INTRUSIONS IN THE SYDNEY BASIN, WITH REFERENCE TO THE GREENACRE DYKE

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ABSTRACT

Doleritic to basaltic dykes ranging in width from centimetres to several metres and with strike lengths tracing up to several kilometres on the mainland intrude the sedimentary country rocks of the Sydney Basin. Exposure of the Greenacre Dyke in the middle of the Enfield Brickworks presented a unique opportunity to collect textural and structural data from a dyke in Sydney. Evidence collected from the 3D exposure of the Greenacre dyke indicates the magmatic source was located towards the coast, possibly offshore. Published coastline mapping suggests a higher prevalence of dykes than have been discovered within the Basin proper. The limited intersections of dykes away from the coast is likely due to the dense coverage of urban development in greater Sydney and that few dykes intersected in excavations and tunnels have been publicly documented. This paper presents the data collected for the Greenacre Dyke and uses indicators of emplacement mechanism to postulate a change in the regional geological understanding of dykes in the basin. A review of the dyke orientations in the Sydney Basin was undertaken with a view to investigate possible magmatic origins. The orientation of the Greenacre Dyke, dykes presented on the Sydney 1:100 000 geological sheet and other published or mapped dykes were traced to see if they coalesced to a single origin, indicative of the magmatic source. The result was multiple dykes radiating from a series of point locations; locations that align along the remnants of the Gerringong Volcanic Ridge, some 10 to 20 km off the present Sydney coast line. This volcanic arc was active in the late Permian, through to the early Triassic. Age dating of the dykes implies a Jurassic age, a period that coincides with a gap in the stratigraphic record of the Basins sedimentary sequences. Apatite fission track studies suggest the Basin was buried some 2.5 to 3km deeper than present during the Jurassic before later uplift and erosion to its present position. This paper discusses the possibility that the Gerringong Volcanic Ridge was active during the Jurassic and is the source of the intrusive dykes. It discusses whether the heat and pressure generated by 3km burial depth was sufficient to have reactivated the assumed inactive magmatic source, but prevent extrusive volcanism. Evidence from the Greenacre dyke is presented that indicates the country rocks were in a semi-ductile phase during intrusion and how this relates to the depth of Basin burial at the time.

1 INTRODUCTION

Doleritic to basaltic dyke intrusions throughout the greater Sydney area intrude sedimentary country rock of the mid-Triassic Hawkesbury Sandstone and Wianamatta Group. Understanding of orientation and continuity of dykes in Sydney is limited due to:

- Preferential weathering of intrusions relative to country rock, reducing the likelihood of exposure,
- Narrow structure widths and
- Private development censoring public documentation of mapping from within their properties.

Coastal exposures along sea cliff rock platforms are common and highlight the narrow widths common to dykes in Sydney. Erosion of the rock platforms is such that the intrusions are eroded or more strongly weathered than the surrounding sandstone, so 3D exposures of the dyke surface are not possible. The spacing of dykes along the coast suggests they may be significantly more common than mapping inland would indicate.

Most dykes mapped in Sydney are less than a metre wide (Pells, 1985); the largest ones average about 6 m wide (Luddenham Dyke, Great Sydney Dyke (Dale et al, 1997)).

The longest mapped traces of dykes in Sydney are:

- Luddenham Dyke – 16 km (Pells, 1985).
- Great Sydney Dyke – 10 km (Dale et al, 1997).
- Barrenjoey Dyke – 13 km (Pells, 1985)

Recent published (Adams, et al. 2001) and unpublished mapping from several civil projects indicate the presence of a dyke in Kyeemagh that is up to 16 m wide, with a traced length of at least 10 km through Arncliffe and Bardwell Valley. The continuity of the dyke is broken by later faulting causing displacement.

By contrast, the Greenacre Dyke was a moderate sized intrusion – about 7 m wide with traced length of about 500 m. The dyke was exposed within the former Enfield Brickworks site in Enfield, an inner western suburb of Sydney. Further observation of the lineal extent of the structure is prevented by surrounding urban development. Until the early 2000’s, when the dyke was excavated and buried as part of redevelopment of the brickworks, the Greenacre Dyke was the only three dimensional dyke exposure in the Sydney Basin. Mapping of the dyke represented a unique opportunity to observe internal and surface structural features of an intrusion and provide evidence towards potential magmatic sources.

This paper presents the textural, structural and mineralogical features of the Greenacre Dyke and postulates how the dyke fits into the overall geometrics of the Sydney Basin. Discussion on the possible volcanic source, timing and intrusive mechanisms are also presented.

2 BACKGROUND

The Greenacre Dyke was exposed in the eastern half of the Sydney Basin. The structural architecture of the basin and position of the Greenacre Dyke within the system is presented in Figure 1.

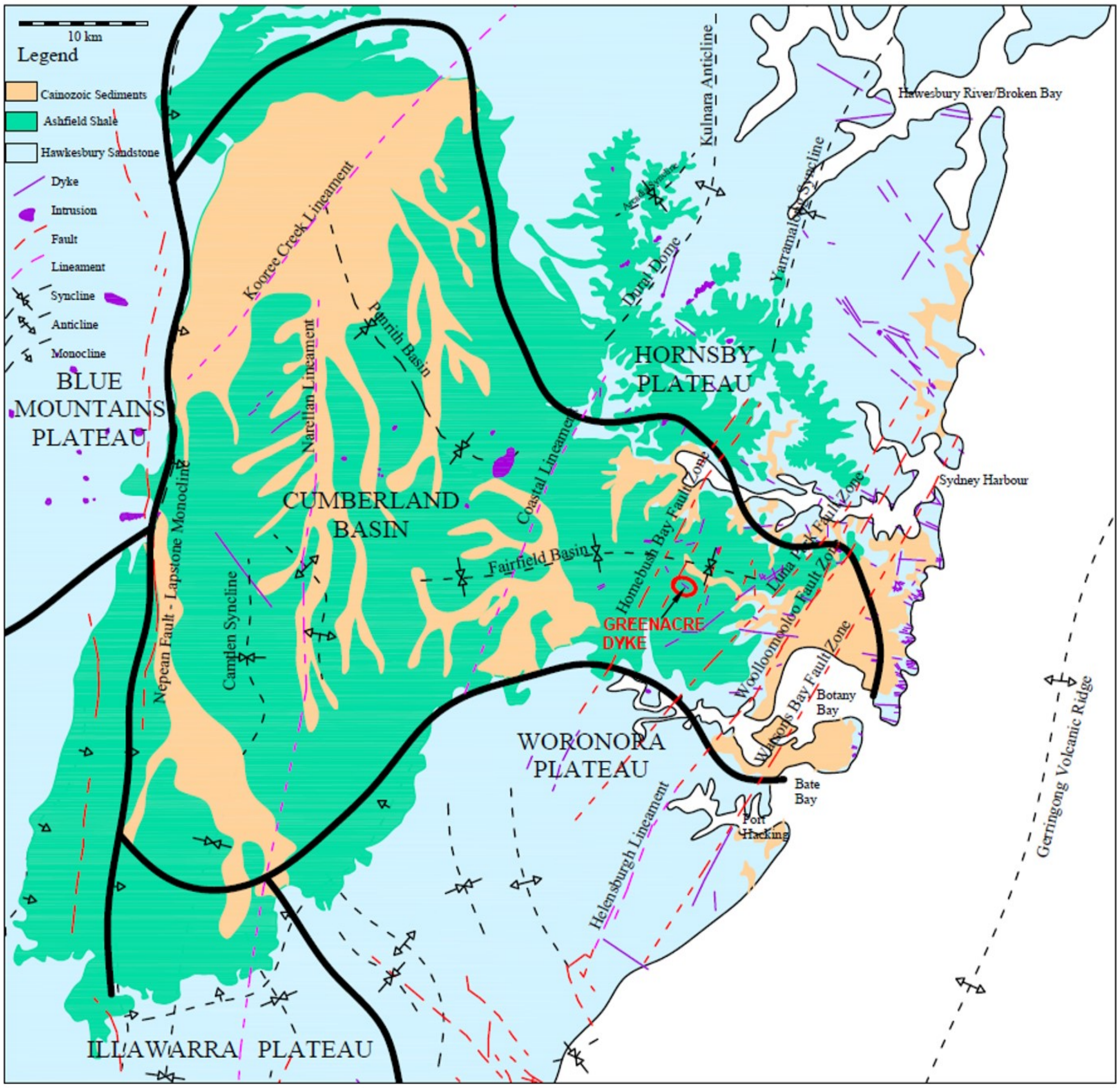

Figure 1: Structural components of the Sydney Basin. After Herbert, 1983; Bradley, 1993; Och, et al, 2009; Branagan, 2000; unpublished mapping known to and by author.

A favourable set of circumstances resulted in temporary preservation of the 3D exposure of the dyke:

1. At the surface, the dyke intruded the Ashfield Shale. The contrast in mineralogy between the intrusive and surrounding country rock resulted in the dyke being more resistant to erosion and therefore well preserved.

2. The dyke was located in an area of relatively low elevation in the flat plains east of the Nepean Fault System and the Great Dividing Range, known as the Cumberland Basin (Branagan, 2000). This positioning made both the shale country rock and intrusion less susceptible to weathering than if it had been located on the slopes.
3. The dyke intruded shale country rock sufficiently weathered to clay to be of appropriate quality for brickmaking. Site personnel chose to leave the dyke in place when excavating the shale to avoid unwanted waste disposal or contamination of the shale. The excavation method also preserved the surface texture of the dyke.
4. Exposure of the dyke to sub-aerial weathering was limited to only a few decades. The brickworks opened in 1950 and quarrying of the shale resulted in the gradual exposure of the dyke. Following the closure of the brickworks some forty years later, the dyke remained submerged beneath water thereby protecting it from the effects of weathering until the redevelopment commenced in 2002.

Excavation of the shale resulted in a three dimension exposure of the dyke as two plinths, Figure 2 with the following dimensions:

1. South-east plinth 42 m long, 6.9 m wide, 10-15 m high
2. North-west plinth 37 m long, 6.1 m wide, 10-15 m high.

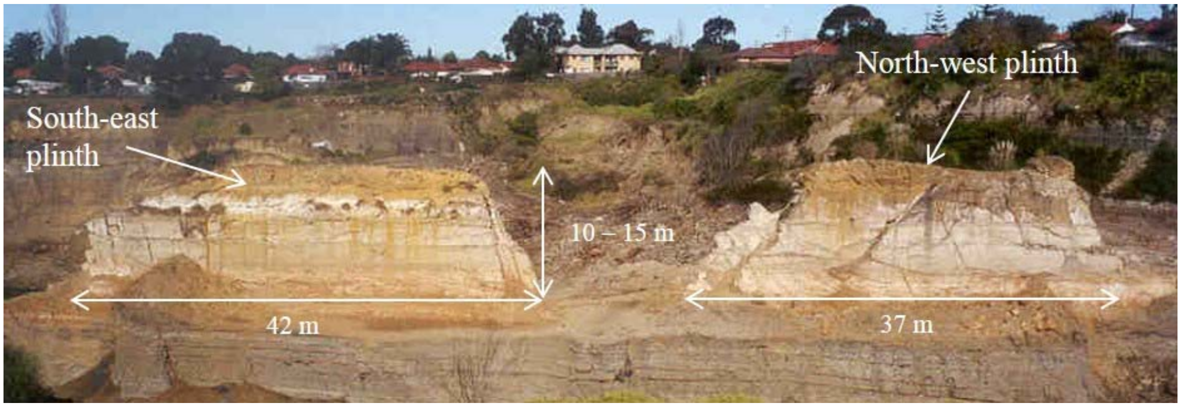

Figure 2: Three dimensional exposure of the Greenacre Dyke, July 2002. View looking south-west.

Redevelopment of the brickworks site began in 2002, with the brickworks drained, the dyke excavated and brickworks backfilled and reclaimed for industrial use. As part of the development approval, the property owners were required to have systematic cataloguing of the geology of the dyke undertaken and reported (PSM, 2002) prior to commencement of development.

Detailed structural and textural mapping of the dyke began in February 2002, prior to commencement of water removal from the brickworks and continued at regular intervals as more of the structure was exposed. Much of the mapping was undertaken by row boat. Some 500 million litres of water was pumped into Cox's Creek over a seven month period in 2002. The exposed dyke was destroyed by excavation in September 2002 and buried when backfilling of the brickworks began in October 2002. Figure 3 shows a time sequence of exposures as waste water was removed.

Drilling of one diamond cored borehole was also undertaken to collect the required mineralogical and geotechnical data to satisfy the development approval conditions. This hole sampled both the surrounding country rock and full cross-sectional profile of the dyke.

Figure 3: Time sequence of increased exposure as draining of abandoned brickworks progressed.

3 THE GREENACRE DYKE – GEOLOGICAL ATTRIBUTES

3.1 STRUCTURE

The Greenacre Dyke is oriented with a long axis trending 126° (magnetic), dipping 80 to 90° to the north. Two defect types are evident – joints and shears, Figure 4.

Two joint sets are apparent. The first are related to cooling of the magma and oriented sub-parallel to the long-axis of the dyke. The second, a planar, steeply west dipping set. The orientation of the latter set is more in keeping in orientation with the regional bedrock joint pattern. Shearing appears to post-date jointing with a distinct brittle texture that suggests shearing occurred post crystallisation. Two sets of shears are recognised:

1. Moderate east dipping shears with a normal shear sense and displacements observed up to 400 mm.

2. Listric shears, starting sub-horizontal and oriented parallel to bedrock shale bedding, steepening to steeply west dipping surfaces.

Both sets of shears are observed to penetrate the shale country rock, resulting in displacement of the dyke contacts.

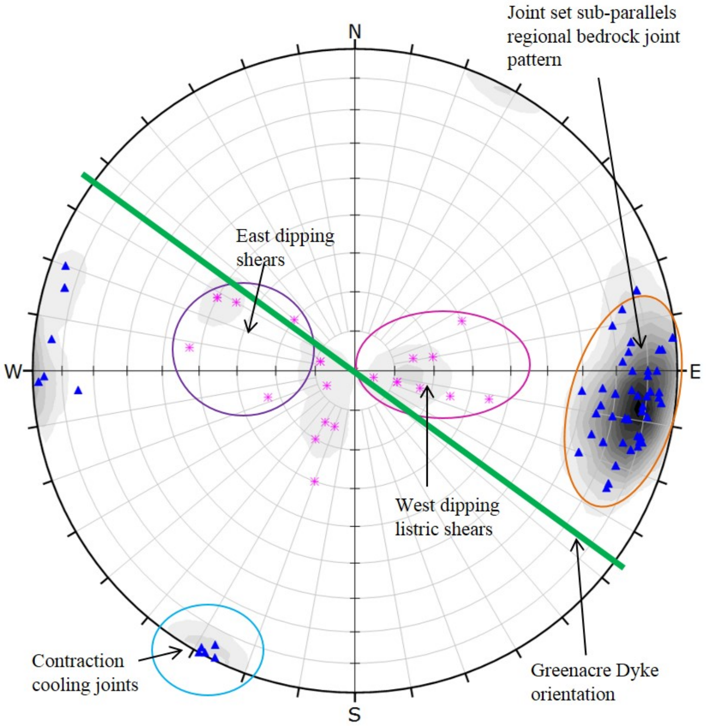

Figure 4: Stereographic projection of the internal structure of the Greenacre Dyke. Equal area, lower hemisphere.

3.2 CONDITION

Weathering of the dyke was observed to emanate from defects with strong evidence of permeability through defects in the past. Some additional surface-down water percolation resulted in mineral decomposition to clays occurring along the upper surface and to a limited extent in the side walls of the dyke.

Field estimations of intact strength are supported by unconfined compressive strength (UCS) testing indicating the fresh to slightly weathered dyke material is strong (60 to 80 MPa), while the weathered outer shell is moderately strong (40 to 60 MPa). Some zones of weaker rock were observed related to shear zones within the mass.

3.3 MINERALOGY

Hand specimen examination indicated the dyke rock is very fine grained and porphyritic, composed predominantly of plagioclase and clinopyroxene. The plagioclase laths were uniformly aligned and typically about 0.25 mm long. Elongate phenocrysts were partly to fully altered to clay and up to 10 mm long. These may have represented infilled vesicles. The long-axis of the plagioclase laths and phenocrysts were oriented sub-horizontally, suggesting a sub-horizontal flow of magma during emplacement.

Thin section petrographic assessment of samples of the dyke indicated the primary modal mineralogy was:

- 50% plagioclase (sodic labradorite), altered to sericitic white mica,
- 30% mafics of olivine and clinopyroxene, altered to iron carbonates,
- 10% oxides,
- <10% interstitial glass, altered to illite/smectite clays and
- Accessory apatite.

Samples of the contact adjacent shale were also petrographically examined which indicated minimal contact metamorphism effects were present.

3.4 TEXTURE

Surface ripples were apparent on the long axis faces of the dyke below the water line in the abandoned brickworks, Figure 5, and are interpreted as emplacement textures. The upper portion of the dyke that had been located above the water line was badly eroded, such that the textures were no longer preserved.

Figure 5: Surface ripples on the long face of the Greenacre Dyke. The long axis of photo equates to approximately 1 m of face.

The sinuous nature of the ripples suggests a gentle intrusive mechanism. Percival (1979) theorised that such emplacement would be into a moist or semi-consolidated sediment. The following section of this paper expands this theory.

The ripples had a mappable preferred orientation and closure direction, suggesting that they reflect the flow direction of magma during emplacement. The orientation of surface ripples, illustrated in Figure 6, indicates an east to west, sub-horizontal to gently dipping sense of flow. This is based on the orientation of the ripple at closure on the face. This orientation is supported by alignment of minerals grains and phenocrysts in the dolerite.

No clearly defined contact metamorphism of the country rock shale was observed, in either hand specimen or petrographically. Additionally, the dyke itself did not exhibit significant chilling effects of the contacts. Both these observations suggest the temperature differential between the intruding magma and country rock was minimal.

Unfortunately while samples were collected for age dating of the dyke, the owners of the development site chose not to undertake the testing and the samples were subsequently destroyed. It is assumed the dyke would be Jurassic age, commensurate with other dykes in Sydney.

3.5 GREENACRE DYKE SUMMATION

The textural and mineralogical alignment features observed in the 3D exposure of the Greenacre Dyke provided insight to apparent gentle and mostly sub-horizontal emplacement of magma into country rock with a flow direction from the south-east or off-shore direction. The lack of contact metamorphism suggests a low temperature differential between the country host rock and dyke magma during emplacement.

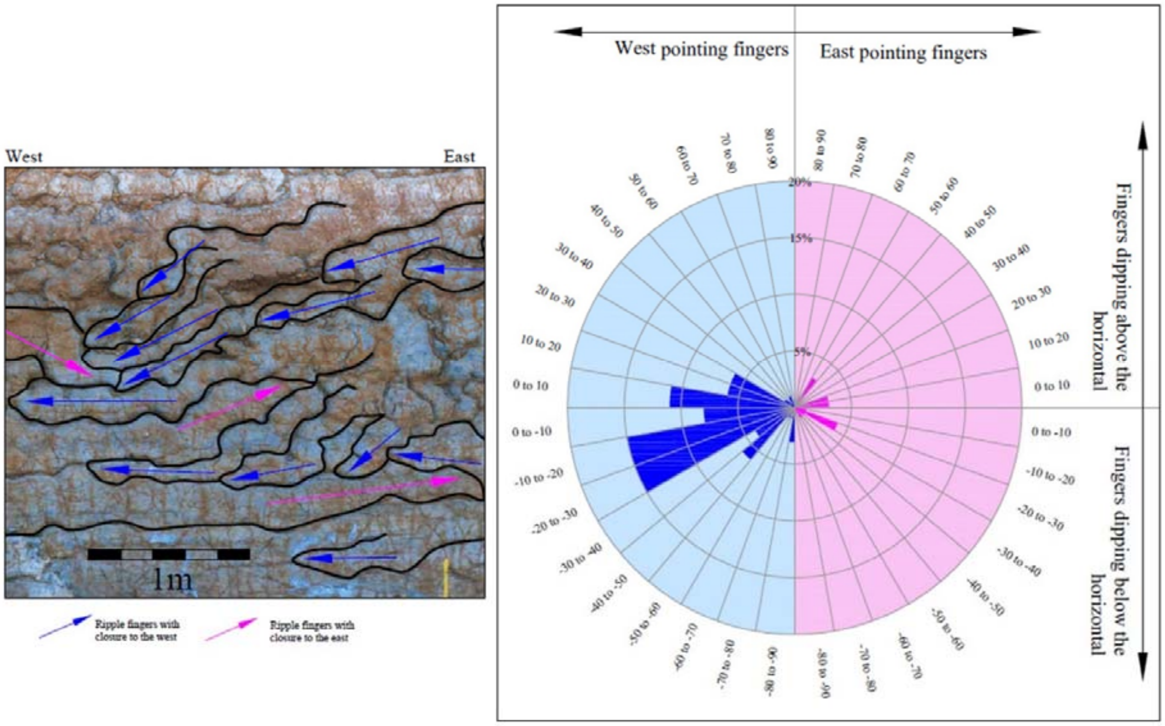

Figure 6: Left: Surface ripple orientation assessment. Right: Graphical summary of ripple closure orientations.

4 POTENTIAL IMPLICATIONS

4.1 EMPLACMENT

The three dimensional exposure of the Greenacre Dyke at Enfield Brickworks represented a unique opportunity to understand the possible emplacement mechanisms responsible for dyke intrusions in Sydney and to capture any characteristics that would indicate source direction. However, it wasn't until the position and orientation of the dyke was reviewed in the context of other dykes within the greater Sydney area that a pattern was recognised that could explain the variability in orientation trends and provide a theory as to the volcanic source.

Branagan (2000) suggests dykes in Sydney have formed along two main trend lines, interpreted as being related to the dominant joint trends in the region:

1. NNE-SSW and
2. WNW-ESE.

The geological architecture of the Sydney Basin is presented in Figure 1. Interpretation of the 1:100 000 geological sheets for Sydney, Penrith and Wollongong/Port Hacking (Herbert, 1983; Clarke et al, 1991; Sherwin and Holmes, 1986) and unpublished project mapping suggested a slightly different picture to the orientation of Sydney's dykes, as shown in Figure 7.

1. Dykes belonging to Set 1 trend NNE-SSW on the plateaus (Woronora and Hornsby), but are oriented more towards NE-SW within the Cumberland Basin. This suggests some rotation of structure with uplift of the plateaus and therefore that the intrusions predate uplift.
2. Dykes with a more E-W orientation are actually radially distributed. The radii coalesce at various centres that correlate with the trace of the remnant Gerringong Volcanic Ridge (GVR) (based on total magnetic surveys (Bradley, 1993; O'Neill and Danis, 2013)), some 10 km or more offshore, Figure 7.

The Greenacre Dyke fits with the second set of dyke alignments.

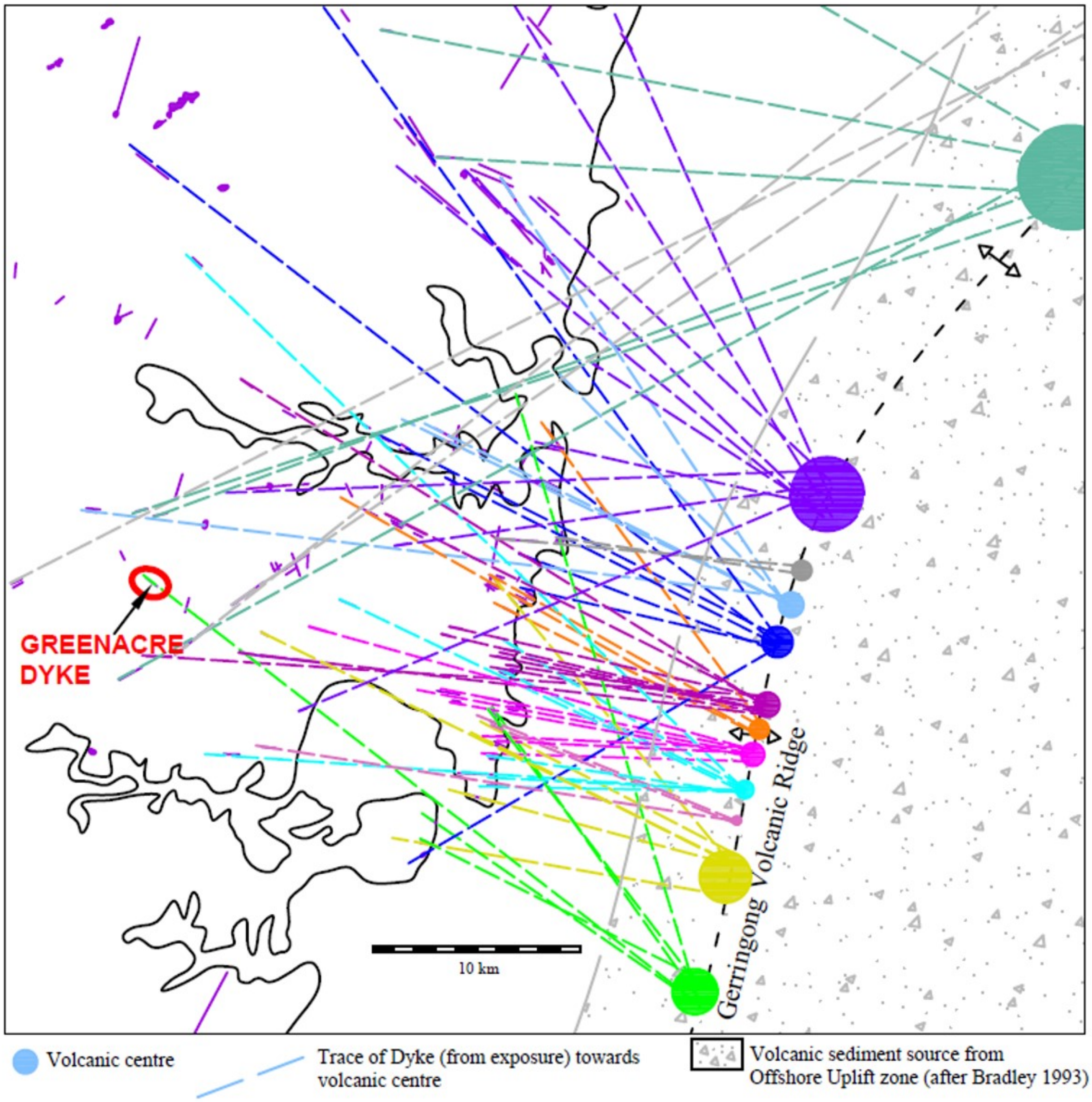

Figure 7: Relationship between east-trending dykes and the Gerringong Volcanic Ridge.

The correlation between a radial distribution and the GVR implies that:

- The largest dykes in the Sydney Basin can be expected to exhibit continuity in excess of 10 km.
- Dykes that emanate from the same volcanic centre may exhibit similar geochemical and mineralogical and therefore geotechnical properties (strength, weathering, internal jointing character).
- Dykes will be more widely spaced in the western half of the Cumberland Basin (Figure 1) than on the coast.
- It is possible that dyke structures may cross-cut each other.

Questions were also raised:

- Does the age of Sydney dykes fit with the timing of volcanic episodes related to the GVR?
- Do the internal and surface structures observed with the Greenacre Dyke match with an offshore volcanic source?
- Are there other potential reasons the alignment of second system of dykes would indicate possible source coincident with an existing geological suture?

The following sections attempt to answer these questions through detailed review of the geological history of the GVR and how that history may relate to structural features observed on the Greenacre Dyke.

4.2 REGIONAL VOLCANISM

The Gerringong Volcanic Ridge, Figure 7, represents the remnants of a (relatively) small volcanic arc active in the Late Permian (250-265 Ma) (Retallack, 1977; Campbell et al, 2001; Bradley, 1993; Mayne et al, 1974) situated on the foreland of the larger magmatic arc and subduction zone of the Lord Howe Rise. The GVR is centred along an offshore structure zone known as the Offshore Uplift (Bradley, 1993; O'Neill and Danis, 2013) with onshore exposures preserved in the Kiama area, south of Sydney (Retallack, 1999).

Magnetic surveys (Sherwin and Holmes, 1986; Mayne, 1974, Bradley, 1993; O'Neill and Danis, 2013) indicate the GVR extends up to 150 km sub-parallel to the current coastline, and located some 10 to 20 km east off shore.

Stratocone volcanism (Retallack, 1999) along the ridge was periodic through to the Early Triassic, with exposed volcanic sediments subject to intense weathering. Erosion of the GVR was cyclic resulting in two end-member detritus types:

1. Episodic periods with slow erosion of weathered volcanics deposited as red-beds within the Narrabeen Group and
2. Periods of more rapid erosion resulting in significant shedding of dark green volcanolithic detritus observed as layers in the Bulgo Sandstone and Bald Hill Claystone and the Newcastle Coal Measures.

Westward deposition of volcanic detritus was blocked 235-245 Ma due to inundation (Bradley, 1993) from cratonic sources to the south (deposition of the upper Narrabeen Group) with the GVR ultimately buried by the Hawkesbury Sandstone and Wiannamatta Group.

The Jurassic-Cretaceous depositional history of the Sydney Basin is mostly lost due to later uplift and erosion, but is inferred through studies on adjacent basins and apatite fission track studies. These suggest the basin was buried some 2.5 to 3.5 km deeper than present day (Grybowski, 1992; Bradley, 1993) and subsequently uplifted and eroded due to rifting in the Tasman Sea.

Age dating of dykes in Sydney while difficult, infers a Jurassic age is appropriate (Pells, 1985). This indicates that dyke intrusion into the Hawkesbury and Wiannamatta Group was occurring simultaneous with the deep burial of the strata.

4.3 EVIDENCE FOR JURASSIC REACTIVATION OF GERRINGONG VOLCANIC RIDGE VOLCANISM

Jurassic-age dykes are the lone remnants of the geological history of the Jurassic period for the Sydney Basin. Some 2.5 to 3 km of the depositional record from this period was lost through erosion and uplift. This implies that the Wianamatta Group and Hawkesbury Sandstone, the country rock into which the dykes have been intruded, were deeply buried at the time of intrusion. Similarly, the GVR was also buried after inundation by the Narrabeen Group (pre-cursor to the Hawkesbury deposition) in the Triassic.

Orientation assessment of the Sydney dykes suggests a volcanic source that coincides with the remnant GVR alignment – however, activity in the GVR was assumed to have ceased post the Triassic inundation.

The implication that the both the country rock and the dykes were deeply buried at the time of intrusion leads question whether the heat and pressure generated by about a 3 km depth of burial sufficient to:

1. Cause limited (re)activation of the magmatic chambers of the GVR to result in dykes (burial depth would have prevented extrusive volcanism) and
2. Assuming the Wianamatta Group and Hawkesbury Sandstone were fully lithified at the time, was the temperature/pressure change enough to transition the country rocks into a semi-ductile to ductile phase, akin to soft sediments.

Evidence collected from the Greenacre Dyke assists with answering the questions. Firstly the orientation of surface ripples and crystals indicate an offshore volcanic source and horizontal emplacement. When the strike direction of other dykes in the Basin is considered, the GVR is the most logical source of magmatic activity. The ripples also suggest a gentle emplacement mechanism into soft-sediment or ductile material. This implies the country rock must either have still been a soft sediment (not fully lithified) or more likely have been heated/pressurised to such an extent to at least be in the semi-ductile (transitional) phase. Additional support for this is the lack of contact metamorphism and chilled margin development along the dyke contacts. This infers a low relative temperature differential between the intrusive and the country rock, which may be attributed to the depth of burial and consequent heat and pressure conditions.

Research by Dragoni, 1993 shows that higher temperatures can be reached under lower confining pressures (shallower depths) in systems under compression, as the GVR was. Incorporating a geothermal gradient of 30-50°/km, this would plot the GVR system in the brittle-ductile transition zone for compression, Figure 8. This does not take into account any additional geothermal gradient related to continued subduction along this tectonic suture.

The duration of burial also appears sufficient to allow for a ductile response in the country rock (Dragoni, 1993).

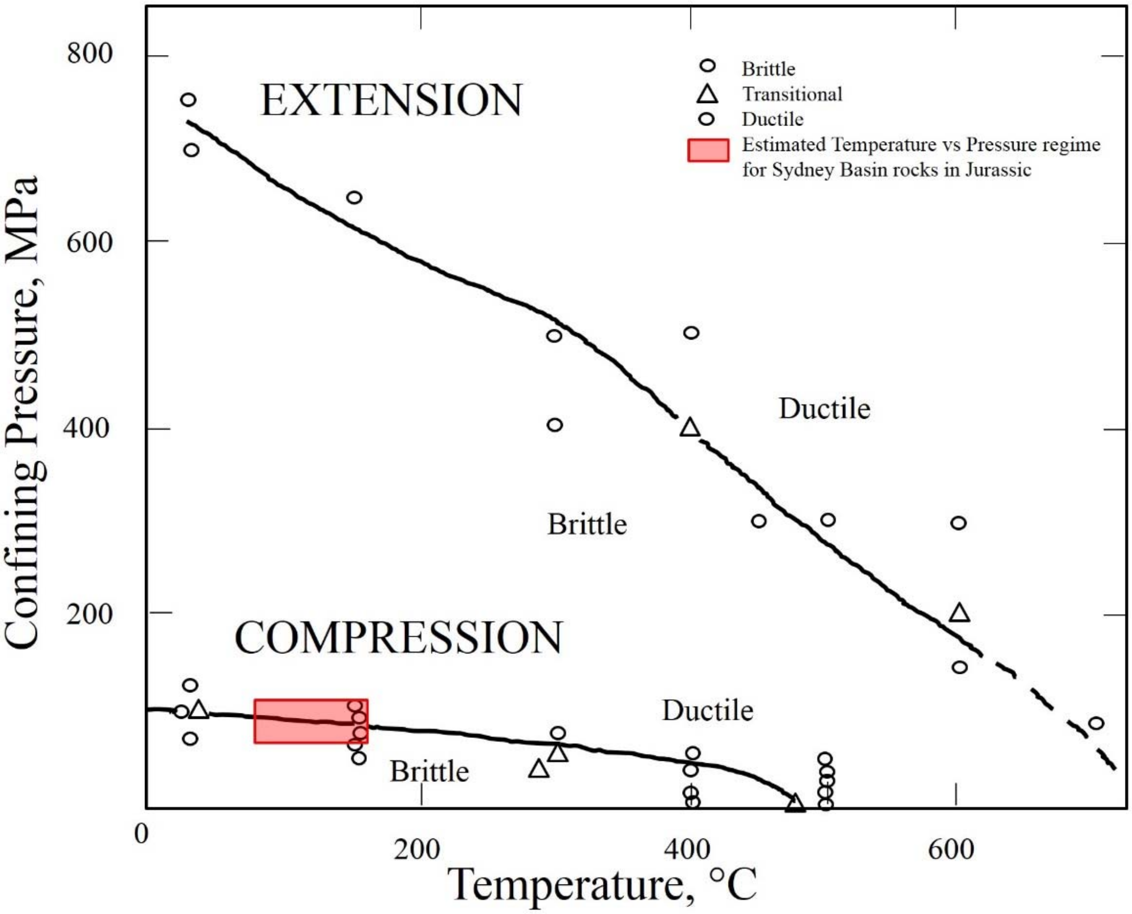

Figure 8: The estimated temperature versus pressure regime experienced by the Wianamatta Group and Hawkesbury Sandstone while buried at 2.5 – 3 km depth during the Jurassic compared to experimental data for the brittle-ductile transition in Solnhofen limestone after Dragoni, 1993.

4.4 EVIDENCE AT VARIOUS SCALES

The previous sections postulated that the volcanic source of the approximately east-west oriented set of dykes in the Sydney (Cumberland) Basin was a deeply buried GVR reactivated during the Jurassic. Intrusion was into in a country rock environment that was either unlithified or had undergone sufficient pressure/temperature gradient such that the rocks were in a transitional to ductile phase.

At the regional scale the evidence to support this theory is:

- The orientation of the dyke traces coalescing at vents along the GVR alignment.
- The timing of dyke intrusion relative to time of GVR burial.

- The depth/length of burial relative to the pressure/temperature required to ensure the buried country rocks being intruded into were within the brittle/ductile transition phase.
- A compressive regime was in place assisting with the brittle/ductile transition.

At the local scale the Greenacre Dyke mapping data provide further evidence to support the theory:

- Textural features on the surface of the dyke indicate that flow from the offshore GVR is possible.
- Sub-horizontal direction of the surface features supports an intrusive emplacement mechanism at the same relative level as the rocks being intruded.
- Surface features indicate similar temperatures in the country rock and intrusive magma at the time of intrusion.
- Surface textures support a “soft-sediment” emplacement.

Data from core samples of the dyke and contacts further supports the theory at the microscopic scale:

- Preferred crystal alignment indicating sub-horizontal flow from offshore.
- Minimal contact metamorphism evident.
- No evidence of a chilled margin.

One question remains – are there any alternative reasons why the “east-west” dyke set would appear to coalesce along the GVR? The NE trending dykes suggest a slight rotation in trend direction on the Hornsby and Woronora plateaus compared to the Cumberland basin. Perhaps the “east-west” set were also rotated due to uplift? Referring to Figure 7, it is apparent that some inferred volcanic centres are linked to dykes that cut through both the plateaus and the basin, implying post-intrusion rotation is unlikely.

5 CONCLUSION

For the time being this theory remains just that – a theory with quality circumstantial evidence but needing further comparative evidence. To further substantiate the theory, additional work is required:

- To compare other dykes with the inferred Greenacre vent (Figure 7) to see if they too indicate offshore source.
- To compare other dykes with the inferred Greenacre vent to see if their geochemistry matches.
- To compare other dykes from the inferred Greenacre vent to see if their surface characteristics also indicate ductile emplacement.
- To repeat for different vent system

Given the limited exposures and rapidity of degradation of exposed dyke surfaces due to weathering, the ability to undertake comparative studies is low and could take years to collect. The author chose to write this paper now to present the theory in order to imprint the concept into the geological community and perhaps collectively promote academic sharing of dyke data in the future.

6 ACKNOWLEDGMENTS

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