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Some thoughts on dolerite intrusions with particular reference to marginal features

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Abstract

The fine-grained rocks at the margins of Jurassic dolerite intrusions have been generally regarded as crucial to any understanding of magma composition, temperature conditions and intrusion forms. These rocks have also been used for age and magnetic pole determinations. While much relevant material can be provided it is often easily misread and must be carefully integrated. Several examples of major demonstrably invalid conclusions are included.

INTRODUCTION

Observations based on contact rocks on both sides of Jurassic dolerite intrusion margins have been used in several fields; these are discussed in order of practical relevance.

Understanding of margins is essential to the formulation of structural interpretations in mapping, hydrogeology and engineering projects, where it is necessary to establish the character of the margin - contact or fault or spatial orientation of the intrusive body - dyke, sill, sheet, wedge or transgression.

Marginal rocks have been frequently sampled for palaeomagnetic studies because of their even properties, rapid passage through the Curie Point and presumed originality and lack of contamination.

Age determinations from such rocks are preferred on the basis that the chilled rock is free of argon loss and representative of the original melting pulse.

Magma composition may be deduced if it is presumed that the chilled margin represents a leading fluid edge which is singular and continuously typical. This implies no contamination.

Temperature conditions at the time of intrusion may also be deduced by consideration of either mineral species and proportions or from the scale and nature of the metamorphic aureole.

Conclusions of a structural nature are the most important and the most confusing and these are emphasised in the discussion below. However, it will be noted that the latter four classes mentioned above depend on the same basic presumption, namely that the samples are derived from the same material, uniformly sampled at both source and in the field, and which were injected in a short time after a rapid unadulterated passage. This may be referred to as the uniform leading edge theory.

LEADING EDGE THEORY

Appreciation of the ramifications of the leading edge theory has never been discussed in the literature, although there is a general presumption of its truth. Early petrologic studies of the Tasmanian dolerites (e.g. Edwards, 1942) were predicated at a time when a simple differentiation theory was commonly accepted. The relationships between analyses of dolerite at Mt Nelson and Mt Wellington tended to support this concept. Subsequent physical and petrographic observations on the same intrusions provided substantial concurrence. A measure of agreement was also given by work on the Great Lake intrusions (McDougall, 1964). Given that no other detailed petrologic work had been undertaken, it was reasonable in the circumstances to presume single pulse intrusion followed by simple differentiation. A corrollary of this presumption was then to examine and compare the marginal materials with a view to the establishment of the properties of the magma. The idea of a single intrusion is an old one in Tasmanian geology and may be inferred in the works of Hills *et al.* (1922) and Carey (1958). It was held until Bradley (1965), Leaman (1970, 1975) and Leaman and Naqvi (1968) demonstrated that it could not be so if several sheets occurred in the same section. Hydraulically this is no different to multiple intrusion of a 'single' sheet. Hale (1953) and McDougall (1959) had suggested sections with two sheets, but Leaman (1970) and Leaman and Naqvi (1968) proved that they were general.

Over the years, most field mappers have ignored the rich detail often available in areas of dolerite outcrop and the relevance such detail has for interpretation of the structure of the intrusion (*see* Leaman, 1975). In most cases, the dolerite boundaries are accurately mapped but the area between has only been cursorily examined. Textural variations, internal contacts and 'xenoliths' have thus been missed. Indeed, few dolerite cores have been examined in detail although many kilometres are available. In 1971 a deep hole was drilled in Glenorchy (*see* Leaman 1972*a*) and a previously unsuspected intrusion was drilled in its entirety. A detailed petrography of the core revealed that the body was not simply intruded or differentiated and its properites did not approximate the concept of Edwards or McDougall. This was in agreement with more frequent notings in other provinces of layered and clearly multiple intrusions.

Careful examination of many local masses of dolerite reveals that these observations may be more common than the past record would suggest. Multiple intrusions can be demonstrated within a few metres of the intrusion margin in several localities, notably Single Hill, along the Southern Outlet Road, Black Charlies Sugarloaf and Battery Point. Some of the subsequent injections are fine-grained, while some are granophyric and thus imply a very late stage introduction.

Since there have been few studies of the petrology of dolerite and no comparative or lateral examination of variations, it is not possible to state how common each of the two intrusion regimes may be. It is likely that multiple, rather than single pulse intrusion is in fact the normal condition. There are many ramifications to such a conclusion. Sampling of marginal rocks may not consistently represent material of the same pulse, even in the same intrusion and, depending on the period between injections, may reflect various palaeomagnetic and petrologic properties.

The latter is a key question in the simplistic view of the leading edge in any event, since it is assumed that the first pulse of the magma from the magma 'pool' is representative of the magma fraction which will form the entire intrusive mass. This argument is tenuous since it presumes a fraction, probably already differentiated, of sufficient volume to supply the province, or a large part of it, coherently and uniformly over a relatively short period. The ultimate requirement is just as important; that the leading edge material remain uncontaminated at high level during injection where it is cooled rapidly and fresh material is continually introduced. If it could be shown that the composition of the chilled margin was consistent in a number of localities and in a number of intrusions, the theory might be established. Such determinations would allow detection of an intermediate chamber where additional differentiation might have occurred and whether there are systematic variations in a contact zone of a 'single' intrusion. No answers are available to these questions since the necessary reseach has not been done. However assertions have been made.

Edwards (1942) noted a uniformity in the few analyses at his disposal. Subsequent work by McDougall (1962, 1964) followed Edwards' approach, was selective in distribution, and included averages of the contact rocks. No close examination has been made of the analyses available.

Consider the treatment of this key question in the latest work (McDougall, 1964). On page 118, he discusses undifferentiated magma and notes that his two analyses from Great Lake differ significantly from each other, but that their average does not differ markedly from the average of thirteen other analyses. Table 1 reproduces his figures (p. 117) and inspection shows that the differences between averages are as major as those between the two analyses, particularly in respect of the major elements iron, calcium and magnesium. These results throw considerable doubt on the leading edge hypothesis but cannot invalidate it. Comparisons by average have confused the issue.

Table 1. ANALYSIS OF GREAT LAKE DOLERITES (AFTER McDOUGALL, 1964)

Analysis	1	2	3	4
SiO_2	53.32	53.04	53.18	53.18
TiO_2	0.70	0.77	0.74	0.65
Al_2O_3	14.18	14.74	14.46	15.37
Fe_2O_3	0.97	1.64	1.31	0.76
FeO	8.54	7.43	7.99	8.33
MnO	0.18	0.17	0.18	0.15
MgO	7.23	6.88	7.05	6.71
CaO	11.22	10.29	10.75	11.04
Na_2O	1.38	1.75	1.57	1.65
K_2O	0.87	1.56	1.21	1.03
P_2O_5	0.20	0.13	0.16	0.08
H_2O^+	1.00	1.13	1.07	0.67
H_2O^-	0.64	0.96	0.80	0.45
Total	100.43	100.49	100.46	100.07

1. DDH 5002, depth 42 m (138')
2. DDH 5084, depth 360.5 m (1183')
3. Average of analyses 1 and 2
4. Average of 13 analyses of chilled Tasmanian dolerites (McDougall, 1962)

Given that the dolerite intrusions are not the result of simple intrusion or single pulse injection, a significant time scale may be implied. The assumption that the marginal material for a given intrusion, or averaged for many, represents the basic matter for that intrusion or for the province is clearly not justified. This observation may well account for the anomalies noted in the palaeomagnetic results and the wide range of K-Ar dates now implied. Questions of the weathering state may be irrelevant for point sampling on a state-wide basis unless comparable values are available along intrusion or through it. As there is a preference for contact or fine-grained rocks in the work of Irving (1956) and Schmidt and McDougall (1977) this matter has not been resolved.

At the present state of research on the Tasmania dolerites, it cannot be validly claimed that the slight sampling of the marginal rocks is representative of that particular intrusion and much may be concealed in their averages across the province.

ROCKS OF THE MARGIN

Before considering the particular uses to which observations on the contact rocks may be put, it is necessary to describe the actual materials.

All marginal rocks, unless faulted, are fine-grained, often glassy with fine, intense and often incipient jointing. It is common for the metamorphosed host rocks to be hardened and jointed. The high joint frequency in both the chilled dolerite and the intruded rocks allows ready access for circulating groundwater and deeper and more extreme weathering. The mineral species produced at the contact are commonly less stable and this exacerbates decomposition. These effects are most pronounced in respect of discordant boundaries. The obvious effects may extend several metres on either side of the contact and may exceed 25 m. It is also common for the actual contact to be difficult to discern, since many mudstone and siltstone units metamorphose to a dark-coloured chert which is very similar to dolerite glass in appearance.

Metamorphism and alteration of the intruded rocks is a further area requiring research. In a few localities, some cursory studies have been undertakenand temperatures of up to 550°C inferred. Readily apparent and obviously interesting mineral species are usually related to calcareous rocks, *e.g.* CascadesGroup of the Hobart area, but even these have not been examined in detail. It is likely that the effects of metamorphism may be more pervasive than realised. Certainly large parts of the Triassic section in the Midlands area reveal thermally altered spore cases when the lithology offers no obvious indication of metamorphism.

STRUCTURAL DETERMINATION

Field workers have always regarded the margin as crucial to their understanding of dolerite intrusions if conclusions or predictions of their form were to be made. Many have recognised that undue emphasis on small, detached non-coastal exposures may be misleading.

General mapping, with its conclusions based on boundary - topography relationships, may be uncertain. A first but sometimes minor problem is accurate placement of the boundary. Due to the topographic dominance of dolerite, many boundaries are concealed by soil creep and talus deposits. Only dissections across slope reveal true form and position.

It is common to map a margin along contour (and many can be relatively straight) and consider the intrusion to be concordant when a section may reveal extreme discordancy. Similarly, intrusions which show overall concordancy, such as the Wellington sheet, may have local margins which are discordant (as near the University of Tasmania sign). This paradox and the extent of deviancy from expectation cannot be resolved by geological means, since mapping merely locates the margin and rarely includes direct or continuous observations of it. Exceptions occur only in coastal exposures.

Recent major road and railway projects have tended to improve this situation. A random scattering of new exposures is available, often more than 25 m high and 300 m long. Examination of these has reinforced concerns only suspected in previous exposures;

a) The base of many concordant bodies may be very irregular.

b) The roof may be even more irregular.

c) Adjacent exposures may be apparently conflicting in interpretation.

d) A significant proportion of contacts are compound.

e) Jointing need not be a reliable guide to intrusion form.

f) Many discordant margins are related to, or include, faults.

Basal margins

Few basal margins of dolerite sheets have ever been naturally exposed. Coastal exposures are rare and inland exposures are limited to a few cuttings. Most margins are concealed by talus or vegetation. In normal circumstances, the mapper suspects significant variations but cannot confirm them and the resultant map is often at a scale which smooths them. Basal margins in Permian rocks are extremely rarely observed and the comments below relate to intrusion in Triassic rocks.

Useful exposures are now available in the Midlands and north of Launceston. These show margins with several metres of undulation and some abrupt steps (plate 1). Unweathered material can be seen, it can be shown that some steps are original variations; most are subsequent faults with small throws. These variations are somewhat unexpected and suggest that the bedding parting was unable to exert control on the initiating wedge, either by termination or irregularity. Both effects are common in all Triassic rocks since the materials are heterogeneous, both laterally and vertically. Such heterogeneity includes such properties as jointing and bedding.

A key question posed by all similar two dimensional exposures is the problem of source direction; was the magma pushed up and down through irregular partings or was it injected laterally in a planar way into a crinkled set of disrupted partings? The latter is more likely and may be directly supported in exposures and general distribution at Antill Ponds. It is unclear at Mt Direction (Tamar) and along the East Derwent Highway at Mt Direction (Derwent).

Roof margins

Intrusion roofs present an alternative position. Classic dilation theory would imply that roof margins should exactly mirror base margins. However few roofs are to be seen in Triassic rocks and few bases are to be seen in Permian rocks. Some of the roof exposures seen in Permian rocks are superbly exposed. In those cases where the exposure is extended, occasional bends and warps may be seen in the roof rocks. In general, the scale is very small; two clear examples are exposed at Mt Nelson. In general, the disruption or warping in the roof rocks, if Permian, is very slight. Examples at Nelson Saddle form part of small monoclines with a total width of about 25 m and maximum relief of 1.5 m. The main zone of curvature is often less than 1.5 m wide and 0.5 m high, indicating that the causal irregularity is quite minor. There is no ground for expecting a similar contortion or bulbous remnant at the base of the intrusion since all beds remain traceable, if compressed, and forcible injection, in part, is indicated. This may well occur at a much larger scale at National Park and Dromedary, where an entire formation shows moderate relief folding (plate 4). Although faults are related to these structures, simple drag dips cannot wholly account for the features.

In one rare, small scale example at Mt Nelson, a small monocline

Plate 1. *Jurassic dolerite/Triassic mudstone contact, Antill Ponds.*

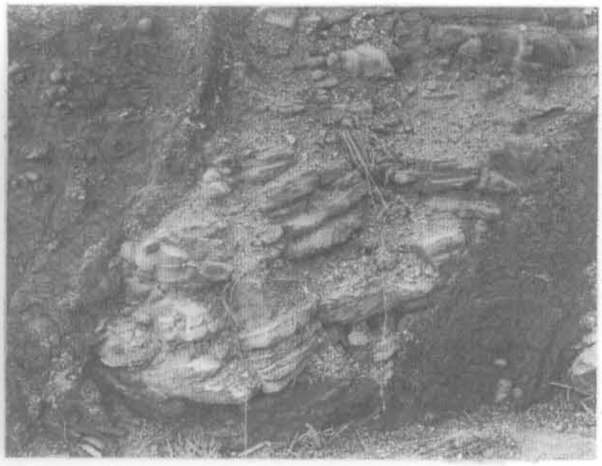

Plate 2. *Irregular intrusion, Little Swanport.*

Plate 3. *Minor irregular intrusion, Little Swanport.*

Plate 4. *Warped upper Cascades Group rocks, Boyer Road.*

Plate 5. *Dolerite contact, southern side, Eastern Outlet Road, Cambridge.*

Plate 6. *Dolerite contact, northern side, Eastern Outlet Road, Cambridge.*

distortion can be related to a small bulbous feeding wedge. The dolerite has been frozen and the space in front filled with now highly weathered debris. This intrusion is the same as that seen in Plate 8. Where small intrusions are visible both surfaces are regular and matching. Since it could be considered, at worst, that the roof is more disrupted than the base, the more regular nature of intrusions in Permian rocks must reflect better compaction, more regular stratification and higher confinement loadings. Small detached intrusions may be found in those cases where intense metamorphism has occurred.

Roofforms in Triassic rocks are very irregular and can range from stongly disrupted (Little Swanport) to domelike (Colebrook). Figure 1 and Plates 2 and 3 indicate something of the situation at Little Swanport. There are several irregular roof blocks, one fault, and at least two dolerite protruberances into the sediments of a very disrupted roof. Marginal features such as fine grain, fine jointing, hornfelsing and delicate weathering all attest to the original character of the roof. The bulk of the disruption visible appears to have been original. Small glimpses of dipping margins have often been regarded as providing a definite indication of the inclination of the sheet. While this may be generally true, sufficient exceptions can be cited to make such interpretation risky without independent supporting evidence (e.g. magnetic or gravity survey). An excellent example of this may be seen on the Eastern Outlet Road near Cambridge.

On the northern side of the road, a contact appears to dip steeply eastward while on the southern side of the road it is concordant but dipping westward. All rocks are chilled or metamorphosed and the presence of a fault in the region complicates interpretation (plates 5, 6). Beside the Tasman Highway in the same area, there is a small quarry where jointing suggests a steep dip to the west. Surface mapping is quite inconclusive, but suggests a major discordance since any concordance appears minimal and does not recur on the hillside. Gravity evidence confirms an overall dip to the west. Allowing for all factors, including some small scale faulting, only one piece of geological observation yielded a true indication, the jointing in the quarries. The localised eastward dips are misleading. The mixed pattern of anomalous observation is consistent only with a source to the north-west as suggested by Leaman (1972*a*; 1975, section 11) with intrusion to the south-east. In this way, all aspects can be produced without complex flow dynamics.

RECOGNITION OF MARGIN TYPE

It was indicated in the introduction that mapping considerations require the determination of the actual character of the margin and identification of any complex interaction. Margin here refers to the boundary between the dolerite of one intrusion and other rocks, including dolerite, of a separate intrusion. Several conditions may arise.

a) Dolerite chilled, intruded rocks not obviously metamorphosed.

b) Dolerite not obviously chilled, intruded rocks metamorphosed.

c) Neither dolerite nor intruded rocks show thermal effects.

d) Key exposures or information absent in region of the margin.

e) Thermal effects obvious but intruded rocks deformed.

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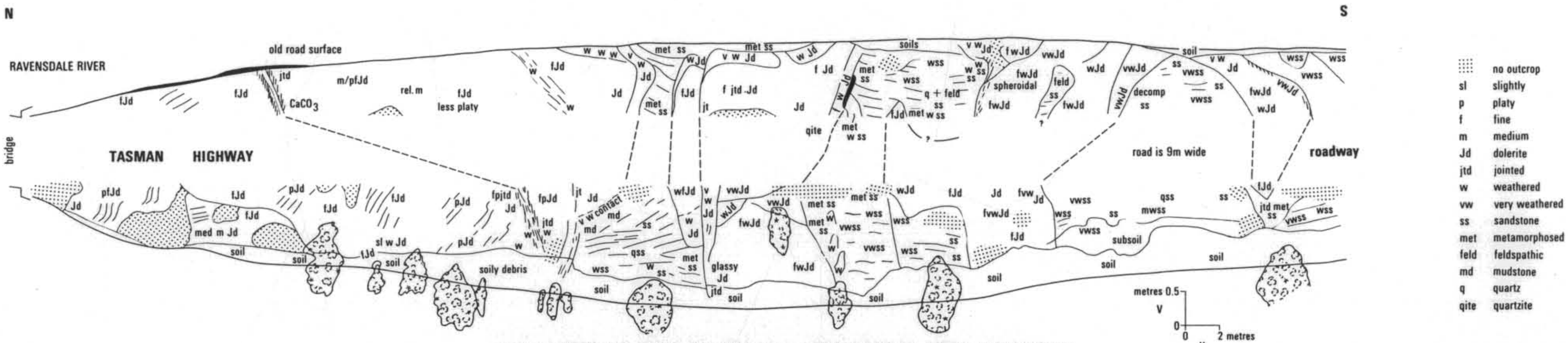

ROAD CUTTINGS NEAR RAVENSDALE RIVER BRIDGE LITTLE SWANPORT

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Figure 1.

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f) Dolerite chilled, intruded rocks deformed but unmetamorphosed.

g) Dolerite and intruded rocks show thermal effects.

Type (g) may be regarded as the normal contact margin, but it is not always certainly recognised. In order of frequency of occurrence in normal mapping these conditions may be listed as (d), (b), (c), (g), (f), and (e). Cases (d) and (b) account for about 80% of all boundaries with (c), (a) and (g) accounting for most of the remainder. Cases (a) and (d) include the situation where the chilled dolerite is an obvious margin to a discrete body within another dolerite intrusion. It must also be recognised that certain units weather readily after metamorphism and appear less cohesive than when unmetamorphosed causing some confusion. This situation is included in (a).

Interpretation of the listed conditions could be:-

(a) Dolerite chilled, intruded rocks not obviously metamorphosed

Post intrusion fault; Where the fault surface is slightly oblique to a discordant and dislocated contact so that the chilled margin remains on one wall. Various exposures along the boundary could reveal very different information.

Weathering; As mentioned above certain sedimentary units, especially in the Triassic rocks, decompose or alter rapidly upon exposure when metamorphosed. All traces of obvious hornfelsing can thus be destroyed. Various exposures can conflict.

Intra-intrusion; Where one dolerite has intruded another there may be little or no alteration in the intruded dolerite. The principal problem in this case arises where the grain size variation in the respective bodies is not great.

Normal post-intrusion fault; Where the detail of mapping permits reliable mapping of a boundary and where its structural character is deducible, any offsets physically and thermally may be visible. This is usually only true of sub-concordant intrusions.

(b) *Dolerite not obviously chilled, intruded rocks metamorphosed*

Post intrusion fault, normal post intrusion fault. As for (a) but where the opposite characters are observed. This is the normal state in field mapping. A major problem exists, however, in relation to the adequacy of observation of the dolerite margin due to weathering. In many instances the fine-grained marginal rocks are altered or decomposed. Where the glassy verge is thin, as in the case of discordant intrusions, observations may be uncertain. Quite often weathering and discolouration effectively conceal the true textural appearance and only fresh kernels or thin sections may resolve the question. Experience has shown this condition to be very common.

(c) *Neither dolerite nor intruded rocks show thermal effects*

Post-intrusion fault. Provided there are no complications due to weathering, this is a straightforward conclusion. There will be no conflicting evidence from any available exposures.

(d) Key exposures or information absent in region of the margin

In this case doubt remains. It will be evident from the discussion related to types (a) and (b) above how uncertainties arise where data are poor or misleading. As for cases (e) and (f) below, resolution is often only possible where cuttings or sections are available and a degree of three dimensionality is possible. In normal field mapping this is not possible and many boundaries are presumed normal although substantiative evidence may be lacking. In most cases this will be a valid conclusion.

(e) *Thermal effects obvious, but intruded rocks deformed*

Pre-intrusion fault. Where a fault previously mating sedimentary rock faces has been occupied by dolerite, previous drag dip and bed contortions will be preserved on the unoccupied side of the fault. The effect of intrusion may involve further deformation but it usually metamorphoses the intruded materials. Normal exposures are rarely good or frequent enough to identify all the features needed to establish this situation. However, its frequency of occurrence in coastal and road sections is such as to imply that many boundaries have this form. Certainly one should suspect near straight 'margins' as being of this type.

Concomitant fault. Concomitant faults are largely a matter of structural semantics since their properties can be identical with those of the pre-intrusion fault. The concomitant fault is a conceptual feature presumed necessary as part of the intrusion process. The only way such faults may be segregated is by inspection of the overall structural layout of faulting within a region and comparing it with the distribution of dolerite margins.

Post-intrusion fault. Where subsequent movement has occurred on an angular margin, materials may be recorded which include chilled dolerite, metamorphosed country rock with either or both deformed. Deformation of the dolerite may not be readily recognised due to lack of reference features. Slickensides may be observed but these must be sighted across a range of materials at the site to be definitive. Natural exposure is rarely adequate.

Note that slickensides are commonly seen along joint surfaces in dolerite intrusions where they are related to settling movements, presumably in the later stages of solidification and consolidation. Rarely can movements in excess of several centimetres be demonstrative in relation to these features.

Note also that post-intrusion faults discussed in context of properties (e) may be of two types. The first simple displacement, not adding extensive new deformation, and the second where most of the disruption relates to new movements. These may only be assessed in section.

(f) *Dolerite chilled, intruded rocks deformed but not metamorphosed*

Post-intrusion fault. This situation is similar in many respects to field situations noted for types (a), (b) and (e) where observations are limited and relate to (a) in particular. Where the boundary was discordant and has suffered disruption, considerable deformation may occur with a display of fine-grained dolerite but no evidence of metamorphism. Exposure will determine whether any disruption is noted. This situation is probably most common within intrusion marginal zones.

It will be clear from the foregoing discussion that interpretation of boundaries is often suspect and dependent on observations of variable quality. An additional problem which may compromise or aid interpretation depending on the topography-structure function is the fact that many boundaries display very rapid changes from concordance or gentle transgression to discordance and yet maintain the appearance of concordance. This results from the erosional resistance of dolerite and hence it tends to dominate landscape. Thus an extended dyke-discordant boundary can appear concordant. This type of interpretation can easily be mixed with fault interpretations where outcrops are restrictive.

The effect of secondary intrusions, whatever their scale, and although mentioned in (a), pose the entire spectrum of problems stated in (e) - (f). The history of events during the intrusion cycle becomes very important. Structures related to one intrusion may be considered post-intrusive, yet to another the same features may be pre-intrusive or concomitant. These issues become important when an apparently single mass of dolerite is composed of two sheets or an apparently staightforward margin is found to include an insert of potentially major proportion.

An example of this is shown in Plates 7 and 8. Selective weathering has done much to pick out multiple injections near the margin of the Nelson intrusion at Nelson Saddle. These variations may be systematically traced around the many quarries and cuts of the region. A further example was described by Edwards (1942), but it is not certain how this relates to the other intrusions in the same area. However, the intrusion of Plate 7 clearly transects the main Nelson mass. Plate 9 provides a contrasting example in 'upper' zone dolerite where inclusions and dykes of granophyre have been introduced. The margin is less than 5 m away. Various sets of joints may be observed indicating a complex history for joint development. Some features clearly predate the granophyre and some post-date it. More typical banding layers which parallel the roof of the intrusion are shown in Plates 10 and 11 from Black Charlies Saddle near Runnymede. Similar structures can also be seen 1 km south of Nelson Saddle on the Southern Outlet Road. Clear displacements are visible and a range of joint characteristics vary from material to material. Thermal jointing is clearly less regular. Forceful separation of non-viscous slabs of material is indicated in Plate 12 where some highly hornfelsed mudstone is preserved in small dyke cores.

As interpretation of structure within intruded areas is often considered to depend on margin observations, it is important that the variable and observation deficiencies be appreciated. Quite often there is no way intrusion form may be determined from surface field observation and some geophysical approach or drilling is necessary. Neither of the latter approaches can relate intrusions to each other and a detailed consideration of the margins remains essential.

STRUCTURAL FEATURES NEAR MARGINS

A number of features directly related to the boundary have been discussed in the previous section. Many subsidiary features have been alluded to (jointing, degree of concordance, discordance, doming, etc.) but none have been specifically examined.

Consider jointing; two prinicpal aspects of jointing around intrusion margins, frequency and orientation, have been utilised in structural assessments. Most observations are restricted to consideration of the dolerite side of the margin, although frequency determination is relevant in the intruded rocks as well. Joint frequency, both real and incipient, increases near normal intrusive boundaries and near faulted boundaries. However, in the former case it is normal for the joints to be persistently platy over a

Plate 7. *Intrusion contacts, Nelson Saddle.*

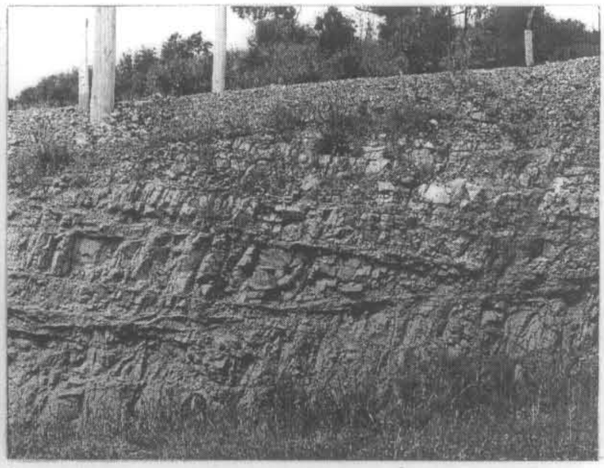

Plate 8. *Multiple contacts in roof of dolerite mass, Nelson Saddle.*

Plate 9. *Granophyre dyke, Single Hill.*

Plate 10. *Multiple intrusion inclusions, Black Charlies Sugarloaf.*

Plate 11. *Multiple intrusion granophyric inclusions, Black Charlies Sugarloaf.*

Plate 12. *Neptunian dykes, Black Charlies Surgarloaf.*

variable but often wide zone near the margin. If the orthorhombic (approx.) axes are a<b<c, then the boundary parallels the Planes b-c if jointing is associated with steeply dipping boundaries.

The other principal joint class, also thermal, is that of columns and these may occur at various scales. Polygon base size may range from a few centimetres to several metres and may at times be very obvious. Columns may also be strongly prismatic. Good examples may be seen at Mt Wellington, Cape Raoul and Tasman Island. Plate 13 provides an example of platy-jointing at a contact exposed in a road cutting at Ravensdale River Bridge, Little Swanport. Although the structural situation is complex (refer fig. 1), the band of platily jointed dolerite relates to the principal discordant edge. At this site it is possible that the plane a-b parallels an upper surface exposed near the old roadway and that the reason for the especially strong development here (and at Lovely Banks, Spring Hill; Stony Bridge, Swansea) is that these joints also represent fine columns. It will be noted that normal prismatic columns may thus be confused with platy joints related to discordant edges since the effect is the same and cannot be separated unless independent information is available about the margin. Jointing need not be a reliable indicator to intrusion form within 50 m of a margin. The large columns within intrusions are, however, reliable indicators, the long axis being perpendicular to the plane of the margin. It is generally noted that the plane perpendicular to the long axis of the column approximately parallels the intrusion boundary. Most columnar jointing appears to be related to essentially concordant intrusions.

Other joints are tectonic and usually form three sets. The two principal sets, usually nearly perpendicular, are extensive and common but may be locally confused with columnar jointing. Aerial photography, especially over the Central Plateau, can usually reveal the status of joints by showing extent, continuity and relative importance. These features are not always distinct or recognised at ground level yet they are very common joint features (*e.g.* Southern Outlet).

Nearly all joint types discussed above show evidence of movement in any given location. Inspection of relationships, especially where more than one injection is involved or where significant tilting has occurred will show that the movement is slight, being rarely more than 1 - 2 cm. However, in even those cases where the movement is virtually undiscernable, a chloritic paste covers the joint surfaces and shows clear polishing and slickensides. Quite often, as in drill core, these effects may give the impression of severe movement.

The final joint type, rarely seen but probably very common, is the sub-horizontal and sub-parallel slope sheet joint, often called a sheet or topographic elastic release joint, produced by surface unloading. These joints may be clearly seen at North Sorell, Oatlands, Southern Outlet and are often visible due to their control of weathering by groundwater. Such joints are commonly curved and transect other joint sets. A good example is shown in Plate 20 from the Southern Outlet about 1 km south of Nelson Saddle. The upper portion of the exposure is strongly discoloured and noticeably weathered and there is a sharp boundary with less weathered material at the upper sheet joint which clearly controls near surface groundwater circulation.

Degree of concordance

Few dolerite intrusions are truly concordant. Close examination of margins show that slight oscillations from bed to bed are common, especially in fine-grained, thinly bedded units. However the overall effect is one of

Plate 13. *Prismatic joints, Little Swanport.*

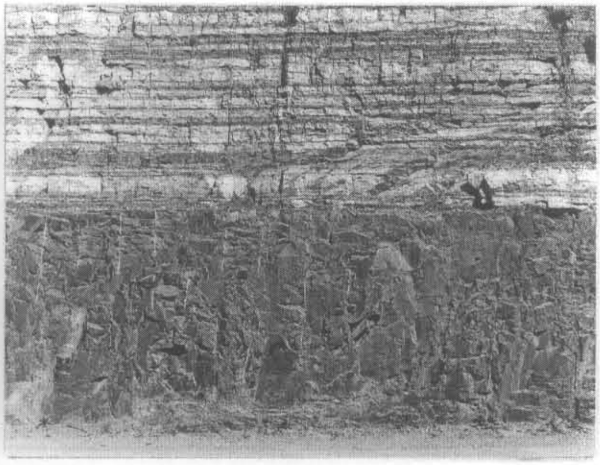

Plate 14. *Planar concordant contact, Southern Outlet.*

Plate 15. *Transgressive steps in generally concordant intrusion, Nelson Saddle.*

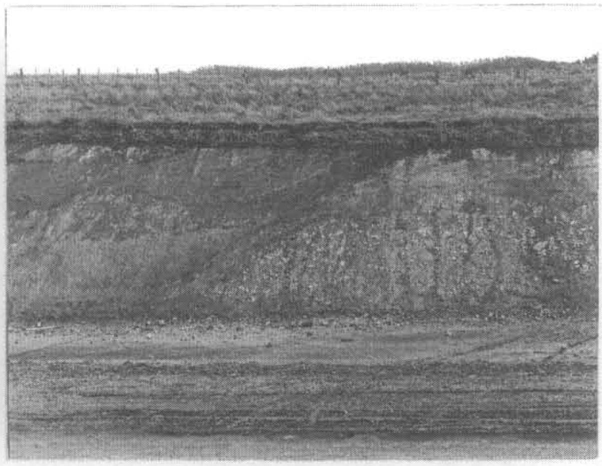

Plate 16. *Faulting in Triassic rocks, Northern Outlet Road, Granton.*

Plate 17. *Severely contorted Triassic rocks, Northern Outlet Road, Granton.*

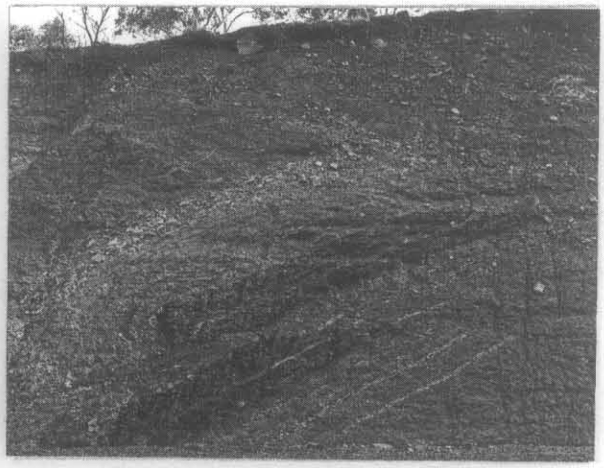

Plate 18. *Thrust in Triassic sediments, East Derwent Highway, Otago Bay.*

concordance since the variation is rarely more than 10 cm. Another common observation is that of risers up to one metre between concordant stages of the type mentioned above. The steps may be one metre to 1 km long and the overall effect may remain one of concordance, even though the intrusion margin is consistently stepping through the beds of the intruded formation. This effect is usually referred to as gentle transgression. It is most common in Permian rocks. Plates 14 and 15 indicate this type of structure. In some rare cases it is possible to view the detailed characteristics of the contact within the transgressed bed. In the first long cut on the Southern Outlet south of Nelson Saddle it is possible to observe compressions of up to 20% in the beds directly overlying the nick point of the transgression. Compressions persist for up to one metre and are of similar lateral extent to those about the monocline described on p. 5. Many of these observations suggest an intrusion process that is not wholly gentle and greater disruptions could be expected in rocks of the Upper Triassic nearly a kilometre higher stratigraphically. Thus the domes and disruptions noted in earlier sections probably similarly reflect forcible intrusion but under possibly negligible roof loadings. Many low angle disruptions seen in Triassic rocks (discussed by Leaman, 1976; Plates 16 - 19) may thus be related to such intrusion. However as noted in the above reference, near surface failure is an alternative solution that can rarely be differentiated. Exposure of steps and risers may often be such as to offer misleading conclusions about a margin. A good example occurs on Mt Wellington at the sign describing the Wellington Sill. The exposure is too small to offer a firm confirmation of marginal form since it reveals a riser and part of a step. The well-mapped extent of the body, possible here but not generally so, indicates overall concordance. Gravity coverage provides additional information and suggests a dome-like intruded structure with the dolerite thinning slightly under the pinnacle. Such a structure, as discussed by Leaman (1970, 1975), implies multi source injection for the Wellington body.

Discordance

Clear, continuous transgression where the overall angle of transection of bedding exceeds 20 - 30° may be termed as discordant. Every intrusion includes several stages of this behaviour which is related to local faulting, bedding continuity, formation homogeneity and source position (see Leaman, 1975). Discordant intrusions may occur at any scale (*e.g.* Black Creek Quarry, Orford). Plate 21 shows an intrusion in granite at Cape Surville. The intrusion shows a dip that is unusual in any stratified material since in latter cases it is either very nearly horizontal or vertical. Even on a small scale (Plates 22, 23, Leaman, 1976) the angle is steep and overall averages 70°, although the portion photographed indicates a shallower dip.

Xenoliths are an additional complication near dolerite margins. The basic implication of xenoliths has been discussed by Leaman (1975). However a high proportion of xenoliths do not escape the chilled zone near the base of an intrusion to float toward the top where they are usually seen. Some irregular forms are visible near the roof of many intrusions in which a ragged piece of intruded rock is surrounded by glassy dolerite. In some exposures the roof may be traced completely and the fragment shape can be seen to exactly match an irregularity in the roof. In such a case, a parting fracture irregularity has been utilised but not expanded; the split fragment being 'frozen' in the margin. Should this process be reversed the fragment may either remain in the basal margin or float through the intrusion. In such a case there is no matching irregularity in the roof.

Plate 19. *Disturbed mudstone and talus, Midland Highway, Dysart.*

Plate 20. *Dolerite with horizontal weathering zones, Southern Outlet.*

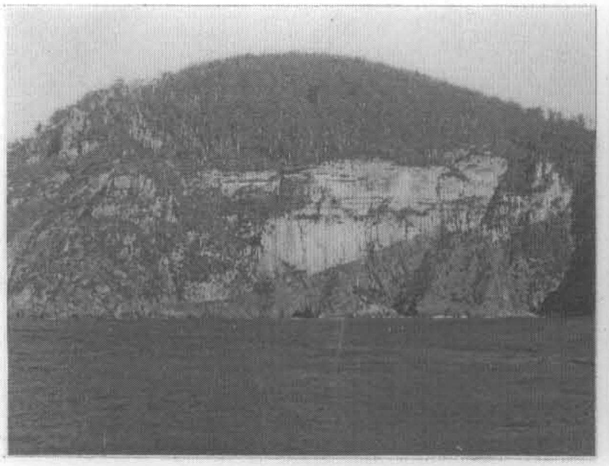

Plate 21. *Jurassic dolerite/Devonian granite, Cape Surville.*

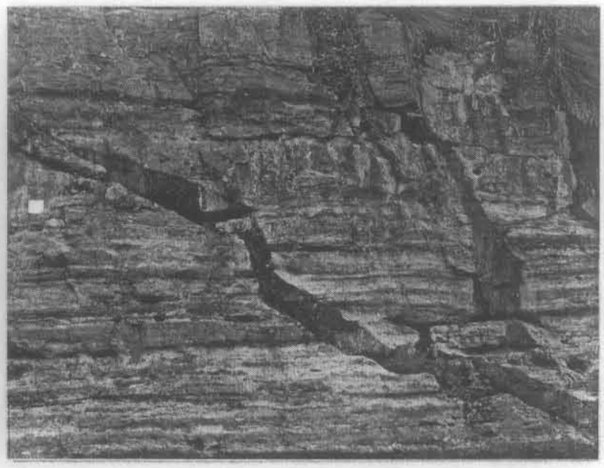

Plate 22. *Small transgressive sheet displaying dilation, Single Hill.*

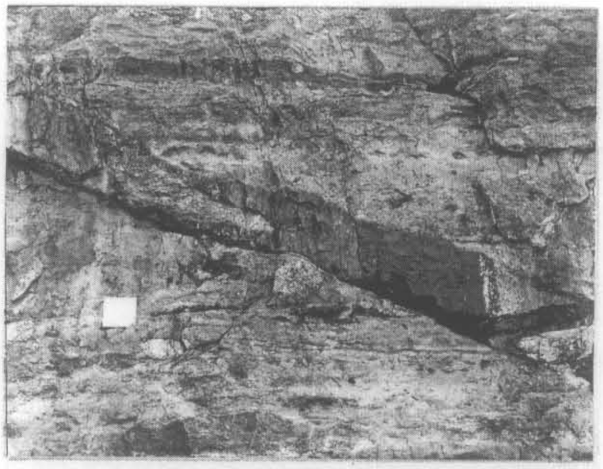

Plate 23. *Detail of Plate 22, showing granite erratic cut by intrusion.*

Role of geophysics in studies of margins

Some uses of geophysical studies have already been alluded to in the foregoing discussion. Nearly all references have been to gravity surveys, which are the most direct and the only currently reliable way of examining dolerite intrusions. Gravity surveys may not reveal fine details about margin distribution and orientation but they do permit integration of the confusing fine details to a whole interpretation. Electrical surveys may be directed at boundary tracing and assessment of jointing and weathering conditions, but as such they are awkward and shallow. Seismic refraction methods are also clumsy and not suited to structural investigations. Seismic reflection methods may be extremely useful, but considerable refinement of technique is necessary before they can be widely used (Leaman, 1978). Magnetic methods offer an obvious means of mapping intrusion margins and while good results may be achieved there are several pitfalls.

The problems relating to the use of magnetic methods derive from the variation of magnetic properties within the intrusion itself. An example of misleading observations at a margin is offered by Leaman (1972*b*) at Rosny College where the deduced position of the boundary was in error. Several possible explanations may be offered; multiple intrusion near margin, one body far less magnetic, faulted intrusion, coarser material to west more magnetic, variations in remanence or orientation, variations due to layers (basal) of differentiation, variations due to marked discordance and sectioning of body. These explanations imply that the state of the boundary is wholly unknown. The overall form deduced from a gravity survey is one of moderate transgression with some slight faulting. The exact nature of the particular boundary remains uncertain and its fit into the overall structure is unknown.

A study of the properties of dolerite magnetism currently underway indicates that substantial variations exist and that many parts of intrusives may yield anomaly patterns and levels comparable with those of the intruded sequence. This clearly shows that care is necessary when using magnetic methods and unless the survey spacing is such as to reveal the high frequency variations definitive of dolerite, they may be most misleading. The methods may locate definite dolerite areas but not always reliably map the margin, even allowing for remanence and orientation effects. A forthcoming report will discuss this subject in detail.

Multiple contacts

In the preliminary discussion relating the implications of simple leading edge theories it was noted that multiple intrusion is commonly observed. In Proctors Road below the Nelson Saddle, a dyke of dolerite is intruded into quite coarse dolerite. Nearby in the saddle area the margin of the main intrusion and another small dyke, visible in the upper quarry, are both composite. In one instance in the low cut on the eastern side of the saddle, a definite wedge may be observed above the main intrusion but in contact with it. The beds of mudstone are bent monoclinally over it and are continuous, but a significant space in front of the wedge is filled with a mush of weathered unrecognisable material (plate 8).

Other large scale examples may be quoted and one of the best exposed occupies the fault zone along the Southern Outlet Road north of Kingston. The fine dolerite interfingers with very coarse dolerite and has also metmorphosed the siltstone. However the section was previously faulted to juxtapose coarse dolerite and siltstone.

PALAEOMAGNETISM

Two major studies of the palaeomagnetic properties of dolerite have been undertaken (Irving, 1956; Schmidt and McDougall, 1977). There have been some minor studies and some are included in the references given by the above authors. Irving's basic study listed some thirty sample sites and concluded with a field inclination of 85°, declination of 325° for the Jurassic pole. However Schmidt and McDougall noted that the data contained some anomalies. Firstly, the pole position did not agree well with other Jurassic poles and secondly, some measurements had an eastward orientation. Since it was thought that inadequate magnetic treatment may have been applied in the older study, the dolerite was resampled. The older results were confirmed and Irving's conclusion found to be in error, but only as a result of averaging two distinct data sets (Declination 63°, dip 81°; 304°, 79°). In each case the bulk of the samples came from marginal or near-marginal dolerite (as far as can be determined by analyses of descriptions and likely localities). This was done presumably to ensure a rapid passage through the Curie Point.

It is interesting to note that neither study observed any reverse magnetisation, but this is doubtless a result of the relative rarity of reversely magnetised dolerite and selection of nearly identical sites. Reversely magnetised dolerite has been observed (Jaeger and Joplin, 1955) and by the author.

Schmidt and McDougall (1977) considered two possible solutions for the determined poles. Firstly, that some unknown magnetic component has not been removed or secondly that an excursion was sampled. The present author believes the latter to be the case in view of the occasionally recorded reversal.

The work done to date leaves many questions unanswered. There is a regular distribution of the dolerite with eastward poles, although the state coverage is poor. There is no convincing study of the variations to be found through a body or along a margin and no detailed analysis has been made of bodies in the same region in order to establish a consistent individual pattern. If it were shown that a particular intrusion reflected the anomalous pole, then clearly age differences would be established. The present level of palaeomagnetic effort is quite inadequate.

It is interesting to speculate that the younger intrusions of the Hobart area, as deduced by the author, north of the River Derwent and exposed up the Derwent Valley show the anomalous pole and that the age determinations of dolerite at Devonport with the same pole are also significantly younger. However some of the older dates are also so correlated. There is inadequate dating to establish periods of excursion, since the period of intrusion could be quite short (<10 Ma) even if multiple. The best means of resolving this matter would be a detailed examination by intrusion. Care must be taken in the case of marginal rocks to ensure that the samples selected relate to the appropriate main intrusion.

AGE DETERMINATIONS

All relevant age determinations on Tasmanian dolerite intrusions are presented in table form by Schmidt and McDougall (1977). Datings range from 152 to 181 Ma but due to various factors are believed to represent a date of about 170 Ma. The ten published results are considered by the writer to be too few and too disparate to have any relevance to arguments on the real age of individual intrusions or pulses of intrusion within the province. Only five bodies have been sampled and a range of materials utilised for dating. In view of the problems of sampling, leakage and general resolution, all fully discussed by Schmidt and McDougall, it would appear that palaeomagnetic studies offer the best approach to separation of intrusion by age.

CONCLUSIONS

Studies of marginal rocks around dolerite intrusions are quite crucial to an understanding of structure, age, petrology and sampling for temperature, dating or palaeomagnetic data. Marginal zones are often compound in terms of either; structures
intrusions
structures and intrusions
and should not be treated lightly. The range of possibilities is such that all possible criteria should be employed in determining whether problems exist around the boundary and it must also be recognised that many criteria may be ambiguous (*e.g.* jointing, chill factors), depending on the quality and quantity of exposure.

A number of matters need urgent research:

a) detailed comparative petrology of margins and related intrusions where age differences are suspected

b) detailed examination of metamorphic effects

c) detailed magnetic analysis of the properties of dolerite and the relationship of these properties to residual magnetisation

d) large scale palaeomagnetic sampling of margins and related intrusions, especially where age differences are suspected

e) full examination of the use of reflection methods to examine dolerite structures

f) a more adequate dating coverage governed by the results of (a), (c) and (d) in particular.

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