Deep water challenges to hydrography stimulated by the United Nations Convention on Law of the Sea (UNCLOS)

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Abstract

The role of Hydrography is expanding to satisfy the ever-increasing demands of new uses of the seas. One example is that over fifty countries are eligible to claim a juridical Continental Shelf under Article 76 of the United Nations Convention on Law of the Sea (UNCLOS). Doing so successfully will give them sovereignty over the resources of the seabed in areas beyond their 200 nautical mile Exclusive Economic Zone (EEZ). Continental Shelves are not automatically granted: a case must be carefully prepared and defended before the Commission on the Limits of the Continental Shelf according to an elaborate set of rules. Preparation involves the disciplines of hydrography, geology, geophysics and geodesy. This paper discusses the responsibility of hydrography to perform its tasks to known levels of accuracy in this important process that will redefine the borders of one third of the world's states, and change the legal status of vast areas of the world's oceans.

Hydrographic elements include the "baselines from which the breadth of the Territorial Sea is measured", the 2500-m depth contour and the "Foot of the Slope". Baselines consist of either low water line as shown on hydrographic charts, or straight lines joining low water points. Accuracy factors include the choice of low water or straight lines, tidal datum and its impact on tidal "elevations", slope of the seafloor and configuration of the coastline. Measurements in 2500 m depths are dominated by variable errors and acoustic beam width, while delineating the 2500 m contour from the measurements varies with sounding spacing, method of contouring, bottom physiography and bottom slope. The "Foot of the Slope" is a feature that may have a physiographic expression or may be non-existent. Where it does exist, it lies in deep water and represents the maximum change of slope of a surface that is sloping only one or two degrees. Finding it and mapping it, or proving that it cannot be found, will tax hydrographic field techniques to an unprecedented extent. If it exists, it will lie

within a zone of uncertainty dominated by the difficulties in isolating the feature, the smoothness of the juncture between Slope and Rise, local physiography, and the scale or intensity to which they can be captured by a hydrographic survey.

This paper describes these hydrographic elements and illustrates them with examples selected from parts of the Canadian continental margin. It produces estimates of the accuracies of locating each one and develops a model error budget for their combined effect. The impact of increasing the accuracies achieved is expressed in terms of the area encompassed within the continental shelf of a Coastal State.

Introduction

UNCLOS must be one of the most important treaties in the history of the world. It attempts to regulate virtually all activities in the world's oceans, their management and use, in one package. The oceans cover two thirds of the earth's surface, regulate the earth's climate, contain major living and nonliving resources, are the ultimate resting place for many pollutants, are the medium over which the bulk of the world's trade is carried. Their safe and equitable use, now and into the future, is one of the driving forces behind UNCLOS. UNCLOS came into force in 1993: 132 countries have now ratified the treaty. The USA, Canada and Denmark are among the hydrographic nations not to have yet ratified.

When reading the convention, it must be born in mind that it took over 150 nations over ten years to produce carefully crafted compromises between competing political interests which are not necessarily as clearly and cleanly written as engineers and scientists might like them to be.

While the entire treaty (United Nations, 1982) is important, the Parts having most immediate relevance to hydrography and this conference are Part II, Territorial Sea and Contiguous Zone, Part V, Exclusive Economic Zone, Part VI, Continental Shelf and Annex II - Commission on the Limits of the Continental Shelf. These reshaped the character of jurisdiction in the oceans. Sovereign rights are now phased down through the several zones defined by these Parts. Some issues in UNCLOS are so complex as to require being referred to "the competent international organisation" or to a body established by UNCLOS itself. Most relevant to this paper are the International Hydrographic Organisation (IHO) and the Commission on the Limits of the Continental Shelf (CLCS). The later is established to examine claims to Continental Shelves, and is

> "…made up of experts on hydrography…".

Within a Coastal State, national experts on hydrography will be expected to contribute to preparing their nation's claim. They will bring knowledge not only of how to make and interpretation the necessary measurements, but also knowledge of how accurate those measurements are.

An extensive literature on the technical elements of UNCLOS exists, and the reader is referred to them for further analyses. Valuable compilations of papers include Wells, 1994, and ABLOS, 1999, while Cook and Carleton, 2000, present a comprehensive overall methodology and analysis, and Monahan, 2000, gives an overview from a primarily hydrographic perspective. Of particular relevance to any in-depth investigation are the Guidelines issued by the CLCS (United Nations, 1999). The essential components of a claim are shown in Figures 1 and 2.

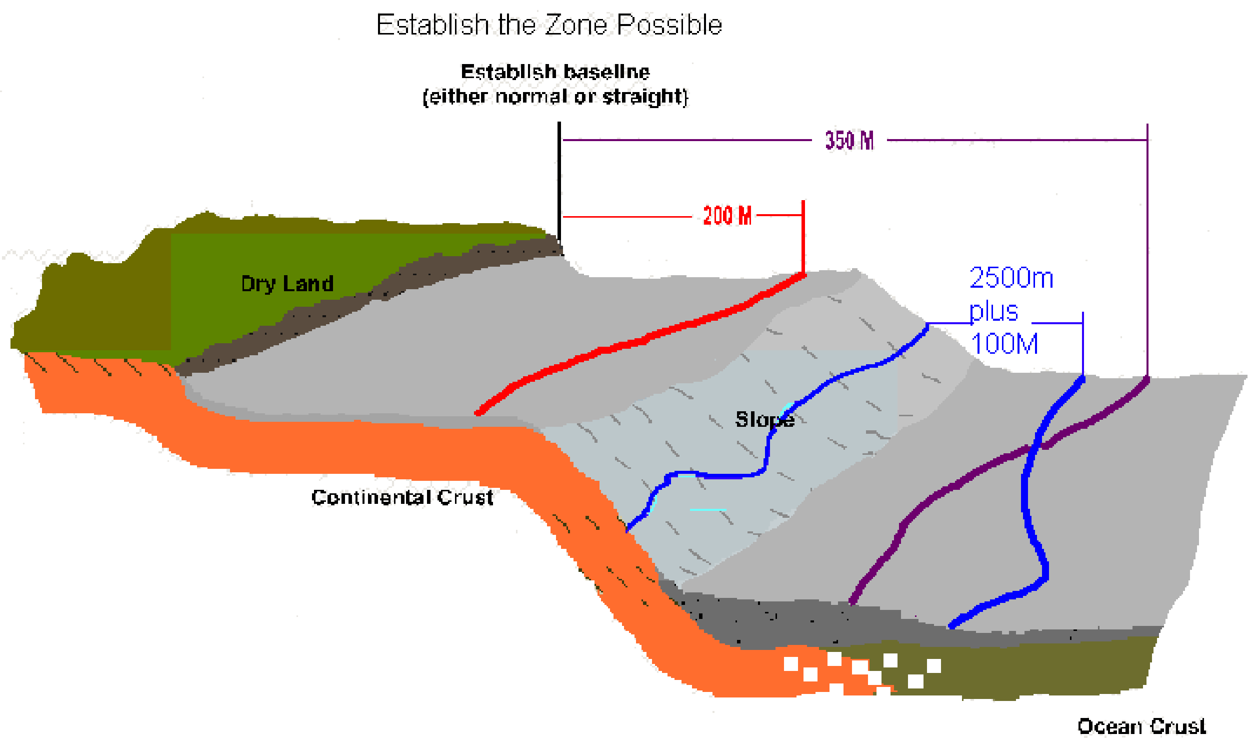

Figure 1. Elements of the outer constraint. The outer constraint is the most seaward of either 350 M from the baselines or the 2500 m contour plus 100 M

Continental Shelves cannot extend forever, and Figure 1 shows that the constraint is constructed from the most seaward of either a line 350M from the Baselines from which the breadth of the Territorial Sea is measured or a line 100M seawards of the 2500m depth contour. The outer edge of the Continental Shelf can be one of these lines, or some line lying between them and 200M from the baselines. In the latter case, Figure 2 shows the two possible lines the outer edge can be based on. Both are drawn from the Foot of the Slope, one to a distance of 60M, the other to a point where

> "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 convention allows for the possibility that the Foot of the Slope does not exist as a surface feature and allows a Coastal State to argue for its location based on "evidence to the contrary". What this evidence comprises is not specified, but it can be inferred that users of evidence to the contrary will have to show where, in gross terms, the continental crust and the oceanic crust abut.

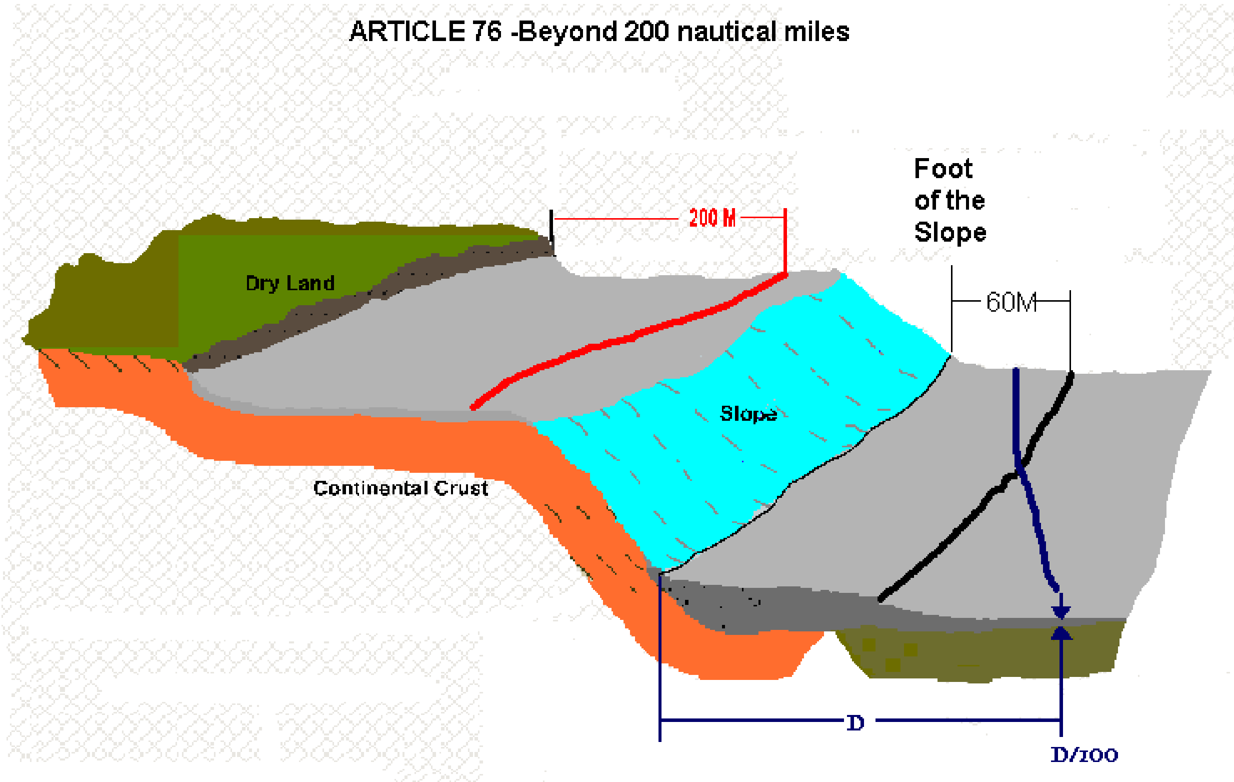

Figure 2. Where the outer constraint is not used, the outer limit is the most seawards of the Foot of the Slope plus 60M or the Foot of the Slope to the sediment thickness line.

Table 1. Sources and magnitudes of uncertainties associated with each of the elements involved in an extended Continental Shelf claim under Article 76 of UNCLOS.

ELEMENT	COMPONENTS	DISCIPLINE	UNCERTAINTY
350 nm	baselines distance	hydrography geodesy	metres
2500 m contour plus 100 nm	depth contouring distance	hydrography geodesy	100s of metres
Foot of the Slope plus 60 nm	bottom morphology distance	hydrography geodesy	kms
Foot of the Slope sediment thickness	bottom morphology sediments	hydrography geophysics	kms
Evidence to the Contrary	bottom morphology structure	geology geophysics	tens of km

Table 1 captures these elements, identifies which are hydrographic, and gives orders of magnitudes for the uncertainty in their locations. In this paper, we focus on the uncertainty associated with the hydrographic elements that contribute to determine the outer limit of a juridical Continental Shelf, namely a) the Baselines From Which The Breadth Of The Territorial Sea Is Measured, b) the 2500 Meter Contour and c) the Foot of the Slope.

Baselines From Which The Breadth Of The Territorial Sea Is Measured

UNCLOS creates a series of zones, namely are the Territorial Sea, the Contiguous Zone, the Exclusive Economic Zone and the Continental Shelf that fringe or border a coastal State on its seaward size. A major element of defining the first three is the 'baselines from which the breadth of the Territorial Sea is measured", since all three are measured seaward from this line. It also functions in defining one of the possible outer constraints on the width of the continental shelf, since the 350 M cutoff is measured from it.

The Convention provides for two possible methods of creating baselines. It provides the "normal" case where Article 6 defines the normal baseline as

> "Except where otherwise provided...the low-water line along the coast as marked on large-scale charts officially recognized by the coastal State."

The exceptions allow States to depart from the low-water line by means of straight lines, for example across the mouths of bays. Article 14 permits a Coastal State to combine of any of the methods for determining baselines to suit different conditions. Hydrographic components of determining the baselines are locating the low-water line, deciding where to depart from the low-water line, selection of critical points, and straightness of baselines.

<u>Low-Water Line.</u>

All hydrographers know that the seemingly simple low-water line on a chart, a representation of the boundary between land and sea, is anything but simple to get onto the chart. On any real shore, the line that appears on the chart must represent some combination of the effects of daily and yearly tidal variations, which must be discriminated from the effects of storm waves, wind push and other meteorological effects, as well as local, tidally-induced, vertical crustal movements. In the interests of safety, navigation charts show as a low-water line the water level at "lowest normal" tides and this is the line referred to in the Convention. The definition of "lowest normal" tides varies among hydrographic offices, with, for example, the Canadian Hydrographic Service (CHS) using Lower Low Water Low Tide (LLWLT) and NOAA building adjacent charts referred to Mean Lower Low Water (MLLW). In 1997, the IHO adopted Lowest Astronomical Tide (LAT) as an international standard, but it will take years before all charts can be converted.

Deciding which datum to use is a beginning: there then must be enough observations, distributed over a long enough time (typically 19 years for LAT) , to establish that datum at a gauge. Expanding from the observations at a single point to encompass and properly delineate an entire shoreline requires a different level of effort, and the accuracy with which the low-water line is charted diminishes with increasing distance from the tide gauge, particularly when tide character is significantly changed over that distance.

Hydrographers have not really expended too much effort on “shorelining” since the actual location of the low-water line has not been very important in the past, and the reduction of soundings to datum has created such a buffer as to allow or even encourage hydrographers to take licence.

However, the Law of the Sea imposes different requirements. Errors in tidal prediction or a badly chosen datum will manifest themselves in the horizontal direction through moving the location of the low-water line landwards or seawards. These movements may effect the outer limits. Consider a shore face sloping at some angle x. A difference of y in the vertical measurement of tide will manifest itself as a horizontal displacement of displacement = y/tan x, perpendicular to the shore face. The horizontal distance between these lines varies from nothing, for perpendicular cliffs, to several kilometres over tidal flats.

So, how large can these differences be? Differences will come from a) errors in measurement or prediction of tides and b) theoretical differences between LLWLT, LLWMT, and LAT. As a worst case, the vertical displacement is unlikely to be more than 2m, and uncertainties are more likely in the decimeter range. Table 2 summarizes this

Table 2 Horizontal displacement of a low-water line as a function of shoreface slope and vertical position errors.

Vertical Uncertainty (m)	Slope degrees 15	10	5	2	1	0.5	0.25
	Horiz	Displ	(m)				
0.1	0.4	0.6	1.1	2.9	5.7	11.5	22.9
0.2	0.7	1.1	2.3	5.7	11.5	22.9	45.8
0.3	1.1	1.7	3.4	8.6	17.2	34.4	68.8
0.4	1.5	2.3	4.6	11.5	22.9	45.8	91.7
0.5	1.9	2.8	5.7	14.3	28.6	57.3	114.6
0.6	2.2	3.4	6.9	17.2	34.4	68.8	137.5
0.7	2.6	4.0	8.0	20.0	40.1	80.2	160.4
0.8	3.0	4.5	9.1	22.9	45.8	91.7	183.3
1.0	3.7	5.7	11.4	28.6	57.3	114.6	229.2
1.5	5.6	8.5	17.1	43.0	85.9	171.9	343.8
2.0	7.5	11.3	22.9	57.3	114.6	229.2	458.4

We can safely assume that vertical uncertainty is usually less than .3m and slopes generally greater than .5 degrees, so that this part of the error budget is not a major issue in Law of the Sea continental shelf determinations.

Where To Depart From The Low-Water Line

States can depart from the low-water line by means of straight lines, avoiding the complications imposed by the physiography of some coasts, and allowing the inclusion of larger areas within internal waters than does using just the low water line. There are a number of UNCLOS Articles that provide instruction on how to construct these straight baselines. For instance, Article 10 deals with constructing baselines across the mouths of bays. The article contains a formula relating the area of the bay to that of a semi-circle whose diameter is a straight baseline across its mouth, restricting the length of the baseline to 24M. Perhaps the real clues on how to interpret these Articles are embedded in Article 7, Paragraph 5,

> *"Where the method of straight baselines is applicable … account may be taken…of economic interests peculiar to the region concerned…", … "The foregoing provisions do not apply to so-called "historic" bays."* .

Collectively the ambiguity of these clauses will likely allow Coastal States to take considerable latitude in what they choose their baselines to be. It is only where their choice of baselines impacts another Coastal State that there may be some challenge to any claimed baselines.

In terms of the lines that are drawn based on the baselines (i.e. outer limits of Territorial Sea, Contiguous Zone, EEZ and the 350 M constraint to the Continental Shelf), the choice of normal or straight baselines does not often make much difference to the final location. Differences that do occur decrease with distance offshore. This arises since the straight lines join points on the same low water line as used by the "normal" baseline, and they are the points of maximum seaward protrusion. Swinging arcs from these points creates the fringing zones, with most of the baseline, be it straight or normal, having little effect. The greater the diameter of the arcs, the fewer points are needed. (See Figure 3).

The effect has been likened to running a wheel with a radius equal to the width of the zone being mapped (i.e. 12, 24, 200 or 350 M) along the baseline and having the center of the wheel trace out the edge of the zone. Alternatively this process can be viewed as subjecting the shoreline to a low-pass filter. Indentations of certain sizes are smothered whether or not straight lines are used. Only a few critical points on the baselines contribute to the outer limits.

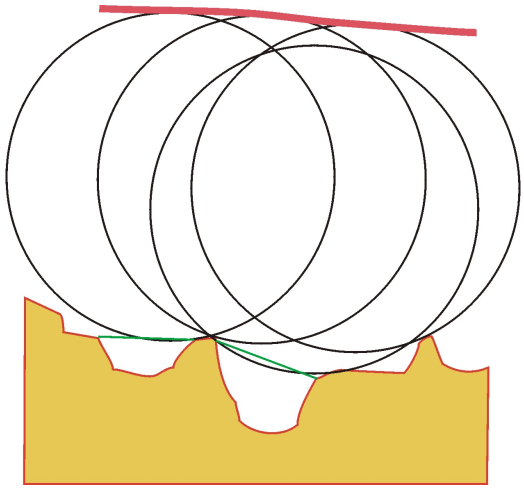

Figure 3 Sketches showing that as the distance a boundary is offshore increases, the number of points on the baseline that contribute to the boundary decreases.

Effect of selection of critical points

What effect can a mislocation of any of the critical points have? Possibly the most extreme case would be a point at the end of a slender peninsula or island, from which an arc of 350M would sweep out a semicircle forming an outer constraint. If the point were located 10m further seawards, the difference in area that the Coastal State might claim would be only 6 sq M. Given that actual differences are likely to be much smaller than this, putting much effort into improving this it is questionable value.

What matters is the selection of points that are to be used as the ends of baselines. Most Coastal States will expend energy on some optimization strategy that maximizes the area inside the baselines. Doing so requires a careful examination of tidal datums, the presence of any physical features, and the social and economic considerations permitted. One approach is to produce a number of possible baselines and calculate the areas enclosed by each, and iteratively search for the largest. CARIS LOTS software includes this capability (van de Poll et al, 2000).

How Straight Are These "Straight" Lines?

UNCLOS does not define "straight' but implies that it means a line that appears straight on "large-scale charts officially recognized by the coastal State." Which are navigation charts. Almost all navigation charts are produced on the Mercator projection. A straight line on a Mercator chart is a loxodrome, or rhumb line, not a "straight" line on the earth, or geodesic. The CLCS, in it's Guidelines, clearly wants to use geodesics, but is restrained by state practice and costs. The Commission hedges by allowing a state to use

> "either geodesics or loxodromes. However, only one line definition can be consistently selected by a submitting State for all of its baselines. In the case of loxodromes, the

> Commission shall use the definition of a line of a constant azimuth on the surface of a geodetic reference ellipsoid. The Commission strongly discourages the use of apparent straight lines as literally drawn on various map projections."

2500 Meter Contour

Approaches to determining the 2500 m contour

Hydrographers faced with producing a 2500 m contour can either extract one from existing maps , produce one from existing data or collect an entirely new data set. The first alternative is very useful for conducting a "desk study" of the area under consideration, which can be used for planning further data collection, but is unlikely to yield results of appropriate scale for an actual submission. Uncertainty is likely to be very high. Uncertainty may be reduced by the second approach, using legacy Single-beam Echo Sounder (SBES) data, unless all of these soundings have already has been incorporated into the map used in the first approach, while the third approach, which likely means collecting new Multi-beam Echo Sounder (MBES) data, has the lowest uncertainty. The later two are examined in some detail below.

Requirements to use the 2500 m contour

Article 76 paragraph 5, is 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 emphasizes that the 2500m contour comprises both depth and connection. Potentially any mislocation 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 deserves careful consideration by hydrographers. The 2500m contour is of primary importance where it lies more than 250 nautical miles from the Baselines.

As a generalization, hydrography has traditionally been extremely concerned with the depths that might pose a hazard to surface navigation, and much less interested and involved with depths in the deep ocean.

Article 76 changes that: it requires that the 2500m contour be developed in absolute terms. The framers of the treaty could have worded it to say that the contour was derived from a depth observed on an echosounder set at a fixed velocity of 1500m/s, for instance, or they could have specified such-and-such a correction to be used, but they did not. 2500m exists in the treaty as an absolute number, and so hydrographers must be concerned with its uncertainty.

There are cases where a Coastal State has jurisdiction over the seafloor out to 2500m, and The Authority (a UN body), has jurisdiction over the seafloor beyond that. Both parties are clearly very interested in how well the depth is measured, since this line determines the limit to their "territory", which both parties will try to maximise. If a measurement were too shallow, for example, the resulting limit would give a portion of the seafloor that should have been granted to the Coastal State to The Authority, a mistake that might prove costly to the Coastal State in the future.

The CLCS issued Guidelines (United Nations, 1999) that describe the evidence they will accept in a submission for a Continental Shelf, including how the 2500m contour is to be determined. For depth measurements, the Guidelines specify the types of instrumentation that can be used (and prohibit some others), define a bathymetric database and its contents, require that estimates of errors be made by the submitting Coastal State, and define how those estimates are to be made. The CLCS expects that the 2500 m contour will be produced from these measurements, and specifies the use of a Bathymetric Model, including cartographic products that will be accompanied by a detailed description of the mathematical methodology and data used to produce it. The Guidelines insist that

> "The Commission may require geostatistical, fractal, wavelet or other tests and analyses, as it feels appropriate, in order to determine the degree of <u>uncertainty</u> underlying a particular bathymetric model."

They do not say what the uncertainty should be, nor what they will do with the results of any such determination: the first case to be submitted to them may test this.

Uncertainty in the 2500m contour is effected strongly by two variables, roughness of the seafloor over a range of scales, and gradient of the seafloor.

<u>Uncertainty due to seafloor roughness</u>

At a gross scale, in areas of complex seafloor morphology, uncertainty arises from trying to decide which sections of the 2500m contour to use. There are many areas where 2500m contours surround "submarine elevations" that are morphologically isolated from the contiguous Continental Slope, yet are close enough to it that a Coastal State is justified in claiming that the elevation forms part of the "natural prolongation' of the land territory. If this can be established, then presumably the 100M seawards is measured from the 2500m contours that fringe the isolated submarine elevations. The sketch maps in Figure 4 illustrates a case in Canadian waters. Orphan Knoll is a seafloor elevation surrounded by a 2500m contour. As can be seen, the area that may or may not lie on the Canadian Continental Shelf, depending on whether Orphan Knoll can be used, is of considerable size.

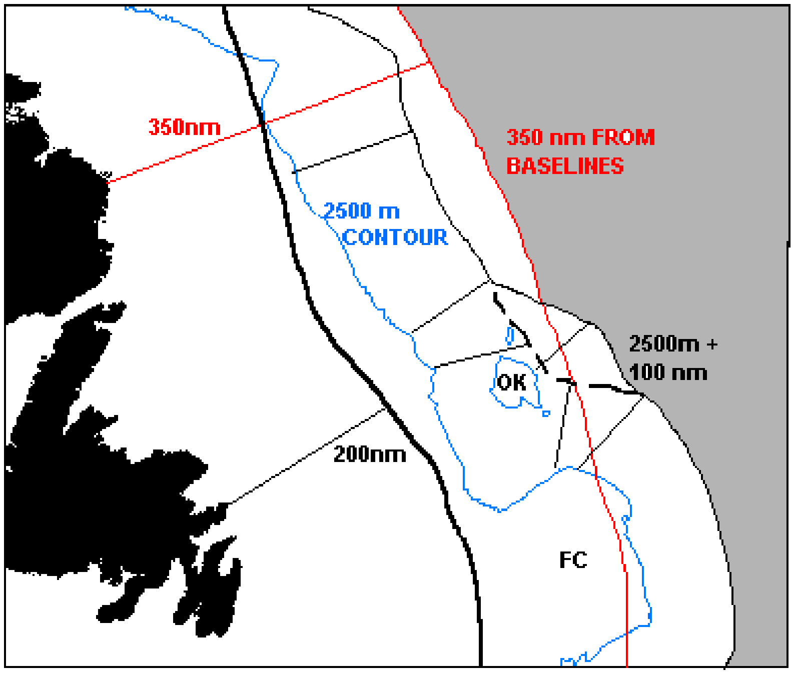

Figure 4 Sketch map showing the zone within which a claim for extended jurisdiction may fall. The inner heavy line is 200nautical miles from the baselines along the shore. The thin blue line is the 2500m contour with a constraint line drawn 100nautical miles seaward of it. Note that in the area of Orphan Knoll (OK), this line is shown in two locations, depending on whether the isolated 2500m contour surrounding Orphan Knoll is used or whether the 2500m contour conterminous with the shelf is used as a basis for projecting 100nautical miles seaward. The thin red line is the 350nautical miles from the Baselines constraint line. The outer limit is constrained by the outermost of these two.

There are also areas where the 2500m contour doubles back on itself parallel to the Continental Slope, and Coastal States will attempt to show that the outermost section of contour should be used. It is evident from the Guidelines (United Nations, 1999) Paragraph 4.4.2, that this will not be accepted automatically by the CLCS, and that the Coastal State will have to demonstrate why the closest landward section should not be used.

Uncertainty introduced by questioning whether or not a feature can be used, or which meander of a contour is the critical one, is considerably greater than any introduced through measurement errors. However, we are not very comfortable with them, since they cannot be quantified. We recognize their importance and the major impact they can have.

As the scale of investigation is enlarged, roughness caused by the presence of smaller features than isolated elevations manifests itself through increased sinuosity of the 2500m contour (assuming there is sufficient data to support the new scale). With increasing scale, smaller and smaller physical features manifest themselves as convolutions in the contour. One challenge is to find a scale appropriate to displaying the 2500 m contour adequately. The framers of Article 76 may have given some guidance since they specify in Paragraph 7

> "The coastal State shall delineate the outer limits of its continental shelf …by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by co-ordinates of latitude and longitude."

Although the outer limit will be smoother than the 2500 m contour, any line defined at point 60M apart is not very sinuous, and can be portrayed at a small scale. on the other hand, a Coastal State seeking the maximum seaward extent of it Continental Shelf will want to select the fixed points carefully, and will probably want to conduct a large scale search to determine which are the most seaward. "Large-scale" in this context means MBES and the use of MBES in 2500 m contour delineation has been described extensively by Hughes Clarke, 2000, who concludes that

> "local absolute maximum protrusions of this discrete contour line can be identified".

His conclusions were tested for an area off New Jersey, USA, by Monahan and Mayer, 1999, 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 contours and found that they occupied a corridor approximately 10 km wide, a value that corresponds well with the horizontal uncertainties shown in Table 8. The MBES- derived contour wove itself through this zone of uncertainty, occasionally, perhaps 5% of the time, "protruding" landward or seaward from the zone. Selecting these seaward-protruding points could contribute to the outer limits by producing a 2500m contour that could be hundreds of meters to several kilometers seawards from the contours derived from other survey techniques.

We return to the issue of scale under the discussion of Foot of the Slope.

<u>Uncertainty due to seafloor gradient</u>

The classic Continental Slope and Continental Rise, have very low gradients which contribute to the second source of uncertainty. Pratson and Haxby, 1996, probably began the modern era of measuring gradient when they compared both regional and local gradients as measured by MBES over five portions of the US Continental Slope. The steepest area they examined was off New Jersey; there they measured a regional slope of 2.5 degrees and a local slope of 7.6 degrees. Monahan and Mayer, 1999, processed the same data and produced color intensity slope maps demonstrating that the locally steepest areas were on the canyon walls and that the lower gradients occurred down-slope from the canyons. Neither paper attempted to map the Continental Rise. Accurately locating a contour on such low gradients is extremely demanding on measurement systems.

A depth is the length of a perpendicular line between a smooth horizontal surface, the sea surface, and a rough sloping surface, the sea floor. There are a number of ways that measurements are taken to arrive at this depth and an examination of their geometry can illustrate where individual errors impact overall uncertainty. The vertical case, analogous to a SBES recording a least depth directly below it, or depths measured by near-nadir beams of an MBES, represents the simplest case. Here, the length of the perpendicular line is being measured directly, and any uncertainty in its length means that the contour will be displaced upslope or downslope 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 / tangent of bottom slope). (Figure 5)

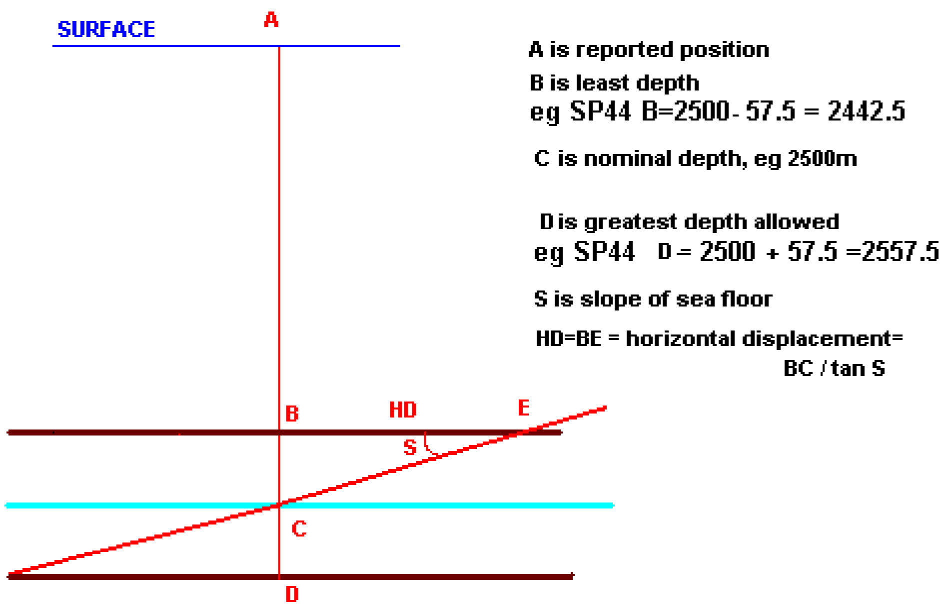

Figure 5 (after Monahan and Wells, 1999) Geometry of horizontal displacement caused by uncertainties in measuring 2500m.

Because the gradient of the sea bottom is so small, horizontal displacement can be quite large. To illustrate this, Table 3 shows the effect of errors of 1% of depth, which was the requirement under IHO S-44 Edn 3, and 2.3% of depth, the requirement under IHO S-44 Edn 4, (International Hydrographic Organization, 1998). In the Table, seafloors slope at 1° typical of many areas of the Continental Slope, and at 2.5 and 7.6 degrees, corresponding to Pratson and Haxby's, 1996 regional and local maxima for the US Continental Slope.

Table 3. Horizontal displacement of the 2500m contour, as a function of the seabed slope and depth measurement errors.

Vertical Error	Percent of Depth	Horizontal displacement on seafloors sloping		
		1 deg	2.5 deg	7.6 deg
m	%	m	m	m
25.00	1.00	1433	568	188
57.50	2.30	3295	1307	432

Elements That Contribute To the Uncertainty of A Single Depth Measurement

Continuing with the simplistic model of depth as the length of a perpendicular line, uncertainties in measuring it are composed of fixed (sometimes referred to as constant) errors and those errors that vary with depth. Paragraph 4.2.8 of the Guidelines (United Nations, 1999) accepts this and instructs that

> "A priori depth error estimates may be computed by means of the following internationally accepted formulae s = square root of(a squared + (b d)squared)
> where:
> > a = constant depth error, i.e., the sum of all constant errors
> > bd = depth-dependent error, i.e., the sum of all depth-dependent errors
> > b = factor of depth-dependent error; and
> > d = depth,
>
> with a 95 per cent confidence interval (IHO, 1998)."

The Guidelines do not specify what values for "a" and "b" are acceptable, but since they refer to Special Publication 44 (S44) of the International Hydrographic Organization (IHO, 1998) it is reasonable to assume that the values in S44 are those to be used. <u>We agree that use of the formula is appropriate but believe that the values for "a" and "b" included in S44 were not intended for, nor are they suitable to, Law of the Sea purposes.</u>

S44 provides performance specifications for surveys undertaken for hydrographic purposes to strive to attain by giving the relative sizes for the two types of errors, arranged in four classes or "Orders" of survey. Hydrographic surveys are not normally carried out in 2500m of water, at least not for navigation purposes. Only the lowest (Third) Order surveys apply to depths as deep as 2500 m, and for them at this depth the constant error (a in formula) should be ±1.0m or less, while the variable errors (bd in the formula) can be as large as (.023 x 2500 =) ±57.5m. Combining the two as RSS yields 57.5086m, confirming that at these depths the constant errors are negligible. The last row of Table 3 shows some of the horizontal displacements that variable errors of the permitted magnitude would produce over various seafloor slopes. An examination of the components of the variable error indicates how this can be reduced, and why we believe that smaller values should be used.

Variable Error 1: The effect of sound speed in the vertical case

Since depth reported depends directly on sound speed, how accurately the profile of the speed of sound as a function of depth in seawater is known will effect the accuracy of the depth measurement. In shallow water hydrography, sound speed profiles can be measured directly during the survey, and echo sounders or soundings adjusted through a variety of methods. How often should this be done? Traditionally, for SBES surveys, Standing Orders would specify intervals of measuring sound speed as times like the beginning and end of each survey day. MBES use is forcing a re-examination of this, and naturally most of the results to date come from shallow (less than 200m) water. For example, during a recent survey, Hughes Clarke ***et al***, 2000, measured salinity and temperature continuously over Georges Bank and concluded

> “the water column was varying significantly over length scales of as small as a few 100 metres”.

In another experiment, Wells (unpub), plotted 12 sound speed profiles from the same location taken over a period of 140 days and showed that in the upper 30 meters or so, their maximum speeds varied from 1468 to 1511m/s. These shallow water results indicate that to reduce uncertainty from both spatial and temporal variability, speed must be measured at a frequently that matches that of the expected variability of the water column.

It is generally believed that the water column to depths of 2500m should be more stable, and therefore predictable. Below one or even two hundred meters depth, the water column tends to change but little, and since the speed required for a depth measurement is calculated as the harmonic mean of the entire sound speed profile, the variability in the upper layer is usually dampened. However, direct measurements of sound speed to confirm this are not as easily obtained in deep water, so that traditionally SBES were set to a fixed sound speed (1463 or 1500m/sec) and depths corrected using tables (usually Carter, 1980). These divide the oceans into areas of similar velocity, based on historical averages, and under stable water conditions, these tables produce depth corrections good to ±5m. However, over some areas that contain the 2500m contour and the Foot of the Slope, ocean currents converge to form an Intense Frontal Zone in which depth errors of ±10 metres can be expected in tabulated speed corrections for these zones. Most of the SBES data that currently exists over the continental slope will have sound speeds that are known no better than this and perhaps not as well. Table 4 shows the horizontal displacement caused by uncertainties in sound speed over bottoms having different gradients.

Table 4. Horizontal displacement over seafloors sloping 1, 2.5 and 7.6 degrees caused by sound speed variations. Note that an error of 34m/s, in the absence of any other errors, would cause a sounding to lie outside the limits of S-44.

Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal displacement on seafloors sloping		
				1 deg	2.5 deg	7.6 deg
m/s	m	m	%	m	m	m
3	5.00	5.00	0.20	287	114	38
6	10.00	10.00	0.40	573	227	75
34	56.67	56.67	2.27	3247	1288	426

These possible displacements can be minimized through reducing the uncertainty in sound speed determinations. Where legacy data from various sources are assembled together and adjusted or gridded, it is assumed that some of the uncertainty is removed, or at least made consistent. For future data collection, several options may be applied. Frequent or continuous measurement of deep-water sound speed profiles is claimed to be possible with new instruments. MBES could be deployed in AUV platforms operating below the surface layer where most sound speed variability occurs. Existing sound speed models and correction techniques could be improved. Carter, 1980, is a condensed synopsis of large databases of oceanographic CTD casts. Accessing these databases will reveal the seasonal SSP variations and indicate where in the water column they occur. Each carries with it its own uncertainty budget, of course, and the contribution each could make would have to be carefully balanced against costs and ease of deployment.

<u>Variable Error 2 - The effect of beam width</u>

We now expand our examination of the geometry of the measurements taken to arrive at a single depth, from the oversimplification of considering the sound emitted as a single ray. The concept of “beam width” is a closer approximation to what really happens to sound in water as it propagates in a beam-like pattern that expands with distance from the face of the transducer. “Beam width” is defined as twice the angle between a line perpendicular to the center of the transducer face and the point where the energy contained in the beam is reduced to half that at the perpendicular. 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.

Beam width effects uncertainties in three ways: a) it can introduce horizontal displacement when the seafloor is sloping, b) it can smooth the shape of large features and c) it can obscure features whose wavelengths are less than twice the ensonified area. Effects b) and c) are discussed under Foot of the Slope, while Effect a) is illustrated in Table 5. The first row shows this effect for a beam width of 30 degrees, a width that typifies most of the legacy data over continental slopes, and which may produce considerable horizontal displacement. The second row shows that a 24.5 degree beam width just meet S44, while the third row illustrates the effect that would be generated by a modern MBES system. (in fact some MBES claim a beam width of 1.5 degrees)

Table 5. Horizontal displacement over seafloors sloping 1, 2.5 and 7.6 degrees caused by beam width at 2500m depth.

Type Of Equip.	Radius ensonified	Nominal beam width	Beam angle effect	Vertical Error	Percent of Depth	Horizontal displacement on seafloors sloping		
						1 deg	2.5 deg	7.6 deg
	m	degrees	m	m	%	m	m	m
SBES	670	30	85.19	85.19	3.41	4882	1936	640
S44	543	24.5	56.92	56.93	2.28	3263	1294	428
MBES	44	2	0.38	0.38	0.02	22	9	3

<u>Variable Error 3: The effect of sound speed in the off- vertical case</u>

The section on beam width shows that, from the geometric point of view, within any one of its extremely narrow beams, MBES is susceptible only to inconsequential uncertainties from this source. However, this may be counteracted to some extent by an uncertainty introduced from a source not present in SBES. As soon as a sound beam is turned away from the vertical and projected at some shallower angle, the harmonic mean of sound speed as it passes through horizontal water layers of different speeds, which was implicit when discussing the effect of sound speed in the vertical case above, is no longer the only sound-speed phenomena the beam encounters. Since the seawater usually exhibits a turbulent or mixed upper layer, with high sound speeds, underlain with an intermediate layer of lower speeds, beneath which is the deep and usually stable deep water, beams projected at angle can be bent as they travel away from the transducer. Figure 6 summarizes the geometry of this case.

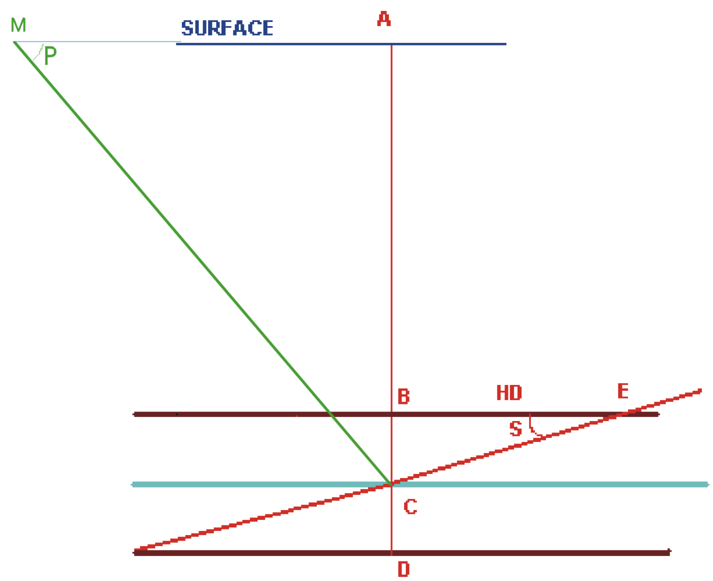

Figure 6. Geometry of MBES sounding. The transducer is at M and measuring the depth AC. Uncertainties come from measuring the angle P, the bending of the ray MC due to sound speed variability and the slope of the bottom, S.

Summary of uncertainties in a single measurement

Sound speed and beam width are the principal variable errors. There may be minor variable error contributions such as the precision to which depths could be manually scaled from the paper trace on old echo sounders (Hare, 1997), but this will be minor. Otherwise, sound speed and beam width combine as RSS to form an error budget for a single measurement of 2500m, Summarized in Table 6 are some values achievable with echo sounding equipment of various types. In practice, these values must be calculated for all the data used in preparing a map.

Table 6. Typical combined magnitudes of horizontal displacement over seafloors sloping 1, 2.5 and 7.6 degrees caused by beam width, sound speed variations and fixed errors.

Fixed errors	Nominal beam angle	Beam angle effect	Sound Speed Var'n	Sound Speed error	Vertical Error	Percent of Depth	Horizontal displacement on seafloors sloping			Radius ensonified
							1 deg	2.5 deg	7.6 deg	
m	degrees	m	m/s	m	m	%	m	m	m	m
1	30	85.19	15	25.00	88.78	3.55	5088	2018	668	670
1	15	21.39	10	16.67	27.13	1.09	1555	617	204	329
1	2	0.38	2	3.33	3.50	0.14	201	80	26	44

Contours from individual depth measurements

The preceding section showed how uncertainties in individual depth measurements manifest themselves as possibly significant horizontal displacement of the location of the depth. Article 76 goes beyond individual depths and requires the 2500 m contour, probably derived from those depths. and the method used to produce it can lead to further uncertainty. Monahan, 2000, discusses contouring of deep-sea data and Table 7, extracted from Monahan and Wells, 1999, list the many factors that can contribute to uncertainty of deep contours.

Table 7. 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 Honoring Data Size of the grid cells if gridding used
Complementary information	bottom composition sidescan predicted (satellite) bathymetry

How large an uncertainty can these factors combine to make? S44 appears to offer error magnitudes for contours under the heading of “bathymetric model”. This model appears to use similar reasoning to that used for single depths, and has considerably larger values for the variable ‘a’ and ‘b’, as summarized in Table 8. It is not immediately obvious how these larger numerical values equate to the factors listed in Table 7, and the Bathymetric Model should be tested against some real seafloor geology before it can be properly evaluated.

Table 8. S-44 Depth and Bathymetry Model fixed error and variable factor. Uncertainties at 2500m are calculated from these values.

ELEMENTS		S-44 ORDER				S-44 ORDER			
		Special	1	2	3	Special	1	2	3
		Depth Accuracy				Bathymetric Model			
Fixed Error		0.25m	0.5m	1m	1m		1m	2m	5m
Variable factor	x depth	0.0075	0.013	0.023	0.023		0.026	0.05	0.05
Vert. Uncertainty at	2500m				57.5				125.1
Horizontal Uncertainty	2500m								
Bottom Slope	1 deg				3295				7167
	2.5 deg				1317				2865
	7.6 deg				431				938

Since MBES is not required by Third Order, it is assumed that the values are to be applied to contours derived from collections of traditional SBES individual tracks. Contours, or contour-like-objects, produced by a single MBES survey are likely to be significantly better.

Foot of the Slope

UNCLOS recognized that the oceanic crust was fundamentally different from that underlying the continents and that States were entitled to claim the continental portion. As a principle, the Foot of the Slope represents a starting point for differentiating continental rocks from oceanic ones. Coastal States can use the Foot of the Slope plus 60 M or the sediment thickness line whose derivation is based on the Foot of the Slope.

What exactly is the Foot of the Slope? Paragraph 4(b) of Article 76 defines it as

> "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. Paragraph 7 points out that a State need only delineate the Foot of the Slope by points up to 60 Miles apart. Clearly there is no "exact" Foot of the Slope but a zone in which judgment must be applied to determine the most likely location of this feature that marks the edge of the continent.

The CLCS Guidelines accept that finding the Foot of the Slope will be difficult and describe it as a two-step process. Paragraph 5.1.2 interprets that Article 76, Paragraph 4 (b)

> "provides a *dual* regime for the determination of the foot of the continental slope",

which requires

> "The identification of the region defined as the *base* of the continental slope"

within which the Foot of the Slope can lie. In those cases where delineating a "base region" will be apparent from simply the surface expression of the sea floor (i.e. morphology and bathymetry), the base so mapped can become the area in which the search for the point of maximum change in the gradient is carried out. On the other hand, should these parameters not yield a "base", then evidence to the contrary in the form of geology and geophysics may (have to) be invoked.

The geometry of the situation, although not particularly complicated, poses some real problems in depth sounding, surface depiction, and feature recognition. Generally, the sea floor slopes gently downward from the physical Continental Shelf to the deep ocean floor. Gradients are commonly 1-2 degrees. The seafloor is interrupted locally by canyons, slump features, and mass-wasting scarps. After a distance that may be tens or even hundreds of kilometers, the gentle descent ends and the seafloor becomes almost horizontal. According to the UN Guidelines there may be 'base region' containing the Foot of the Slope, and at some scale this will be true. In reality, the Continental Slope does give way to the Continental Rise or to the deep sea floor and at small scales where this occurs this will appear to be a region. Will larger scales reveal a single physiographic feature that can be termed the Foot of the Slope within this base region, or is the Foot of the Slope simply a useful diagrammatic concept with no physical reality? Will the transition between descending seafloor and horizontal occur in a region of rough physiography or will there simply be a smooth transition with no identifiable surface expression? We predict that the areas where a physical feature which can be unambiguously labeled the Foot of the Slope occurs will be greatly outnumbered by those which have no discernable Foot of the Slope.

Following is an evaluation of some approaches to possibly detecting and mapping the Foot of the Slope, or of showing that it does not exist. They are arranged from small scale to larger, except for mathematical approaches for which scale may or may not exist.

Contoured Bathymetry Maps

Conventional hydrographic navigation charts are not intended or designed for this purpose. On the other hand, contoured bathymetry maps are readily available, are in widespread use and exist as international series (e.g. GEBCO,1997), covering the margins of all nations. Gradients are steeper where contours are closer together and less steep where contours are further apart, so that the Base of the Slope zone, and possibly the Foot of the Slope, may in theory be shown in the region where the relatively closely spaced contours of the Slope widen apart as they depict the Rise or the Abyssal Plain. The horizontal scale of bathymetry maps covering the Slope and Rise is usually quite small, with 1:250 000 being the best and 1:1 000 000 and smaller being more usual, so that the width of an inked line designating the Foot of the Slope line will represents a zone several hundred meters wide on the sea floor. The vertical scale is predetermined by the contour interval in that a Foot of the Slope line can only be located somewhere between two contours. Although the actual dimensions are not too important while *seeking* a feature like the ‘base’, they may be too crude to *portray* the Foot of the Slope, if it is found.

Since the Convention requires that the outer limit be defined at points as widely separated as 60M, it could be argued that this scale of presentation is all that the crafters of the treaty envisioned as being necessary. Since then, the Commission’s Guidelines seem to indicate that a much greater level of detail is required.

Small-scale bathymetry maps are very useful for desk studies that can probably identify the base region as well as it can be defined and as well as it needs to be defined.

Echo-Sounding And Seismic Profiling

In addition to bathymetry maps, a certain quantity and spatial arrangement of echo-sounding and seismic profiling records will already exist for the margin of a Coastal State. (Holcombe and Moore, 2000, Monahan and Macnab, 1994).These are a digital or analogue cross section of the sea floor as measured by the instrument along the track followed by the ship, and have not been subject to the filtering inherent in producing a contoured map. Since echograms may have been collected randomly by different ships in different years, or have been collected before the actual slope was known, they might not run perpendicular to the Slope, which may make detection of the Foot of the Slope even more difficult. The beam width effect discussed above can also limit the profile's ability to detect small features. Tables 5 and 6 in the column entitled "Radius ensonified" illustrates this effect at 2500 m depths, and Foot of the Slope will usually be deeper and thus produce larger numbers than those shown. In effect, the ensonified area acts like a spatial filter smoothing out any features of that size or smaller. It will also make a feature detected on a narrow beam sounder difficult to trace onto profiles measured with a wide beam sounder. Against that, one must weight the fact that the profile is as original a piece of data as possible. The echogram is what the instrument recorded, and that may be paramount in cases of dispute.

Profiles can be examined, by eye or by mathematical techniques, to pick changes in gradient, which may be interpreted as the Base or the Foot of the Slope and possibly correlated from one profile to the next. Visual inspection of analogue records can be carried out by searching the paper trace for all changes of slope that might intersect the possible Base of the Slope zone identified from examination of bathymetric maps. One record alone is unlikely to prove sufficient, but if a similar feature occurs on adjoining traces, then it is possible that the feature is continuos between them. Candidate points are selected, and there may be more than one per echogram, and plotted onto a bathymetry map to help determine continuity between the possible points. Continuity does not guarantee that the points chosen represent the Foot of the Slope, but strong continuity is a major contributing factor. Although using existing data this way can be very valuable to investigators, it must be noted that the Guidelines point out in paragraph 5.4.7.

> Methods based on a purely visual perception of bathymetric data will not be accepted by the Commission.

The same paragraph points out

> The determination of the location of the point of maximum change in the gradient at the base of the continental slope will be conducted by means of the mathematical analyses of two-dimensional profiles, three-dimensional bathymetric models and preferably both.

What would a "mathematical analysis of a two-dimensional profile" consist of? In CARIS LOTS, and no doubt in other software, a function exists that will produce a continuous graph of the second derivative of the curve representing the sea k floor: in theory, it peaks at the max change of slope. In practice, this approach produces multiple peaks, one of which must be selected (visually) as corresponding to the Foot of the Slope.

Multibeam Surveys

Mapping the Foot of the Slope from MBES surveys has been addressed extensively by Hughes Clark 2000. Initially, it appears that the advantages of multi-beam surveys are the complete coverage as well as the much finer resolution that they provide. (see Table 5 and 6 column entitled “Radius ensonified”). While this is clearly an advantage over SBES in delineating the 2500 m contour, at times MBES data may be too detailed to isolate one feature as the Foot of the Slope out of the several changes of slope that it reveals. The main disadvantage of this type of data is that there is not yet much coverage available on a world wide scale.

Mathematical and Statistical Techniques

The three approaches above have been arranged in order of the increasing detail they return. It is not always obvious where mathematical and statistical techniques fit in the spectrum of scales: some are crude and offer only low level of detail, while others are locally very detailed. The Commission insists that mathematical techniques must be used to determine the Foot of the Slope, mentions one or two, then states that it does not favor any one approach and that it will examine any approach used in a submission as long as it is well described. Statistical techniques complement mathematical techniques, providing estimates of uncertainty to temper the impression of exactness coming from the application of mathematical estimates.

These devices operate on numerical values, the basic numerical value being the raw sounding. In two dimensions, tools like CARIS LOTS (ref) can automatically scan a profile of raw soundings and calculate and plot the second derivative of the gradient: in theory, maximum second derivative corresponds to max change of slope. In three dimensions, it is possible to operate on a geographic array of soundings as they were collected. Unfortunately, the irregular spatial arrangement of older soundings is often not conducive to numerical processing, and consequently a regular grid of derived depth values must be created. Doing so involves numerous calculations based on the original data. Factors that go into the calculation of grid values include: number of real soundings to be included in each calculation, contribution of distance from grid point to real soundings, importance of isolation or clustering of real soundings, and method of curve-fitting to real soundings and candidate grid point. Grids can also be constructed from contour maps, meaning that they are at least one step further removed from the original data. In this case, the values of nearby contours, rather than soundings, contribute to the calculated grid. Grid size must be selected with care based on what the data will support and the risk of aliasing, the introduction of false wavelengths, must be avoided. These must be evaluated carefully when the grid is being used as the scale at which the results of operations can be shown on depends on them. Mutlibeam sounders avoid the additional steps of gridding since they produce a data set that under ideal conditions is a regular grid, and under poor conditions does not depart significantly from one.

From such grids, one can use a number of mathematical techniques to estimate the position of the Foot of the Slope. Bennett, 1998 and Hughes Clarke, 2000, for example, calculated the surface of the second derivative through each point, and used the crests of the calculated surface to locate a maximum change of slope. Vanicek *et al* 1994, used least squares to fit surfaces of various orders to sounding data. Other approaches are being developed and can be expected to appear in the literature in the next few years.

Conclusions

a) hydrography has a major role to play in defining a Continental Shelf under Article 76
b) hydrography has an official role to play in Article 76 and other Articles of UNCLOS
c) mapping deep water is not the same as mapping shallow water – deep water needs oceanographic and geological input
d) measuring shape is more than just recording numbers, and the scale of the Foot of the Slope is a determining factor
e) uncertainties in measuring any of these elements can lead to horizontal displacement of the boundaries of Coastal States that can amount to significant areas
f) there is a need to add to S44 or create an entirely new standard for mapping in deep water

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