SEDIMENT CONTINUITY AND STRAIGHT BRIDGING LINES IN ARTICLE 76

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Abstract

The practical application of the terms and formulae of article 76 to the almost limitless complexity of real continental margins has required the New Zealand Continental Shelf Project team to address both technical issues (e.g., how to establish foot of the continental slope positions) and issues related to the practical application of article 76. This paper will address three of the latter issues:

- Establishing sediment continuity to foot of the continental slope positions,
- Depth conversion and determination of sediment thickness, and
- The use of straight bridging lines up to 60 nautical miles in length.

Geological and geophysical issues related to determining sediment thickness and the distance to the foot of the continental slope position are well understood. The CLCS guidelines discuss the requirement for continuity of the sedimentary section between the fixed points based on sedimentary thickness and the foot of the continental slope positions. This talk illustrates some of the complexities that can affect the continuity of the sedimentary section along a continental margin, and what impact they might have on establishing the outer limit of the continental shelf.

Paragraph 7 of article 76 states that straight lines not exceeding 60 nautical miles in length are used to connect fixed points and define the outer limits of the continental margin. In most cases the use of straight lines only smoothes the outer envelope of the margin, but along some continental margins it could have a significant impact on the extent of the continental shelf.

Introduction

Article 76 defines the means by which coastal States establish the extent of their continental shelf. The fundamental principle is that the continental shelf is the submarine prolongation of the land mass of the coastal State, as distinct from the deep ocean floor. The terms and formulae in the article describe procedures for determining the limits of the natural prolongation of the land territory. They are based on the morphology and geology of the sea floor and how it is related to the land mass.

This paper discusses two aspects of the definition of the outer limit of the continental shelf: continuity of the sediment apron at the foot of the continental slope, and straight bridging lines.

The sediment apron is often a composite sequence built by a number of sedimentary processes, and can be disrupted by seamounts and other features. The geology of the margin may require additional data to be collected to demonstrate the regional context in which sediment continuity is interpreted.

Straight bridging lines are used to simplify the definition of the outer limit of the continental shelf. In general, the areas enclosed beyond the arcs defined in accordance with article 76 are small, but there is no inherent size limit and in some circumstances the areas enclosed by straight bridging lines can be quite large.

Sediment continuity

One of the formulae for determining the outer edge of the continental margin, wherever the margin extends beyond 200 nautical miles from the baselines from which the territorial sea is measured, is based on sediment thickness beyond the foot of the continental slope positions. Article 76 (4(a)) states

> "*The coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured by:*
>
> > *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;*"

There is no mention in the article of the continuity or minimum thickness of the sedimentary layers between the fixed point and the foot of the continental slope position used for the 1% calculation.

The Commission Guidelines (1999) extend the wording of article 76 to include a requirement for continuity of the sedimentary layers between the fixed points and the foot of the continental slope positions. The Commission Guidelines (8.2.21 & 8.5.3) state

> *"In principle, the survey must be designed to prove the continuity of the sediments from each selected fixed point to the foot of the slope."*

and

> "*The Commission is guided here by paragraph 4 (a)(i), which states that the line shall be delineated by reference to "the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent ..." The Commission invokes a principle of continuity in the implementation of this provision to state that:*
>
> > *(a) To establish fixed points a coastal State may choose the outermost location where the 1 per cent or greater sediment thickness occurs within and below the same continuous sedimentary apron; and that*
> > *(b) For each of the fixed points chosen the Commission expects documentation of the continuity between the sediments at those points and the sediments at the foot of the continental slope."*

The guidelines introduce the concept of a "continuous sedimentary apron", but do not define it. The sedimentary apron beyond the foot of the continental slope positions can be formed by a number of depositional processes, and which processes are active can change with time as the margin evolves. The thickness of the sedimentary section that is required to constitute a "continuous apron" is also not specified.

At the foot of the continental slope, the sedimentary apron often consists of sediments deposited by turbidites, mass-flow deposits transferring material from the shelf to the ocean floor. However, sediments in the apron can also be deposited by contour currents, volcanic activity, or as prograding sediment wedges or hemipelagic and pelagic oozes. Between a fixed point based on sediment thickness and the foot of the continental slope, sediments may be deposited by several of these processes and therefore not form a simple apron.

Similarly, the relief of seamounts and other basement structures influence sediment deposition. In most cases these basement structures are relatively small and do not significantly disrupt the regional continuity of the sediment body. In some instances, however, they can be very large and could form barriers between the fixed point and foot of the continental slope positions.

The New Zealand Continental Shelf Project has followed the guidelines, and at each fixed point based on the 1% sediment thickness criteria we have identified the stratigraphy of the sedimentary apron and the connection of these sequences to the relevant foot of the continental slope position. The interpretation of the stratigraphy and connection are based on analysis of seismic character and velocities on seismic reflection and refraction data. The stratigraphy reflects the sedimentary processes that formed the apron, and the evolution of the continental margin. Other geological and geophysical data are used to support an interpretation of a continuous sedimentary apron if required.

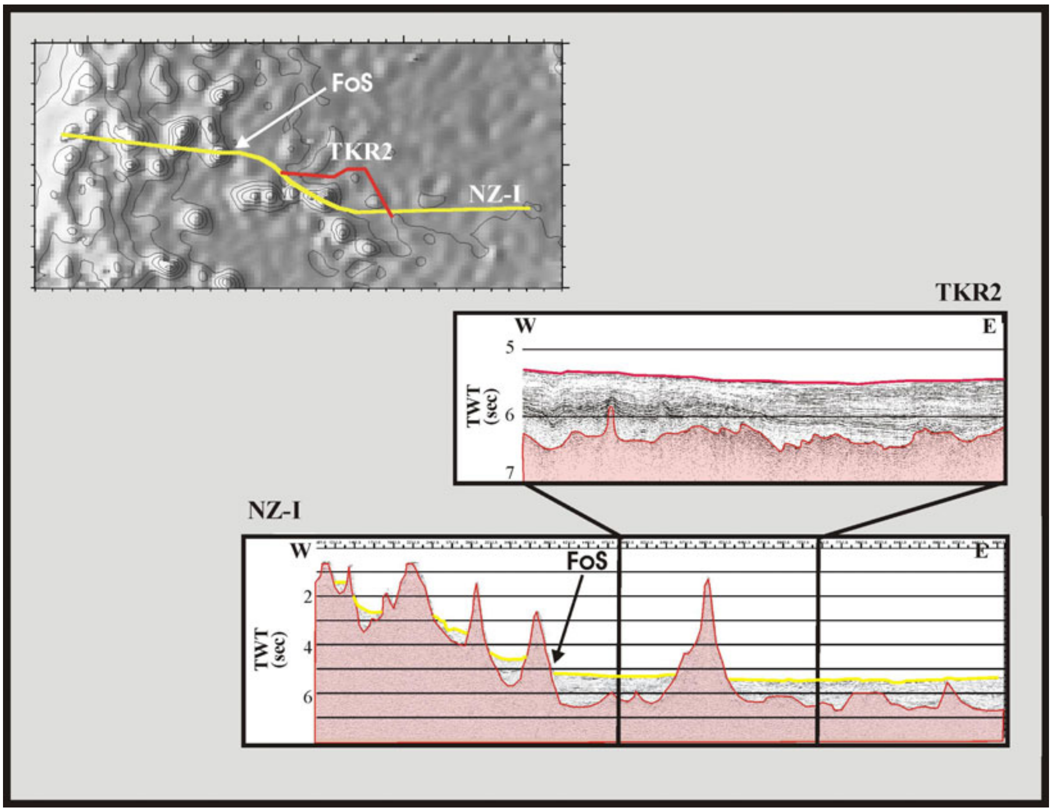

Figure 1. A map and two interpreted seismic lines showing a seamount near the foot of the continental slope that locally interrupts the continuity of the sedimentary apron. The location of a possible foot of the continental slope position is indicated.

Figure 1 shows two interpreted seismic lines across New Zealand's continental margin. The sedimentary apron at the foot of the continental slope is interrupted by a large seamount on line NZ-I. The sediment thickness at the end of this line is greater than 1% of the distance to the nearest foot of slope position, and fixed points based on this formula may be used to define the outer limits of New Zealand's continental margin. In this location another seismic line was recorded to demonstrate that the seamount is an isolated feature and the sedimentary apron along the margin is continuous in a regional context.

Where the continuity of the sedimentary apron is disrupted by seafloor morphology or other complexities, a regional interpretation of the distribution of sediments along the margin can support the interpretation of continuity of the sedimentary apron. The regional interpretation of sediment distribution can be based on analysis of adjacent seismic profiles, regional bathymetry determined by marine surveys, or analysis of marine and satellite gravity data.

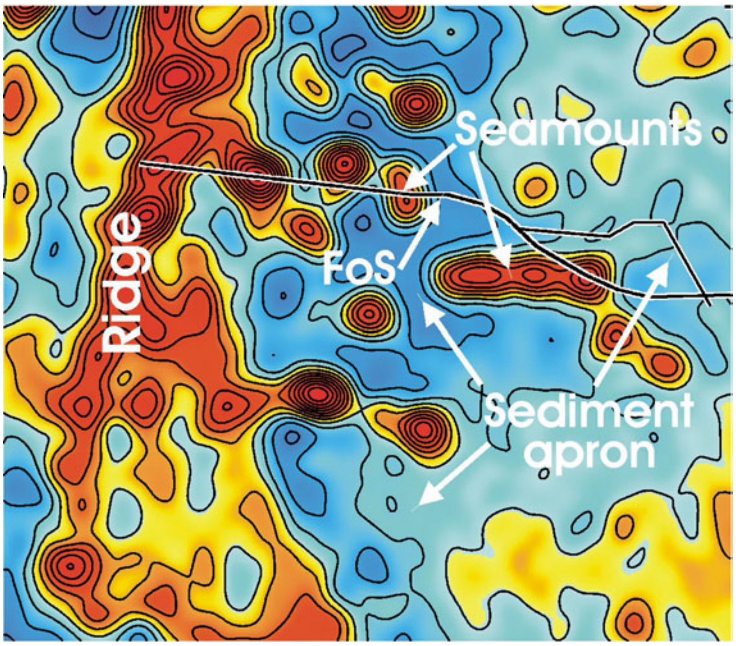

Figure 2. Map of satellite gravity anomalies in the same region as Figure 1. The anomalies show seamounts (isolated red features) extending into the ocean basin from a ridge that is part of the continental margin (large north-south trending red feature), and the sediment apron at the foot of the continental slope (blue features). The two seismic lines in Figure 1are shown as heavy lines, and the location of a possible foot of the continental slope position is indicated..

Figure 2 shows a map of satellite gravity anomalies from a portion of the New Zealand continental margin. The high anomaly values are coloured red and generally correspond to shallow bathymetry, in this case ridges and seamounts. The low anomaly values are coloured blue and correspond to deep bathymetry, in this case the ocean basin at the foot of the continental slope. Comparison of the gravity data with seismic reflection data as indicated in Figures 1 and 2 shows an empirical relationship between the sediment apron and low gravity values. The thickness of sediments along the margin can be more rigorously estimated from these data by 2- or 3-D gravity modelling (e.g., Ramillien & Wright 2002, Wood &

Woodward 2002), but other information such as interpretations of seismic reflection data are necessary to constrain the solution.

Although it seems clear that in cases like Figure 1 where the entire thickness of the sediment apron is interrupted by basement structure it may be necessary to use other evidence to demonstrate continuity between the foot of the continental slope and the outer limit of the continental shelf, it is not clear what proportion of the sediment apron must be uninterrupted in order for it to be considered continuous.

For example, Figure 3 shows a cartoon with four basement features interrupting the sediment apron. The sediment apron in this model has several layers, perhaps reflecting different depositional processes. Basement feature 1 is similar to that discussed above, and it is likely that additional information would be required to demonstrate continuity of the sediment apron around this feature. Basement feature 2 does not rise above the sea floor, but disrupts 90% or more of the sedimentary sequence. Similarly, basement features 3 and 4 disrupt about 50% and 30% of the sedimentary sequence, respectively. Would a sediment apron interrupted by features such as these be considered continuous? How does lateral extent of the feature influence the interpretation?

We suggest that basement features 3 and 4 in Figure 3 do not break the continuity of the sediment apron. There is still a significant component of the apron that is not interrupted by the features and the depositional processes for the younger parts of the apron have not been influenced by them.

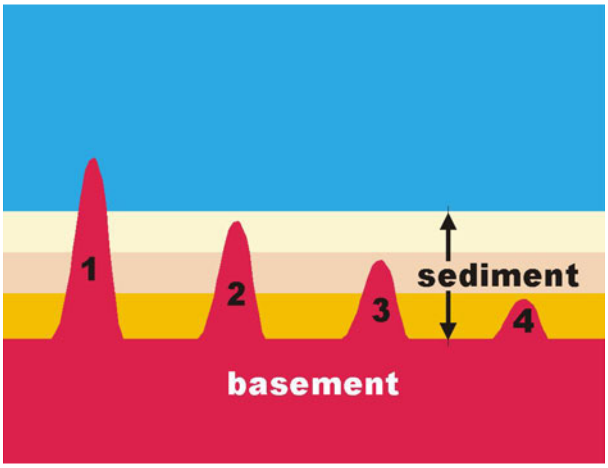

Figure 3. Cartoon showing basement features that disrupt the sediment apron.

It is unlikely that article 76 and the Commission Guidelines envisaged that a thin veneer of sediments would qualify as a continuous sediment apron. There will always be grey areas such as basement feature 2 in Figure 3 that will have to be judged on a case-by-case basis. Along some margins continuity of a relatively thin portion of the sediment apron over a local basement high may be sufficient to satisfy the Commission. Along other margins it may be necessary to provide other evidence that the basement high is a local feature that does not disrupt the regional continuity of the sediment apron. Relevant evidence could include documentation of the evolution of depositional and/or erosional processes along the margin, and discussion of the tectonic history of the margin and its influence on the nature of basement structures expected there.

Depth conversion and determination of sediment thickness

Article 76 (4)(a) describes how sediment thickness can be used to define the extent of the continental shelf. Estimating sediment thickness, particularly in deep-water areas at the edge of the continental shelf, is not a trivial task (e.g., Brekke 1999). This paper shows a comparison of two common methods for estimating sediment velocity, but is not a thorough review of velocity analysis and depth conversion.

Depth conversion is not just an issue for Coastal States defining their continental margin, it is very important for the oil exploration industry, and vast monetary investment has been made to develop and apply velocity analysis and depth conversion techniques. Depth conversion is a key factor in exploration and production planning, and internationally important in unitisation discussions where reservoirs straddle international boundaries. Calibration of depth estimates by correlation with wells greatly increases their accuracy. In areas with no well control a rule of thumb is that the depth uncertainty is likely to be at least ±5%.

Issues arising from the application of velocity analysis and depth conversion techniques to the particular requirements of article 76 have been discussed elsewhere (e.g., Kasuga et al. 2000) and that discussion is not repeated here. This paper shows an example of depth conversion using velocities derived from seismic reflection data and from seismic refraction data, and what effect use of those velocities could have on the extent of the continental shelf.

Drilling is the most accurate way to determine sediment thickness beyond the foot of the continental slope, but the most practical way is to use seismic reflection data. Seismic reflection data provide a cross-section image of the rock layers beneath the sea floor, displayed as a function of the time it takes for the sound waves to travel from the energy source, reflect from the layers and travel back to the sensors (two-way travel time).

There are two major sources of uncertainty associated with converting these travel times to sediment thickness. The first is the difficulty identifying the contact between the rock layers, particularly between sediments and basement along some continental margins. The latter is often difficult to recognise due to the presence of volcanic rocks or the thickness of the sediments. This problem is discussed elsewhere (e.g., Symonds et al. 2000). The second source of uncertainty arises from the difficulty of accurately estimating the velocity of sound in the sediments, information necessary to convert the two-way travel times to depth and thickness.

The two most common and inexpensive ways of estimating the velocity of sound in the sedimentary section are analysis of the arrival time-offset relationship of reflections on seismic reflection data, or of this relationship for refractions and reflections on seismic refraction data collected using a sonobuoy.

The advantages of estimating velocities from analysis of seismic reflection data are (i) a basic velocity analysis is a routine part of the seismic processing sequence and is readily available, and (ii) these analyses can be made frequently and therefore can provide an indication of lateral changes in velocity. The disadvantages of this technique are (i) it derives stacking velocities which must be converted to interval velocities for depth conversion, (ii) the quality of the result is heavily dependent on the acquisition system, particularly the length of the hydrophone array, (iii) stacking velocities derived as part of the normal processing sequence are chosen to improve the appearance of the section and are not necessarily the best for depth conversion, (iv) the result can be biased by the interpreter's perception of the geology, (v) the result can be affected by anisotropy, and (vi) the result can be strongly influenced by factors such as dip of the reflectors and out-of-the-plane structures.

Another technique commonly used to estimate velocities for depth conversion, particularly by academic and research scientists, uses seismic refraction (sonobuoy) data. The data collected by this technique are fundamentally the same as those collected by the reflection technique, but the distance between the energy source and the receiver can be much greater than that of a seismic streamer, allowing analysis of other modes of waves.

The advantages of this technique are (i) it provides the *only* velocity information where single-channel reflection data are collected, (ii) the technique is designed to estimate velocities rather than improve the interpretability of the reflection section, (iii) it has longer offsets and therefore can potentially provide more accurate estimates of velocities in deep water, and (iv) it provides more direct measurements of the sediment velocities. The disadvantages of this technique are (i) sonobuoys are not routinely collected as part of most surveys, (ii) it is rarely practical to include lateral variations in layer velocities, (iii) the solutions can be affected by currents and sonobuoy drift, (iv) noise can make it difficult to interpret direct, refracted or reflected waves at long offsets, (v) the refracted waves do not reveal velocity inversions and tend to sample the faster components of the sequences, and (vi) the result can be biased by the interpreter's perception of the geology.

Figure 4 shows interval velocities estimated from routine stacking velocity analyses for a seismic line collected for the New Zealand Continental Shelf project with a 3,000 m streamer. Figure 5 shows interval velocities estimated from analysis of several sonobuoys along this margin, including two on this line. The sonobuoy velocities were constrained by the interpretation of the sediment sequences and are consistently higher.

Figure 6 shows the sediment thickness estimated from depth conversion using these two interval velocity functions, and the 1% thickness line from a possible foot of the continental slope position on this line. In this example the difference in velocity functions could make a difference of over 60 km to the position of the outer edge of the continental margin.

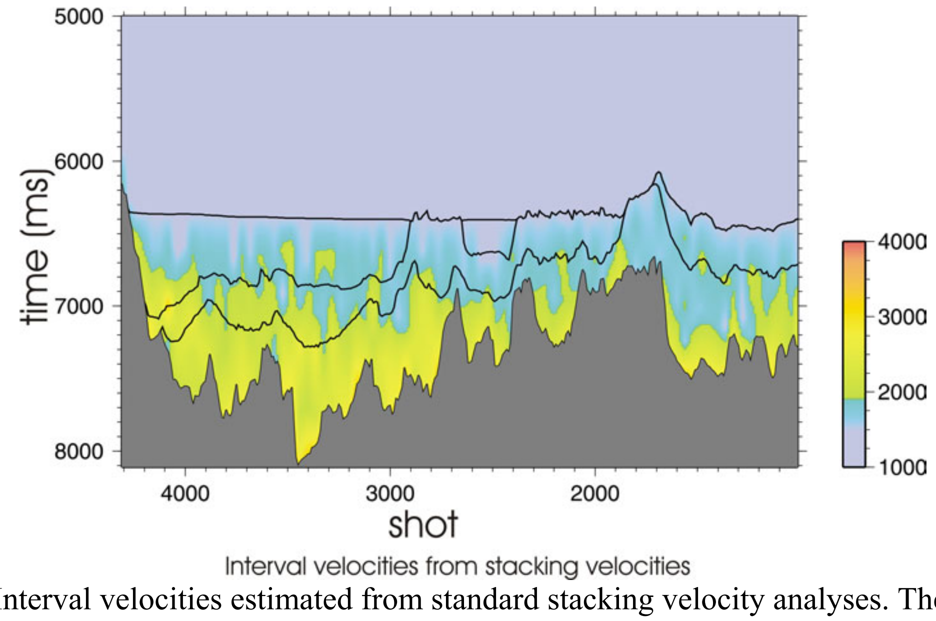

Figure 4. Interval velocities estimated from standard stacking velocity analyses. The length of this portion of the seismic line is about 165 km. The boundaries of the three major sediment units are marked, and basement is shaded grey. The velocity scale on the right is in m/s.

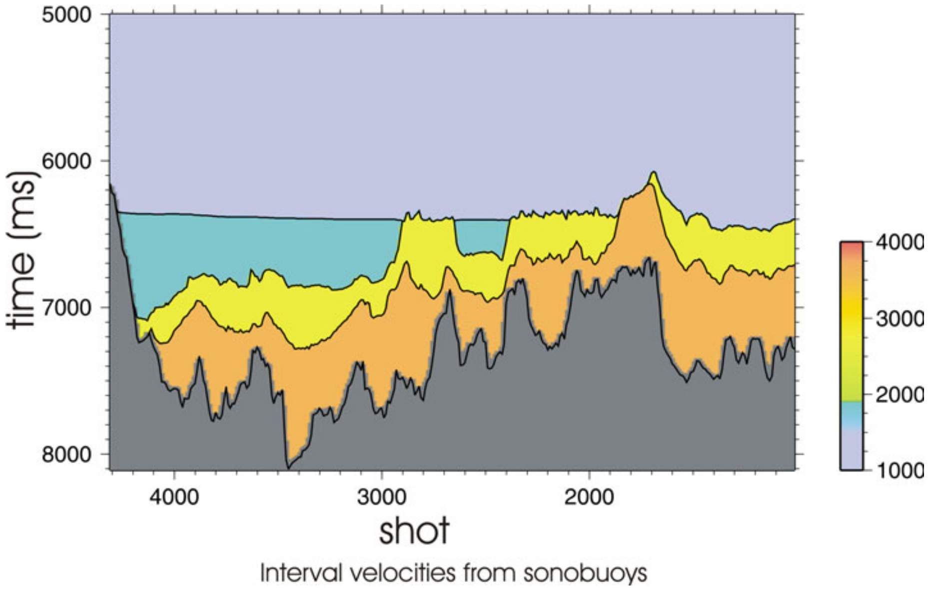

Figure 5. Interval velocities estimated from analysis of seismic refraction (sonobuoy) data. The velocities are constrained to be laterally constant in each sedimentary sequence.

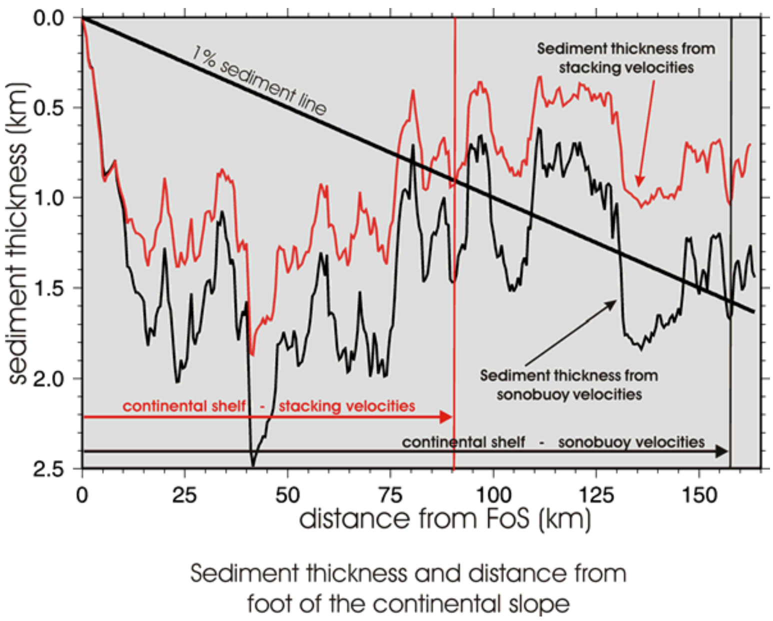

Figure 6. Depth to basement and sediment thickness were estimated using the two velocity functions. A line showing 1% sediment thickness from a possible foot of continental slope position is shown, and the possible extent of the continental shelf for both velocity models is indicated.

Our study of velocity analysis techniques is still in progress and it is too early to say if one of these velocity models is better than the other. However, along this margin the geology is thought to be relatively simple, with most of the sediments consisting of deep-water carbonates. Wells drilled in similar environments around the world show that compaction of these sediments can result in relatively high velocities in the deeper section (e.g., Carlson et al. 1986), so the sonobuoy results may be more appropriate for calculating sediment thickness in this case.

The choice of velocities for depth conversion will depend on the type and quality of the data available. Velocities derived from analysis of seismic reflection data collected with a streamer length comparable to the depth to basement may be suitable for estimating sediment thickness in many areas, particularly if a special effort is made to derive velocities for this purpose. In areas where only single channel seismic reflection data are available, sonobuoy refraction data should be recorded and analysed to derive velocities suitable for estimating sediment thickness. If seismic reflection data collected with a moderate streamer length (perhaps half the depth to basement) and sonobuoy data are available, then their analysis can be integrated to provide a more robust assessment of velocities suitable for estimating sediment thickness.

Straight bridging lines

Continental margins are rarely straight. They are interrupted by ridges, plateaus, canyons, embayments and other features of various scales. The components of the outer limit of the continental shelf that are derived from the *shape* of the margin – 60 nautical miles from the foot of the continental slope, 100 nautical miles from the 2,500 m isobath, and points where the sediment thickness is greater than 1% of the distance to the foot of the continental slope – can be correspondingly convoluted.

In order to simplify the potentially very complex definition of the outer limit of the continental margin, article 76 (7) provides for the use of straight bridging lines between fixed points. The straight bridging lines are formed according to article 76 (7) by

> *"straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by coordinates of latitude and longitude".*

The constraint on the length of the straight lines can be used to help determine the level of detail required for surveys of the margin.

The Commission Guidelines (2.3.8) state that

> *"These straight lines can connect fixed points located on one of, or any combination formed by, the four outer limits produced by each of the two formulae and the two constraints contained in article 76"*

and that the straight lines should enclose (2.3.9, 2.3.10)

> "*only the portion of the seabed that meets all the provisions of article 76*".

For fixed points other than those based on sediment thickness, there is no other restriction on their use to construct straight bridging lines.

In the case of fixed points based on sediment thickness, the Guidelines (2.3.9) state that

"These straight lines should not be used to connect fixed points located on opposite and separate continental margins".

The meaning of "*separate continental margins*" is unclear. Article 76 (1) states that continental margins derive from the prolongation of the land territory. The concept of "*separate continental margins*" therefore implies prolongation from separate land masses. Fixed points that are located on prolongations of the same land mass are part of the same continental margin.

In most cases the use of straight line segments only has the effect of smoothing the outer limit of the continental shelf. Within the terms of article 76 there is no limit to the size of the enclosed area.

Figure 7 is a cartoon showing areas enclosed by straight bridging lines between fixed points. The enclosed areas "A" and "B" lie beyond the extent of the continental shelf as defined article 76 (4). Article 76 (7) only stipulates that the straight lines connect fixed points. As these fixed points could lie on the constraint arcs, the area encompassed by the straight lines could include parts of the seafloor that lie more than 350 nautical miles from the baselines and more than 100 nautical miles from the 2,500 m isobath.

Area "A" on Figure 7 shows how a relatively large area in an embayment might be included in the continental shelf by a straight bridging line. The "B" areas on the figure show how the arcs defining the outer limit of the continental shelf are smoothed by straight bridging lines.

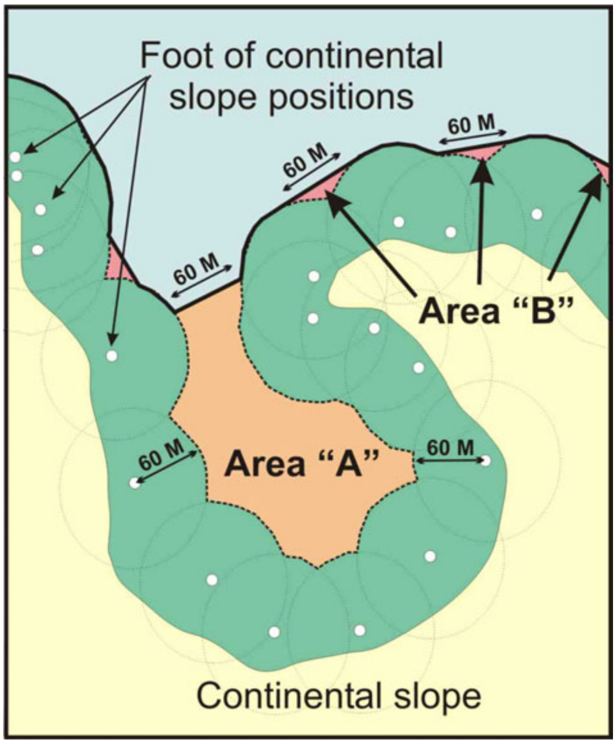

Figure 7. Cartoon showing smoothing of the outer limit of the continental shelf by straight bridging lines.

The method of construction of the straight bridging lines in Figure 7 is the same, and the only difference between areas "A" and "B" is one of scale. All these areas conform to the terms of article 76 (7), and cover seafloor that is beyond the limits of the continental shelf as defined in article 76 (4).

Conclusions

The concept of a continuous sediment apron introduced by the Commission Guidelines (8.2.21 & 8.5.3) may require additional documentation on continental margins characterised by seamounts, current scour, or other features that disrupt the sedimentary section. It may be necessary to collect additional data around these features to demonstrate that there is a continuous sediment apron between the fixed points defined by sediment thickness and the corresponding foot of slope positions. Ideally these data would include seismic sections that tie the fixed points to the foot of slope positions, but data that establish a regional context for the sediment apron and extent of features that disrupt it may be sufficient. The degree of disruption that will be acceptable to the Commission before additional information is required has not been established.

There are several practical techniques available to estimate sediment thickness beyond the foot of the continental slope, each of which has strengths and weaknesses. Where modern seismic reflection data with a streamer length comparable to the depth to basement have been acquired, sediment thickness may be estimated from the velocities derived from analysis of the common depth point gathers. Where single channel seismic reflection data are the only data available, velocities derived from sonobuoy refraction data should be used to estimate sediment thickness. Where seismic reflection data collected with a moderate streamer length (perhaps half the depth to basement) and sonobuoy data are both available, then sediment thickness can be estimated using velocities derived from an integration of both data sets.

Straight bridging lines no more than 60 nautical miles long may be used to simplify the definition of the outer limit of the continental margin. These lines can join fixed points on any of the constraint or formulae lines as defined in article 76 (4) and (5). The end points of the bridging lines can be chosen to maximise the area encompassed by the outer limit of the continental margin. The views expressed here are those of the authors and do not necessarily represent those of the New Zealand Government.

Acknowledgements

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