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# Deformation of the Zeehan Tillite and re-evaluation of the Tabberabberan Orogeny in Tasmania

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*Abstract*

A strong penetrative vertical cleavage, trending NW–SE, is developed throughout the entire 4.5 km long section of outcropping Zeehan Tillite near Zeehan. This rock unit lies on an undulating angular unconformity that has been folded, in sympathy with bedding in the tillite, around an approximately NW-trending axis. Deformation of the tillite is here correlated with the latest folding event of the Tabberabberan Orogeny also of NW-trend ($D_4$ after Seymour, 1980).

In addition to numerous Oonah Formation clasts, the Zeehan Tillite contains clasts of fossiliferous Silurian sandstone (Crotty Sandstone), keratophyre-tuff of the Dundas Group, and presumed Early Carboniferous Heemskirk Granite clasts (Spry, 1958). Furthermore, the tillite has been lithologically correlated with the Late Carboniferous Wynyard Tillite (Spry, 1958). Such age constraints on the Zeehan Tillite suggest that both its deformation and the last fold event of the Tabberabberan Orogeny ($D_4$) are of post-Early Carboniferous age. Such an interpretation is not inconsistent with the previously accepted minimum age constraint of the Tabberabberan Orogeny based on the Eugenana cave deposits. This is because only one Tabberabberan Orogeny cleavage, the earlier N-trending $D_3$ of Seymour (1980), is developed in the limestone blocks contained within the cave sediments.

Consequently the NW-trending episode of folding ($D_4$), previously grouped with the Early–Middle Devonian Tabberabberan Orogeny, is here proposed to be a temporally distinct deformational event of post-Carboniferous age. Furthermore, $D_4$ may also be tectonically distinct from the Tabberabberan Orogeny (deformations $D_1$–$D_3$, after Seymour, 1980). This is based on $D_4$ having NE over SW transport, which is contrastingly opposed to the W over E transport during $D_3$ (Williams and Turner, 1974).


## INTRODUCTION

A large exposure of Zeehan Tillite occurs 5 km northwest of Zeehan (fig.1). This rock is very well exposed, nearly continuously for the entire 4.5 km length, in road cuttings along the Zeehan–Granville Harbour road. A structural section through this exposure is presented here (fig. 2). The work was undertaken as part of the revision of geological mapping in the Zeehan Quadrangle. This is the first report defining the tectonic fabrics developed in this unit, though Spry (1958) previously reported the existence of a weak cleavage and quartz veins. All orientations are relative to true north. The time scale used in this report is after that of the Geological Society of America (1983). All isotopic ages quoted have been recalculated according to Steiger and Jaeger (1977) by D. C. Green (pers. comm.) and I. McDougall (pers. comm., 1983).

## ZEEHAN TILLITE DESCRIPTION

The Zeehan Tillite (Spry, 1958), or Zeehan Glacial Formation (Blissett, 1962), has not been formally defined. It was first described by Moore (1896), and good descriptions of the sedimentary and lithological features of the Zeehan Tillite are presented in Spry (1958) and Blissett (1962).

The tillite is dominantly a muddy and/or sandy unsorted siltstone diamictite, although predominantly mudstone and predominantly coarse-grained sandstone units do exist. Scattered throughout this unsorted matrix are numerous rounded to sub-angular clasts of up to boulder grade (300 mm). Clasts are matrix supported, and no exposures of clast-supported diamictite have been observed. Striated surfaces of cobbles have been observed. The majority of clasts are quartzite and lesser slate of the Oonah Formation. Also present are granite clasts, reported to be indistinguishable from the Heemskirk Granite (Spry, 1958); keratophyre-tuff equivalent to those of the Dundas Group (Spry, 1958); and pale fossiliferous sandstone, considered equivalent to the Crotty Sandstone, has been reported by H. Bartlett (see Spry, 1958).

The tillite is very well indurated to a very hard competent unit. This was noted by Spry (1958) and because of its contrast to the Permian rocks of Tasmania, led to the suggestion that it was older than Permian (Spry, 1958). Bedding is recognisable in many outcrops, although it is not very distinct. The most discernible beds are unsorted silty sandstone beds, typically 200–300 mm thick. Bedding is typically gently dipping but dips of up to 50° have been recorded. Contorted bedding with an essentially flat-lying isoclinal fold of nearly 1.5 m amplitude has been identified

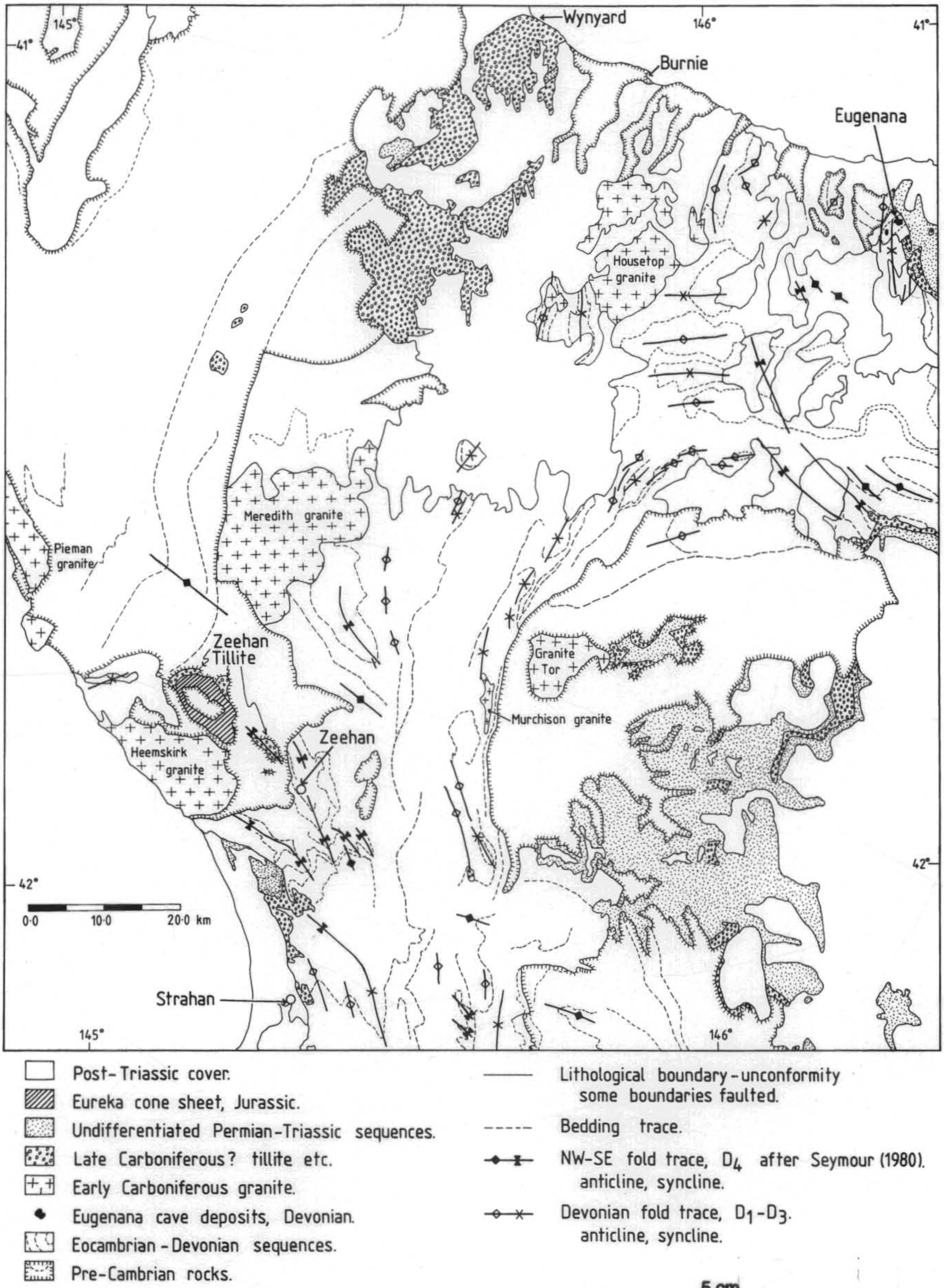



**Figure 1.**

Simplified geological map of the Mount Read Volcanic Belt and Dundas, Dial Range and Fossey Mountain Troughs and adjacent regions. Major Tabberabberan Orogeny fold trends and rock units relevant to discussion in text are presented. Map largely based on the Burnie (Williams and Turner, 1973) and Queenstown (Corbett and Brown, 1975) 1:250 000 sheets, and the 1:500 000 structural map of Pre-Carboniferous rocks of Tasmania (Williams, 1976).

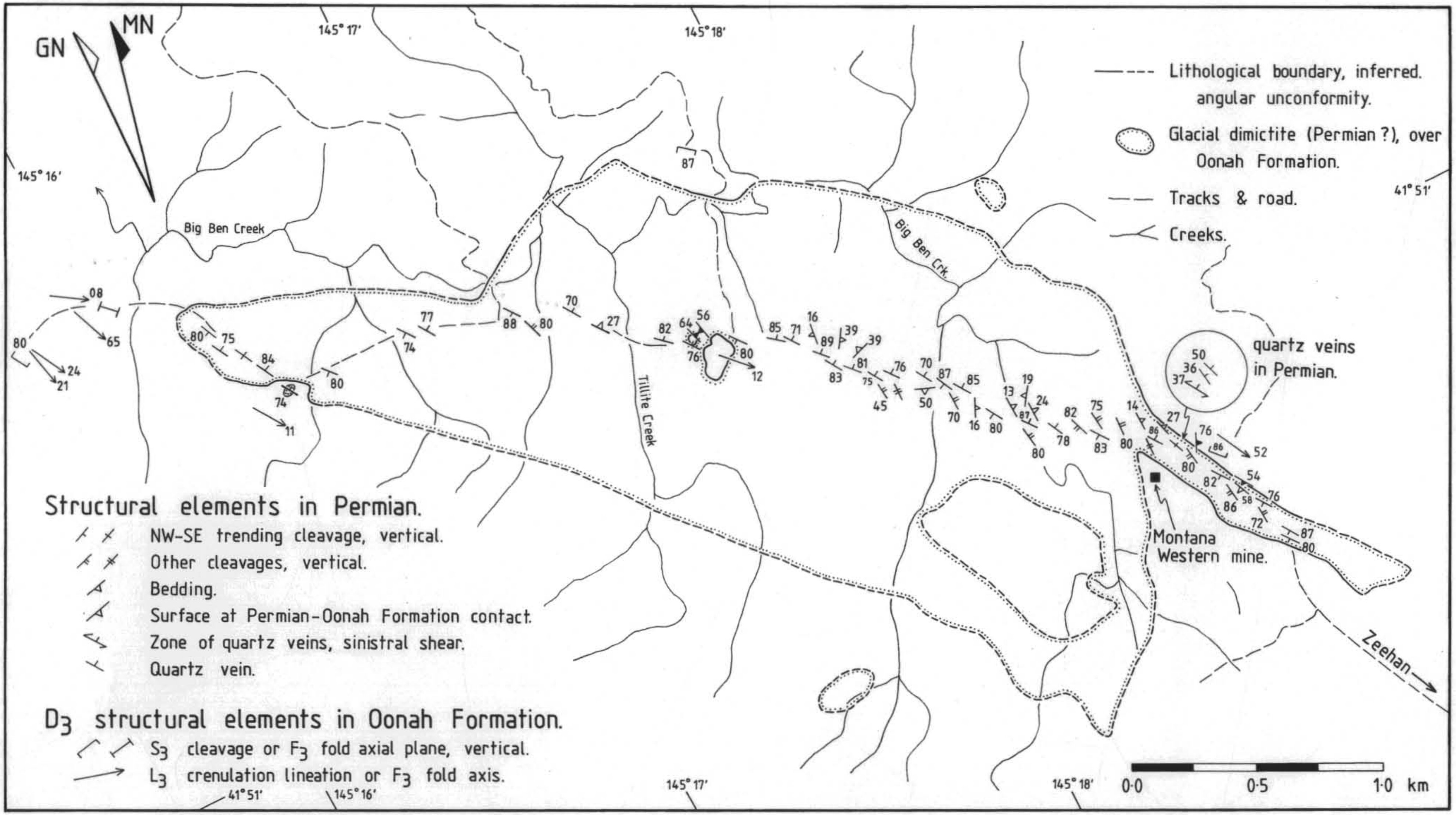



**Figure 2.**

Geological map and structural traverse through the Zeehan Tillite and underlying Oonah Formation along the Zeehan–Granville Harbour Road. Blanket peat and recent alluvium are ignored. Lithological boundaries are modified after Blissett and Gulline (1962) by recent mapping in February 1991 by Goscombe. All structural data are by the author.

5 cm

in one outcrop (fig. 3), and is attributed to soft-sediment slumping.

The Zeehan Tillite is deposited on an angular unconformity on the Late Proterozoic Oonah Formation (fig. 4) (Spry, 1958). This angular unconformity surface is relatively steep in all outcrops in which it is exposed. In one outcrop the unconformity can be shown to have been tilted-folded 54° to the SW. At this locality (the northeast margin of the tillite near Montana Western Mine, fig. 2) a well-defined sandstone bed is parallel to the unconformity surface (fig. 4). The unconformity dips 54° towards 236° and the sandstone bed, immediately adjacent to the unconformity, dips 58° towards 243°. The undulating unconformity surface and bedding in the tillite is proposed to be due to folding (see later discussion) in contrast to being a landscape unconformity.

No faulting is observed within or bounding the tillite at the four localities where the unconformity is exposed (see also Spry, 1958). The steeply-dipping unconformity locality described above is at the same location described by Spry (1958) as overturned tillite with overhanging Oonah Formation. Although the Oonah Formation does outcrop at a higher elevation, it does not overhang the tillite here or at any other known locality (see later discussion).

## DEFORMATIONAL ELEMENTS IN THE ZEEHAN TILLITE

The silty matrix of the Zeehan Tillite has developed a strong penetrative planar cleavage throughout every outcrop for the entire traverse studied (fig. 2). This cleavage is apparently defined by aligned platy minerals in hand specimen, and has given rise to a finely spaced (<1 mm) foliation in many outcrops (fig. 7). In outcrop the cleavage is most easily discernible as very obvious cleavage planes spaced at 1–8 mm and accentuated in definition by recent weathering (fig. 5). Two well-defined orientations of essentially vertical cleavage are identified. A NW-trending cleavage (128°–159°, averaging 145°) is every where developed, while a less dominant cleavage of NNW-SSE trend (158°–191°, averaging 166°) (fig. 6) is identified mainly in the southwest of the tillite exposure (fig. 2). Together these cleavages form a "diamond" cleavage, with neither crenulating the other. A very similar bimodal distribution of cleavage trends has been documented for the last folding event of the Tabberabberan Orogeny in the St Valentines Quadrangle (Seymour, 1989).

The dominant cleavage encloses the clasts symmetrically (fig. 8), indicating shortening orthogonal to the cleavage plane (ie. along a NE–SW axis). Less commonly the cleavage is also developed, without refraction, within the clasts (fig. 9). The cleavage described above is in no way confused with the bedding-parallel parting described by Blisset (1962), as the cleavage is always at a high angle to bedding where discernible (fig. 6).

The unconformity surface at the base of the tillite has been noted previously (Bradley, 1954; Spry, 1958; Blissett, 1962) and in this study to be an undulating surface (figs 10 and 11). Blissett (1962) described this surface as a landscape unconformity. The topographic high of outcropping Oonah Formation to the northeast of the SW-dipping tillite–Oonah unconformity, described in the previous section (near Montana Western Mine), has been variably attributed to thrust faulting of Oonah over tillite along a NE-dipping fault (Blissett, 1962), and as being overturned by folding (Twelvetrees and Ward, 1910; Spry, 1958) (fig. 11). Neither of these interpretations are compatible with the outcrops exposing the northeast margin of the tillite. No faulting is observed at or near the angular unconformity, as was also noted by Spry (1958). Most significantly, the unconformity surface dips consistently to the SW along this margin of the tillite (see previous description of outcrop), thus the Oonah Formation does <u>not</u> overlie the tillite and the unconformity is <u>not</u> overturned.

As previously described, the outcrop near Montana Western Mine displays bedding within the tillite parallel to the unconformity surface. The unconformity surface is presumed to have been horizontal at the time of deposition of the tillite, and has subsequently been rotated to its steep inclination. This rotation is interpreted as being due to folding by an approximately NW- to NNW-trending fold (fig. 10). Such an interpretation is consistent with the few orientation measurements of the unconformity surface available (fig. 6). Similarly, although not as well defined, the bedding orientations within the tillite are not inconsistent with NW- to NNW-trending folding (fig. 6). The entire outcrop shape of the Zeehan Tillite is consistent with being an elongate synformal fold basin trending approximately 140°–145° (fig. 10). This proposed folding of the unconformity, bedding within the tillite, and overall basinal structure of the whole exposure, is consistent with the NE–trending shortening defined by the cleavage developed within the tillite (fig. 10). Furthermore, two sets of interpretive fold trends folding the tillite–Oonah unconformity are consistent with the two sets of cleavage orientations (fig. 10).

Strong cleavages and steep orientations of bedding have been observed in the Wynyard Tillite near Burnie and Permo-Carboniferous sequences at Pt Hibbs, and these are typically closely associated with faulting (D. B. Seymour, pers. comm.). However a genesis of the cleavage in the Zeehan Tillite by faulting is unsupported because no faulting has been observed and because of the penetrative nature of the cleavage throughout the entire 4.5 km section of exposure.

Thin (5 mm wide) planar milky quartz veins up to two metres long and with gently tapered terminations are present in the tillite at its steeply inclined northeast flank, near Montana Western Mine. These veins are consistently inclined as *en echelon* sets at very low angles to the 200 mm wide zone bounding them (fig. 12). The bounding surface of these zones is partially delineated by thin quartz veins, some containing rotated blocks of host siltstone. The consistently inclined *en echelon* geometry of the veins within the zones suggests a component of sinistral shear within this zone to be compatible with the dilation of these veins (fig. 2).

A "devils-advocate" argument that the cleavage and folding within the Zeehan Tillite is due to over-riding ice cannot be substantiated. The apparent folding of the unconformity surface, vertical cleavage (in contrast to an anticipated inclined orientation), and the intense and pervasive nature of the cleavage do not support such an interpretation.

## CORRELATION OF TILLITE DEFORMATION WITH DEFORMATION IN OLDER ROCK UNITS

At least three deformational events have been confidently and consistently constrained in relative timing with respect to each other in the adjacent Oonah Formation. It is common to find all three deformations in the one outcrop (fig. 13) and the relative timing, fabric style and orientation is consistent between different outcrops. This sequence of deformations is summarised below.

- $D_3$ NW-trending crenulation cleavage ($S_3$) and open folds
- $D_2$ NE-trending crenulation cleavage and tight to open folds
- $D_1$ NE?-trending planar cleavage at low angles to bedding and tight to isoclinal folding.

Other crenulation cleavages and folds which post-date $D_1$ and pre-date $D_3$ are identified but these are as yet not well constrained. However in all outcrops $D_3$ is the last deformational episode recorded.

The $S_3$ crenulation cleavage has an average trend of 139° (fig. 14), which is sub-parallel to the cleavage developed in the tillite (average of 145°, fig. 6). Brown (1986) also found that the last crenulation cleavage and folding in the Oonah Formation trended NW–SE. Consequently deformation in the tillite is correlated with $D_3$ in the Oonah Formation. No consistent tectonic transport direction has as yet been evaluated for $D_3$ in the Oonah Formation.

Early to Middle Devonian deformation, of Eocambrian through to Early Devonian rocks, in the Mount Read Volcanic Belt and Dundas, Dial Range and Fossey Mountain Troughs has been well documented and attributed to the Tabberabberan Orogeny (Browne, 1950). These deformations typically involved large scale upright to steeply inclined, open to close folding with variable axial planar cleavage development. Seymour (1980, 1989) has defined the temporal sequence of these fold events in the St Valentines Quadrangle. This temporal sequence appears consistent with data from other map explanatory notes throughout the wider region of northwest Tasmania defined above. This information is summarised in Table 1. In all regions, the last deformational event attributed to the Tabberabberan Orogeny is the NW-trending folding ($D_4$, after Seymour, 1980). Stereographic projections of bedding and cleavage data that define $D_4$ folding from different quadrangles in northwest Tasmania are presented in Figure 15. The regional $D_4$ trend parallels the cleavage and trace of the proposed folding in the Zeehan Tillite, consequently the two are correlated. The consequences of such a correlation are discussed in a later section.

The co-planarity of the regional $D_4$ (Seymour, 1980) folding and deformation of the Zeehan Tillite may be argued as coincidence and the above correlation refuted. If so, the consequent post-$D_4$ ($D_4$ after Seymour, 1980) deformation of the Zeehan Tillite still leaves a previously unrecognised deformational event that has no reported expression in any other rock unit apart from the Zeehan Tillite. Such an interpretation is highly unlikely.

Permo-Carboniferous sequences in the south of the Zeehan Quadrangle (Blissett and Gulline, 1962) and within the Strahan Quadrangle (Baillie *et al.*, 1977) have bedding dipping up to 42°. Bedding data from these rock units are distributed around a very gently SE-plunging fold axis that trends 145° in the Strahan Quadrangle and 138° in the Zeehan Quadrangle (fig. 16). This bedding data does not include readings near faults, thus the data reflects a real NW-trending folding in these sequences. Although no cleavage has been reported from these sequences, the above data suggest that the deformation recognised in the Zeehan Tillite may be more widespread, particularly to the south.

The Permo-Carboniferous sequences to the north are essentially flat-lying, such as in the Burnie Quadrangle (Gee *et al.*, 1967) (fig. 16). Steep bedding in the Wynyard Tillite correlate in the St Valentines Quadrangle (Baillie *et al.*, 1986) is attributed to deformation by over-riding ice with transport from SW to NE (Williams and Lennox *in* Seymour, 1989) (fig. 16). In this quadrangle, steep bedding closely associated with faulting has also been reported by Seymour (pers. comm.).

## AGE CONSTRAINTS OF RELEVANT ROCK UNITS AND DEFORMATIONS.

To fully evaluate the consequences of the deformational episode recognised in the Zeehan Tillite, the available absolute and relative age constraints for relevant rock units and deformational events need to be discussed.

### *Northwestern Tasmanian Granites*

Except for the Murchison and Darwin granites, all isotopically dated northwest Tasmanian granites are tightly constrained to be of Early Carboniferous age (332–367 Ma, fig. 17). In particular the Heemskirk Granite (fig. 1) is dated at 347 ± 3 to 351 ± 7 Ma by Rb-Sr total-rock (Brooks and Compston, 1965) and 332–352 Ma by K-Ar total-rock (McDougall and Leggo, 1965).

### *Age of the Zeehan Tillite*

The Zeehan Tillite referred to here includes the outcrops underlying the Eureka cone sheet, the large outcrop on the Zeehan–Granville Harbour Road (the subject of this report), and scattered outcrops within the immediate region overlying the Oonah Formation. Since discovery, the age of the Zeehan Tillite has been controversial; a summary of the early (pre-1958) interpretations is presented in Spry (1958) and Blissett (1962). In the above outcrops the matrix of the tillite is un-fossiliferous and to this day age constraints of the tillite are based on lithological correlations.

It is indisputable that the Zeehan Tillite unconformably overlies the Late Proterozoic Oonah Formation (see earlier) and pre-dates intrusion by the Eureka dolerite cone sheet (fig. 1) of presumed Middle Jurassic age (see later). However, the maximum age limit of the tillite can be constrained much more tightly by the cobble clast assemblages reported. A fossiliferous sandstone clast

**Table 1.**

Summary of relative timing, as published, of post-Silurian fold generations in western Tasmania. Time proceeds from right to left. Authorship of data and quadrangle the data is derived from are given. Nomenclature at the top of the table in bold is used throughout text. Nomenclature elsewhere in table is as presented by respective authors. Present = relative timing unknown.

| | | | | | | |
|---|---|---|---|---|---|---|
| Seymour, 1980: **St Valentines** | | | | | | |
| | **$D_4$** | | **$D_3$** | | **$D_2$** | **$D_1$** |
| | NW-SE to NNW-SSE<br>Deloraine/Railton trend | | N–S (±10°)<br>West Coast Range/<br>Valentine trend | | ENE-WSW to NNE-SSW<br>Belvoir trend | E–W (20°)<br>Loongana/Wilmot trend |
| Williams, 1978 | | | | | | |
| | Deloraine/Railton trend<br>Zeehan/Gormanston trend | | West Coast Range/Valentines trend | | | Loongana/Wilmot trend |
| Jennings, 1963: **Middlesex** | | | | | | |
| | present | | | | | present |
| Jennings, 1979: **Sheffield** | | | | | | |
| | $D_2$ | | | | | $D_1$ |
| Brown, 1986: **Dundas–Mt Lindsay–Mt Youngbuck** | | | | | | |
| Oonah Fm. | $D_5$ | | $D_4$ | | | |
| Success Creek Fm. | $D_2$ (325°) | | $D_1$ (350°) | | | |
| Crimson Creek Fm. | | | present | | | |
| Dundas Group | | | present | | | |
| Silurian-Devonian | present | | present | | | |
| Gee, 1977: **Burnie** | | | | | | |
| | | | | | present | |
| Burns, 1965: **Devonport** | | | | | | |
| at Eugenana | | $D_3$ (E–W) | $D_2$ | $D_1$ (N–S) | | |
| Forth Metamorphics | | | $D_1$ | | $D_2$ | |
| Williams and Turner, 1974: **Burnie** | | | | | | |
| Dundas and Dial R. | $D_2$ | | $D_1$ | | | |
| Fossey Mt Trough | $D_2$ | | | | $D_1$ | |
| Baillie and Corbett, 1985: **Strahan** | | | | | | |
| Cambrian-Devonian | present (and a later crenulation) | | present (NNW) | | | |
| Baillie and Williams, 1975: **Strahan** | | | | | | |
| Bell Shale equivalent | $D_1$ (and $D_2$ WNW and NNW) | | | | | |
| Blissett, 1962: **Zeehan** | | | | | | |
| Cambrian-Devonian | present | | present | | present | present |
| Collins *et al.*, 1981: **Mackintosh** | | | | | | |
| | | | | | present | |

equivalent to Crotty Sandstone was reported by H. Bartlett (1954) in communications with Spry (1958), thus inferring a post-Silurian age of the tillite. Mapping by the author has identified granite-adamellite clasts in at least ten localities and these clasts are also reported by Spry (1958). The granite clasts are the most abundant after Oonah Formation clasts, and are tentatively correlated with the Late Devonian–Early Carboniferous granites of northwestern Tasmania, particularly the Heemskirk Granite (Spry, 1958). Older Cambrian granites are not thought areally abundant and close enough to be the likely source of these clasts. Consequently, the Zeehan Tillite is thought to be best constrained to be of Early Carboniferous to Middle Jurassic age (fig. 17).

Furthermore, Spry (1958) has correlated the Zeehan Tillite with the lithologically very similar Wynyard Tillite at the base of the Permo-Carboniferous sequences to the north. If such a correlation is correct, the Zeehan Tillite can be tightly constrained to be of Late Carboniferous (Gulline, 1967; Evans *in* Banks and Clarke, 1973; Riek 1976; Truswell, 1978) to earliest Early Permian (Pre-Sakmarian) age (Banks, 1962; Balme, 1964), based on palynological, entomological and plant fossil data in the Wynyard Tillite and overlying Quamby Group (fig. 17). Parts of the Wynyard Tillite could conceivably be older than Late Carboniferous. Basal tillite of the Permo-Carboniferous sequences to the south in the Strahan Quadrangle are of Late Carboniferous age by palynology (Truswell, 1978), and are correlated with the Zeehan Tillite (Baillie and Corbett, 1985).

Both the correlation of the Zeehan Tillite with the Wynyard Tillite and correlation of the granite clasts with provenance from Early Carboniferous granites are tentative. If both these correlations are refuted, an explanation for a consequent post-Silurian deposition of the Zeehan Tillite, on a peneplain in the absence of post-Silurian to Middle Devonian sequences common in northwest Tasmania, must be found.

### *Eureka Dolerite*

No isotopic data from this intrusion has been obtained. The Eureka dolerite is chemically and mineralogically similar to the Middle Jurassic dolerite sills in eastern and central Tasmania and is correlated with this episode of intrusion (Spry, 1958).

### *Age and deformational sequence of the Tabberabberan Orogeny*

The age of the Tabberabberan Orogeny is very tightly constrained biostratigraphically to be late Early Devonian to mid Middle Devonian (approximately 380–395 Ma, fig. 17) (Williams *et al.*, 1989). This is based on deformation pre-dating the late Middle Devonian Eugenana cave deposits (Balme, 1960; Burns, 1965) and post-dating the deformed Bell Shale of Early Devonian (Banks *in* Talent and Banks, 1967; Adams *et al.*, 1985).

Numerous fold trends, and associated axial planar cleavages, attributed to the Tabberabberan Orogeny have been identified from throughout northwest Tasmania (discussed earlier, Table 1). Of these, only $D_3$ (after Seymour, 1980), the West Coast Range–Valentines Peak trend (Williams, 1983), is tightly constrained by the evidence at Eugenana. This $D_3$, of N–S trend, gave rise to the penetrative cleavage in the Gordon Group limestone blocks contained within the undeformed Eugenana cave deposits. Thus any folding subsequent to $D_3$, for example $D_4$ of NW–SE trend, has no direct minimum age constraint at Eugenana.

Williams *et al.* (1989) infer that all deformation in the Eugenana region ceased prior to deposition of the cave sediments, as they are undisturbed. However $D_4$ folding is not recorded in the Eugenana region (Burns, 1965; Table 1). Consequently the NW-trending folding associated with the Tabberabberan Orogeny ($D_4$) has no minimum age constraint at Eugenana and could be younger than Middle Devonian. Elsewhere in northwest Tasmania the minimum age of $D_4$ folding is constrained by these folds being unconformably overlain by undeformed Tertiary basalts (Jennings *et al.*, 1959; Burns, 1963) and the absence of folding of Middle Jurassic dolerite sills. It is felt that the Wynyard Tillite and the more southerly Permo-Carboniferous sequences in the Zeehan and Strahan Quadrangles (Blisset and Gulline, 1962; Baillie *et al.*, 1977), do not offer a clearly defined minimum age for all folding, as bedding in these rock units is often steep (fig. 16) and folding cannot be discounted (see earlier discussion).

Northwest Tasmanian granites are considered to be undeformed, and deformations are thought to have ceased prior to their intrusion. Although no strong penetrative foliations have been reported in these granite bodies, there is indirect evidence of the Heemskirk and Pieman batholiths having been deformed. Brooks (1966*b*) reported bent chlorite and biotite cleavage traces, and cracked and undulose quartz and feldspar grains closely (3 m) associated with a fault in the Pieman Granite.

In the Heemskirk Granite, Brooks (1966*a*) presents a proportional correlation between progressively younger Rb-Sr K-feldspar ages and increasing triclinicity in the K-feldspars. These ages are significantly younger than the total-rock crystallisation age (fig. 17). Brooks equates the increase in triclinicity with deformation of the K-feldspars and consequently defines the maximum age of deformation as the youngest Rb-Sr K-feldspar age with highest triclinicity. Thus deformation of the K-feldspars occurred at some time subsequent to $285 \pm 5$ Ma (fig. 17). Brooks (1966*a*) equates this deformation with faulting in the Heemskirk Granite.

Post-$285 \pm 5$ Ma deformation is further supported by an apparent 296 Ma Rb-Sr chlorite age in the Heemskirk Granite (Brooks, 1966*a*). This chlorite is secondary, replacing biotite, and no correlation with deformational features has been presented. In addition, a Rb-Sr total-rock age from a sample closely (3 m) associated with a fault in the Pieman Granite, is significantly younger than the emplacement age and with large errors (fig. 17). Brooks (1966*a*) interprets this as being due to radiogenic Sr-loss during deformation, and correlates this with the mineral deformation described above.

In conclusion it is felt that the Heemskirk and Pieman granites, at least, have partitioned some strain, apparently by faulting, at some time younger than approximately 285 Ma.

### *Age of deformation of the Zeehan Tillite*

The maximum age limit of deformation of the Zeehan Tillite is post-Carboniferous (approximately post-285 Ma), if correlation with the Wynyard Tillite is accepted. Such a maximum deformation age is equivalent to that defined by the Rb-Sr chlorite and K-feldspar ages discussed above (285 ± 5 Ma and 296 Ma). If correlation with the Wynyard Tillite is not accepted, the maximum age of deformation may be as old as Early Carboniferous (approximately 332 Ma) as constrained by 332–367 Ma old granite clasts in the tillite.

There is no direct minimum age constraint for deformation of the Zeehan Tillite. The only potential minimum age constraint is the Middle Jurassic, if it can be proved that the Eureka dolerite is not deformed by NE–SW shortening. The synclinal basin form of this dolerite body is thought to be the intrusive shape, that is a cone sheet (Spry, 1958). An alternative argument is that the synclinal form, the long axis of which trends 135° (figs 1 and 18), may be due to post-intrusion folding by NE–SW directed shortening. If such an interpretation can be substantiated, the minimum age of deformation of the Zeehan Tillite may be younger than Middle Jurassic. However such an interpretation is inconsistent with the consistently vertical orientation of the joints (fig. 18), and the absence of joints orthogonal to the margins of this dolerite (Spry, 1958). Consequently the form of the cone sheet is most plausibly due to pre-existing anisotropy (fold ?) of the country rocks (Spry, 1958).

## IMPLICATIONS FOR THE TABBERABBERAN OROGENY

A post-Early Carboniferous deformational episode with NE–SW shortening has been recognised in the Zeehan Tillite. Deformation may be as young as post-Carboniferous (post-285 Ma) if correlation of the Zeehan Tillite with the Wynyard Tillite is accepted. Such a deformational age is indirectly supported by isotopic data from the Heemskirk Granite. Deformation of the Zeehan Tillite has been correlated with NW-trending folding in older rock units, such as the Late Proterozoic Oonah Formation, and in the Eocambrian to Devonian rocks to the south and east (fig. 1).

All post-Silurian folding and penetrative cleavage-forming events in northwest Tasmania have previously been grouped as the Tabberabberan Orogeny (approximately 380–395 Ma). The age of both the deposition and deformation of the Zeehan Tillite is incompatible with the NW-trending fold event ($D_4$, after Seymour, 1980) being of Tabberabberan age (Browne, 1950; Williams *et al.*, 1989). There are three interpretations of the Zeehan Tillite deformation reported.

(1) The Tabberabberan Orogeny occurred over a more protracted period, to younger ages, than previously thought.

(2) Post-Early Carboniferous deformation of the tillite is a later deformational event unrelated both temporally and tectonically to the Tabberabberan Orogeny.

(3) NW-trending fold structures may have formed in the Tabberabberan Orogeny prior to deposition of the Zeehan Tillite, and these structures may have been tightened further during post-Early Carboniferous shortening.

As previously discussed the trend of structuring in the Zeehan Tillite (NW–SE) is parallel to the last widely spread folding episode of the Tabberabberan Orogeny (Table 1) (Williams, 1978; Seymour, 1980, 1989; Williams and Turner, 1974; Brown, 1986). This trend has been labelled $D_4$ by Seymour (1980) and called the Deloraine–Railton and Zeehan–Gormaston trends (Williams, 1978). Stereo projections of bedding and cleavages defining the NW-trending folding from throughout northwest Tasmania are presented in Figure 15. This fold trend has been mapped throughout a large part of northwest Tasmania (fig. 1). Folding subsequent to the NW–SE trend is only suspected in a few regions (Table 1), although timing relationships are apparently not very well constrained in these areas (Burns, 1965; Baillie and Corbett, 1985; Brown, 1986; see Table 1).

NW-trending folding has been shown by Williams and Turner (1974) to have NE over SW directed transport; this is between orthogonal and directly opposing the earlier W over E directed transport associated with N–S folding ($D_3$, after Seymour, 1980). This lends support to the $D_4$ post-Carboniferous deformation involving tillite having occurred under a different stress field to the earlier episodes of the Tabberabberan Orogeny. This favours interpretation 2, and is inconsistent with a continuous and protracted Tabberabberan Orogeny from Middle Devonian to Early Permian times (interpretation 1).

No direct observations or constraints are available to distinguish between interpretations 2 and 3. Thus in conclusion, it can only be proposed that the NE–SW shortening in northwest Tasmania occurred either entirely, or by tightening of earlier-formed structures, at some stage subsequent to the Late Carboniferous. The NE–SW shortening and NE over SW transport is not only temporally distinct but also tectonically distinct from the earlier W over E transport and N-, E- and NE-trending fold events of the Tabberabberan Orogeny.

Tentative evidence for favouring interpretation 3 in preference to interpretation 2 is that folding in both the Zeehan Tillite and Permo-Carboniferous sequences to the south of the Zeehan Tillite (fig. 1) is not as tight as in older rock units underlying these sequences (fig. 6, 15, 16). Cleavage is only developed in the Zeehan Tillite, and is not reported from any other Permo-Carboniferous sequence in Tasmania. However such an interpretation is not entirely consistent with the intensity of the cleavage in the Zeehan Tillite and the absence of post-$S_3$ reactivation features in the underlying Oonah Formation.

It is thought that the findings of this report warrant tighter constraints on the definition of the Tabberabberan Orogeny, particularly from a structural point of view, as the present biostratigraphic definition of the Tabberabberan Orogeny apparently excludes the NW-trending ($D_4$) folding episode. For example, does the Tabberabberan Orogeny constitute all post-Silurian folding events, or is it constrained solely to folding in the biostratigraphically-defined period of late Early Devonian to mid Middle Devonian? If the latter, generally accepted definition is rigorously applied, the post-Carboniferous folding event documented in this report must constitute a new deformation separate from the Tabberabberan Orogeny.

## CONCLUSIONS

The Zeehan Tillite unconformably overlies the Late Proterozoic Oonah Formation and is constrained by Late Devonian–Early Carboniferous granite clasts to have a maximum deposition age of Early Carboniferous. A tentative correlation with the Wynyard Tillite (Spry, 1958) may imply a depositional age of Late Carboniferous. This tillite has a strong penetrative and pervasive NW-trending vertical cleavage. A less pervasive 166°-trending cleavage, forming a "diamond" cleavage with the dominant one, is recognised. The dominant cleavage is very similar in orientation to the last-formed crenulation cleavage and folding in the underlying Oonah Formation, the Eocambrian Success Creek Formation (Brown, 1986), and in Cambrian through to Devonian rocks (Jennings, 1979; Seymour, 1980; Williams and Turner, 1974; Brown, 1986) throughout northwest Tasmania. NW-trending folding has been previously grouped with the Tabberabberan Orogeny (Jennings, 1979; Seymour, 1980; Williams and Turner, 1974; Brown, 1986; etc.). However, this deformation of a presumed Late Carboniferous tillite is incompatible with the presently defined biostratigraphic age of the Tabberabberan Orogeny.

It is proposed here that this last-formed fold event in northwest Tasmania is of post-Carboniferous age, and is thus temporally distinct from the Tabberabberan Orogeny as presently defined. This late-stage folding involved tectonic transport between orthogonal and directly opposed to the earlier N-trending fold event of the Tabberabberan Orogeny (Williams and Turner, 1974). Consequently the late-stage NW-trending folding may also be tectonically unrelated to the Tabberabberan Orogeny.

It appears that NW–SE folding ($D_4$) is largely restricted to the more western portion of the region discussed (fig. 1). This is represented by the major fold trends in rock units of Eocambrian to Devonian age, folding of the Zeehan Tillite (fig. 1), and buckling of Permo-Carboniferous sequences south of the Zeehan Tillite (fig. 16). In contrast, Permo-Carboniferous sequences to the north and to the east appear to be essentially flat lying and undeformed apart from faulting (also recorded in Permian at Pt Hibbs; D. B. Seymour, pers. comm.) and deformation due to glacier loading (Williams and Lennox *in* Seymour, 1989).

## FURTHER WORK

Further work is needed to clearly define what constitutes the Tabberabberan Orogeny from a structural point of view. The major N–S trend, and hence the earlier NE–SW and E–W trends, are very well constrained in time by the Eugenana cave deposits. However, the NW–SE trend is not reported in this region, thus this trend remains unconstrained. As a result, further work is needed in this "type section" locality in an attempt to find expressions of and constrain the timing of NE–SW shortening.

Early Carboniferous granites of northwest Tasmania potentially contain microstructural features resulting from NE–SW shortening. The Eureka dolerite is worthy of further study to define if this body has been deformed or not, thus potentially offering a minimum age of deformation of the Zeehan Tillite.

Obviously the age of the Zeehan Tillite matrix needs to be more accurately constrained, without correlation to the Wynyard Tillite. This can involve two avenues; a palynological study, and a detailed petrological study of the granite clasts in the tillite to determine their provenance. Deformation of other Permo-Carboniferous sequences in west Tasmania is worthy of further investigation.

## ACKNOWLEDGMENTS

Discussions with Clive Calver and Dave Seymour have contributed greatly to this report.

## REFERENCES

ADAMS, C. J.; BLACK, L. P.; CORBETT, K. D.; GREEN, G. R. 1985. Reconnaissance isotopic studies bearing on the tectonothermal history of early Palaeozoic and late Proterozoic sequences in western Tasmania. *Aust. J. Earth Sci.* 32:7–36.

BAILLIE, P. W.; CORBETT, K. D.; COX, S. F.; *et al.*. 1977. Geological atlas 1:50 000 series. Sheet 57 (7913N). Strahan. *Department of Mines, Tasmania.*

BAILLIE, P. W.; CORBETT, K. D. 1985. Geological atlas 1:50 000 series. Sheet 57 (7913N). Strahan. *Explan. Rep. geol. Surv. Tasm.*

BAILLIE, P. W.; WILLIAMS, P. R. 1975. Sedimentary and structural features of the Bell Shale correlate (Early Devonian), Strahan Quadrangle, western Tasmania. *Pap. Proc. R. Soc. Tasm.* 109:1–15.

BAILLIE, P. W.; WILLIAMS, P. R.; SEYMOUR, D. B.; LENNOX, P. G.; GREEN, G. R. 1986. Geological atlas 1:50 000 series. Sheet 36 (8015S). St Valentines. *Department of Mines, Tasmania.*

BALME, B. E. 1960. Palynology of a sediment from Halletts Quarry, Melrose, Tasmania. *Palynol. Rep. Dep. Geol. Univ. West. Aust.* 62:1–14.

BALME, B. E. 1964. The palynological record of Australian pre-Tertiary floras, in: CRANWELL, L. M. (ed.). *Ancient Pacific floras, the pollen story*: 49–80. University of Hawaii Press : Honolulu.

BANKS, M. R. 1956. The Middle and Upper Cambrian series (Dundas Group and its correlates) in Tasmania, *in: El Sistema Cambrico su Paleogeografia y el Problema de su Base.* 2:165–212. 20th International Geological Congress, Mexico.

BANKS, M. R. 1962. Permian, *in:* SPRY, A.; BANKS, M. R. (eds) The Geology of Tasmania. *J. geol. Soc. Aust.* 9(2):189-215.

BANKS, M. R.; CLARKE, M. J. 1973. Tasmania: Parmeener Supergroup, *in: Field Trip 1, Upper Carboniferous to Triassic rocks in southeastern Australia.* 23–46. Third International Gondwana Symposium, Canberra, Australia.

C/120


BLISSETT, A. H. 1962. One mile geological map series. K/55-5-50. Zeehan. *Explan. Rep. geol. Surv. Tasm.*

BLISSETT, A. H.; GULLINE, A. B. 1962. Geological atlas one mile series. Zone 7 sheet 50 (7914S). Zeehan. Department of Mines, Tasmania.

BRADLEY, J. 1954. The geology of the West Coast Range of Tasmania. Part 1: Stratigraphy and metasomatism. *Pap. Proc. R. Soc. Tasm.* 88:193–243.

BROOKS, C. 1966*a*. The effect of mineral age discordancies on total-rock Rb-Sr isochrons of the Heemskirk Granite, western Tasmania. *J. Geophys. Research.* 71:5447–5458.

BROOKS, C. 1966*b*. The rubidium-strontium ages of some Tasmanian igneous rocks. *J. Geol. Soc. Aust.* 13:457–469.

BROOKS, C.; COMPSTON, W. 1965. The age and initial $Sr^{87}/Sr^{86}$ of the Heemskirk Granite, western Tasmania. *J. Geophys. Res.* 70:6249–6262.

BROWN, A. V. 1986. Geology of the Dundas–Mt Lindsay–Mt Youngbuck region. *Bull. geol. Surv. Tasm.* 62.

BROWNE, W. R. 1950. Metallogenic epochs and ore regions in the Commonwealth of Australia. *J. Proc. R. Soc. N.S.W.* 83:96–113.

BURNS, K. L. 1963. Geological atlas one mile series. Zone 7 sheet 29. Devonport. *Department of Mines, Tasmania.*

BURNS, K. L. 1965. One mile geological map series. K/55-6-29. Devonport. *Explan. Rep. geol. Surv Tasm.*

COLLINS, P. L. F.; GULLINE, A. B.; WILLIAMS, E. 1981. Geological atlas one mile series. Zone 7 sheet 44 (8014N). Mackintosh. *Explan. Rep. geol. Surv. Tasm.*

CORBETT, K. D.; BROWN, A. V. 1975. Geological atlas 1:250 000 series. SK-55/5. Queenstown. *Department of Mines, Tasmania.*

CORBETT, K. D.; BROWN, A. V. 1976. Geological atlas 1:250 000 series. SK-55/5. Queenstown. *Explan. Rep. geol. Surv Tasm.*

GEE, R. D. 1977. Geological atlas 1 mile series. Sheet 28 (8015N). Burnie. *Explan. Rep. geol. Survey Tasm.*

GEE, R. D.; GULLINE, A. B.; BRAVO, A. P. 1967. Geological atlas one mile series. Zone 7 sheet 28 (8015N). Burnie. *Department of Mines, Tasmania.*

GULLINE, A. B. 1967. The first proved Carboniferous deposits in Tasmania. *Aust. J. Sci.* 29:332–333.

JAGO, J. B. 1972. Geology of the Maydena Range. *Pap. Proc. R. Soc. Tasm.* 106:45-57.

JENNINGS, I. B. 1963. One mile geological map series. K/55-6-45. Middlesex. *Explan. Rep. geol. Surv. Tasm.*

JENNINGS, I. B. 1979. Geological atlas 1 mile series. Sheet 37 (8115S). Sheffield. *Explan. Rep. geol. Surv. Tasm.*

JENNINGS, I. B.; BURNS, K. L. 1958. Geological atlas one mile series. Zone 7 sheet 45. Middlesex. *Department of Mines, Tasmania.*

JENNINGS, I. B.; BURNS, K. L.; MAYNE, S. J.; ROBINSON, R. G. 1959. Geological atlas one mile series. Zone 7 sheet 37. Sheffield. *Department of Mines, Tasmania.*

MCDOUGALL, I.; LEGGO, P. J. 1965. Isotopic age determinations on granitic rocks from Tasmania. *J. Geol. Soc. Aust.* 12:295–332.

MOORE, T. B. 1896. Notes on further proof of glaciation at low levels. *Pap. Proc. R. Soc. Tasm.* 1894-1895:73–77.

RIEK, E. F. 1976. *Neosecoptera*, a new insect suborder based on specimen discovered in the Late Carboniferous of Tasmania. *Alcheringa* 1:227–234.

RUNNEGAR, B. N. 1969. The Permian faunal succession in Eastern Australia. *Spec. Publs. geol. Soc. Aust.* 2:73–98.

SCHMIDT, P. W.; MCDOUGALL, I. 1977. Palaeomagnetic and potassium-argon dating studies of the Tasmanian dolerites. *J. geol. Soc. Aust.* 24:321–328.

SEYMOUR, D. B. 1980. *The Tabberabberan Orogeny in northwest Tasmania.* Ph.D. Thesis, University of Tasmania : Hobart.

SEYMOUR, D. B. 1989. Geological atlas 1:50 000 series. Sheet 36 (8015S). St Valentines. *Explan. Rep. geol. Surv. Tasm.*

SPRY, A. 1958. Some observations of the Jurassic dolerite of the Eureka cone sheet near Zeehan. Tasmania. *in: Dolerite: a Symposium.* 93–129. Department of Geology, University of Tasmania : Hobart.

STEIGER, R. H.; JAEGER, E. 1977. Subcommission on geochronology; convention on use of decay constants in geo- and cosmo- chronology. *Earth Planet. Sci. Lett.* 36:359–362.

TALENT, J. A.; BANKS, M. R. 1967. Devonian of Victoria and Tasmania, *in:* OSWALD, D. H. (ed.). *International Symposium on the Devonian System.* 2:147–163. Alberta Soc. Pet. Geol. : Calgary.

TRUSWELL, E. M. 1978. Palynology of the Permo-Carboniferous in Tasmania: an interim report. *Bull. geol. Surv. Tasm.* 56.

TWELVETREES, W. H.; WARD, L. K. 1910. The ore-bodies of the Zeehan field. *Bull. geol. Surv. Tasm.* 8.

WILLIAMS, E. 1976. Structural map of Pre-Carboniferous rocks of Tasmania. *Department of Mines, Tasmania.*

WILLIAMS, E. 1978. Tasman Fold Belt System in Tasmania. *Tectonophysics* 48:159–205.

WILLIAMS, E. 1983. The areal distribution of rock-units during Early Palaeozoic times in Tasmania. *Unpubl. Rep. Dep. Mines Tasm.* 1983/61.

WILLIAMS, E.; TURNER, N. J. 1973. Geological atlas 1:250 000 series. Sheet SK55-3. Burnie. *Depaartment of Mines, Tasmania.*

WILLIAMS, E.; TURNER, N. J. 1974. Geological atlas 1:250 000 series. Sheet SK-55/3. Burnie. *Explan. Rep. geol. Surv. Tasm.*

WILLIAMS, E.; MCCLENAGHAN, M. P.; COLLINS, P. L. F. 1989. Mid-Palaeozoic deformation, granitoids and ore deposits, *in:* BURRETT, C. F.; MARTIN, E. L. (eds). Geology and mineral resources of Tasmania. *Spec. Publs. geol. Soc. Aust.* 15:238–292.


[1 March 1991]

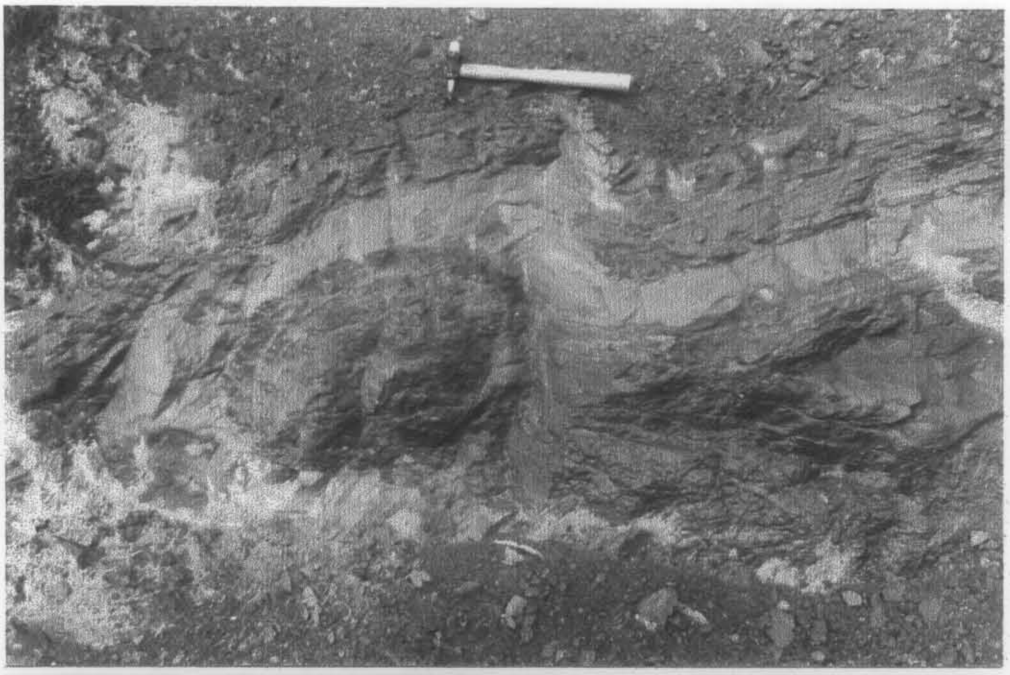


**Figure 3.**

Soft sediment slump feature defined by silty sandstone bed in Zeehan Tillite.

**Figure 4.**

Angular unconformity to the east of Montana Western Mine. Sandstone bedding in the overlying Zeehan Tillite is parallel to the angular unconformity with the Oonah Formation. Both bedding in the tillite and the unconformity surface are inclined 50° to the SW.

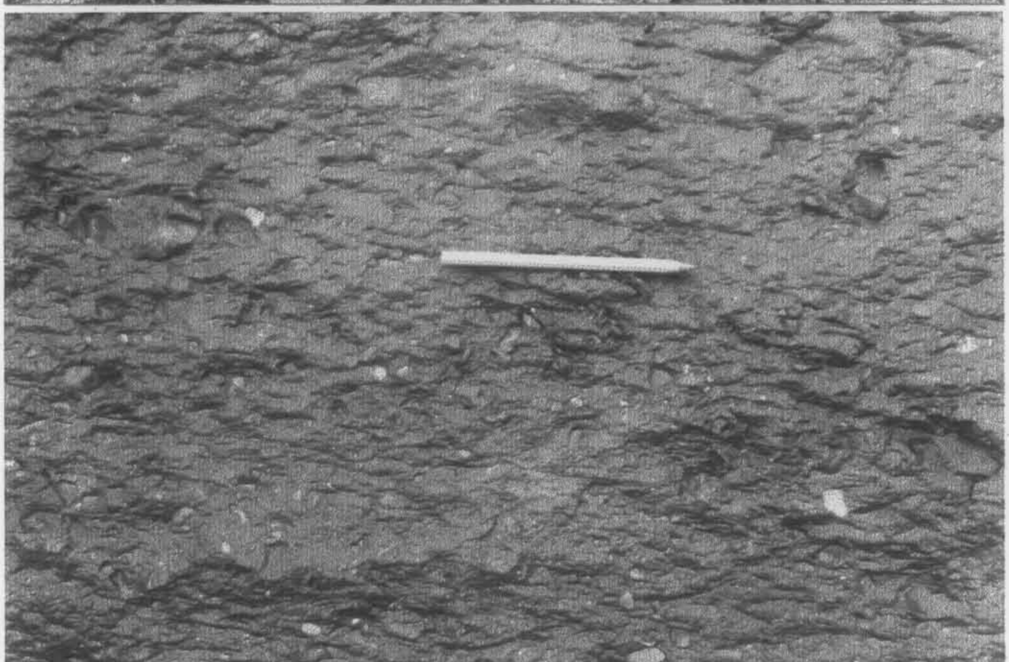


**Figure 5.**

Strong penetrative vertical cleavage (approximately parallel to pen) in Zeehan Tillite.

Cleavage accentuated by recent weathering.



5 cm

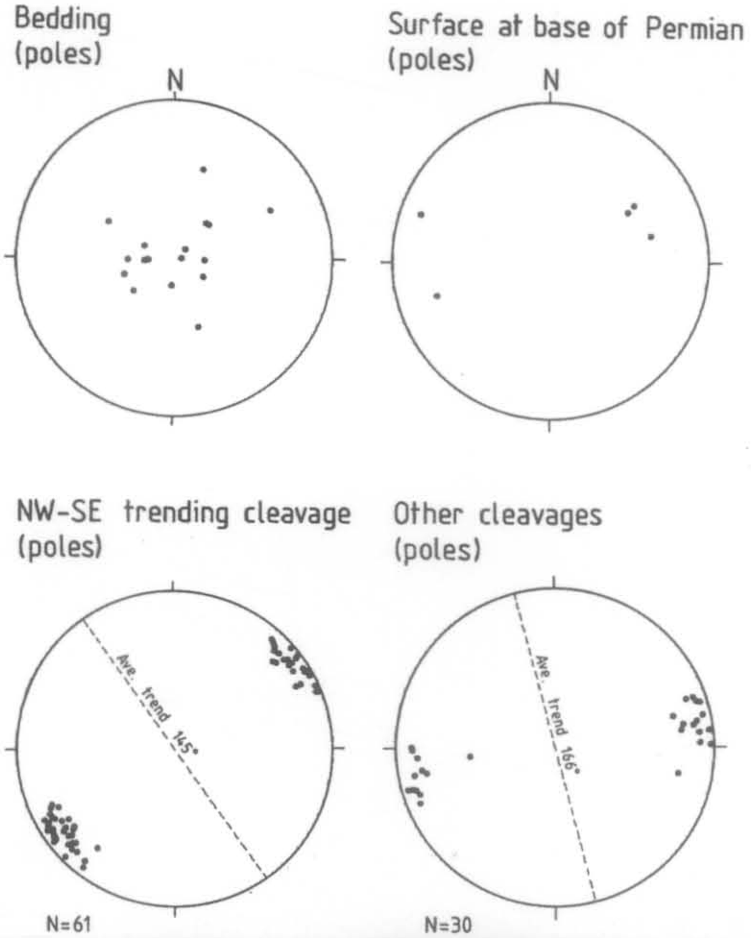



**Figure 6.**

Lower hemisphere, equal area stereo projections of orientation data in the Zeehan Tillite. Bedding in tillite is from where beds are of constant orientation over a sizable section, thus avoiding bedding influenced by soft sediment slumping.

**Figure 7.**

Close up of finely-spaced (≤1 mm) cleavage, vertical.

5 cm

**Figure 8.**

Vertical cleavage in the siltstone matrix of the Zeehan Tillite symmetrically enclosing a round clast.

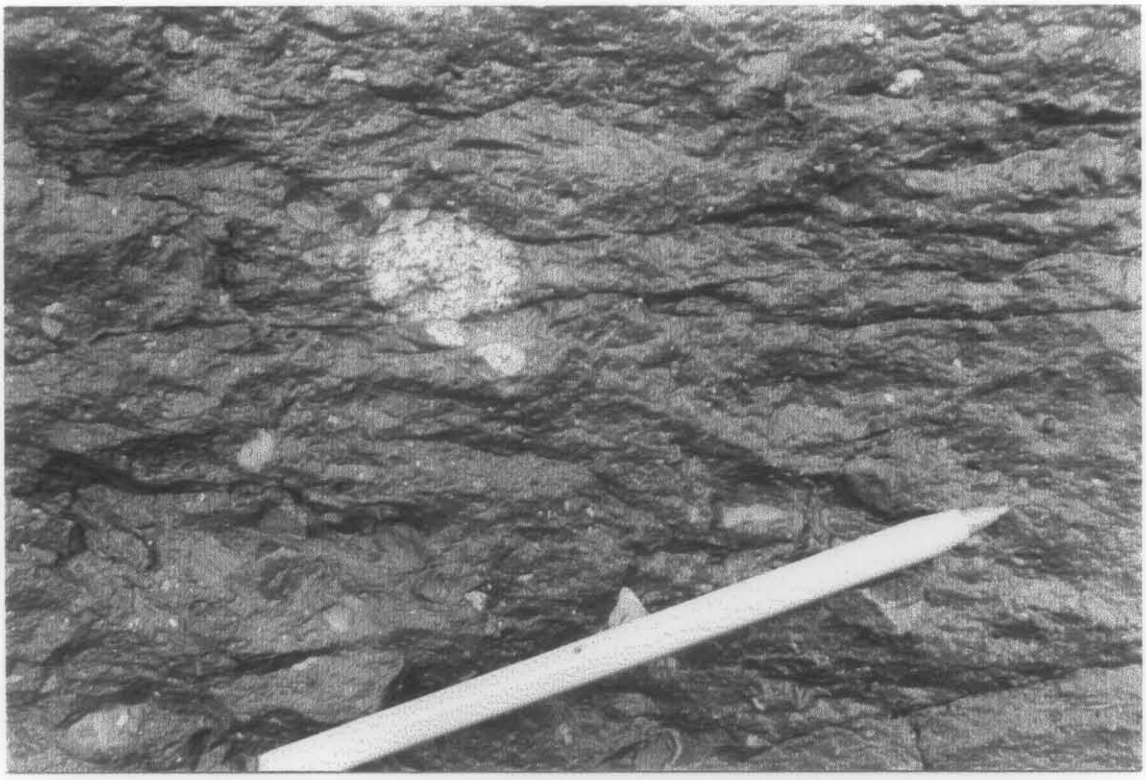


**Figure 9.**

Granite clast within the Zeehan Tillite. Cleavage is developed through this clast with no refraction with respect to cleavage in the siltstone matrix.



5 cm

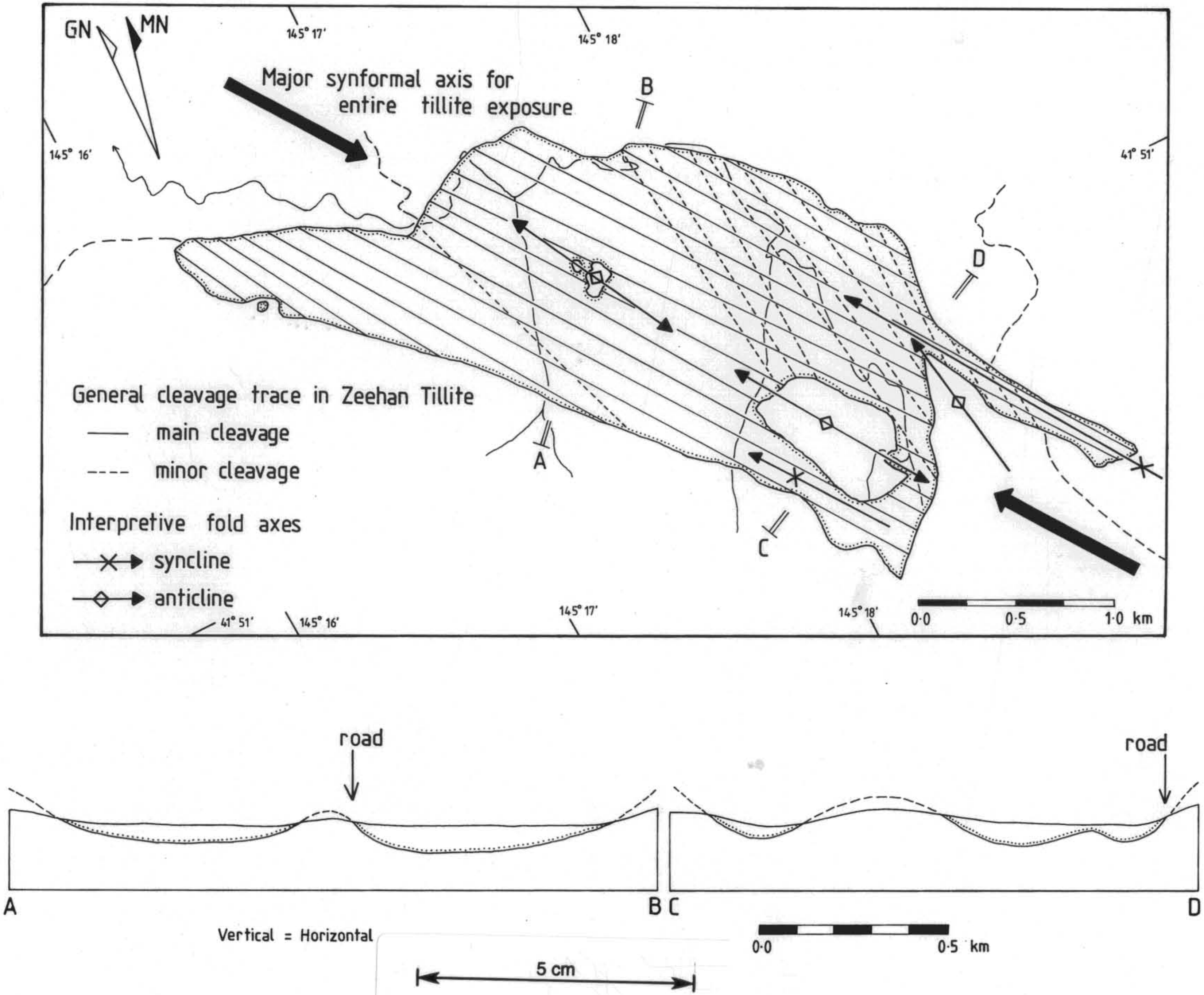
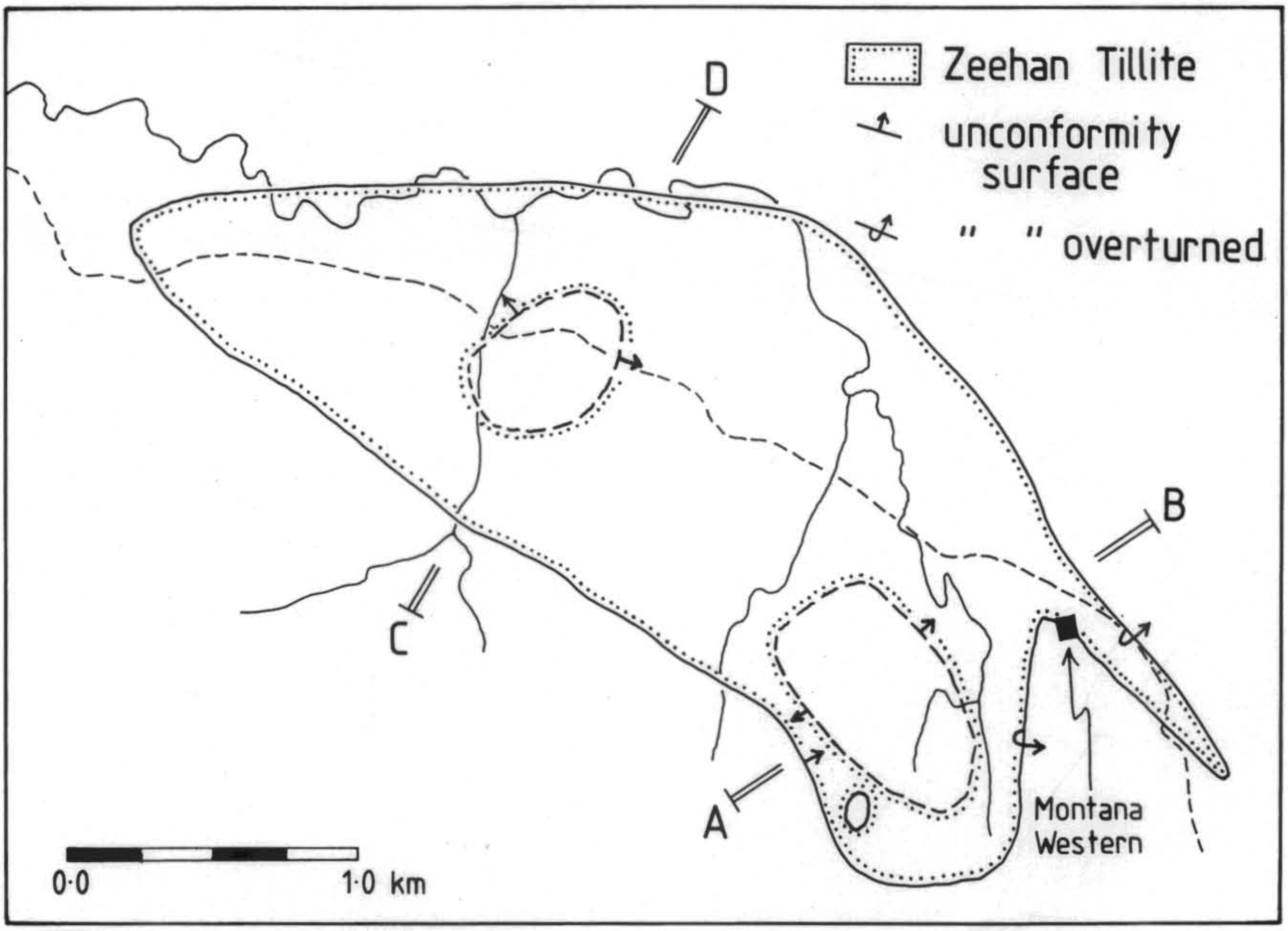



**Figure 10.**

Interpretive map and cross-section of folding of the angular unconformity and beds in the Zeehan Tillite. Extended cleavage traces from Figure 2 are presented. Note difference in interpretation to Figure 11 of the eastern margin of tillite exposure.



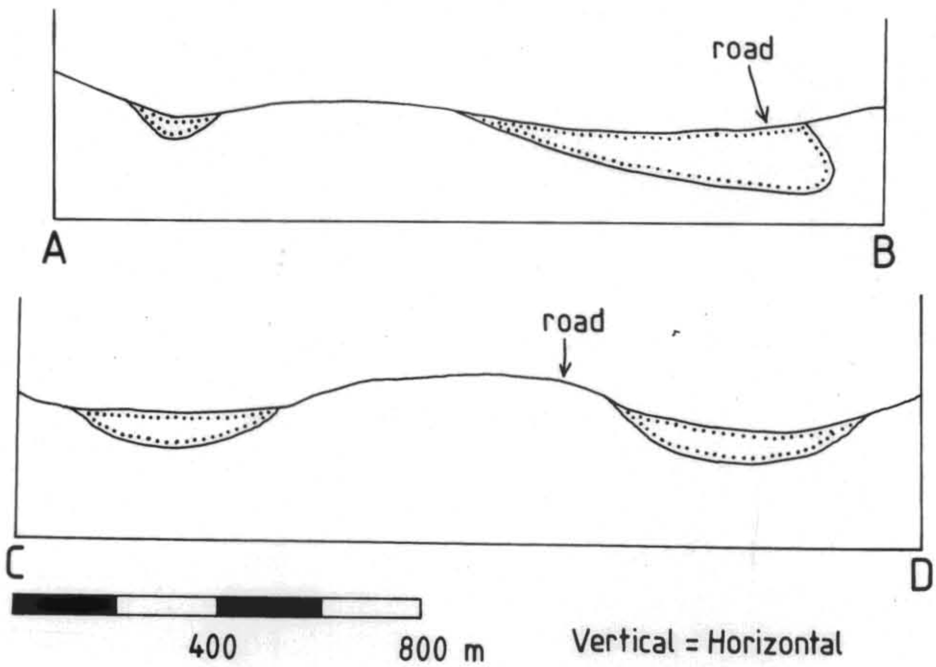




**Figure 11.**

Cross-section through the Zeehan Tillite as presented by Spry (1958).

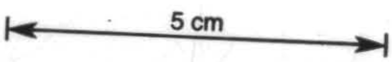


**Figure 12.**

Zone of *en echelon* quartz veins in siltstone matrix of the Zeehan Tillite.

**Figure 13.**

Oonah Formation shale, from immediately north of the Zeehan Tillite, which has $S_3$ crenulation cleavage well developed (vertical). Parting surface is bedding. $S_1$ cleavage is sub-parallel to bedding. $S_3$ crenulation cleavage is the last-formed cleavage recognised in the Oonah Formation.



5 cm

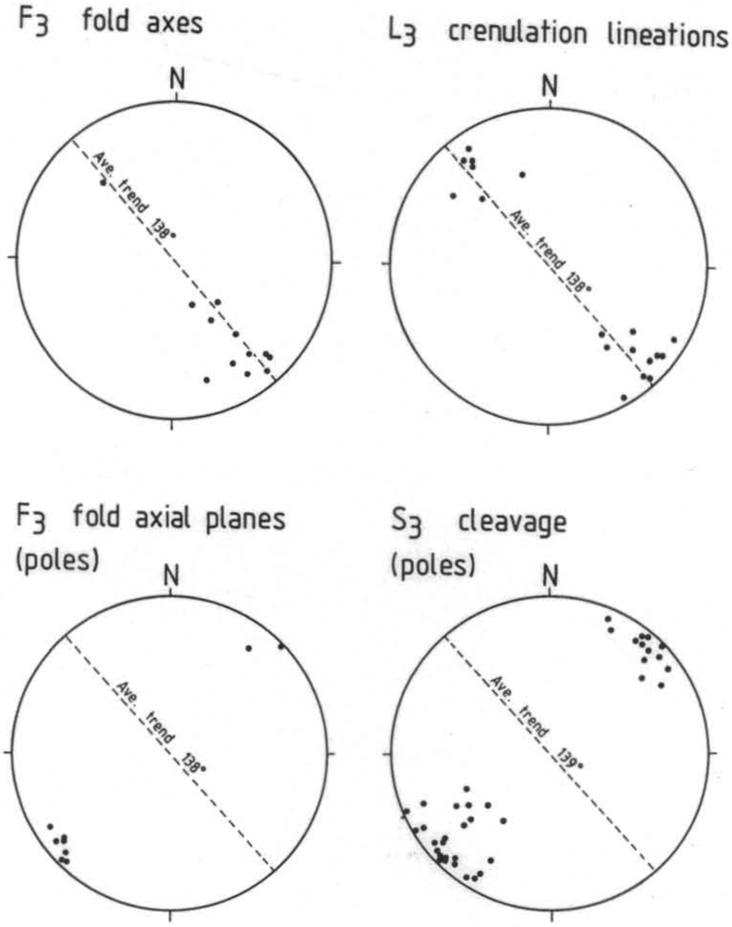



**Figure 14.**

Lower hemisphere, equal area stereo projections of $D_3$ orientation data from the Oonah formation in the region immediately north of the Zeehan Tillite.

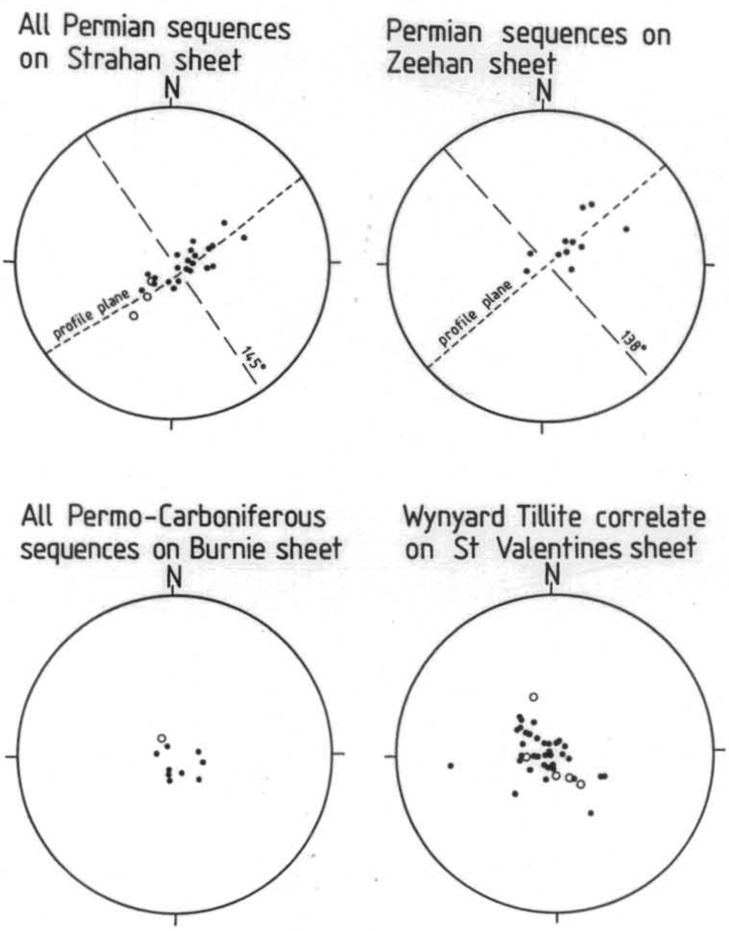



**Figure 16.**

Lower hemisphere, equal area stereo projections of bedding in Permo-Carboniferous sequences from western Tasmania. The region and stratigraphic units the data were derived from and the published map sources of the data are as labelled. All readings are plotted as poles. Open circles are readings within approximately 200 m of mapped faults.

5 cm

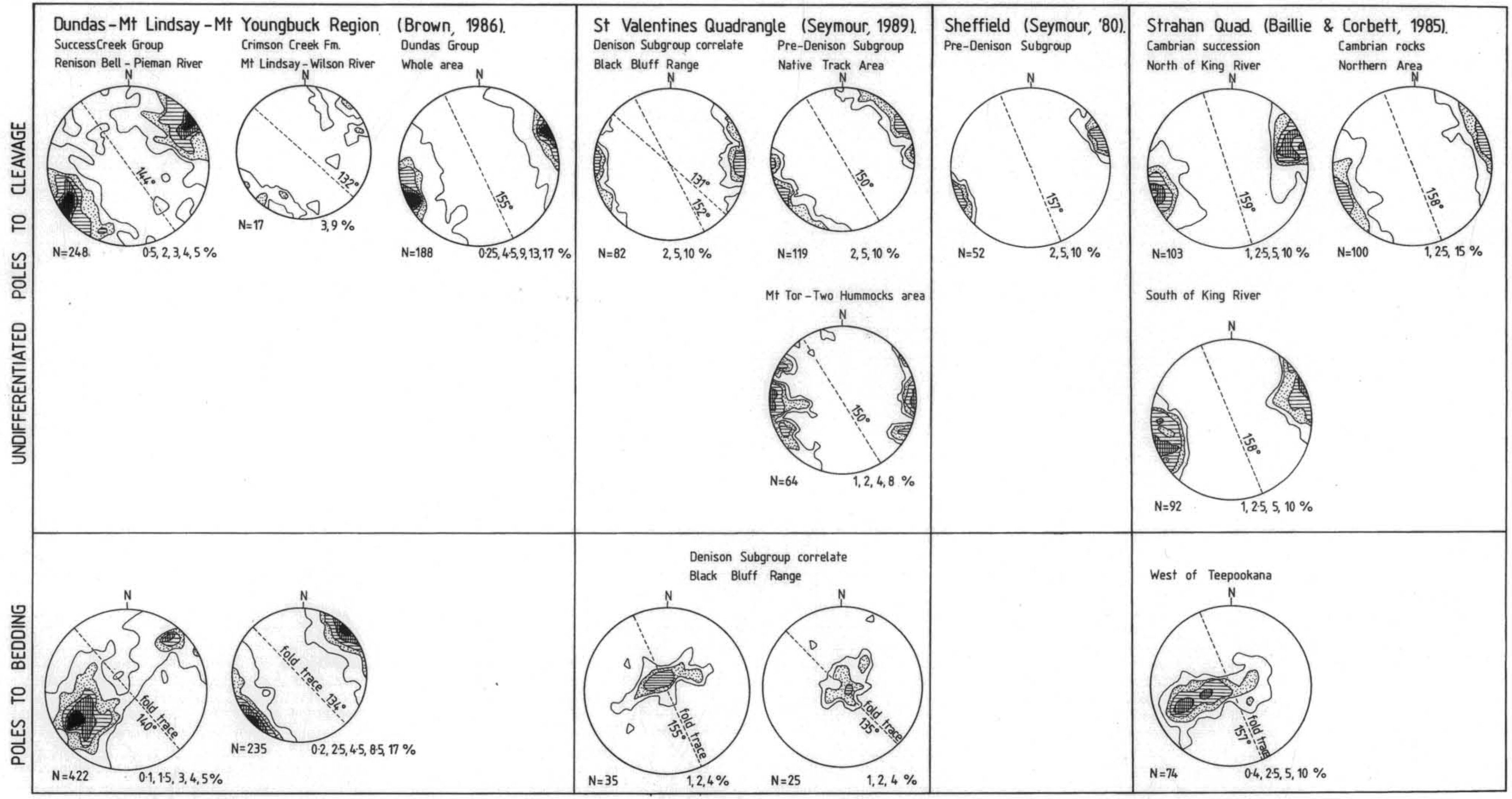



**Figure 15.**

Lower hemisphere, equal area stereo projections of bedding and cleavage data that define the orientation of the late-stage NW-trending folding (D4, Table 1) previously associated with the Tabberabberan Orogeny. The region and rock unit that data were derived from, and the published source of this data, are as labelled.

5 cm



18/20

19/20

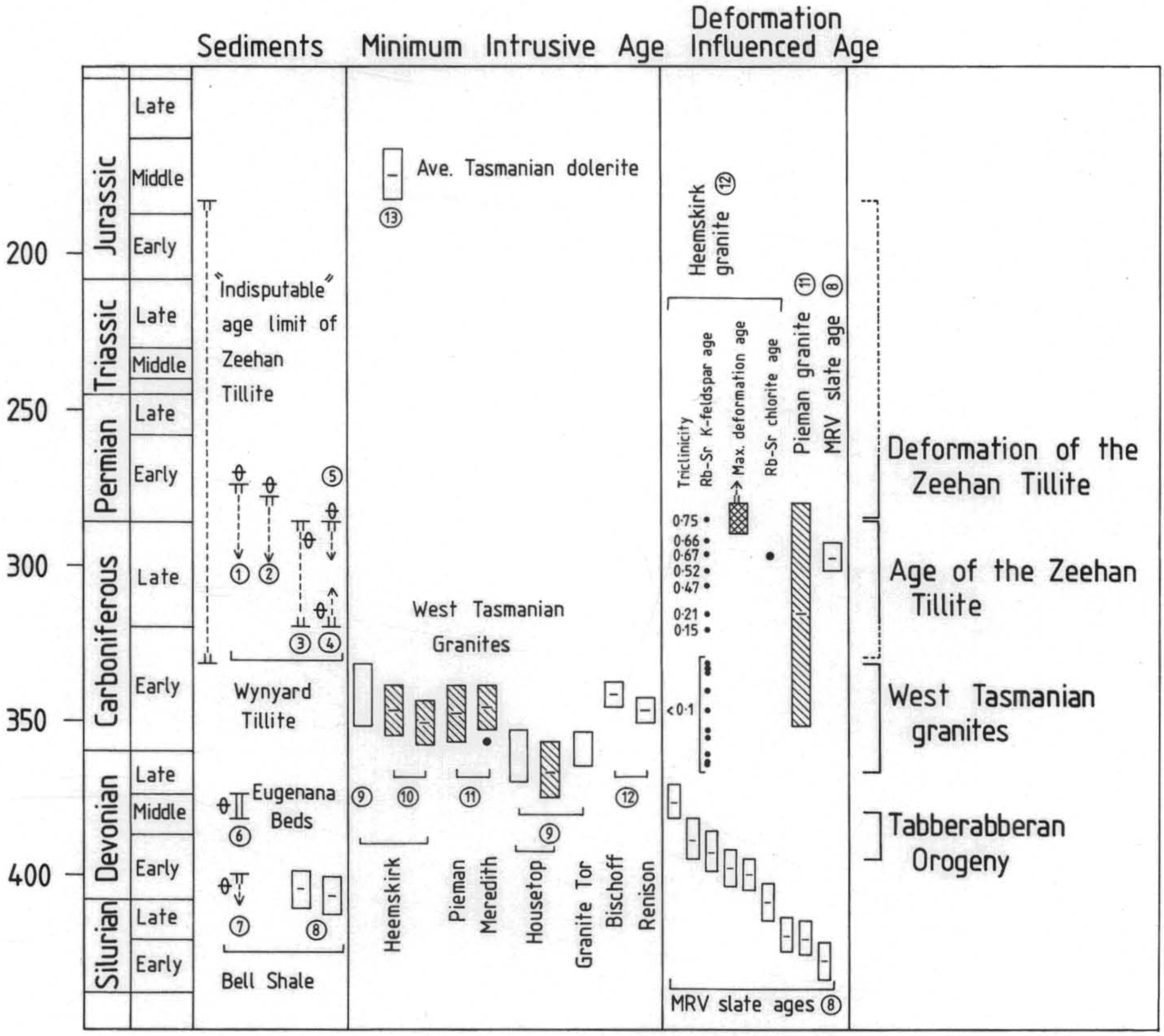



**Figure 17.**

Summary of available published biostratigraphic and isotopic minimum age constraints for rock units and deformational events in northwest Tasmania. Only data considered relevant to the discussion in the text are included. Time scale after Geological Society of America (1983) and isotopic ages recalculated as discussed in introduction. Source of data is as listed below.

(1) Banks (1962)
(2) Balme (1964)
(3) Evans *in* Banks and Clarke (1973); Truswell (1978); and Gulline (1967)
(4) Riek (1976)
(5) Truswell (1978)
(6) Balme (1960); Burns (1965)
(7) Banks *in* Talent and Banks (1967)
(8) Adams *et al.* (1985)
(9) McDougall and Leggo (1965)
(10) Brooks and Compston (1965)
(11) Brooks (1966*b*)
(12) Brooks (1966*a*); Rb-Sr K-feldspar ages have not been recalculated for updated decay constants
(13) Schmidt and McDougall (1977).

5 cm

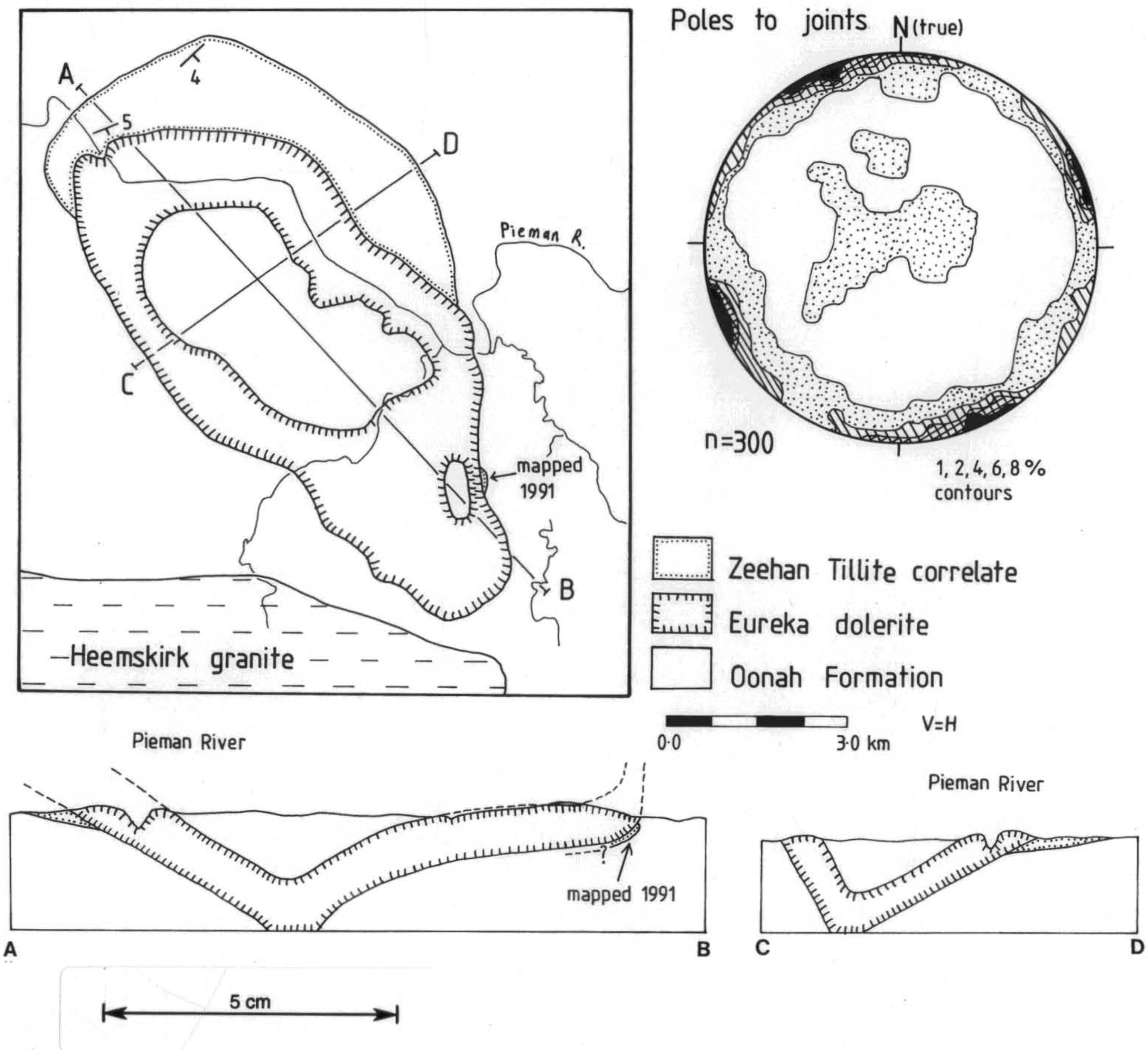



**Figure 18.**

Cross-section of the Eureka cone sheet after Spry (1958). The lower hemisphere projection of poles to joints in this dolerite body is also after Spry (1958). Note additional tillite outcrop mapped in 1991 on the southeast margin of the dolerite. This infers that tillite underlies a large part of the cone sheet. Such an interpretation presents a problem in explaining the Oonah Formation overlying both the tillite and dolerite. Did the dolerite intrude along a folded thrust plane?, or is the cone sheet antiformal in shape?