Read at the Annual Conference of the Ussher Society, January 1988

Seismic characteristics of buried rock-valleys in Plymouth Sound and the River Tamar

R.D. EDDIES and J.M. REYNOLDS

Eddies, R.D. and Reynolds, LM. 1988. Seismic characteristics of buried rock-valleys in Plymouth Sound and the River Tamar. Proceedings of the Ussher Society, 7, 36-40.

Recent high-resolution seismic surveying of Plymouth Sound has established the existence of an extensive system of buried rock-valleys which extend northwards into the River Tamar. In June 1987, two site-specific surveys were undertaken to investigate the sediment infill of the buried rock-valleys within Plymouth Sound. A preliminary interpretation of the data obtained has indicated the existence of at least three major acoustic facies, namely, bedrock, a complex of several seismic sub-facies within the main sediment body and a drape of modern estuarine sediments. These sub-facies indicate a possible point bar sequence and at least one major incision event. In order to translate the facies interpretation into a geological model, two boreholes have been drilled at the sites already surveyed. The resulting analysis of the core lithostratigraphy will facilitate the geological interpretation of a further 150 line-kilometres of seismic profiles obtained in Plymouth Sound. A map of posted Two-Way Travel Times for the intrepreted sediment/bedrock interface for the Hamoaze reach of the River Tamar reveals a rock-valley to the East of Inswork Point for which there is now no surface expression. Two creeks which drain eastwards into the Hamoaze from Millbrook and St. John's Lake have downcut only through the surficial sediments. The latter creek appears to have migrated north-eastwards and a small infilled gulley has been found nearby. The differences between the present-day drainage and that inferred from the seismic data demonstrate that although the River Tamar appears to have been dominant throughout, local tributaries have changed considerably. The acquisition of a digital seismic database for the areas adjacent to the boreholes in Plymouth Sound will form an integral part of a quantitative investigation into the seismic attributes of unlithified sediments. Comparisons with the existing analogue database will allow an assessment of the accuracy in and limitations of the interpretation of analogue seismic data.

R.D. Eddies and J.M. Reynolds, Department of Geological Sciences, Plymouth Polytechnic, Drake Circus, Plymouth PL4 8AA.

Introduction

It has been known for many years that buried rock-valleys exist in many of the estuaries in south-west England (Colenso 1832; Codrington 1898; Worth 1898). The material which infills the channels had not been studied in much detail until the work by McFarlane (1955) and by Durrance (1969, 1971). As part of an integrated study of Start Bay, east Devon, by the Institute of Oceanographic Sciences (Hails 1975), Kelland (1975) identified more buried channels. The bases of the channels grade generally to a depth of about 42-46m below Ordnance Datum (Clarke 1970; Kelland 1975). A similar depth was calculated for the base of a buried cliffline found south of Plymouth by Cooper (1948). Since 1984, high-resolution seismic reflection surveys have been undertaken by the Department of Marine Science and Technology for specific geological research projects for the Department of Geological Sciences at Plymouth Polytechnic (Roxborough 1985; MacCullum and Reynolds 1987). Since 1985, the seismic surveys have concentrated on investigating the nested buried channels found within Plymouth Sound (Reynolds 1987), and the subsurface features of the Hamoaze at the southern extent of the River Tamar.

The purpose of this preliminary paper is to examine aspects of the seismic stratigraphy of the surveys within Plymouth Sound, aspects of channel development within the Hamoaze and to highlight certain general problems associated with their interpretation.

`Buried channels' or 'rock-valleys'

The term 'buried channel' has been extensively used in several investigations of river valleys which were drowned during the Flandrian transgression (McFarlane 1955; Durrance 1969, 1971). However, the term `buried channel' should not be used unless the sub-surface features can be attributed to channel processes. Instead, we have adopted Codrington's terminology (Codrington 1898) buried 'rock-valley' which describes a broad depression with low relief in the bedrock. The sediment infill within a buried rock-valley is referred to as 'valley-fill'.

Seismic data acquisition and processing

Analogue seismic data were obtained using a sparker source and an 8-element hydrophone array both of which were towed aft of the Plymouth Polytechnic catamaran M. V. Catfish. Details of the configuration of equipment are given by MacCullum and Reynolds (1987, submitted). Seismic sections were produced by direct output to the recording system as paper records. A correction was made to the Two-Way Travel Times (TWTT) to take into account changes in water depths which occurred over the duration of the survey due to tidal variations and to reduce the data to Ordnance Datum. The Two-Way Travel Times were also adjusted to those for normal incidence ray-paths to make allowance for the geometry of the source-receiver configuration. Further details of the data processing are given by MacCallum and Reynolds (submitted). For a more comprehensive account of the CSP method see, for example, Sieck and Self (1977).

An initial analysis of over 100 line-kilometres of high-resolution CSP data has revealed the existence of a north-south orientated buried rock-valley beneath the modern sediments of Plymouth Sound. The provisional lateral extent of the valley-fill is shown in Fig. 1.

Reflection characteristics and interpretation

Plymouth sound central area

The overall morphology of the buried valley-fill in the central part of Plymouth Sound is dominated by four major sub-seabed reflectors which can be seen in the representative section (Fig. 2) the position of which is marked by the line A-A' in Fig. 1. Reflector A represents the deepest of the reflectors so far identified (equivalent to a depth of about -41m O.D. assuming a seismic velocity of 1. 5km/s). From the initial results of a borehole (borehole 1, Fig. 1) drilled in February 1988, Reflector A is provisionally correlated with the top of a 2m thick gravel. The acoustic impedance contrast between the gravel and silty-clays which lie immediately above produces a reflection which effectively masks that caused by the infill/bedrock interface.

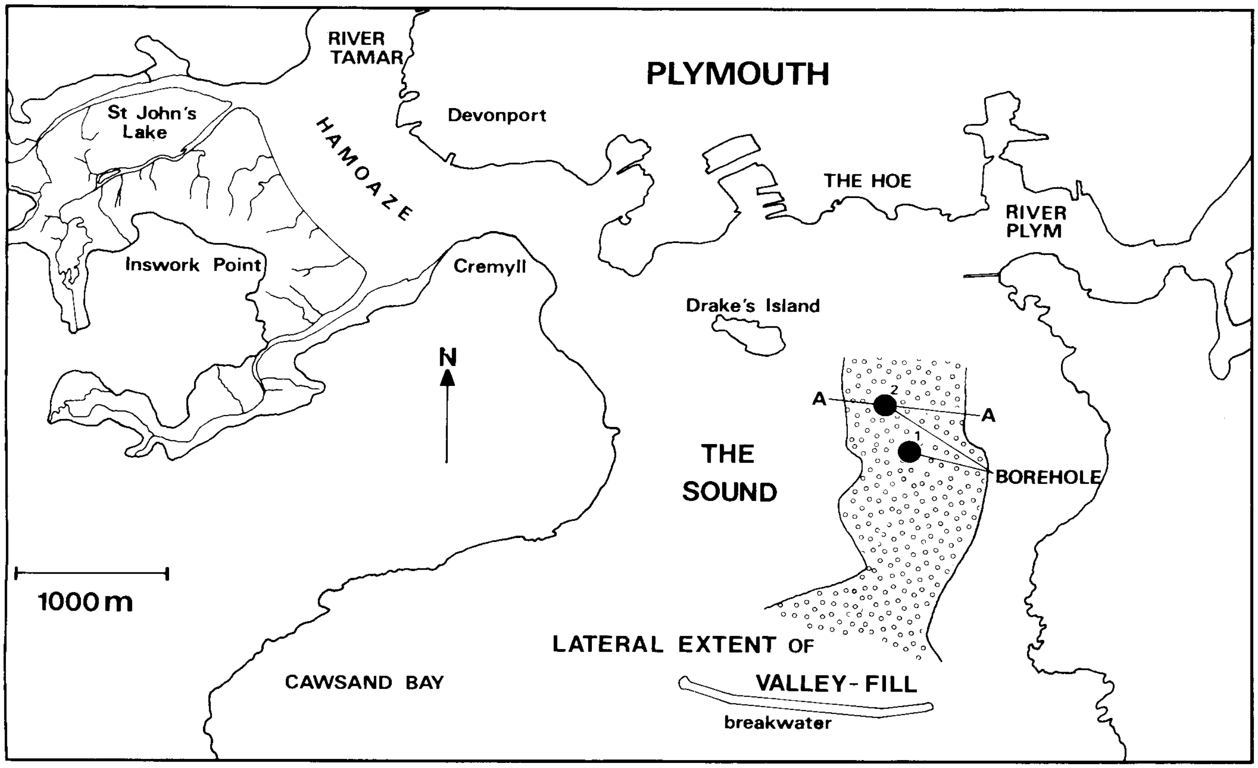

Figure 1. Map of the possible extent of the valley-fill in Plymouth Sound as determined from seismic profiling. The positions of two boreholes drilled in February 1988 are also shown. The seismic profile Line A-A' is shown in Figure 2.

Reflection B (Fig. 2) dips to the east from about 20ms TWTT beneath fix position 2 to about 43ms TWTT beneath fix position 10. The event has a shallower upper part which dips at about 2° and a steeper lower part which dips about 5°. This event has a lateral extent of about 350m in the line of the section. Beneath fix positions 4 and 5, Reflection B truncates a series of subhorizontal events at about 22-26ms TWTT. Reflection B is correlated provisionally with the base of sands and top of clays, an erosion surface which may extend down to bedrock (see for example at fix position 10). If so, then the vertical range of this reflection interface is at least 13m.

Reflection C also dips to the east, from about 22ms TWTT beneath fix position 6 to about 45ms TWTT beneath fix position 18. This event was calculated to have an apparent dip of about 3° over a horizontal distance of about 450m in the line of the section. The angular relationships between reflector C and the more minor reflectors immediately beneath are interpreted as indicating another easterly dipping erosion surface with a vertical component of erosion of about 10m and with bedrock being reached at about -34m O.D. beneath fix position 19.

A sequence of sigmoidal, easterly dipping events occurs above Reflection C and below Reflection D between fix positions 11 and 19. From the borehole data these are now known to be associated with a 9m thick sand unit. The sequence has a maximum lateral extend of about 350m and a maximum vertical extent of about 11m. The base of the sequence appears to be partly erosional between fix positions 12 and 15. The top of the sequence also appears to have an erosional relationship with Reflection D between fix positions 11 and 14. Each internal reflection within the sequence can be broadly divided into two parts, an upper, shallower section with an apparent dip of about 2° and a lower, steeper section with an apparent dip of about 6°, with a point of inflection in between which migrates about 120m to the east in the line of section and about 4m vertically. This sequence of reflections is interpreted as being caused by interfaces within a point bar feature although it is premature to state this categorically.

Reflection D occurs as a sub-horizontal series of half-cycles at about 20ms TWTT. The upper dilational half-cycle (white) is seen between fix positions 10 and 21, although some of the later half-cycles from the same event extend as far west as fix position 8. This event appears to be terminated near the sea bed between fix positions 6 and 8. Reflection D is provisionally interpreted as a possible erosion surface, or a surface of reworking of the channel sediments described above.

Hamoaze area

The broad morphology of the seabed is that of an incised river channel with several `deeps' which, presumably, have been scoured out by the flow of the River Tamar. Two notable `deeps' occur; one is due west of Devonport and the other is between Devonport and Cremyll. In between the two and to the north of the main river channel is a flat expanse of bedrock adjacent to Mount Wise.

The Two-Way Travel Times to the bedrock reflection within the Hamoaze area have been digitised and posted onto the track plot and contoured by hand (Fig. 3). Five `deeps' in excess of 50ms TWTT are evident corresponding to an approximate depth of-38 to -40m O.D.. This base level is comparable to that found within Plymouth Sound. The Devon margin of the channel has changed little whereas the position and shape of the Cornish margin has altered significantly. The edge of the present day channel is marked as a dot-dashed line in Fig. 3 and this can be compared with the 20ms contour. It can be seen that the present channel margin has two identations which correspond to the mouths of the present creeks which drain from St John's Lake and Millbrook (Fig. 3). The 20ms contour also reveals a channel near to that of the present one from St John's Lake, but displaced to the south west. This suggests that the creek has migrated 80m

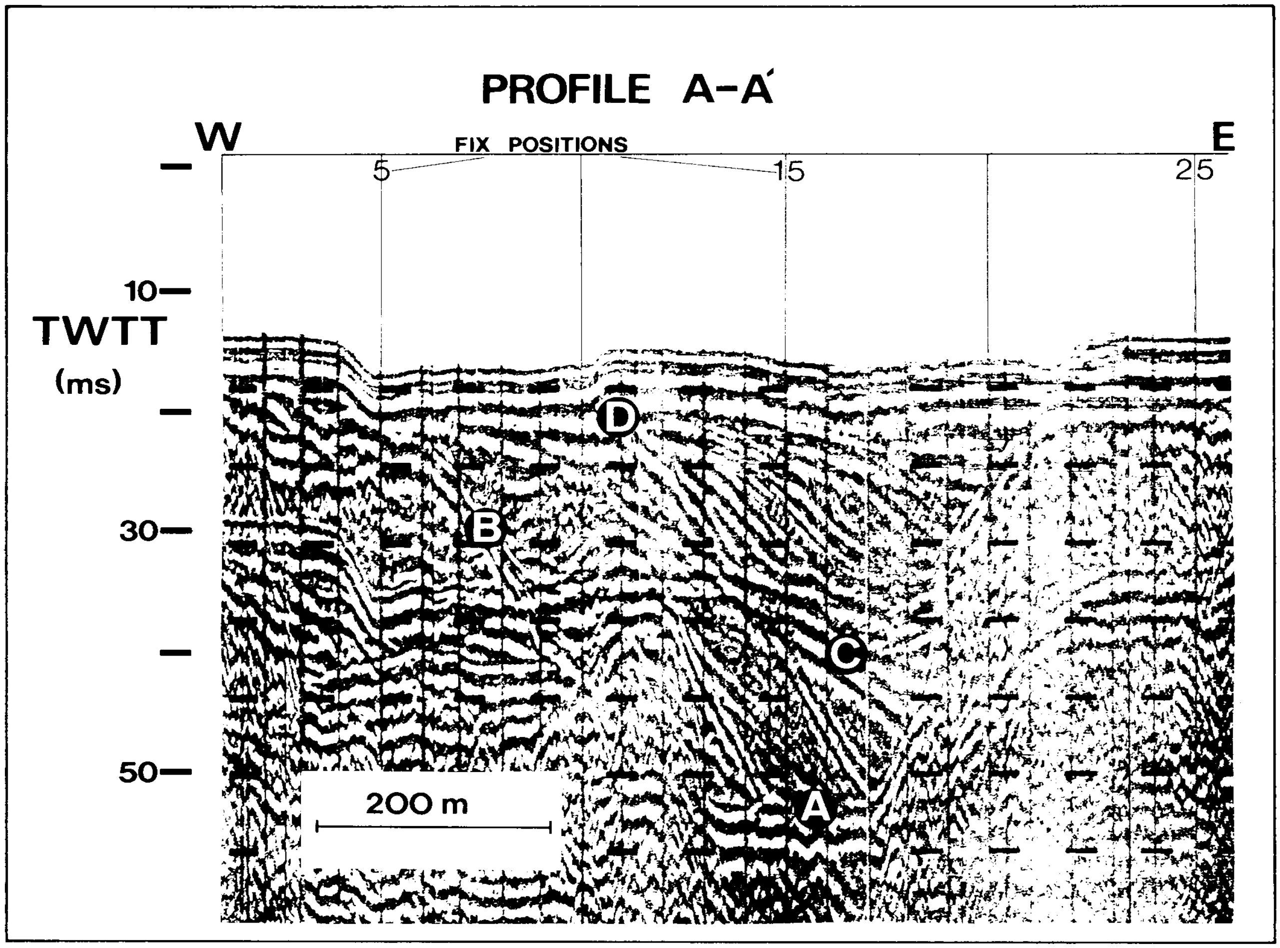

Figure 2. Seismic reflection profile across the buried rock-valley, Plymouth Sound. Principal reflections A-D are discussed in the text.

towards the north east. In addition, the 20ms contour reveals a second, but smaller creek, about 300m to the north east of the first but which is no longer evident from the seismic data. In addition, neither of these 'older' creeks penetrates to the 25ms contour level suggesting that the creeks have incised only through the sediment cover. Similarly, Millbrook creek does not appear to have incised into bedrock either as there is no indentation of the 25ms contour. In contrast, an old channel cutting down to over 35ms TWTT has been discovered to the east of Inswork Point but which is now completely covered over by mudflats and other sediments. The old channel is about 130m wide and almost 30m deep and would appear to have been more substantial than the channel associated with either the present Millbrook or the creek from St John's Lake. Whether the old creek drained from the north or from the south of Inswork Point is not known from the current seismic dataset as the area in question lies outside the survey zone. It may be that this channel has exploited a lithological boundary between Middle and Upper Devonian slates which are known to occur to the south and north of St John's Lake respectively (Geological Survey of Great Britain, Sheet 348 - Plymouth; 1:50,000; 1977). The east-west trend of major lithological boundaries locally may have influenced the similarly-orientated southern reach of the Hamoaze between Devonport and Cremyll. What is not known as yet with any certainty is whether the channel exploited Tertiary or older topographic features such as weathered fault zones or has incised its particular path since the onset of the Pleistocene. The interpretation of the seismic database tends to favour the former.

Neither is it possible to state with any certainty whether the flanks of the channel have been fault-controlled.

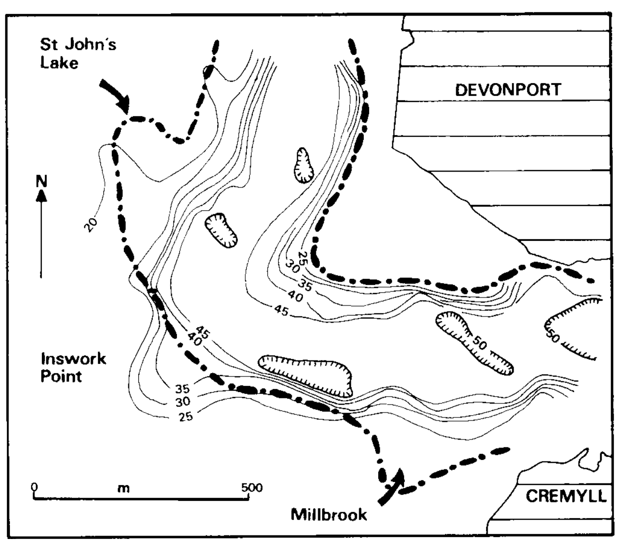

Figure 3. Posted Two-Way Travel Time map of the interpreted subsurface bedrock reflection beneath the Hamoaze. Contour interval is 5ms. The heavy dot-dashed line marks the edge of the present-day channel.

Interpretation problems

The seawater/seabed interface normally produces a reflection with a large reflection coefficient as a result of the marked contrast between the acoustic impedances of the water and sediments. Usually being the first reflecting interface beneath the source, the seabed reflection provides valuable information about the nature of the downgoing pulse, the initial wavetrain from the source and about the ghost of this initial wavetrain reflected from the sea surface. In Fig. 2 the seabed reflection occurs as a series of parallel half-cycles with a total period of 5.4ms, equivalent to about 8m total pulse length. From the extensive seismic database used for this present study, it was seen that the nature of the seabed reflection did not vary within the time span of any particular survey. However, it did vary from survey to survey particularly in the total duration of the pulse and in the number and duration of half cycles within the seabed reflection.

Fig. 4 shows parts of two adjacent but different CSP sections from Plymouth Sound acquired from two surveys in 1987 both using a 500J sparker source located at an approximate depth of 0.5m. Profile A (Fig. 4) was acquired with an input frequency range of 400 to 1500Hz; profile B (Fig. 4) was acquired with an input frequency range of 200 to 2000Hz. The difference in the seabed reflection is clearly visible between the profiles. Profile A has a seabed reflection consisting of four positive half cycles, whilst profile B has a seabed reflection consisting of three more evenly spaced but thicker half cycles. Both profiles show Reflection C (as described above) dipping to the east. The character of Reflection C in profile A (Fig. 4) is clearly different to that in profile B (Fig. 4). In the interpretation of any seismic event it is crucial to determine whether such variations are due to different source parameters or to geological factors or to both. As the source depth is shallow, the water wave motion associated with different sea states may affect the character of the ghost reflection from the sea-surface. In turn this may then affect the nature of the downgoing source wavetrain. Whilst it may be possible to correlate strong events from one survey to another using tie-lines, it would be difficult to detect more subtle changes in the seismic character of sequences between those strong events.

The seabed reflections above probably indicate that the variation in the nature of the seabed return was not a function of variation in the physical properties of the seabed, such as grain size, or bed smoothness, but was probably a function of acquisition parameters, such as actual source depth, filter settings, and the nature of the sea-surface ghost reflection. This has a major implication for seismic stratigraphic analysis of CSP data in that if the seabed event varies from survey to survey, then the nature of any sub-seabed reflector is also likely to vary. This obviously causes problems in interpretation of analogue CSP data as much interpretation is based solely on the character of reflections in the absence of amplitude information. Great care must therefore be taken in the interpretation of multi-survey CSP datasets, especially where variations of acquisition parameters have occurred.

For this particular profile, it has been shown that the sediment/water interface is capable of generating a series of several half cycles of about 5.4ms total duration, from the downgoing wavetrain of the energy from the source plus the ghost reflection from the sea-surface. The fourth black half-cycle of the seabed reflection appears to have a much longer duration than the earlier half-cycles, possibly due to constructive interference between a bubble pulse and part of the reflected ghost signal. At present it is not clear how many of the sub-seabed events are reflections of this late part of the downgoing wavetrain. Given the seismic response from the seabed, it is not possible to quantify the vertical resolution achieved within, for example, the point bar sequence at this stage of the investigation. This is primarily due to lack of knowledge concerning the downgoing wavetrain; the assumption of a zero-phase pulse to apply the quarter-wavelength rule (Sheriff 1985; Hosken 1988) does not model realistically the nature of the downgoing source energy.

The acquisition of digital seismic data from the areas peripheral to the boreholes drilled in Plymouth Sound will facilitate the use of standard processing procedures such as stacking and deconvolution. A quantitative investigation of the seismic attributes of the individual components of the detailed litho-

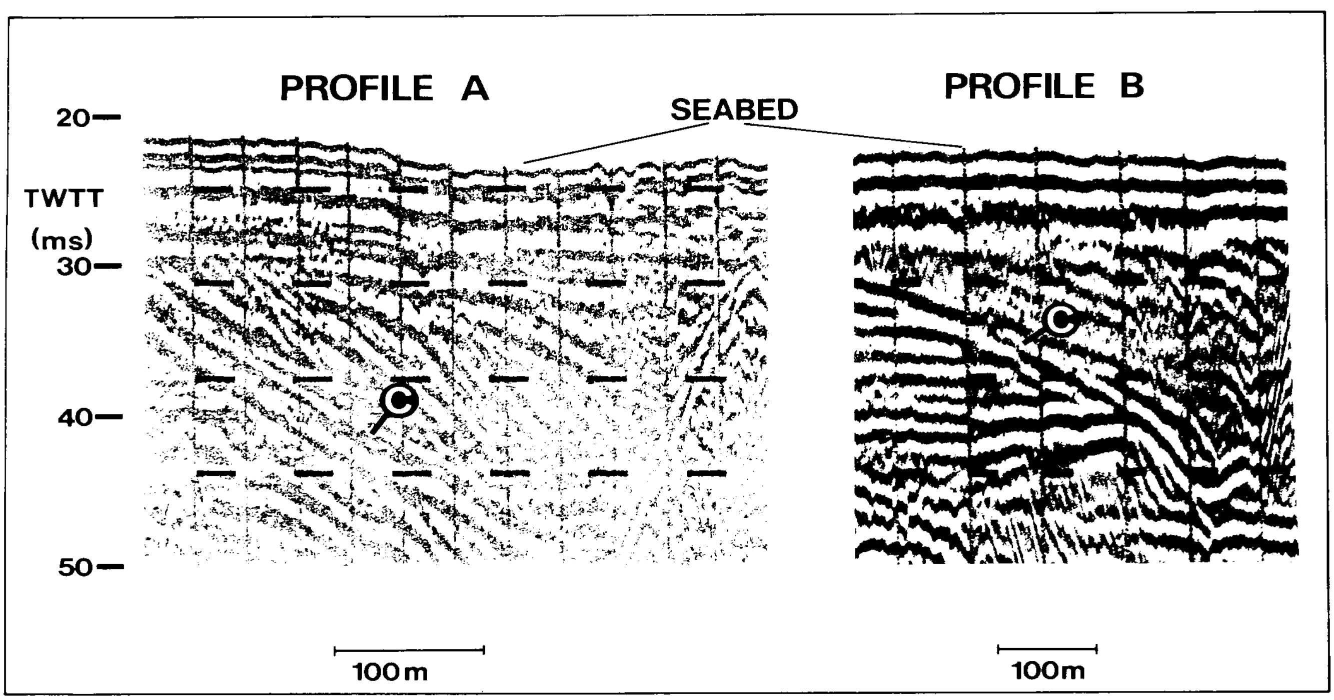

Figure 4. Reflection C as it appears on portions of two seismic sections obtained using different source filter settings. Note the difference in reflection character between the two profiles.

stratigraphy can then be carried out, which may yield a valuable insight into the limitations of interpreting analogue CSP data. These limitations would then be considered in the historical interpretation of the more extensive analogue CSP database for Plymouth Sound and the River Tamar

Conclusions

Several seismic events are laterally extensive within the buried rock-valley beneath Plymouth Sound. Given that a true threedimensional view of the buried valley-fill has not been presented, the profile has shown the presence of a buried rock-valley, with a maximum depth of about -44m O.D., containing a succession of sediments with much lateral and vertical variation in seismic character. Four major erosion surfaces have been identified, the three oldest of which show a large vertical component of erosion, despite having shallow dips. A possible point bar sequence has been identified and which has been subjected to erosion or reworking at the top of the sequence. The high-resolution seismic survey of the Hamoaze has delineated a buried rock-valley about 40m deep and that the present river channel flows within the old valley. East of Inswork Point a palaeochannel 130m wide and 30m deep has been discovered but which is now completely infilled by sediments and covered over by mudflats. The creeks draining from St. John's Lake and Millbrook have incised through only the sediment cover and have not penetrated into bedrock. The confluence of the creek draining from St. John's Lake and the Hamoaze has migrated about 80m northeastwards. A smaller creek 300m north-east of that from St. John's Lake no longer exists.

In the seismic stratigraphic interpretation of Continous Seismic Profiling (CSP) data, great care must be taken in the identification of apparent lateral changes in the seismic character of events, especially where different acquisition parameters have been involved, such as source depth, filter settings, and sea state. This paper has shown that the duration and irregularity of the complex downgoing source wavelets used in CSP work makes the quantification of vertical resolution limits difficult. However, it is hoped that a more quantitative investigation of the characteristics of the known lithologies will enhance the accuracy and resolution of the seismic interpretation of CSP data significantly.

References

Clarke, R.H. 1970. Quaternary sediments off South East Devon. *Quarterly Journal of the Geological Society of London*, 125, 277-318.

Codrington, T. 1898. On some submerged rock valleys in South Wales, Devon and Cornwall. *Quarterly Journal of the Geology Society of London,* 54, 251-278.

Colenso, J.W. 1832. A description of Happy Union tin streamwork at Pentuan. *Transactions of the Royal Geological Society of Cornwall*, 4, 29-39.

Cooper, L.H.M. 1948. A submerged cliff line near Plymouth. *Nature*, 161, 280.

Durrance, E.M. 1969. The buried channels of the Exe. *Geological Magazine*, 106, 174-189.

Durrance, E.M. 1971. The buried channel of the Teign Estuary. *Proceedings of the Ussher Society*, 2, 299-306.

Hails, J.R. 1975. Submarine geology, sediment distribution and Quaternary history of Start Bay, Devon. *Quarterly Journal of the Geological Society of London*, 131, 19-35.

Hosken, J. W.J. 1988. Ricker wavelets in their various guises. *First Break*, 6, 24-33.

Kelland, N.C. 1975. Submarine geology of Start Bay determined by continuous seismic profiling and core sampling. *Quarterly Journal of the Geological Society of London*, 131, 7-17.

MacCallum, K.D. and Reynolds, J.M. 1987. High-resolution seismic profiling in Plymouth Sound and the River Tamar. *Proceedings of the Ussher Society*, 6, 562.

MacCallum, K.D. and Reynolds, J.M. (submitted) The role of highresolution seismic surveying in under- and post-graduate education, *Hydrographic Journal.*

McFarlane, P.B. 1955. Survey of two drowned river valleys in Devon. *Geological Magazine*, 92, 419-429.

Reynolds, J.M. 1987. Geophysical detection of buried channels in Plymouth Sound, Devon. *Geophysical Journal of the Royal Astronomical Society*, 89, 457.

Roxborough, I.S. 1985. Groundwater chemistry change due to tidal fluctuations in the Stonehouse Brewery Well, Plymouth, England. *Water Resources Research*, 21, 616-618.

Sheriff, R.E. 1985. Aspects of Seismic Resolution. In: Berg, O.E. and Woolverton, D.G. (eds) Seismic Stratigraphy II, *American Association of Petroleum Geologists, Memoir* 39, 1-10.

Sieck, H.C. and Self, G.W. 1977. Analysis of High Resolution Seismic Data. In: Payton, C.E. (ed) Seismic Stratigraphy-Applications to Hydrocarbon Exploration. *American Association of Petroleum Geologists, Memoir* 26, 353-385.

Worth, R.H. 1898. Evidences of glaciation in Devon. Reports of the *Transactions of the Devon Association for the Advancement of Science*, 30, 378-390.