA can be used as a basemap, Figure 1 shows a portion of GEBCO bathymetry off eastern Canada.

2.3 Establish the zone possible

The inner limit to an extended continental shelf is the 200 nautical mile line which marks the outer edge of a Coastal State's EEZ. In areas where an EEZ is less than 200 nautical miles wide since it terminates at a boundary with another State, there can be no claim.

The outer constraint line is made up of the most seaward combination of a line 350 nautical miles from the baselines and the 2500m plus 100 nautical mile line. Neither of these lines can infringe on similar lines drawn by neighbouring States and where they do, some median line will have to be drawn. At this stage the median line is for planning purposes: if at a later date, the extended continental shelf reaches the median line, it will probably become the subject of an agreement between the adjacent States. There is one limitation imposed here; over 'ridges', only the 350 nautical mile line is permitted as the constraint. "Ridges" are discussed as part of the "Areas to include" exposition below.

An extended continental shelf around an island will have no lateral limit, but where two States abut (e.g. Canada - USA), a lateral limit will consist of the extension seaward of the boundary they share within their EEZs. For planning purposes, a simple geometric extension will suffice.

Drawing a 350 nautical miles line is straightforward. The 2500m plus 100 nautical miles line can raise the issue of isolated elevations. Figure 2 continues the example area shown in Figure 1 and shows the alternative 2500m plus 100 nautical miles line that including or not including such elevations can produce. Alternatives like this are discussed under "Areas to include" below.

2.4 Define the basis for going beyond 200 nautical miles

2.4.1 The Foot of the Slope

Taken together, the i inner limit and the outer constraint line produced in the preceding section circumscribe an area within which a State may be able to prove that an extended continental shelf exists. That proof and any claim are based on the location of a geomorphic feature, the Foot of the Slope, which may or may not exist on any stretch of continental margin. Paragraph 4(b) of Article 76 defines the Foot of the Slope as follows:

> "In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base".

Note that there is no quantification of the gradients involved: all that is required is to find the point where the gradients change the most. Nor is there any specific depth associated with the Foot of the Slope, although Article 76 does give some guidance in that it uses the word “base”, meaning towards the deeper part of the Slope. “Evidence to the contrary” is not defined, but inclusion of this phrase in the definition leaves scope for using arguments other than morphometric gradient determinations. The Guidelines provide extensive elaboration of “Evidence to the contrary”. Essentially, they support an argument that the edge of the continental crust may not have a surface expression manifested as a geomorphic Foot of the Slope. Rather the edge of the continental crust may be found by other, primarily geophysical, means.

At this preliminary stage, a State will first examine the sometimes complicated question of whether a morphometric Foot of the Slope exists and it's location, before addressing the necessity and value of invoking the ‘Evidence to the contrary’ clause. Finding a Foot of the Slope is a multi-part problem, beginning with finding the appropriate break in slope in any one place complicated by two ancillary problems, namely, what to do with isolated elevations, and whether a continental shelf is formed on an ‘ridge’ or not.

2.4.2 Areas to include

Some continental margins will consist of a single cohesive block, but many will have elevated features separated from the main margin by deeper sea floor. Article 76 gives some guidance on how these are to be dealt with in Paragraph 6 where it acknowledges the existence of

> " submarine elevations that are natural components of the continental margin, such as it's plateaux, rises, caps, banks and spurs".

The Commission’s Guidelines elaborate as follows:

"Submarine elevations are exempted from the provisions applied to submarine ridges...Common to all of these elevations is that they are natural components of the continental margin...Consequently, the Commission will base its views on "submarine elevations" mainly on the following considerations: ...In the active margins...any crustal fragment or sedimentary wedge that is accreted to the continental margin should be regarded as a natural component of that continental margin ...In the passive margins... seafloor highs that are formed by this breakup process should be regarded as natural components of the continental margin where such highs constitute an integral part of the prolongation of the land mass."

These clarifications make it evident that the geology of an elevation and not its physiography will determine whether it can be included or otherwise within a continental shelf. Although neither the Guidelines nor Article 76 specifically say so, it is implicit that a Foot of the Slope will occur, if it occurs at all, on the seaward flanks of these isolated continental elevations.
The question of whether an extended continental shelf is on formed on a "ridge" or not is important since if it is, Article 76 restricts the outer constraint line to the 350 nautical miles cut-off, and prohibits the use of the 2500m plus 100 nautical miles line. The Commission debates at great length what is meant by the term "oceanic ridge" in this context and concludes:

> “ the Commission feels that for the purposes of the Convention the term "oceanic ridges" includes all ridges located on the deep ocean floor which do not have any connection with the continental margin".

Although not specifically stated, the Guidelines infer that all other ridges are part of the continental shelf. This interpretation means that no geological evidence need be invoked in deciding whether a feature is an “oceanic ridge” or not; bathymetry alone can be used. If this interpretation by the Commission appears in the final version of the Guidelines, then a Foot of the Slope can be mapped on geomorphic grounds along

ridges that adjoin a continent and possibly an island, perhaps occurring as far seaward as the 2500m plus 100 nautical miles constraint.
Clearly, the inclusion of elevations and ridges can greatly influence the ultimate size of a claim and must be considered carefully.

2.5 Prepare options beyond 200 nautical miles

The reasoning in this section should be applied to prepare a draft map showing the area within which the final Outer Limit claim will fall and the options available for where a Foot of the Slope will occur and where "evidence to the contrary" might usefully be invoked. Doing so will require some maps and tools, as discussed below.

2.5.1 Working example using publicly available bathymetric maps

A very tentative Foot of the Slope line can be produced using the bathymetric contours on GEBCO. On a contour map, gradients are steeper where contours are closer together and less steep where contours are further apart (provided of course that the contour interval is the same). In theory, the Foot of the Slope may therefore be shown at the place where the more closely spaced contours of the Slope give way to the more widely spaced contours of the Rise. The horizontal scale means that measurements between contour lines cannot be very accurate but some continuity can be established. Working with contour maps alone, it is possible to arrive at more than one interpretation of the Foot of the Slope, which shows where effort will have to be focussed as the investigation continues.

Figure 1 provides an example of this off Eastern Canada. In the northern part of the diagram the situation is fairly straightforward: a linear continental slope with regular contours. The zone within which the Foot of the Slope must fall is easy to determine at this scale. Moving south, a widening of the spacing between contours complicates the situation, with no easily apparent zone within which the Foot of the Slope can easily be fitted. Even further south, the presence of an isolated elevation, Orphan Knoll, illustrates the issue of whether isolated elevations may be included. Bathymetry alone will not clarify whether these are continental fragments or not, and at this stage they can be left as questions, or the preliminary investigation can expand into a literature search to determine what is known of the geological history and composition of the feature in question. In the example, Orphan Knoll would be shown to be continental fragments (data from a JOIDES hole, smaller drill cores, gravity, magnetic and seismic data), meaning the Foot of the Slope can be unambiguously extended to encompass it. If the geological and geophysical data did not exist or were scarce, the origin of these features would have to be investigated.

The Foot of the Slope line produced as described can be plotted onto the map of the possible zone within which the extended continental shelf may occur as shown diagrammatically in Figure 3. This is a valuable exercise since it shows

a) Areas where the morphological Foot of the Slope may be inside the 200 nautical miles line. These are obvious candidates for sediment thickness investigations, and less obviously, possible candidates for where "evidence to the contrary" may be applied.
b) An area where the Foot of the Slope is seaward of the constraint line and simple bathymetry will suffice.
c) A situation where two locations of the Foot of the Slope can be predicted depending upon whether an isolated elevation is included or not. These are areas where "evidence to the contrary" may be applied, and areas where some geological evidence will be needed.

d) An area where the Foot of the Slope is difficult to determine from contours.

None of this is to say that a Coastal State would not examine all possible avenues for all of its geographic area. It may well do so, but this process shows where emphasis can most advantageously be placed soonest.

2.6 Results of first iteration

The results of the preliminary investigation should yield a small scale map showing very approximate outer limits, areas where different parts of Article 76 apply and a zone wherein the Foot of the Slope is probably to be found. It will also show the intent to try to include certain physiographic features within the claim. It will not have investigated sediment thickness in any detail, nor the use of "evidence to the contrary", but will have identified where they might be important. (Carpenter et al, 1996, provide an example of results of this level of investigation for the eastern continental USA. Monahan and Macnab, 1994, do the same for Canadian waters.)

2. SECOND ITERATION

2.1 Reasoning

States will enter this second loop armed with some small scale planning maps, produced during the first iteration, that largely reveal where different portions of Article 76 can be applied, where some decisions need to be made and where further investigation is needed.

As an example, consider the 2500m contour. The preliminary investigation will have shown approximately the region where it will be used to determine the outer constraint line. There will be cases where it is not used at all, the 350 nautical miles being further seawards, and energy can be focussed on other parts of the claim. Where it is to be used, the contour will need to be supported by echo-sounding data. The following questions then arise. Is there enough data of acceptable quality and spatial layout? Has more data been collected but not incorporated into the maps used in the preliminary investigation?

Because it may be based on the same data set, these questions can also be applied to determining the Foot of the Slope on morphologic grounds. The two may not be strictly comparable since Foot of the Slope is probably more demanding of data than is the 2500m contour.

2.2 Databases

GEBCO, in both its paper and digital versions, shows the position of the sounding track data available when the maps were compiled. The transfer of these tracklines onto the base maps will assist identifying possible source data that might be available to support the claim. Of particular value will be a search of the echo-sounding data available at the IHO Data Centre for Digital Bathymetry - a trackline display of the available data (at the date of publication of the CD-ROM) may be viewed from the GEBCO Digital Atlas CD-ROM. These steps are useful in gaining an appreciation of whether additional data will be needed and, if so, where there is most to be gained from adding new data. It is virtually certain that other data already exist not only in the updated files of the IHO Data Centre but also on the ocean plotting sheets and databases of national Hydrographic Offices.

The IHO Data Centre for Digital Bathymetry (http://www.ngdc.noaa.gov/mgg/bathymetry/iho.html) is operated by the US National Geophysical Data Center in Boulder and is co-located with the World Data Centre-A for Marine Geology and Geophysics. The echo-sounding data holdings at Boulder are regularly published on the Global Trackline Geophysical Data Base (GEODAS) CD-ROM (Sharman et al. 1998). As of December 1998, it contained almost 35 million echosoundings covering 13 million miles of track in the world ocean. In addition to echo-sounding data, the Boulder Center also holds major global collections of marine geophysical data that may be of use to the understanding of the geological context of the continental margins of Coastal States. Examples include inventories of where seismic reflection data have been collected, global gravity maps collected from spaceborne altimeters, underway gravity and magnetics profiles (published on the GEODAS CD-ROM), as well as data from the international Ocean Drilling Programme. Further information on these data may be obtained from http://www.ngdc.noaa.gov/mgg/aboutmgg/wdcamgg.html . Other data, including seismic data, may be available from WDC-B for Marine Geology and Geophysics in Russia (http://www.sea.ru/cmgd/wdc.html).'

2.3 Results

Production of small scale maps that illustrate approximately where a state may make a claim, that show the sections of Article 76 that apply to a State's offshore, and that allow planning for more detailed investigations at further iterations of the model. By the end of the second iteration, a start will have been made in identifying existing data that might be available for use in developing the claim.

3. SUCCEEDING ITERATIONS

Deciding how far to continue through succeeding iterations will involve judging the amount of territory that might be claimed against the difficulty and expense of making the claim. For some States, the first two iterations will have produced a convincing picture to proceed, while others will want to investigate more fully, while still not committing many resources. Both will probably continue almost automatically to the next iteration, investigating sediment thickness and "evidence to the contrary" more fully using the available data.

As the picture develops, succeeding iterations will be used to narrow down the zone of uncertainty and point the way to where more data are needed. At each iteration, greater detail will be built into the suite of maps and their supporting data bases until eventually sufficient information is available to support the claim. Where justified by the potential benefits of the claim, such iterations will invariably involve the collection of field data to refine the Outer Limit and to resolve ambiguities.

4. DATA SOURCES

The printed sheets of GEBCO are available from:
Hydrographic Chart Distribution Office,
Department of Fisheries and Oceans,
P.O.Box 8080,
1675 Russell Road,
Ottawa,
Canada K1G 3H6

The GEBCO Digital Atlas CD-ROM is available from:
GEBCO (Orders),
British Oceanographic Data Centre,
Bidston Observatory, Birkenhead,
Merseyside CH43 7RA,
United Kingdom.
Information is available at URL http://www.bodc.ac.uk/

The Global Trackline Geophysical Database CD-ROM is available from:
Data Services, National Geophysical Data Center,
NOAA Mail Code:E/GC,
325 Broadway,
Boulder, Colorado 80303,
USA.

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United Nations, 1999. Scientific And Technical Guidelines Of The Commission On The Limits Of The Continental Shelf. UNCLOS document CLCS11, 13 May 1999, 91 pp.

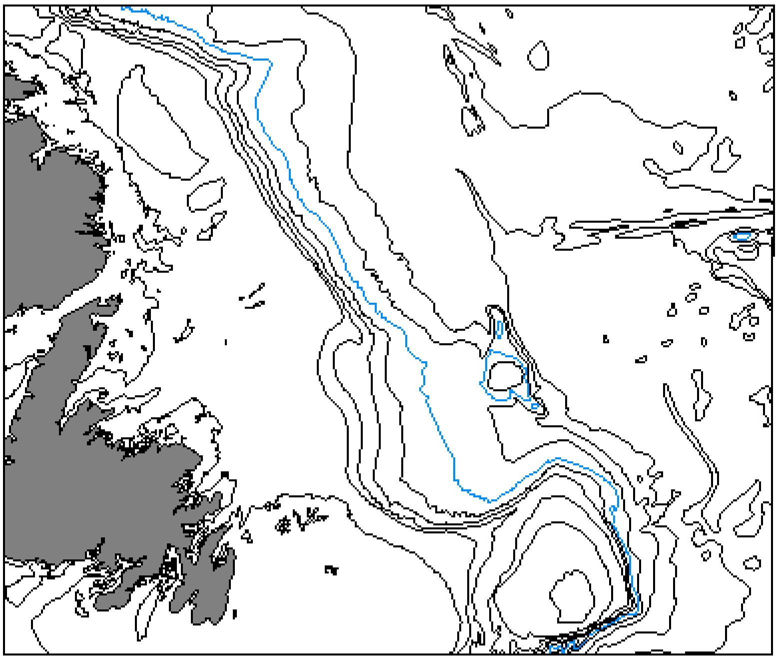

Figure 1 As an example of how the GDA can be used, a portion of GEBCO bathymetry off eastern Canada is shown. Contours are at 200m, 500m and every 500m thereafter.

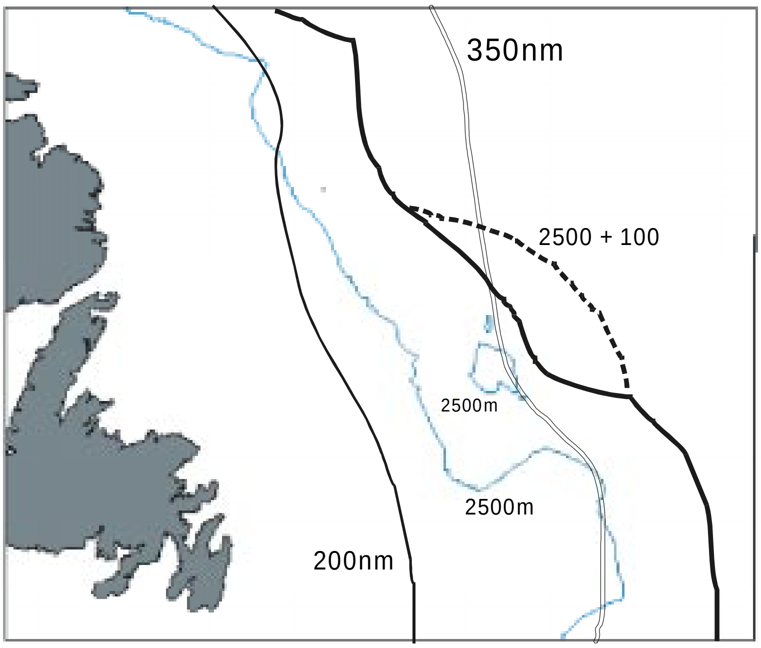

Figure 2. Summary of lines that can be quickly sketched on the base map using the GEBCO Digital Atlas. Inner fine line labelled 200nm marks the EEZ. Dashed fine line is the 2500m contour (contours except the 2500m have been omitted for clarity). Fine double line labelled 350nm is the 350 nautical mile constraint. Heavy solid line labelled 2500 +100 is the 2500m contour plus 100nautical miles line: heavy dashed line shows an alternative more likely position.

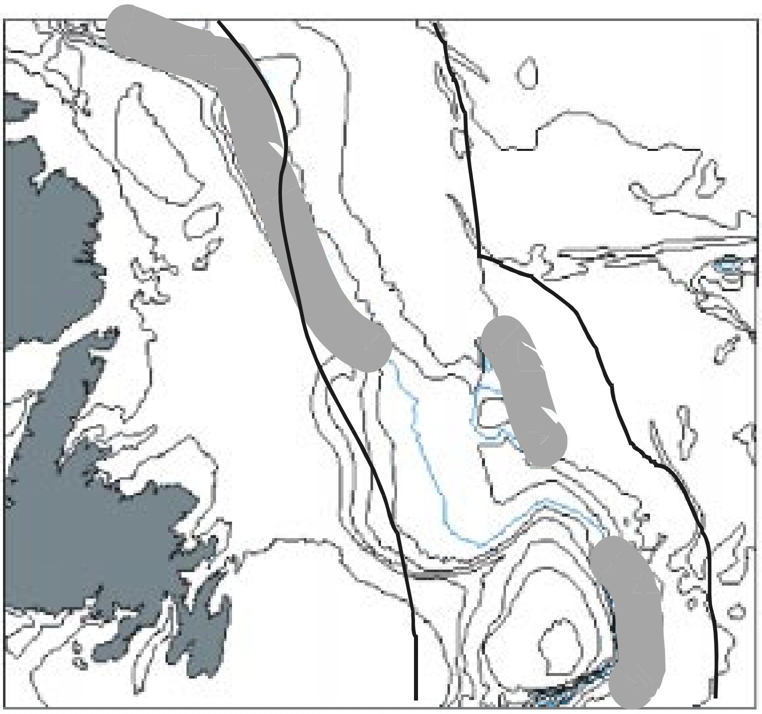

Figure 3. Same location as Figures 1 and 2. The zone where the claimed Outer Limit of the continental shelf lies will be between the EEZ and the outer constraint line, both shown as solid medium lines. Grey areas indicate where the Foot of the Slope, or in early iterations, the Base of the Slope, may lie, based on analysis of the contours. Other areas shown on this diagram but not labelled are discussed in the text.

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SESSION 3 – Paper 3

AN EXAMINATION OF PUBLICLY AVAILABLE BATHYMETRY DATA SETS USING DIGITAL MAPPING TOOLS TO DETERMINE THEIR APPLICABILITY TO ARTICLE 76 OF UNCLOS

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ABSTRACT

During the planning stages of preparing a submission for Extended Jurisdiction under Article 76, a Coastal State will probably begin with an examination of existing publicly available data sets. Such data can be contoured using readily available contouring software or may already be contoured. These data sets include ETOPO5, the Predicted Bathymetry from NOAA, the GEBCO gridded data set and the GEBCO contours. There are also national data assemblages that states have access to. These data sets can first be examined for their depiction of the 2500m contour followed by a search for the Foot of the Slope within them.

The value of comparing these data sets and the 2500m contour and Foot of the Slope they yield include

1) One set or some attribute of it (grid size) may produce better results than another
2) The effect on the outer limit of adding extra data points may be shown through the d different data densities
3) Blunders within the data sets may be found.
4) The impact of orientation of slope relative to grids or tracks may be shown.
5) The different contours produced from the different data sets can be compared to give an estimate of the areas that may be 'gained or lost' by using different data densities, data sets, or techniques. (The area "at risk").
6) The value of producing another gridded data set may be examined.
7) The return (in terms of area gained) of building a national data set as opposed to simply using one of the public domain data sets can be established.

A further benefit of such an exercise may arise from determining how multibeam data might be incorporated into the much coarser data that exists over much of the Continental Slope.

This paper presents the results of such a comparison for areas off Eastern Canada and the USA.

Introduction

With the coming into force of the United Nations Convention on Law of the Sea (UNCLOS), (United Nations, 1983), Coastal States have an obligation to examine their physical continental shelves and decide whether they wish to claim 'extended jurisdiction' over part of the seafloor beyond the 200 nautical mile-wide Exclusive Economic Zones (EEZ) which the Convention grants them automatically. Extensive, potentially resource-rich, areas may be claimed, provided certain conditions are met, and the world-wide mood seems to be one where Coastal States will attempt to claim the greatest area possible. States wishing to claim are regulated primarily by Article 76 of UNCLOS which defines the legal continental shelf and establishes the United Nations Commission on the Limits of the Continental Shelf (CLCS) to which States must submit their claims. This Commission has only recently (i.e. May, 1999) produced Guidelines (United Nations, 1999) which elaborate the types of evidence it will accept, as well as detailing how that evidence must be arranged, mapped and supported by data bases, and how its accuracy must be reported. Coastal States now have a clear framework within which to prepare their claims.

Options available to a Coastal State

To make a claim under Article 76, a State is faced with either:
1) Using existing maps and the contours on them
2) Making new maps from existing data
3) Collecting an entire suite of new data and produce contours from it
4) Using a combination of old and new data to produce contours

The advantages and disadvantages of these approaches are summarized in Table 1. Deciding which of these to use will consist of trying to optimize the quality of existing maps and contours and the degree to which they might be improved by the recompilation of existing data sets or the collection of entirely new data, the complexity of the morphology of the sea floor in the area, and on financial considerations. The size of the ocean and the slow speed of data acquisition from ships, to say nothing of the expense, dictate that most States will probably begin with examining Option 1) use existing maps and the contours on them followed by exploring Option 2). This paper examines these two options through the example of publicly available data and tools

Table 1. Comparison of possible options for data and maps on which to base a claim under Article 76 and the Guidelines.

OPTIONS	USE EXISTING MAPS AND DATA SETS	PERFORM NEW INTERPRETATIONS	COLLECT NEW DATA	COMBINATION
FACTORS				
COST	Insignificant	Low	High	Varies
TIME FRAME	Immediate	Up to One Year	Several Years	Several Years
AVAILABILITY	Presently Available	Present to one year	Several Years	Several Years
SCALE - DETAIL	Low	Better	High	High
ACCURACY	Low	Better	High	High
COMPLETENESS	Low	Better, Variable	Can be total	High to total
SUPPORTING MATERIAL REQUIRED BY CLCS				
META DATA	May not be available	At least partly available	Available	Available
ESTIMATES OF ERROR	May not be possible	A posteriori possible	Possible	To be developed
INTERPRETATION METHOD	May not be known	Describable	Describable	Describable

Sources of existing maps and bathymetry data

The generally internationally recognized series of bathymetry maps, GEBCO, (IHO, IOC and CHS, 1984) is up to 23 years old in places, although parts of it are updated regularly. Other IOC programs have produced maps in selected areas, with more under active development (for example, see IOC and HDNO, 1981). Some Coastal States have national bathymetry mapping programs (e.g. Japan has extensive coverage at scales of 1:20 000 to 1:200 000), but these are the exception rather than the rule. Clearly, worldwide bathymetry maps at any detailed scale is extremely variable in its quality and availability.

In addition to maps, a number of digital bathymetry databases are readily accessible. Holcombe (in press) gives an extensive listing of International, US and European sources. Gridded data sets that are easily accessible include ETOPO5 and Predicted Bathymetry (Smith and Sandwell, 1997).

It might be argued that most maps and databases that have been produced in the past are out of date since new technology is rapidly becoming available. With the exception of predicted bathymetry the new technology still has to be operated from ships, and ships unfortunately are slow and expensive. Eventually, all the sea floor will be covered by the new data, but for some time bathymetry maps interpreted from single beam data will remain the most widely available maps of the sea floor. In any case, a Coastal State will begin it's planning to prepare a claim, and its planning of where to deploy the new technology, by examining existing maps and data bases.

Digital exploration of the database:

The rapid advances we have seen in computing and particularly visualisation capabilities have opened a range of options for the exploration and manipulation of bathymetric and other data sets relevant to Law of the Sea issues. Inasmuch as much of the publicly available data is in digital form (and often accessible over the web), one of the initial criteria for selecting a data exploration tool should be the ability to quickly and easily input the public data sets and to extract the desired subsets of them. Ideally, the data should be displayable in many forms (i.e., surfaces, contours, gradients, etc.) and the software should allow quantitative measurements to be made on the data (i.e., distances, gradients, depths, positions, etc.) in a simple and interactive manner. The user should be able to control colour mapping of displays and be able to import or create other critical data sets (i.e., juridical boundaries). Additionally, the ideal tool would also allow for the quantitative comparison of multiple data sets (i.e. difference calculations) and allow true geodetic determination of areas. Once operations are complete on a data set (or multiple data sets) the software should also provide the ability to export both images and tables representing the results of the analyses.

Operations: Applying the tools to the data

Given there are data sets available in the public domain, what information can be extracted from them that will be of value in the early stages of preparing a claim, using existing tools? More specifically, we set out to determine how, within the zones where the different sections of Article 76 apply, how different data sets compare. Knowing more about these data sets will help in deciding how far through the process they can be used.

For this exercise we used data from the following sources:
Off Eastern Canada: Data from a region of the Scotian Shelf was extracted from both the ETOPO-5 data set and the Predicted Topography data set of Smith and Sandwell (1997). Both of these data sets were downloaded from the NGDC web site. A national data set consisting of single beam sounder data collected over the past 30 years was supplied by the Geological Survey of Canada (Ron MacNab, pers comm.). Finally, GEBCO contours were extracted from the GEBCO-97 Digital Atlas CD (IOC, IHO and BODC, 1997).

Off New Jersey, USA: Data for the New Jersey margin was also extracted from the ETOPO-5, Predicted Topography and GEBCO databases. In addition, a high-resolution bathymetric data set which included both multibeam and single beam sounder data was extracted from NGDC's new Coastal Relief Model CD's.

The tool we used, Fledermaus, like some other modern digital mapping tools, produces screen size, multicoloured three-dimensional images that are dynamic, they can be rotated, stretched and moved, and the entire image can be "flown" through, as if in a helicopter flying over land. These types of images do not reproduce well on a static medium like paper, and we cannot reproduce them here. Examples and a "movie" of a flythrough are always available at the University of New Brunswick's Ocean Mapping Group web site at www.omg.unb.ca.

These data sets will be similar to those held by some Coastal States and some of the source data will in fact be the same. For several reasons, often there are data already ashore but not yet incorporated in data set Coastal State is using, usually from other agencies, universities or from industry. There is also some degree of auto-correlation between the publicly available data sets, since some ship tracks are used in more than one of them. At the early stages, using whichever is most readily accessible will not detract from the final result.

Grid size in some of the data sets is predetermined. Users may be able to make grid cells larger, but seldom can they be made smaller. As scale is increased, grid size will begin to effect the accuracy of the resulting contours and Foot of the Slope, but at the early investigative stages, this is not an issue.

Findings

Comparing data sets is not straightforward. This study concentrated on comparing the 2500m contour produced by or contained within the data sets, in part because of the importance of the 2500m contour in determining the outer constraint line, in part because the 2500m contour is more tangible than the Foot of the Slope. Contours can be compared visually, but no real statements can be made about which is the more likely to be true since the data sets all contain some common source depths. To overcome this, a modern multibeam data set (NGDC Coastal Relief Model, Vol. 2.) was plotted together with the older public data. The multibeam should be better positioned, internally consistent, suffer little from beamwidth problems, and have no gaps in its coverage of the sea floor.

Plotting the four 2500m contours together allowed comparison in both qualitative and quantitative terms. Visual inspection shows that the three ocean-scale data sets interweave each other and form a corridor or confidence zone approximately 10 km wide. Naturally, these contours contain only long wavelengths. The much shorter wavelengths captured by the multibeam contour weave amongst the other three, and appear to be centred on the zone created by the older three. Assuming the multibeam-derived contour to be true, the horizontal distances from it to the each of the other contours were measured at intervals of 1 km along a 70-km stretch. The magnitude of these differences, as shown in Figure 1, is never more than 10 km, and is usually less than 5 km. From a histogram of these differences, (Figure 2) it appears that the predicted bathymetry has a systematic horizontal bias of 2-3 km. GEBCO and ETOPO5 do not appear to have a bias, with GEBCO being more closely located to the multibeam contour.

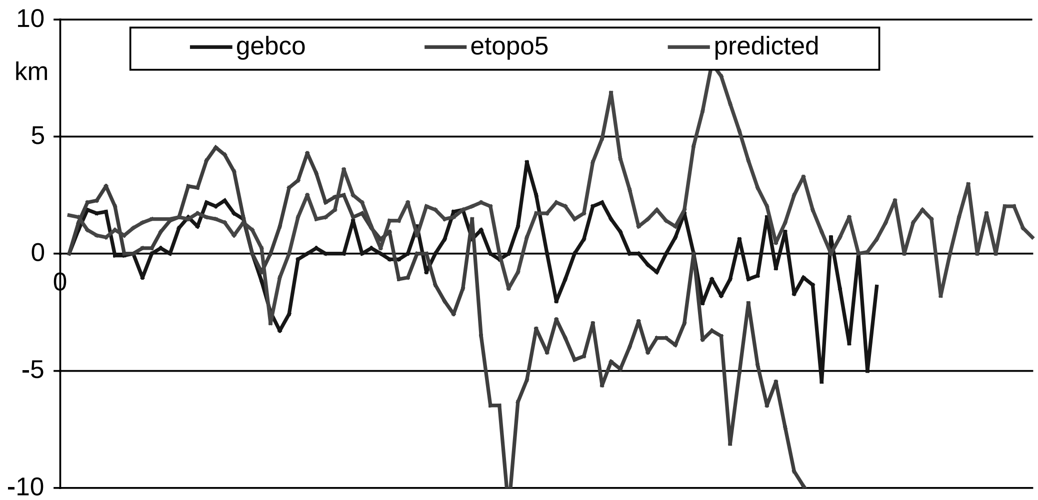
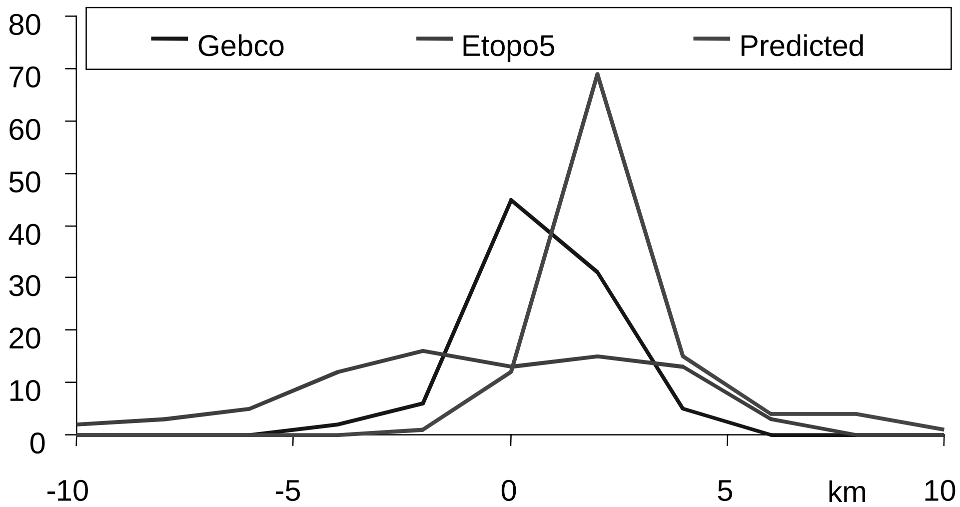


Figure 1 Magnitude of horizontal differences between 2500m contours produced from ETOPO5, NOAA Predicted (Satellite) Bathymetry, GEBCO and a multibeam survey from NGDC Coastal Relief Model.

From these limited observations, it can be concluded that publicly available bathymetry data is of high enough quality to permit a Coastal State to produce a credible early version of its 2500m contour. Multibeam data will be required to produce a soundly based contour in the spaces left by the older data sets. multibeam is likely to find areas of contour that protrude seawards of the existing contours.

Figure 2 Histogram of horizontal differences between 2500m contours produced from ETOPO5, NOAA Predicted (Satellite) Bathymetry, GEBCO and a multibeam survey from NGDC Coastal Relief Model. The multibeam data is considered as true and the displacement of the other three measured seawards (+) or landward (-).



Other operations with the tools

With a sophisticated set of tools there are other operations that can be performed on the data sets that can be used to help establish a claim.

For example, finding and justifying the Foot of the Slope will be extremely difficult in many locations, and any device that contributes to the solution is valuable. This set of tools can automatically create gradient maps that are colour coded according to maximum gradient through each data point. (Figure 3). Maps produced this way show that gradients on the Continental Slope are dominated by local maxima on the walls of canyons. Away from canyons, colour changes on these maps reflect changes in gradient that can be examined as possible Base of Foot of the Slope locations**.**

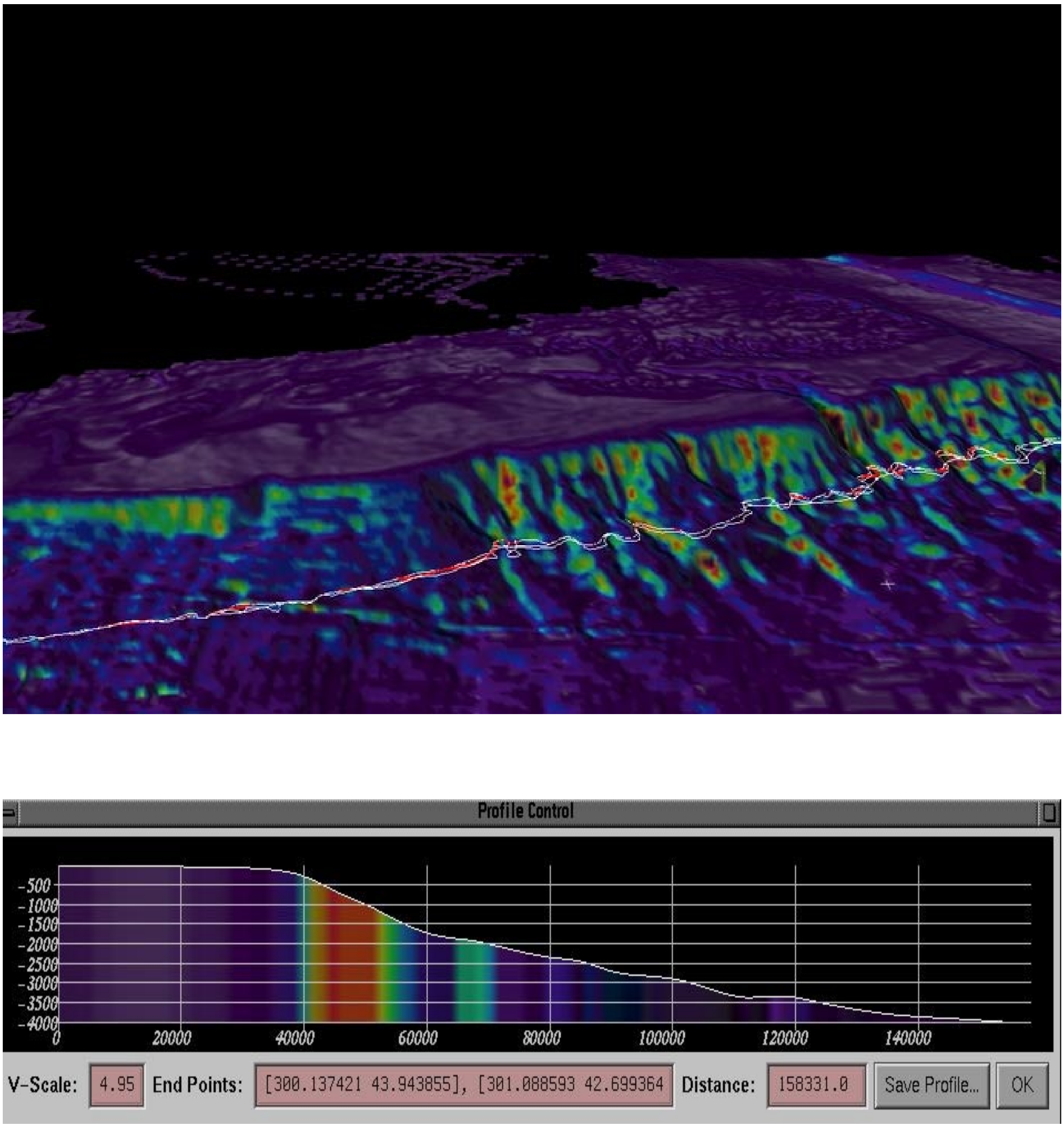


Figure 3. Gradients map and profile of the area south of Nova Scotia, Canada, drawn using Fledermaus. Gradients are portrayed by colours, with blue being the lowest and red the highest. Gradients are highest on canyon walls. Rapid change in color along the profile indicates areas of highest change of slope. In the map view, the three lines are the 2500m contour from the ETOPO-5 and Predicted Topography data sets and from GEBCO.

Profiles are drawn instantly through the depth data and through the gradient data. Profiles of physiography can be examined for Foot of the Slope locations, which may be confirmed by profiles across the gradient surface. These profiles are colour-coded by gradient as is the surface, and patterns of changing colours are instantly recognisable and help narrow the search for maximum change of slope.

Another way to use the existing data and software to close in on the Base of the Slope (if not the Foot of the Slope) is a feature that highlights cells with large differences between the values of soundings in that cell. Cells with a large range of sounding values will not contain the Foot of the Slope. The tool also highlights cells with no differences between the soundings, and those cells will not contain the Foot of the Slope either. The resulting map is divided into three bands, the middle one of which must contain the Foot of the Slope. The band can be narrowed through varying the thresholds in the cells in the fringing bands. A variant on this is to calculate the standard deviation of the depths in each cell and work with them rather than the range of depth values.

Conclusions

This paper has examined the feasibility of using existing maps and data sets together with a modern digital mapping suite to perform the early stages of preparation of a case for an extended Continental Shelf. For the two areas we examined, both off the east coast of North America, the three data sets (ETOPO-5, Predicted Topography and GEBCO) produced results that were similar enough that using any one of them, for the first iteration of preparing the case, would be justifiable and useful. Given that the area tested is among the better sounded sections of the ocean, this conclusion may not apply everywhere. We intend to perform similar tests in other areas.

Multibeam data has been shown to add a considerable amount of short wavelength detail to the 2500m contour in the one area tested. The much more sinuous contour produced from the multibeam data was generally located within the combined positional envelope created by the three older data sets. It did extend beyond this envelope in localised protuberances in both landward and seaward directions.

Using a powerful readily available mapping tool like Fledermaus permits rapid cartographic portrayal of the 2500m contour and offers a variety of promising methods that will allow analysis of the other morphologic elements of Article 76, the Base and Foot of the Slope. To be useful in this regard, a tool must provide for visual techniques, such as the rapid portrayal of profiles, as well as those based on calculations on the data. For instance, this paper discussed the use of automatic gradient mapping, in map and profile views. There are also a number of operations that can be performed on data that are gridded, and these will grow in number over the next few years as more work is done to meet Article 76 requirements.

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SESSION 3 – Paper 4

AN OVERVIEW OF AUSTRALIAN MARITIME ZONE BOUNDARY DEFINITION

by Bill HIRST, Brian MURPHY and Philip COLLIER, Australia

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ABSTRACT

Australia became legally bound by the provisions of the United Nations Convention on the Law of the Sea (UNCLOS) when that convention formally entered into force on 16 November 1994. Because of Australia's extensive and sometimes complex coastline, defining the Territorial Sea Baseline (TSB), computing the various maritime zone boundaries, and defining areas of extended continental shelf under the provisions of the relevant UNCLOS Articles, has presented many technical challenges.

This paper briefly outlines progress in defining maritime zone boundaries in Australia and the national administrative structure that exists in support of this important work. Details on some of the more complex technical issues are presented including; the need for a comprehensive GIS to manage and manipulate maritime boundary data, problems arising in the accurate definition of the Territorial Sea Baseline where detailed charting data is not available, the need for rigorous geodetic computations, and some of the challenges presented by compliance with UNCLOS Article 76.

Introduction

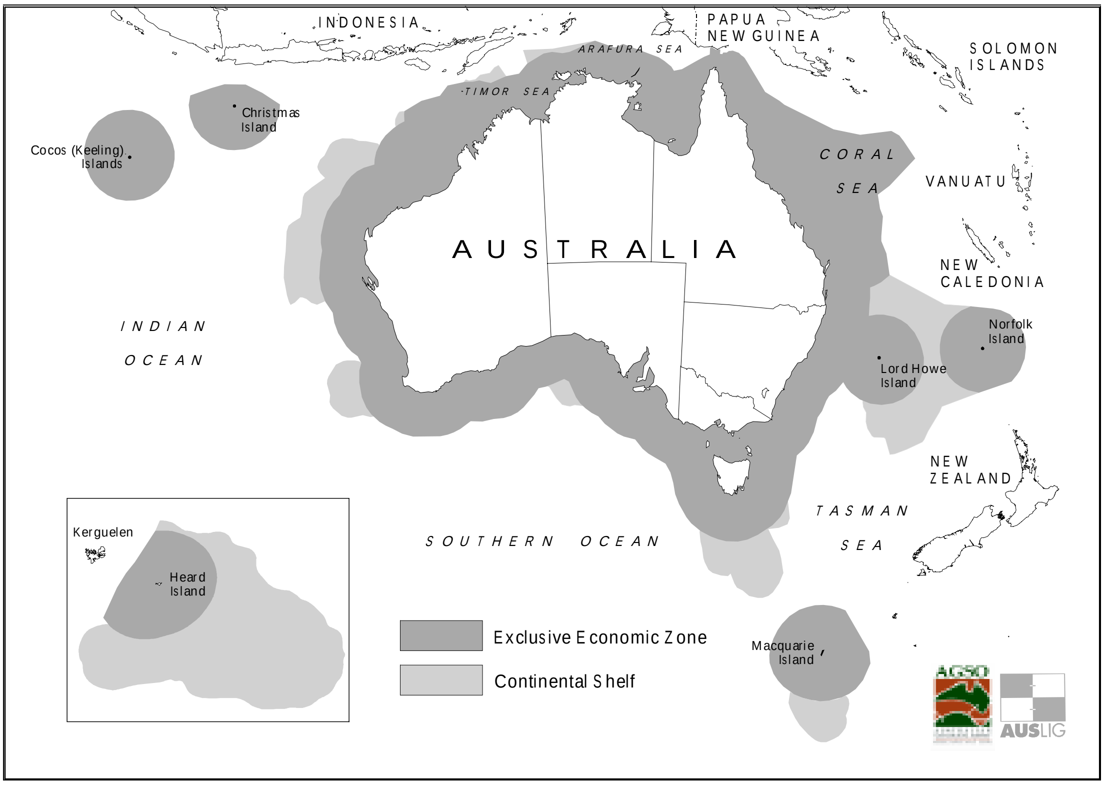
Australia has a coastline length of approximately 59,700 km[1], which includes numerous islands and a number of external territories. In this environment, defining the Territorial Sea Baseline (TSB), rigorously computing the various jurisdictional boundaries, and defining areas of extended continental shelf are all challenging tasks.

[1] Besed on 1:100 000 scale topographic map data produced by the Australian Surveying and Land Information Group (AUSLIG) 1993.

At the time of writing (July, 1999), Australia has almost completed the validation of its TSB and is progressing with development of software to rigorously compute the geodetic position of all zone boundaries. The majority of survey work required to define the limit of the legal continental shelf has been completed and computations, in accordance with UNCLOS Article 76, have commenced in order to define the final boundary location.

Negotiations with most neighbouring countries on delimitation boundaries have been successfully carried out and discussions aimed at resolving issues relating to overlapping marine areas have recently commenced.

Although based on provisional information only, the map shown below indicates the extent of Australia's maritime responsibilities under UNCLOS.



Administration of Australia's Maritime Boundaries

In Australia, defining national maritime boundaries is beyond the responsibilities and capabilities of any one particular government agency. The following table provides a summary of the main agencies involved in maritime boundary determination and the role played by each.

Agency	Role
Australian Surveying and Land Information Group (AUSLIG)	• Defining the TSB • Computation of zone boundaries • Provision of advice on boundary delimitation • Computations to define the limit of the legal continental shelf
Australian Geological Survey Organisation (AGSO)	• Ocean survey work • Analysis to determine limits of the continental shelf
Royal Australian Navy (RAN) Hydrographic Service	• Provision of charting and bathymetric data • Expert advice on tidal datum and symbology
Attorney General's Department	• Legal advice on international law • Treaty negotiations • Interpretation of UNCLOS Articles
Department of Foreign Affairs and Trade	• Treaty negotiations • Communication with the United Nations
State and Territory Governments	• Provision of large scale coastal mapping data

Table 1 – Major Agency Responsibilities for Maritime Boundaries in Australia

To administer the relationship between these and other relevant Agencies, the Australian government has established an Interdepartmental Committee (IDC) on the Law of the Sea. This committee meets twice a year to discuss issues of major concern. The more technical aspects of maritime boundary determination are dealt with by a technical subcommittee of the IDC. This subcommittee meets quarterly and has been successful in coordinating various activities and in identifying and solving some significant technical problems.

Examples of the issues addressed by the Technical Sub-Committee include:
- consideration of areas where TSB determination is difficult or ambiguous,
- development of comments on the draft Technical and Scientific Guidelines produced by the Commission on the Limits of the Continental Shelf (CLCS), and,
- review of the location of straight baselines within the TSB.

Australian Maritime Boundary Information System (AMBIS)

Mapping and attribute data relating to Australia's maritime boundaries is stored and managed in a Geographic Information System (GIS) known as the Australian Maritime Boundaries Information System (AMBIS).

Explanation and Structure

Managing the vast quantity of digital mapping and attribute data relating to Australia's maritime boundaries is a significant task. Originally AMBIS was based on the VISION software[2]; however, the data is now being transferred into the ARC/INFO environment[3]. The GIS provides the ability to answer queries efficiently and to produce maps and diagrams as required.

The advantage of using a GIS for data management is that it provides the ability to maintain the linkage between the TSB vector data and attributes relating to it. The attributes stored in AMBIS include the origins of the baseline data, data acquisition methods and data quality.

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[2] VISION originally registered to GeoVision Systems Incorporated, CANADA
[3] ARC/INFO registered trademark of Environmental Systems Research Institute, Inc. (ESRI)

Status

Currently, the AMBIS database contains almost all of Australia's TSB including comprehensive attribute data. The remaining sections of TSB will be added by December 1999.

A complete and rigorous re-computation of all zone boundaries at 3, 12, 24 and 200 nautical miles, based on the revised TSB, is scheduled for completion by June 2000.

Several areas of extended continental shelf have been defined by AGSO and are to be incorporated into AMBIS. AGSO expects to complete data collection and analysis of the remaining areas by 2002.

Maintenance Plans

Although Australia will soon have rigorously computed maritime boundary data, it will still be based on baseline information which is, in places, defined only to limited accuracy. It is therefore likely that Australia will require a small, on-going, program of revision to critical baseline areas as the need arises.

Progress Reports

The progress of Australia's TSB validation and computation of the related boundaries can be monitored through AUSLIG's home page at:
http://www.auslig.gov.au

Defining Australia's TSB
History

In the late 1960s and early 1970s, Australia defined a complete TSB based on the best available data at that time. In most cases this was 1:100,000 and 1:250,000 topographic mapping data, supported to a limited extent by tide-controlled infra-red aerial photography. The location of the drying line, where depicted on Hydrographic Office charting, was digitised and adopted. A decision was made at this time to adopt Lowest Astronomical Tide (LAT) as the baseline datum. This is consistent with the chart datum used by the RAN Hydrographic Service.

Validation

Since 1996, AUSLIG has been validating the original TSB by comparing it with more recent and accurate charting, topographic, aerial photographic and remote sensing data. An important part of this validation process has been the recording of attribute information relating to the origin and accuracy of all TSB data.

Alternative Data

Australia's TSB is being defined so that it will always be compatible with the latest available charting information. However, in many cases the charting coverage lacks detail in very shallow areas, which are of particular interest when determining the LAT line. In these cases, other information such as large-scale topographic maps, remote sensing data, aerial photography and Laser Airborne Depth Sounding (LADS)[4] data is used to supplement the definition of the TSB. Where this additional data is in conflict with existing chart information, the Australian Hydrographic Office is notified in order to carry out verification and to amend the relevant chart(s).

Straight Baselines

The straight baseline components of Australia's TSB were determined in the early 1980s and the coordinates of the terminal points have since been proclaimed in domestic legislation. More recent charting data has revealed some anomalies in the proclaimed positions of these terminal points. In the

[4] LADS Corporation Limited, Australia

cases so identified, an amendment to the proclaimed positions is being proposed by AUSLIG for consideration by the relevant Commonwealth and State government Departments.

Geodetic Computations

Australia has placed a considerable emphasis on ensuring that the geodetic calculations involved in maritime boundary delimitation, and in the definition of the limits of the legal continental shelf, are all carried out as rigorously as possible. The recently released *Provisional Scientific and Technical Guidelines of the Commission of the Limits of the Continental Shelf* illustrate some of the significant complexities that are involved in the geodetic aspects of the law of the sea. In Australia, work is on-going to ensure a rigorous, robust and efficient solution to these problems.

Software Development

AUSLIG has let a tender to the Department of Geomatics at the University of Melbourne, for the development of algorithms and software capable of rigorously computing critical points on the TSB, and from these, computing the various zone boundaries, and the limit of the legal continental shelf in accordance with the provisions of UNCLOS Article 76. A related paper entitled *Maritime Zone Boundary Generation from Straight Baselines Defined as Geodesics* (Murphy et al., 1999), describes a part of the work being carried out under the AUSLIG tender. In particular some of the technical complexities of dealing with geodesic straight baselines in the context of maritime boundary delimitation are presented along with a proposal for their practical solution.

Baseline Accuracy

The positional accuracy of the various maritime zone boundaries is directly related to the positional accuracy of the TSB. The accuracy of the TSB data, however, is not always consistent or readily determined. There are essentially three components to TSB accuracy :

- data capture process
- determination of the LAT line
- stability of the baseline over time (some areas of the coastline are influenced significantly by erosion and/or accretion.)

As previously explained, the AMBIS database holds details of the data lineage and quality. This information allows users to estimate the accuracy of the data capture process, and provides some indication of the quality of the LAT determination. The date of survey of the source information is recorded to assist in later evaluation of baseline stability. Areas identified on charts as approximately located are attributed as such.

In practice, most of the critical TSB points which determine the outer boundaries in the southern areas of Australia are stable and easily determined, resulting in an overall positional accuracy in the order of ±100 m. In some areas of northern Australia however, where foreshore gradients are generally flat and often associated with large tidal ranges, the method of determination and baseline stability are less certain and positional accuracy is estimated at ±500 m in many areas, with greater uncertainty in some isolated instances.

Horizontal Datum

Definition of much of Australia’s TSB is currently referred to the Australian Geodetic Datum, 1966 or 1984 (AGD66 or AGD84). In 2000, Australia is officially converting to the Geocentric Datum of Australia (GDA94) which will use the GRS80 ellipsoid and will be based on the ITRF92 reference frame at the epoch of 1 January 1994 (ICSM, 1998).

It is AUSLIG's intention to convert all TSB data to GDA94 for national and international consistency. It should be noted that GDA94 is, for all practical purposes, identical to WGS84, the datum for GPS (absolute coordinate differences in the order of a few centimetres Malays et al., 1997)).

Straight Baselines

Straight baselines, as adopted by Australia, are legally promulgated as geodesics. It is also the case that the 'straight line' segments of a zone boundary derived from a straight baselines are also geodesics. It can be shown that the baseline and the zone boundary geodesics are not parallel. Therefore, the computation of a zone boundary from a straight baseline, ensuring the maintenance of a consistent zone width, is not trivial.

This issue is highlighted in the paper by Murphy et al., (1999) included in these Proceedings.

Areas of Extended Continental Shelf (UNCLOS Article 76)

Australia is well advanced in the preparation of its submission to the UN Commission on the Limits of the Continental Shelf (CLCS). Symonds et al., (1999) and Borissova et al., (1999) included in these proceedings, describe the processes involved in preparing this submission, in particular the location of foot of slope points. The discussion here is limited to identifying some of the computational complexities of determining the limit of the extended continental shelf in accordance with UNCLOS Article 76.

Computational Complexities

Bridging Lines

Paragraph 7 of Article 76 states that '*The coastal State shall delineate the outer limits of its continental shelf ….beyond 200 nautical miles….by straight lines not exceeding 60 nautical miles in length…*'. This requirement allows a State to smooth the outer limit boundary by inter-connecting boundary arcs with straight lines, as shown in Diagram 1. In Australia, these lines have become known as 'bridging lines'.

Paragraph 7 also requires arcs to be represented as a series of straight lines. This issue is discussed under a separate heading later in this paper.

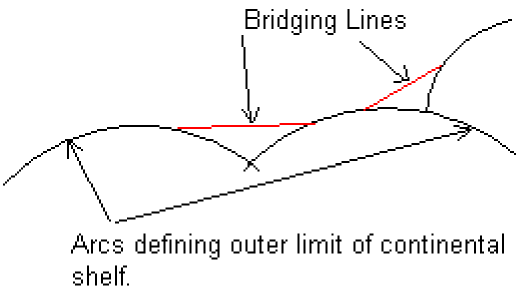


Diagram 1 - Bridging Lines

Applying the principle of bridging lines not only allows a State to simplify the delimitation of the legal continental shelf, but also to maximise the area which can be claimed, as shown in Diagram 2. Computation of the optimal location of the terminal points of these bridging lines can be complex, particularly when trying to ensure that the *total area* beneath the bridging lines is a maximum.

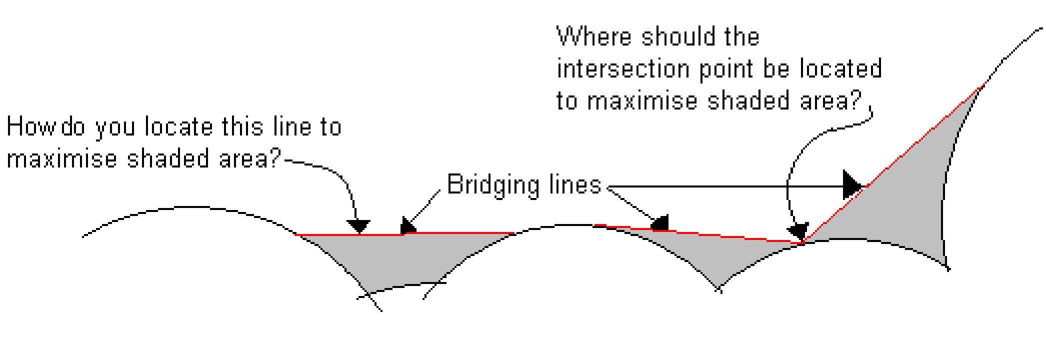


DIAGRAM 2 - More complex bridging lines

Computations are made more complicated when trying to maximise the area under a bridging line that spans arcs of different radii.

Sediment thickness

Paragraph 4 (a)(i) of Article 76 allows for determination of the outer limit of the continental shelf based on sediment thickness, which must be at least 1% of the distance from the closest point on the foot of the continental slope. This criteria is not trivial to compute as illustrated in Diagram 3.

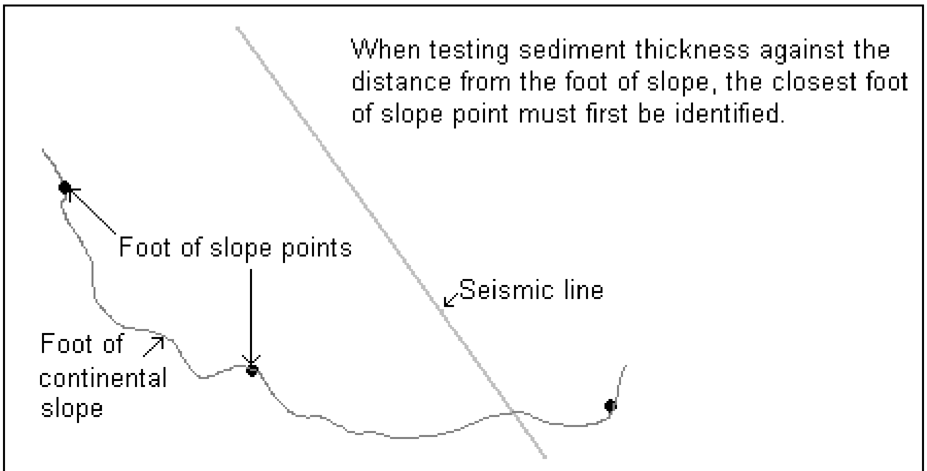
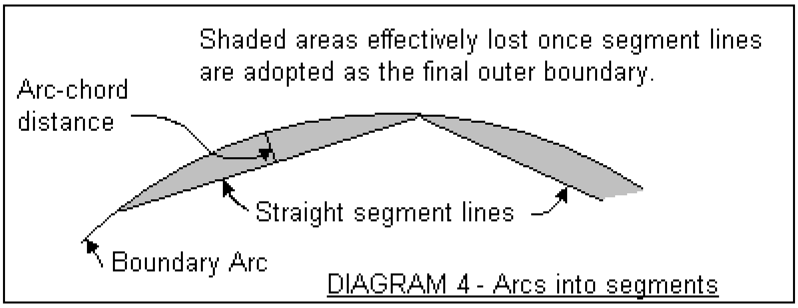


DIAGRAM 3 - Sediment thickness from foot of slope

As shown in the diagram, determination of the location of points to define the 1% sediment thickness line is complicated by the fact that the foot of the continental slope is rarely perpendicular to the seismic line from which sediment thickness is assessed. The problem is to determine the location along the seismic line of a point where the thickness of the sediment is 1% of the distance from the *nearest* point on the foot of the continental slope.

Subdivision of Arcs

As identified in the section on 'Bridging Lines', Paragraph 7 of Article 76 requires the outer limit of the legal continental shelf to be composed of straight lines not longer than 60 nautical miles. Therefore, whenever the legal limit is composed of arcs, these arcs will need to be divided into a series of straight line segments. As such arcs are always convex to seaward, approximation by straight lines results in the loss of claimable area to the State, as shown in Diagram 4.



The requirement to divide arcs into straight line segments results in having to strike a balance between the length of the line segments used and the consequent loss of area. The challenge is to select a segment length (or equivalently an arc to chord separation), which results in a manageable number of segments and an acceptable (minimal) loss of area.

Conclusion

Defining maritime boundaries represents a fascinating combination of technical, legal, and, in the case of overlapping areas, diplomatic challenges. Australia's experience has demonstrated the need for a broad level of commitment from all agencies involved, requiring both leadership and technical expertise.

Rigorous computation of all boundaries is far from trivial and requires careful consideration and management to ensure total and credible compliance with the provisions of UNCLOS.

Australia is well advanced in defining its maritime areas; however, it is aware of some significant challenges ahead. We would welcome further international cooperation and consultation to meet these challenges and to develop a more consistent global approach to maritime boundary delimitation.

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SESSION 3 – Paper 5

A SET OF INTEGRATED TOOLS BASED ON ARCVIEW FOR DEFINING THE OUTER LIMIT OF AUSTRALIA'S EXTENDED CONTINENTAL SHELF

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ABSTRACT

The resource jurisdiction of a coastal State such as Australia extends beyond its land territory and throughout its adjacent continental margin. In the areas between adjacent countries, the limit of jurisdiction is subject to negotiations based on international conventions and principles of customary international law, whereas in areas facing open ocean and the international community, it is subject to rules set out in the 1982 United Nations Convention on the Law of the Sea (UNCLOS). The entry into force of UNCLOS on 16 November 1994 was an important milestone for Australia because it provided new rules for defining its vast marine zones, as well as setting out rights and obligations for managing the environment and resources within them.

There are nine areas around Australia where seabed jurisdiction could be extended beyond the 200 nautical mile Exclusive Economic Zone (EEZ) providing Australia justifies the claim defining their outer limits according to the terms set out in Article 76 of UNCLOS by the 2004 deadline. Once the claim is accepted these areas will become part of Australia's Alegal@ Continental Shelf (CS). The data supporting the claim includes information on the morphology, sediment thickness distribution and bathymetry of the margin and adjacent sea floor. During the last four years AGSO has been conducting surveys over the margins of Australia collecting new data, as well as assembling existing data, relevant to the claim. Large volumes of diverse digital data required systematic handling and processing. Over the past two years AGSO's Law of the Sea project has been developing new strategies for constructing digital databases supporting Australia's claim for the CS, as well as tools enabling simple and effective access to the data.

The new ALaw of the Sea@ ArcView extension has a series of tools to load the data, create bathymetric gravity and magnetic profiles and to analyse them. Specialised tools include analysis of the change in gradient, automatic selection of the sediment thickness points, defining critical points for the 2500 m contour, and creation of stacked bathymetric profiles. Projects created with the help of the extension represent an integrated system where profile and map views are interactively linked, and each point in the database can be queried from the map and/or a profile. Critical seismic sections can also be linked to their corresponding bathymetric profiles. General survey information can be accessed through an ORACLE (OZMAR) database, which enables queries to be made on the geophysical data and navigational systems available.

The new Law of the Sea extension is easy to load and use, and could also be employed as a more generic tool. Its ability to view survey data in either plan or profile view, and link it to a variety of other spatial information, makes it an attractive tool in any geological interpretation project based on geophysical survey data.

INTRODUCTION

Australia was one of the original ratifiers of the 1982 United Nations Convention on Law of the Sea (UNCLOS). Ratification of UNCLOS meant that Australia has to delineate the outer limit of its continental shelf where it extends beyond 200 nautical miles (M) – the extended continental shelf (ECS) – and submit its coordinates, along with supporting scientific and technical data, to the Commission on the Limits of the Continental Shelf (CLCS) within the following ten years i.e. by 2004. The Australian Geological Survey Organisation (AGSO) has a crucial role to play in collecting, processing and analysing the data to define Australia's ECS. Initial analysis of the continental margin around Australia and its island territories (Symonds & Willcox, 1989) revealed nine areas that could provide extensions of the continental shelf. Some of these areas had very poor bathymetric coverage with the survey line spacing exceeding 100 M. A number of specially designed Law of the Sea surveys were conducted in these areas to collect new data crucial for the ECS claim.

Currently, almost all of the Law of the Sea surveys have been completed and we are at the stage of systematic data analysis and preparation of the scientific evidence to support definition of the ECS. This includes analysis of all available bathymetric and seismic reflection profiles, and other geophysical and geological data, over the continental slope in the targeted areas; compilation of the Law of the Sea (LOS) databases; and evaluation of the results of the analyses for extending the continental shelf around Australia.

UNCLOS information requirements

Article 76 of UNCLOS (UNCLOS, 1983) defines the continental shelf as the sea-bed and subsoil that extends beyond the territorial sea throughout the natural prolongation of the land territory to the outer edge of the continental margin, or to a distance of 200 M from the territorial sea baseline (TSB). It provides two methods for establishing the outer edge of the continental margin wherever the margin extends beyond 200 M, and both of these are based on measurements from foot-of-continental-slope (FoS) reference points. The most commonly used method, particularly around Australia, is by constructing a line lying not more than 60 M beyond the FoS – hereinafter referred to by its colloquial name, Hedberg line. The other method is based on a line delineated by the outermost points at which the thickness of sedimentary rocks is at least 1% of the shortest distance from the FoS. This method only applies in a few areas around the generally sediment-starved margins of Australia. Both the Hedberg and sediment thickness lines are formed by straight lines not exceeding 60 M in length. The Hedberg and sediment thickness lines only form the outer limit of the ECS provided that they do not extend beyond either of two cut-off or constraint lines: 350 M from the TSB, or 100 M beyond the 2500 m isobath (hereinafter referred to as the isobath cut-off). If the Hedberg or sediment thickness lines extend beyond both cut-offs, then the outermost cut-off line defines the limit of the ECS. Therefore, the final outer limit of the ECS can consist of straight-line segments of the Hedberg line, the sediment thickness line, the 350 M cut-off line and the isobath cut-off line. To address all aspects of data compilation and analysis, as well as to produce a preliminary outline of the ECS, we developed specialised software. Requirements for this software included the ability to handle large volumes and varieties of data/information in map and profile form; compilation of easily updateable databases; specialised tools for ECS analysis; good visualisation capabilities; and the ability to use the same software for presentation of the information to the CLCS. Due to the relatively sparse and irregular data coverage over many of the remote parts of Australia's margins, preference was given to the analysis of real survey data along track rather than derivatives, such as gridded or contoured bathymetry maps. This ensures that it is always possible to relate the original survey metadata to the results of the ECS analysis, and data type and accuracy (e.g. navigation and sounding information) can be readily verified and documented.

Our approach uses an existing GIS application – ArcView - with its functionality increased by adding specific ECS modules. All modules are written in Avenue language and integrated into a specialised Law of the Sea ArcView extension. The extension contains tools for creating and analysing profile data, deriving foot-of slope and 2500 m point databases, and accessing associated survey metadata. Spatial relationships between different lines/boundaries, such as the Hedberg line and the cut-offs, are adequately addressed by the GIS capabilities of ArcView. At this stage the LOS extension does not perform the rigorous geodetic calculations required to derive the various Article 76 points, arcs and lines, but uses the ArcView projection-based buffering technique to create and visualise the information. AGSO passes all the critical point data, such as FoS and 2500 m depth points, to the Australian Surveying and Land Information Group (AUSLIG) as it has the national responsibility for rigorously computing Australia's maritime boundaries. In the near future, rigorous geodetic distance computations will be incorporated into the LOS extension, particularly to derive the 1% sediment thickness points.

Displaying and examining profile data

The first step in the ECS definition process involves loading survey line data into the ArcView format - shape files. The original survey data, such as navigation, raw water depth, and field values of gravity and magnetic field, as well as calculated values of Carter-corrected water depth, free-air gravity anomaly and magnetic anomaly, are stored in an ORACLE database. The three calculated parameters, along with the navigation and survey attributes, are exported into the shape files. Each survey is represented by a line shape file, essentially delineating the ship's track, and a point shape file containing values of all the parameters at whatever time interval has been stored for the survey. On most AGSO surveys the data is stored at 1-minute intervals (about every 150 m); however, on some older foreign surveys this interval could be up to 5-6 minutes.

A screen snapshot (Fig.1) illustrates the process of creating and analysing a bathymetric profile using our software. In the left part of the screen a point shape file has been loaded into a view with the gravity image of the area. The abrupt change in the character of the anomalies near the point marks the transition from continental to oceanic crust beneath the lower continental slope. Within this slope zone points from the loaded survey line are selected to create the bathymetric, gravity and magnetic profiles, shown in the right part of the screen. The bathymetric profile is represented both by line and point shape files. Viewing and analysing all bathymetric values along the profile is a critical part of the ECS analysis. A zoom-in view of the base of the slope zone is shown in a separate window at the bottom of the screen. Using both geological and bathymetric information a FoS point is identified on the profile. In this example it is shown by the large light grey dot in the various views. Selecting the point highlights the corresponding record in the attribute table, part of which is shown at the top of the screen. This record is then edited to add information about the particular FoS pick, including a unique identifier, morphological characteristics (e.g. edge of abyssal plain) and the name of the person who picked the point.

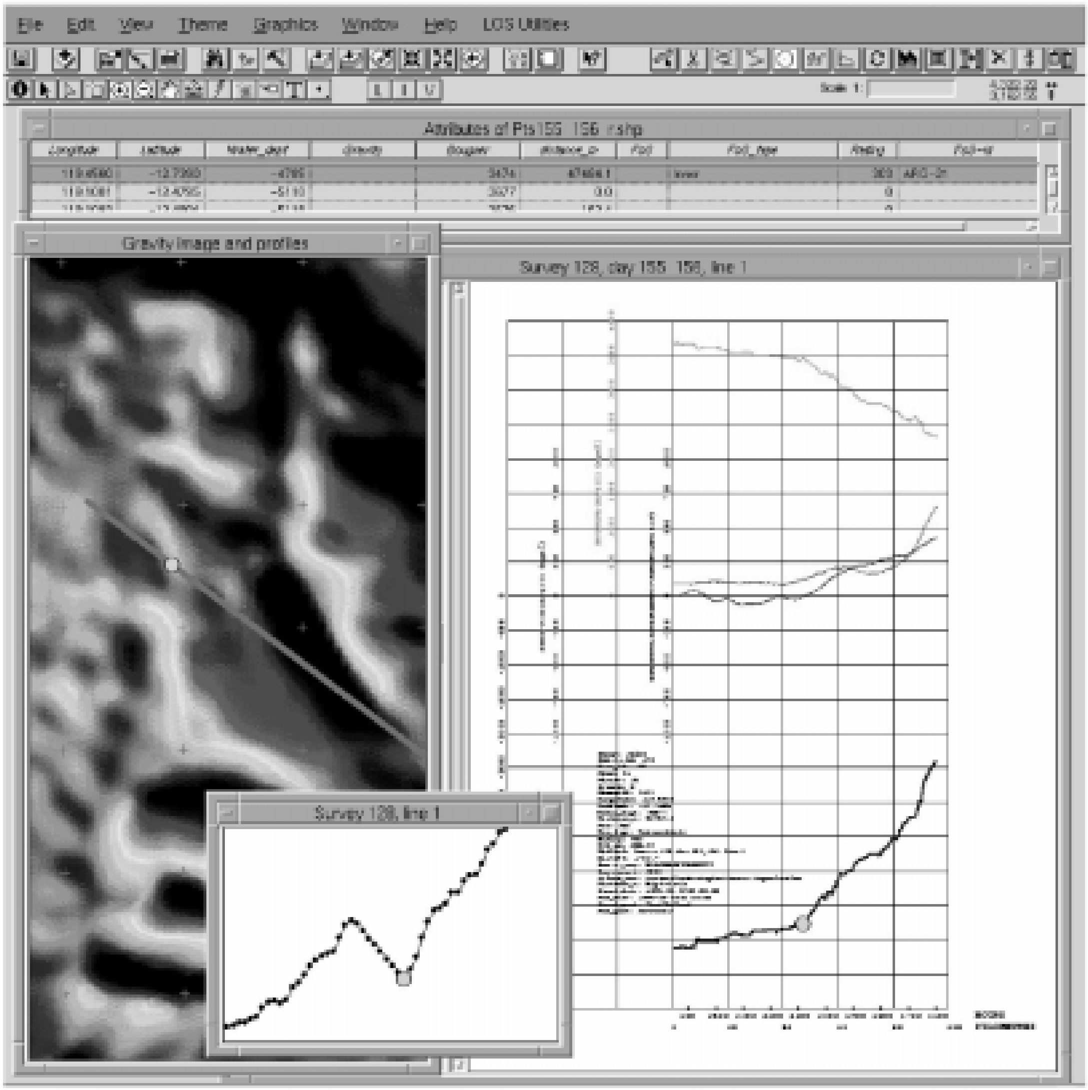


Figure 1. A screen snapshot of the LOS extension at work. See text for explanation.

Once the point has its unique attribution it can be displayed on maps, as shown by the grey dot on the survey line in the left window. The location of this point relative to other spatial data, such as gravity, gridded bathymetry, previously picked FoS points and geological features, provides a valuable crosscheck essential for ensuring a consistent interpretation.

The ArcView LOS extension contains a comprehensive set of tools to build and update the FoS database. Records corresponding to FoS picks can be automatically added, replaced or deleted from the database. Consistency between the profile view and information in the database is maintained automatically.

Examining the change in gradient to determining the FoS

Article 76 of UNCLOS defines the FoS, in the absence of evidence to the contrary, as *"the point of maximum change in the gradient at its base"*. The LOS extension contains a set of tools for gradient analysis to address this aspect of the analysis. These tools are very useful for determining FoS locations on morphologically complex slopes. Bathymetric profiles are typically displayed with a high vertical to horizontal ratio, commonly 1:25, which significantly distorts the perception of angles. The maximum change in gradient does not always correspond to the most visually obvious position of a FoS on vertically exaggerated profiles. Gradients steeper than about 5° appear almost as vertical cliffs when viewed at 1:25 exaggeration, and therefore changes in gradient on steeper parts of slopes can be overlooked. Also, exponentially shaped slopes are particularly difficult to interpret, as the change in gradient is much the same all the way down the slope, except for local perturbations.

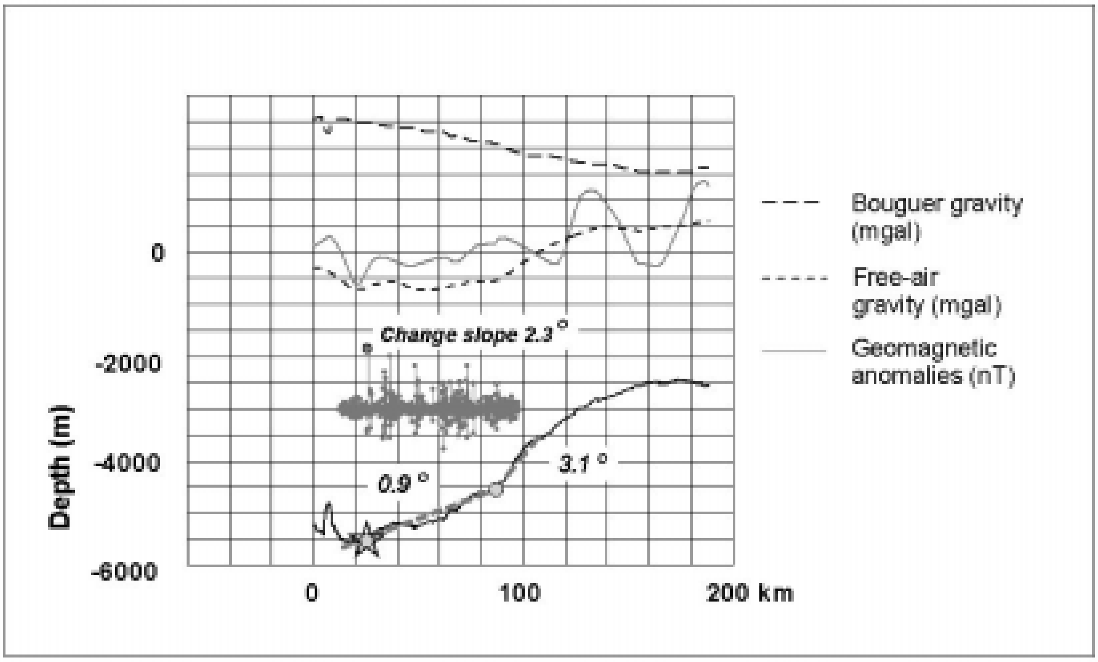


Figure 2. Example of the gradient analysis. Changes of gradient between adjacent sample points are shown by the dark grey line above the bathymetric profile; the maximum change in gradient is marked by the dark grey dot. The dashed lines show the results of the linear regression analysis. The large light grey dot shows the innermost possible FoS pick, and the star marks the preferred FoS pick. See text for further explanation.

Our current approach to FoS determination firstly involves locating the “base of slope zone” using linear regression analysis. The slope is visually subdivided into segments, each with its own characteristics and average gradient, anda linear regression line and an average slope value are calculated for the segments. The slope segments lying seaward off the steep part of the slope and landward off the abyssal plain are considered to lie within the FoS zone. The deepest segment adjacent to the abyssal plain is examined to determine if it is part of the “basal zone” of the slope or part of a continental rise. When the average slope of this basal segment is in the range of about 0.5-1° , seismic data can be very useful in deciding whether it is part of a low-gradient slope or a rise.

Figure 2 shows an example of a bathymetric profile, where the slope is subdivided into two main segments - an inner segment with an average slope of 3.1^{o} and outer segment with a slope of 0.9 ^{o}. The outer segment is interpreted as the “basal zone”, and is further analysed to identify the location of the FoS. Once the “basal zone” of the slope has been defined, another set of tools is used to calculate and visualise the change of gradient between adjacent sample points. A graphical representation of the gradient variation is shown above the bathymetric profile (Fig. 2). Maximum changes in gradient can be identified visually on the gradient profile and referred back to the corresponding sample points on the bathymetric profile. This direct link between the two data sets enables quick and accurate targeting of points with the highest gradient changes in the basal zone.

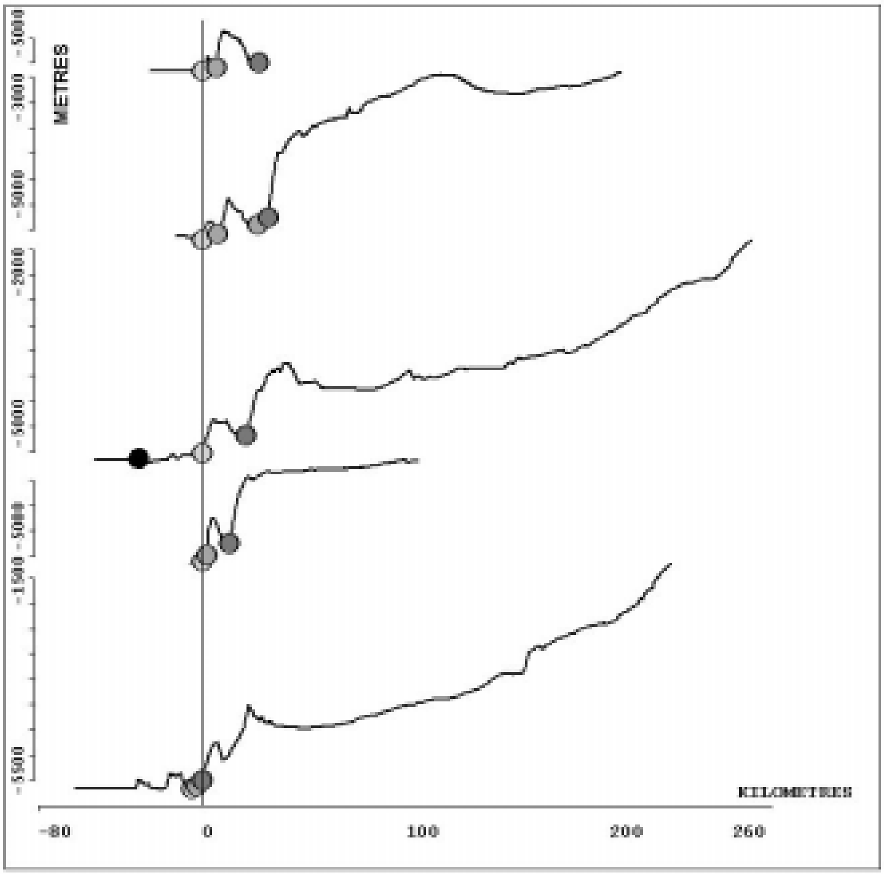


Figure 3. Example of a composite view featuring five adjacent bathymetric profiles of the continental slope centred on the preferred FoS pick.

In the example shown in Figure 2 several points are characterised by similar gradient changes and could therefore be considered as potential FoS picks. The preferred position of the FoS is often determined by reference to additional geological or spatial information: whether the morphology of the basal zone reflects the basement structure or an accumulation of sediments that may represent a rise; and how the location of the FoS on this line agrees with the picks on adjacent lines.

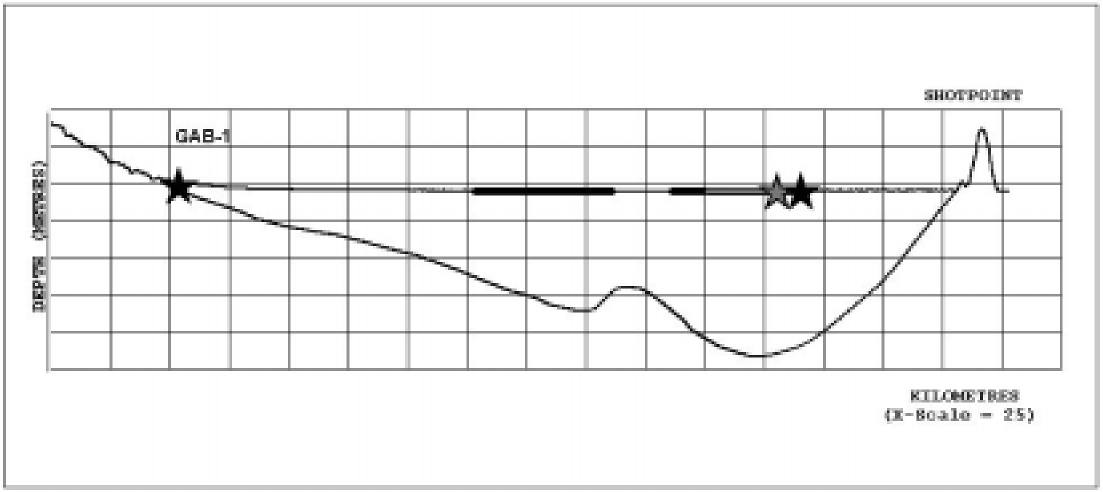
Analysing consistency in FoS picking

When analysing hundreds of bathymetric profiles from different quality data sets it can be difficult to maintain consistency in picking FoSs. One method of maintaining consistency is to correlate the spatial distribution of the FoS points with gridded bathymetry and satellite gravity. Another method uses a special module developed to visualise changes in slope morphology along the strike of the margin. Bathymetric profiles are sorted into N-S or W-E groups, depending on the orientation of the continental slope, and are then displayed in a composite view of all the profiles centred on the preferred FoS picks. An example of such a composite view is shown in Figure 3. Any inconsistencies in interpreting the data stand out very clearly when profiles are displayed in this way. This approach also allows the use of short profiles (upper profile in Fig. 3), which could be meaningless on its own.

Applying the sediment thickness approach

Where thick sediments occur over a substantial distance beyond the FoS seismic data becomes the most crucial piece of information for determining the outer edge of the continental margin through the determination of1% sediment thickness points. In Australian waters, direct information on sediment thickness from wells and reliable isopach maps are very sparse and generally only occur on the shallow geomorphic shelf. Therefore sediment thickness determination in the remote deep-water areas relevant to ECS definition is based almost solely on the interpretation of the seismic data. The depth conversion of seismic data can be performed using a variety of standard approaches and specialist applications. Once sediment thickness and basement depth values have been determined for each shotpoint they are imported into ArcView and joined to the attribute tables of the corresponding bathymetric profiles. Estimation of sediment thickness from seismic data is a complex and multi-step process. It includes computation of velocity profiles from sonobuoy refraction experiments and stacking velocities deduced during seismic processing, and their application to time-depth conversion. This means that use of the 1% sediment thickness criteria is one of the most time-consuming processes in the preparation of an ECS claim.

Sediment thickness points **-** the outermost points at which the thickness of sedimentary rocks is at least1% of the distance to the closest FoS, are determined within the ArcView LOS extension using a variety of tools. Imported values of basement depth are used to produce a “basement” profile (Fig. 4A). Another tool identifies all points satisfying the 1% sediment thickness criteria for each of the FoSs in the database for that segment of ECS and stores them into a separate file. It also locates and tags the outermost sediment thickness point on each seismic line and can display them in both profile and map views.



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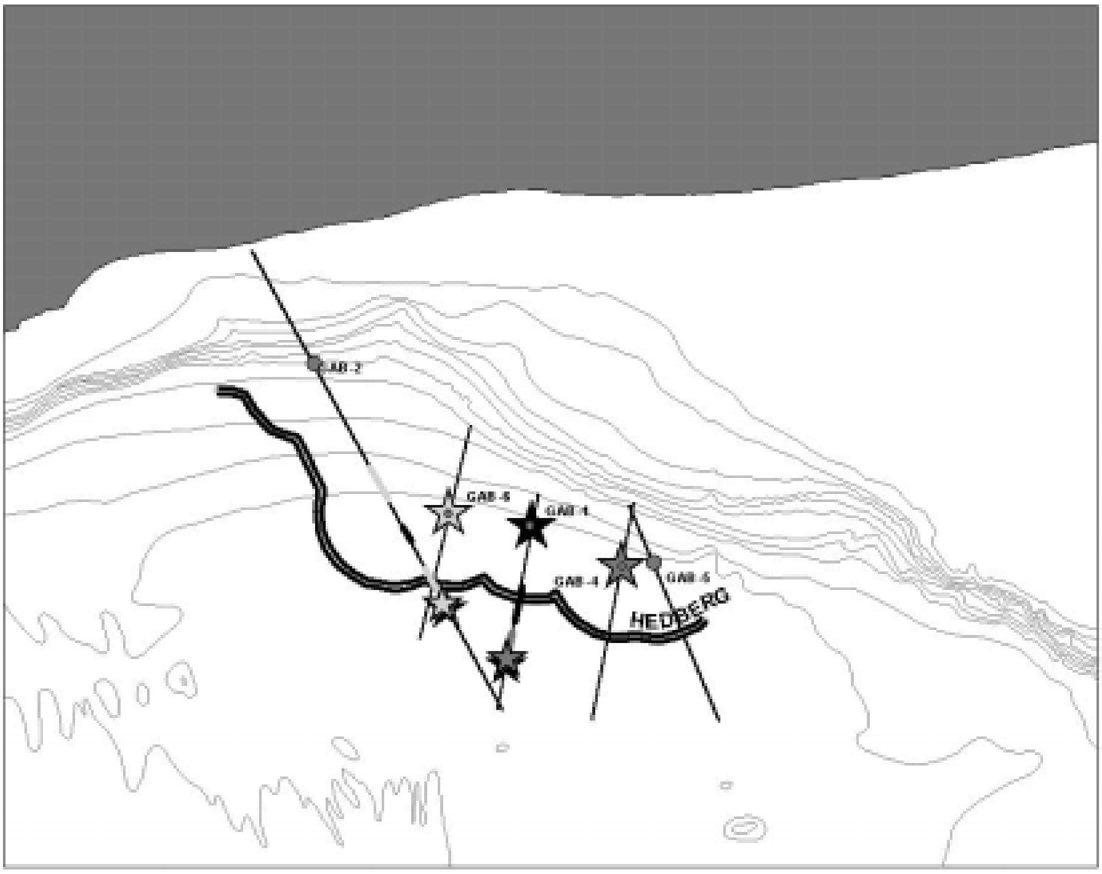

B

Figure 4. A. Cross-section showing bathymetry, basement depth and results of the sediment thickness analysis. The FoS point on this survey line is shown by the black star; the sediment thickness points by the thick black and grey lines; and the outermost sediment thickness points by the grey and black stars. The interval shown by the grey line and the grey star are produced by the FoS on an adjacent survey line. **B.** Results of the sediment thickness analysis shown on the map. Thick segments of the survey lines correspond to intervals where the sediment thickness criterion is satisfied. Stars on the landward side of the Hedberg line show the FoS points, and those beyond the Hedberg line show the outermost sediment thickness points with respect to each FoS. See text for further explanation.

For example, the points corresponding to the whole interval satisfying the sediment thickness criteria with respect to two FoS points are shown in Figure 4A by thick black and grey lines - the outermost points for each FoS are indicated by the black and grey stars. The most confusing part of the analysis is that the FoS producing some of the 1% sediment thickness points may have been picked on a different survey line to the one where sediment thickness has been recorded. Figure 4B illustrates this concept in the map view. The intervals where the 1% sediment thickness criteria is satisfied and the outermost points are shaded the same as the FoS points producing them. In the example (Figs 4A & B), FoS GAB1 and GAB4 both produce relevant sediment thickness intervals of different lengths on the central seismic line shown in Figure 4A with the outermost point corresponding to the FoS GAB1. In this case, although there is a sediment thickness interval produced by the FoS on the adjacent line to the east, it does not provide the outermost point and will therefore not be used to define the ECS.

Defining the 2500 m depth points for construction of the isobath cut-off

The isobath cut-off would normally be constructed from a 2500 m water depth contour; however, many bathymetric contour maps often incorporate relatively old poorly positioned data, and can be quite inaccurate in remote areas with sparse survey data. In order to support ECS definition where the isobath cut-off is relevant, and adequate bathymetric contour maps are difficult to produce, an ArcView module was developed to analyse the real survey data for 2500 m crossings and compile a database of the relevant points.

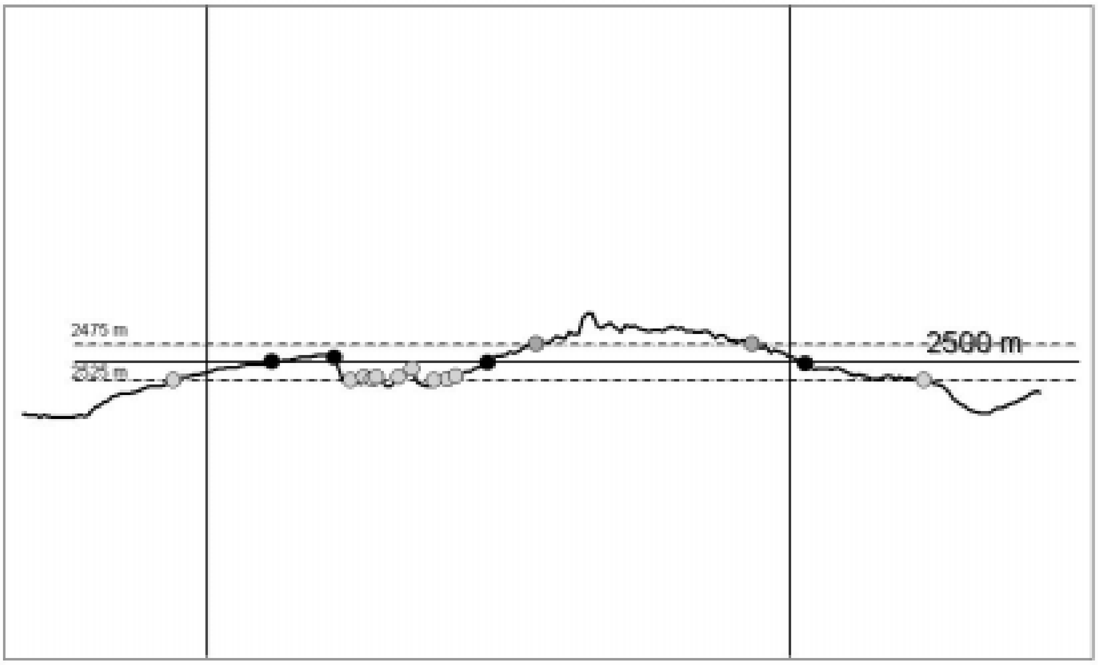

Figure 5. Example of automatic selection and attribution of the 2500 m water depth crossings. Black dots – crossings; light and dark grey dots – outermost points within the 1% accuracy interval. See text for further explanation.

The module works on both bathymetric profiles and on the original point shape files. On the profiles it automatically picks up all crossings of the 2500 m depth level; the outermost points that lie within the International Hydrographic Organisation's accuracy range of 1% of water depth at intersecting survey lines (i.e. 25 m above or below the 2500 m crossing); and displays this information on the screen (Fig. 5).

The profile view allows ready identification of crossings that are likely to be crucial for the 2500 m isobath cut-off. Comments on the significance of a particular crossing can be added to the attribute table at this stage, and then the data are transferred to the database. The module has been extensively used in areas where the location of the 2500 m isobath is critical for defining the outer limit of the continental shelf. It is particularly useful for defining and substantiating isolated closures of the 2500 m isobath.

A similar module designed for the map view works on the combined data from all surveys to pick up all the 2500 m crossings in an area. Although this method is very fast, it is not suitable for detailed analysis and has been designed to work in non-critical areas.

The approach we have developed for extraction of the 2500 depth points is based on real survey data and is independent of contouring techniques and other mathematical manipulation of the data, such as filtering. It allows the depth points to be related back to the survey metadata, thus readily providing information on navigational and depth sounding approaches and accuracy.

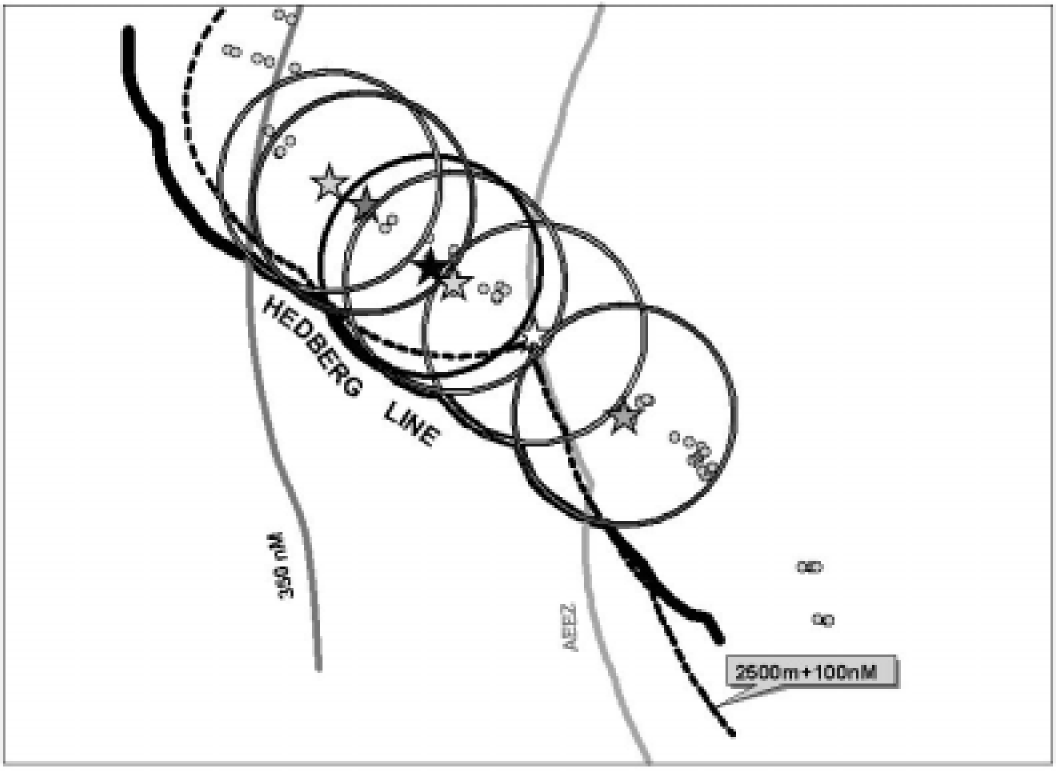

Figure 6. Example of the evaluation of critical FoS points for delineation of the ECS. FoS points contributing to the Hedberg arcs (black) are shown by stars and the associated 60 M buffers by circles shaded in the same way as the stars. See text for further explanation.

Constructing the preliminary outer limit of the ECS

Individual segments of the line forming the outer limit of the ECS can be readily attributed to the various Article 76 approaches that were used to derive them. In particular, sections of the Hedberg line can be attributed to the FoSs from which they were derived. This is achieved in the LOS ArcView extension using a modified buffering tool that allows the attributes of the FoS points to be transferred to the arcs of the resulting 60 M buffer (Fig. 6).

Identification of the FoS points contributing to the outermost 60 M buffers, and thus to each segment of the Hedberg line, provides a means of assessing the most critical FoSs for the ECS claim. There are considerably fewer critical FoSs than the number contained in the whole FoS database. In Figure 6 the critical part of the Hedberg line lies inside the 350 M cut-off, where six FoS points, shown by differently shaded stars, determine the shape of the Hedberg arcs. Individual 60 M buffers around these points are shown by the similarly shaded circles. Analysis and presentation of positional and instrumental accuracy of these critical points will form an important part of the preparation of the submission to the CLCS. As the Hedberg line is constructed by joining selected points on the Hedberg arcs by straight lines not more than 60 M long even some of the six critical FoS points shown in Figure 6 are likely to be irrelevant to the final outer limit of the ECS in this area. Such an approach allows critical evaluation of the data and can be used to ensure that the definition of the ECS is only based on good quality data.

Conclusions

- Development of the ArcView LOS extension has been an important aspect of AGSO's role in defining the outer limit of Australia's ECS, as it has allowed the integration of all of the tasks involved in the ECS analysis within one application.

- The use ArcView as the basis of the LOS extension ensured that along with the newly developed tools standard GIS techniques and capabilities could be utilised for displaying and analysing the data.

- Although the ArcView extension has been designed specifically for LOS analysis, a lot of its functionality may have a more generic use for viewing and analysing a variety of survey data in both profile and map formats.

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SESSION 3 – Paper 6

CONTRAST OF THE "SURFACE OF DIRECTED GRADIENT" WITH THE "SURFACE OF MAXIMUM CURVATURE" TO COMPUTE THE FOOT OF THE CONTINENTAL SLOPE

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Biography

The author is currently employed by the U. S. government in The Department of The Interior's Mineral's Management Service. He has been given permission to start a new part time company, Paradigm Imaging Inc., to provide commercial services to do geophysical digital data processing in the areas of seismic data, remote sensing data, numerical analysis, and computation of the foot of the continental slope. He has a Ph.D. in applied mathematics from Rice University and an MA in Geophysics from the University of Oklahoma. He has over 30 years of experience in government and industry in research and development in the above areas.

ABSTRACT

This paper contrasts two methods of digitally computing the foot of the continental slope (FCS) in accord with the United Nations Law of the Sea's legal definition(UNFCS). The first method is called the Surface of Directed Gradient (SDG) presented by Bennett in the 1996 Geodetic Aspects of the Law of the Sea Conference in Bali. The second method is the mathematical procedure called the Surface of Maximum Curvature (SMC) which was adapted to find the FCS and presented at this same conference by Ou and Vanicek.

These methods are used in this paper to compute the FCS for three mathematical functions. They are: Case I, a monocline slope; Case II, a slightly distorted monocline slope; and Case III, a distorted surface with ridges and valleys. The SDG and the SCM for all three cases generated the location of the FCS in approximately the same place as the U N legal definition suggests.

The SMC and the SDG get essentially the same surface in case I. In case II the SMC generates a minor lobe. In Case III the SMC generates much more pronounced lobe than it did in Case II. The more complicated the surface the more pronounced are the lobes that appeared for the SMC.

In none of the three cases did the SDG generate any lobes.

The SMC is sensitive to scaling. It requires all three axes to have the same units for it to work. Whatever scaling is required to use the SMC, care must be taken to re-scale the results to recover the proper aspect ratio of the data.

The SDG never requires scaling for most data sets. All three axes are scale independent.

INTRODUCTION

The United Nations Commission on the Limits of the Continental Shelf (See reference 4, page 41) in their publication, "Provisional Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf ," cite two references for the computation of the Foot of the Continent Slope (FCS). They are my papers given at the 1996 Bali Galos Meeting (See Reference 1) and that of Ziqiang Ou and Peter Vanicek (OV) (See Reference 6) which uses the Surface of Maximum Curvature (SMC). In their paper they first presented the motivation, practicality, and necessity of computer generated second derivative methods as a means of implementing the U.N. legal definition to compute the FCS via the SMC.

In the Bali paper the author presented a method developed by Carl de Boor called the "Surface of Directed of Gradient (SDG)." The SDG approach is suggested by United Nations Law of the Sea (LOS) legal definition of the FCS (UNFCS) which reads "the point of the maximum change in the gradient at its base" in reference 5. The SDG assumes the UNFCS suggested an approach which should use planes determined by the gradient to compute the FCS.
This paper will contrast the two methods and show how they differ in their results on three specific mathematical functions. The functions which generated the surfaces presented in this paper were originated by Ou and Vanicek in references 6 and 7.

Three different continental slope surfaces were generated to run the two methods on. They are: Case I, a mono-cline slope; Case II, a slightly distorted monocline slope; Case III, a very distorted slope with ridges and valleys.

The scale used for the three OV functions is the same as in reference 7 which is x = y = [0,600] with units in Kilometers.

Both the SDG and the SMC located the FCS in the same place, which both gave a reasonable estimate of the UNFCS.

The SMC had lobes or spurs that became larger as the surface became more complicated.

The SDG had no lobes or spurs for any of the surfaces.

The SMC was sensitive to scaling. It requires the x, y, and z, axes to have the same units. The SDG is scale independent i.e., the units on the x, y, and z, axes do not have to the same units on each axis for it to locate the FCS.

This paper in not an endorsement of the SDG as an official method to be used by the U. S. government to compute the FCS.

DISCUSSION

Some definitions are needed to begin. The UNFCS is " the point of maximum change of the gradient at its base." Suppose that a digital representation, z(x, y), of a monocline continental slope as in figure 1, is presented on a map by contours of equal with constant contour intervals. Where should the UNFCS fall on this contour map? It falls somewhere on the line determined by where the gradient plane through (x, y) intersects with the x-y plane of the map. The UNFCS on the map is on the gradient line and is bracketed by two contours, called <u>bracketing contours</u>. The <u>first of the two bracketing contours</u> is the last of the closest together contours representing steepest slope down the gradient of the continental slope. The <u>second of bracketing contours</u> is the first one seaward where the contours which cut the gradient plane begin to widen out indicating a flattening out at the base of this gradient plane. Note the gradient (dashed line with arrow head) will always be perpendicular to the contour through the point (x,y). In practice for real data the bracketing contour may be the pair of contours seaward of the ones just descried. The intent of defining the bracketing contours is to give a general location of where one might reasonably expect to find the UNFCS. There is also a maximum rate of change of the gradient at its top. My understanding of the use of the wording in the UNFCS “at its base” is to distinguish the lower maximum rate of change from the upper one in a purely mathematical sense. Real data can present very complicated cases of many possible FCSs. Some analysts want to interpret this phrase to extend the FCS farther seaward than the mathematical interpretation would indicate even in the simple cases presented in this paper. If there are several possible FCSs , then “ at its base” would seem to imply choosing the most seaward one. In this paper the simpler conditions are considered. Consider z(x,y) to be the a simple monocline continental shelf parallel to a straight coast line as shown in figure 1.

```
                          LAND
                          (x, y)
 _________________________._________________ Coast line
                          |
                          |
 _________________________|_________________ 1
                          |
                          |
 _________________________|_________________ 2
                          |
 _________________________|_________________ 3
 _________________________|_________________ 4
 _________________________|_________________ 5
                          |                  <--- UNFCS
 _________________________|_________________ 6
                          |
                         \ /
                          SEA
```

For this monocline continental shelf, the UNFCS would be the bracketed by contours 5 and 6, because somewhere between these contours the maximum change in the gradient at its base would occur. Contour 5 is the last of the close together contours (i.e.,1st bracketing contour) Contour 6 is the contour that begin to widen out (i.e. The 2nd bracketing contour). Three different cases are used to contrast the two methods of computing the FCS.

CASE I: MONOCLINE CONTINENTAL SLOPE

This function presented by Ou and Vanicek (OV Function) in their paper
(See Reference 7, page 29, figure 1) is as follows:
let

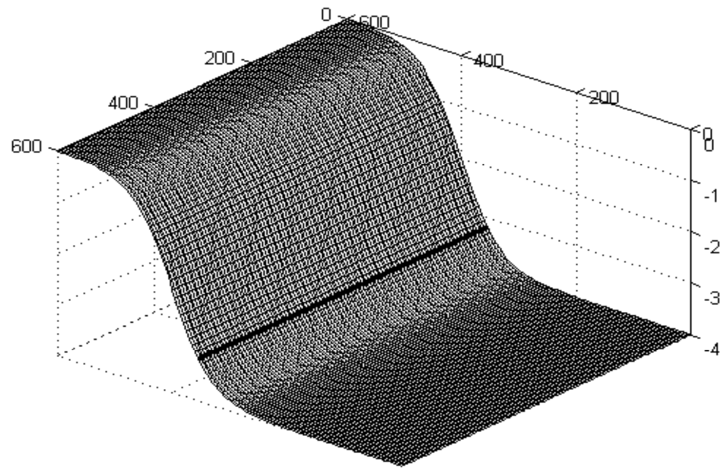
$$a = b * (c*(x - d) + e *(y - f) + g),$$

and

$$z (x,y) = h*((\exp(-a) - \exp(a)) / (\exp(- a) + \exp(a)) +i), \qquad (1)$$

where
pi = 3.14159 ... .
It is a monocline continental slope. The function of equation (1) is defined on the domain:
x= [0, 600] and y= [0, 600], where b=.00003, c= -.1, d=10., e= -500, f=400, g=-2, h=2, i= -1.
The values for a, ...,i are the ones used to generate z in this paper. OV did not give their values in reference 7. The units are in kilometers on the x and y axes with a grid interval of 10Km on both axes. This gives a 61 x 61 grid. A 3-D net display of z (x, y) is given in figure 1.

FIGURE 1: 3-D Net Display of OV Function



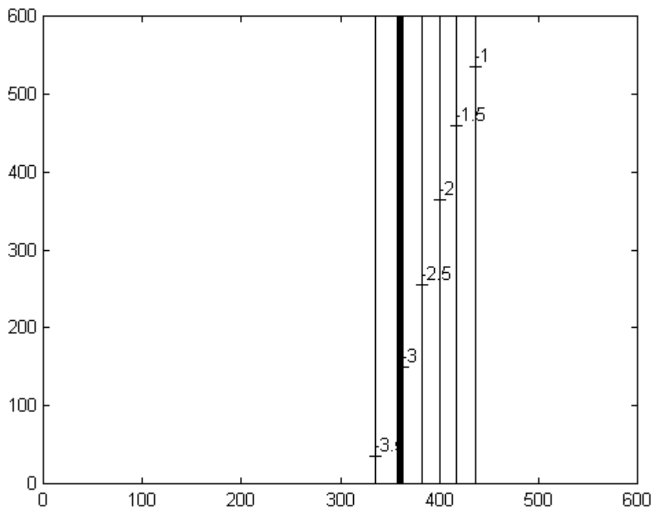
LAND---->   <----SEA

The z axis is in kilometers below sea level. Note the similarity of figure 1 here to figure 1 on page 29 of reference 7. Every effort was made to use the same scale and perspective that Ou and Vanicek used in their paper when possible.

The heavy black line shows the location of the FCS for the SDG and the SMC on the 3-D net diagram. Note that both the SDG and the SMC place the FCS where the UNFCS would dictate. FCS is well above where the continental slope intersects the sea floor. OV do not plot the FCS they obtain in reference 7 on the 3-D net diagram. They do obtain a theoretical solution for the SMC and show that their computed SCM is very nearly the same.

Although this is a mathematical surface, a similar real world continental shelf is quite possible in all three cases. Figure 2 is a contour map of figure 1.

FIGURE 2: CONTOUR MAP OF OV FUNCTION, C.I.=.5 Km



SEA ---->   <---LAND

The argument given above would place the UNFCS somewhere between contours -3.5 and -3.0 in figure 2, because the contours are closer together between contours -3.0 and -2.5 indicating steep slope but then begin to widen out between contours -3.5 and - 3.0. These contours would bracket where the maximum change in the gradient at its base should occur and thus the location of the UNFCS which is indicated by the heavy black line. This is also where the SDG and SMC put the FCS. The SDG and the SMC are now computed. They got the same results shown in figure 3.

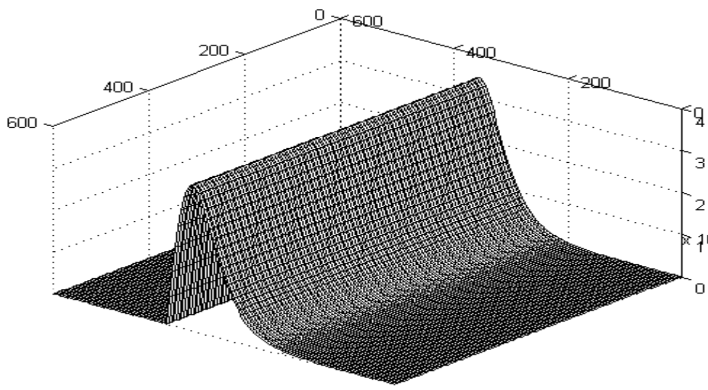


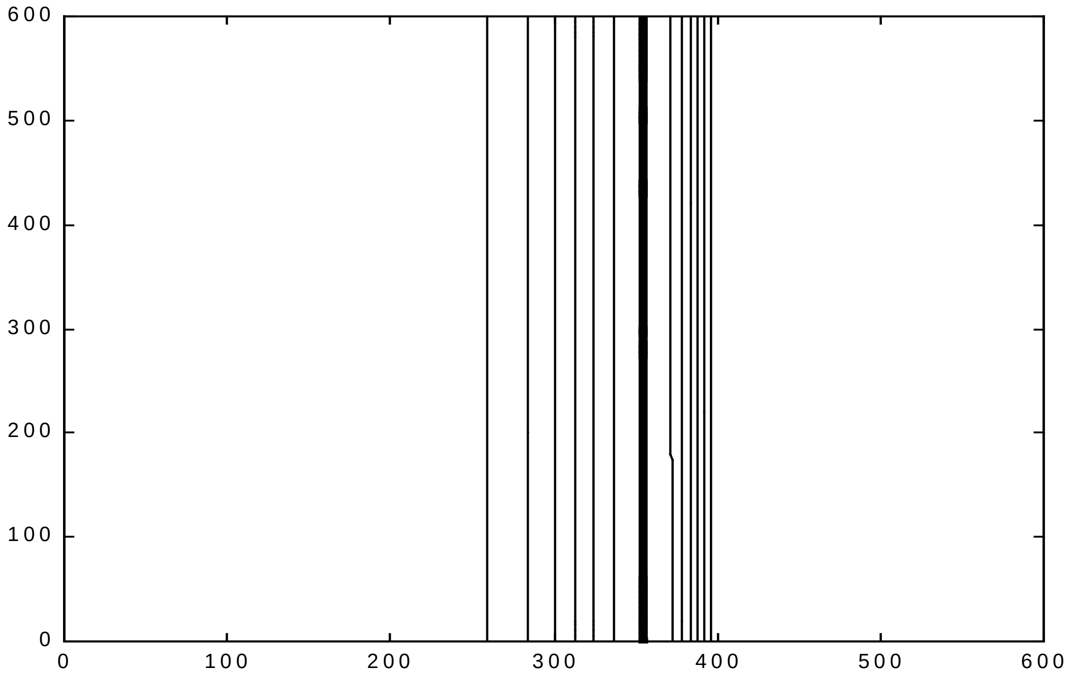
FIGURE 3: 3-D NET DISPLAY of the OV FUNCTION for SDG and the SM

LAND---->   <---- SEA

The x, y coordinates of the crest of the highest ridge (CHR) in figure 3 locates, on the map, the FCS for both the SDG and SMC methods. This procedure is also suggested by the UNFCS, because the crest of the highest ridge is there by way of its being the point where the maximum change in the gradient at its base occurs. The CHR a very reasonable way to locate the FCS for the SDG and the SMC. The CHR algorithm used in this paper keeps track of the index of the maximum value of z(x,y) in the columns and then connects these points from column to column to outline the FCS. This is a simple 1-D search. A 2-D search on the rows and columns would be a better algorithm for real data. This 1-D approach worked well for the functions in this paper. A two criteria search is presented by OV in reference 6.

If the SDG and the SMC are contoured and the computer located FCS is as indicated in figure 4 by the dark line, the result is:

1505 FIGURE 4: CONTOUR MAP of the OV FUNCTION for the SDG and the SMC



SEA----> <----LAND

In this simplest case where the continental shelf is a monocline the SDG and the SMC get the exact same results for the second derivative surface. All contours are parallel to the FCS for the second derivative surfaces obtained by using each of the two methods.

CASE II: SLIGHTLY DISTORTED MONOCLINAL CONTINENTAL SLOPE

This function presented by Ou and Vanicek (OV Function) in their paper
(See Reference 7, page 30 figure 2) is as follows:
let

$$a = b * (c*(x - d) + e *\sin(pi* y /f) + g),$$

and

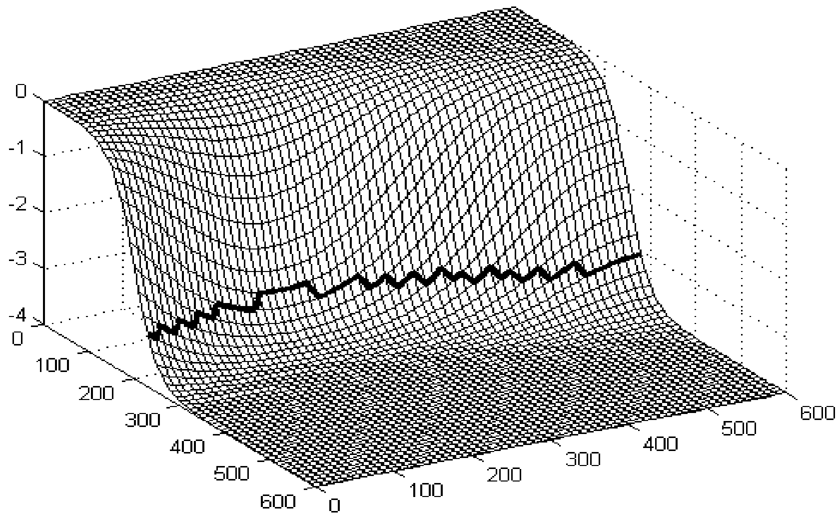
$$z (x, y) = h*((\exp(-a) - \exp(a)) / (\exp(- a) + \exp(a)) +i), \qquad (2)$$

where

$$pi = 3.14159 \ldots .$$

It is a slightly distorted monocline continental slope. The function of equation (2) is defined on the domain: x = [0, 600] and y= [0, 600], where b=.02, c=.1, d=0, e=50,f=400, g= -200, h=2, i= -1. The values for a,...,i are the ones used to generate z in this paper. OV did not give their values in reference 7 . The units are in kilometers on the x and y axes with a grid interval of 10Km on both axes. This gives a 61 x 61 grid. A 3-D net display of z(x,y) is given in figure 5.

FIGURE 5: 3-D Net Display of OV Function



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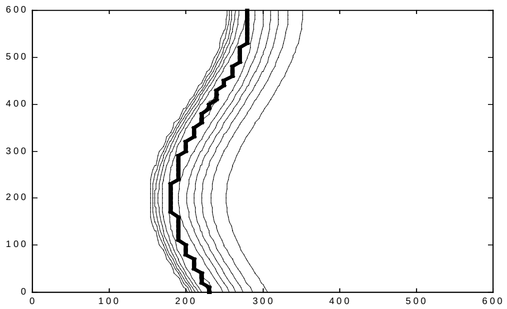
The z axis is in kilometers below sea level. Note the similarity of figure 5 here to figure 2 on page 30 of reference 7. This figure shows the FCS obtained for both the SDG and the SMC. They were essentially the same. Note that the FCS is well up on the continental slope as the UNFCS suggests it should be for the mathematical interpretation of the UNFCS for this simple example.
The first signs of differences of results from the second derivative surfaces obtained from the SDG and the SCM now begin to show in this case II.

If the SDG and the SMC are contoured and the computer located FCS is indicated by the dark lin, the results are presented in the next two figures:

FIGURE 6: CONTOUR MAP of the OV FUNCTION for the SDG



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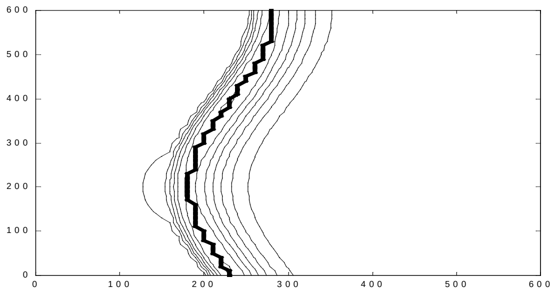


FIGURE 7: CONTOUR MAP of the OV FUNCTION for the SMC

LAND----> <---SEA

Note how tight the contour lines on the left side of the SDG in figure 6 continue on with no sign of a lobe. Note in figure 7 the contour display of the SMC that even for this slight distortion of the monocline slope the SMC is beginning to show the fist sign of the lobe appearing with the left most contour beginning to bulge out.

CASE III: DISTORTED CONTINENTAL SLOPE WITH RIDGES AND VALLEYS

This function presented by Ou and Vanicek (OV Function) in their paper
(See Reference 7, page 30, figure 3) is as follows:

let

$$a = b * (c*(x - d) + e *\sin(pi* y /f) + g),$$

and

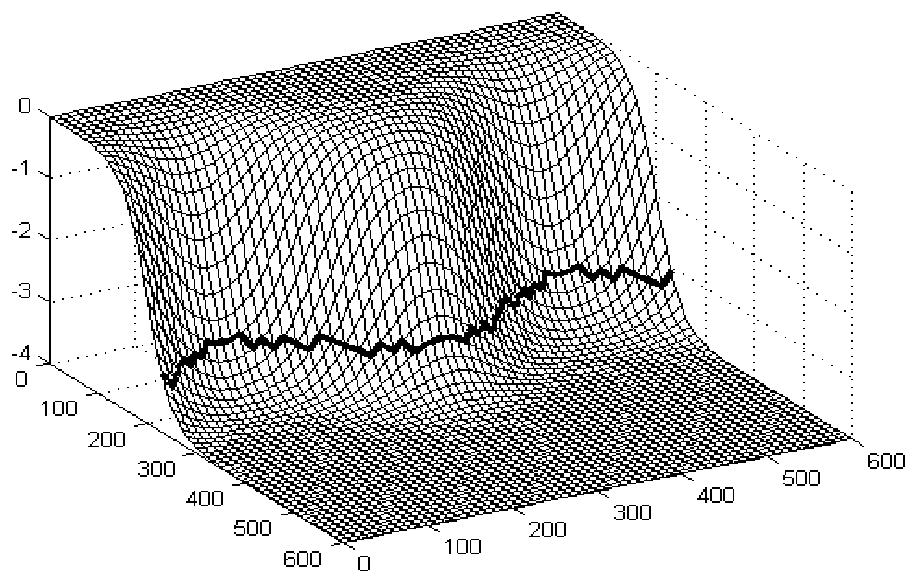
$$Z(x,y) = h*((\exp(-a) - \exp(a)) / (\exp(- a) + \exp(a)) +i), \qquad (3)$$

where

$$pi = 3.14159 ... .$$

It is a quite distorted continental slope with ridges and valleys. The function of equation (3) is defined on the domain: x = [0, 600] and y = [0, 600], where b=.02, c=.1, d=0., e=50, f=200, g=-200, h=2, i=-1. The values for a, ... ,i are the ones used to generate z in this paper. OV did not give their values in reference 7. The units are in kilometers on the x and y axes with a grid interval 10Km on both axes. This gives a 61 x 61 grid. A 3-D net display of z (x, y) is given in figure 8. The heavy black line locates the FCS for the SDG and the SMC.

FIGURE 8: 3-D Net Display of OV Function



LAND---->　　　　　　　　　　　　　　<----SEA

The z-axis is in kilometers below sea level. Note the similarity of figure 8 here to figure 3 on page 30 of reference 7. Figure 8 shows the FCS obtained for both the SDG and SCM. Note that the FCS is well up on the continental slope as the UNFCS suggests it should be. OV in reference 6 got a close correlation for the computed SMC and the theoretical SMC in figure 10 on page 190.

If the SDG and the SMC for this function are contoured and the computer located FCS is indicated by the dark line, the result is shown in figures 9 and 10, respectively:

FIGURE 9: CONTOUR MAP of the OV FUNCTION for the SDG

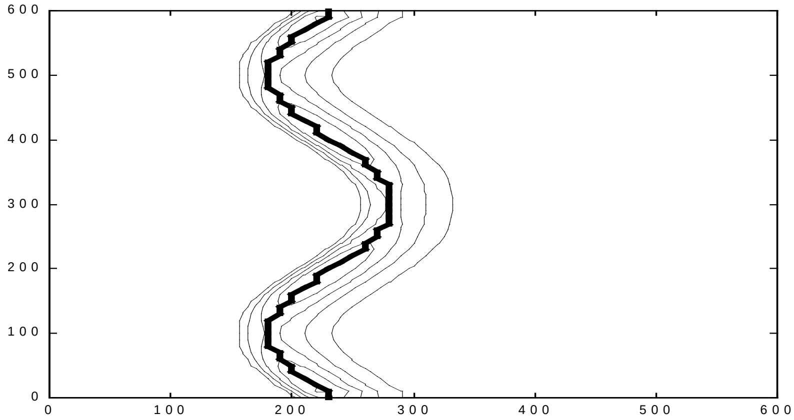


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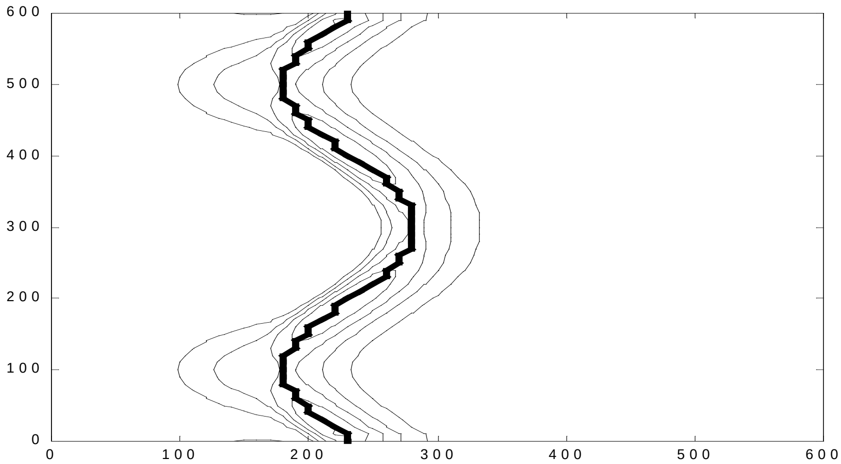
FIGURE 10: CONTOUR MAP of the OV FUNCTION for the SMC



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In figure 9 the SDG still has none of the bulging contours. In figure 10 the lobes on the SMC are becoming quite evident as seen by the bulging contours on the left. In figure 3 of reference 6, the lobes or spurs show up on the SMC in the location where the valleys occur in the original bathymetric data as in this example. In this example, the lobes get higher than the CHR (crest of the highest ridge) which locates the FCS.

CONCLUSIONS

For these three simple examples both methods locate the FCS where the UNFCS suggests it should be.

The SMC has lobes or spurs that got larger the more complicated the function became. The SDG had no lobes or spurs for any of the three cases considered for this function.

The SMC is sensitive to scaling. It requires that all axes have exactly the same units on all three axes. The SDG does not require that any of the three axis have the same units; however the x and y axes usually do. In Bennett (reference 2, figure 6, page 60), the ETOPO5 data used has the x and y axes in longitude and latitude, respectively and the z-axis in meters. The SDG was able to run the ETOPT5 without modification and located the Atlantic FCS properly. The SMC could not run the ETOPO5 data without editing. The data had to be scaled (reference 2, figure 13, page 65) so all three axes were in kilometers before the SCM could be run. It then generated the same location of the FCS as the SDG did after scaling back to longitude and latitude to obtain the proper aspect ratio.

The UNFCS legal definition becomes ambiguous very quickly in applying it to real digital data. It works well on the U S Atlantic East coast. This area is, perhaps, as simple as real data can get. The UNFCS is the legal definition given by the UN to work with. This paper shows three simple examples that provides some insight into its application. These are just three simple examples and are in no way conclusive.

For an exact statement of the SDG see Bennett reference 2, Table 1, page 56. For a complete statement of OV's SMC see reference 6, pages 182 and 183, equations 1-10, and page 185, equation 19.

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SESSION 3 – Paper 7

THE HH CODE: FACILITATING THE MANAGEMENT, MANIPULATION, AND VISUALIZATION OF BATHYMETRIC DATA

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ABSTRACT

The HH (Helical Hyperspatial) Code has been implemented in a number of databases as the format of choice for handling and storing large quantities of geospatial and other types of spatial data. HH Code is multidimensional and expresses dimensions (such as latitude, longitude, and depth) in interleaved binary integer format in order to achieve high levels of compaction, as well as rapid indexing and retrieval.

In preparing to implement Article 76 off Canada's Atlantic and Arctic margins, the GSC and the CHS have imported significant quantities of historical and modern soundings into the HH environment, to take advantage of existing tools that support automatic cleaning operations, as well as interactive manipulation and visualization.
Significant efficiencies have been realized through the use of these tools - for instance, the GSC/CHS data base in question had previously been edited and corrected through a manual process that was labor-intensive and error-prone, with a duration that was measured in months; in contrast, when the process was repeated through the application of an HH-based statistical procedure, comparable results were achieved in only minutes of computer execution time. This level of performance is attractive to Article 76 implementors who are faced with the task of assembling, qualifying, and rationalizing numerous sets of disparate observations in order to create a coherent data base.

This paper will describe and illustrate the application of various software operations on HH-encoded data, with particular emphasis on Article 76 considerations such as the assessment of data quality in zones that encompass the foot of the continental slope and the 2500-metre isobath.

INTRODUCTION - BLENDING HISTORIC AND MODERN DATA

Worldwide, the new generation of echo-sounding systems is fuelling a veritable explosion of bathymetric data sets in specific target areas, whereas the quantity of observations being collected with conventional instruments remains relatively static due to their low rates of acquisition. In terms of accuracy and resolution, data sets collected with modern instruments are an indisputable improvement over those obtained with older equipment, however the older legacy data sets, collected as they were during an era of wide-ranging, traditional survey missions, often feature a much broader geographical coverage. Representing the cumulative output of survey programs that have been mounted over the past several decades, many of these legacy data sets are likely to remain in use for several decades more before they are supplanted by modern observations. The anticipated longevity of these data sets provides ample justification for adopting an organized approach to their management and utilization.

Modern techniques for studying, managing, and exploiting the sea floor have spawned a growing demand for better representations of bathymetry, both in hardcopy and in digital form. In many instances, these representations can only be derived from a mix of modern and legacy data, which raises a host of problems in assembling, combining, and utilizing data sets that are not only fragmented and incompatible, but which exist in multiple formats and which feature a wide range of accuracies, resolutions, and geographic densities. Given the high cost of mounting field operations, prospects are not promising for solving these problems by embarking upon large-scale survey programs to collect better data; rather, the most practicable solution will likely entail initiatives for rationalizing existing data sets so they can be used to portray the seafloor in a fashion that is as accurate and as coherent as possible.

A MODEL FOR THE FLOW OF BATHYMETRIC DATA

In their metamorphosis from raw soundings to accurate representations of ocean depths, bathymetric data sets may flow along a variety of paths. Figure 1 illustrates a typical flow pattern, featuring three primary phases from acquisition to application:

- *Information capture/processing.* Original measurements are collected directly in the field, or recovered from pre-existing representations of the sea floor. Measurements are reduced to render basic observational attributes for each data point in digital form, e.g. depth, position, and where available, date and time of acquisition. For each set of data points, various administrative and technical specifications (metadata) are assembled, e.g. vessel name, sponsoring agency, type(s) and characteristics of instrumentation, horizontal and vertical accuracies, processing history, etc. Data and metadata are stored together in a standardized Spatial Data Structure (SDS) for further processing and refinement with common editing tools.

- *Data assimilation/management.* Corrected data sets are compared with adjacent and overlapping information that is already in the DBMS; appropriate adjustments and registrations are performed to create acceptable matches between new and old. Quality factors are assigned to define observational accuracy and reliability. New data sets may then be archived individually, or alternatively loaded into a Relational DBMS for full integration with previously-loaded data.

- *Data utilization.* With standard tools, individual or combined data sets are retrieved and manipulated for use in a full spectrum of applications.

THE SPATIAL DATA STRUCTURE (SDS) - KEY TO SMOOTH DATA FLOW

Figure 1 illustrates how primary data handling operations are interconnected by a standardized Spatial Data Structure (SDS) that effectively pipelines data from the output of each process to the input of the next. By design, the SDS is not tied to the format or the content requirement of any particular package, but features instead a high level of generality. The advantage of this concept is that the SDS supports near-universal operability with a wide range of processing packages, permitting considerable latitude for the user in selecting tools and processing techniques that are most appropriate to the needs of the application.

HH CODE - THE KERNEL OF SDS

The HH (Helical Hyperspatial) Code has been incorporated in a number of GIS implementations as the format of choice for handling and storing large quantities of geospatial and other forms of spatial data. HH Code is multidimensional and expresses dimensions in interleaved binary integer form to achieve high levels of compaction, as well as rapid indexing and retrieval.

Figure 2 illustrates graphically the concept of HH Code construction for a given Latitude and Longitude - in this case the position of a navigation light situated at the end of the pier in front of the Bedford Institute of Oceanography in Halifax, Canada. Through successive binary division of the global coordinate space in the N-S and E-W directions, a series of diminishing quadrangles are defined until eventually an arbitrarily small quadrangle encloses the target location. Each binary division generates a one or a zero to indicate whether the target location falls in the upper/lower or right/left half of the resulting quadrangle. With a 32-bit integer format, the binary division is performed 32 times in succession, which in this case terminates with the definition of a quadrangle that measures about 2 mm by 2 mm.

Figure 3 illustrates the numerical outcome of the above process, with HH Codes for the target Latitude and Longitude expressed in Binary, Hexadecimal, and Decimal forms. HH Codes are further compacted by the process of interleaving, so that successive pairs of bits define the locations of progressively diminishing quadrangles within the global coordinate space. The interleaved format permits extremely rapid localization and retrieval of individual data points through the inspection, comparison, and manipulation of binary patterns within integer variables.

HH Codes can be easily expanded to three and more dimensions. The third dimension is immediately applicable when the location of a data point includes a temporal component that complements its spatial components; this is shown conceptually in Figure 4, where the coordinate system defines a space-time cube, and where three sets of binary coordinates are interleaved to define the location of a volume element within that space.

BATHYMETRIC OBSERVATIONS OFF EASTERN CANADA

For the past several decades, numerous survey and research cruises have collected soundings off the east coast of Canada, mapping the sea floor accurately in many places, and less accurately in others. Characterized by significant instrumental and procedural variety, these operations have produced a large number of disparate data sets; reducing them all to a coherent data base presents a serious challenge, given their inhomogeneous distributions and their mix of pedigrees. This accumulation of soundings has thus provided a useful test bed for a range of tools and procedures for data handling and visualization.
The remainder of this paper describes how a suite of software tools that operate in the HH environment were used to treat the Canadian data base. This package of programs operates in Windows NT, and was developed by Helical Systems Limited in collaboration with the Canadian Hydrographic Service. Unless otherwise indicated, all the data illustrations that follow were created with this software, operating upon HH-encoded data.

DATA VISUALIZATION AND CLEANING

Figure 5 illustrates the bathymetric data base off eastern Canada, an area characterized by wide continental shelves, incised continental slopes, and flat abyssal plains. The data sets shown here have been treated with an automated cleaning algorithm that applies a statistical process to identify errors and bad points. Operating on this particular data base, the process required only minutes to complete; in contrast, previous operations when the data was coded in conventional lat-long coordinates involved tedious, labour-intensive techniques that consumed the better part of one year.

An HH-coded data base lends itself easily to a variety of visualization techniques. Figure 5 is an oblique view that emphasizes the shape of the seabed; a plan view can be just as easily produced to portray the distribution of data points without distortion. As illustrated in Figure 6, which portrays a portion of the data base prior to cleaning, oblique views are also useful for identifying errors: in this example, several erroneous profiles stand out clearly against a background of coherent data points. These profiles can be manually selected by the operator to enable inspection of the numerical observations and their attributes - identification of the originating institution, cruise number, date and time of observation, position coordinates, etc; these are listed in the inset. When displayed in this form, the observations may be flagged or edited.

Figure 7 is another example of visualization, where original observations have been extracted from a thin section across a portion of the data base for display in profile form. The size, position, and orientation of the thin section can be varied to suit the purpose of the analysis.

A major advantage of the HH Code is an internal structure that lends itself well to intensive manipulations such as automated data cleaning; this functionality eliminates many of the tedious, time-consuming, and error-prone steps that are the norm when editing and correcting conventionally-coded data. Simply put, the automated cleaning process is based upon an assessment of the statistical compatibility of each data point with its neighbours, the degree of compatibility being selected by the operator.

The effectiveness of the cleaning technique is demonstrated in Figure 8. Constructed from uncorrected data, the upper image shows a series of bad points crossing a broad channel on the continental shelf, along with a single outlier on the continental rise. The lower image shows the same data set after it has been subjected to an automated cleaning procedure: the bad crossing points have been eliminated, along with the outlier on the continental rise.

GRIDDING AND TILING

Large sets of randomly-spaced observations can be converted into grids and tiles to facilitate their storage and manipulation. Grids are constructed by distributing observations over a regular network of equal-sized cells, according to the locations of the data points in a corresponding coordinate matrix. When tiles are built, the locations of the data points are also taken into account, however their values are aggregated into cells of unequal sizes containing points that are statistically compatible. Different techniques exist for allocating data points to grids and tiles, but regardless of the method used, the original large set of observations is reduced to one value for each grid or tile.

Data sets that are HH-encoded lend themselves well to the tiling technique and its inherent benefits. To compare the relative advantages of gridding and tiling, both methods have been applied to the data sets portrayed in Figure 9, which features a dense accumulation of continental shelf soundings adjacent to an area of relatively sparse data over the adjacent continental slope and rise.

Figure 10 illustrates the differences when all these data points are reduced to a coarse grid, to a fine grid, and to variably-sized tiles. If stored in their original form, the observations require nearly 30 megabytes of storage space, an unwieldy quantity that does not lend itself well to efficient manipulation. If the points are reduced to a coarse grid, the storage requirement is dramatically decreased by a factor of 60, however the resolution of the resulting depiction of the sea floor is significantly degraded. If reduced to a fine grid, the storage requirement diminishes to about a third, with an acceptable level of resolution in the depiction of the sea floor. If reduced to variably-sized tiles, the storage requirement shrinks to nearly a fifth, with no degradation in the depiction of the sea floor. The combination of reduced storage and more efficient manipulation therefore makes the HH code an attractive option for handling the data in this particular instance.

DATA MANIPULATION

Data sets in the HH environment can be easily modified through the addition and combination of attributes that describe characteristics of the observations, such as quality or significance. An example will be given here to demonstrate how this functionality can be applied when assessing the need for improved data in a given area to determine the location of the foot of the continental slope, as defined in Article 76 of the Law of the Sea.

The top portion of Figure 11 illustrates the assignment of data quality factors in the range of 1 to 5 (represented by patches of varying shades), based upon a visual inspection of the density and distribution of data points. The middle portion shows in dark gray a zone of likelihood for the foot of the continental slope, derived from a visual examination of the profiles. The bottom portion is a composite of the two upper images, showing data quality factors in the foot of slope likelihood zone only. This form of presentation can provide a quantitative basis for planning future mapping operations to improve the data base.

CONCLUSIONS

Software tools that function in the HH environment have been used in a variety of operations on an existing assemblage of bathymetric observations, and have performed well by enabling (a) the efficient storage and fast retrieval of geospatial data; (b) interactive data manipulation and visualization; (c) the rapid, automated cleaning based on a statistical approach; and (d) the assignment and merging of attributes in the data records.

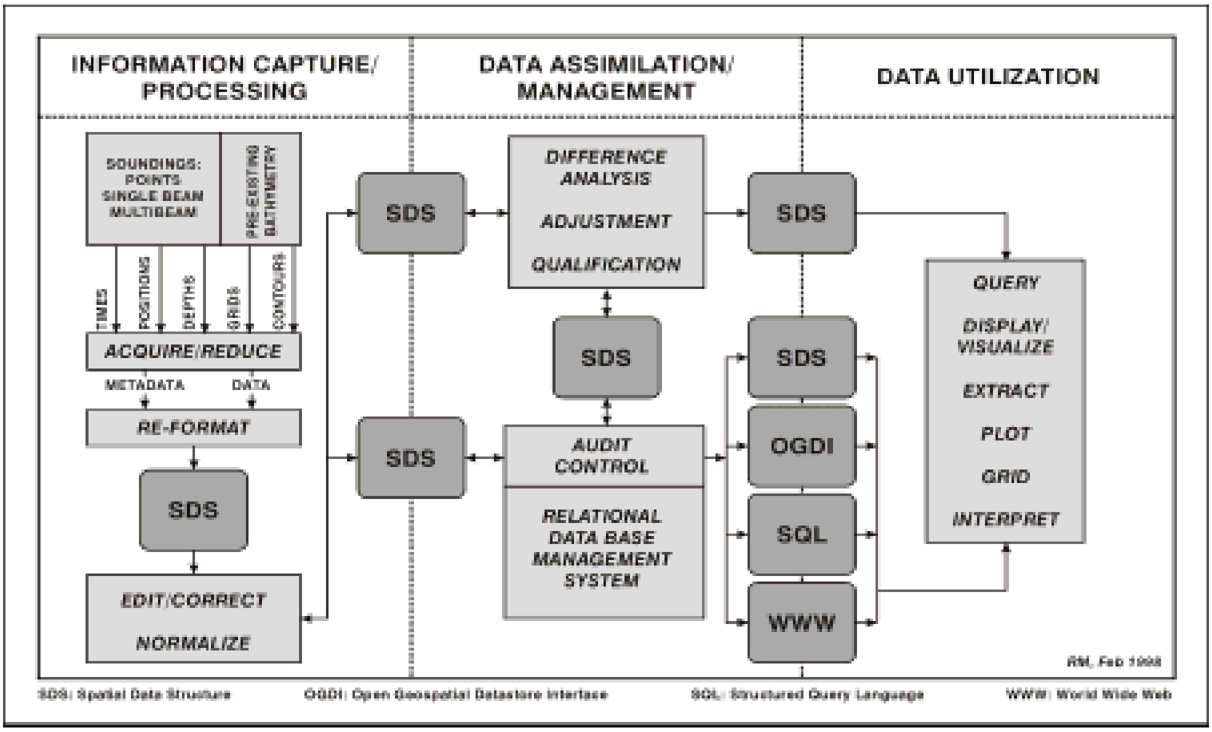

Figure 1. The three stages in the data life cycle, beginning with acquisition and finishing with utilization. Transfer between the three stages is facilitated through the use of a uniform Spatial Data Structure, which in some GIS applications has been implemented in HH Code.

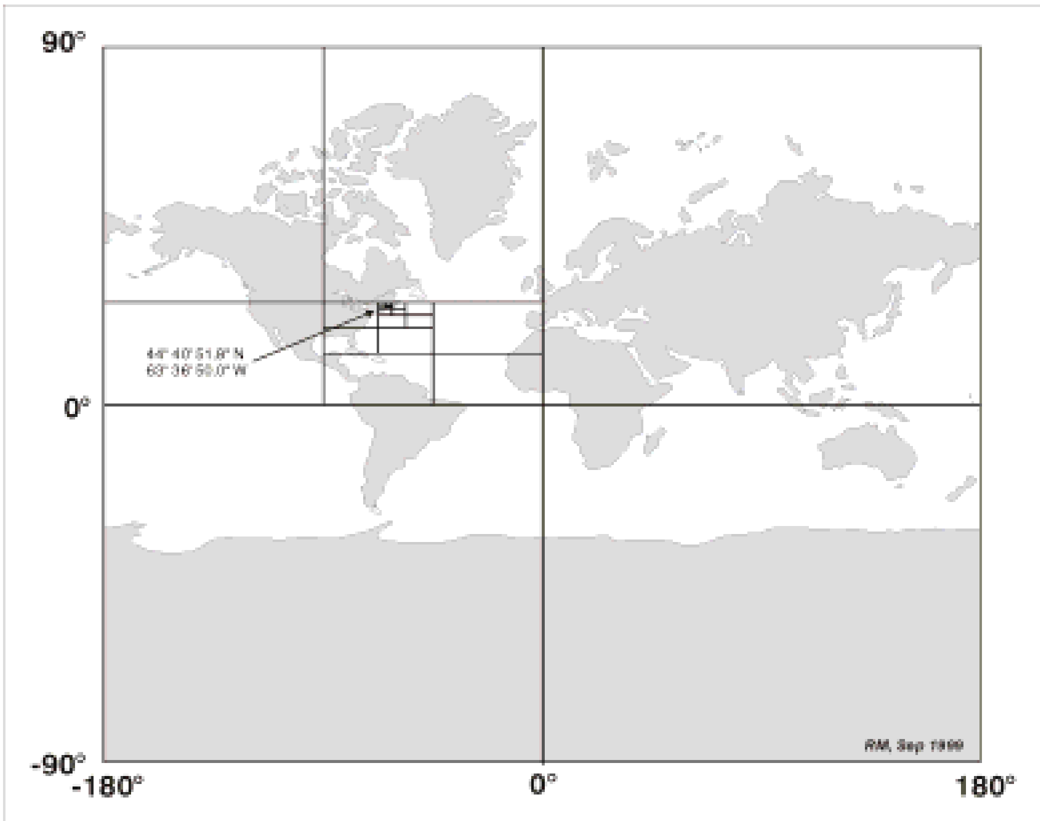

Figure 2. The HH Code defines the location of a point on the surface of the earth through a binary process whereby the globe is divided into successively smaller quadrants until the point in question is contained in an arbitrarily small area (2 mm by 2 mm in this example).

Example Location: Light at end of BIO Pier, Halifax, Canada

	DEG-MIN-SEC	DECIMAL DEGREES	BINARY HH CODE	HEXADECIMAL HH CODE	DECIMAL HH CODE
LATITUDE	44° 40' 51.8" N	44.68105...	1011... (32 BITS)	BF8BE54C	3213616460
LONGITUDE	63° 36' 50.0" W	-63.61388...	0101... (32 BITS)	52C37251	388540497
INTERLEAVED LAT & LON	N/A	N/A	01100111... (64 BITS)	675DE04F-7E193252	7448355990-763287122

Figure 3. The HH Code combines two or more coordinates into a single number through a bit-by-bit interleaving of their binary representations. The latitude and longitude coordinates shown here are converted into two 32-bit binary numbers, which are then interleaved to create one 64-bit number which contains a full definition of the point's location. The HH-coded coordinates of this example are also shown in hexadecimal and decimal form to further illustrate the reduction of two sets of degrees, minutes, and seconds, to one number.

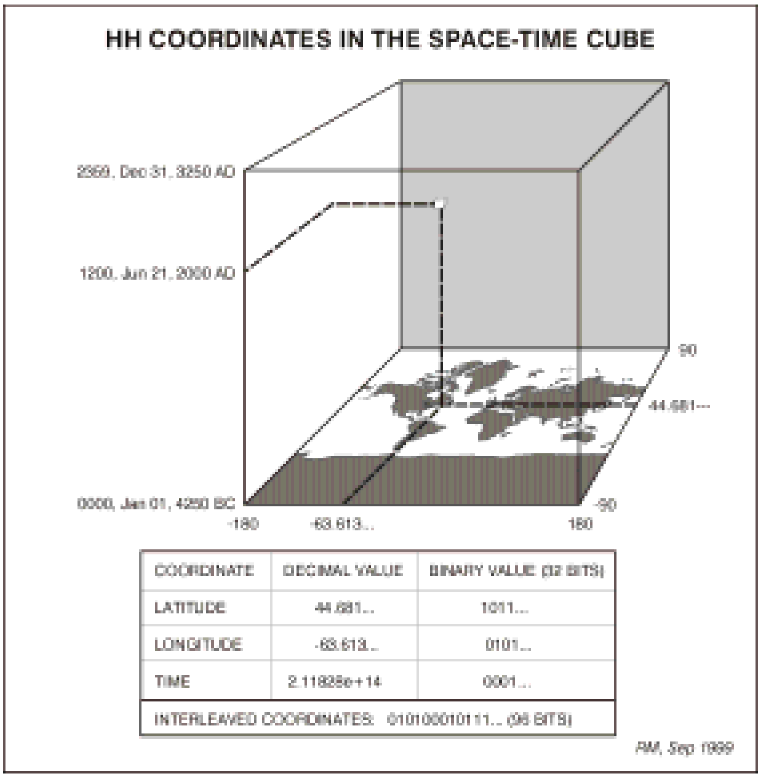

Figure 4. The location of a data point in the space-time cube, along with attributes and observations at that point, can be expressed by a single number. This leads to a significant compression of positional information, along with important efficiencies in data storage and retrieval.

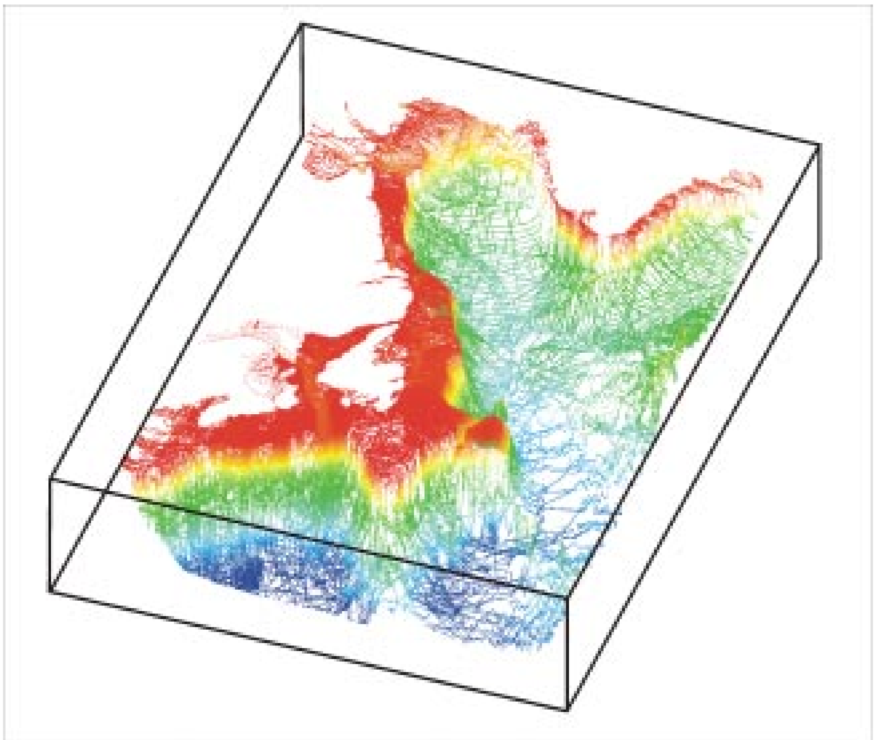

Figure 5. This oblique view illustrates the bathymetric data base that was used in this study for evaluating software tools that operate in the HH environment. Cleaning this data base with automated tools took only minutes, whereas previous efforts when the data points were conventionally coded in lat-long coordinates consumed the better part of one year.

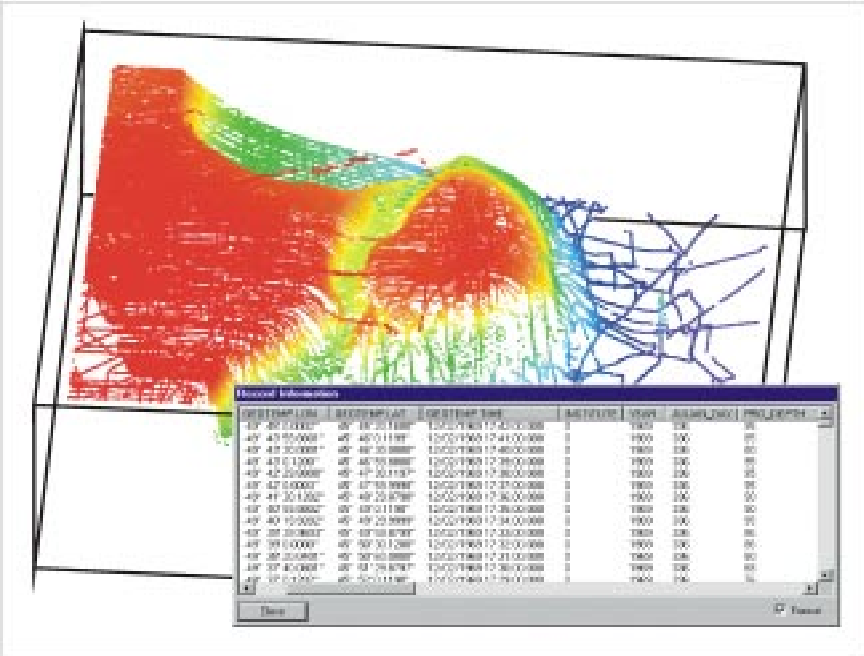

Figure 6. Main image: an oblique view of the uncorrected data base over Flemish Cap and the Grand Banks of Newfoundland, portraying the distribution of ship tracks which are colour-coded according to observed values of depth at each point of observation. A few bad profiles stand prominently clear of the coherent data points in the background. Inset: a listing of the values and attributes of the bad profiles, following selection by the user.

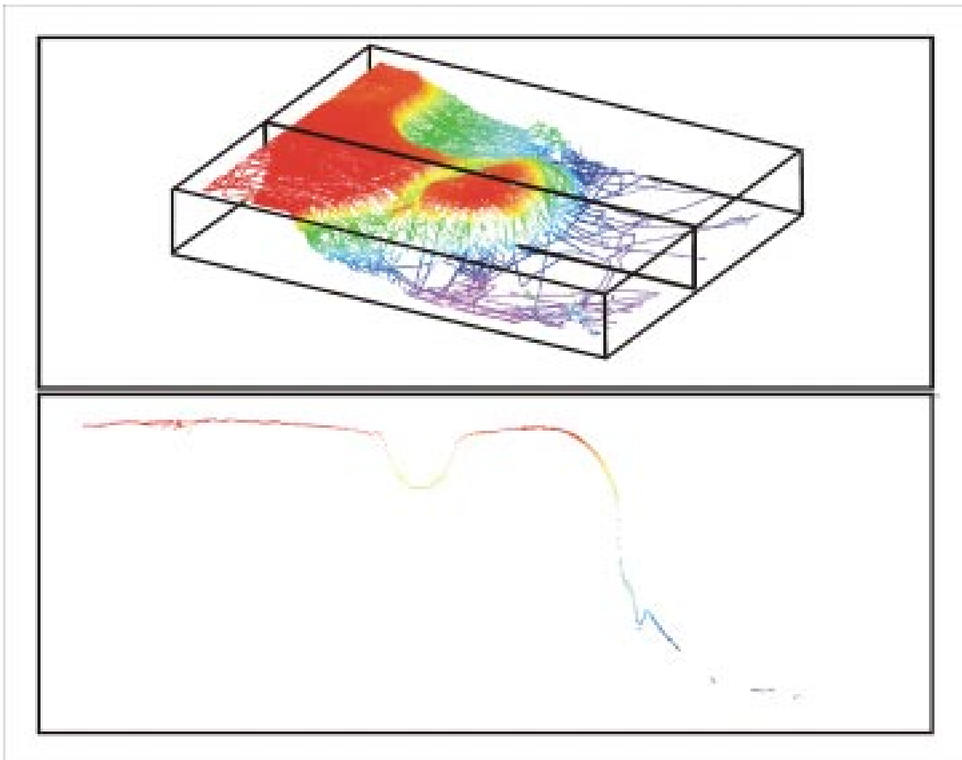

Figure 7. Original observations have been extracted from a thin section across the Flemish Cap and the Grand Banks (upper image), and displayed in profile form (lower image). The size, position, and orientation of the thin section can be varied to suit the purpose of the analysis.

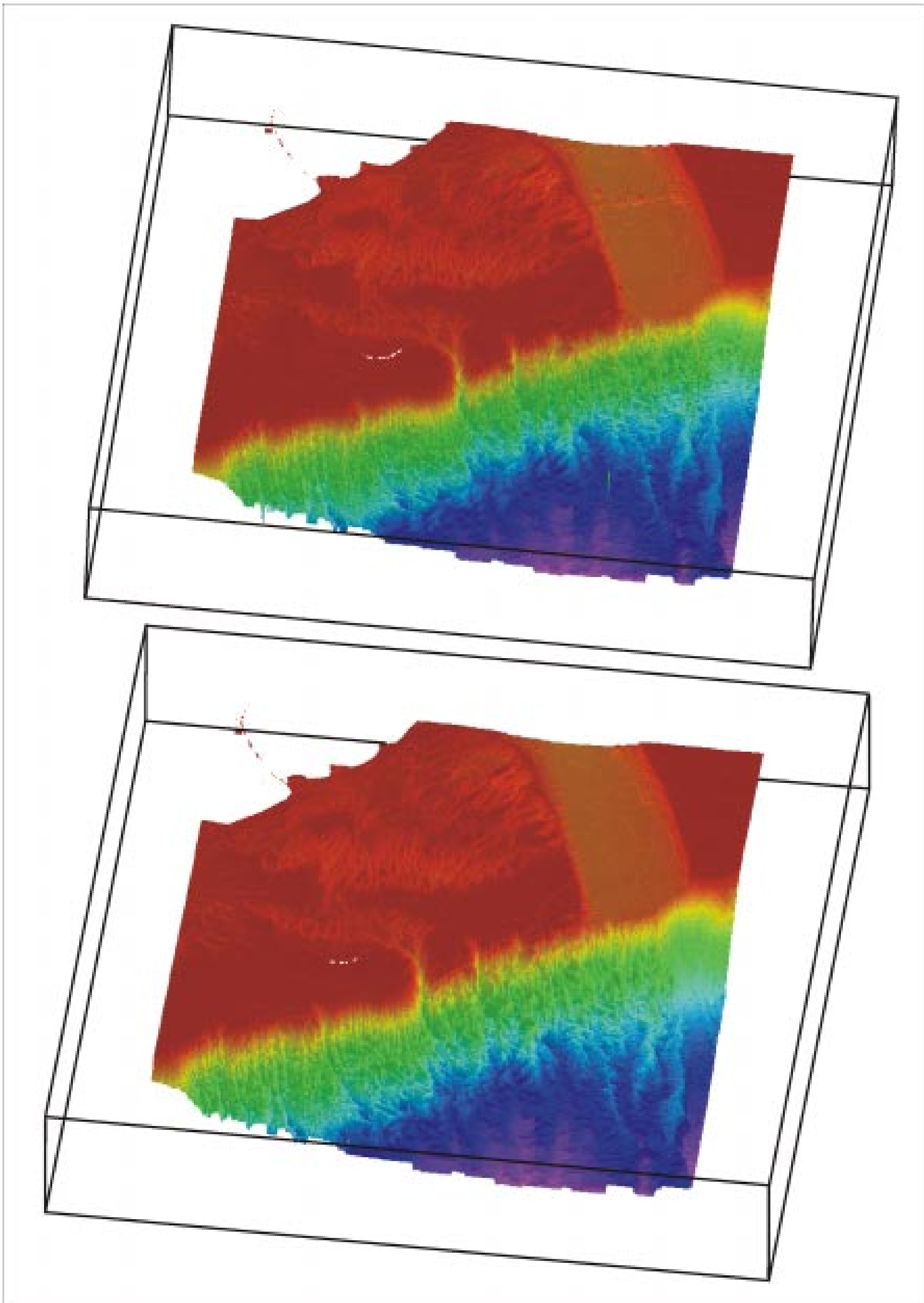

Figure 8. Upper image: an oblique view of the sea floor, constructed from uncorrected data and showing a series of bad points across a channel on the continental shelf, as well as a single outlier on the continental rise. Lower image: the same data set after it has been subjected to an automated cleaning procedure, which assesses each observation point for its level of coherence with the surrounding points; bad points in the channel have been eliminated, as well as the outlier on the continental rise.

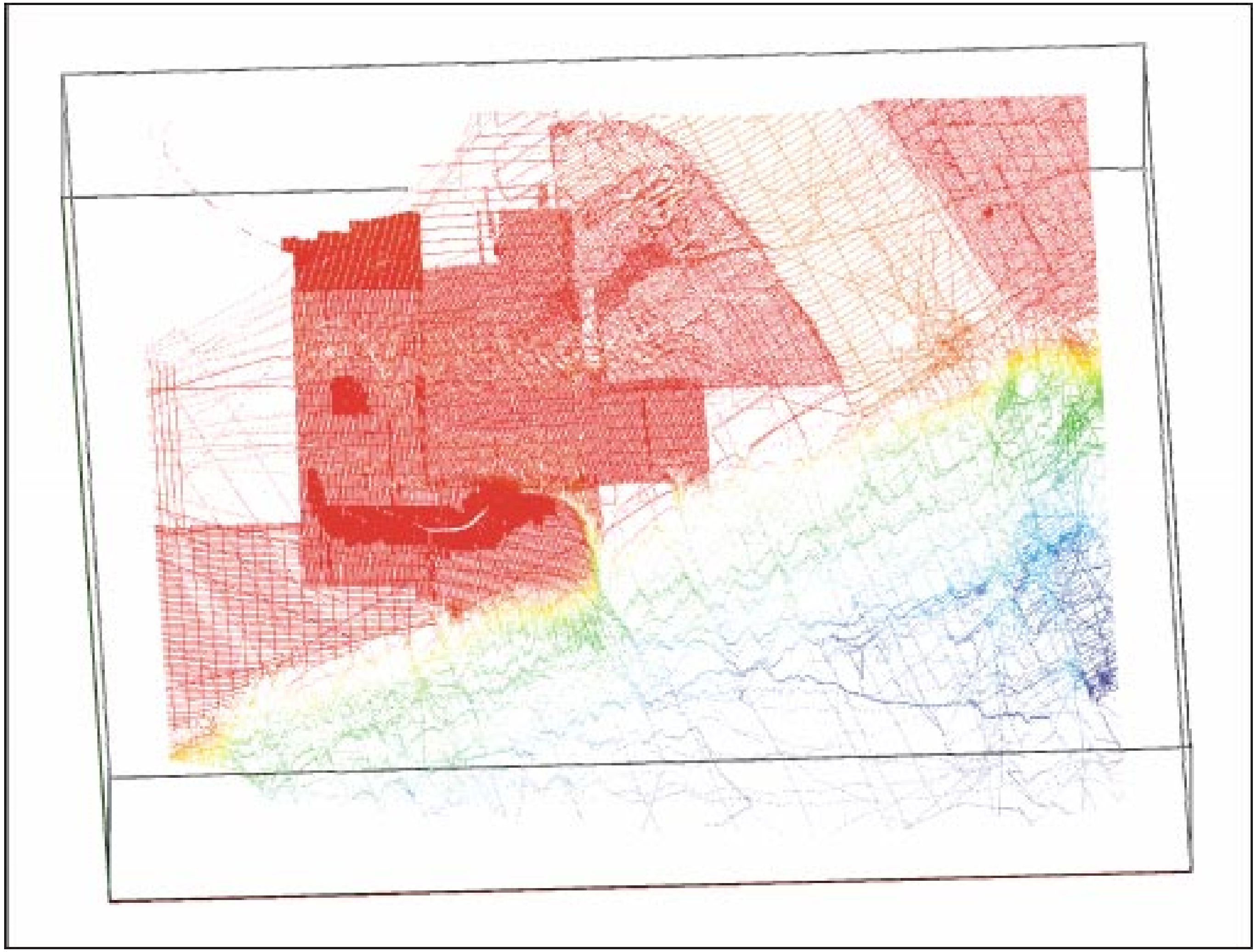

Figure 9. Distribution of original data points used to compare the effects of gridding and tiling. If stored in their original form, the observations require nearly 30 megabytes of storage space, an unwieldy quantity that does not lend itself well to efficient manipulation.

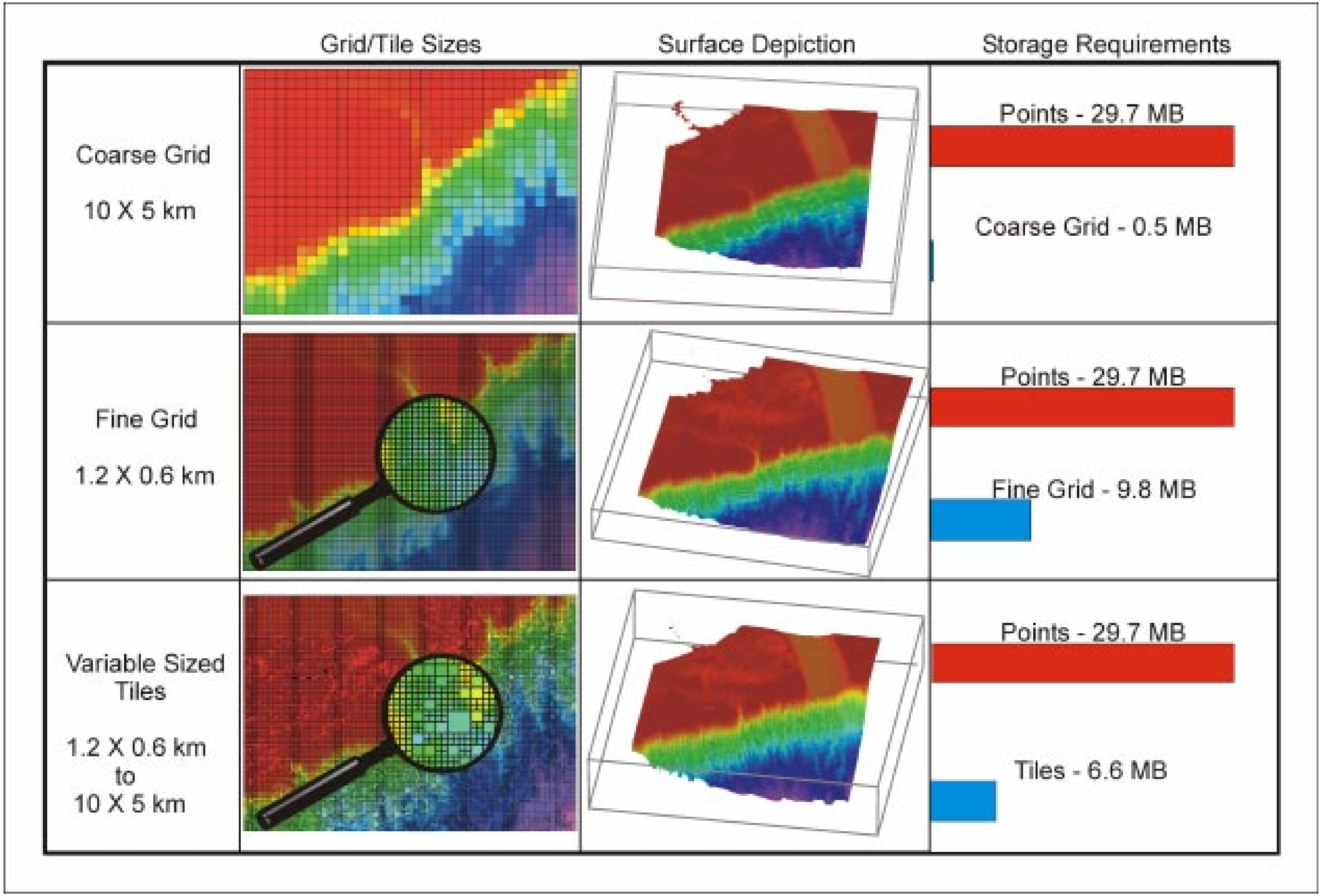

Figure 10. This figure illustrates the differences when the data points shown in Figure 9 are reduced to a coarse grid, to a fine grid, and to variably-sized tiles. <u>Coarse grid</u>: storage decreased by a factor of 60, degraded sea floor resolution. <u>Fine grid</u>: storage diminishes to about a third, acceptable sea floor resolution. Variably-sized tiles: storage reduced to nearly a fifth, unchanged sea floor resolution.

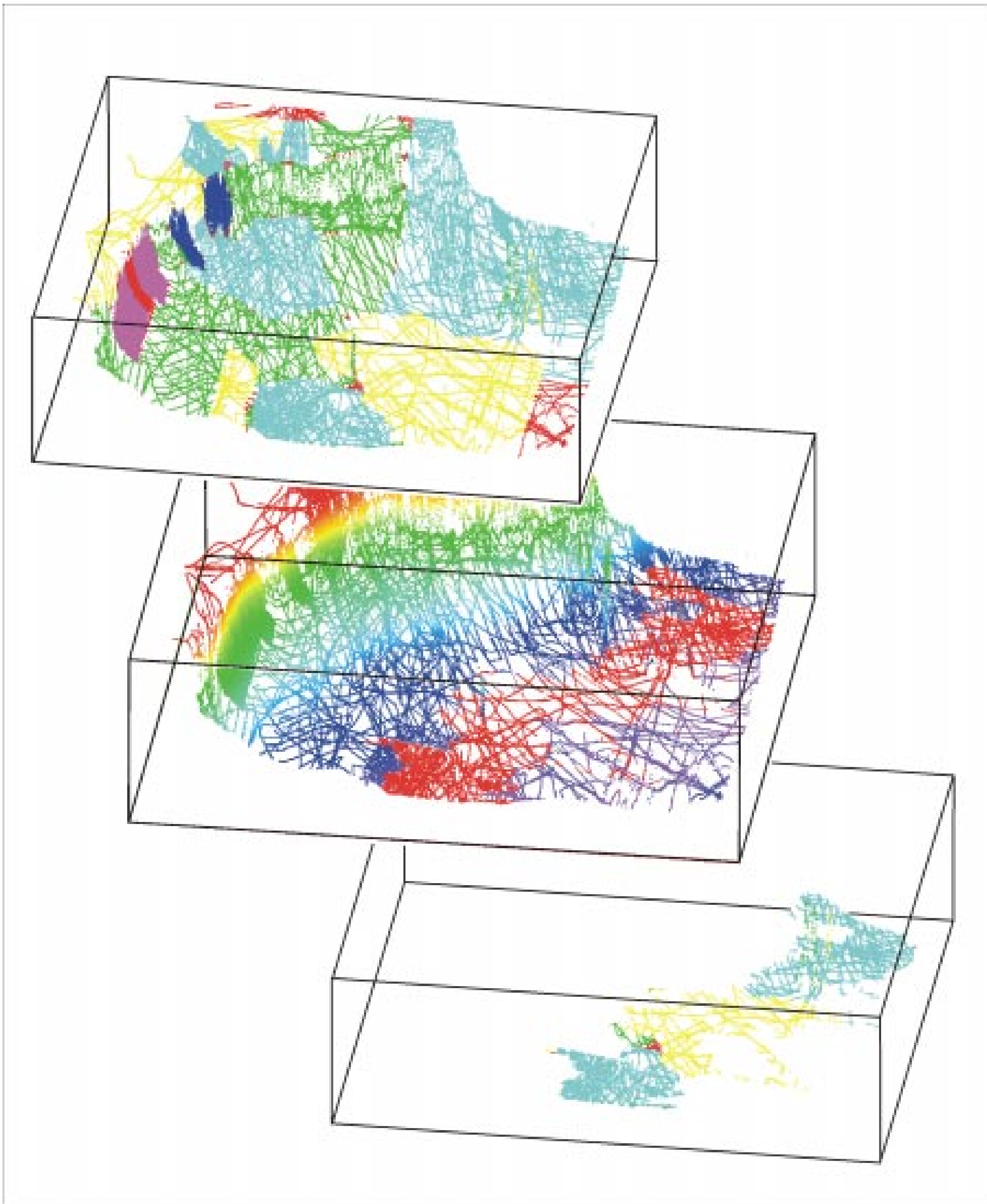

Figure 11. Demonstration of addition and combination of observational attributes. Top image: assignment of data quality factors in the range of 1 to 5 (represented by patches of varying shades), based upon a visual inspection of density and distribution. Middle image: zone of likelihood for the foot of the continental slope (dark grey), derived by visual examination of the profiles. Bottom image: composite of upper and middle images, showing data quality factors in the foot of slope likelihood zone only.

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SESSION 3 – Paper 8

INTEGRATED PROCEDURES FOR DETERMINING THE OUTER LIMIT OF THE JURIDICAL CONTINENTAL SHELF BEYOND 200 NAUTICAL MILES

by Magdy HALIM, Rob van de POLL, Mark D'ARCY, Jennifer HARDING, Ron MACNAB and Dave MONAHAN, Canada

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ABSTRACT

Canada has not yet ratified the Law of the Sea, however for the past several years investigators of the Geological Survey of Canada and the Canadian Hydrographic Service have been engaged in preparatory work for continental shelf delimitation. Among other activities, they have constructed data bases and have evaluated techniques for their manipulation and visualization. This work has led to the development of a suite of Windows NT procedures that cover the gamut of Article 76 requirements, and which have been combined into a single package that operates under the control of a common user interface. The integration of these procedures was performed by technical staff of Universal Systems Limited.

Implementing Article 76 of the Law of the Sea requires an analysis of bathymetric and geological information, complemented by computations of a geodetic nature. The process tends to be iterative, involving repeat cycles to determine the end effects of different combinations of interpretive criteria, and to investigate the impact of new information as it becomes available. These operations must be performed systematically and with care; in anticipation of eventual scrutiny by the UN Commission on the Limits of the Continental Shelf, they must also be clearly documented, along with the reasons for pursuing particular courses of action.

The suite of software tools described in this paper features a full range of operations that streamline the tasks associated with data handling and management, thereby allowing investigators to maintain a focus upon data analysis. Among others, these operations include: (a) the construction of envelopes of geodetic arcs that are centred upon Territorial Seas Baselines and which define 200 and 350 nautical mile limits; (b) the selection of points that define the location of the foot of the continental slope; (c) the construction of envelopes of geodetic arcs that define projections of 60 and 100 nautical miles from the foot of the continental slope and the 2500 m isobath, respectively; (d) the construction of equidistant boundaries between adjacent and/or opposing states; (e) the construction of the >Gardiner Line=, where the thickness of sedimentary rock is equal to one percent of the distance back to the foot of the slope; and (f) the joining of appropriate segments of the foregoing to develop the most advantageous outer limit of the juridical continental shelf.

INTRODUCTION

This report outlines the principles and a generic procedure for defining the outer limit of the juridical continental shelf of a coastal state in accordance with the provisions of Article 76 of the Law of the Sea, when the continental margin of that state extends beyond 200 nm. In collaboration with the Geological Survey of Canada and the Canadian Hydrographic Service, Universal Systems Limited has implemented this procedure in a comprehensive suite of programs known as CARIS LOTS. In many instances, the software package can be applied provisionally to the analysis of existing public-domain data sets, i.e. global or regional compilations of bathymetry and sediment thickness. If the results of the provisional analysis are promising, the coastal state may then choose to develop a better data base, and to use the same tools to repeat the analysis in a more rigourous fashion.

The basic procedure is illustrated in simple cartoon form in Figure 1. In essence, Article 76 can be considered to embody two sets of rules: the first for designing and constructing an envelope, and the second for creating a piece of paper that differs from the envelope in both shape and size. The envelope represents the maximum claimable region beyond 200 nm, as circumscribed by two cutoff lines that will be described below. The paper represents the portion of the continental margin that extends beyond 200 nm, as determined by two formulae that will also be described below. The final outer limit of the continental shelf is represented by the paper once it has been trimmed to fit inside the envelope.

The above procedures are illustrated in greater detail in the flow diagram of Figure 2, and are outlined in point form in Table 1. They are further described in Table 2, which categorizes them according to the type of operation (computation vs analysis/interpretation) and to the kind of information that is required or generated at each step in the process. It is important to note that some of these procedures are iterative, and that they may be repeated any number of times as new data sets become available, or to accommodate different interpretations that promise to yield a more advantageous solution. Under these circumstances, there are definite requirements for treating the data sets in a controlled and consistent fashion, with provision for maintaining a complete record of processes and of their outcomes.

INITIAL PARAMETERS

The 200 nm limit

The essence of Article 76 is to empower a coastal state with a wide continental margin to claim jurisdiction over certain resources of the seabed beyond the 200 nm limit. It follows that the location of the 200 nm limit should be known with a reasonable degree of reliability, and in fact it is portrayed on the official charts of many nations. However for analytical and illustrative purposes, it may be necessary from time to time to portray the 200 nm limit on a chart that is custom-built, or which covers a specific region. The best way to do this is to perform accurate geodetic computations that calculate a series of circular arcs centred upon points that describe the coastal state's official Territorial Seas Baseline; the latter are normally promulgated in official publications. The coordinates of a 200 nm limit so developed can be preserved in digital form for subsequent use in the construction of charts at a variety of scales and projections.

Natural prolongation

For a given coastal state, the decision to proceed with the implementation of Article 76 depends almost entirely upon the perceived dimension of the submerged component of its land mass, defined as the *natural prolongation of its land territory*. The state must first identify the seabed features beyond 200 nm that it proposes to enclose within the new outer limit of its continental shelf, and to determine whether a case exists for claiming jurisdiction over the region that contains these features. This determination will require a review of known morphological and geological factors that touch upon the nature of the seabed and the sub-seabed.

DEVELOPING THE CASE FOR AN EXTENDED CONTINENTAL SHELF

If an assessment of initial parameters leads to the conclusion that a coastal state could satisfy the criteria for claiming resource jurisdiction beyond 200 nm, then it may proceed with the definition of the outer limit. In many cases, this could begin with a compilation of existing data (bathymetry, geology, morphology), although in other situations, existing public-domain information may be adequate for a qualitative first look In either instance, the data is subjected to the mixture of operations described in the following paragraphs and outlined in Table 2.

DELINEATING THE FOOT OF THE SLOPE

Article 76 states that *the foot of the continental slope is defined as the point of maximum change in the gradient at its base*. This feature provides a point of departure for subsequent procedures; errors at this stage can propagate into the interpretations and derivations that follow, with a significant effect upon the determination of the outer limit of the continental shelf, and hence upon the size of the area enclosed by this limit.

APPLYING THE FORMULAE OF ARTICLE 76 - *CUTTING THE PIECE OF PAPER*

Following the delineation of the foot of the continental slope, the next operation involves the construction of at least one and perhaps two distinct lines whose locations are determined with respect to the foot of the continental slope, in accordance with the two formulae explained in the following paragraphs: the *distance formula* and the *sediment thickness formula.*

The distance formula

The *distance formula* is the more straightforward of the two formulae, involving a simple projection of the foot of the slope seaward for a distance of 60 nm. This is best accomplished numerically, using geodetic software that automatically calculates a series of coordinates which define a series of intersecting arcs centred upon a succession of points located along the line that delineates the foot of the slope.

The sediment thickness formula

The *sediment thickness formula* tends to be more involved and more expensive, because it requires measurements of the thickness of sedimentary rock beneath the ocean floor, coupled with an analysis for determining the point where this thickness equals one percent of the distance back to the foot of the slope (Figure 5). The limit defined by a succession of such points is known colloquially as the *Gardiner Line*, after one of its principal architects (Gardiner, 1978). Uncertainties in measurement and interpretation may give rise to significant ambiguities in the application of this formula, however once the interpreter has made some reasonable assumptions about the nature and distribution of the sedimentary material, the determination of the one percent line should be relatively straightforward.

The formula line

It is not mandatory to apply consistently the distance formula or the sediment thickness formula throughout the study area, and in any particular location, the coastal state may apply the formula that is most advantageous to its interests. A coastal state may therefore opt initially to apply both formulae in some or all areas, developing one line segment with the distance formula, and another segment with the sediment thickness formula. The two lines may then be compared to determine which single line, or which combination of segments from both lines, encloses the largest possible area beyond 200 nm. The process of developing a composite line is illustrated in Figure 6. For convenience and to acknowledge the technique of its derivation, the term *formula line* has been coined to describe this line.

DETERMINING THE CUTOFF LIMITS - *CONSTRUCTING THE ENVELOPE*

Regardless of the method chosen for its delineation, the outer limit cannot in general extend beyond a maximum of 350 nautical miles from the state's territorial sea baselines, or 100 nautical miles beyond the 2500 metre isobath, whichever is the greater.

350 nm limit

The 350 nm limit consists of a series of circular arcs centred upon the coastal state's Territorial Seas Baseline. As in the case of the 200 nm limit, it is recommended that this limit be constructed numerically by means of geodetic computations. In addition to its accuracy, this approach has the added advantage of creating a series of coordinates in digital form that can be saved for later use in portraying this feature on charts at a variety of scales and projections.

2500 metre isobath plus 100 nm

The location of the 2500 metre isobath plus 100 nm is more problematic because it necessitates the measurement of absolute water depths with the utmost accuracy, which in the present state of the art is considered to be plus or minus 1% of the water depth. Again, it is left to the interpreter to make reasonable assumptions about the location of this feature, after which the 100 nm projection can be constructed in a manner that is entirely analogous to the method applied when applying the distance formula (foot of slope projected 60 nm seaward).

The cutoff line

To simplify their use, segments of the two limits constructed above may be combined into a single *cutoff line* that encloses the largest possible area beyond 200 nm and which defines the maximum extent of the outer limit of the continental shelf. The process of developing this line is illustrated in Figure 7.

BUILDING THE OUTER LIMIT - *FITTING THE PAPER INTO THE ENVELOPE*

This step begins with a comparison of the formula and cutoff lines. If the formula line is located entirely inside the cutoff line, then the former will be used to define the outer limit of the continental shelf; this is analogous to having a paper that fits entirely within the envelope. Conversely, if the formula line is everywhere outside the cutoff line, then the latter will be used to define the outer limit; this is analogous to having a paper that is everywhere bigger than the envelope.

As is often the case, some segments of the formula line are likely to be situated within the cutoff line while others extend beyond the cutoff line - then the final outer limit will consist of a composite line, where outlying segments of the formula line are discarded and replaced by intervening segments of the cutoff line, as shown in Figure 8; this is analogous to the situation outlined in Figure 1, where some parts of the paper extend beyond the limits of the envelope. Note that the final outer limit is not a curved line, but that it must be defined by a succession of straight line segments not exceeding 60 nm in length.

Table 3 indicates the potential levels of uncertainty that are inherent in each operation that is stipulated implicitly or explicitly by Article 76, and which will affect the final accuracy of the outer limit. These figures underscore the necessity of understanding the limitations of the information and of the methodology that are fundamental to the delimitation process, and of exercising constant quality control.

CONCLUSION

As prescribed in Article 76, the fundamental process of continental shelf delimitation is conceptually straightforward, however its implementation requires care in the handling and analysis of variegated data sets, plus constant attention to the maintenance of accurate and thorough records. These tasks are best handled in a coherent operating environment that includes a range of tools and procedures that enable interactive and iterative data analysis while supporting a variety of operator aids for managing the process.

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Ou, Z., and P. Vanicek. 1996. Automatic Tracing of the Foot of the Continental Slope. Marine Geodesy, Vol. 19, p. 181-195.

Royal Society. 1982. A guide to the provisions of the 1982 United Nations Convention on the Law of the Sea relating to marine scientific research. Royal Society Publication, London.

Shimeld, J. 1997. Estimating the Point of Maximum Change in Bathymetric Gradient: A Study in Support of the United Nations Law of the Sea, Article 76. Internal report, 100 p. Geological Survey of Canada, Dartmouth.

Table 1

THE GENERIC IMPLEMENTATION OF ARTICLE 76 OF THE LAW OF THE SEA

A. Determine whether a *natural prolongation* exists

- The prolongation extends beyond the 200 nm limit
- The prolongation is morphologically continuous with or geologically connected to the land mass

B. Locate the *foot of the slope*

- Mathematically determine (a) points of maximum change of gradient on original bathymetric profiles, or (b) a line of maximum change of gradient on a surface constructed from a regular grid of bathymetric values
- If *evidence to the contrary* exists, determine the location according to alternative criteria

C. Apply the *distance formula*

- Project the foot of the slope 60 nm seaward

D. Apply the *sediment thickness formula*

- If relevant information is available, project the foot of the slope seaward to where the thickness of sedimentary material equals 1% of the distance back to the foot of the slope

E. Construct the *formula line*

- Combine segments of Lines C and D to enclose the largest possible area

F. Construct the *350 nm limit*

- Apply geodetic calculations to derive lat-long coordinates that define a succession of intersecting 350 nm circular arcs centred on the territorial seas baseline

G. Construct the *2500 metre isobath plus 100 nm limit*

- Apply geodetic calculations to derive lat-long coordinates that define a succession of intersecting 100 nm circular arcs centred on the 2500 metre isobath

H. Construct the *cutoff line*

- Combine segments of Lines F and G to enclose the largest possible area

I. Construct the *outer limit of the juridical continental shelf*

- Combine segments of the formula line (Line E) and the cutoff line (Line H) to enclose the largest possible area without extending beyond the latter
- Approximate the combined segments with straight lines that join fixed points no more than 60 nm apart

J. Assess the resource potential

- Review existing material to appraise current and potential value of living and non-living resources of the seabed and subsoil

K. Further action

- If prospects are favourable and definitive, proceed to the preparation of a continental shelf claim
- If prospects are unfavourable or inconclusive, consider the acquisition of new data that might lead to better results

1506 *Table 2*

OPERATIONS FOR DETERMINING THE OUTER LIMIT OF THE JURIDICAL CONTINENTAL SHELF

OPERATION	**COMPUTATION**	**ANALYSIS/INTERPRETATION**		
	Geodesic (horiz. distance)	Bathymetry (depth of water)	Geology (sediment/bedrock)	Morphology (shape of seabed)
A. Determine whether a *natural prolongation* exists		□	□	□
B. Locate the *foot of the slope*			□	□
C. Apply the *distance formula*	□			
D. Apply the *sediment thickness formula*			□	
E. Combine Lines C & D to construct the *formula line*				
F. Construct the *350 nm limit*	□			
G. Construct the *2500 m isobath plus 100 nm limit*	□	□		
H. Combine Lines F & G to construct the *cutoff line*				
I. Combine Lines E & H to construct the *outer limit*				

RM, GSC Atlantic, September 1999

Table 3

POTENTIAL UNCERTAINTIES IN DETERMINING THE OUTER LIMIT OF THE JURIDICAL CONTINENTAL SHELF

OPERATION	PARAMETER	TECHNIQUE	SOURCE(S) OF UNCERTAINTY	POTENTIAL UNCERTAINTY
Locate the foot of the slope	Sea floor morphology (primarily)	Acoustic measurement & interpretation	Measurement errors, interpretive criteria	10's of kilometres
Apply the distance formula	Horizontal distance	Graphical or geodetic	Graphical or computational errors	Low or none
Apply the sediment thickness formula	Sediment thickness	Acoustic measurement & interpretation	Measurement or interpretation errors	10's of kilometres
Construct the 350 nm limit	Horizontal distance	Graphical or geodetic	Graphical or computational errors	Low or none
Locate the 2500 m isobath	Water depth	Acoustic measurement	Measurement errors	100's of metres
Construct a line 100 nm seaward of 2500 m isobath	Horizontal distance	Graphical or geodetic	Graphical or computational errors	Low or none

RM, GSC Atlantic, January 1998

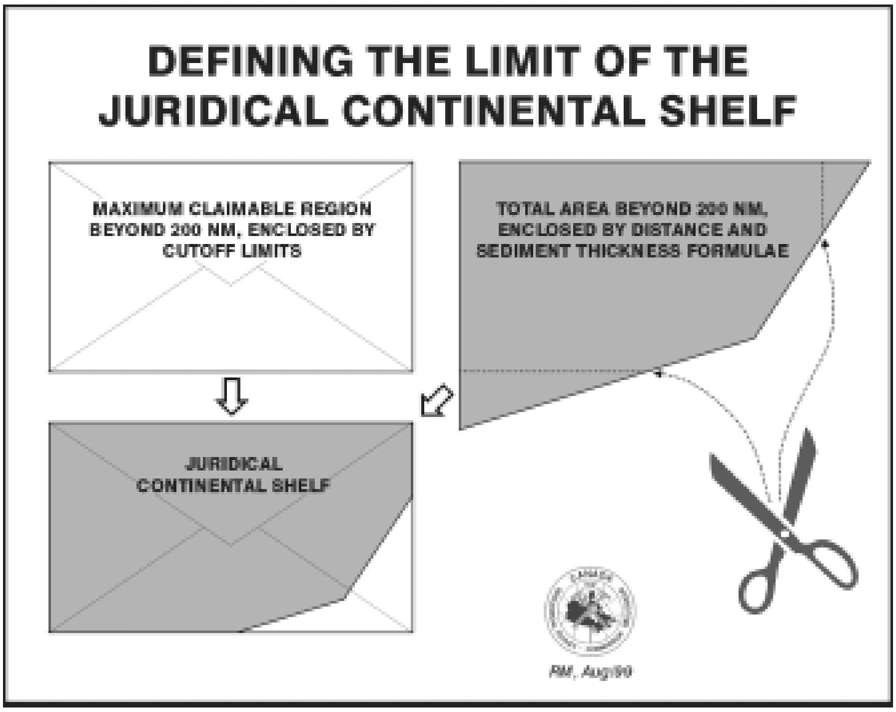

Figure 1. In simplest terms, defining the outer limit of the juridical continental shelf can be likened to a process of trimming an odd-shaped piece of paper to fit inside an envelope of arbitrary shape and size. The size and the shape of both the envelope and the paper are determined in accordance with the provisions of Article 76 of the Law of the Sea.

Figure 2. A generic flowchart illustrating the procedures and decisions to be adopted by a wide-margin state when implementing Article 76.

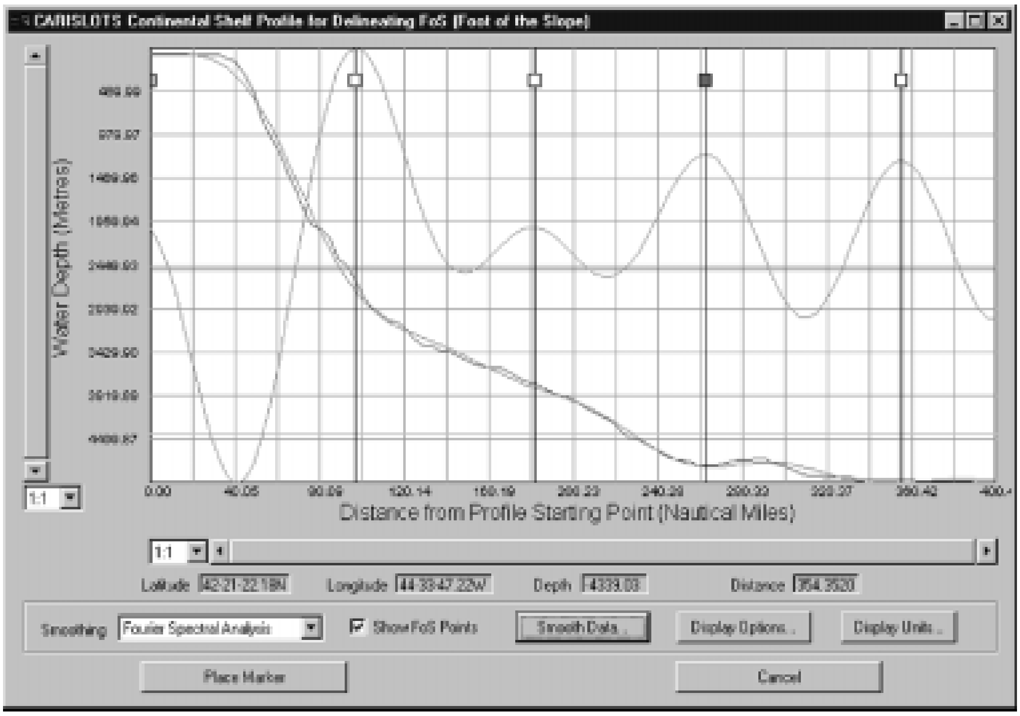

Figure 3. A common approach for the numerical determination of the foot of the slope, based upon treatment of a depth profile. A mathematical curve is fitted to a series of original bathymetric observations along a profile perpendicular to the continental margin, or to a synthetic profile extracted from a digital bathymetric model. The quasi-sinusoidal second derivative of the mathematical curve closely approximates the change of bottom gradient, and its positive peaks provide objective indicators for locating the points of maximum change.

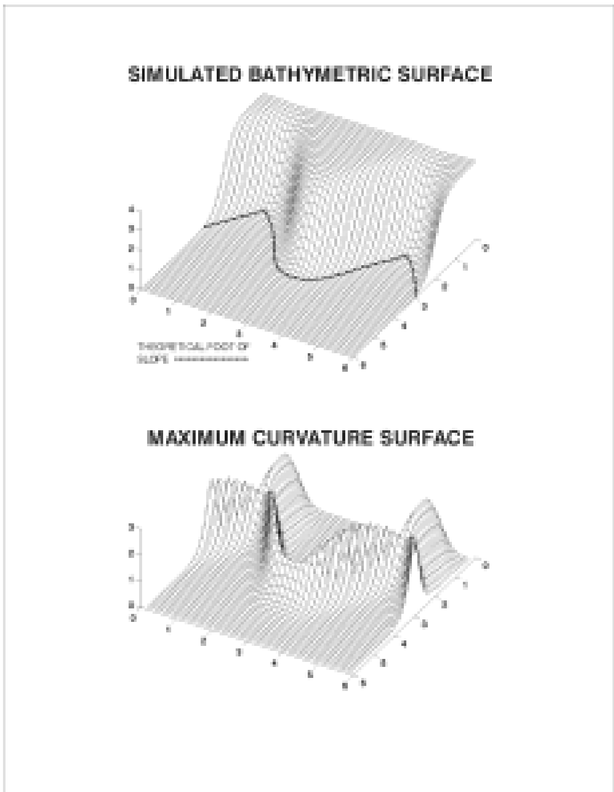

Figure 4. An alternative approach for the numerical determination of the foot of the slope, based upon the treatment of a digital bathymetric model (DBM) represented by a regular grid of depth values. The upper part of the figure illustrates an idealized segment of a continental margin as defined by a simulated DBM. The lower portion portrays a surface of maximum curvature derived from the DBM, indicating the location of foot of the slope by a well-defined ridge structure. (from Ou and Vanicek, 1996)

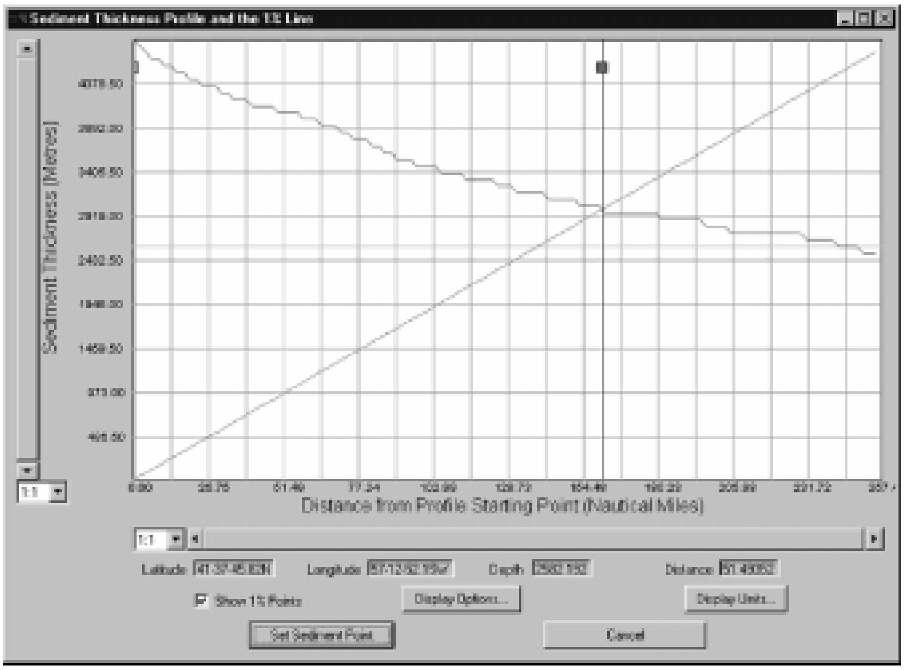

Figure 5. Illustrating the principle of the sediment thickness rule, where the irregular line represents the thickness of material along a profile through a sediment model, and where the intersection with the diagonal line represents the point at which the thickness of sediment is equal to one percent of the distance back to the start point of the profile.

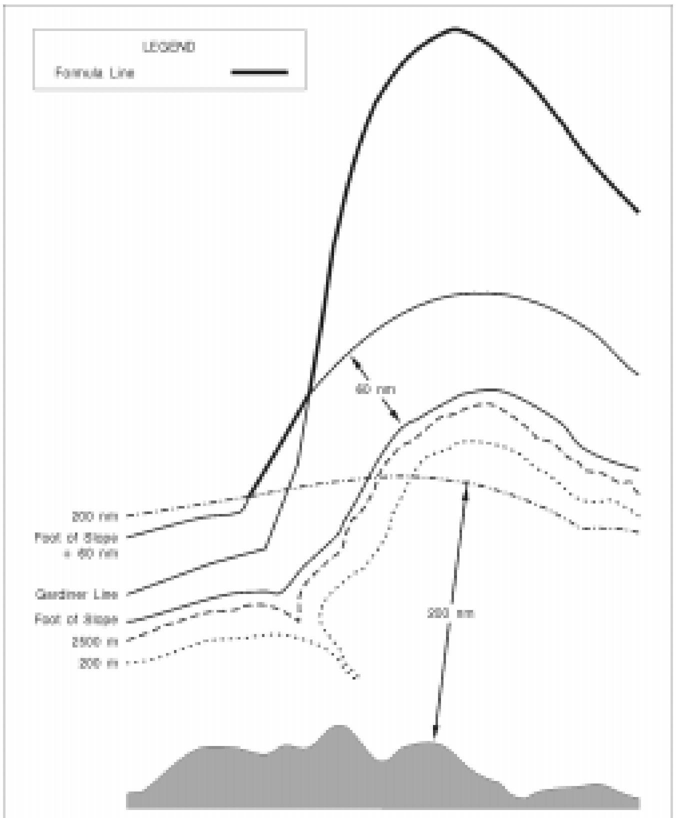

Figure 6. Illustrating the process of amalgamating segments of lines developed with the distance formula and the sediment thickness formula of Article 76, to develop a composite *formula line*. The drawing is not to scale. (adapted from Royal Society, 1982)

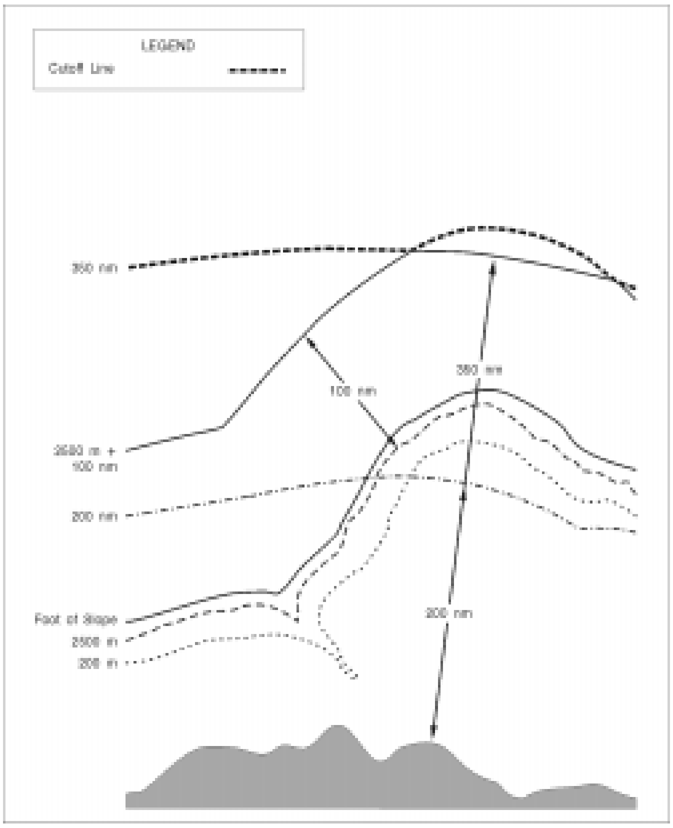

Figure 7. Illustrating the process of amalgamating segments of the 350 nm limit and the 2500 metre isobath plus 100 nm, to develop a composite *cutoff line.* The drawing is not to scale. (adapted from Royal Society, 1982)

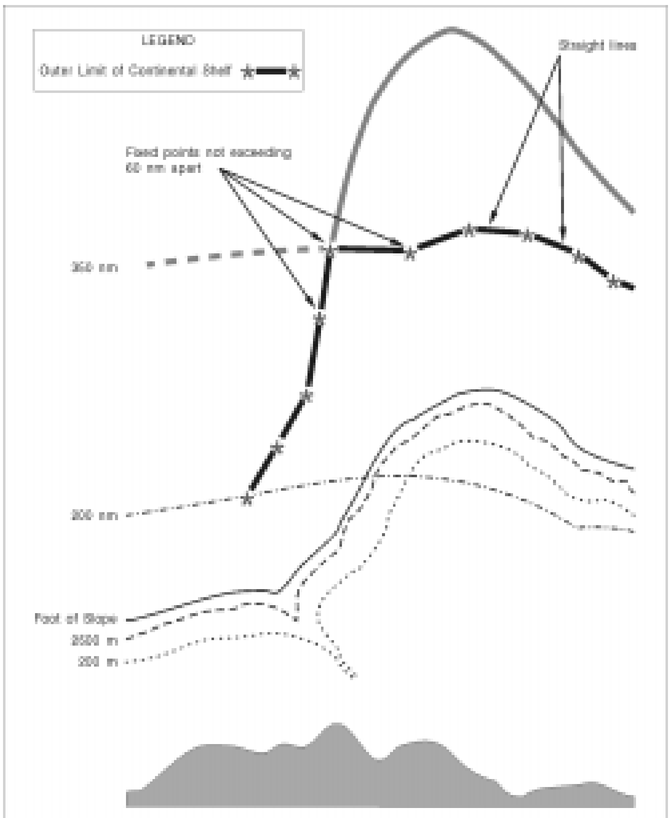

Figure 8. Illustrating the integration of components of the formula line (developed in Figure 6) and of the cutoff line (developed in Figure 7), and their subsequent approximation by straight lines to define the *outer limit of the continental shelf*. The drawing is not to scale. (adapted from Royal Society, 1982)

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SESSION 4 – Paper 1

ARTICLE 76 IN THE ARCTIC OCEAN: A CATALYST FOR INTERNATIONAL COLLABORATION

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ABSTRACT

The Arctic Ocean is almost totally surrounded by the land masses of five coastal states: Canada, Greenland (Denmark), Norway, Russia, and the United States of America. Each of these states appears to be in a position to develop an extended outer limit of its juridical continental shelf on the basis of a "natural prolongation of its land territory" projecting northward into the Arctic Ocean. However, the development of accurate and credible outer limits is hampered in several areas by a lack of information needed to satisfy the criteria of Article 76, i.e. water depth and sediment thickness. Moreover, basic geometric considerations suggest the possibility that claims by some if not all of the neighbouring states are likely to overlap, leading to contention in the equitable sharing of seabed resources beyond 200 nautical miles.

To facilitate the consistent development of outer continental shelf limits in the Arctic and to eliminate some of the grounds for contention arising from overlapping claims, technical experts from the five coastal states agreed in 1996 that it would be advantageous to pool their information holdings in order to develop a common perception of the bathymetric and geological factors that bear upon the implementation of Article 76. The following year, a project was initiated to construct a database of all available bathymetric information north of 64N, to be followed by the construction of the International Bathymetric Chart of the Arctic Ocean (IBCAO). At the international level, this activity has been endorsed by IASC, IOC, and IHO; at the same time, participation has expanded to include investigators from Iceland, Sweden, and Germany, who are contributing data and specialized expertise. Significant progress has been made to date; it is expected that intermediate products in digital and map form will be ready for public distribution in the year 2000.

Joint initiatives are also in hand for developing a complementary database of sediment thickness information in the region. These initiatives do not yet feature the broad sponsorship and participation of the bathymetric project, however the level of progress so far augurs well for expanded cooperation in the future.

INTRODUCTION

It is commonly accepted that published portrayals of the seabed and sub-seabed of the Arctic Ocean Basin are woefully inadequate. In many places, significant discrepancies have been noted between observed and charted depths, while public knowledge concerning the sediment layers that blanket the floor of the deep Arctic Ocean is patchy and fragmented. The main reason for this situation has been a lack of information needed to construct reliable and detailed charts: certain regions remain poorly mapped on account of difficult operating conditions, or because the critical data sets that do exist have not been available for widespread public use.

Present levels of knowledge are thus inimical to a full understanding of the nature and composition of the sea floor, an understanding that is fundamental to the resolution of many problems. For instance, the definition of the outer limit of the juridical continental shelf according to the provisions of Article 76 of the Law of the Sea rests fundamentally upon the analysis and interpretation of bathymetric and geological information; without adequate data sets to support such work, outer limit determinations will remain suspect.

It is recognized that Canada, Denmark, Norway, Russia, and the USA are all likely to have valid grounds for developing continental shelf claims beyond their 200 nautical mile limits in the Arctic Ocean. As seen in Figure 1, even a cursory examination of existing information reveals at least seven >natural prolongations' extending from the continental margins of these five coastal states. In clockwise order, the prolongations consist of: Chukchi Cap, Mendeleev Ridge, Lomonosov Ridge (both ends), Yermak Plateau, Morris Jesup Plateau, and Alpha Ridge. It is also easy to see that some of these features could affect the continental shelf configurations of more than one state, raising the possibility, if not the likelihood, of overlapping claims between neighbouring states.

At present there exists no single coherent body of information for describing in suitable detail the depth, morphology, and sediment characteristics of these Arctic prolongations and their surrounding areas. Lacking homogeneous data sets, individual states could opt to develop their continental shelf limits on the basis of whatever unique data assemblages were available to them. This in turn could lead to situations where neighbouring claims were based upon incompatible data sets, adding to levels of contention where overlaps existed. It seems self-evident that many problems in this respect could be minimized by basing neighbouring claims upon common data sets.

The Arctic data situation in the Article 76 context was discussed at an informal Workshop held October 16-18, 1996 at the Polar Marine Geosurvey Expedition in St. Petersburg- Lomonosov, Russia (Kazmin and Macnab, 1996). To promote the orderly definition of continental shelf limits around the Arctic Ocean, participants recommended that coastal states consider joint action to develop integrated data bases by pooling their respective data holdings. This would not necessarily prevent overlapping claims that arose from differences of interpretation, but at least it would provide a common departure point for analysis.

At the same time, it was recognized that other important objectives would be well served by the availability of coherent regional perspectives on bathymetry and sediment cover in the Arctic Ocean basin, e.g. elucidation of tectonic framework and history; assessments of resource potentials; studies of paleoclimate and paleoceanography; investigations of riverine discharge, shoreline erosion, and sediment transport on the continental shelf; and interpretation of modern circulation patterns and their relationship to climate change.

BATHYMETRY

For the past twenty years, GEBCO Sheet 5.17 (Canadian Hydrographic Service, 1979) has provided one of the most widely-used portrayals of the sea floor north of 64N. This chart was developed from a very limited data set, and while it described adequately the approximate positions and orientations of the major bathymetric features of the Arctic Ocean basin, numerous discrepancies were reported by field investigators when comparing chart values with in-situ observations.

Since 1979, a number of cruises in the Arctic have contributed to the development of a public-domain data base in certain regions, notably off northern Canada and in the Norwegian-Greenland Seas. However prospects for real advancement have brightened only in recent years as a result of important initiatives of the US and Russian Federation Navies: (1) the US Navy's SCICEX program, which since 1993 has been mobilizing unclassified mapping and research missions aboard submarines operating beneath the polar pack; (2) the de-classification of historic data sets collected in the same region during US submarine patrols beginning in the late 1950's; and (3) the publication of a new Arctic map based upon observations gathered during surveys by agencies of the former Soviet Union (Head Department of Navigation and Oceanography et al, 1999). Whether modern or historic, these sources of information are providing important new insights into the depth and morphology of the floor of the Arctic Ocean, and are making it possible for marine scientists and cartographers to undertake the creation of data bases that can be applied to the construction of better charts.

In light of these developments, a follow-up Workshop was held September 18-19, 1997 at the Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia) in St. Petersburg (Macnab and Grikurov, 1997), with the objective of initiating an international collaboration for the development of a modern bathymetric data base. As envisaged, the data base would incorporate in digital form all available bathymetric information north of 64N, for the benefit of mapmakers, researchers, and others whose work requires a detailed and accurate knowledge of the depth and shape of the Arctic seabed.

Participants at this Workshop described their data holdings, and agreed upon a broad plan for consolidating some or all of these data sets into a single, coherent data base. A Working Group was nominated to carry this activity forward, and plans were developed to seek formal endorsement from three international organizations: the International Arctic Science Committee (IASC), the Intergovernmental Oceanographic Commission (IOC), and the International Hydrographic Organization (IHO). In due course, these activities converged in the formal establishment of the Editorial Board for the International Bathymetric Chart of the Arctic Ocean (EB-IBCAO).

A third Workshop was held October 19-20, 1998 at the Royal Danish Administration of Navigation and Hydrography, Copenhagen (Macnab and Nielsen, 1998). Participants described progress made since the preceding Workshop in releasing and/or treating data, reviewed general procedures for handling digital data, and considered issues related to the release of the various types of products generated by the activity. By this time, the activity had expanded to include Iceland.

In light of considerations relating to data sensitivities, workload, and resources, it was agreed that project tasks would be partitioned between the EEZ's of six coastal states and the three High Seas zones north of 64N (Figure 2). Institutional responsibilities for each of the six national EEZ's were provisionally allocated as follows:

Canada	Geological Survey of Canada; Canadian Hydrographic Service
Denmark	Royal Danish Administration of Navigation and Hydrography
Iceland	Icelandic Hydrographic Service
Norway	Norwegian Petroleum Directorate; Norwegian Hydrographic Service
Russia	Head Department of Navigation and Oceanography; Research Institute for Geology and Mineral Resources of the World Ocean
USA	Naval Research Laboratory; Tulane University

Joint responsibilities for the three High Seas zones were proposed on a national, rather than institutional basis:

Arctic Ocean	Canada, Russia, USA
Norwegian-Greenland Sea	Denmark, Iceland, Norway
Barents Sea	Norway, Russia

While this approach to partitioning gives prominence to coastal states north of 64N, it is in no way intended as an exclusionary measure: investigators from institutions in other states, e.g. Sweden (Stockholm University) and Germany (Alfred Wegener Institute) are already involved in the initiative, and other countries with Arctic interests are encouraged to assume active roles. Also, there is an explicit understanding that the partitioning scheme is not to be construed as the erection of barriers to cooperation and to the exchange of information: active and constant interaction among all participants is essential to harmonize operational procedures, to negotiate data exchanges, to discuss problems of mutual interest, to seek advice and consultation, to maintain the compatibility of outputs, etc.

Figure 3 illustrates the current state of the new map, representing work performed at Stockholm University by Martin Jakobsson and Norman Z. Cherkis, who melded all available information in digital form and created a grid of depth values for the upper half of the map area. The lower half of the map is presently under construction; the expectation is that a provisional version of the complete map will be ready for review in late 1999, when prospects for further additions and refinements will be considered.

The map and the gridded data used in its construction are scheduled for public release in the year 2000. It should be noted that these will not be final products, given the prospects for a continuation of the US Navy's SCICEX operations into the foreseeable future. If current proposals come to fruition, future under-ice surveys will generate significant quantities of new data on a regular basis. A challenge for project participants, therefore, will be to devise a mechanism for ensuring that the new information is assimilated into the data base in a timely manner.

SEDIMENT THICKNESS

While no less important for Article 76 purposes than bathymetric observations, sediment thickness measurements have not yet been accorded the same level of public attention and formal international cooperation as have bathymetric measurements. This is partly due to the fact that seismic reflection and refraction records in the public domain are far less numerous than bathymetric records, although it is understood that significant accumulations of seismic information do exist (Head Department of Navigation and Oceanography, 1996), and that selected components of those holdings may become accessible in due course.

Figure 4 illustrates the locations of three geotransects that describe the deep crustal and sediment structures of continental prolongations in the Arctic Ocean. The Makarov-Delong Geotransect (Sorokin et al, 1995) and the Amundsen-Podvodnikof Geotransect (Sorokin, 1994) were constructed by Russian investigators from extensive sets of seismic refraction and reflection data complemented by a dense network of potential field observations. Substantially less information was available for the construction of the Alpha-Lomonosov Geotransect (Jackson and Sweeney, 1993) which consists essentially of a crustal section developed on the basis of two-dimensional gravity models with limited seismic refraction control.

Figure 5 is a partial portrayal of public-domain seismic measurements north of 64N, assembled by two international teams (Jackson et al, 1996; Sorokin et al, 1996), and funded in part through NATO Linkage Grants. While far from complete, these accumulations of data are scientifically interesting, plus they have served a useful purpose by establishing linkages between investigators in a number of different countries, and by laying the groundwork for the more extensive interactions that will be needed to incorporate the remaining data sets. General discussions are now under way on how best to achieve this objective.

The activities described above have dealt with existing seismic data, but it is worth noting that bilateral initiatives are also being proposed to collect new information in critical areas. For example, Figure 6 illustrates an imaginative proposal to perform a two-ship under-ice seismic refraction experiment, using a source deployed from a Canadian icebreaker and a receiver array towed by a US submarine. Such an experiment was actually scheduled to occur in Canada Basin in 1998 as a proof of concept prior to a more ambitious program, however it had to be cancelled when the submarine was forced for technical reasons to withdraw from the operating area. The experiment has been provisionally re-scheduled for the year 2000.

CONCLUSIONS

The Arctic Ocean is completely encircled by the continental shelves of five coastal states, and simple geometric considerations suggest that implementing the provisions of Article 76 of the Law of the Sea could easily lead to overlapping outer limit claims. Contention may well be inevitable as each coastal state attempts to maximize the area of its juridical continental shelf, however a significant cause of disagreement among the affected states could be eliminated through the adoption of common descriptions of bathymetry and sediment thickness. The development of a standard bathymetric data base is now well in hand, while the creation of a complementary data base of sediment thickness is currently a topic of exploratory exchanges.

ACKNOWLEDGMENTS

Progress in the activities described above is due in no small measure to the levels of commitment and enthusiasm that have been demonstrated by participants and their institutions, and by the moral and organizational support of the three international organizations that have endorsed the bathymetric initiative: IOC, IHO, and IASC; the latter also provided financial assistance to the project when it was in its start-up phase. Additional support has been received in the form of Department of the Navy Grants N00014-98-1-1075 and N00014-99-1-1060, issued by the US Office of Naval Research International Field Office – Europe. The aims and objectives of the compilation activities described in this report do not necessarily reflect the formal positions or policies of the participants' respective Governments, and no official endorsement should be inferred.

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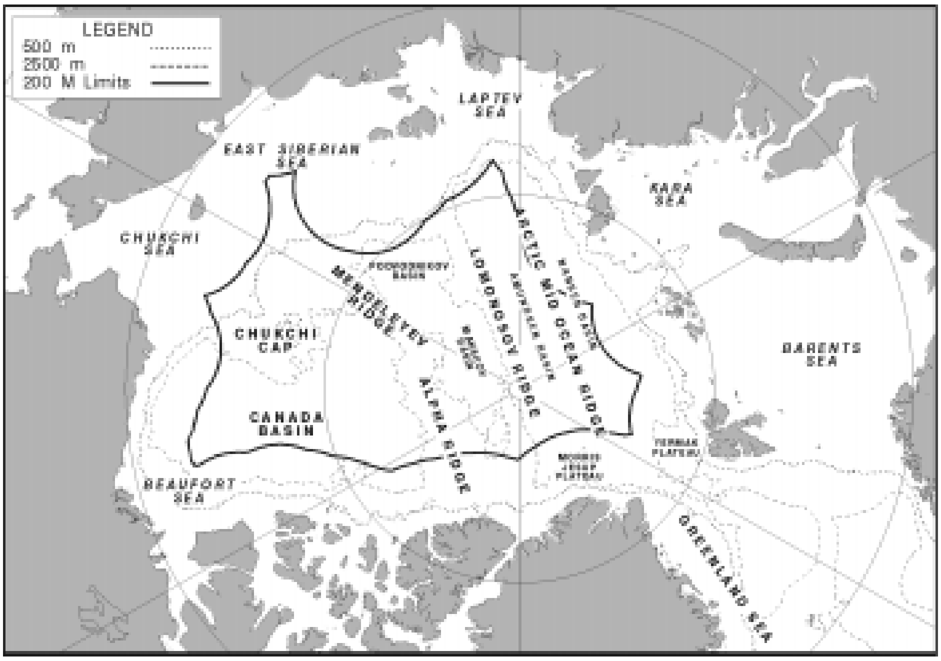

Figure 1. The constituent seas and principal physiographic features of the Arctic Ocean, including continental margin prolongations that will likely figure in the definition of juridical shelf outer limits according to the provisions of Article 76 of the Law of the sea: Chukchi Cap, Mendeleev Ridge, Lomonosov Ridge (both extremities), Yermak Plateau, Morris Jesup Plateau, and Alpha Ridge.

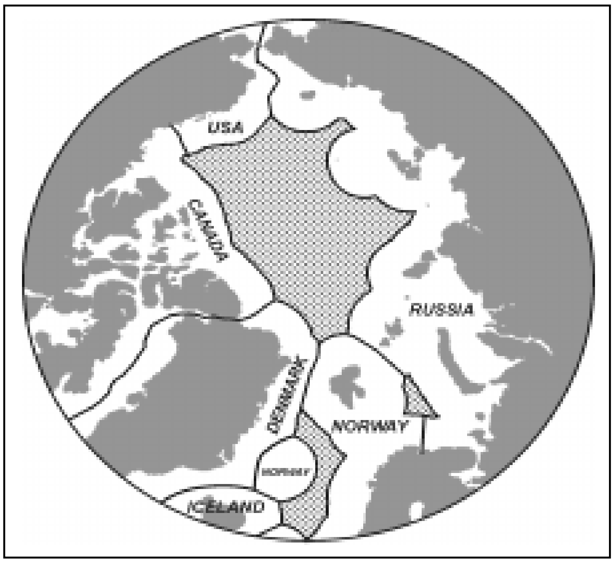

Figure 2. High Seas (patterned) and approxi- mate limits of Exclusive Economic Zones north of 64N.

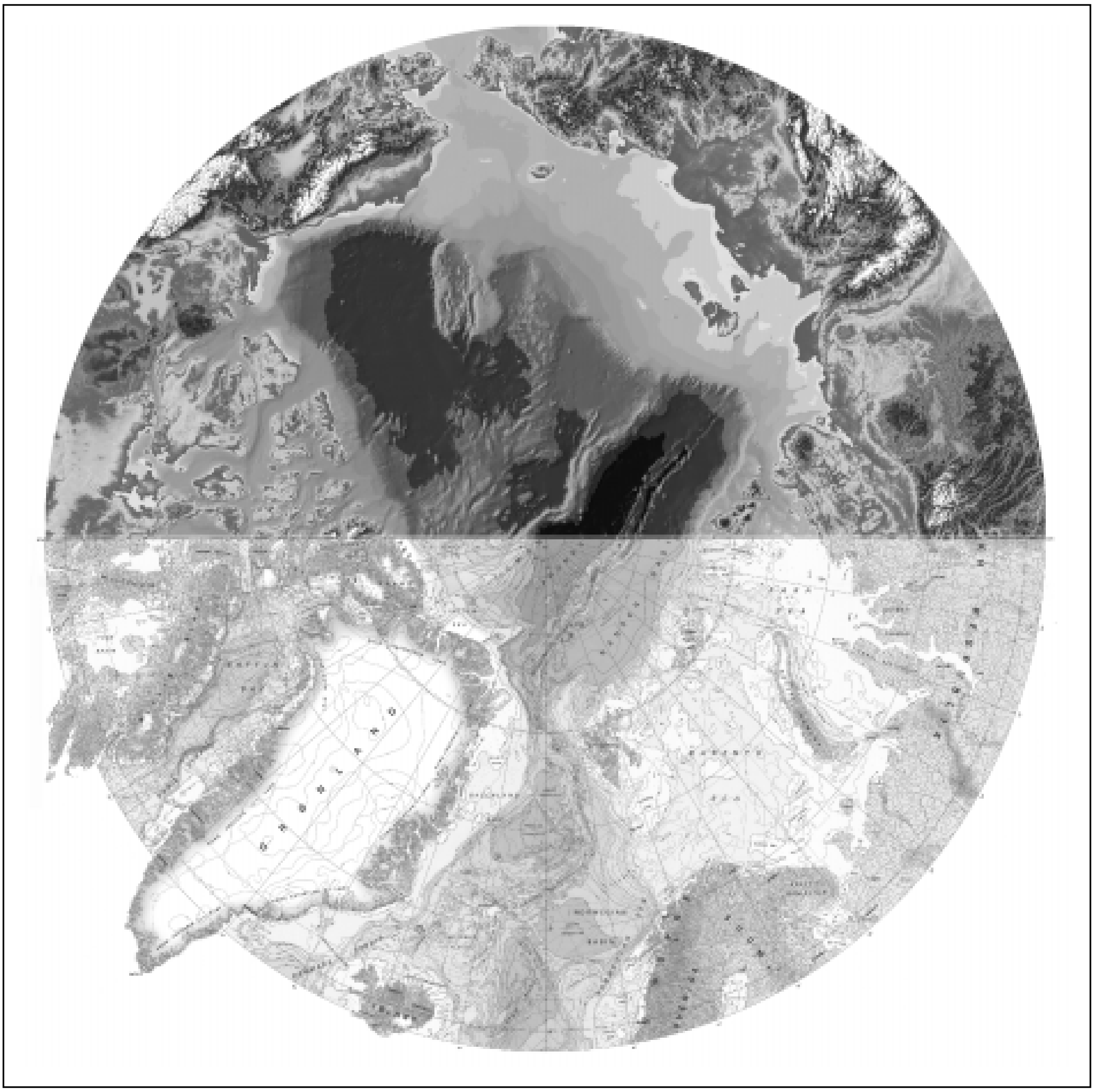

Figure 3. A composite illustration that contrasts the characteristics of the new International Bathymetric Chart of the Arctic Ocean (upper half) and the existing Sheet 5.17 of the General Bathymetric Chart of the Oceans (lower half). The former is a working prototype constructed in February 1999 by Martin Jakobsson and Norman Cherkis from newly-available data sets and with modern techniques for data manipulation and digital cartography. The latter was constructed in 1979 by the Canadian Hydrographic Service from contemporary data sets and with manual cartographic techniques

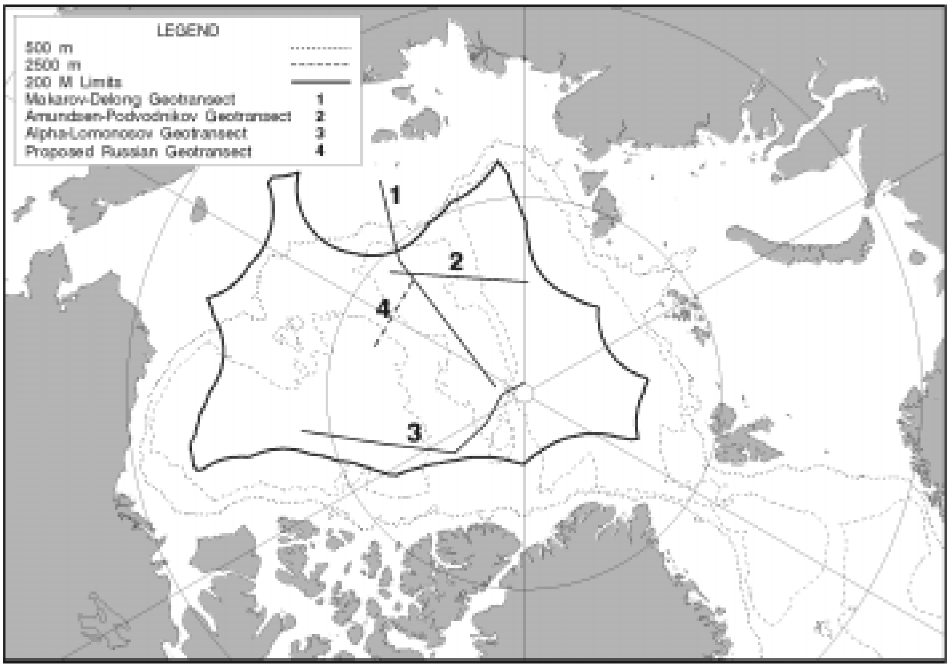

Figure 4. Locations of geotransects in the Arctic Ocean. Profiles 1 and 2 are based on seismic refraction and reflection measurements, complemented by a dense network of potential field observations. Profile 3 is derived primarily from two-dimensional gravity modelling, with limited seismic refraction control. Profile 4 has been proposed by Russian investigators to develop a deep crustal section across the Mendeleev Ridge.

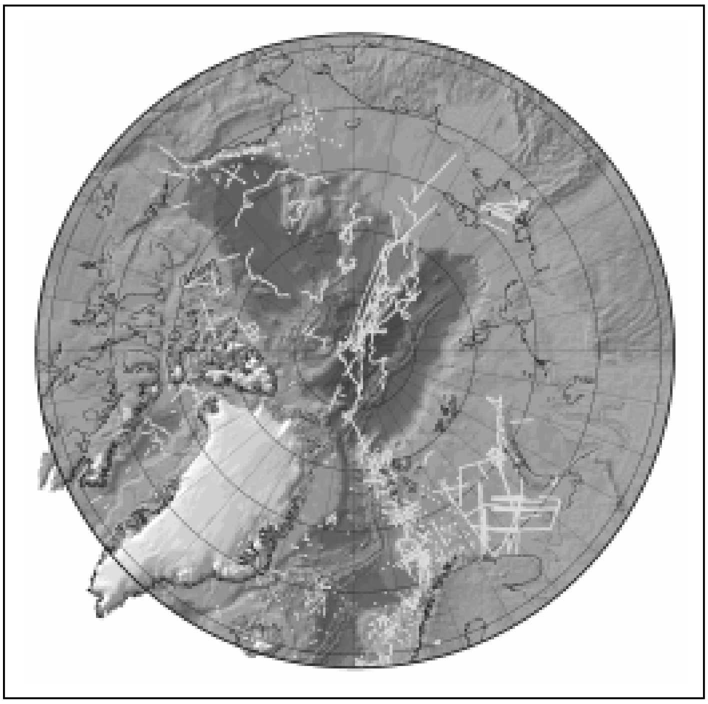

Figure 5. Distribution of public-domain marine seismic reflection and refraction data north of

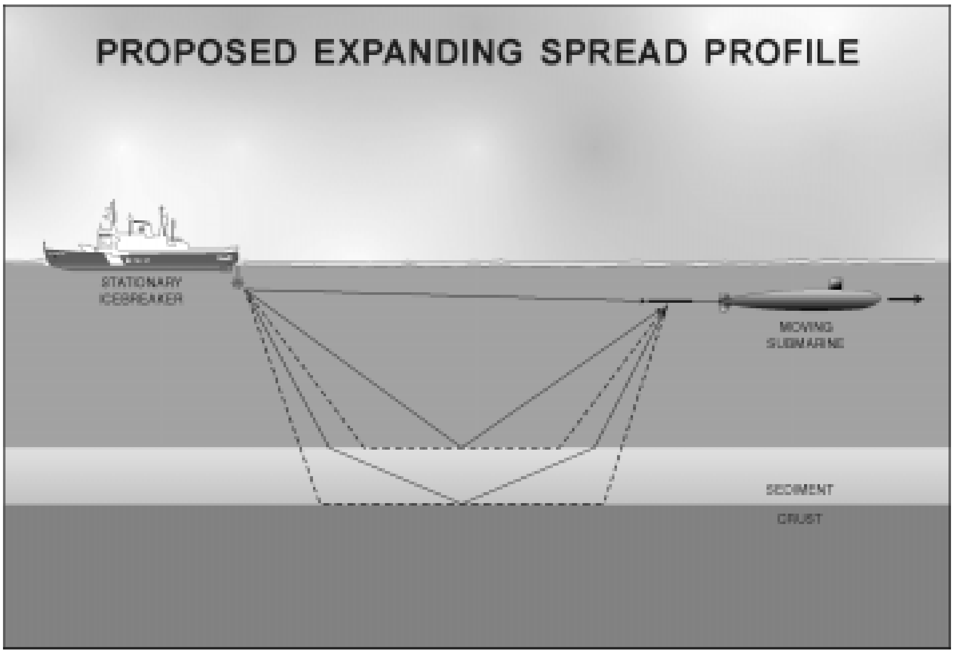

Figure 6. Configuration of a proposed under-ice seismic refraction experiment, featuring a sound source deployed at the surface, and a US Navy submarine as a receiving vessel.

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SESSION 4 – Paper 2

BATHYMETRY AND DEEP STRUCTURE OF THE ARCTIC CONTINENTAL MARGIN OF RUSSIA IN THE CONTEXT OF ARTICLE 76 OF THE UN CONVENTION ON THE LAW OF THE SEA

by Georgi CHERKASHOV (1), I.S. GRAMBERG (1), A.P. MAKORTA (2), V.D. KAMINSKY (1), G.D. NARYSHKIN (1), V.A. POSELOV (1) and M. SOROKIN (3), Russia

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ABSTRACT

Russia has the most extensive continental margin in the Arctic, and this margin is the region of special scientific, political, economic and defense interest. According to Federal Law N 30-FZ of February 26, 1998 Russia has ratified the UN Convention on Law of the Sea (1982). This requires the definition and validation of the Continental Shelf Outer Boundary (CSOB) in the Arctic outside the limits of 200-mile zone in juridical context of the Convention.

According to the Convention bathymetric, geomorphological and geological criteria are to be used for the establishment of the CSOB outside of 200-mile zone. Bathymetric and morphological criteria are based on the identification of the 2500 m isobath and the location of the Continental Rise (CR) respectively. Our investigations made it possible to accurately determine the positions of 2500 m isobath and CR and to plot them on the basis of original bathymetric survey with the accuracy
M_{oi} <600m and M_{zi} < 0.5%.

The geological validation of the position of CSOB is based on the recognition of the geological integrity of oceanic structures.The boundaries of these structures determined by bathymetric, geomorphological and geological criteria may contradict juridically established shelf boundaries. Therefore, the comprehensive investigation of the structure and nature of the Earth crust (continental or oceanic) becomes one of the most important geological problems.

We have characterized the morphology and deep structure of the Arctic ocean based on airborne magnetic and gravity surveys, regional refraction, reflection and deep seismic surveys. These data were obtained over a period of more than 30 years mostly from drifting stations "Severny Polyus" ("North Pole") and from high latitude expeditions "Sever".

Some geological and geomorphological results indicate that continental crust is not limited by the continental slope but may extend far into the Arctic Ocean.

The processing of geophysical data using up-to-date soft- and hardware made it possible to study in detail the structure of the sedimentary cover, the lower crust and the upper mantle.

The following new data relevant to determining the CSOB were obtained:

- the thickness of the sedimentary cover on the Lomonosov Ridge is 5.0 - 5.5 km. The seismic velocities of the upper (6.0 - 6.6 km/s) and lower (6.8 - 7.5 km/s) crust imply a continental pattern of the ridge,

- total crust thickness in the Podvodnikov Basin is 20-25 km. Along with the thick sedimentary cover (10 km), low velocities of the lower crust, and the mantle structure, the new findings imply a continental nature of the the Podvodnikov Basin,

- in the Makarov Basin, a thick (up to 7 km) sedimentary cover at a depth of 12 km rests on thin (up to 2-3 km) oceanic layer 3 or directly on the mantle. Based on these we presume that the crust of the Makarov Basin is very similar to the oceanic type,

- the data obtained so far for the Alfa-Mendeleev Ridge do not allow unambiguous interpretation of the nature of its crust.

The current concepts of the deep structure of the Arctic region, data on the thickness and structure of the sedimentary cover, as well as geomorphological and bathymetric data were used to compile a project Map showing the present Russian viewpoint on the position of the CSOB in the Arctic Basin.

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SESSION 4 – Paper 3

CONTRIBUTION OF THE SCICEX PROJECT TOWARDS THE IMPLEMENTATION OF ARTICLE 76 OF THE UN CONVENTION ON THE LAW OF THE SEA IN THE ARCTIC OCEAN

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ABSTRACT

Research conducted from icebreakers in the Arctic Ocean has been limited by the demanding environment; isolation, extreme temperatures and drifting pack ice restrict access and make systematic surveys of the ocean floor impossible. The polar oceans drive world ocean circulation, are rich in plant and animal life, and shape the world's climate. Our understanding of the continents that ring the Arctic Ocean is restricted by how little we know about the history of this deep ocean basin. If we are to have truly global models for climate or plate tectonics, we must understand how the Arctic Ocean formed and how it influences climate variations at lower latitudes. Given the restrictions imposed by the drifting pack ice, a submarine is the only practical means to efficiently observe the Arctic Ocean.

The SCICEX program of unclassified Arctic science cruises aboard Sturgeon-class nuclear-powered submarines has, since 1993, provided the only regular, reliable access to the deep Arctic Ocean basin for science. These US Navy submarines operate efficiently in the Arctic, below the permanent floating pack ice, conducting the first systematic surveys of Arctic bathymetry and water composition. The first six cruises have yielded new data on the structure of the ocean basin, and the distribution of heat and salinity and composition of the water. Peaceful use of these fast attack submarines has provided an extra-ordinary opportunity to explore the Arctic Ocean basin.

While the US Navy has provided an exceptional opportunity, the potential of these cruises was not fully exploited due to a lack of suitable instrumentation. To remedy this situation, the National Science Foundation funded development of a suite of active sonars which were used on SCICEX cruises in 1998 and 1999 and may be used for future cruises. These instruments were installed for SCICEX 98 on the USS Hawkbill and were just removed in June of this year, after the completion of SCICEX 99.

One of these sonars, a SeaMARCJ type sidescan swath bathymetric sonar, maps a stripe of the seafloor, as much as 16 kilometers across, revealing the detailed bathymetry and surface sediment texture of the Arctic for the first time. The other instrument, a high-resolution chirp sub-bottom profiler, penetrates as much as 100 meters into the seafloor to reveal the stratification of the Arctic sediments. Approximately 40,000 track km of swath and sub-bottom profiler data was collected during SCICEX 98 and 99.

The geophysical program carried out from these submarines has focused on the Gakkel and Lomonosov Ridges and the Chukchi Borderland, but data was collected throughout the basin during the oceanographic investigations carried out during SCICEX. Processing of the swath data collected in 1998 and 1999 is underway at the Hawaii' Mapping Research Group in Honolulu. Much of this data will be on shown at the Fall meeting of the American Geophysical Union in San Francisco.

Prior to SCICEX 99, the US Navy has restricted the SCICEX program to an operational area defined by the exclusion of all non-US EEZs and a few shallow shelf areas. This year, for the first time, the USS Hawkbill collected data in the EEZ of Norway, along the Yermak plateau, operating in these waters at the invitation of the Norwegian government. While invitations from the other circum-Arctic nations, particularly Canada and Greenland, would substantially expand the scientific utility of future SCICEX cruises, no invitations have been received as yet.

SCICEX 99 will be followed by at least one more cruise, scheduled for the USS L. Mendel Rivers in the early Fall of 2000. Discussions are presently underway between the US National Science Foundation and the US submarine fleet on whether a program of SCICEX-like cruises might extend beyond 2000.

The data collected during SCICEX is the largest addition to the unclassified data base for the Arctic Ocean since the early seventies. Approximately 60,000 km of narrow beam bathymetry data, approximately 100,000 km of gravity anomaly data and 40,000 km of swath and sub-bottom profiler data have been collected during roughly 210 days in the operational area. This data is being used to study some of the outstanding features in the basin, but it has a second use. The aggregate data set also builds the scientific infra-structure of the basin. The data set is being employed to build a new bathymetric map of the Arctic Ocean and to develop international proposals for future icebreaker cruises to sample the seafloor. This data set is also a resource for the determination the limits of circum-Arctic EEZ under article 76 of the revised Law of the Sea.

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SESSION 4 – Paper 4

AUSTRALIA’S APPROACH TO DEFINING ITS EXTENDED CONTINENTAL SHELF : PROGRESS AND ISSUES ARISING

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ABSTRACT

Australia has nine areas of extended continental shelf (ECS), totalling about 3.8 million km5, beyond the 200 nautical mile (M) Exclusive Economic Zones (EEZs) around the continent and its island territories. If the ECS adjacent to the Australian Antarctic Territory (AAT) is included the total area is about 5.6 million km5. In 1994 Australia began an intensive phase of survey work to acquire the data necessary to support definition of the outer limits of its ECS. To date the Australian Geological Survey Organisation (AGSO) has conducted a total of nine surveys for this purpose and acquired about 30 000 km of seismic and other data over six of the seven areas requiring new information. This phase is now largely complete except for a follow-up survey east of the EEZ around Norfolk Island and a survey south of the EEZ around Macquarie Island, that will both be finished by mid-2000.

Since mid-1998 AGSO has been involved in a phase of rigorous compilation and interpretation of pre-existing and newly acquired data in the ECS areas using a team of about 16 scientists and technicians. So far, AGSO and the Australian Surveying and Land Information Group (AUSLIG) have completed the interpretation and necessary geodetic calculations for areas off Western Australia, and are currently finishing-off areas in the Great Australian Bight and the southern Lord Howe Rise. It is expected that definition of the outer limit of the ECS in all areas, except off the AAT, will be complete by mid-2001.

During the interpretative phase several issues have arisen that have important implications for the application of Article 76 of the United nations Convention on the Law of the Sea (UNCLOS) and the recently adopted Scientific and Technical Guidelines of the UN Commission on the Limits of the Continental Shelf (CLCS), as well as the extent of Australia’s ECS and that of similar broad-margin States. The main issues relate to: the selection of points for the delineation of the 2500 m isobath + 100 M limit; determination of the foot of the continental slope on complex margins, particularly those modified by magmatism associated with continental breakup; application of the “in absence of evidence to the contrary” provision; treatment of ridges and submarine elevations; and selection of the outermost fixed points under the 1% sediment thickness provision. The manner in which some of these issues are handled in the CLCS guidelines could be viewed by some coastal States as somewhat restrictive, and introducing the need for additional requirements or evidence that are not necessarily supported by Article 76. In some cases the preferred CLCS approach could impose an additional financial burden on coastal States through the need to acquire extra survey data.

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SESSION 4 – Paper 5

Achievable uncertainties in the depiction
of the 2500m contour and their possible impact
on continental shelf delimitation

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ABSTRACT

The 2500m contour plus 100 nautical miles line is one of two possible outer constraints to continental shelf limits under Article 76 and will consequently form the outer limit of some Coastal States in some areas. Consequently, it's location may be of extreme importance to some limit determinations. This paper examines **1** the status of 2500m contours world-wide, **2** how 2500m contours are produced and **3** how the associated accumulated measurement uncertainties can translate into horizontal displacements over seafloors of varying slopes.

Article 76 defines the 2500m contour as " a line connecting the depth of 2,500 metres", a definition that emphasises that the 2500m contour is a linear feature comprising depth and connection. World-wide, few areas containing the 2500m contour have been systematically mapped, with most continental slope areas being covered by assemblages of individual single-beam tracks collected over many years. Depth uncertainty estimates are derived for bathymetry contours produced from this type of data. These estimates are depicted as horizontal displacements over slopes typical of those on which the 2500m contour is usually found.

In contrast, the uncertainty estimates from systematic multibeam surveys at these depths are compared and shown to be higher. The impact this may have on the area claimed is discussed.

1.0 Introduction

Under the United Nations Convention on Law of the Sea (UNCLOS), Coastal States may claim jurisdiction over their continental shelves beyond 200 nautical miles using a set of formulae contained within Article 76 of the Convention. This paper addresses paragraph 5, quoted here in its entirety (underlining added):

> 5. The fixed points comprising the line of the outer limits of the continental shelf on the sea-bed, drawn in accordance with paragraph 4 (a)(i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depth of 2,500 metres.

Article 76's definition emphasises that the 2500m contour comprises both depth and connection. To construct such a contour, depths are measured at discrete locations, and they are connected together using some method that tries to achieve some specified purpose. Since the methods of measuring depth and the methods of connecting measured depths are many and varied, the term contour can only be properly understood through investigating both elements.

2.0 Context –the Importance of the 2500 m contour

2.1 It's role as a basis for a constraint line

The 2500m contour is to be used as the line from which a constraining line can be constructed, at a distance of 100 nautical miles seaward from it. This 2500m plus 100 nautical miles line is one of two lines that must be combined to form a constraint on the outer limit of the area that a State can claim. The other constraint line is one "350 nautical miles from the baselines from which the breadth of the territorial sea is measured". The two constraints are blended together by choosing sections of whichever is most seaward. Potentially then, any miss-location of the 2500m contour can substantially effect the area that could be claimed by a State beyond 350 nautical miles. Consequently how it comes to be mapped where it is consequently deserves careful consideration.

2.2 Areas of the world where the 2500m contour is important

The widely internationally accepted map showing the 2500m contour for the entire earth is GEBCO (IHO, IOC and CHS, 1984, Jones 1997). Figure 1 shows the 2500m contour as depicted by this map (excepting the Arctic). Clearly it extends to most areas of the World Ocean, and in places is highly irregular. Although at first glance, the 2500m contour appears to be one of the most straightforward elements of Article 76, attempting to map it illustrates the complexity of the Article and the amount of judgement and interpretation that must be applied.

Not all of the 2500m contour of the world will be needed for Law of the Sea purposes. Some of it is rendered unnecessary by geography, some by Article 76 itself. The simplest case is the one where a piece of land is flanked by a smooth and regular continental shelf, where the 2500m contour roughly parallels the coastline. With Article 76 allowing a distance of "350 nautical miles from the baselines..." as an alternative to the 2500m plus 100 nautical miles line, the 2500m contour is only of primary importance where it lies more than 250 nautical miles from the Baselines. Figure 2 shows areas of the world where the first 2500m contour encountered when going seawards is more than 250 nautical miles from a coastline. It is valuable to compare this with Figure 1 since the two maps represent the extremes of probable interest in the 2500m contour.

2.3 The complication caused by submarine elevations

One difference between Figure I and Figure 2 are the many areas where 2500m contours surround "submarine elevations" that are morphologically isolated from the contiguous continental slope yet may be close enough to a Coastal State to form part of the "natural prolongation of it's land territory". Demonstrating that such elevations are part of an Extended Continental Shelf will require investigation of their geological origin. Of relevance here is the following question; from which 2500m contour is the 100 nautical miles measured seaward to form the outer constraint line? Does a Coastal State measure from the 2500m contour that adjoins its continuous shelf or does it measure from the 2500m contours that fringe isolated submarine elevations? On a simple margin with only one 2500m contour, there is only one answer. On a margin that is convoluted and the 2500m contour is continuous but sinuous so that a profile extending from land to the deep sea crosses it more than once, the Guidelines advise

4.4.2. ... Unless there is evidence to the contrary, the Commission may recommend the use of the first 2,500 m isobath from the baselines from which the breadth of the territorial sea is measured that conforms to the general configuration of the continental margin.

2.4 The 350 nautical miles cut-off

Submarine elevations are dealt with in the Guidelines under their own Section, one required since Article 76 contains a “cut off” rule,

> “on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured.”

In other words, the 2500m plus 100 nautical miles provision may not be used to extend a continental shelf beyond 350 nautical miles where the sea floor comprises a Ridge. The Convention does not define the term ‘ridge’ and the Guidelines indicate that the Commission has struggled with the term at some length, concluding

> 7.2.11. As it is difficult to define the details concerning various conditions, the Commission feels it appropriate that the issue of ridges be examined on a case-by-case basis.

Immediately following this is section 7.3, which concludes

> (b) ...seafloor highs that are formed by this breakup process should be regarded as natural components of the continental margin where such highs constitute an integral part of the prolongation of the land mass.

Again this does not directly address the issue of whether the 2500m plus 100 nautical miles can be measured from the 2500m contour which fringes such a submarine elevation. However, since it establishes that some submarine elevations can be part of the continental shelf, a Coastal State is likely to argue that the 100 nautical mile constraint be measured from the fringing 2500m contour.

From this we conclude that most Coastal States will wish to examine all the 2500m contours within their area of interest. A map somewhere between Figure 1 and Figure 2 would represent the world-wide interest in this feature.

3.0 What we currently know about the 2500m contour

3.1 Factors that influence the accuracy of any contour

Contours drawn to represent the sea floor differ form those on land in that the surface being mapped is never seen in it entirety. It is sampled at discrete points or along sounding tracks. Only areas surveyed by Multi-beam Echo Sounders (MBES) have any chance of being totally acoustically ensonified. Elsewhere the fidelity with which the contour reproduces the sea floor is a function of the factors summarised in Table 1:

Table 1. Factors which contribute to the fidelity with which contours reproduce the sea floor.

ELEMENTS THAT CONTRIBUTE TO THE UNCERTAINTY OF A DEPTH CONTOUR	
A. Factors that add to the uncertainties associated with a single sounding	
Depth measurement	Sound speed variations Beam width Constant errors
Positioning	Of survey platform Of seafloor sensed by instrument
Datums	Vertical or tidal datum Geodetic datum
B Factors that effect soundings collected along a track or profile	
Depth measurement	Masking of short wavelength features due to beam effect Smoothing of the seafloor
Positioning	Position of the survey platform at fixes and between fixes
Sounding selection	Distance between soundings selected along track Selection at even intervals introduces wavelengths
C Factors that effect the fitting of contours to sounding data	
Arrangement of soundings	Density of soundings Pattern of tracks, including crossovers Orientation of tracks to seafloor features
Seafloor physiography	Simplicity or complexity
Method of contouring	Methods of surface fitting Honouring Data Size of the grid cells if gridding used
Complementary information	eg bottom composition eg sidescan eg predicted (satellite) bathymetry
D Complications particular to legacy data (collections of older data)	
Compilation errors or blunders. Non-availability of original echograms Scale and accuracy of hand plotted data Biases in sounding selection Accuracy of older instruments	

When planning to collect new data, many of these factors can be controlled, or at least optimised. When working with a collection of previously collected soundings, there is little control and effort is focussed on the contouring methods.

3.2 How well the 2500m contour has been surveyed

Survey coverage is not consistently dense throughout the oceans. Generally, the physical continental shelves have been the most intensively surveyed, but the survey vessels usually turned landward once they had found the shelf break, without continuing far enough seaward to map the 2500 metre contour. In the deep ocean, most scientific attention has focused on the oceanic ridges. The result is that there the continental slope has not been received a great deal of attention, there being few detailed and systematic surveys covering it. The area around the 2500 metre contour is generally not well surveyed.

4.0 Geometry of depth measurement

4.1 Geometry of continental slopes, the surface being measured

Although 2500m contour can occur over any type of sea floor, those that will be used as part of a submission will lie on seafloors having gentle gradients, in geologic terms the Continental Slope and Continental Rise. Clearly 2500m contours do occur on steeper seafloors, in trenches for example, but there they are usually lie within 250 nautical miles of land and consequently will not be used as part of the constraint line. The areas where the 2500m contour will be used have very low gradients (Conventionally, the Slope averages 1-3 degrees, Rise less than 1 degree). Locally these values are exceeded in canyons and around seamounts, for example, but generally low gradients predominate. Accurately locating a contour on such low gradients is extremely demanding on measurement systems.

4.2 Horizontal displacement caused by uncertainties in vertical measuremnt at a single point

The clearest exposition of the displacement caused by uncertainties comes from examining the geometry of a single depth measurement over a sloping sea floor. Geometrically, a depth measurement is a straight line between a horizontal line, the sea surface, and a sloping line, the sea floor, the variables being the slope of the seafloor and the uncertainty in depth measurement. In Figure 3, the distance AB between the sea surface and sea floor is exactly 2500m, locating the 2500m contour at B. The uncertainty in AB, (delta d) means that the contour will be displaced landward or seaward by a distance that is a function of the bottom slope and the difference between 2500m and the true depth. (Horizontal displacement = uncertainty in depth measurement / cosine of bottom slope).

5.0 Elements that contribute to the uncertainty of a single measurement

5.1 The IHO Standards for Hydrographic Surveys

Although primarily aimed at surveys for conventional hydrographic purposes (i.e. shallow water where the safety of navigation must be paramount), Special Publication 44 of the International Hydrographic Organization (IHO, 1998) provides a valuable framework for examining the uncertainty of a single depth. It provides the general case in which total error estimates are calculated as the RSS of the constant errors plus the errors that vary with depth, at the depth in question. The standard goes on to provide the relative sizes for the two types of errors in its table of minimum standards which suggests the constant errors should be 1.0m or less, while the variable errors can be as large as (.023 x 2500 =) 57.5m. (2.3% of depth). Combining the two as RRS yields 57.5086, showing that at these depths the constant errors are negligible. What then are the components of the variable error?

5.2 Variable errors

5.2.1 The effect of sound speed

Depth reported depends directly on sound speed: how accurately we know the velocity of sound in seawater will clearly effect the accuracy of the depth measurement. There are two methods of dealing with variations in sound speed. In one, sound speed is measured directly during the survey and soundings are corrected to true depths using the measured values.

In the second method, the echo sounder is set at a fixed sound velocity (1483 or 1500m/sec) and the depths it measures are corrected using tables (Carter, 1980) which divide the oceans into areas of similar velocity, based on historical averages. Under stable water conditions, these tables produce data that are consistent and uniform, although there are minor “steps” at the boundaries of each correction area. However, there are some parts of the oceans where ocean currents converge to form an Intense Frontal Zone in which the water column is spatially and temporally non-uniform, making the prediction of the velocity of sound very difficult. Such Zones typically occur over Continental

Slopes, the areas that contain the 2500m contour and the Foot of the Slope. In fact the standard tables for sound velocity warn that errors of plus or minus 10 metres per second are to be expected in tabulated velocity corrections for these zones. At the opposite end of the spectrum to the areas of Intense Frontal Zones, Figure 4 shows how well velocity can be determined for a restricted area over a limited time period. Harmonic mean sound speed at 2500m depth for the month of July at 70 locations in the South China Sea is shown to vary over a range of only two metres. Similar results are expected in stable areas with data sets that are localised in space and carried out over a short time period.

Legacy data, the data which currently exists over the continental slope, will have sound speeds that are known no better than this and perhaps not as well. Table 2 shows the horizontal displacement caused by uncertainties in sound speed over bottoms having different gradients.

Table 2. Magnitudes of horizontal displacement over seafloors sloping 1, 3 and 5 degrees caused by sound speed variations.

Fixed errors m	Nominal beam angle degrees	Beam angle effect m	Sound Speed Var'n m/s	Sound Speed error m/s	Vertical Error m	Horizontal displacement on seafloors sloping 1 deg m	3 deg m	5deg m	Radius ensonfied m
0	0	0.00	2	3.33	3.33	191	64	38	0
0	0	0.00	10	16.67	16.67	955	318	191	0
0	0	0.00	15	25.00	25.00	1433	477	286	0

<u>5.2.2 The effect of beam width</u>

The preceding section deliberately oversimplifies in that it considers the measurement of depth as a single ray. This is useful but not a true picture of what happens since sound emitted propagates outwards in a pattern that expands away from the face of the transducer. Sonar design engineers use the concept of “beam width” to rate sounders: beam width is twice the angle between a line perpendicular to the centre of the transducer face and the point where the energy contained in the beam is reduced to half that at the perpendicular.

As shown in Figure 5, as the propagating sound wave radiates away from the transducer face it occupies an area that becomes increasingly large with depth. The advancing wave front encounters the bottom everywhere within the beam, and immediately some of its energy is reflected back to the surface. Older echosounders record the energy that travels the shortest two-way distance as the ‘first arrival’ or ‘first return’ which produces the depth that will be reported at the position of the transducer at the surface. More modern echosounders permit the examination of the entire returned signal and the calculation of some point within it as depth.

This effects uncertainties in three ways: it can introduce horizontal displacement when the seafloor is sloping, it can smooth the shape of large features and it can obscure features whose wavelengths are less than twice the ensonified area.

Table 3. Magnitudes of horizontal displacement over seafloors sloping 1, 3 and 5 degrees caused by beam width.

Fixed errors m	Nominal beam angle degrees	Beam angle effect m	Sound Speed Var'n m/s	Sound Speed error m/s	Vertical Error m	Horizontal displacement on seafloors sloping 1 deg m	3 deg m	5deg m	Radius ensonfied m
0	2	0.38	0	0.00	0.38	22	7	4	44
0	10	9.51	0	0.00	9.51	545	182	109	219
0	30	85.19	0	0.00	85.19	4882	1626	975	670

5.4 Constant errors

In shallow waters, particularly those used for navigation, there is a necessarily strong interest in determining all errors in depth measurement (Hare and Monahan, 1993). Constant errors are those that are of constant value no matter the water depth (e.g. tidal correction, vessel squat). In shallow waters, these can be a large percentage of depth, while in deep water they dwindle to insignificance. SP 44 allows a maximum value of 1m for constant errors.

5.5 Summary of uncertainties in a single measurement

The uncertainties discussed in the preceding sections combine as RSS to form an error budget for a single measurement of 2500m, Summarised in Table 4 are some values achievable with echo sounding equipment from various eras. In practice, these values should be calculated for all the data used in preparing a map.

Table 4. Typical combined magnitudes of horizontal displacement over seafloors sloping 1, 3 and 5 degrees caused by beam width, sound speed variations and fixed errors.

Fixed errors m	Nominal beam angle degrees	Beam angle effect m	Sound Speed Var'n m/s	Sound Speed error m/s	Vertical Error m	Horizontal displacement on seafloors sloping 1 deg m	3 deg m	5deg m	Radius ensonfied m
1	2	0.38	2	3.33	3.50	201	67	40	44
1	10	9.51	10	16.67	19.22	1101	367	220	219
1	30	85.19	15	25.00	88.78	5088	1694	1016	670

6.0 Uncertainties in the 2500m contour

6.1 Expanding from single depth measurements to contours

The preceding section discusses only the first factor, of those listed in Table 1, which contribute to uncertainty in the location of the 2500m contour. Sequentially following Table I will lead to the production of seafloor contours, but doing so is beyond the scope of this paper. Positioning has been summarised by Vanicek et al, 1994 while the preparation of deep-sea contours has been described by Monahan (in press). As a general rule, the uncertainties created by sound speed variations and beam width in the first step are not improved during the subsequent expansion to the contouring phase.

6.2 Probable status of legacy data

Large portions of the world’s continental slope, encompassing the 2500m contour have not been surveyed systematically but have been sounded to greater or lesser degree. The results are contained in legacy data. Generally, the Continental Slope has not been received as much attention as has continental shelves or the oceanic ridges. As a consequence this sounding collection has a variable density of tracks, an uneven distribution of crossovers, and a generally haphazard orientation of tracks to seafloor features. Positioning of the survey platform and of the seafloor sensed by the instruments varies from tens of meters to km. All of which means it is unlikely that 2500m contours based on legacy data are located to better than 5 -10 km.

7. Possible improvements through the use of multibeam data.

7.1 Multibeam data

The legacy data discussed above will provide a 2500m contour up to a certain level of accuracy, which may be sufficient for a Coastal State's circumstances. It is more likely, however, that it will not meet requirements, nor will there be sufficient data to determine the Foot of the Slope, leading most States to conduct a program of data collection, which will almost certainly include Multibeam echo sounding (MBES). The use of MBES in continental shelf delineation has been described extensively by Hughes Clarke (in press) who concludes that MBES can "markedly improve the exact location of the 2500m contour" and that "local absolute maximum protrusions of this discrete contour line can be identified".

These conclusions are tested and illustrated for an area off New Jersey, USA, by Monahan and Mayer (this volume), who combined contours derived from ETOPO5, the Predicted (Satellite) Bathymetry from NOAA, the GEBCO contours and the 2500m contour from a multibeam survey undertaken for the USGS. They measured the horizontal distances between the MBES contour and the earlier contours and found that the greatest differences are in the order of 10km, with most of the differences being between 3 and 5 km. Since the eastern margin of the United States is perhaps the best surveyed of all, these differences are probably as good as will be obtained anywhere.

In the area of this comparison, it is clear that MBES surveys reduce overall uncertainty to one to two hundred metres and generally lie within the envelope of uncertainty in the legacy data. Furthermore, MBES surveys introduce considerably more sinuosity into the contours, some of which manifests itself as Hughes Clarke's "maximum protrusions". These might effect the outer limits by producing a 2500m contour (from which 100 nautical miles will be measured) that could be hundreds of meters to several kilometres landwards or seawards from the existing published contours.

8. Summary

The 2500m contour must be considered for use as the outer constraint line by a number of Coastal States. In cases where the first 2500m contour is more than 250 nautical miles from the Baselines, its use is obligatory. In cases where an isolated elevation surrounded by a 2500m contour lies adjacent to the continental slope, justification will have to be established for using it as a basis for measuring seaward. Few areas of continental slopes have been systematically surveyed. The legacy data that does exist covering them is may support contours with horizontal positioning uncertainties of up to 10 km. Multibeam surveys can reduce this uncertainty to hundreds of metres as well as finding morphological features that were not discriminated by the earlier surveys.

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Figure 1 Map of the world (excluding Polar Regions) showing the 2500m contour. Extracted from GEBCO Digital Atlas (IOC, IHO and BODC, 1997)

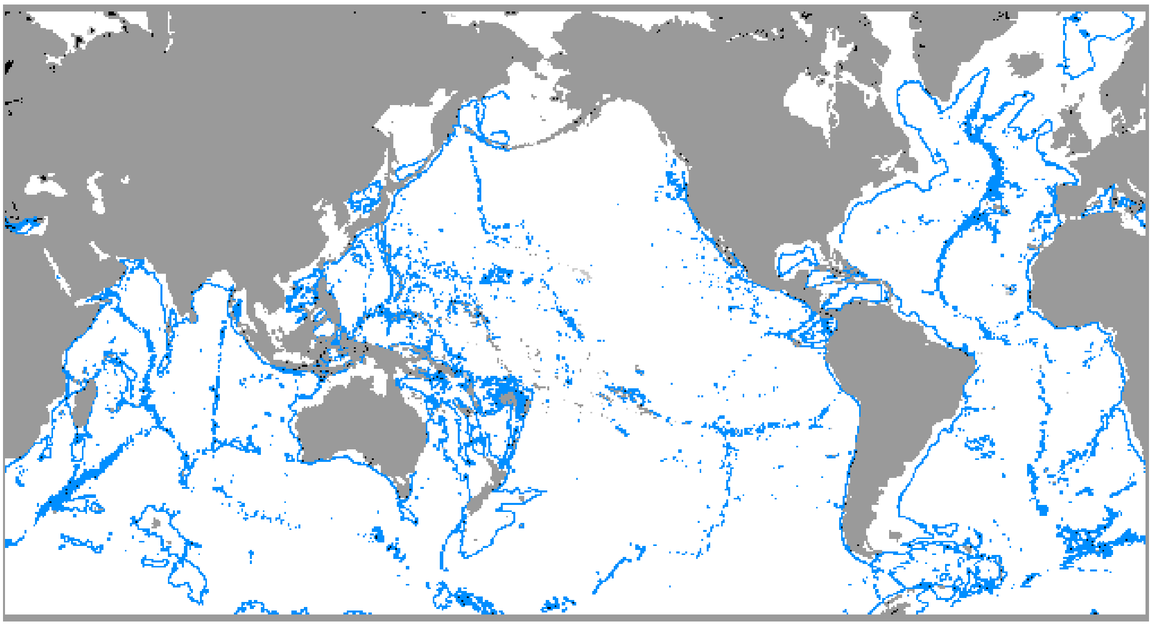


Figure 2 Map of the world (excluding Polar Regions) showing the 2500m contour where its first occurrence when moving seawards is more than 250 nautical miles from land. Extracted from GEBCO Digital Atlas (IOC, IHO and BODC, 1997)

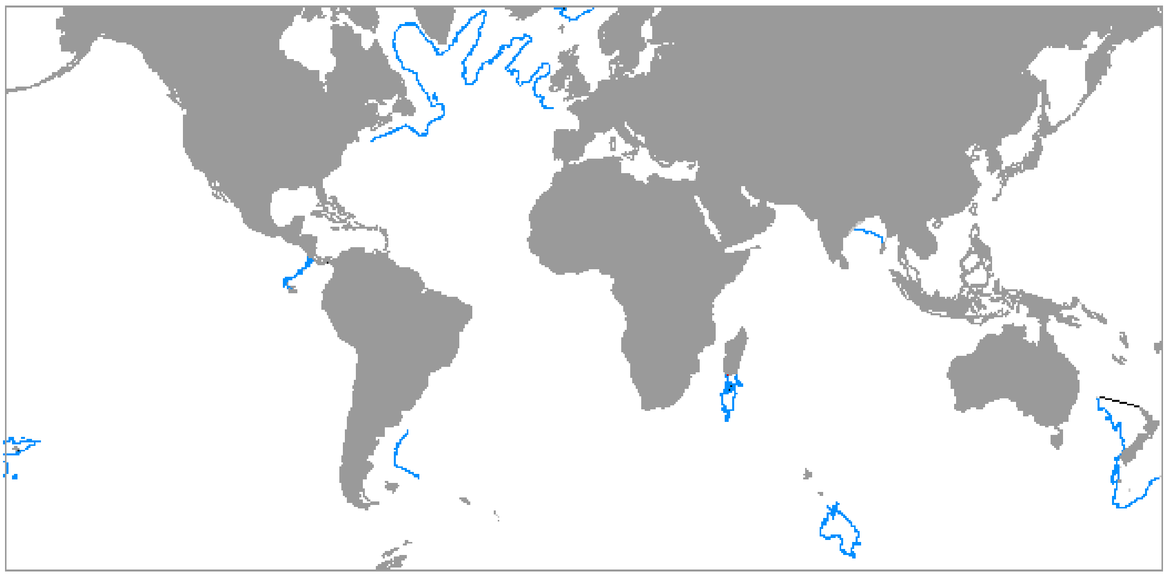


Figure 3 Geometry of horizontal displacement caused by uncertainties in measuring 2500m.

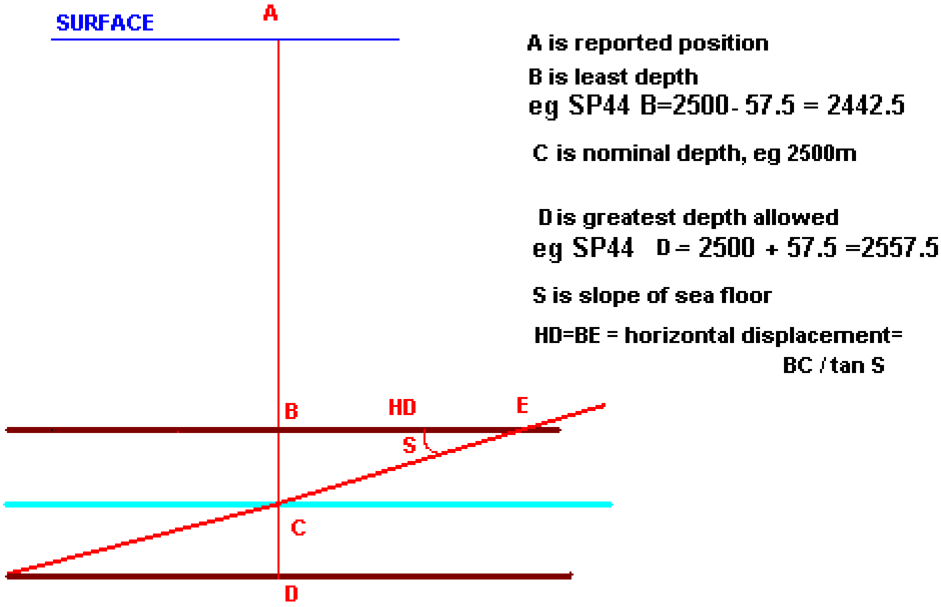


Figure 4 distribution of harmonic mean sound speed at 2500m depth for the month of July at 70 locations in the South China Sea.

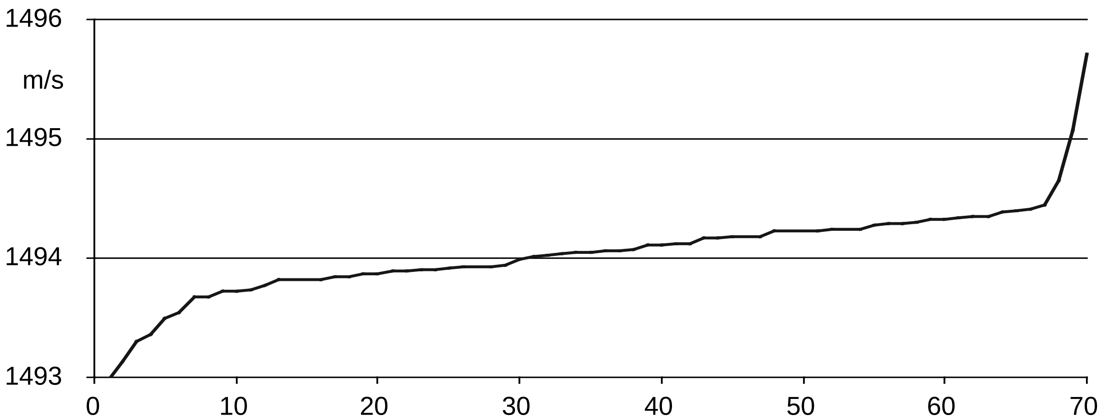
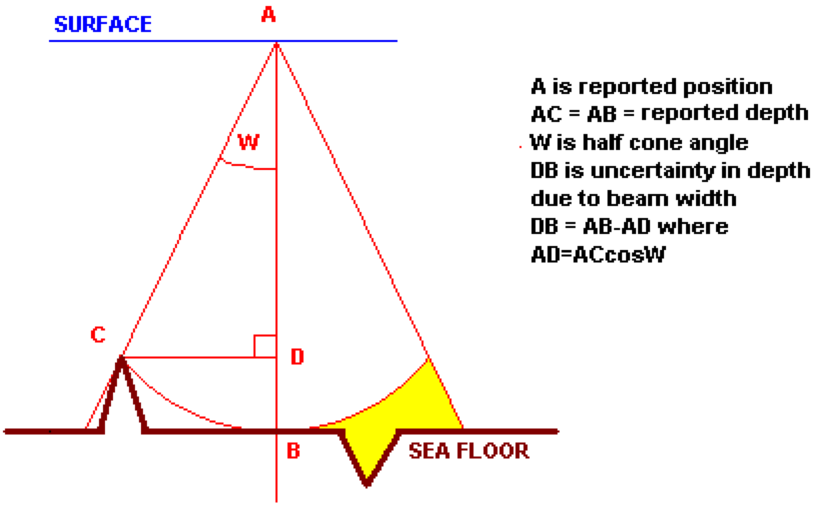


Figure 5. The effects of echo sounder beam width on horizontal uncertainty.



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