FEATURES AND HISTORY OF ACTIVITY OF MAJOR FAULT ZONES IN THE BERRIDALE REGION, SNOWY MOUNTAINS, SOUTHEASTERN AUSTRALIA.

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INTRODUCTION

Berridale ($36^{o}24'S$, $148^{o}48'E$) is a small town in the foothills of the Snowy Mountains (or Australian Alps) of southeastern New South Wales. It is approximately 40 km east-northeast of Mount Kosciusko, which is the highest point in Australis (2250 m above sea level). In terms of structural province, it lies within the so-called Molong-South Coast Anticlinorial zone of the Lachlan Fold Belt (Fig. 1), which developed from an early to middle Palaeozoic mobile zone. The present topography of the Snowy Mountains region is reflecting Cainozoic epeirogenic uplift of eastern Australia, coupled with deep dissection by river systems. Crustal thickness in the region is 45 to 50 km (Finlayson, 1979).

The first detailed geological mapping around Berridale was published by Lambert and White (1965), who studied an area of approximately 500 km^2. Subsequent mapping to complete the Berridale 1:100,000 map sheet was summarized by White *et al.* (1976, 1977), who also assessed the larger scale significance of the structural, petrological and geochemical features of the region. Wyborn (1977) suggested correlations with the region he mapped to the north of the Berridale map sheet and questioned some of the extrapolations of White *et. al.* (*op. cit.*). The seismicity of the Snowy Mountains has been described by Cleary *et. al.* (1964).

This paper draws together information from the above publications.

REGIONAL GEOLOGY

Figure 2 is a detailed map of the area studied by Lambert and White (*op. cit.*), and Figure 3 shows the generalized geology of the entire Berridale map sheet, with areas of Cainozoic cover deleted in order to clarify the features of the Palaeozoic geology.

The oldest recorded rocks are low-grade metasediments of Ordovician age, mainly comprising turbidites and graptolitic slates, both lithologies being quartz-rich. These are intruded by numerous Silurian granite (sensu *lato*) plutons in large, composite batholiths. Remnants of Tertiary basalt flows occur east and southeast of Berridale; these are chiefly alkaline olivine basalts with rare nepheline-analcime basanites. Discontinuous lenses of silicified conglomerate ("greybilly" or "silicrete") commonly occur beneath basalt flows, and in some cases they occur independently of basalts (Taylor and Smith, 1975). They formed as alluvial deposits Tertiary river valleys, and the fact that they are commonly covered by basalt is simply reflecting the tendency of the lavas to flow into these valleys.

Granites

The granites warrant further consideration in so far as they relate to interpretations of the structure of the region.

The plutons can be divided into two distinctive groups, which have been termed I- and S-types (White et. al., 1976, 1977). The criteria for making this distinction are summarized in Table 1. The I-types are considered to have formed by partial melting of igneous source rocks in the deep crust, whilst the S-types were generated by anatexis of metasedimentary rocks that have been through a weathering cycle. Both types comprise mainly granodiorites and adamellites. The oldest plutons are S-type, but geological relationships and age determinations (Williams et al., 1976) about that both S- and I-type plutons were forming within a few millions years of the commencement of granite emplacement.

Individual plutons are commonly elliptical in outcrop shape with major axes oriented in a general north-south direction. Their contacts are approximately vertical on the basis of limited exposures in road-cuttings, the fact that most boundaries are independent of topography, and the intersections of a few contacts in tunnels for the Snowy Mountains Hydroelectric Scheme. Both granite/metasediment and granite/granite contacts are sharp; in the former cases, distinct thermal aureoles, up to 1 km wide, are developed in the Ordovician sedimentary sequences. The order of granite emplacement can be readily ascertained in many cases by mapping of intra-batholithic contacts, as shown schematically in Figure 4. The granites appear to have forced their way upwards, displacing the roof rocks without greatly affecting the structure of the wall rocks.

FAULTING

General considerations

Faults are difficult to recognize in the sedimentary units because of the rubbly nature of outcrops of these rocks, but they are easily recognized in the granites where there is distinctive development of brecciated and mylonitized granite.

Since many of the granite plutons appear to be essentially vertical cylinders, wrench faults can be recognized, and their horizontal displacements measured, in the manner summarized schematically in Figure 5 (A,B). This essentially involves locating displaced segments of the same granite pluton and measuring the distance now separating them. Thrust faults (Fig. 5C) give rise to semi-elliptical-shaped granite outcrop patterns, and one segment of the plutons is commonly lost by erosion or covered (overthrust) by other rocks. Steeply dipping normal faults give no apparent displacement where they intersect granites with vertical contacts, but no simple faults of this type have been authenticated from the Snowy Mountains.

Three sets of faults have been recognized in the Berridale region using these principles. These are evident in Figure 6, which is at the same scale as the simplified geological map, Figure 3. Those trending northwesterly are left-lateral (sinistral) wrench faults and those trending northeasterly are a conjugate set of right-lateral (dextral) wrench faults. The approximately vertical nature of these wrench faults is implied by the fact that they are straight irrespective of topography. The final set of faults has more variable, but roughly north-south trends and their non-vertical dips are indicated by topographic control on their strike directions.

A block diagram of the region showing the significant faults is shown in Figure 7. The two most important of these faults, the Berridale Wrench Fault and the Jindabyne Thrust, are described in more detail below.

Berridale Wrench Fault

The Berridale Wrench Fault (Lambert and White, 1965), which has no prominent scarp along its length, is the largest of the left-lateral, northwest-trending structures. It is actually a fault zone, with parallel, discontinuous faults separated from the main fault by several hundred metres of brecciated, and sometimes silicified rocks (Fig. 2).

The fault zone is never perfectly exposed but its trace on the surface can be accurately located as it shows up on aerial photographs as lineaments, and on the ground as a combination of lithological contrasts, breccia and shear zones, groundwater springs and occasional small scarps in alluvium. It can even be traced as discontinuous lineaments and lines of groundwater springs in areas covered by veneers of Tertiary basalt flows and Quaternary alluvium.

The total horizontal displacement near Berridale township has been measured by the method shown in Figure 5A to be 11 km. In contrast, the largest recorded horizontal displacement associated with the right-lateral wrench faults is only ca. 2.5 km on the Crackenback Fault (Fig. 6).

There is evidence for a vertical component of movement on the Berridale Fault in the Cainozoic. Basalt flows to the northeast of the fault are occasionally found in contact with granite on the southwest side. The field evidence indicates that there was post-basalt downthrow of the northeast side, that the basalt flowed agsinst a pre-existing scarp facing in this direction, or that both events occurred. A less equivocal indication of post-basalt down-throw of the northeast side is the occurrence of silicified conglomerate at several localities to the west of the Berridale fault at a higher level than basalt immediately to the east, as shown schematically in Figure 8; such conglomerates, it will be recalled, formed as stream deposits that were covered by later basalt flows. An accurate measure of the vertical component of this post-basalt movement cannot be obtained, but it cannot exceed the thickness of the adjacent basalt, and this is less than 100 m.

No unequivocal field evidence has been found for recent movement on the Berridale Fault. The linear escarpments, up to 3 m high, and several hundred metres long, which occur in alluvial cover along the fault do not appear to be fault scarps. They are confined to areas where active springs are washing away the unconsolidated materials on the downslope side (Fig. 9).

Jindabyne Thrust

The Jindabyne Thrust (White et. al.,1976) is the most prominent of the meridional structures in the region. Structural contouring on this fault where it intersects a major river gorge below Jindabyne dam indicates an easterly dip of ca. 20°, but this may be unreliable as the gorge is the site of a 30° change in the strike of the fault. Cataclastic and mylonitized zones are common along the fault but individual shear planes are too irregular for any meaningful estimates of dip direction; however, a low angle of dip is confirmed by the topographic control on strike direction, and by the existence of the situation illustrated in Figure 5C; for example the distinctive aplite body just south of Eucumbene dam (Fig. 3; cross-hatched) is truncated by the fault and is not seen on the eastern side.

The Jindabyne Thrust has a west-facing fault scarp, particularly in the southern part of the region. This appears to be related to Cainozoic block movement rather than differential erosion, as similar lithologies occur on either side of the fault in some places.

Relationships between thrust and wrench faults.

White et. al., (1976, 1977) considered the Jindabyne Thrust to be the master fault of the Berridale region, with the left- and right- lateral wrench faults being terminated by it, at least in plan, and their movement being taken up by the thrust. These workers argued that the thrust and wrench faults are related and they systematized the truncation or transition from one to the other in the manner shown schematically in Figure 10. It will be noted from Figure 7 that, whilst the wrench faults are terminated in plan by the Jindabyne Thrust, White et. al. (1977) suggested that the Crackenback Fault continues beneath the overthrust block.

The Berridale Fault splits in two as it approaches the Jindabyne Thrust. The southern branch is a direct continuation of the Berridale Wrench Fault as mapped to the southeast, but its horizontal displacement is reduced to only 3 km, as measured by the method in Figure 5 A; it terminates against the thrust.[5] The northern branch curves northwards to become an east-dipping thrust, or fault with a large thrust component, which joins the Jindabyne Thrust; it is characterized by truncation of several plutons which cannot be matched accross the fault.

However, Wyborn (1977) presented a different view of relationships between the Berridale and Jindabyne structures on the basis of his mapping to the north of the Berridale region. As can been seen from Figure 11, he contended that the Berridale Wrench Fault is the master structure. He proposed that it turns north-northwestwards near Eucumbene dam and continues, with a 5 km left-lateral displacement east of Kiandra, until it meets the Long Plain Fault. Furthermore, he suggested the Tantangara Fault, which has a steep easterly dip, could be the northern continuation of the Jindabyne Thrust, displaced 7 km north by the Berridale Fault.

Further detailed mapping immediately to the south and north of Eucumbene dam is necessary to resolve which of the above interpretations is correct.

FOLIATIONS IN GRANITES

Foliation with an average near-meridional strike and steep dip occurs to varying degrees in many of the granite plutons. White et. al. (1976) note that there is a close spatial, and probably genetic relationship between this foliation and the thrust fault regime, with the intensity of foliation broadly increasing from east to west across the Jindabyne Thrust. The same authors (1977) describe the foliation as "a penetrative planar structure analogous to slaty cleavage in folded slates and sandstones ... : just as the sandstones remain virtually uncleaved compared with the slates, so the I-type granitoids rich in resistant plagioclase remain virtually unfoliated. The foliation may further be considered as a type of slaty cleavage in that its regional orientation is fairly consistent with the fault and fold pattern of the region". Alternatively the better development of foliation in S-type granites could be explained if they were emplaced as magmas with low liquid to crystal ratios, thereby behaving more or less as solids and developing a foliation reflecting the stress field at the time of their intrusion. Provided the I-type magmas had higher proportions of liquid, they would have behaved more as liquids during their emplacement; then they would not have developed the same intensity of foliation as penecontemporaneous S-type granites.

STRUCTURAL SYNTHESIS

The structural features of the region appear consistent with deformation resulting from a maximum principle stress oriented approximately east-west, possibly reflecting mid-Palaeozoic subduction of easterly migrating oceanic lithosphere. The left- and right- lateral wrench faults form conjugate sets nearly at right angles to each other; this is somewhat higher than the average 60^{o} predicted by the dynamic theory of faulting (Anderson. 1959). The elongation of granite plutons, their foliation, the strike direction of some aplitic dykes, the fold directions in the sedimentary rocks and the general strike of the thrust faults, are all close to meridional, bisecting the angle between the northwest and northeast trending sets of wrench faults.

There is active debate as to when the horizontal compressional regime which generated these features was active. White et. al. (1974) speculated that it was already in existence before intrusion of the Middle to Upper Silurian granites and that wrench faults formed by it may have partly controlled the shape of some of the intrustions. They also suggested that further wrench and thrust movements occurred during granitoid intrusion as some aplite dykes, which are considered to have been emplaced during late-stages of this igneous event, are aligned parallel to the directions of these faults. As mentioned above, the same authors also suggested that the granite foliation formed as a result of continued east-west compressional stress after emplacement of the plutons.

Wyborn's (1977) structural synthesis differs in that he postulated the Silurian batholiths were emplaced into anticlinorial zones in the Lachlan Fold Belt during latitudinal extension which resulted in normal faulting and possibly related wrench faulting. He considers that the thrusts, high angle reverse faults and conjugate wrench faults now occurring in the region were produced from the Silurian tensional structures when these were reactivated by subsequent east-west compression.

Lambert and White (1965), White et al. (1977) and Wyborn (1977) all conclude that the major period of trans-current movement and thrust/reverse faulting was associated with the middle Devonian Tabberabberan orogeny. There is no evidence for major geological processes, other than weathering and erosion, between the Middle Palaeozoic and the Tertiary. During the Tertiary, major uplift and basaltic volcanism commenced, possibly in association with the opening of the southern Tasman Sea, some 60-80 m.y. ago.
The major scarps are all associated with Palaeozoic thrust and wrench faults and it appears much of the Cainozoic up-lift can be accounted for by rejuvenation of these ancient structures. It seems likely that the Cainozoic movement on the thrusts was along the pre-existing fault planes. How-ever, some of the wrench faults obviously had a considerable component of Cainozoic vertical movement, particularly the right-lateral Crackenback and Mowamba faults (Fig. 7). These were mainly responsible for elevation of the high Kosciusko Plateau, together with warping along the eastern flank of this block on the Jindabyne Thrust. The Berridale Fault has only had a minor vertical component of movement (<100 m) since the Tertiary volcanic activity, on the basis of the basalt-conglomerate relationships discussed earlier.

White et. al. (1977) suggested that the Tertiary uplift also occurred in a latitudinal compressive regime, but Wellman and MacDougall (1874) considered the Tertiary alkaline volcanism was related to tensional stress as the Australian plate moved northwards over a "hot spot" in the asthenosphere. A present-day east-west compressive stress regime in eastern Australia is suggested by most of the reliable earthquake focal mechanisms and by over-coring measurements in mines and quarries (Denham et. al., 1979).

EXTENSIONS OF THE MAJOR FAULTS

Lambert and White (1965) suggested that the Berridale Fault could continue to the northwest and link up with the Kiandra Serpentine Belt, but this has now been shown to be untenable as the Berridale Fault either terminates or changes direction at the Jindabyne Thrust, near Eucumbene dam (c.f. Figs. 11,12).

As noted by Lambert and White (1965) there is evidence for continuation of the Berridale Fault to the southeast, possibly as far as the coast. Lineaments on aerial photographs and the geological map of New South Wales, extend to near Cathcart (Fig. 12), where there is brecciated and sheared granite of the Bega Batholith. The fault-line projects beyond this point along the straight course of the Towamba River, meeting the coast at Disaster Bay. The existence of a structure along this extension of the Berridale Fault, or parallel to it, was supported by Steiner (1972) who showed that Devonian sedimentation in the Eden area (Fig. 12) was controlled by a southwest trending structure. Furthermore, Davies (1975) reported a basement depression on the continental shelf off Disaster Bay which aligns with the Berridale fault-line. On the other hand, a reconnaissance survey of the Towamba River area by Beams (1975) has not produced evidence for major shearing or rock displacements. The same worker mapped the major, right-lateral Burragate Wrench Fault which trends northeast accross the Towamba River (Fig. 12); this has a horizontal displacement as high as 23 km and no positive evidence has been found that it is cut by the Berridale fault.

THE I-S LINE

White et. al., (1976) noted that the eastern limit of the S-type granites (i.e. the I-S line; Figs. 2 and 3) is close to the eastern boundary of the regime of thrust faulting in the Berridale region. They suggested that the I-S line is a major tectonic feature, probably coinciding with the eastern margin of a thick block of continental crust, possibly Precambrian crystalline basement. This offers an explanation for the absence of metasedimentary source rocks for S-type granites to the east of this region. The deep crust to the east could comprise meta-igneous rocks accreted to the margin of the Precambrian shield.

However, once again Wyborn (1977) espoused a differing viewpoint. He claimed that, in southeastern New South Wales, both wrench and thrust faults occur either side of the I-S line with thrusts and steep angle reverse faults occurring at the margins of the Silurian sedimentary troughs and wrenches mainly occurring in the intervening highs (c.f. Fig. 1). Thus, he sees neither fault type as being related to the I-S line, nor to any ohange in basement type, but he acknowledges that recumbent folds are present to the east and not known to the west of the I-S line.

SEISMICITY

The absence of any active plate margins around the Australian coast is reflected in the generally low seismicity of the continent, with the Snowy Mountains being no exception (c.f. Fig. 13).

Cleary et. al., (1964) showed that the highest concentration of earthquake epicentres in the Snowy Mountains (Fig. 14) occurs in a zone trending in a general northwesterly direction which includes Berridale. The largest earthquake in the region was of magnitude 5 (Richter scale). This occurred on May 18, 1959; its epicentre was some 22 km northwest of Berridale (Fig. 13) and its focal depth was roughly 17 km. The fault plane analysis by Cleary *et al.* (*op. cit.*) provided two alternative solutions: (i) A high angle reverse fault striking about 050° and dipping about 55° northwest or (ii) a low angle reverse fault with a possible range of strikes between 040° and 090°, dipping about 35° southeast or south. They favoured the former interpretation, with the focus of the tremor on the Crackenback fault plane close to where it terminates on the Jindabyne Fault, which they presumed to have a moderate westerly dip. However, there is no evidence for such a dip on this structure and it is difficult to relate the main shock to any of the mapped faults. After-shocks with sinistral wrench component occurred in a broad zone paralleling the Berridale Fault.

The isoseismal map of the Berridale earthquake is shown in Figure 15. Near Berridale, there was some breaking of glass and crockery, cracking of masonary and a few instances of overturned furniture.

SUMMARY

1. The Berridale region comprises Ordovician sedimentary rocks intruded by Silurian granite (sensu *lato*) plutons. Parts of it are covered by Tertiary alluvial deposits and basalt flows.
2. There are three main sets of faults in the region, these are (i) northwesterly-trending, left-lateral wrenches, (ii) a conjugate set of northeasterly-trending, right-lateral wrenches, and (iii) northerly-trending, low-angle thrusts. The two major structures are the Berridale Wrench Fault, which has a sinistral displacement of 11 km near Berridale and the Jindabyne Thrust which has a shallow easterly dip near Jindabyne.
3. The structural grain of the region is compatible with a horizontal, east-west, compressive regime which was probably most active during or after the Middle Devonian. There is debate whether this stress regime was active before and during emplacement of the Silurian with latitudinal crustal extension. Cainozoic uplift appears to be related mainly to rejuvenation of Palaeozoic structures, with considerable vertical displacement on some of the old right-lateral wrench faults.
4. The seismicity of the Snowy Mountains region is only moderate by world standards, largely because of the absence of active plate margins off the Australian continent. The only significant earthquake (magnitude 5) recorded in the Berridale region, which, occurred in 1959, was not obviously

related to any of the faults known in the area; after-shocks with a sinistral wrench component occurred in a broad zone along the direction of the Berridale Fault.

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Table 1: Distinctive properties of the two types of granites recognized in southeastern Australia, after Chappell and White (1974). These granites are interpreted as being derived by anatexis of two different types of source rock: igneous (I) and sedimentary (S).

The chemical properties of the S-type granites are seen as reflecting the removal of sodium into sea water (or evaporites) during sedimentary fractionation, and calcium into carbonates, with subsequent relative enrichment of the main sedimentary pile in aluminium. High initial Sr^{87}/Sr^{86} ratios also reflect the sedimentary sources of the S-type granites.

I-types	S-types
Relatively high sodium, Na_2O normally >3.2% in felsic varieties, decreasing to >2.2% in more mafic types	Relatively low sodium, Na_2O normally <2.2% in rocks with approx. 2% K_2O
Mol $Al_2O_3/(Na_2O+K_2O+CaO)<1.1$	Mol $Al_2O_3/(Na_2O+K_2O)>1.1$
C.I.P.W. normative diopside or <1% normative corundum'	>1% C.I.P.W. normative corundum
Broad spectrum of compositions from felsic to mafic	Relativeiy restricted in composition to high SiO_2 types
Regular inter-element variations within plutons; linear or near-linear variations diagrams	Variation diagrams more irregular
Hornblende common, sphene is common accessory	Hornblende absent, muscovite and biotite common. Alumino-silicates garnet and cordierite may occur.
Initial Sr^{87}/Sr^{86} ratios generally <0.706	Initial Sr^{87}/Sr^{86} ratios generally >0.708.

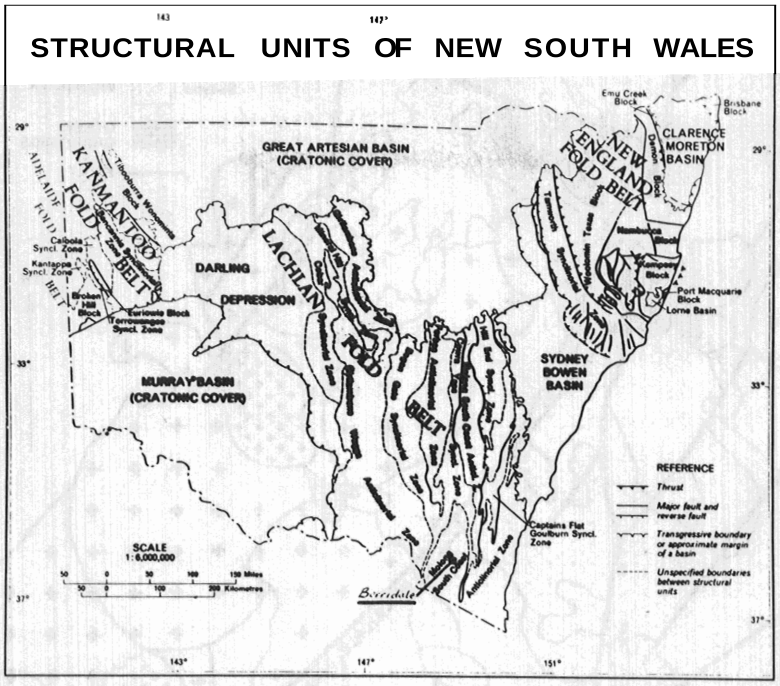


Figure 1. Structural provinces of New South Wales after Scheibner (1975). Note Berridale in the southern part of the Molong-South Coast Anticlinorial zone.

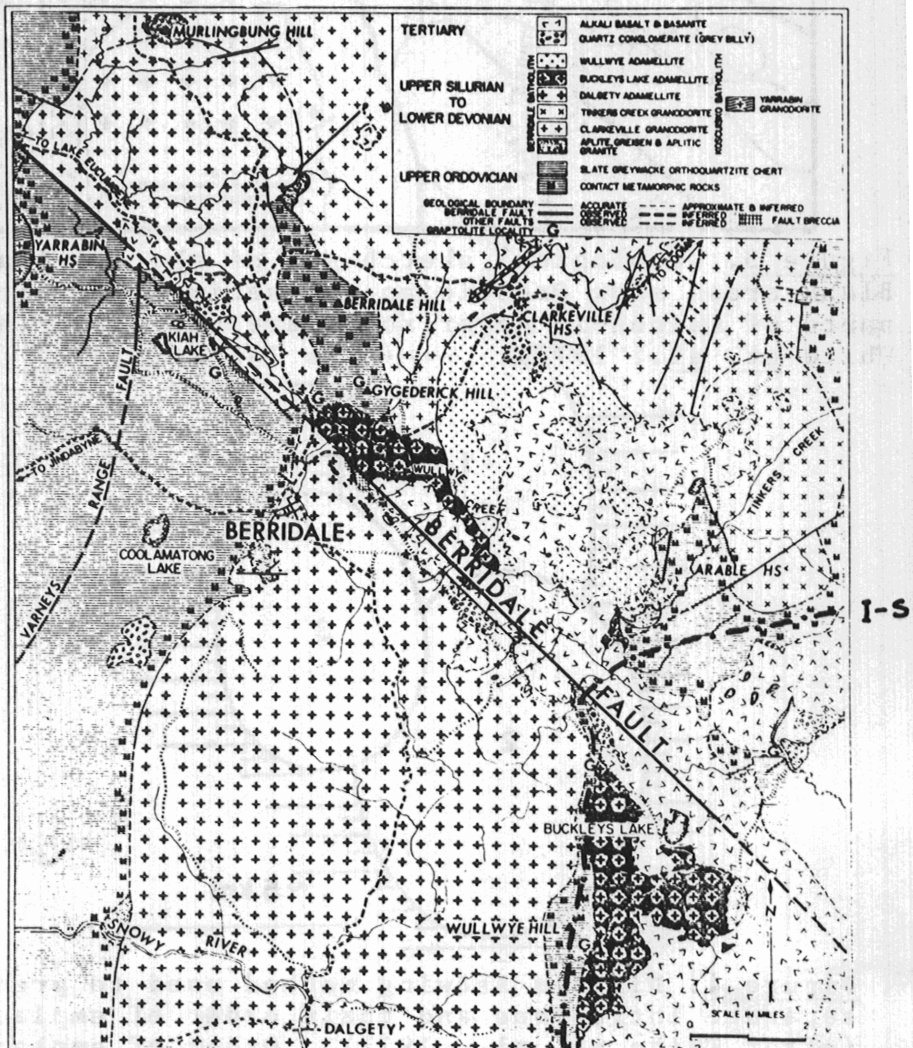


Figure 2. Detailed geological map of the area around Berridale (after Lambert and White, 1965). —•—• is I-S line, to the east of which there are no S-type granites.

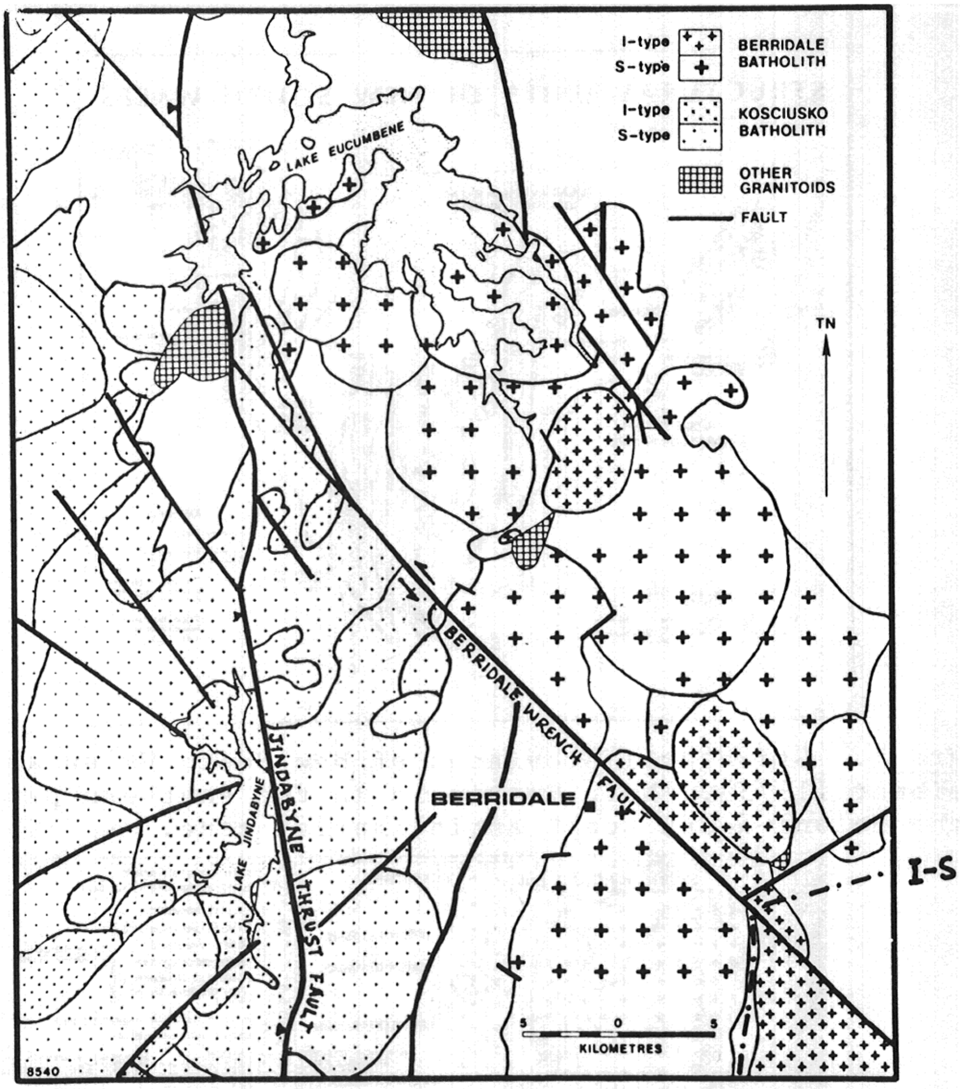


Figure 3. Geological sketch map of the Berridale region. Blank areas show Ordovician metasedimentary rocks. Remnants of Cainozoic cover rocks are not shown (after White et. al., 1977). –·–·–· is I-S line.

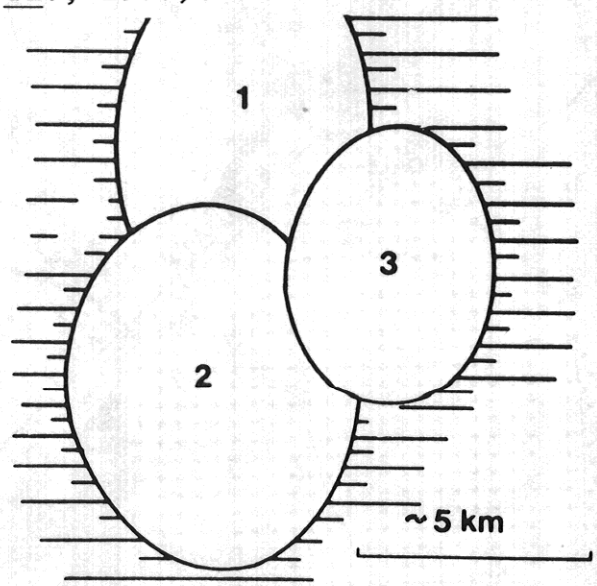


Figure 4. Diagram showing method used to predict separate intrusions and their order of emplacement (after White et. al., 1977). Order of emplacement is 1, 2, 3. Careful mapping, complemented by petrographic and geochemical studies indicates that many such elliptical-shaped (in plan) plutons can be distinguished within granite batholiths.

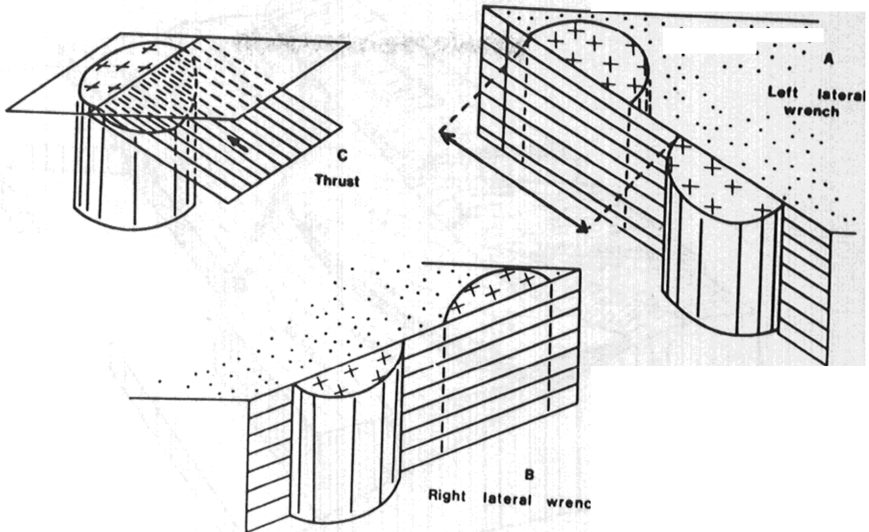


Figure 5. Schematic diagram showing how faults and their nature can be recognized in the Berridale region (after White *et. al.*, 1977). Horizontal component of movement on wrench faults can be estimated by measuring displacements of granite segments.

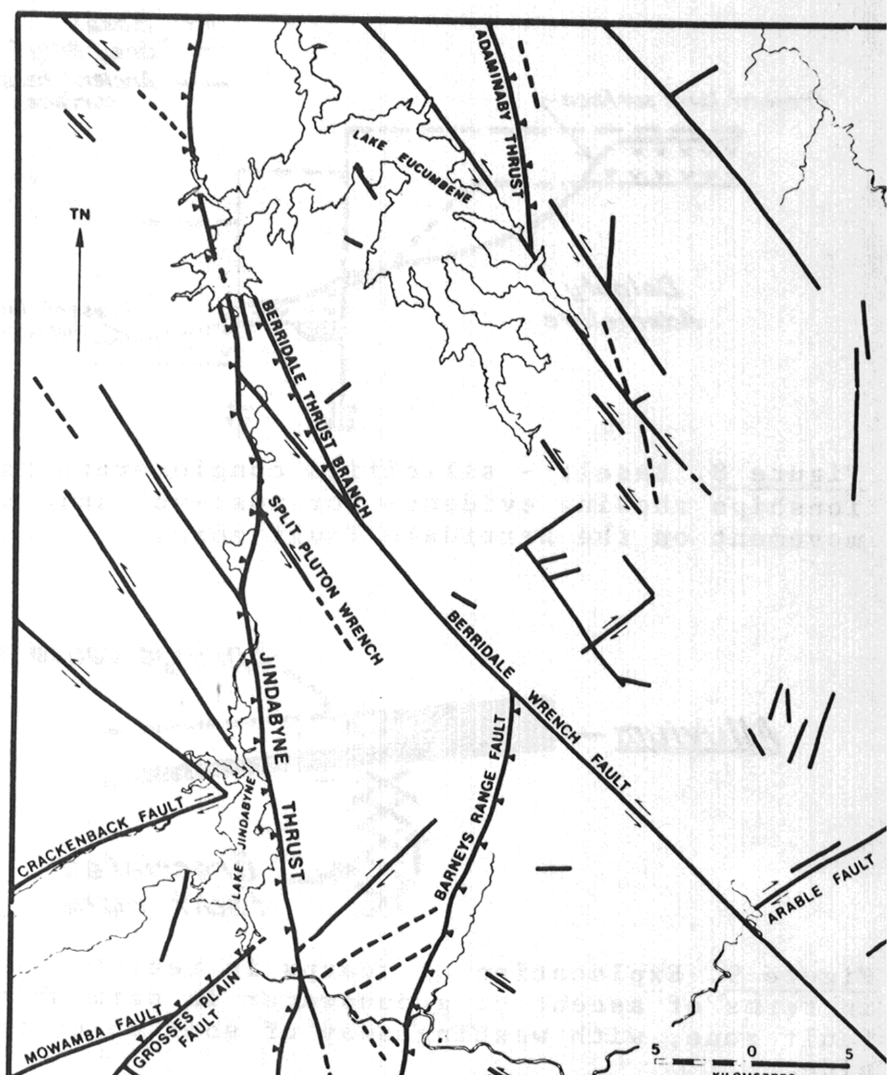


Figure 6. Major faults in the Berridale region (after White *et al.*, 1977).

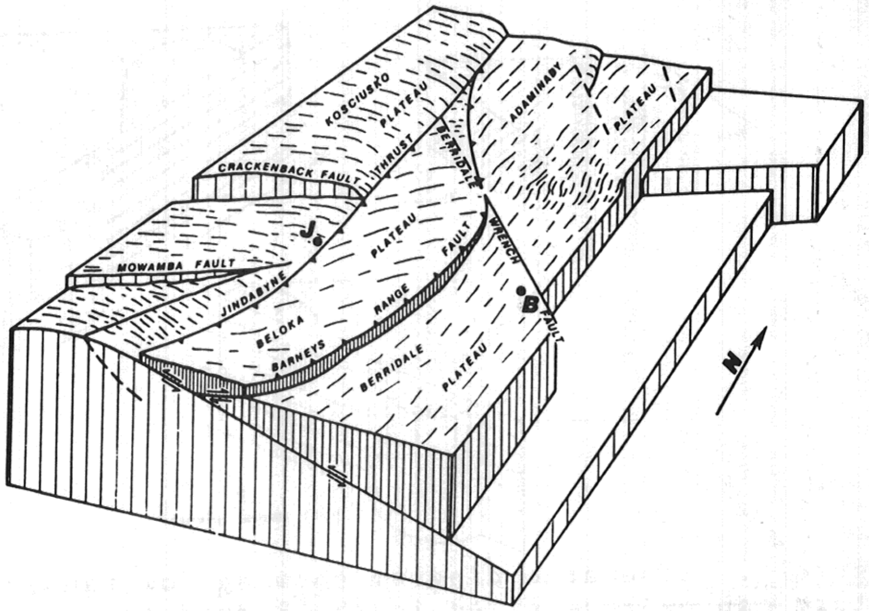


Figure 7. Block diagram of the Berridale region showing the relationships of faulting and geomorphic features (after White et. al., 1977).

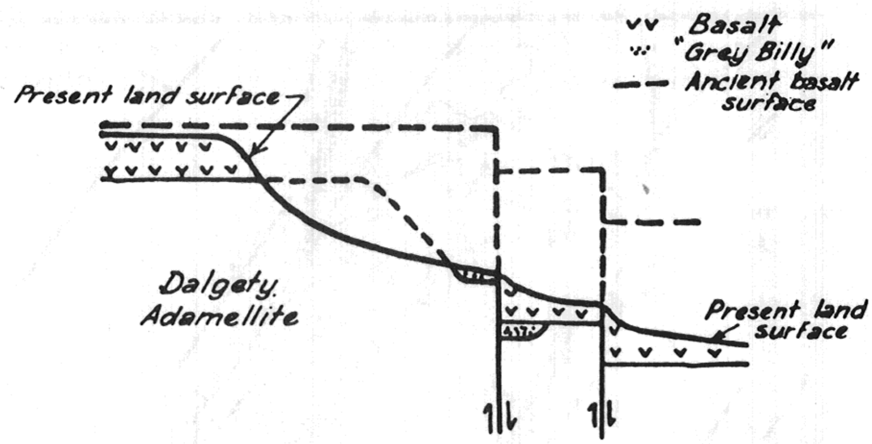


Figure 8. Basalt - silicified conglomerate relationships showing evidence for post-volcanic vertical movement on the Berridale Fault zone.

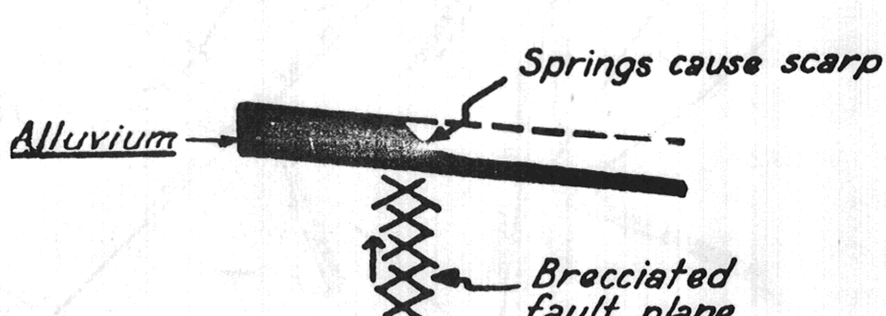


Figure 9. Explanation of scarps in recent alluvium in terms of ascent of groundwater in permeable fault zone, with washing away of soil on downslope side.

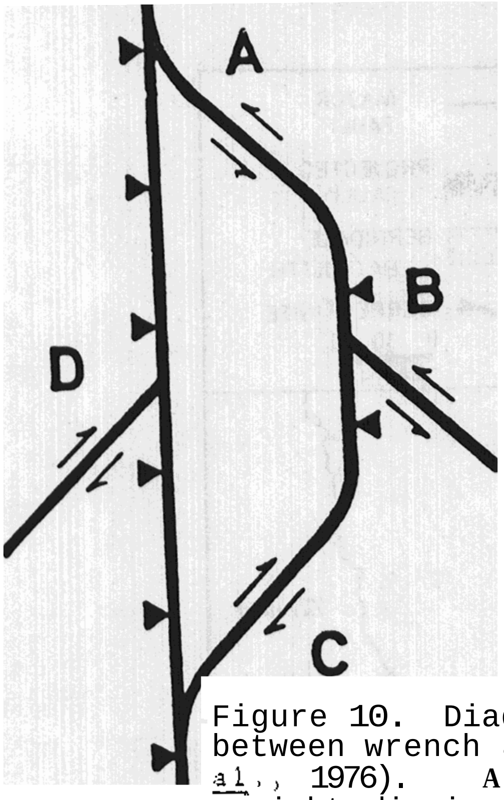


Figure 10. Diagram showing apparent relationships between wrench and thrust faults (after White et. al., 1976). A: left-lateral wrench passes **into** a right-dipping thrust. B: left-lateral wrench intersecting a left-dipping thrust is terminated in plan. C: right-lateral wrench passes into a left-dipping thrust. D: Right-lateral wrench intersecting a right-dipping thrust is terminated in plan.

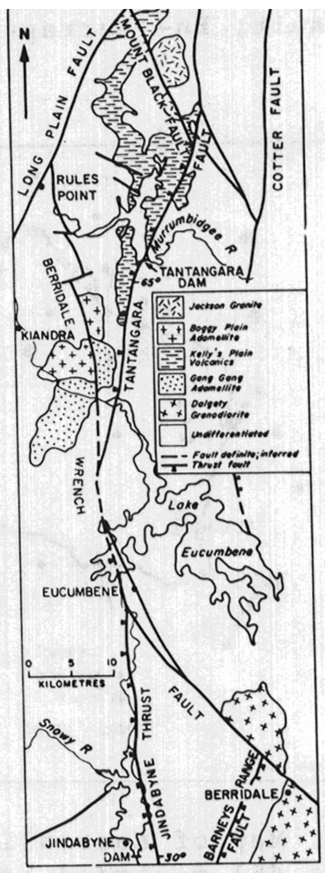


Figure 11. Major faults in the Berridale-Tantangara region. according to Wyborn (1977). Note the proposed continuation of the Berridale Wrench Fault, which is considered to displace the Jindabyne Thrust.

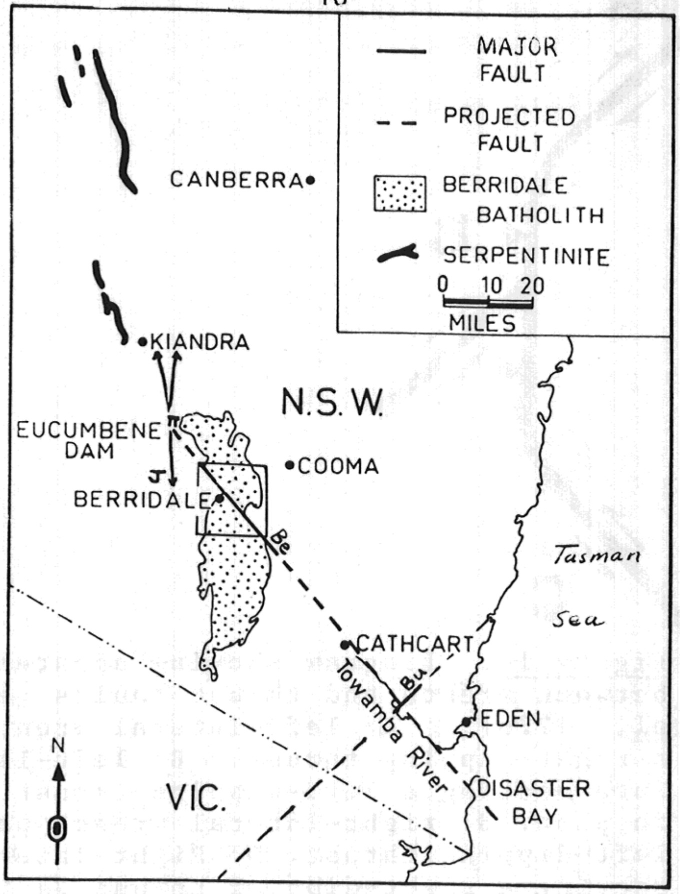


Figure 12. Map showing possible extensions of the Berridale Wrench Fault, modified after Lambert and White (1965). Be = Berridale Fault; Bu- Burragate Fault (Beams, 1975).

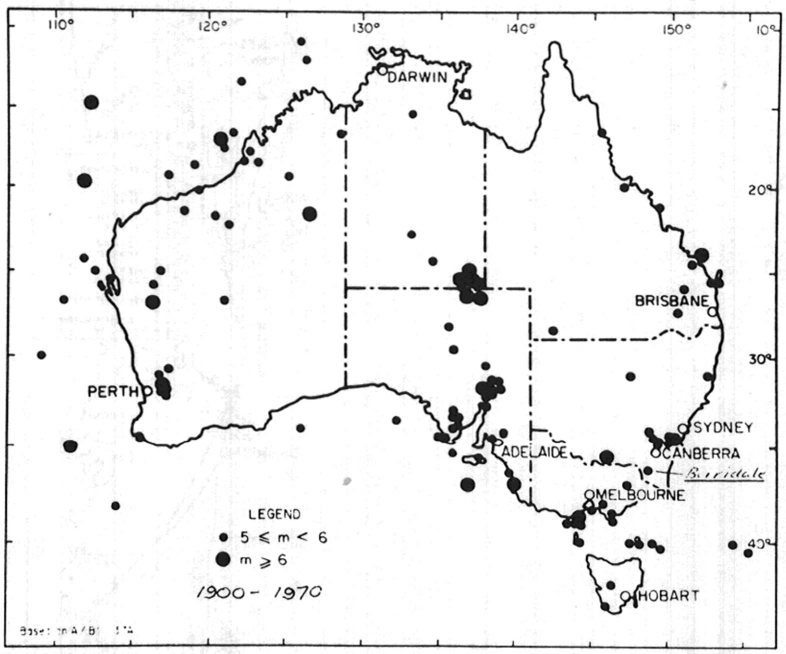
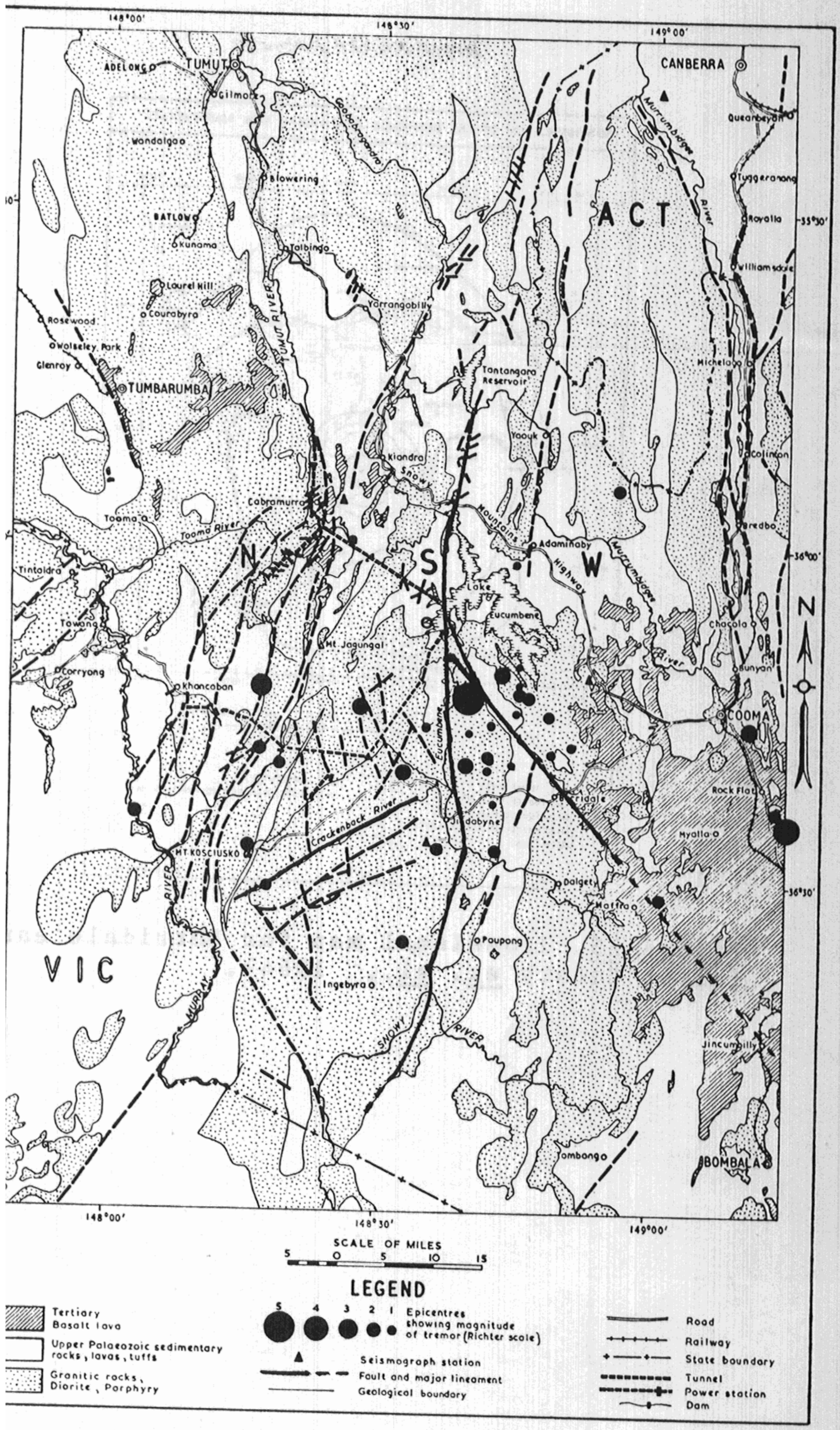
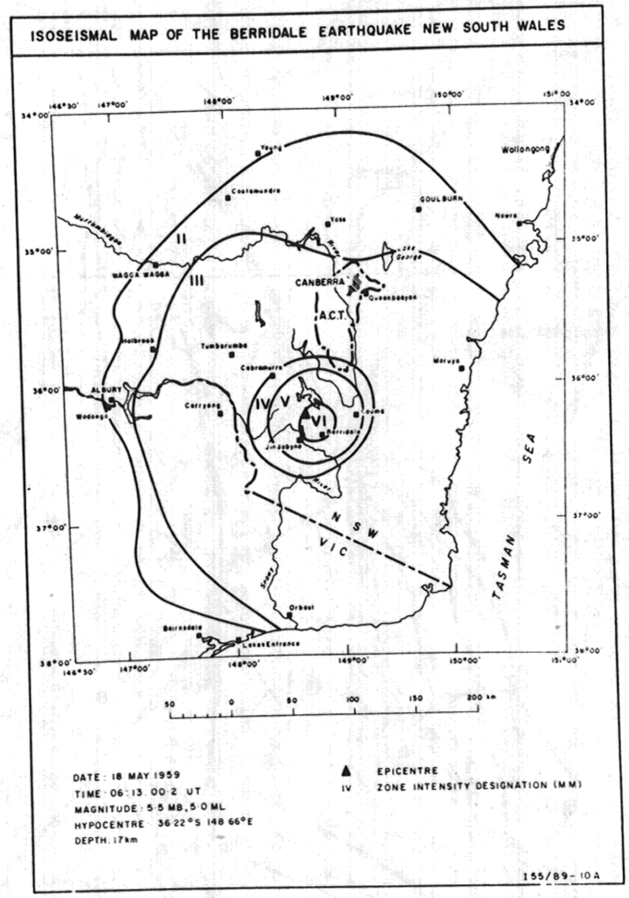


Figure 13. Map of Australia showing earthquake epicentres (magnitude ≤5) recorded between 1900 and 1970. In part, blank areas reflect lack of recording stations. Courtesy of the Bureau of Mineral Resources.



<u>Figure 14</u>. Geological sketch map of the Snowy Mountains showing earthquake epicentres. After Cleary <u>et</u>. <u>al</u>.,)1964), with relevant portions of Jindabyne and Berridale Faults added.



<u>Figure 15</u>. Isoseismal map for Berridale earthquake (after Cleary <u>et</u>. <u>al</u>., 1964).