LITHOLOGICAL CHARACTER AND STRUCTURAL GEOLOGY OF THE COOKS RIVER AREA WITH FOCUS ON THE M8 TUNNELS

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ABSTRACT

The M8 is a 9 km long dual road tunnel excavated south of Sydney connecting the M5 at Kingsgrove to the future M4-M5 link and Sydney Gateway at St Peters. The tunnel traverses beneath the Cooks River, one of the main sources of sediment for the Botany Basin. The Cooks River has been reconfigured by land reclamation, so the palaeotopography is no longer reflected. A 40 km^2 palaeotopographic surface was developed during the M8 design phase to assist in understanding the sub-surface soil and rock mass, and locations faults may be intersected. The mainline and access ramp tunnels for the M8 also spanned the stratigraphic profile from the top of the Ashfield Shale to 80 m into the Hawkesbury Sandstone, allowing a detailed understanding of the facies profile for this part of the Sydney Basin to be formed. During excavation, several fault zones were confirmed with data collected providing geological insight to the fault character in various lithologies. One of these faults is inferred to correlate with the regional fault zones/joint swarms of Och, Pells and Braybroke, 2004 in the CBD, with a further three inferred to continue to the south based on the palaeotopographic surface generated for the M8 project. Several dyke systems were also intersected, correlatable eastwards to the coast, inland (westwards) using the palaeotopographic surface and one correlatable via the palaeotopography to a diatreme located to the north.

1 INTRODUCTION

Sydney's M8 motorway is a dual road tunnel covering 9 km of mainline excavation linking the M5 East surface motorway at Kingsgrove to the subterranean future M4-M5 Link Tunnels under St Peters. It also includes the St Peters Interchange which provides connects the M8 and M4-M5 Link entry and exit ramp viaducts to the future Sydney Gateway also at St Peters, and the local road network, Figure 1. This link forms a pivotal part of the WestConnex Project. The tunnels follow an arc-alignment, west to east from Kingsgrove to Arncliffe turning to a more north-south alignment through to St Peters. Access shafts were excavated at Kingsgrove, Bexley and Arncliffe. Declines and adits were also constructed at Bexley, Arncliffe and St Peters. The tunnels were excavated by road-header with minor drill and blast. Tunnelling commenced in 2016 with the M8 officially opened in July 2020.

This crescentic alignment is geologically fortuitous as it enabled sub-perpendicular intersection of excavation with both the Sydney's major NNE trending fault set (Och, Pells, & Braybrooke, 2004), (Och, Offler, Zwingmann, Braybrooke, & Graham, 2009), (Offler, Och, Phelan, & Zwingmann, 2009) and the regional east-west trending dyke sets. The transition from Hawkesbury Sandstone in the mainlines to Ashfield Shale in the St Peters exit ramps not only allowed observations of the variation in behaviour of major faults when intersecting the different lithologies, but also provide insight to the lithological form of the bedrock of the southern limb of the Fairfield Basin Syncline (NSW Department of Mineral Resources, 1983).

Additionally, predictive modelling of the rock/soil interface (top of bedrock) was completed for the project at the design phase, covering a much larger area (approximately 40 km^2) to suit modelling requirements. A sound understanding of this interface was critical as the tunnel access infrastructure at Arncliffe was to be developed on Quaternary age alluvial deposits. The alluvial deposits had buried the bedrock palaeotopography masking the deeply incised valley formed by the palaeo-Cooks River when it acted as a feeder to the Botany Basin sedimentary deposition. The Basin extends from Sydney's Eastern Suburbs, south covering the airport precinct and Botany Bay through to the Kurnell Peninsula, Figure 2. The western margin skims the land along the edge of Botany Bay.

Topics covered in this paper are:

- The palaeotopography of this part of southern Sydney.
- The lithological and facies character of the Hawkesbury Sandstone, Mittagong Formation and Ashfield Shale in the southern limb of the Fairfield Basin Syncline.
- Fault zone and joint swarm occurrences, their structural orientations and textural character.
- Condition and character of dykes intersected in the tunnels, their structural orientations and influence on surrounding bedrock.
- A discussion on possible regional correlations of the above with previously published works.

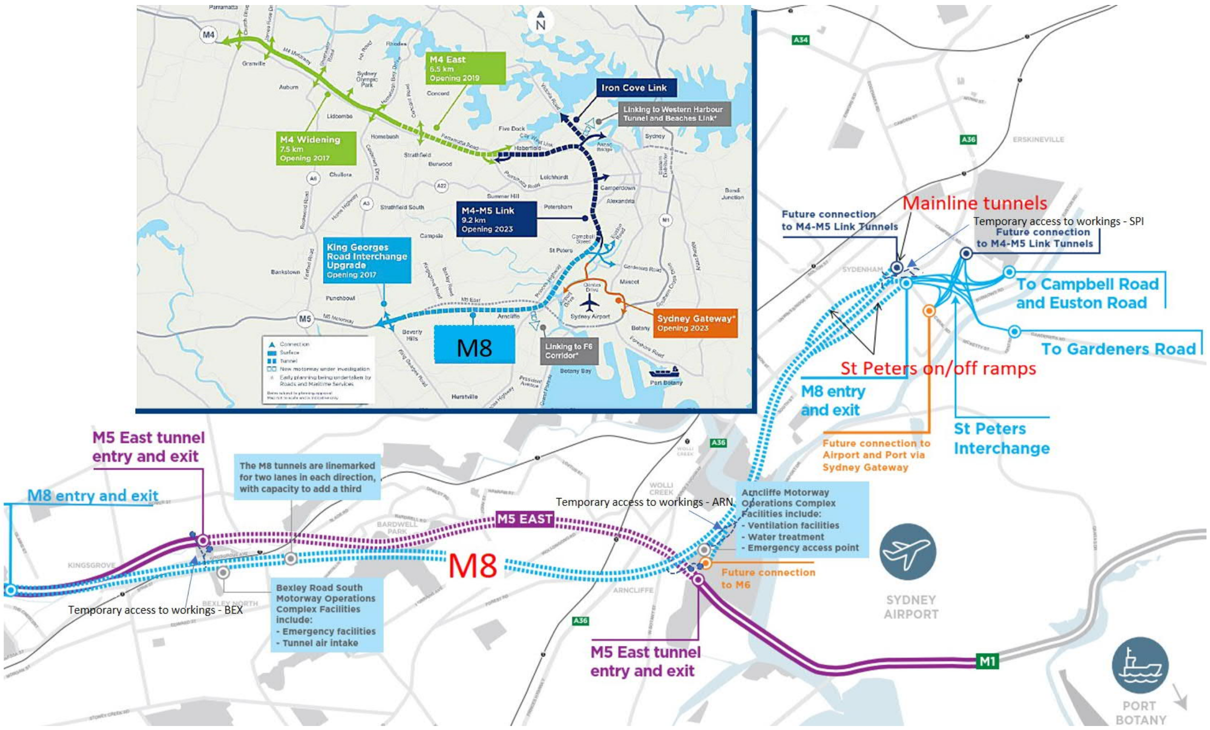


Figure 1: Map of the M8 within the WestConnex project (modified from https://www.westconnex.com.au/)

2 PALAEOTOPOGRAPHY OF COOKS RIVER

For the project design phase, a 3D model of the sub-surface geology was constructed. This covered a larger area than the actual lineal alignment, some 40 km^2. While the primary purpose for the model was to provide an understanding of the lithological and rock mass conditions along the tunnel alignment, from a purely geological standpoint, the critical surface developed was the rock-soil interface. This surface provided a visualisation of the original Cooks River, a feature buried by Quaternary age sands and fluvial sediments of the Botany Sands, and later reconfigured as part of land reclamation associated with the Sydney Airport development. The model dimensions were expanded beyond the immediate project area to assist in:

1. Identifying structural features that may intersect the tunnels, but were not encountered in the drilling investigation,
2. Calibrate the channel gradients and erosional course of palaeochannels and tributaries anticipated as crossing the alignment and
3. Hydrogeological modelling for the project.

The extent of the palaeotopographic model generated is presented in Figure 2, with the detailed model for the Cooks River presented in Figure 3. The surface morphology was developed from assessment of the depth of rock/soil interface from a combination of historic boreholes, project specific boreholes, surface outcrop mapping, historic tunnel mapping, geophysics and bathymetry data from Botany Bay complimented by thalweg constructs. Segments of the palaeochannel and associated tributaries correlate with fault and dyke occurrences, indicative of structure continuity and preferential erosional relationships. Each of these occurrences is discussed in the following sections.

The palaeotopographic surface does not distinguish between shale and sandstone bedrock. However, the topographic highs align with Ashfield Shale hilltop capping while the incised channels are developed cutting through the Hawkesbury Sandstone, Figure 2 (NSW Department of Mineral Resources, 1983). The St Peters Brickpit, which was reclaimed for the M8 St Peters Interchange is the only brickpit excavation presented in the model for this paper. This interchange comprises viaducts and ramps linking the M8 and future M4-M5 Link Tunnels to the Sydney Gateway and local surface road network.

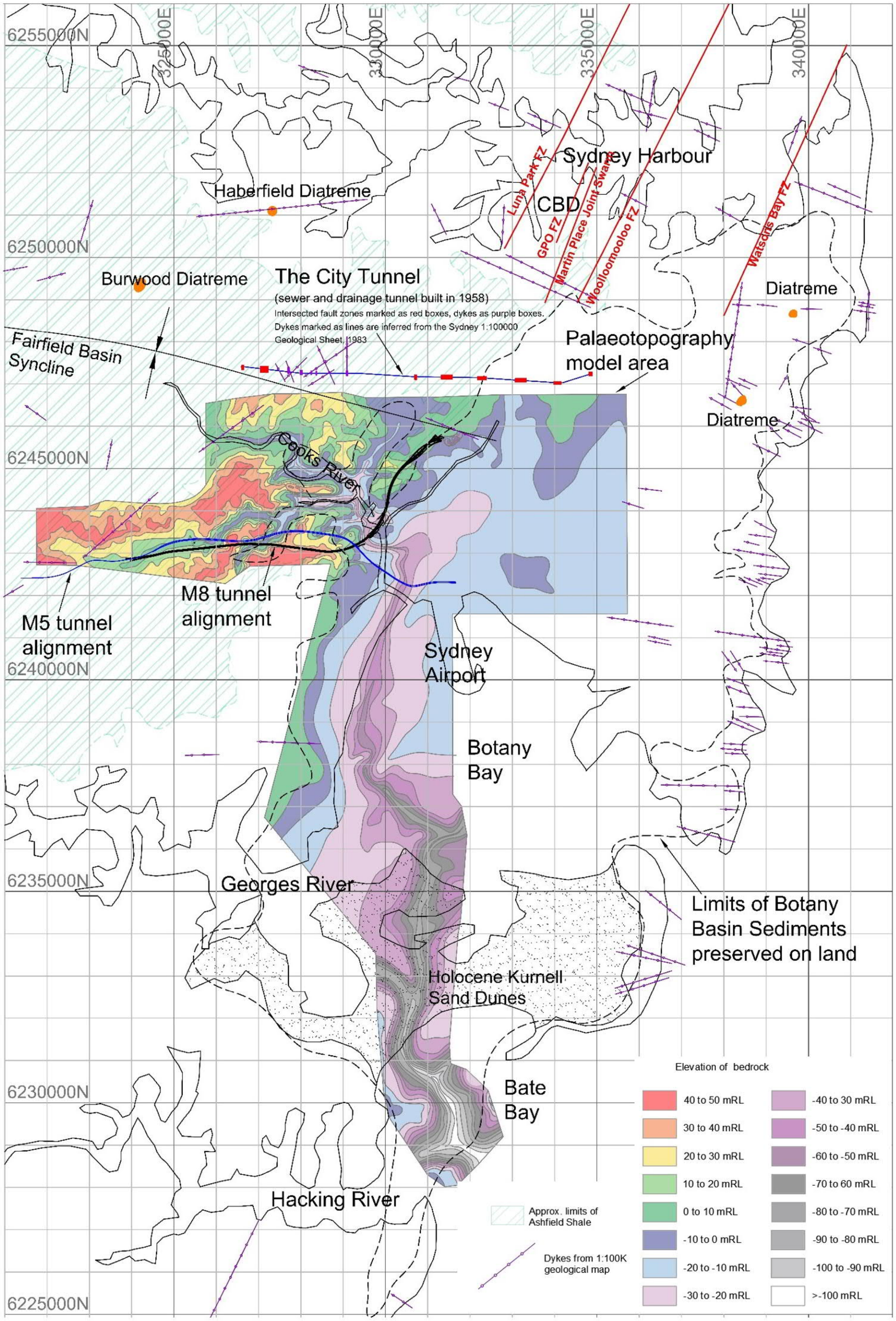


Figure 2: Extent of Palaeotopographic Surface Generated for the M8 project.
After (Och, Pells, & Braybrooke, 2004), (NSW Department of Mineral Resources, 1983)

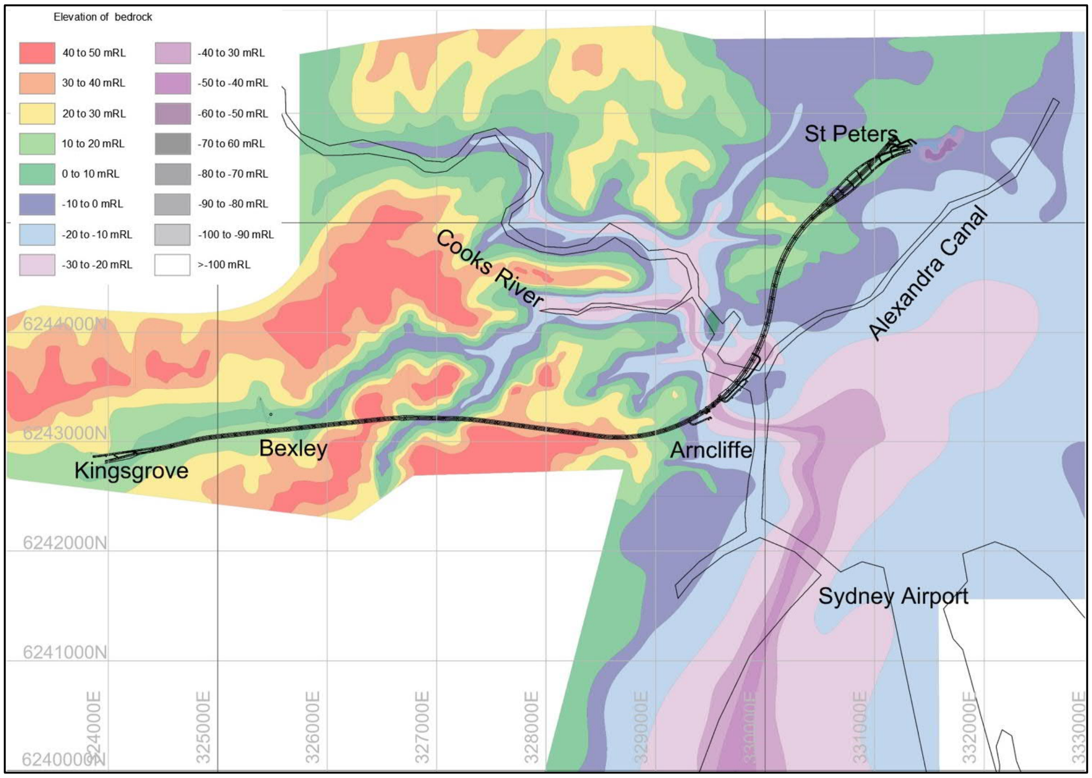


Figure 3: Palaeotopography of Southern Sydney, Cooks River area. Current Cooks River configuration presented in black along with M8 alignment. Coloured top of rock elevation contours as per legend

3 LITHO-STRATIGRAPHY OF COOKS RIVER AREA

The M8 provides a fascinating understanding of the bedrock within the southern limb of the Fairfield Basin Syncline. This fold is an open syncline, oriented west to east, Figure 2. Basement and tunnel excavations from the Central Business District (CBD) and along Sydney Harbour, which are located on the northern synclinal limb provide the majority of geological data contributing to the understanding of Sydney's bedrock (Herbert & Helby, 1980), .

The CBD is predominantly developed in Hawkesbury Sandstone with alluvial deposits along the Harbour shorelines. Younger sequences of the Mittagong and Ashfield Shale form topographical highs inland of the Harbours northern shore and to the south and southwest of the CBD, Figure 2.

The CBD specific historic work suggests a dominant north-northeast trending structural fault zone orientation (presenting as joint swarms) and a generalised facies sequence of repeating beds of massive sandstone with beds of cross-bedded sandstone (the massive facies and the cross-bedded facies (Herbert & Helby, 1980), (Pells, P.J.N, 2004)); a pattern considered ubiquitous across the Hawkesbury Sandstone. Dykes are known to cross-cut the city from intersection in basement excavations and historic tunnels (Pells, P.J.N, 1985).

For the Cooks River area, the M8 project has provided a detailed insight to the facies distribution, orientation, character and variability of fault zone development, and dyke-bedrock interactions. The project starts and ends in Ashfield Shale, with underlying Mittagong Formation and Hawkesbury Sandstone exposed in unweathered condition along the mainline tunnels. As sub-vertical fault zones are difficult to target with drilling investigations, a detailed facies differentiation of the Hawkesbury Sandstone from borehole data was undertaken at the design phase to assist with recognising possible displacement across both inferred fault zones and dykes, and therefore the viability to include their presence in the model. Boreholes which transitioned through Mittagong into Hawkesbury Sandstone were assessed first to allow clear identification of a defined contact and develop the understanding of the facies sequencing patterns in the sandstone for the local area. Other boreholes were added to the assessment once the notional local facies sequence was formulated.

The findings of this study and other observations of the bedrock are presented in the following sections.

3.1 ASHFIELD SHALE

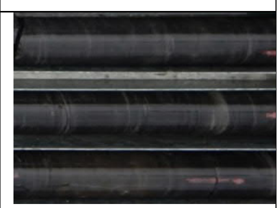
The Ashfield Shale is a marine basin sedimentary sequence, comprising four sub-units, youngest to oldest:

1. Mulgoa Laminite,
2. Regentville Siltstone,
3. Kellyville Laminite and
4. Rouse Hill Siltstone.

All four sub-units were observed in the excavation for the on and off ramps at St Peters. The Ashfield Shale excavations were unweathered, however the St Peters exposure coincided with a major fault zone, disrupting the ability to estimate sub-unit thickness and variation.

The unit thickness has been tabulated from drilling data collected for the project. The thickness of Ashfield Shale sub-units local to the Cooks River area are presented in Table 1.

Table 1: Thickness of Ashfield Shale Sub-Units Based on Drilling around Cooks River

Member	Thickness (m) All intersections – upper contacts may be eroded and/or borehole does not penetrate unit	Full thickness (m) Both upper and lower contacts with adjacent sub-unit are intersected by borehole	Description	Type Photo
Mulgoa Laminite	Range: 0.1 - 23.2 m Average: 7.18 m Boreholes: 148	Range: 6.25 – 11.9 m Average: 8.99 m Boreholes: 6	Interlaminated siltstone and very fine sandstone.	
Regentville Siltstone	Range: 0.05 - 24.7 m Average: 5.53 m Boreholes: 178	Range: 3.3 – 15.45 m Average: 8.76 m Boreholes: 24	Dark grey mudstone, shale and siltstone.	
Kellyville Laminite	Range: 0.79 – 16.8 m Average: 6.17 m Boreholes: 112	Range: 2.3 – 16.8 m Average: 8.39 m Boreholes: 34	Interlaminated siltstone and very fine sandstone, distinctly ‘zebra” striped appearance. Distinct pale grey claystone marker bed.	
Rouse Hill Siltstone	Range: 0.05 – 13.1 m Average: 4.50 m Boreholes: 148	Range: 2.95 – 13.1 m Average: 6.79 m Boreholes: 27	Dark grey to black mudstone or shale often associated with shearing at basal contact of formation. Bedding is so fine as to appear massive.	

Only boreholes where both the upper and lower contacts were intersected were included in this assessment. The thicknesses observed in the Cooks River area vary from those indicated as typical for the Ashfield Shale (Herbert & Helby, 1980):

- Mulgoa Laminite, 6 to 12 m compared to regional 17 to 32 m.
- Regentville Siltstone, 3 to 16 m compared to regional 12 to 20 m.

- Kellyville Laminite, 2 to 17 m compared to regional 1 to 10 m.
- Rouse Hill Siltstone, 3 to 13 m compared to regional 5 to 15 m.

This discrepancy is likely due to the portion of the project within the Ashfield Shale coinciding with a major fault zone, hence the majority of site investigations boreholes for M8 exhibit some loss or repetition of unit sequences, depending on the position within the fault zone.

The variability in unit thickness highlights the importance for projects to uniquely identify Ashfield Shale sub-units in both boreholes during investigation as well as in exposures during excavation. A blanket “adopted” thickness may result in inappropriate modelling of tunnel crown conditions, predictions of unit intersection and potential inappropriate support design.

3.2 MITTAGONG FORMATION

The Mittagong Formation separates the Ashfield Shale from the underlying Hawkesbury Sandstone. The formation represents the transition from the fluvial / terrestrial environment of the Hawkesbury Sandstone deposition to the marine delta deposition environment of the Ashfield Shale. The Mittagong Formation consists of medium-grained quartzose and micaceous quartzose sandstone, interlaminated with siltstone. As it is a transitional unit between the Ashfield Shale and the Hawkesbury Sandstone, the unit margins are gradational and can be difficult to define. For the M8 the following was adopted as the contact indicator, Figure 4:

- Upper contact with Ashfield Shale – The contact was taken as the position were the first occurrence of sandstone is observed following the uniformly siltstone composition of the Rouse Hill Member of the Ashfield Shale.
- Lower contact with Hawkesbury Sandstone – The contact was taken as the position were the lithology changes from interbeds of siltstone and sandstone to coarser grained sandstone with silty laminations.

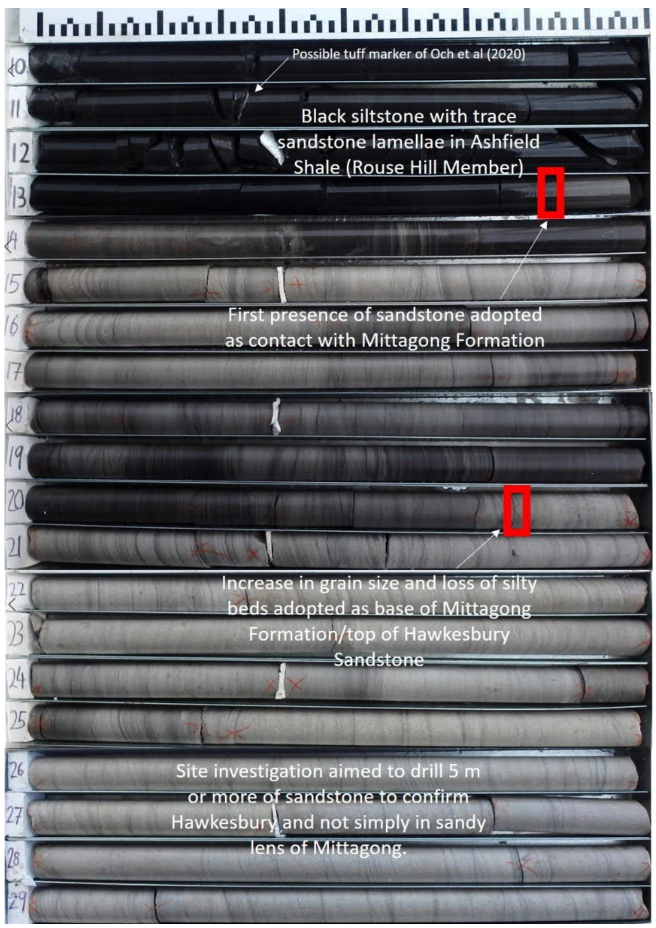


Figure 4: Adopted contacts of the Mittagong Formation with the Ashfield Shale and Hawkesbury Sandstone

Based on boreholes drilled for the M8 project, the Mittagong Formation ranges from 0.4 to 12.85 m thick, with an average thickness of 3.86m, from 58 boreholes where both upper and lower contacts were intersected (so full unit thickness was encountered). 138 boreholes intersected part of the Mittagong Formation, indicating a unit thickness up to 16.17 m. Isopach contours of the Mittagong Formation unit thickness around St Peters are presented in Figure 5. West of the alignment, between Arncliffe and St Peters the Hawkesbury – Mittagong contact trends locally NNE based on borehole interpretations. This coincides with the extrapolated position of the Arncliffe Fault Zone (AFZ), intersected by the M8 tunnels at Arncliffe, Figure 5, with Mittagong Formation displaced and eroded out within and west of the fault zone.

Mittagong is locally thickest between the AFZ and St Peters Fault Zone (SPFZ) thinning to less than 3 m within the SPFZ, before again thickening again to the east. This suggests a strong relationship between unit shortening or thickening in relation to the deformation generated by the NNE trending regional fault zones. The AFZ and SPFZ are wide structural features intersected by the tunnel excavation that are potentially correlatable with regional fault zones mapped in the CBD, discussed further in the following sections.

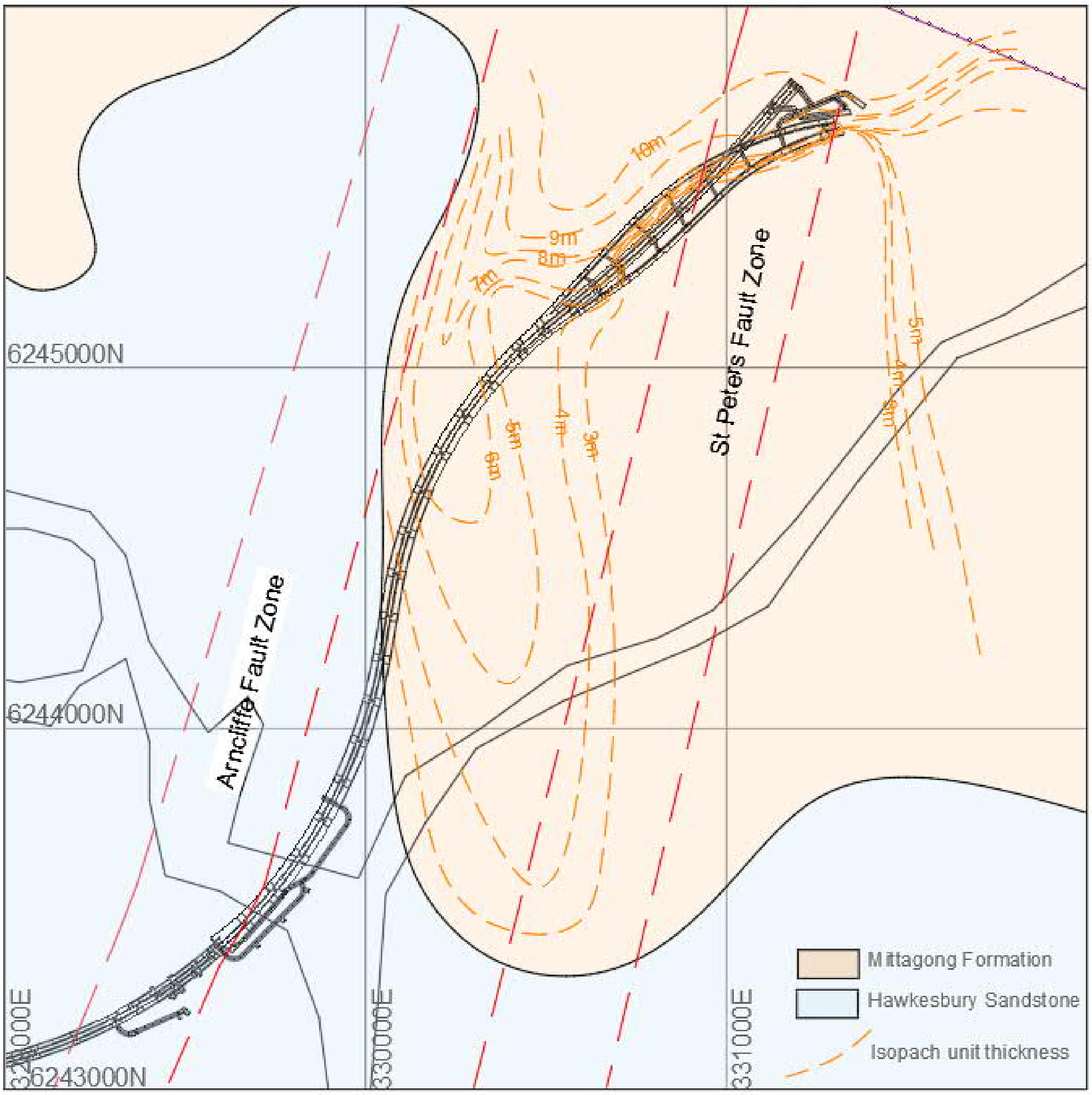


Figure 5: Isopach Contours of unit thickness for the Mittagong Formation

3.3 HAWKESBURY SANDSTONE

The Hawkesbury Sandstone is a fine to coarse grained quartzose sandstone fluvial river deposit, deposited in an environment inferred as analogous to the braided river system of the Ganges today (Veevers, 2000). It comprises sequences of sheet (cross-bedded) facies, massive facies and thin shale/laminite beds interpreted to have resulted from overbank and swamp deposits during quiescent periods. The facies are differentiated by their appearance and are the results of changes in the energy of the alluvial environment of deposition. The Hawkesbury Sandstone formation is in excess of 290 m thick and is made up of repetitions of the three facies.

About 98% of the mainline tunnel excavation of the M8 was in Hawkesbury Sandstone. A review and correlation of facies within the Hawkesbury Sandstone was undertaken during the design phase to inform if mapped and inferred fault structures and lineaments from the wider project area could be continuous and possibly intersect the tunnels. The facies correlations enabled an assessment of possible displacement of beds across the inferred structure, thereby providing confidence that such features were or were not continuous as well as improve confidence in predictions of the location of tunnel intersection.

The facies study utilised the boundary with the Mittagong Formation in the western end of the alignment as the start point for the youngest sub-facies in the sandstone, gradually reviewing and interpreting facies within each borehole moving east.

A repetitive sequence was apparent as boreholes were systematically compared and correlated. The distribution of facies is presented in Figure 6 for the section of tunnel from Kingsgrove to Bexley (approximately 3.5 km) where a repeated sequence of cross-bedded sandstone, massive sandstone and shale marker beds were identified. Type photographs are presented in Figure 6 for each of the major facies types. The thickness of individual beds did vary and as would be expected for such a length, some horizons were missing. The missing horizons were notably most commonly, the shale beds. The “shale beds” vary from siltstone lenses several metres thick to a few relic siltstone pebbles. Due to the pattern of deposition within the Hawkesbury with the shale beds representing flood over-topping events, typically eroded by the subsequent depositional phase, this reflected expectations on facies continuity.

Overall the following sequences were recognised in the facies assessment:

- Thick deposits of fluvial cross-beds during periods of “typical” wave action for fluvial system. This is effectively the “background” deposition.
- Thick deposits (relatively) of siltstone in channels at quieter times, with some preservation of thinner lenses along the banks of channels.
- Turbulent erosion of siltstone horizons by stronger wave action resulting in formation of rip-up clasts and preservation of these clasts in the turbulent sand deposit as shale breccia horizons.
- Thick “dumps” of sand without bedding structure preserved as massive sandstone from large flood events at various times throughout the depositional history.

In the Cooks River area, the facies assessment indicated the upper 15 to 25 m of the Hawkesbury Sandstone comprised micaceous silty sandstone cross-beds interbedded with more sandy quartzose cross-beds. This is likely indicative of the transition in the depositional environment from fluvial to shallow marine (and formation of the Mittagong and overlying Ashfield Shale sequences).

From 25 m to about 85 m below the Mittagong contact, the sequence comprised sandy quartzose cross-bed facies with regularly spaced massive beds and shale beds. The shale beds are thickest and most uniform at the upper portion of this zone, with shale breccia and shale clasts increasing with depth. The lower portion of the drilled intersections (maximum 120 m vertical thickness of the unit was drilled) tended to be dominantly comprised of thick bands of sandy quartzose cross-beds and lesser thin (less than 0.5 m) dominantly shale breccia horizons. Massive beds are rarer also in the lower portion.

This depositional sequence pattern was reflected at the Mittagong-Hawkesbury contact at St Peters at the junction with the M4-M5 tunnels, despite some disruption from regional faulting. Overall, the correlations proved to be beneficial in demonstrating offsets across lineament features inferred to be faults and dykes.

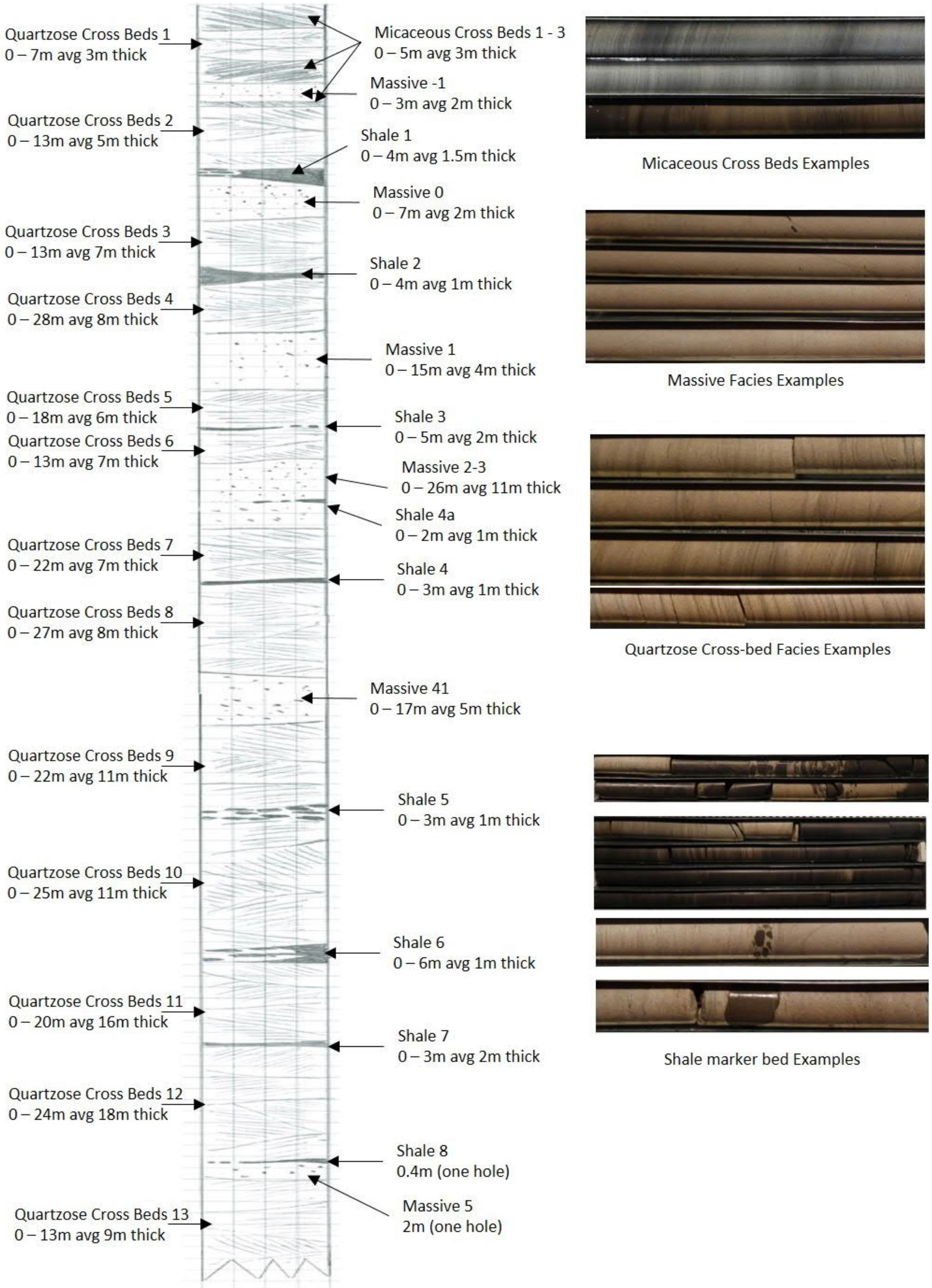


Figure 6: Distribution of facies within the Hawkesbury Sandstone from boreholes drilled between CH2000 and CH5700

4 FAULT ZONES

Several zones of defined brittle fracturing and deformation were encountered along the M8 alignment. The zones comprised groups or swarms of closely spaced sub-vertical to steeply dipping, variably continuous to discontinuous joints with spacing within each group typically 100-600 mm. A zone would comprise a few to several of these joint swarms with quality intact rock in between. Some joints within the zone were more continuous and had obvious crushed rock infill. These often could be observed to displace bedding and other features in the surrounding rock. The zones, from here-on termed Fault Zones, varied from a few metres to a few hundred metres wide. Two particularly wide fault zones are discussed in this paper – The Arncliffe Fault Zone (AFZ) and the St Peters Fault Zone (SPFZ). Figure 7 presents the faults, fault zones and dykes encountered by the M8 excavation.

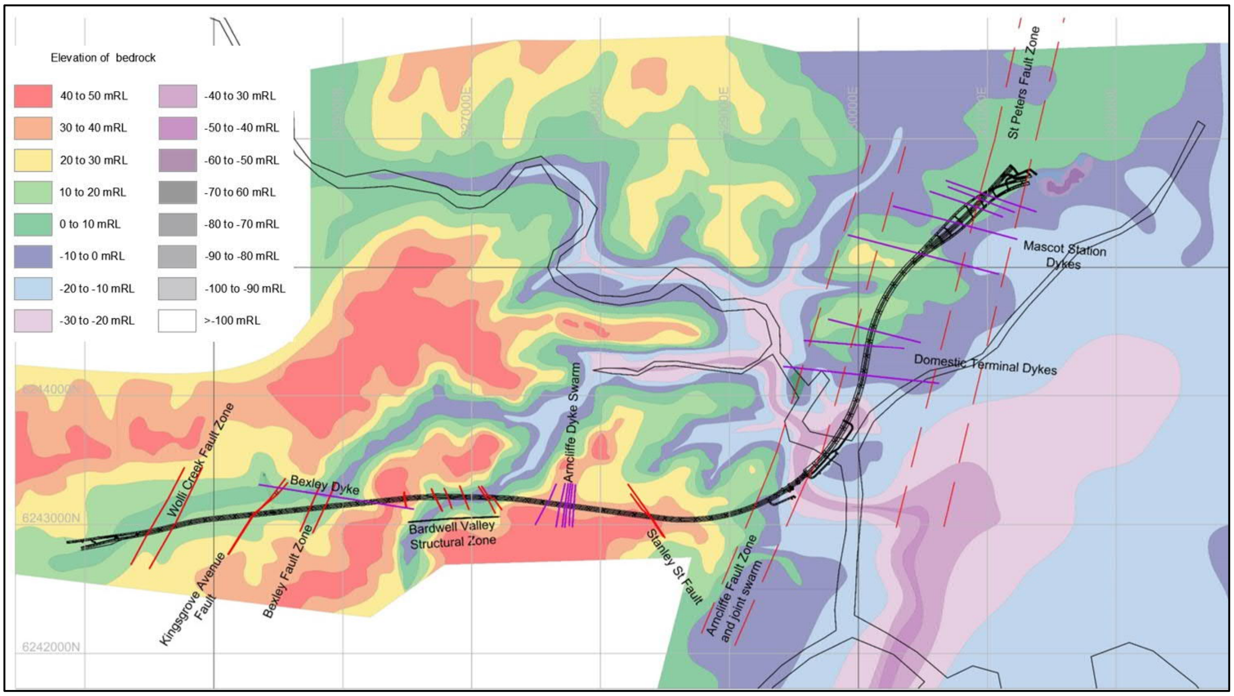


Figure 7: Faults, Fault Zones and Dykes encountered by the M8, overlaid on palaeotopography of Cooks River. Note the 6th dyke in the Mascot Station Dykes group is too narrow to display at the scale of the figure

4.1 ARNCLIFFE FAULT ZONE

The Arncliffe Fault zone comprises a 50 m wide central core of faulted joints, high angle shears and thick crush zones with an overall orientation of 50-70°/290° (dip/dip direction), with >100 m of highly fractured, joint swarm-rich rock mass either side, making an overall fault zone width of 300 m (true), Figure 8. The joint swarms are slightly steeper dipping than the central shears, dipping 70-90° and mostly westward (270-300° dip direction). Shears within the central core of the fault zone are spaced <1 to 10 m and the surrounding joint swarms are spaced 2 – 10 m. A conjugate set of joints is also apparent within the zone. Displacement of bedding and development of shear surfaces and gouge was observed in the central core of the fault zone, Figure 9 and Figure 10. Displacements ranged from a few centimetres to >6 m (maximum observable face excavation at any one time). The cumulative total displacement was in the order of 10 to 12 m with the west side down, commensurate with the borehole correlations from the facies assessment.

Outside of the tunnel excavation, borehole assessment from the wider project area and the development of the palaeotopographic surface suggests that the AFZ can be traced both to the north and south. To the north, the AFZ marks the contact between the Mittagong and Hawkesbury Sandstone before locally following the alignment of the Cooks River palaeochannel. To the south, it forms the easterly limits of Hawkesbury outcrop, just inland of the Botany Bay foreshore.

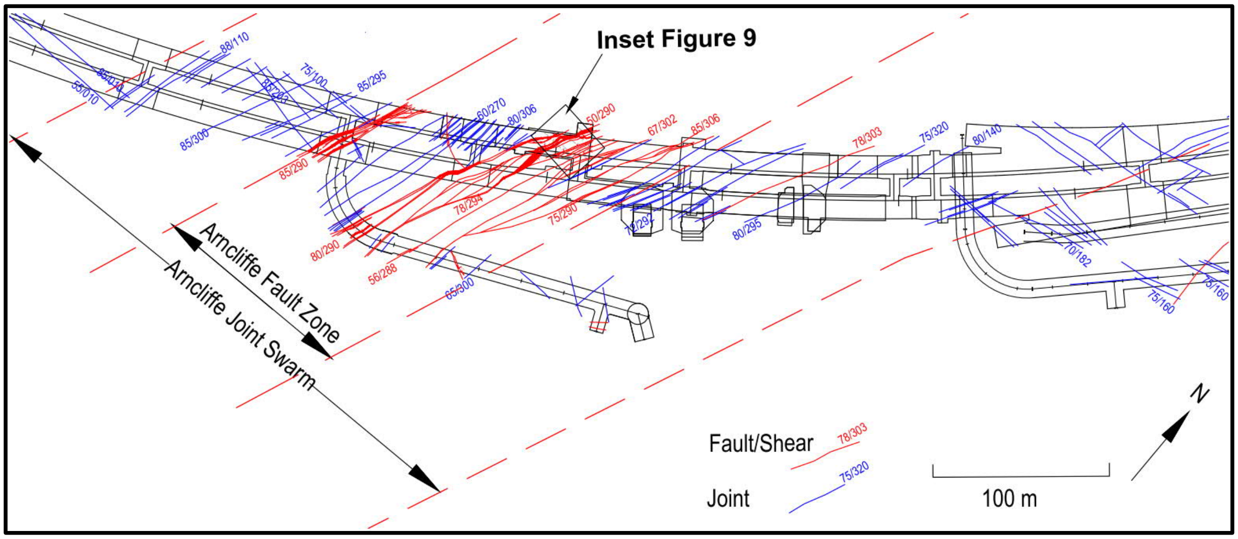


Figure 8: Faults and joints that comprise the Arncliffe Fault Zone from M8 tunnel mapping. Not all orientation information shown for clarity.

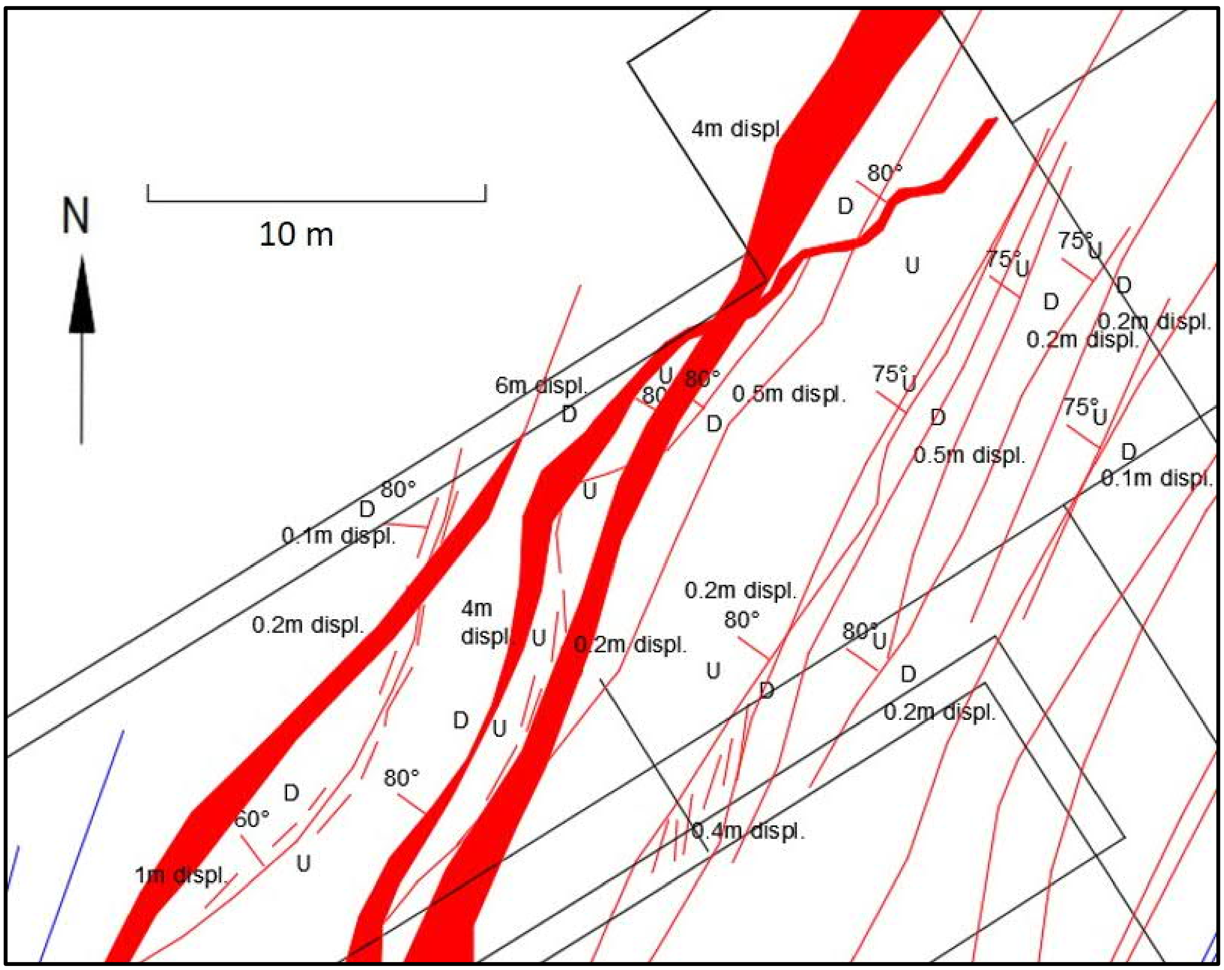


Figure 9: Detailed displacements mapped on faults at Arncliffe, location is the inset in Figure 8

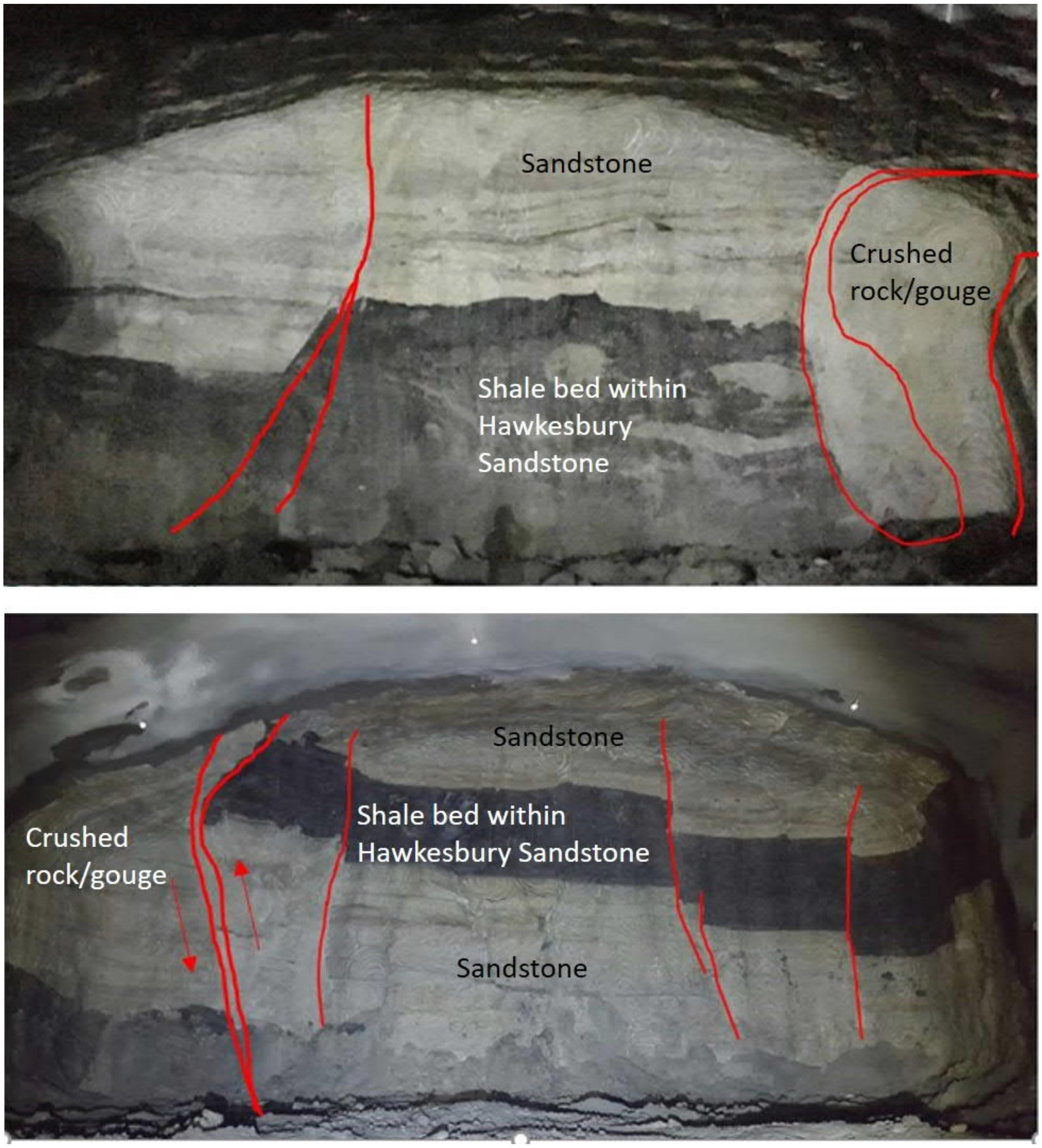


Figure 10: Photographic examples of the crushed rock structures in the Arncliffe Fault Zone observed during the daily face mapping. Tunnel height approx. 3 m

4.2 ST PETERS FAULT ZONE

The St Peters Fault Zone is a series of mostly high angle joint swarms, shears and crush zones as well as low angle bedding shears. Joint swarms are spaced 2-10 m. Significant block fault movement along both high angle and low angle shears was observed, making stratigraphic sub-unit identification a critical component of the mapping, Figure 11.

A portion of the St Peters exit ramp tunnels vertically overlies the mainline tunnels that connect the M8 to the M4-M5. The mainline tunnels are at depth, excavated in the Hawkesbury Sandstone before crowning in the Mittagong Formation at the junction with the M4-M5 tunnels. The on and off ramps to St Peters Interchange are excavated in Ashfield Shale. The various construction access tunnels descend from Ashfield Shale into Mittagong Formation.

A feature observed was that the intensity of shearing was most obvious in the shale units, decreasing markedly in the underlying more competent sandstone, though still present. This could indicate that the SPFZ is a flower structure, splaying into shallower shears in the less competent shale, or may simply be due to the mainline tunnels not penetrating far enough into the most deformed portion of the fault zone. Excavation of the M4-M5 Link Tunnels may provide the pertinent information needed to resolve this.

Overall, the SPFZ has a true width of some 360 m. Displacements, again with overall west side down were typically in the order of 100 to 500 mm, up to 2500 mm, Figure 12, though graben-style block movement was also observed. The total cumulative displacement was difficult to discern in outcrop, however borehole correlations suggest it is in the order of 10 to 15 m.

Outside of the tunnel excavation, the SPFZ can be traced from borehole interpretation and the palaeotopographic surface well to the south, aligning y well with the main axis of the Cooks River palaeochannel in Botany Bay and possibly further south, correlating with the alignment of bays in the Hacking River. This is discussed further in Section 6.

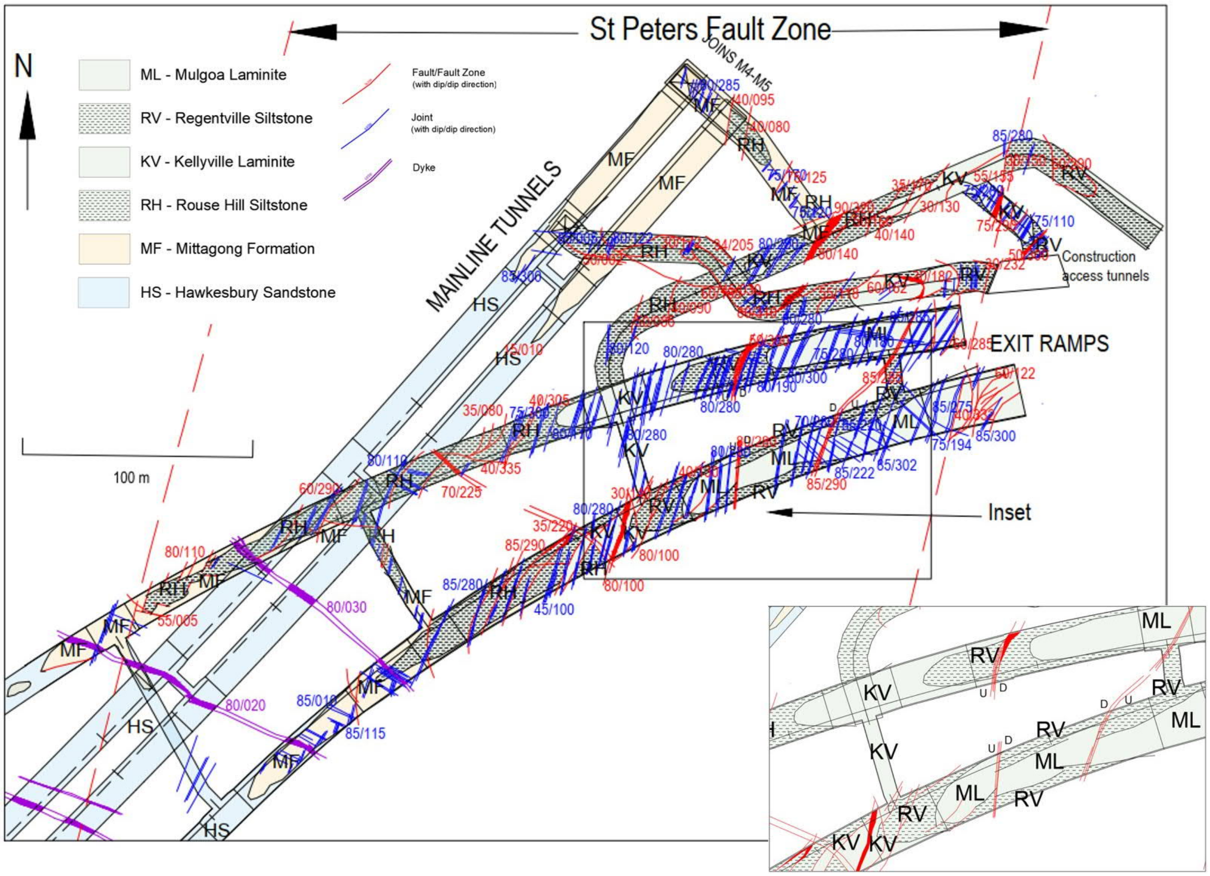


Figure 11: Faults and joints that comprise the St Peters Fault Zone from M8 tunnel mapping. Not all orientation information shown for clarity

5 DYKES

From previous projects, four dyke systems were anticipated prior to excavation of the M8:

1. Bexley Dyke – 2 to 6 m wide structure observed in excavations near the M5E portal (2 m wide) and at the M5E coffer dam (6 m).
2. Dyke swarm near Arncliffe, intersected in the M5E tunnel as a series of 0.2 to 1 m thick dykes over 65 m lineal distance.
3. Domestic Airport Dyke – 2 m wide dyke intersected in the Domestic Terminal train station excavation.
4. Mascot Dyke – 6 m wide dyke intersected in the Mascot Station excavation.

All four were encountered in the M8 excavation, Figure 7, though presented slightly differently to the previous observations. The encountered observations are presented below. Correlations between the intersected dyke locations and wider Sydney area are discussed in Section 6.

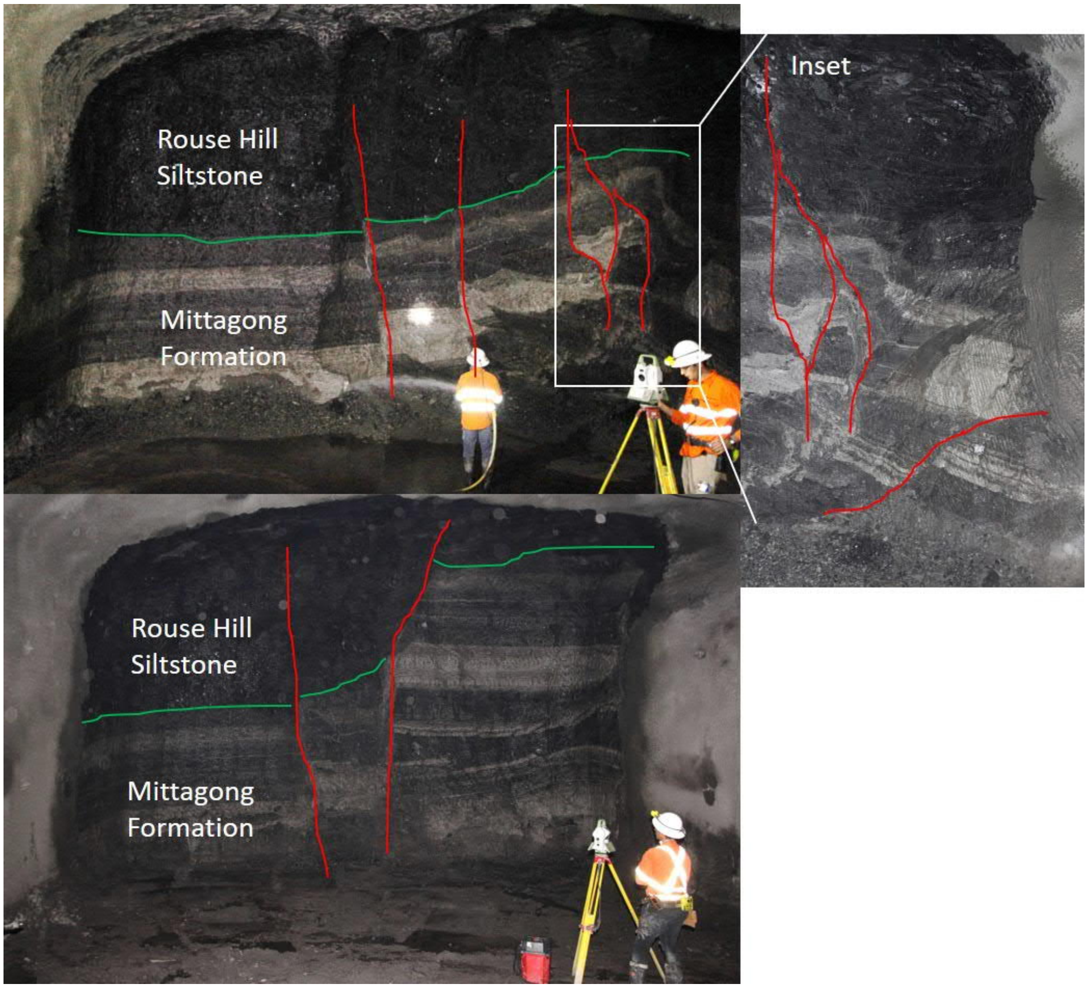


Figure 12: Photographic examples of the crushed rock structures in the St Peters Fault Zone observed during the daily face mapping. Tunnel height approx. 5 m

5.1 BEXLEY DYKE

This dyke ranged from 5.1 to 11.5 m true width in three intersections (both mainline tunnels and an adit access tunnel).It exhibited a strongly weathered margin and less weathered inner core, Figure 13. The dyke exhibited a strongly sheared texture, mostly parallel to the contacts. While it could not be confirmed in the tunnel mapping, facies distribution assessment either side of the dyke suggested a displacement of the bedrock across the intrusion with north side down by 10 to 12 m. The overall trend of the dyke was 280-100°, dipping sub-vertically.

Baking of the contacts was minimal at the hand specimen to excavation scale. The dyke did act as a significant barrier to the movement of groundwater, with in excess of 100 litres/minute water flow occurring from probe drillholes drilled through the dyke.

5.2 ARNCLIFFE DYKE SWARM

This swarm of dykes was completely different character and continuity to those typically observed in Sydney. Over a zone 200 m wide, multiple dyke intersections were mapped – 11 traceable across the east bound mainline, with a further two discontinuous dykes not traceable for the full tunnel width; six traceable across the westbound mainline. The dykes ranged from 0.1 m to 0.5 m thick, averaging 0.15 m, with one wider 2.5 m thick structure. The dykes showed several different structural patterns – boudinage development, anastomosing, bifurcation then merging back together as examples. The dyke contacts were often sheared and any sandstone incorporated between bifurcating lenses was deformed, Figure 14. Observed displacements where in the order of 0.5 m. Additionally, it was observed that the sandstone bedrock rapidly altered from fresh, grey, sandstone to strongly oxidised within the space of 24 hours upon excavation over a zone extending some 200 m either side of the outer-most dykes (total zone with 600 m). This area was the only location within the tunnels where this phenomenon occurred, so is considered to be related to the dyke geochemistry. Nine dykes from this system were also observed in the M5 East tunnel during construction, located 400 m to the north, with the variation in number of dykes likely attributable to their bifurcating, discontinuous nature.

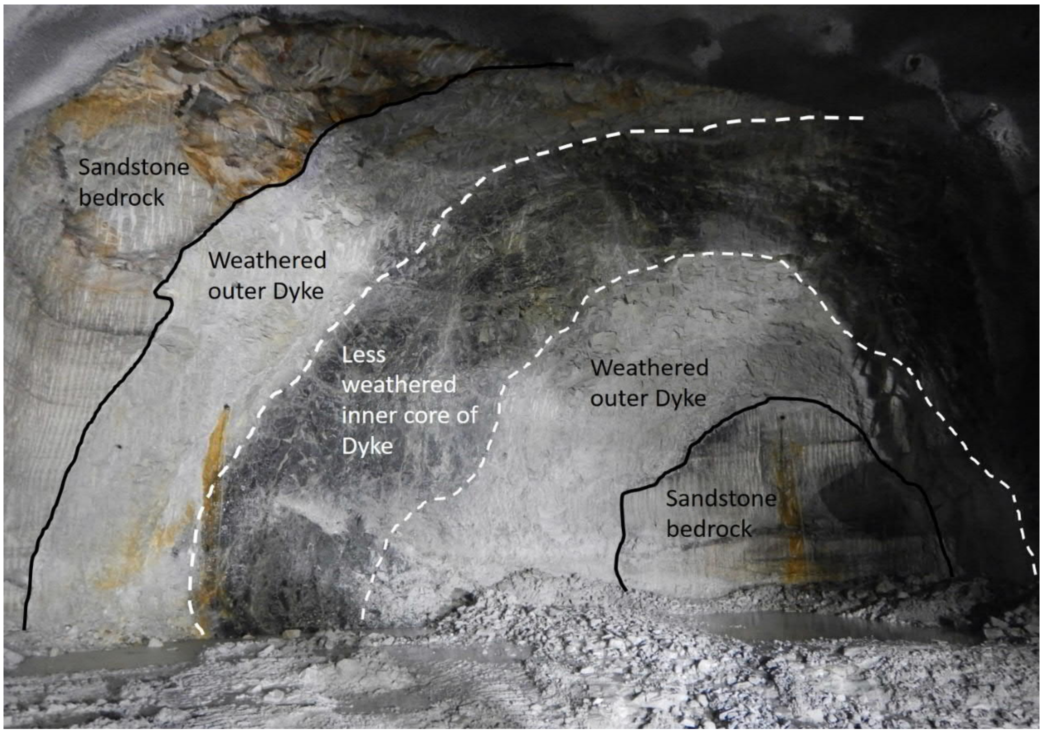


Figure 13: Tunnel face photograph of the Bexley Dyke

5.3 DOMESTIC TERMINAL DYKES

Three dykes were encountered by the M8 excavation trending along the interpreted trajectory of the dyke encountered by the Domestic Terminal Train Station excavation. The dykes occurred over a 300 m wide zone. It is uncertain if all three are present around the Domestic Terminal (but only one was encountered within the station footprint) or if that dyke splays into a series of dykes to the west. Due to the observed thicknesses, the former is considered most likely. Ten dykes are indicated by the 1:100 000 Sydney Geological Sheet on the coast, due east of the section of tunnel from Arncliffe to St Peters and this aligns with observations in the M8.

The dykes are 2 m, 3 m and 1.5 m wide (southern-most to northern-most), and trend east-west. There was minimal shearing or baking of contacts observed and disturbance of the bedrock was limited to apparent displacements of less than 0.5 m from correlating bedding across the dyke structures. There was a minor increase in the inflow of water along the contacts, only slightly more than observed within the bedrock itself. Both the dolerite dyke rock and surrounding bedrock were unweathered at the depth of intersection by the tunnels.

5.4 MASCOT STATION DYKES

Six dykes were encountered over a 700 m zone of M8 mainline tunnels, oriented east-west and in the line of apparent extrapolation to the Mascot Station Dyke. The dykes were spaced 70 – 100 m apart and were 0.5 to 2 m wide, with the exception of the southern-most dyke which was 4 m wide and located some 380 m south of the rest. This could suggest that the southern-most dyke is a separate entity and unrelated to the intrusion of the other dykes.

Similar to the Domestic Terminal Dyke, it is uncertain if the six dykes intersected in the M8 are splays of the 6 m wide Mascot Station Dyke or if only one of that cluster was intersected at Mascot Station due to the station footprint.

Shearing along the contacts was minimal and inferred displacements of bedding were again in the order of 0.5 m. Both the intrusive dolerite and surrounding sandstone were unweathered. The northern-most dyke was exposed in Ashfield Shale excavation in the St Peter's on and off ramps and rapidly deteriorated with exposure.

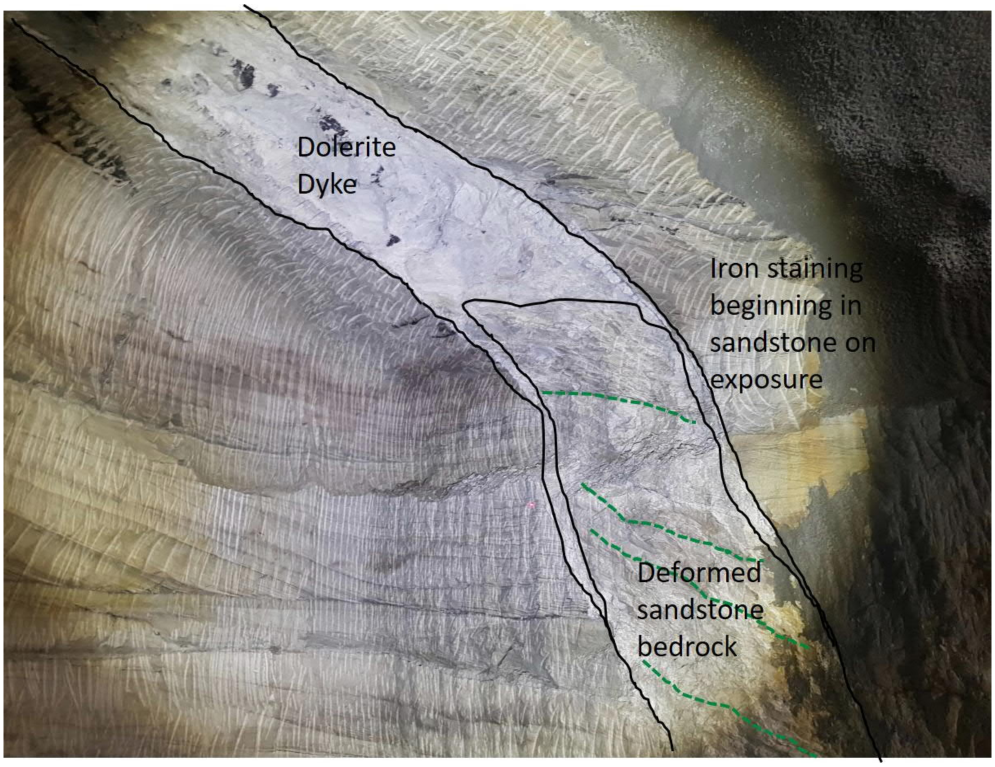


Figure 14: Tunnel face photograph of one dyke from the Arncliffe Dyke Swarm

6 REGIONAL CORRELATIONS

6.1 FAULT ZONES

The location and character of Sydney's major fault zones is understood from observations and publicised information pertaining to basement excavations and tunnels that have been developed in the CBD, collated by authors such as Herbert and Helby, 1980 and Och, Pells and Braybrooke, 2004. Outside of the CBD, fewer intersections of major structures have been encountered due to lesser deep basement development, limited tunnelling and again, limited publication.

The work of Och et al, 2009 (Och, Offler, Zwingmann, Braybrooke, & Graham, 2009), postulated the continuation of the fault zones observed in the CBD to the south, using correlations with lineaments observed in the surface geomorphology. The postulated fault traces included a number of kinks, some varying the alignment of individual faults by as much as 12°. Additionally, many were postulated to intersect various bays within the Georges and Hacking River systems, south of the CBD, but cross these eroded valleys obliquely.

A revisitation of the fault traces from the CBD intersections to the south of Sydney has been completed here, using the palaeotopographic surface created for the M8 project. Fault zones in Sydney are observed to form zones of poorer rock mass quality. These zones are more likely to form weaknesses in the rock that will be preferentially eroded by fluvial systems. As such, correlating the zones of deep erosion in the Hawkesbury Sandstone with known fault observations, for example mapping from the City Tunnel, a sewer tunnel constructed in 1958, Figure 1 and the M8 observations, improves the confidence in the trace of the faults.

The City Tunnel mapping fills an important gap between the CBD and M8. It is recognised there is a vast quantity of tunnel excavation presently underway in Sydney and this too with improve certainty on fault correlations and alignment variability moving forward.

Table 2 summarises the possible fault zone correlations between the CBD and M8 and extrapolation to the south. Figure 15 presents this information in plan.

Within the CBD the inferred distance between fault zones range from 300 to 900 m. Mapping from the M8 and City Tunnel both indicate that the faults zones can be up to 300 m wide with distances of 700 to 1000 m between zones, centre to centre. This suggests that the CBD fault zones may be wider than the limited data sharing would suggest or that the fault zones splay into narrower fracture zones, potentially due to the added complication of Sydney Harbours palaeo-history.

South of the M8 alignment, fault zone locations have been inferred from outcrop mapping, the Cooks River palaeochannel and alignment of various topographic features. The extrapolations suggest a distance between fault zones of 1200 to 2000 m. The width of the zone cannot be accurately defined. The inferred widening of competent rock between fault zones could be an artifice of the improved competency of the Hawkesbury Sandstone with depth, as south of the M8 the outcropping Hawkesbury Sandstone progresses deeper through the unit profile culminating at the basal contact located within the Royal National Park, south of the Hacking River. The variation in behaviour of fault zone with rock competency was observed in the M8 with the SPFZ.

As expected, the extrapolated fault zones are not straight lines – the dykes post-date fault zone development and facies assessment of bedrock either side of the Bexley Dyke indicated movement of the bedrock by the intrusions is possible. The alignment of the fault zones are sub-parallel and in keeping with the detailed mapping completed in the M8. There is an inflexion point in the trend of some faults between the City Tunnel mapping and the CBD correlations. An observation is that the more northerly trends correlate with the palaeochannels developed in the Hawkesbury Sandstone, while the more north-easterly trends correlate with intersections in the Ashfield Shale, Mittagong and upper-most Hawkesbury. The apparent rotation could be an artifice of displaying curved or shallower dipping faults within flower structures in the younger units as a straight line on a plan. The observations of fault character within different lithologies at St Peters in the M8 mapping support this.

Smaller, mostly parallel, faults are likely between these zones and to the west, as inferred by the alignment of tributaries within the palaeotopographic surface. The next named major fault to the west of Arncliffe is the Homebush Bay Fault Zone (Och, Offler, Zwingmann, Braybrooke, & Graham, 2009), however others are inferred. The planned Sydney Metro West tunnels from the CBD west to Westmead may enlighten further the understanding of fault development and history in Sydney.

6.2 DYKES

The CBD basement excavations and historic tunnels uncovered several dykes. Further understanding has been developed from coastal mapping where the dykes either outcrop or are otherwise inferred from the erosional gullies generated by the wave action on rock platforms removing the lower strength dyke material, preserving small bays in the bedrock.

The east-west oriented dykes intersected by the M8 correlate well with coastal observations, Figure 16. This system of dykes is considered to be a product of offshore volcanism and the formation of arrays of reltated dykes associated with specific volcanic centres is expected. The limited deformation of the bedrock contacts is attributed to the depth and mechanism of emplacement.

Inland (west of the M8), segments of the palaeo-Cooks River tributaries align well with the intersected dykes indicating continuation of these features inland. The lineations are best developed in the Hawkesbury Sandstone, likely due to the more pronounced difference in erosion potential between the sandstone and dolerite of the dykes. Weaker lineaments are visible where the surface bedrock is Ashfield Shale, as the differential in erosion potential is lower.

The Bexley Dyke has been intersected during the M5 construction and within the M8 and aligns both in orientation and width with the eroded bay south of Magic Point, Figure 17. The distance between sandstone outcrops within the bay is 10 m, which is commensurate with the observed width of the dyke in the M8.

The Arncliffe dyke swarm is the only north-south oriented intrusive system that intersected the M8 tunnels and also had a structural character that differed significantly from the dykes that can be correlated with coastal outcrops (the dykes inferred to be related to off-shore volcanism). The dyke swarm was observed I the M5 East tunnel and aligns with approximately north-south oriented valleys in the palaeotopography. The valleys can eb traced to the north potentially aligning with the Haberfield Diatreme, Figure 15. The discontinuous character of this dyke system is not the same as the coastal dykes. It is postulated that the Arncliffe Dykes are related to diatreme activity. The Western Sydney Metro tunnels are expected to intersect dykes associated with the Haberfield Diatreme and may provide further insight to this possible association. It is noted that dykes were mapped in the City Tunnel that align with the Arncliffe observations and link to the Haberfield diatreme, however, no orientations were available. Further dykes are inferred from the 1:100000 Sydney Geological Sheet (1983) which were not indicated in the City Tunnel mapping.

Table 2: Inferred correlations between CBD and M8 - Fault Zones

Fault Zone	Interpreted intersections (north to south)	Inferred continuity and orientation
Arncliffe Fault Zone	1A) Trend of Johnsons Creek, Sydney Harbour 2A) Intersected in City Tunnel 3A) Hawkesbury-Mittagong contact, Sydenham 4A) Cooks River Palaeochannel, Tempe 5A) Intersected in M8 at Arncliffe 6A) Mapped easterly limit of Hawkesbury outcrop west of Botany Bay shoreline 7A) Approximately aligns with Kogarah Bay, Georges River 8A) Approximately aligns with Hacking River at Mansion Point 9A) Potentially extends past Winifred Falls, Royal National Park, aligning with Southwest Arm Creek	>25 km, Trending towards 018-020°
St Peters Fault Zone	1B) Trend of Johnsons Bay, Sydney Harbour 2B) Intersected in City Tunnel 3B) Intersected in M8 at St Peters Interchange on and off ramps (St Peters Fault Zone) 4B) Axis of Cooks River Palaeochannel, Botany Bay 5B) Approximately aligns with Hacking River from Lilli Pilli to Gooseberry Bay 6B) Potentially extends to Curracurrong Creek, Royal National Park	>25 km, Trending towards 013-020
Luna Park Fault Zone[1]	1C) Luna Park Car Park, Millers Point (Och, Pells, & Braybrooke, 2004) 2C) Star City Casino (Speechely, Walker, & Scholey, 2004) 3C) Intersected in City Tunnel 4C) Indicated by drilling around St Peters Brickpit for M8 investigation 5C) Potentially extends to align with dog-leg in Cooks River Palaeochannel under Botany Bay 6C) Potentially aligns with axis of Burraneer Bay	>25 km Trending towards 015-025°
Martin Place Joint Swarm[1]	1D) Various CBD locations (Och, Pells, & Braybrooke, 2004) 2D) Intersected in City Tunnel 3D) Indicated by drilling east St Peters Brickpit from historic projects from supplied data pack for M8 design phase 4D) Western edge of Cooks River Palaeochannel under Kurnell Sand Dunes 5D) Potentially aligns with axis of Gunnamatta Bay	>25 km, Trending towards 014-018°
Woolloomooloo Fault Zone[1]	1E) Various CBD locations (Och, Pells, & Braybrooke, 2004) 2E) Intersected in City Tunnel 3E) Eastern edge of Cooks River Palaeochannel under Kurnell Sand Dunes 4E) Potentially aligns South Cronulla coastline and limits of Botany Basin (topographic boundary)	>29 km, Trending towards 012-025°
Watsons Bay Fault Zone[2]	1F) Various CBD locations (Och, Offler, Zwingmann, Braybrooke, & Graham, 2009) 2F) Potentially aligns with deepest part of Cooks River Palaeochannel under Bate Bay 3F) Potentially aligns Royal National Park coastline and limits of Botany Basin (topographic boundary)	>33 km, Trending towards 018°

[1] Naming convention adopted from Och, Pells and Braybrooke, 2004 [2] Naming convention adopted from Och et al, 2009.

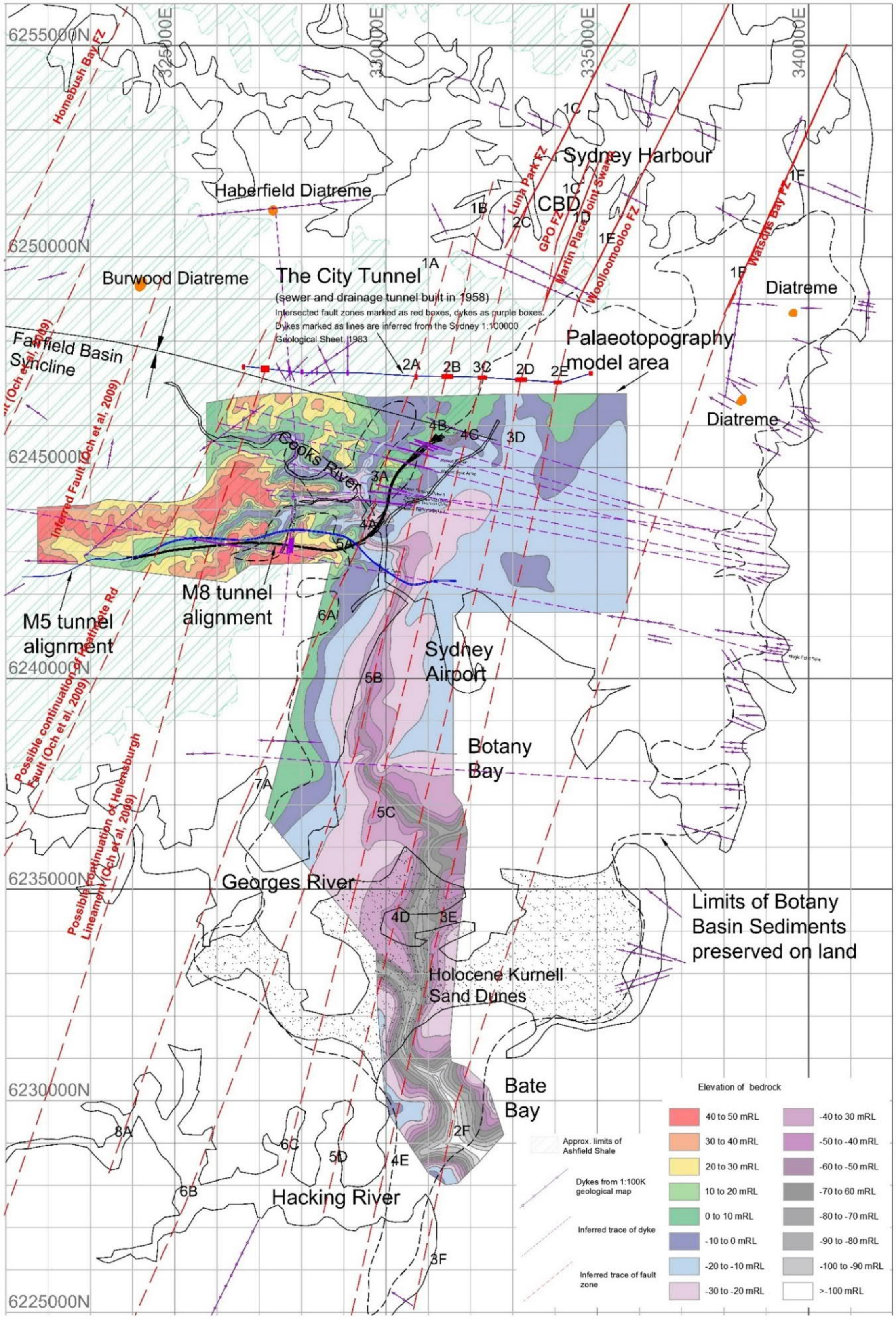


Figure 15: Correlations of Fault Zones and Dykes from CBD to M8. Locations from Table 2 marked on plan

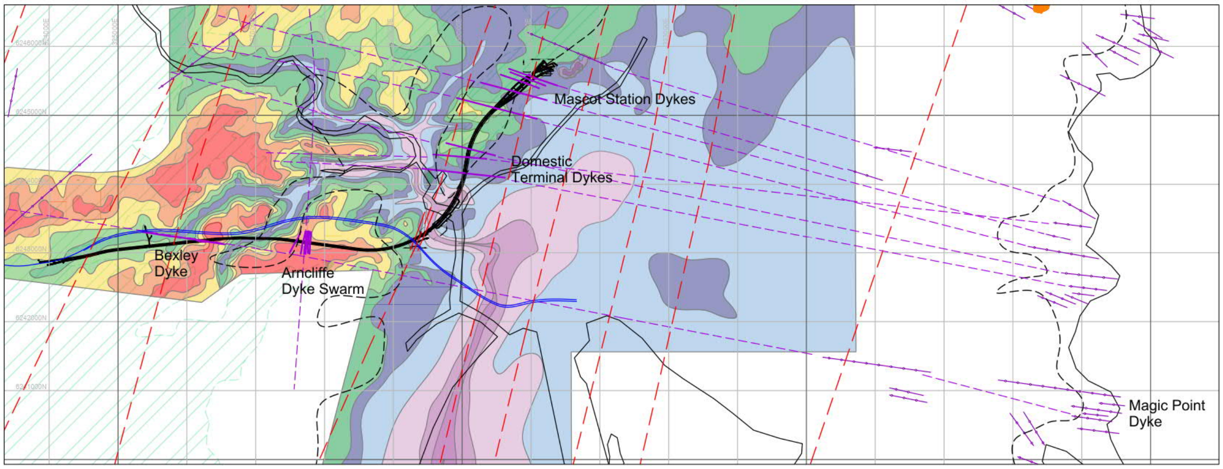


Figure 16: Correlations of Dykes from the CBD to M8

Figure 17: Aerial photograph of the bay south of Magic Point, inferred to be related to erosion of a dyke, potentially the coastal outcrop of the Bexley Dyke. (Source – Google Earth)

7 CONCLUSIONS

The structural features intersected by the M8 construction and palaeotopographic understanding of the Cooks River region have provided important data enabling refinement to major structural correlations for Sydney. The coastal river systems, like the Cooks River created in deeply incised valleys and shed significant sediment into the preserved basins like the Botany Basin. This has masked the surface expression of faults and dykes previously. The fault zones exhibit strong continuity and consistency in orientation when the palaeotopography is examined. Their width and form vary depending on the relative strength and conduciveness to brittle or more ductile deformation of the bedrock. They behave as joint swarms with some gouge development in the sandstone-rich bedrock with more curved, flower-like formation in shale-dominated bedrock.

The ability to trace these structures south and west of Sydney Harbour may be limited to surface lineament expression and project sharing/publications as the current surface topography conforms more closely to the palaeotopography inland of the coastal river systems.

Dykes also exhibit good continuity and penetrate deep inland. The dykes related to off-shore origin cause the least deformation to the sandstone bedrock, while those related to an inland diatreme sheared the bedrock and altered the rock chemistry.

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