MARINE GEOPHYSICAL INVESTIGATIONS OF PALAEO-DRAINAGE SYSTEMS IN THE HAWKESBURY RIVER ESTUARY, NEW SOUTH WALES, AUSTRALIA.

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ABSTRACT

The Hawkesbury River is a key element in a major river system in eastern Australia. The river and its tributaries virtually encircle Sydney's metropolitan area, extending northward to the Pittwater and Brisbane Water embayments and entering the Tasman Sea at Broken Bay, some 35 km north of Sydney Harbour. Since the 1960's marine geophysical techniques, principally seismic reflection, supported by land gravity surveys have revealed extensive and deep palaeodrainage systems incising the underlying sedimentary rocks mainly beneath the River and its tributaries. These are masked by considerable thicknesses of recently deposited sandy sediments.

Case studies from three recent infrastructure and research projects, completed near the mouth of the Hawkesbury River system demonstrate the application of marine seismic and gravity technologies in the mapping parts of this palaeodrainage system. These projects are within the maritime zone of the Hawkesbury River. In this zone the Hawkesbury River estuary is a drowned river valley within steeply incised gorges surrounded by dissected plateaus. The terrain is dominated by the sandstone geology with an extensively dissected and generally rugged landscape.

Installation of a wastewater transfer main beneath the Hawkesbury River between the then unsewered Dangar Island and Brooklyn on the mainland was required. This involved a 1400 m long directional bore beneath tidal mud flats and a deep tidal channel. The marine geophysics mapped the bedrock profile, identified a fault and strong seismic reflectors within the bedrock near the centre of the palaeochannel at about 45 m depth. These were interpreted as regions of stress concentration in the Newport Formation created by valley bulging processes following rapid erosion. The geotechnical model inferred from these investigations was applied in the design of the directional drilling operation that was successfully completed in rock. This upgraded sewer system is now in operation and has removed a significant pollution source from the Hawkesbury River.

Upgrading of the electricity supply from Wagstaffe to Booker Bay required installation of an 11kV power cable across Brisbane Water, a distance of 630 m. Previous regional gravity surveys in this area had identified a deep palaeodrainage system beneath the Woy Woy and Ettalong peninsulas. A marine seismic reflection and refraction survey along the proposed crossing confirmed the presence of a palaeochannel margin extending to about 25 m below the seabed. The conduit was subsequently successfully installed by horizontal directional boring up to 30 m below sea bed.

Development of an airborne electromagnetic system for bathymetric mapping and sea-floor characterisation required independent calibration using marine geophysics within Broken Bay. A broad and deep channel representing a high energy palaeo-fluvial drainage system in the Hawkesbury River outreaches was identified. This extended to approximately 80 m depth below river level and was somewhat shallower than indicated by previous studies suggesting that there may be some uncertainty in seismic bedrock depth possibly due to the dense basal sediments. Also in another nearby area a dendritic fluvial pattern extending to approximately 70 m depth was observed. A moderately narrow palaeochannel extending to 90 m depth either side of the Palm Beach tombolo was also clearly identified.

1 INTRODUCTION

The Hawkesbury River system is a major river system in eastern Australia that drains about 22,000 km^2 of the eastern highlands of New South Wales (Martens, 1999). This River and its tributaries virtually encircle Sydney's metropolitan area, extending north to Pittwater and Brisbane Water and entering the Tasman Sea at Broken Bay about 35 km north of Sydney Harbour. Pittwater and Brisbane Water are major embayments north and south of Broken Bay. This system has maintained virtually the same drainage pattern that developed in the Early Tertiary, some 40 million years ago. During the Pliocene, about 5 million years ago, the river system was rejuvenated initiating intensive erosion of the Triassic sedimentary rocks deepening and widening the drainage system. This process was repeated at the start of the Quaternary about 2.6 million years ago and was followed extensive infilling mainly during the Pleistocene about 1.6 million years ago. This infilling effectively masked the pre-existing drainage system. This was little known until the 1960's when marine geophysical techniques, principally seismic reflection, supported by land gravity surveys mapped parts of an extensive and deep palaeo-drainage system beneath the Hawkesbury River.

Case studies from three recent projects, demonstrate the results of marine seismic and gravity investigations over parts of this palaeo-drainage system. These projects are located in Figure 1 (labelled 1, 2 and 3) and are within the estuarine zone of the Hawkesbury River that extends roughly 15 km inland from the coastline. In this region the Hawkesbury River estuary is a drowned river valley bordered by steeply incised gorges and surrounded by dissected plateaus. The terrain is dominated by the sandstone geology with the landscape being unrelentingly dissected and generally rugged. In its current condition the Hawkesbury River estuary is best described as a micro-tidal estuary with a very low discharge rate delivering a very low sediment supply to the estuary head except during infrequent short-lived, large magnitude fluvial flood events (Hughes *et al*., 1998).

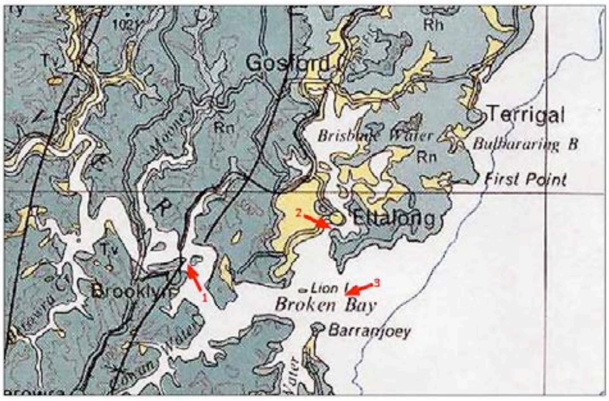

Figure 1: Location of Case Studies Areas in the Hawkesbury River Estuary: 1 - Waste Water Pipeline, Brooklyn to Dangar Island; 2 - Electrical Conduit, Wagstaffe to Booker Bay; 3 - Bedrock Mapping, Broken Bay and Pittwater.

2 CASE STUDIES

2.1 CASE STUDY 1: WASTE WATER PIPELINE INSTALLATION, BROOKLYN TO DANGAR ISLAND

In order to reduce potential contamination of the Hawkesbury River from wastewater overflows and leaks a 150 mm diameter transfer main beneath the River and within a conduit created by Horizontal Directional Drilling (HDD) was proposed. This main linked the reticulation system on Dangar Island with a transfer main to a sanitary treatment plant (STP) in the Seymour Creek valley (Figure 2). Two preferred HDD alignments about 650 m in length were initially considered as shown in Figure 2.

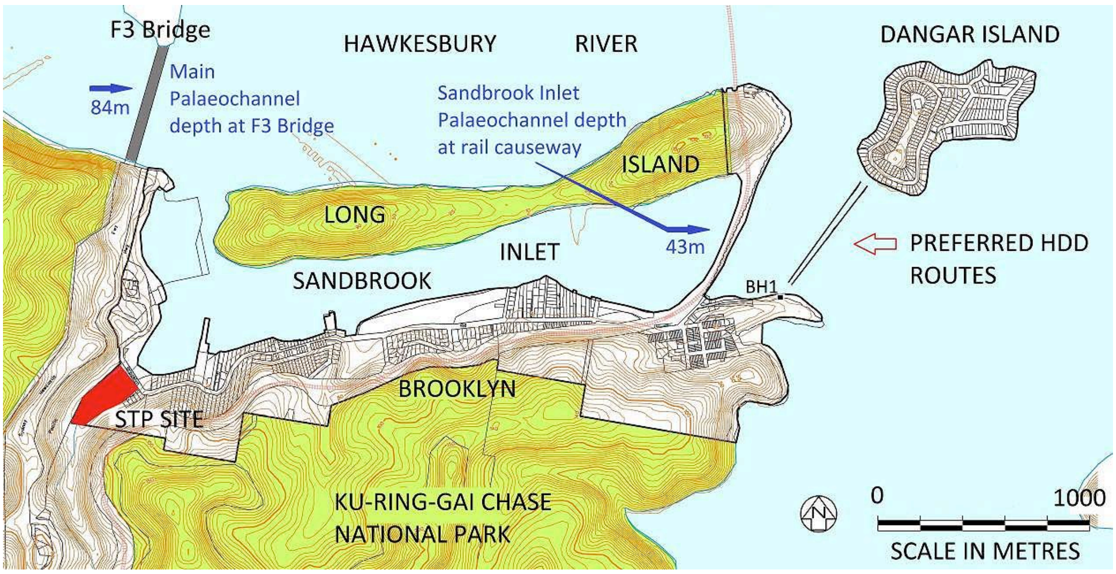

Figure 2: Site Plan with proposed Waste Water Transfer Main Crossings from Brooklyn to Dangar Island.

Details of the geotechnical aspects of this project are provided by Waddell *et. al*. (2011). Test holes and piling records for the F3 Freeway (now the M1 Motorway) bridge over the main Hawkesbury River channel to the west of the site (Figure 2) shows the palaeochannel infilled with alluvium to at least 84 m below river level with the current channel floor about 20 m below river level. The presence of Long Island (Figure 2), being parallel to the southern shoreline of the Hawkesbury River and forming a barrier to the main river channel, suggests a separate watercourse (possibly originally Seymours Creek) may have incised into the bedrock to form Sandbrook Inlet. The depth of the palaeochannel beneath the 750 m wide Sandbrook Inlet appears to be shallower than, and separate from, the palaeochannel beneath the Hawkesbury River at the bridge.

On the Brooklyn shoreline a single deep borehole (BH1, Figure 2) was drilled to 80 m depth near the preferred HDD entry for both alignments. This intersected approximately 2.5 m of fill and residual soil overlying a relatively thin layer (~1.5 m thick) of Hawkesbury Sandstone and interbedded laminite, shale and sandstone from the Newport Formation of the Narrabeen Group. The Newport Formation is predominantly quartz-lithic sandstone interbedded with siltstones, mudstones and laminite. This ranges from low and medium strength to about 20 m depth, medium and high strength to about 25 m and high strength with bands of medium strength and very high strength rock to the borehole depth at 80 m.

Marine seismic reflection using single channel continuous seismic profiling (CSP) was completed in the area of the proposed crossings (Figure 2) with the objectives of mapping the bedrock profile, locating any possible impediments to the proposed HHD and testing whether the Sandbrook Inlet palaeochannel extends beneath the preferred alignments or whether a deeper palaeochannel associated with the main Hawkesbury River palaeochannel was present. The marine reflection survey was completed along both of the proposed alignments with shorter cross-lines at 50 m intervals. Bathymetric data was also acquired. This showed that the river floor levels along the proposed HDD alignments varied from about RL-3 m AHD to RL-12 m AHD. Levels rise abruptly on the Dangar Island side of the HDD alignments which is consistent with the outcropping rock on Dangar Island.

Figure 3 shows the interpreted bedrock contour plan based on all the marine seismic data with an interpreted fault and the approximate extent of a region where there was a strong sub-bottom reflector at depth. The bedrock rises abruptly to the north-east close to the landfall on Dangar Island and it is likely that this side of the palaeochannel is also faulted.

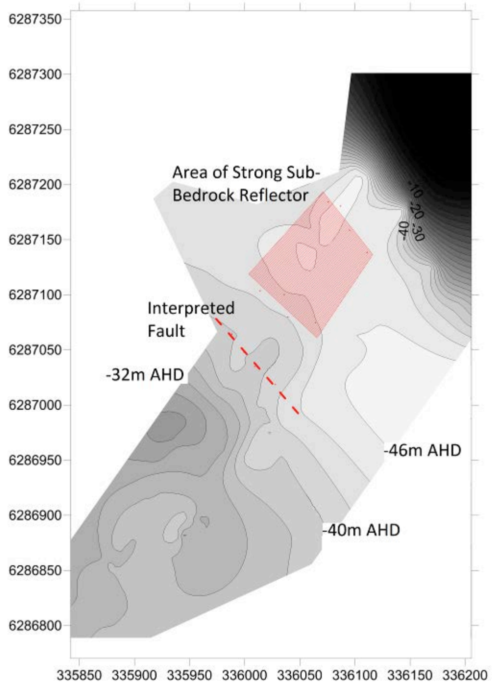

Figure 3: Interpreted bedrock contour plan from Brooklyn to Dangar Island.

Figure 4 shows the interpreted seismic section (not tidally corrected) acquired with an air-gun source along one of the HDD alignments.

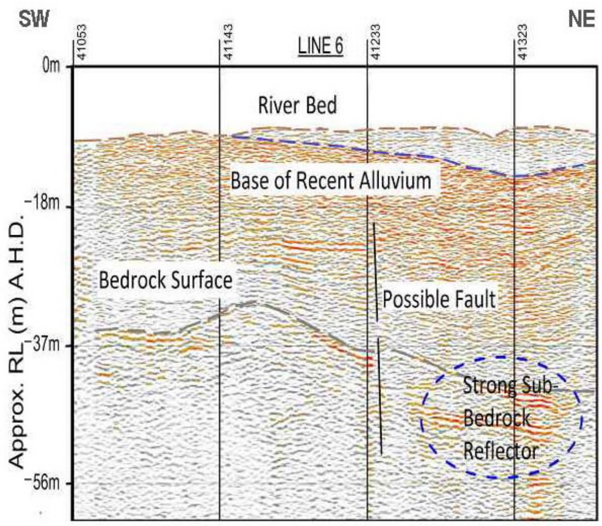

Figure 4: Sample marine seismic reflection section along HDD alignment

The river floor, base of recent sediments and the bedrock reflector are marked with dashed lines. There are other reflectors that are evident on this section including younger palaeochannels within inferred bedded sandy sediments but these have not been marked. The bedrock reflector marked on Figure 4 is complex in shape and deepens to the north-east from about RL-37 m AHD to about RL-45 m AHD. This could be due to a combination of erosion and tectonic activity. A fault with possible shear zone from 5 m to 22 m wide near Station 41233 has displaced the bedrock surface and the overlying sediment reflectors. To the north-east of this fault, in the rectangular area shown on Figure 4, bands of strong sub-bedrock reflectors demonstrate an increased acoustic impedance (density x seismic velocity) that often indicates stress-concentrations that have been observed in earlier tunnelling operations in Sydney Harbour beneath palaeochannels (Whiteley, 2005).

Based on the rock levels predicted from the geotechnical investigation, the HDD was bored with 25 m to 35 m of rock cover. Figure 5 shows the 'as-built' HDD vertical section.

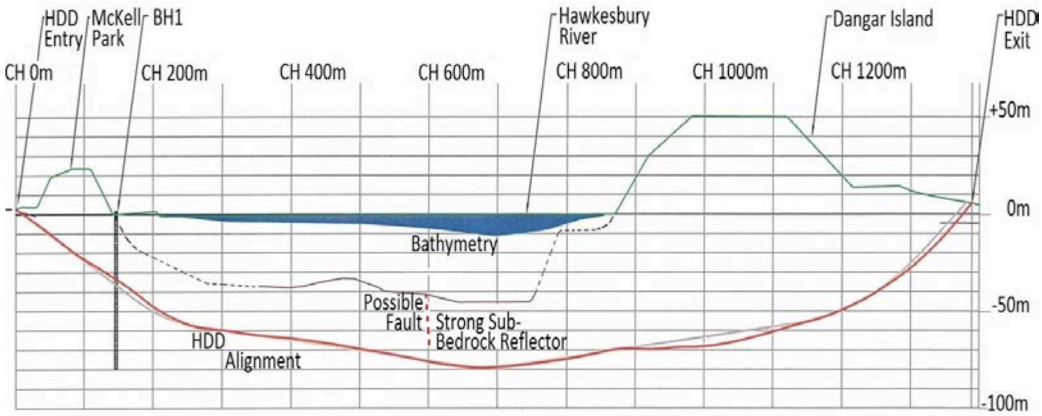

Figure 5: 'As-built' HDD vertical section from Brooklyn to Dangar Island

Allowing 25 m to 35 m of rock cover was considered prudent, given the inferred likely faulting and the potential high rock stress zone in the base of the palaeochannel shown in Figure 5. Such features increase both the risks to drilling and to drilling fluid breakout if the HDD encounters poor quality rock or there is insufficient rock cover. Anecdotal information from the HDD contractor indicated that the HDD may indeed have passed through a fault zone as indicated by the seismic survey, but was drilled without incident. The HDD was successfully constructed entirely in rock.

2.2 CASE STUDY 2: ELECTRICAL CONDUIT INSTALLATION, WAGSTAFFE TO BOOKER BAY

Brisbane Water forms the northern arm of Broken Bay (Figure 1). It was originally an inland lake system that only became a tributary of the Hawkesbury River in recent times. A proposed energy supply upgrade for residents of the south-eastern shores of Broken Bay required HDD installation of a 630 m length power cable across the waterway from Booker Bay on the Ettalong Peninsula to Wagstaffe. Recent sand deposits cover the Ettalong Peninsula while sandstones and siltstones outcrop at Wagstaffe. The proposed HDD crossing lies near the southern border of an area where a previous regional gravity survey had been completed (Qureshi, 1981). This survey involved gravity measurements, at a nominal 100 m spacing, along the road network on both sides of Brisbane Water but no overwater gravity data was gathered. Gravity has previously proved to be useful in mapping palaeochannels incising bedrock in connection with major tunnel projects in the Sydney region (Whiteley, 2005). These are typically observed as linear gravity lows produced by the increased thicknesses of lower density (relative to rock) sandy sediments within the palaeochannels.

Figure 7 shows the regional gravity contour plan (the contour interval is 5 Gravity Units from Qureshi, 1981, 1 GU = 10^{-3} ms^{-2} SI) with a qualitative interpretation of the palaeo-drainage pattern. This shows a highly irregular bedrock profile with many deeply incised palaeochannels. The approximate location of interpreted palaeochannel axes are marked in Figure 7. The major north-south palaeochannel appears to extend from Woy-Woy Creek to Ocean Beach and is intersected by another interpreted large east-west trending paleochannel that extends beneath St. Huberts Island to Davistown. A number of palaeo-tributary channels are interpreted to join both these major channels at various locations. A palaeo-tributary or bedrock depression is also interpreted in the vicinity of the HDD crossing.

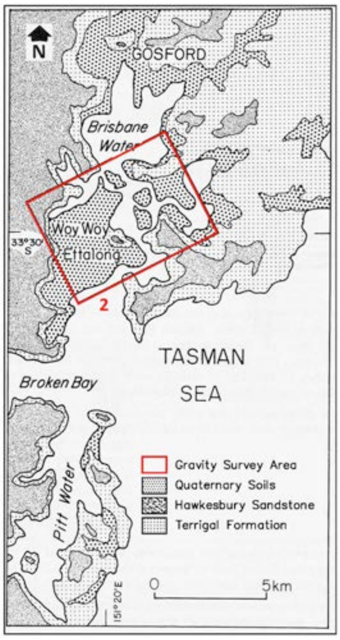

Figure 6: Site plan, Booker Bay and location of regional gravity survey area.

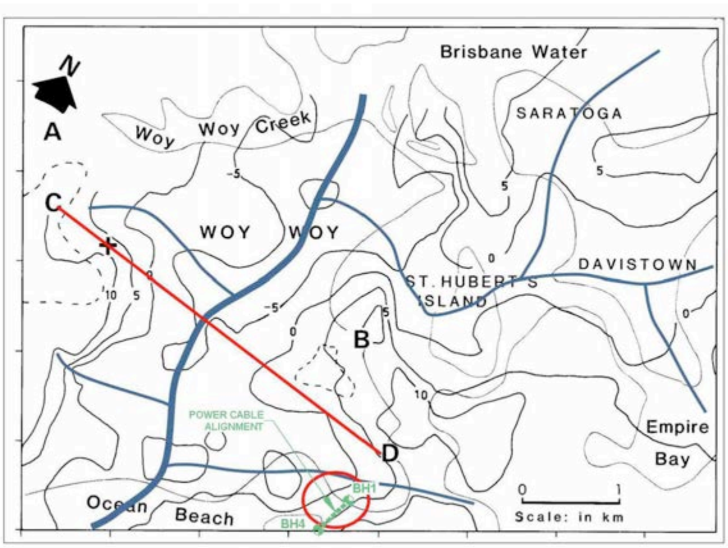

Figure 7: Interpreted gravity contour map, Brisbane Water. The conduit crossing is shown within the red circle.

Qureshi (1981) also provided an interpreted gravity along a 4 km length Line CD (Figure 7) that crosses the major north-south palaeochannel. This interpreted section is shown in Figure 8. The eastern end of this profile is only about 500 m north of the HDD crossing. A density contrast of -0.5 T/m^3 between the infilling sandy sediments and the sandstone/siltstone bedrock has been used to provide this interpreted bedrock profile. This density contrast is close to that used previously by Whiteley (2005) near Sydney Harbour and Botany Bay. Two palaeochannels are interpreted on Line CD. The major north-south trending channel is about 2 km wide and extends to a depth of about 70 m. Its eastern margin is marked by an interpreted bedrock high near Ch. 3 km that is inferred to represent a southern extension of Blackwall Mountain (marked by the dashed line in Figure 6) beneath the sands at Woy Woy. From Ch. 3 km to 4 km Line CD crosses near the northern margin of an interpreted palaeo-tributary (Figure 7) with bedrock at a maximum depth of about 40 m. This gravity interpretation suggested that a significant deepening of the bedrock from Wagstaffe to Booker Bay could be expected as the HDD crossing enters the palaeo-tributary from the southern side.

Figure 7 shows the approximate location of the two land boreholes BH1 and BH2 that were drilled for this project near the proposed landfalls of the HDD crossing. BH4 at Wagstaffe encountered extremely weathered sandstone beneath fill at about 2 m depth and BH1 at Booker Bay was drilled through mainly sandy sediments to about 23 m depth but did not encounter rock. This is consistent with the decreasing gravity values in the direction of BH1 towards the interpreted gutter of the east-west trending palaeo-tributary to the north of BH1.

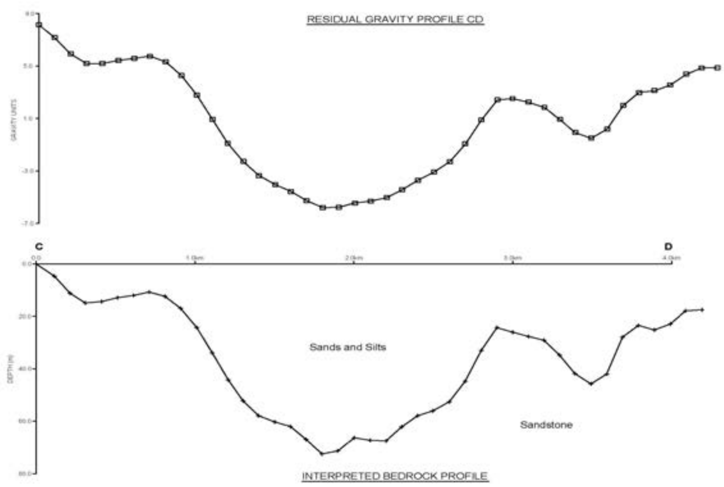

Figure 8: Interpreted gravity section on Line CD.

This interpretation led to the drilling of two additional overwater boreholes (BH2 & 3) along the HDD alignment and to a marine geophysical survey using both seismic reflection and underwater seismic refraction (USR, Whiteley and Stewart, 2008) methods.

Figure 9 shows the cable alignment with the borehole locations and trackplots for one of the reflection lines (CSP 1) and refraction lines (USR 3). CSP1 is adjacent to Wagstaffe and approximately orthogonal to the alignment while USR 3 follows the alignment near Wagstaffe but was deviated southward because of a shallow water shoal.

Figure 9 Marine reflection (CSP 1) and underwater seismic refraction (USR 3) trackplots with borehole locations.

The interpreted seismic record obtained along CSP1 is shown on Figure 10. A simplified borehole log for BH4 has been projected onto this record and the depth to rock correlates closely with the interpretation. The bedrock deepens rapidly to the north and south of the alignment.

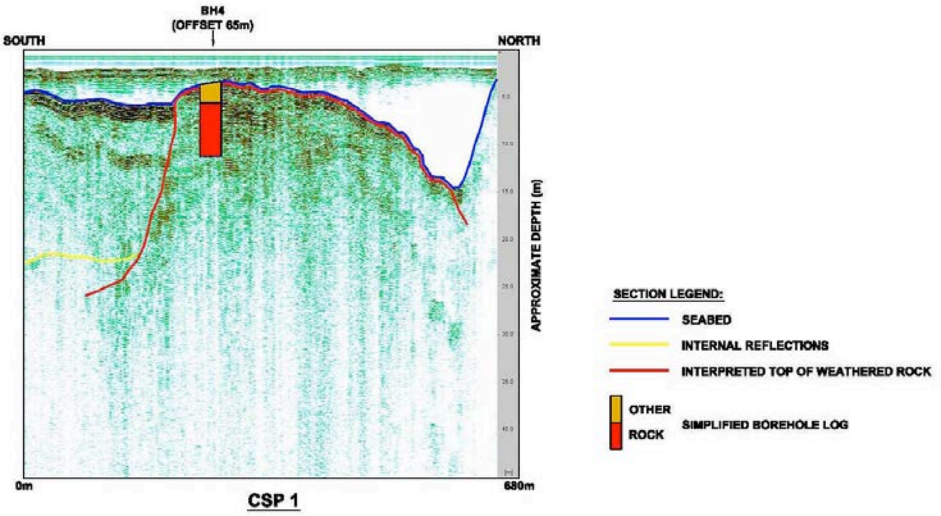

Figure 10 Interpreted seismic reflection record along CSP 1

The interpreted refraction section for USR 3 is shown on Figure 11 with simplified boreholes for the two overwater boreholes (BH 1 and BH 2) projected onto the line. The top of the weathered bedrock has been associated with seismic velocities greater than about 1900 m/s and is marked by the dashed line while the deeper base of the weathering has been associated with velocities in excess of 3000 m/s. The deeper interface has not been mapped along the entire line, however, the weathered rock extends along the alignment from at about 15m depth near the Wagstaffe shoreline then deepens rapidly to about 20 m to 25 m depth near BH 3, maintaining this level along most of the alignment.

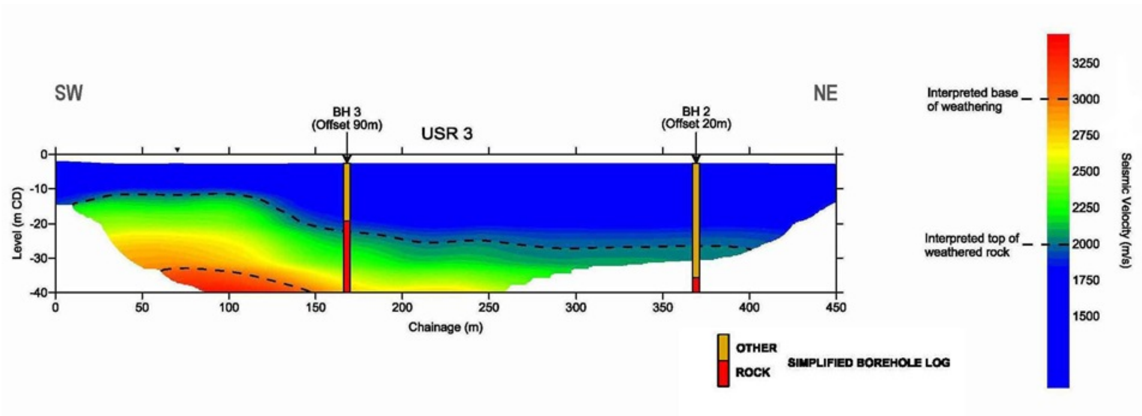

Figure 11 Interpreted underwater seismic refraction section along USR 3 with simplified borehole logs (see Figure 10.)

Using this information the power cable was recently installed in three welded sections from Wagstaffe to Booker Bay within in the HDD conduit that was created in rock 30 m below the floor of the river channel.

2.3 CASE STUDY 3: BEDROCK MAPPING, BROKEN BAY AND PITTWATER

Pittwater forms the southern arm of Broken Bay (Figure 1). Previous studies in this region by Albani and Johnson (1974), Albani *et al.* (1988) and Albani *et al.* (1991) have shown that Broken Bay was formed by fluvial erosion of Triassic sandstone during marine regressions with further erosion of the palaeochannels by coastal streams during the Pleistocene. Subsequent sea-level rise drowned this drainage system, forming the estuary and reworking the offshore sediments that presently fill the seaward section of the drowned palaeochannels. As part of a project to test an new airborne bathymetric and sub-seafloor mapping system (Vrbanchich *et al*., 2011) geophysical studies in Broken Bay were undertaken using continuous marine seismic reflection profiling supported by shallow vibrocoring. The objectives were to map the bedrock and to provide shallow sediment information to assist calibration of the airborne system.

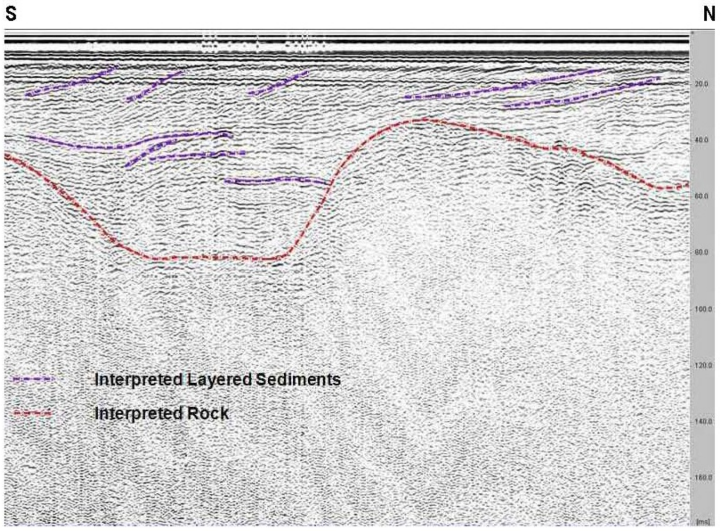

Figure 12: Interpreted seismic record near West Head (8, Figure 13).

Figure 12 shows an interpreted seismic record obtained along a transect near West Head (8, Figure 13). The southern end of this transect is on the left side Figure 12. This section is about 1 km long and uncorrected for tidal variations. Reflection travel time was converted to depth assuming average seismic velocities of 1550 m/s and 1700 m/s for sea water and marine sands respectively (Whiteley and Stewart, 2008). Coherent seismic reflectors, interpreted as representing sea floor, planar and steeply dipping sediment layers and an irregular bedrock interface were identified from the seismic records. The interpreted bedrock topography is highly irregular. Uncertainties could exist in the interpreted bedrock levels, especially where these levels are deep and/or steeply dipping.

Figure 13 shows the sediment sample locations and a contour plan of interpreted bedrock depths along the various seismic transects that were completed. The term 'bedrock' in this context implies a graduation rather than an abrupt interface as the boundary between sediments, partially weathered bedrock and fresh bedrock are not always clearly or unambiguously observed. The presence of indurated sediments (due to regression/transgression of sea level) can reduce the depth of penetration of the seismic signal at some locations. The acoustic impedance contrast between deeper sediments and the anticipated sandstone bedrock was variable suggesting the presence of very dense sands (i.e. tighter packing) and variably weathered sandstones.

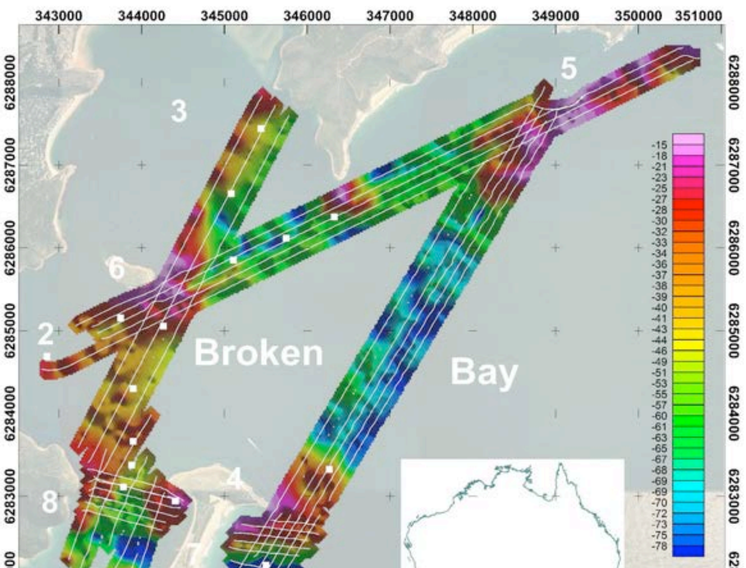

Figure 13: Contour plan of interpreted rock level in Broken Bay and the entrance to Pittwater.

Between West Head, 8 in Figure 13 and Barrenjoey Head (4, Figure 13) at the current entrance to Pittwater a relatively shallow rocky saddle linking these locations has also been mapped. To the south of this, in the area on the eastern and western sides of the Palm Beach tombolo a moderately narrow channel extends to levels down to approximately –90 m AHD with steep banks on either side. This may represent an earlier entrance to Pittwater and this interpretation is in good agreement with palaeochannel levels of approximately –100 m AHD beneath the Palm Beach tombolo obtained from an earlier seismic refraction study by Merrick and Greenhalgh (1990). These features were also detected by Albani *et al.* (1988) at similar depths. However, at some locations, between Lion Island (6, Figure 13) and West Head and in the main Hawkesbury River outlet in Broken Bay our interpreted bedrock levels differ from those presented by Albani and co-workers and are considerably shallower. In these areas, Albani *et al*. (1988) present bedrock contours with maximum depths of ~100 m and 140–180 m, respectively. Vrbanchich *et al*. (2011) provide additional discussion.

3 CONCLUSIONS

Case studies from recent infrastructure and research projects that were completed within the maritime zone near the mouth of the Hawkesbury River system clearly demonstrate the usefulness of marine seismic reflection, underwater seismic refraction and gravity technologies in mapping this extensive palaeodrainage system. These technologies support overwater geotechnical and geological investigations in this and similar environments.

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