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A discussion on tunnelling issues within the East Coast Bays formation of Auckland

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ABSTRACT

Strong population growth in Auckland, combined with the city's location on a constrained isthmus and local government plans to minimise urban sprawl, is placing increasing demand on existing infrastructure. The construction of tunnels and underground infrastructure is being used to meet the demand for new infrastructure in some built up areas. As tunnelling works have expanded across the region new geotechnical problems are being encountered and known problems are becoming better understood. This paper discusses specific examples encountered by the authors relating to the East Coast Bays Formation during the construction of tunnelling, pipe-jacking and horizontal directional drilling projects. Specific issues described include conglomerate lenses such as the Albany Conglomerate and the Parnell Volcaniclastic Conglomerate, and marked strength contrasts within the East Coast Bays Formation including strongly cemented bands and uncemented sand pockets. These variable conditions present challenges for certain tunnelling methodologies. This paper describes the issues encountered, discusses the extent of knowledge to date, and makes recommendations for future projects to help avoid problems during construction.

Keywords: Tunnelling, Auckland, New Zealand, East Coast Bays Formation, Uncemented sandstone, Parnell Grit, Albany Conglomerate, Cementation, Diagenesis

1 INTRODUCTION

Auckland is the largest city in New Zealand. Historically it has had a low population density typical of New World cities. Infrastructure was normally constructed on or near ground level due to relatively low land costs and few space limitations. Recent strong population growth is expected to continue, and according to the 2006 Census projections the population will reach 1.93 million by 2031, a 25% increase over current numbers (Statistics New Zealand, 2012).

Population growth, combined with the city's location on a constrained isthmus and local government plans to minimise urban sprawl (Auckland Council, 2012), is placing new demand on existing infrastructure. The construction of tunnels and underground infrastructure is increasing across the globe as nations wrestle with the demand of growing and increasingly urbanised populations. Auckland is no different, and a surge in tunnelling projects has started.

Construction is currently taking place on a major motorway tunnel (the Waterview Tunnel) as well as a number of tunnelled sewers and water supply pipes. Many more are planned including large scale projects such as an underground rail extension in the Central Business District, a new road crossing under the harbour, and numerous water and waste water schemes across the region. Tunnel Boring Machines (TBMs), including Earth Pressure Balance Machines (EPBMs), have recently emerged as the preferred method of mitigating tunnelling construction risks on large projects in Auckland after a number of successful applications in the past few years (Asche et al, 2009).

As tunnelling works have expanded across the region new geotechnical problems are being encountered and known problems are becoming better understood. This paper discusses specific examples encountered by the authors relating to the East Coast Bays Formation (ECBF) during the construction of tunnelling, pipe-jacking and horizontal directional drilling projects.

A number of the issues described are known by some of the geotechnical community, but this knowledge is not yet widespread and publications on these issues are extremely limited. This paper is not intended to be a comprehensive assessment of all the tunnelling risks applicable to the ECBF, but to set out the current state of knowledge identified by the authors and to act as a discussion point. Anyone with additional information on the issues raised is encouraged to contact the authors.

2 GEOLOGICAL SETTING

The Auckland area is located within the Australian tectonic plate, some 300-500 km north west of the subducting Pacific plate. During the early Miocene, plate boundary reorganisation between the Pacific and Australian plates caused rapid subsidence in Auckland and Northland, forming the Waitemata Basin (Whattam et al, 2005).

Deposition in the basin took the form of turbidity currents, pelagic fallout, debris flows and slumping, and resulted in the myriad of rock types that comprise the Waitemata Group (Balance 1976, Hayward 1976). These rocks include a number of formal stratigraphic Groups and Formations, including the well-studied interbedded soft sandstones and mudstones of the East Coast Bays Formation (ECBF). The ECBF incorporates lenses of harder conglomerate including Parnell Volcaniclastic Conglomerates (sometimes referred to as Parnell Grit), Helensville Conglomerate and Albany Conglomerate (Shane, Strachan and Smith, 2010; Edbrooke, 2001). Detailed stratigraphy is obscured by widespread deformation and a dearth of fossils and marker beds (Spörli, 2007). This complex sedimentary origin has resulted in a sometimes unpredictable variability between benign and challenging tunnelling conditions.

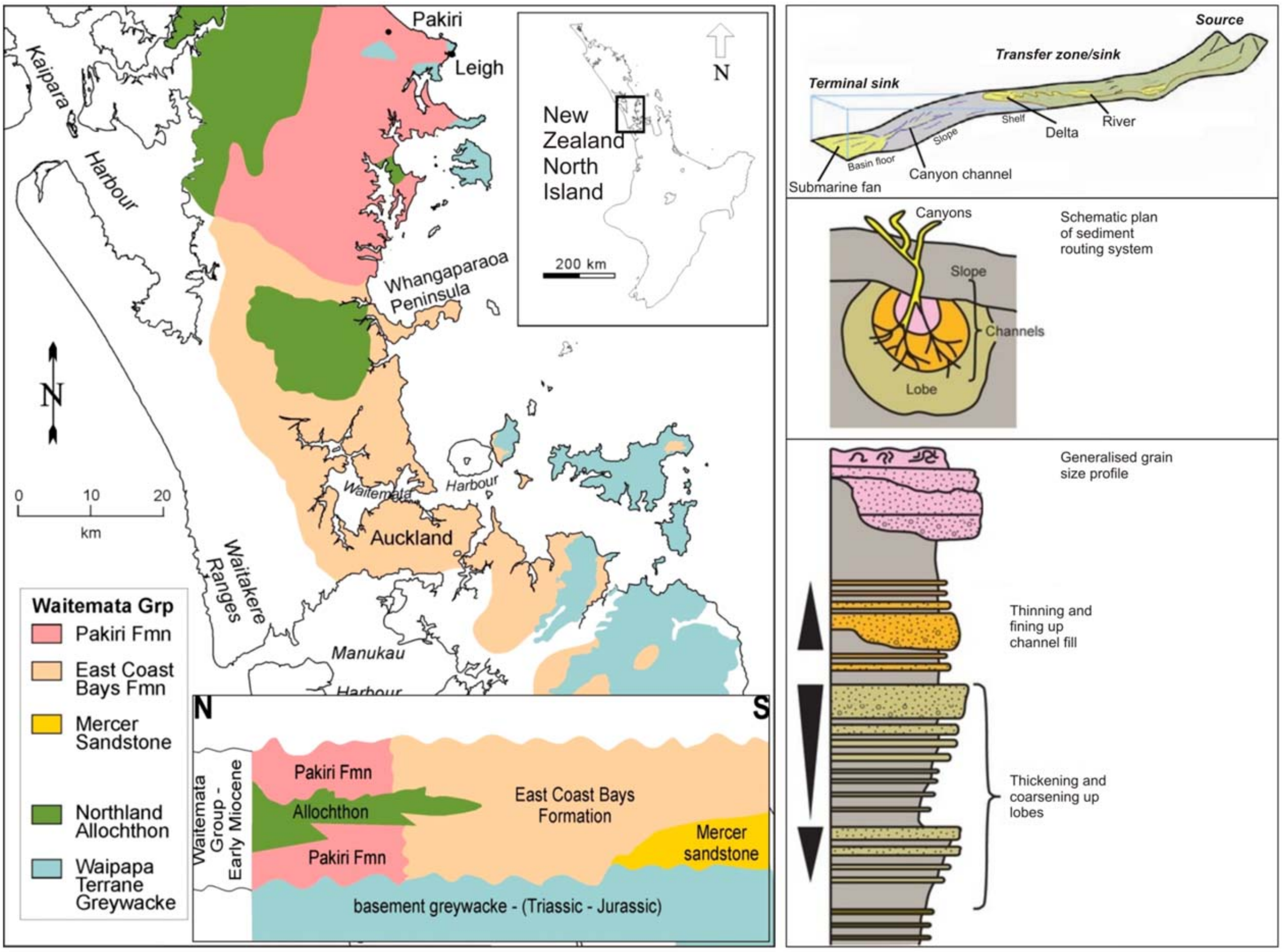

Figure 1. Schematic geological map and section of Auckland, after Edbrooke et. al., 2001. Model of submarine fan and turbidite sequence, after. Generalized sediment-routing system (top right) modified from Graham et al. (2011) and Covault (2011). Submarine fan model (middle right) resulting in vertical stacking of sedimentary rocks (bottom right) modified from Mutti (1992)

The East Coast Bays Formation comprises flysch sequences of interbedded turbidite sandstones and pelagic mudstones. The nature of the detrital clasts in ECBF sands suggest they are derived almost entirely from an ancient Northland island and obducted Cretaceous ocean floor material.

Most of the ECBF sediments can be regarded as deposited in the lower fan or abyssal (basin) plain and are mudstones enclosing thin medium to fine grained, laterally continuous turbidite sandstones. The mudstones are hemipelagic, consisting of a mixture of terrestrial detrital clay to silt-sized material and pelagic (non- terrestrial) material largely consisting of siliceous skeletons of organisms such as radiolaria and foraminifera. Most of the sandstones are litharenites, with clasts from fragments of mudstone or siltstone sourced from beds deposited on the margins of the sedimentary basin.

3 DIGENESIS

The process of diagenesis is briefly explained here as this process is important for some properties of the ECBF. The term diagenesis covers a wide spectrum of post-depositional changes that occur in sediments as they transition from sediment to sedimentary rock. These changes include:

- Chemistry (eg oxidation, pH and breakdown of unstable detrital minerals liberating active ions).
- Temperature (as the material moves lower in the crust).
- Pressure (as more material is deposited above).

These changes commonly result in compaction, cementation, and the transformation of clay from one species to another, and are associated with a reduction in porosity and permeability. Diagenetic minerals crystallize after the deposition of the sediment. They draw on amorphous gels in the sediment, biological activity and its products, ions liberated by the breakdown of unstable clastic minerals and other components in the sediment, as well as those ions naturally contained in seawater, to react and nucleate new minerals causing cementation of the rock. Diagenesis is commonly divided into three conceptual regimes. Most studies of the diagenesis of sandstone found in the literature are focused on the Mesogenetic stage because of the economic importance of oil and gas which are generated in this regime. Studies on early siliciclastic sandstone diagenesis are focussed on sediments that are loaded with glassy volcanic debris which quickly break down in ambient to low temperature marine conditions to provide complex and exotic mineral assemblages, which is not particularly relevant to the ECBF.

Eogenetic stage - The Eogenetic stage, includes all processes that occur at or near the surface before the rock is compacted. The influence of the original depositional pore water (in this case sea water) dominates and facilitates the transfer and deposition of chemicals liberated by the breakdown of unstable detrital components. The sediments can be considered as an open chemical system. The maximum temperature range of this regime is up to approximately 70ºC and to depths of burial of around 1 km.

The characteristic minerals formed in siliciclastic rocks during early diagenesis are smectite clays and zeolites, plus chalcedony, orthoclase and amorphous silica. Any new minerals that precipitate from pore-solutions require a local source of appropriate chemical reactants. These components can only come from the breakdown of unstable detrital material already in the sediment such as glasses, gels and feldspar minerals. Volcaniclastic sediments containing abundant glassy material will contain large amounts of diagenetic minerals (zeolites and clays). Clastic sediments containing little reactive material will be poor in diagenetic minerals and as a result will have little cement in the early stages of diagenesis.

Mesogenetic stage - As sediments become compacted or cementation proceeds to the extent that the porosity and permeability of the sediment is much reduced, ions liberated by temperature-related breakdown of minerals accumulate in the interstitial solutions. This closed system regime begins at around 1-2 km depth of burial and, in siliciclastic sandstones, at around 60ºC. Mineral cements and diagenetic minerals grow rapidly. Clay minerals dehydrate and transform to other clay species with increasing temperature. The smectite of the early diagenetic regime transforms to illite or chlorite.

Telogenetic stage - Quartz only occurs as a major cement in rocks that have been heated to temperatures above approximately 80ºC. In nature sandstones buried to less than 2.7 km have negligible quartz cements. Quartz also will only deposit on clean surfaces; thus the crystallization of diagenetic clays and zeolites on the surface of clastic grains severely inhibits the deposition of quartz.

Subsequent changes in pore water chemistry, such as the introduction of meteoric water into formerly marine sediments when they are inverted, uplifted or eroded, can cause earlier minerals to break down and be replaced by new minerals. The form and nature of clay aggregates can also change.

4 TUNNELLING PROPERTIES AND ISSUES

In general the East Coast Bays Formation provides a benign tunnelling environment with very weak rocks which stand up well and are easily excavated. Although there have been significant recent successes, experience of tunnelling in Auckland is relatively limited. As a result of the lessons learned on some of these projects, Asche et al. (2009) concluded that EPB tunnelling can be undertaken in the ECBF with a large degree of cost and programme certainty.

Where problems have been encountered they fall into the following categories.

4.1 Uncemented Sands

Pockets of uncemented sands have been reported in projects across Auckland including Trunk Sewer 30, Waterview Tunnel, and Victoria Park Tunnel. These unconsolidated and uncemented sandstones can cause significant issues for open face or unpressurised tunnelling techniques. They are very porous, allowing water to freely enter and permeate through them, and reports from recent projects suggest that groundwater inflows of 10-20 litres per second are likely (personal communication, Tom Ireland).

In order to provide an understanding of why uncemented sands appear in the otherwise consolidated rock detailed examination was undertaken including X-ray diffraction, thin-section petrography and high resolution scanning electron microscopy to identify clastic and diagenetic minerals and determine their depositional history.

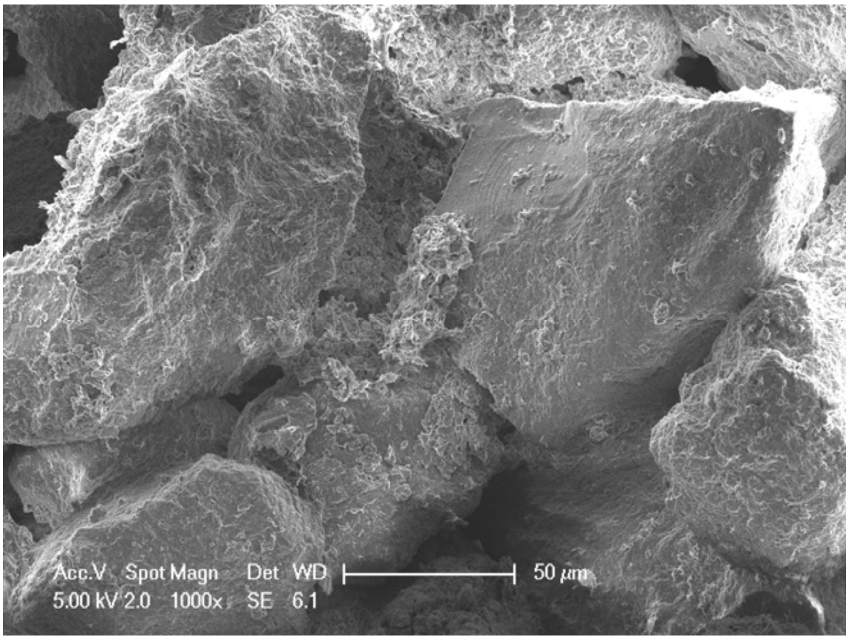

Figure 2. SEM image of quartz grains recovered from core showing absence of cement and conchoidal impact fracture which could only have happened during deposition; this impact surface is almost clean suggesting that no cementing matrix has existed during the history of this sandstone.

The majority of the lithic clasts were found to be hemipelagic mudstones (see Fig 5, right hand image). Other clastic material does occur including igneous material which contains hornblende (a mineral typical of the oceanic volcanics contained in the Northland Allochthon) and rare felsic fragments of volcanic origin. Most quartz and feldspar grains have relatively clean surfaces. Some quartz grains may have acquired a thin clay coating believed to be from the early stages of an extended sedimentation process (ie before they were deposited in their present depositional environment). Feldspar grains frequently show dissolution features. The reaction products of dissolution will contribute to the growth of diagenetic minerals.

A notable feature of the sands is the intermittent nature of the diagenetic matrix. Volumes of the sand with more abundant detrital lithic material tend to be more cemented; adjacent volumes that are rich in clastic quartz tend to have little diagnetic cement. The paucity of feldspars in the sediments may be a factor that contributes to the paucity of diagenetic minerals (particularly zeolites) in the sediments. All available data for the clay mineral assemblages in the samples studied have shown that the detrital and diagenetic clays are smectites (Black et al, 2010).

The temperature range of diagenesis experienced by the sediments, the textural features that they contain (particularly the general absence of compaction features in the matrix of the sediment and to a lesser extent within its clastic sedimentary grains), and the nature of the diagenetic minerals found in the sediments all locate the diagenesis as having occurred in the eogenetic stage of diagenesis shortly after deposition and before compaction.

It is believed that the unconsolidated sand horizons are caused by the general lack of detrital material that is “fertile” as far as providing material for the crystallisation of cementing minerals. The ECBF sediments have been never been seriously compacted and they contain within them little in the way of unstable material that would provide reactants needed to produce abundant diagenetic and cementing products into the sandstone pores. By comparison although the sediments of the adjacent Pakiri Formation have been deposited in similar sedimentary environments they contain abundant volcaniclastic debris which is very reactive in the marine environment and thus produces more diagenetic and cementing products that will provide much greater cohesion.

4.2 Sawtooth Weathering

The ECBF weathering zone is known to be of variable thickness. Experience from the Waterview tunnel (personal communication, Neil Jacka) suggests that weathering depth and pattern is significantly influenced by bedding angle, with deep weathering occurring along dipping bedding planes resulting in ‘saw-tooth’ weathering profiles that can appear in vertical boreholes as a sequence of weathering grades decreasing then increasing with depth.

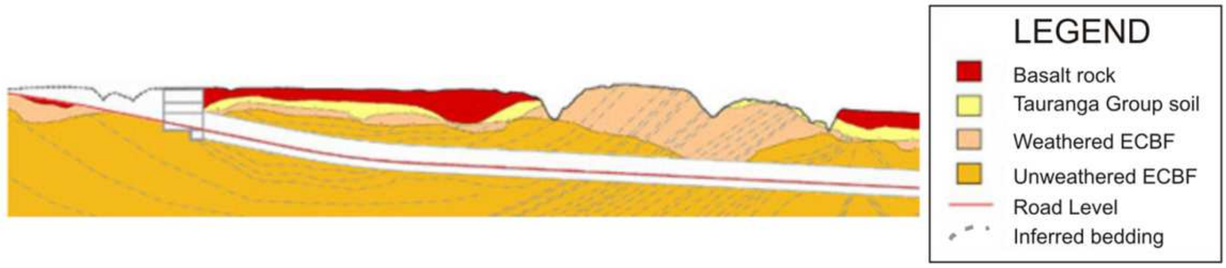

Figure 3. Waterview tunnel long section showing dip and weathering variability, with deeper weathering in zones of high bedding dip. Amended from Kenyon, 2014.

This can result in unanticipated mixed face conditions where unweathered rock would normally have been assumed if a consistent ‘top down’ weathering profile had existed.

4.3 Conglomerate Lenses

Harder lenses within the ECBF commonly include the Parnell Volcaniclastic Sandstone (‘Parnell Grit’), Albany Conglomerate and Helensville Conglomerate. These were encountered during drilling of the Davis Crescent tunnel, Trunk Sewer 30, and the Rosedale Outfall. The Roesedale Outfall was a 3 km long sewer tunnel constructed with an EPBM, while the first two project examples were pipe-jacked with open face microtunnelling machines. The source and relative age of these conglomerates is still debated, and the Parnell Volcaniclastic Conglomerate (PVC) is distinctly different from the Albany and Helensville Conglomerates. The inferred depositional environment of a submarine fan complex with channelised high-density turbidity currents (Balance, 1974; Sprott, 1997; Johnston, 1999) means that these conglomerates can occur in in relatively narrow lenses and unpredictable locations. These can easily be missed by conventional ground investigation resulting in poor decisions being made over machine choice and risk allocation.

PVC commonly has a uniaxial compressive strength in the order of 10-20 MPa, significantly higher than the typical ECBF, which has resulted in some tunnels utilising medium-size microtunnelling machines needing to be changed to drill and blast with significant cost, programme and environmental consequences. The Albany and Helensville conglomerates contain boulders with uniaxial compressive strengths of up to 250 MPa which can cause significant problems for most tunnelling methods such as machine wear, blocking of guillotine doors, and overbreak. These are discussed in more detail in Roberts et al, 2014.

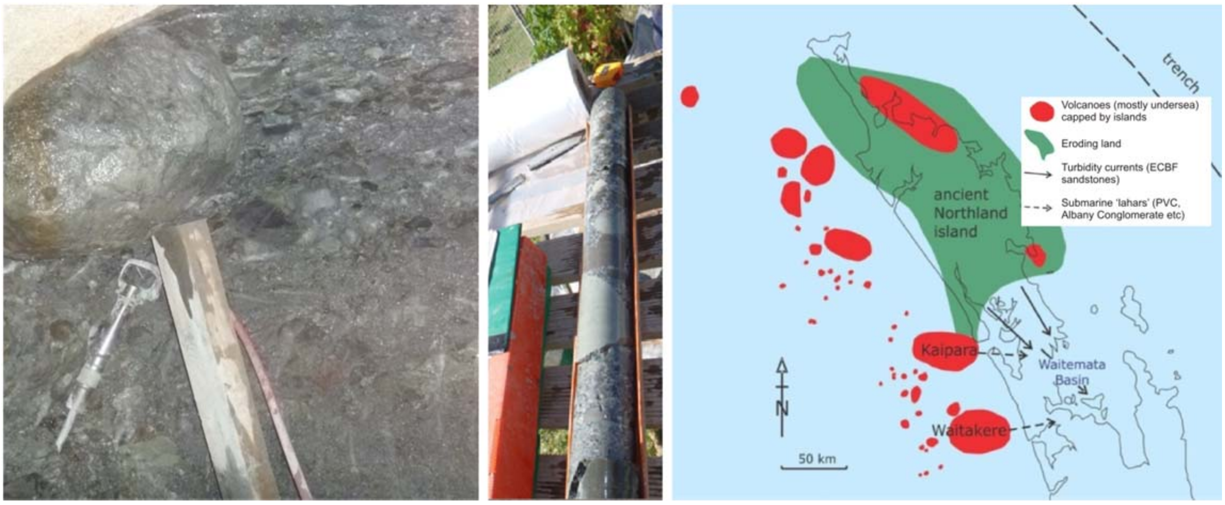

Figure 4. Left and centre:Typical Albany Conglomerate as found in a hand jack tunnel face and core (Roberts et al, 2014). Right: Potential volcanic sources for the Parnell Volcaniclastic Conglomerate shed volcanic detritus into Waitemata basin. Diagram modified from Hayward et al., 2011.

All of these conglomerates have been anecdotally associated with high groundwater inflows of 20-30 litres/sec. Dowler at al, 2010, reported flows of over 60 litres per second in the Rosedale Tunnel with apparent infinite supply despite constant draining and water pressures ranging from 0.5 to 6 bar.

4.4 Calcite veins and cementation

Calcite veins have been encountered in a number of Auckland tunnelling projects including the Waterview Tunnel (personal communication, Stuart Cartwright) and Birkdale twin 600 mmID microtunnel and 450 mmID horizontal directional drilled pipe.

Figure 5. Left and centre: Calcite encountered on Trunk Sewer 30. Right: Microphoto thin-section in plane polarized light. Calcite cemented sandstone clast enclosed in unconsolidated sand. Note white rims of calcite on large rounded lithic (mudstone/siltstone) grains and fragment of volcanic material bottom left.

In Birkdale bands up to 200 mm wide were encountered and the strength differential caused issues for the drilling. Solid inclusions of calcite could have strengths of approximately 250 MPa, although those encountered at Birkdale recorded UCS of 10-20 MPa (personal communication, Dietmar Londer).

Microphotographs taken in unconsolidated sand from the ECBF show that, in some locations, calcite has nucleated on and coated clastic grains creating coherent “chunks”. Since the depositional site of the sandstones must have been below the calcite compensation depth we can presume that this calcite has crystallized since or during the uplift of the ECBF. It is believed that late Tertiary and

Quaternary uplift and erosion has allowed egress of fresh (meteoric) water into the unconsolidated sandy sediments. The change from marine to meteoric pore waters then started a new round of diagenetic changes and minerals. The new diagenetic minerals include a green smectite and calcite.

4.5 Sticky Spoil

X-ray diffraction shows that unweathered ECBF sediments have matrices dominated by smectite. Smectite clays have a particularly high plasticity and form smooth gels when mixed with sufficient water or other liquids. Surface samples also have kaolin clays as a result of weathering. Kaolin decreases while smectite content increases with depth. Disaggregation of ECBF sandstones to separate "sand grains" from matrix has shown they have identical clay mineral contents; both are dominated by smectite.

The Vector CBD Reinforcement Project, a 6 km long tunnel, was constructed in two sections. The section from Penrose towards Newmarket was excavated with a TBM (Rahman & Barber, 2002). The project was completed in October 2000 after being delayed by the poor performance of the TBM, which was significantly hindered by the sticky nature of the ECBF when excavated (Asche et al, 2009). It was discovered that when subjected to aggressive mechanical excavation methods the clastic grains of ECBF rocks disaggregate into their fundamental clay sized particles forming material with the constituency of porridge. In its natural state the water content of the ECBF is close to the plastic limit of the pulverised fraction. The resulting clay is prone to swelling and can easily clog openings, auger flights etc (Dowler et al, 2010).

Fortunately this problem can be overcome with appropriate technology. Project Hobson, a 3 km long sewer tunnel, was constructed with an EPBM capable of operating in open and closed modes. The contractor finished ahead of programme in 2009 and the project was generally considered a success. The reason for this success has been attributed to the use of spoil conditioning agents to minimise problems with sticky spoil (personal communication, Victor Romero).

5 CONCLUSIONS AND RECOMMENDATIONS

In general the ECBF provides a benign tunnelling environment with very weak rocks which stand up well and are easily excavated. However, there are a number of issues which can cause significant problems with serious implications for safety, programme and cost. All of these issues can be overcome by a combination of appropriate ground investigation and tunnelling techniques.

Experience has shown that the key risks that need to be considered on tunnelling projects in the ECBF are:

- High groundwater inflows, particularly where conglomerate beds or uncemented sands are present.
- Unforeseen stronger rocks causing additional wear or delays if the equipment is not suitable.
- Unforeseen cobbles and boulders of very strong rock (up to 250 MPa) which can damage machinery, block emergency doors, and result in overbreak.
- Zones of calcite veins and cement which can cause additional wear and may cause particular problems for small tunnels and horizontal directional drilling.
- Mixed face conditions as a result of sawtooth weathering or lenses of conglomerates.

Given the challenges in identifying some of these issues with a ground investigation a process of risk management should be undertaken involving:

- High quality, detailed ground investigation to minimise the potential for encountering unforeseen conditions.
    i. Pumping tests in uncemented sands and conglomerates
    ii. Closely spaced boreholes to identify channelised deposits
    iii. Defect orientation to characterise defects for the assessment of sawtooth weathering profile.
- Assessment and management of residual risks using a combination of:
    i. A targeted Geotechnical Baseline Report
    ii. Appropriate tunnelling specifications and conditions of contract

6 REFERENCES

Asche, H, Ireland, T, Sheffield, M, Bonnette, M, 2009. Hobson and Rosedale tunnels - new technology in Auckland, in Proceedings of the 2009 Rapid Excavation and Tunnelling Conference. Society for Mining, Metallurgy and Exploration (ed: G Almeraris and B Mariucci). pp450-462.

Auckland Council, 2012. The Auckland Plan. Retrieved on 15 March 2014 from: http://www.aucklandcouncil.govt.nz/EN/newseventsculture/OurAuckland/Documents/Auckland%20Plan_OurAuckland.pdf

Ballance, PF, 1974. An inter-arc flysch basin in northern New Zealand: Waitemata Group (upper Oligocene to lower Miocene). J. Geol. 82, pp439–471

Balance, PF, 1976. Stratigraphy and bibliography of the Waitemata Group of Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 19, pp897-932.

Black, P., Riddolls, B. and Horey, P., 2010. 'Petrographic determination of clay content within East Coast Bays Formation for mechanized tunneling projects.' Geologically Active (Williams et al (eds) (London 2010) 1703-1708.

Covault, J. A., 2011. Submarine Fans and Canyon-Channel Systems: A Review of Processes, Products, and Models. Nature Education Knowledge 3(10):4

Dowler, M, Cooper, J, Ireland, T, Frenke, M, 2010. TBM Design for Rosedale Waste Water Treatment Plant Outfall Tunnel. Proceedings of the ITA-AITES 2010 World Tunnel Congress.

Edbrooke, SW (compiler), 2001. Geology of the Auckland area. 1 : 250 000 geological map 3. 1 sheet + 74p. Institute of Geological & Nuclear Sciences Limited. Lower Hutt, New Zealand.

Graham, S. A. et al. Source-to-sink in the stratigraphic record: Capturing the long-term, deep-time evolution of sedimentary systems. AGU Chapman Conference Program, 32-33 (2011)

Hayward, BW, 1976. Lower miocene stratigraphy and structure of the Waitakere Ranges and the Waitakere Group (new). New Zealand Journal of Geology and Geophysics 19, pp871-895.

Haywood, BW, Murdoch, G and Maitland, G, 2011. Volcanoes of Auckland: The Essential Guide. Auckland University Press. ISBN 9781869404796.

Johnston, GI, 1999. Geophysical and structural aspects of the Albany Conglomerate, North Auckland, New Zealand. Unpublished MSc thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Kenyon, P, 2014. Online article "Ramping up mega-TBM progress in Auckland", TunnelTalk, 13 Feb 2014. Retrieved 27 Sep 2014. http://www.tunneltalk.com/New-Zealand-12Feb2014-Mega-TBM-ramping-up-speed-for-Waterview-highway-tunnel-delivery-in-Auckland.php

Mutti, E. Turbidite Sandstones. Parma, Italy: Agip-Instituto di Geologia, Università di Parma, 1992.

Rahman, NU and Barber, K, 2002. Auckland CBD Reinforcement Project. Project highlight from Nexans Olex website (http://www.nexans.co.nz/NewZealand/2012/02.09.2002%20-%20Auckland%20CBD%202.pdf). Retrieved on 31 March 2014.

Roberts, RC, Hawes, OJ, Crossen, SW and Strachan, LJ, 2014. Underground Construction Challenges Associated with the Albany Conglomerate in Auckland. 15th Australasian Tunnelling Conference 2014.

Shane, P, Strachan, LJ, Smith, I, 2010. Redefining the Waitemata Basin, New Zealand: A new tectonic, magmatic, and basin evolution model at a subduction terminus in the SW Pacific. Geochem. Geophys. Geosyst. 11, Q04008, doi:10.1029/2009GC002705.

Spörli, KB and Rowland, JV, 2007. Superposed deformation in turbidites and syn-sedimentary slides of the tectonically active Miocene Waitemata Basin, northern New Zealand. Basin Res., 19, pp199–216.

Sprott, A, 1997. Aspects of the Albany Conglomerate, Waitemata Group, North Auckland. Unpublished MSc thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Statistics New Zealand, 2012. Subnational Population Projections: 2006 base to 2031, October 2012 update. Retrieved on 15 March 2014 from: http://www.stats.govt.nz/browse_for_stats/population/estimates_and_projections/SubnationalPopulationProjections_HOTP0631UpdateOct12.aspx

Whattam, SA, Malpas, J, Ali, JR, Lo, C-H and Smith, IEM, 2005. Formation and emplacement of the Northland ophiolite, northern New Zealand: SW Pacific tectonic implications, J. Geol. Soc., 162, pp225–241, doi:10.1144/0016- 764903-167