Multiple Folding of the Ordovician Sequence, Tambo River, eastern Victoria

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Ordovician quartz-rich clastics of the Tambo River region in the Tabberabbera Belt of eastern Victoria show the effects of four folding episodes. A strong to weak bedding-parallel slaty cleavage is developed throughout the region and predates the earliest folds so far identified. F_1 folds are tight to close with steep easterly trending axial surfaces and large amplitude-to-wavelength ratios. The F_1 folding is thick-skinned and is responsible for major crustal thickening in the area. F_2 folding is only locally developed and is associated with a pervasive stripy cleavage in sandstones. F_3 folds are widespread upright northerly-trending structures with close to open interlimb angles. Superimposition of F_3 on F_1 has caused bending of F_1 fold trends and formed an eye-type interference fold pattern in one instance. F_4 folds consist of warps and kink-like folds.

The east-west F_1 folds extend into the Omeo Metamorphic Complex and predate the Late Silurian volcanic and sedimentary sequence near Benambra. F_3 folds have been traced westwards to Tabberabbera where they are of the Middle Devonian age and are related to east-west compression.

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INTRODUCTION

The Palaeozoic tectonic history of the Lachlan Fold Belt in eastern Victoria is characterized by several intermittent compressional events (VandenBerg and Wilkinson, 1982). The styles and orientations of structures produced by these deformations are known only from some restricted areas (e.g. Beavis, 1967; Fagan, 1979; Wilson *et al.*, 1982). The aim of this paper is to describe the structure of the Ordovician rocks in the Tambo River region of eastern Victoria (Fig. 1) and to relate the two main deformations to the Early-Middle Silurian Benambran and Middle Devonian Tabberabberan deformations respectively.

REGIONAL SETTING

The Ordovician sequence of the Tambo River region lies partly in the southern Omeo Metamorphic Complex and mainly in a belt of very low-grade metamorphosed rocks called the Tabberabbera Sub-zone by VandenBerg (1978) and the Tabberabbera Belt by Fergusson (1985). The eastern boundary of the Tabberabbera Belt is the Kiewa Fault which has a steeply dipping mylonite zone up to 2km in width (Scott, 1985). East of the Kiewa Fault is the Omeo Metamorphic Complex which consists of lower greenschist to upper amphibolite facies metamorphics derived from Ordovician quartzose clastics and intruded by S- and I-type 'granitoids' (Fagan, 1979).

Fagan (1979) has shown that major folds in the metamorphics are upright and easterly trending. This deformation extends throughout the Tabberabbera Belt and is the major folding in the Tambo River region (Fergusson, 1985). North and east of Benambra the Late Silurian volcanic and sedimentary sequence postdates the major metamorphism and deformation in the Omeo Metamorphic Complex (Fig. 1; Bolger, 1982; Bolger *et al.*, 1983). The Silurian sequence was strongly deformed prior to the deposition of the unconformably-overlying Lower Devonian Snowy River Volcanics (VandenBerg and Wilkinson, 1982).

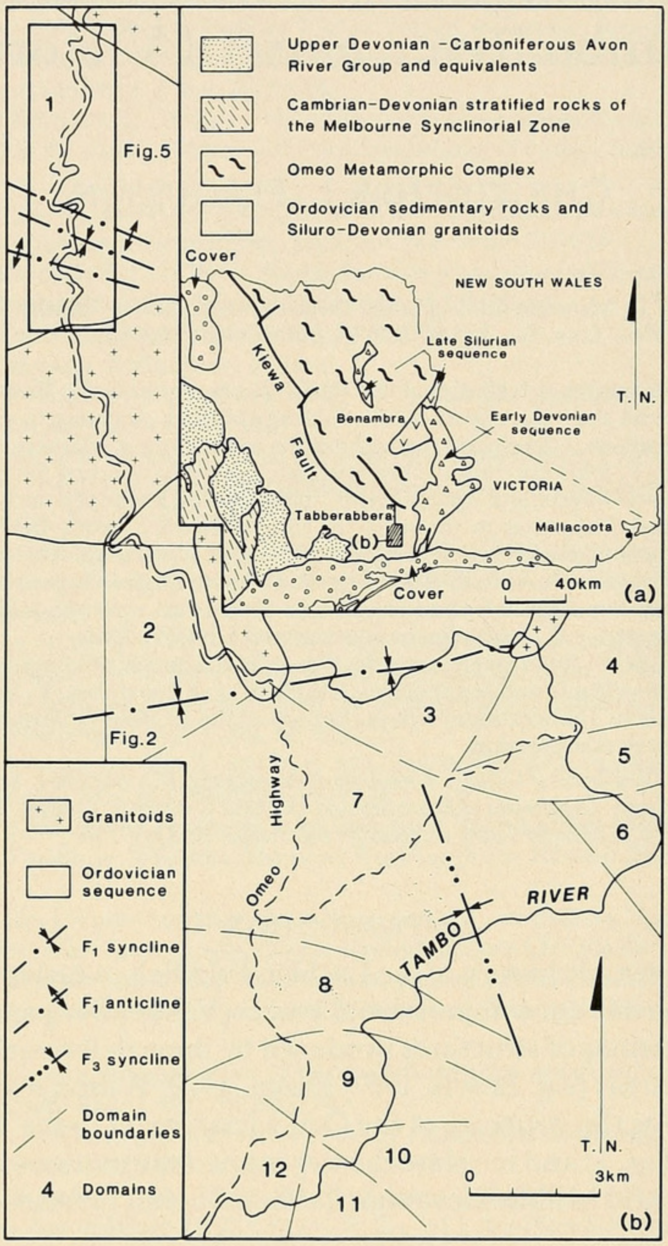

Fig. 1. **a.** — Geological sketch map of eastern Victoria with the location of the Tambo River region shown by the shaded inset.
b. — Geological map of the Tambo River region showing the locations of Figs 2 and 5 and domains 1 to 12. Note that the Kiewa Fault is not shown as it is cut by the 'granitoid' between domains 1 and 2.

At Tabberabbera the Ordovician sequence is overlain with a high angular unconformity by the Emsian Wentworth Group and both are, in turn, overlain with a high angular unconformity by the Upper Devonian-Lower Carboniferous Avon River Group (Talent, 1963). The latter surface was called the Tabberabberan Unconformity by Harrington *et al.* (1974) and VandenBerg (1977). This was caused by uplift and erosion associated with the deformation that formed a tight northerly-trending syncline in the Wentworth Group. The deformation is commonly referred to as the Tabberabberan Orogeny.

West of the Tabberabbera Belt lies the Melbourne terrane of Fergusson *et al.* (1986). The Melbourne terrane consists of Cambrian mafic volcanics and a conformable Ordovician to Middle Devonian quartzose clastic succession. Structurally the Melbourne terrane is dominated by northerly-trending upright folds with a major fault zone along its eastern margin. The Cambrian rocks occur as slices within the fault zone which is unconformably overlain by Upper Devonian—Lower Carboniferous fluviatile sediments and volcanics. These relations establish that the deformation that affected the Melbourne terrane was the Tabberabberan Orogeny (VandenBerg and Wilkinson, 1982).

STRUCTURE

The Ordovician strata of the Tambo River region consist of a monotonous quartz turbidite succession (Stewart and Fergusson, in preparation). The structure of the region is dominated by two main deformations with two additional deformations of lesser extent and significance. Each deformation is characterized by folds and accordingly each event is labelled F_1, F_2, F_3 and F_4 in order from oldest to youngest. These fold episodes are mapped on the basis of orientation and fold style groups whose age relations have been determined by overprinting criteria. The nature of axial plane foliations associated with each fold generation has been the least useful guide in structural mapping (cf. Williams, 1985). Macroscopic structure is indicated by many sections of homoclinal strata and the abundance of younging criteria (Figs 2, 3, 4, 5 and 6).

The earliest structure developed in the Ordovician sequence is a bedding-parallel slaty cleavage that predates all folding (Fig. 7**d**). A similar fabric has been described from the Ordovician at Mallacoota (Wilson and de Hedouville, 1985). The significance of this fabric will be discussed elsewhere (C. L. Fergusson and D. R. Gray, unpub. data).

F_1 FOLDING

The F_1 folding is the most pervasive structural event developed throughout the Tambo River region. F_1 folds are upright isoclinal to open structures with northeast to southeast trends that were initially easterly trending (Figs 8 and 9). Hinges are narrow and angular with long planar limbs (Fig. 7**a**). Sandstone layers have class 1B and 1C shapes whereas mudstones have class 3 shapes (Fig. 7**a-c**). Many of the F_1 folds are flattened chevron folds, and probably formed by flexural slip along bedding planes with accompanying flexural flow in mudstones, and fold flattening.

An S_1 axial surface cleavage is associated with the F_1 folds (Fig. 7**c**). In mudstones the cleavage has formed from microfolding, accompanied by dissolution, of the early bedding-parallel slaty cleavage and forms a zonal crenulation cleavage (Fig. 7**d**). On the limbs of some F_1 folds the angle between S_1 and the early cleavage is low and the two fabrics are indistinguishable. Throughout domains 9-11 (Fig. 1) a pervasive S_1 stripy cleavage is developed in sandstones. The stripy cleavage consists of planar domains of aligned micas and other pressure solution residue up to 0.5cm in width separated by microlithon domains of quartz sandstone up to 2cm in width. The microlithons have abundant chlorite overgrowths (especially on quartz grains) indicating extension within the cleavage plane.

On the map-scale the main F_1 structures are an anticlinorium in domains 1 and 2 and a synclinorium, with a refolded southern limb, in domains 3 to 12 (Fig. 1). These structures are described separately below.

Domains 1 and 2: Domains 1 and 2 lie to the north and south of the Kiewa Fault respectively but as there are no major differences in structure these domains are described together. Domain 1 contains the hinge region and the northern limb of the F_1 anticlinorium (Figs 5 and 6) whereas domain 2 has the relatively planar south-younging limb of the anticlinorium (Figs 2 and 4).

Four orders of folding are developed within the anticlinorium. Fourth order folds are slightly overturned Z-shaped structures, with wavelengths up to 5m, found on the upright limbs of third order S-shaped folds on the steeply dipping to overturned northern limb of the anticlinorium (Fig. 6). Third order folds have wavelengths of 10-20m. The core of the

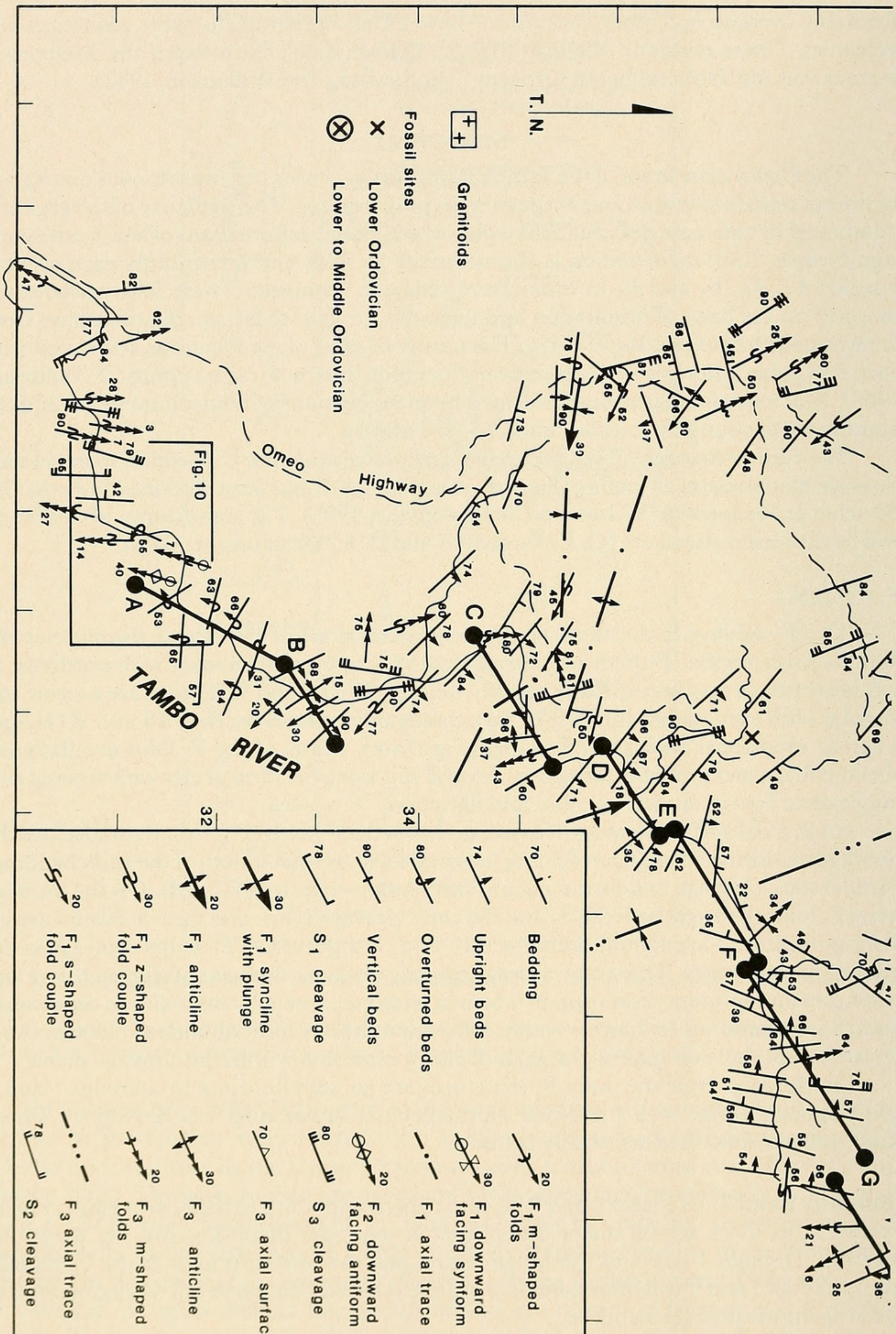

Fig. 2. Geological map of the Ordovician sequence in the southern Tambo River region showing the main structural features and locations of cross sections and Figs 10 and 12. Note the small amount of overlap across the double page.

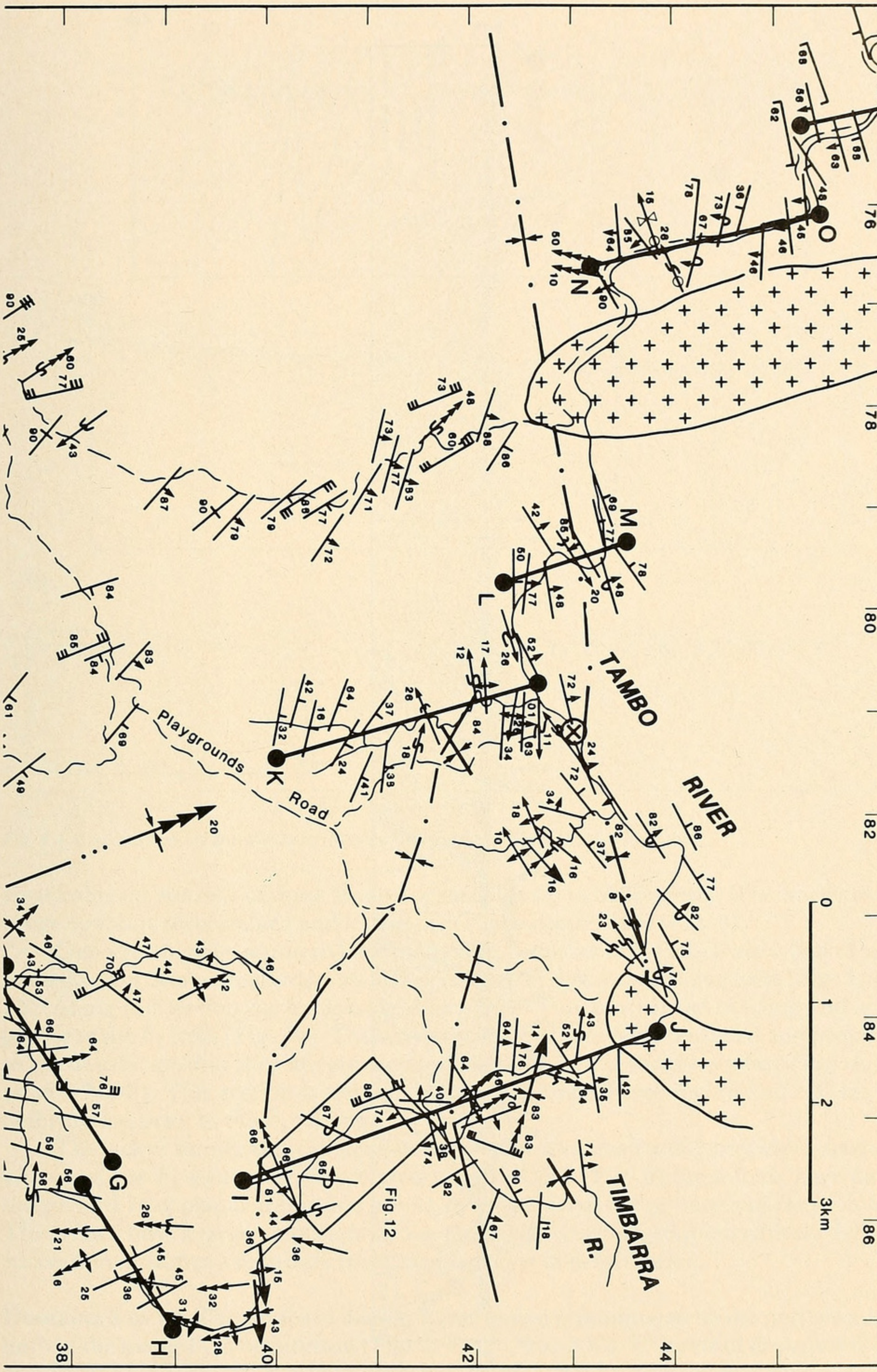

Fig. 2. For explanation see opposite.

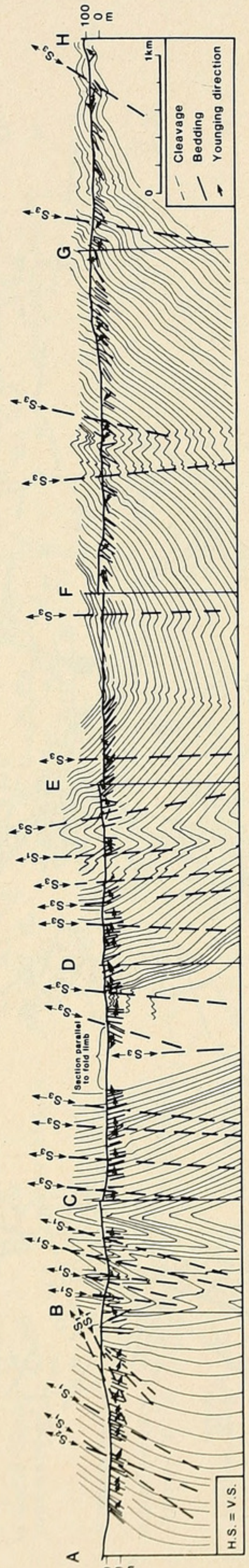

Fig. 3. Regional cross section across the major F_3 syncline in the southern Tambo River region. See Fig. 2 for location.

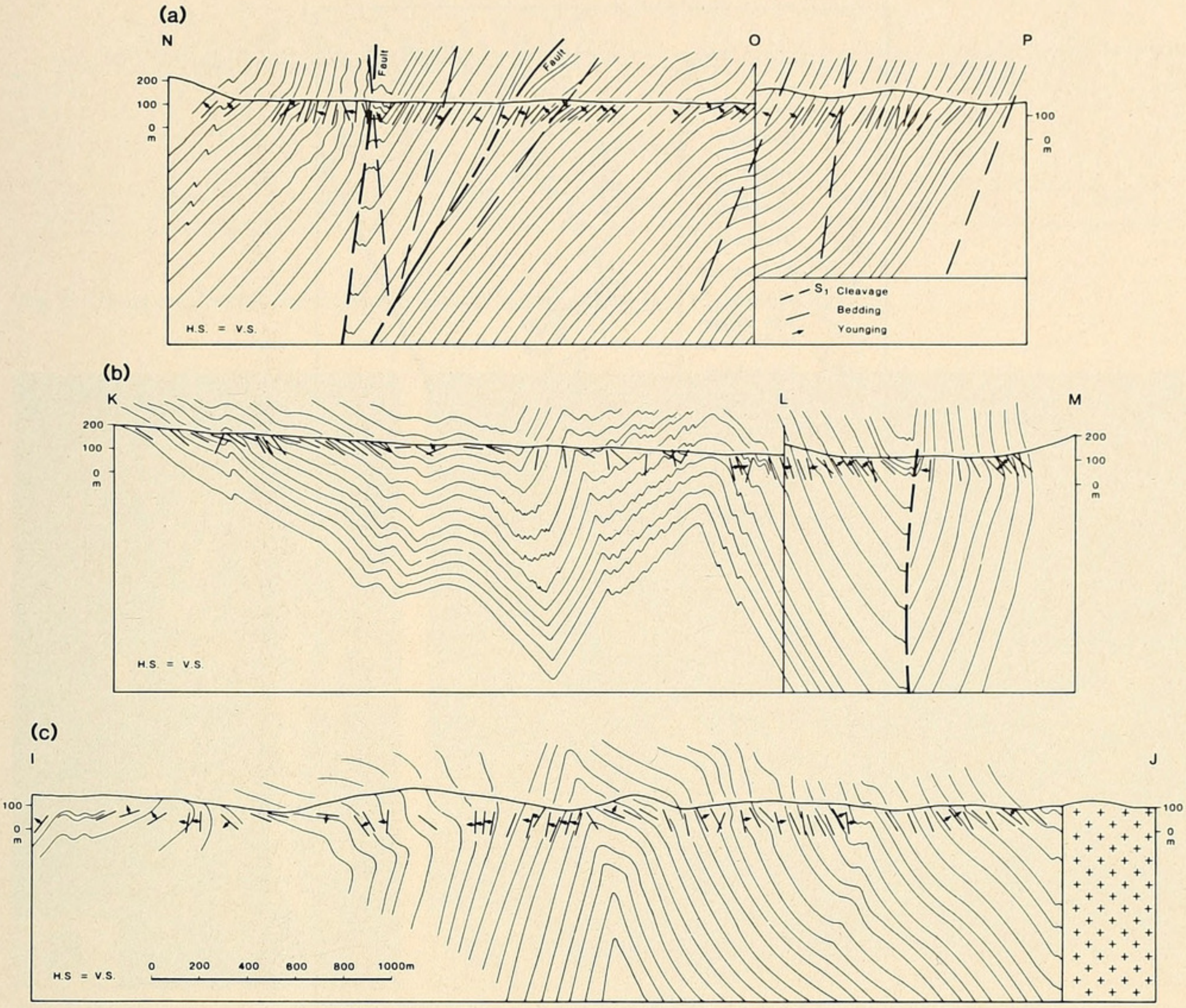

Fig. 4. Cross sections for the southern Tambo River region. See Fig. 2 for location.

anticlinorium consists of three second order folds up to 600m apart. The northernmost hinge contains several third and fourth order mesoscopic folds (Fig. 6).

One stretch of the southern limb in domain 2 consists of approximately 1km of southward dipping overturned beds with some parasitic F_1 downward facing folds (Figs 2, 4 and 7**b**). Along this section the S_1 cleavage dips steeper than overturned bedding and is axial planar to the F_1 folds (Fig. 7**b**). These overturned beds are fault-bounded and projections to depth indicate that they are pinched out at about 1km below the surface (Fig. 4, cross section NOP). This section is unique within the Tambo River region and reflects local deformation prior to the F_1 folding.

The lack of significant younger deformation in domains 1 and 2 provides a clear cross section of the F_1 structures. From cross section QRS (Fig. 6) these folds have narrow hinges and long planar limbs and a fold style characteristic of flattened chevron folds. These folds have a large amplitude-to-wavelength ratio which coupled with the 4-5km of succession indicates a relatively thick-skinned style of deformation.

Domains 3 to 12: The southern Tambo River region is dominated by the north-younging limb of the major F_1 synclinorium (Figs 2, 3, 4, 8, 9 and 10). The axis of the synclinorium occurs along the Tambo River in domain 3 (Figs 1 and 2). The hinge is angular with a planar and locally overturned northern limb (Fig. 4, cross section KLM). Throughout domains 6 and 7 the southern limb of the F_1 synclinorium is shallowly dipping and

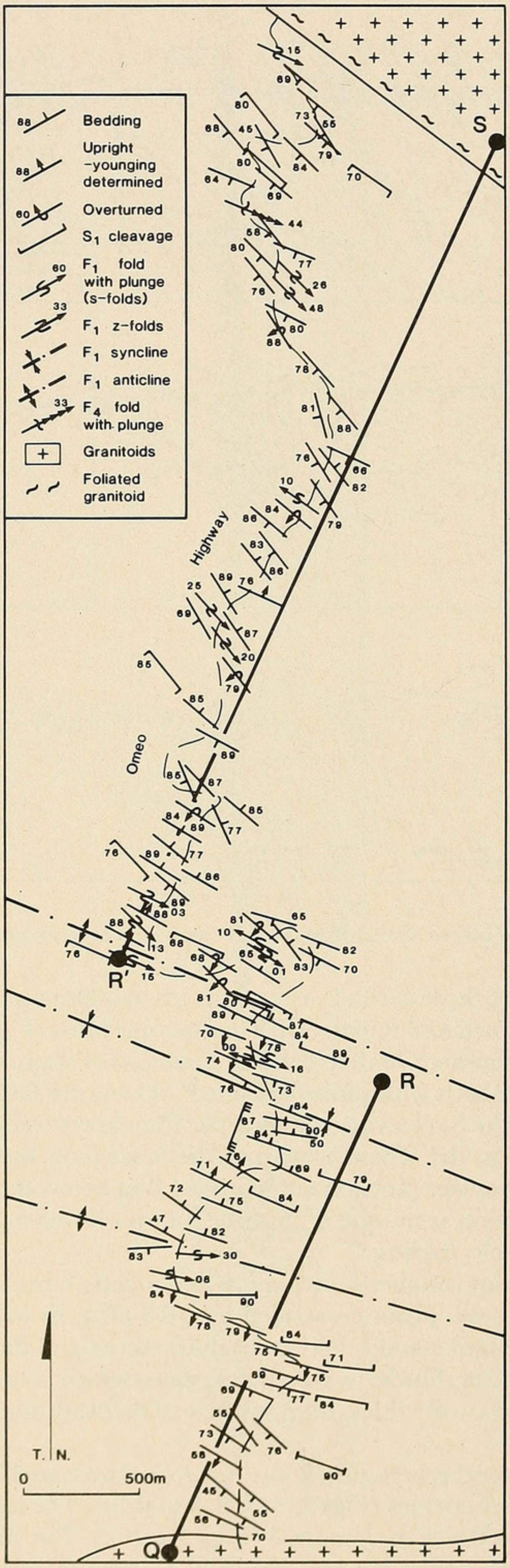

Fig. 5. Structural map of the Ordovician sequence in the northern Tambo River region.

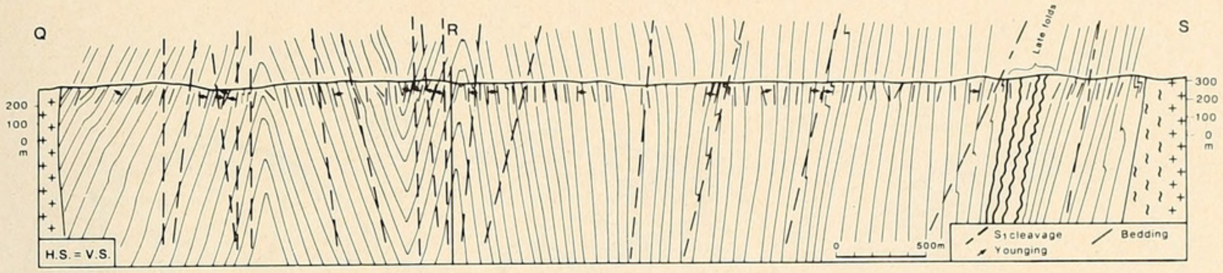

Fig. 6. Cross section for the northern Tambo River region (see Fig. 5 for location).

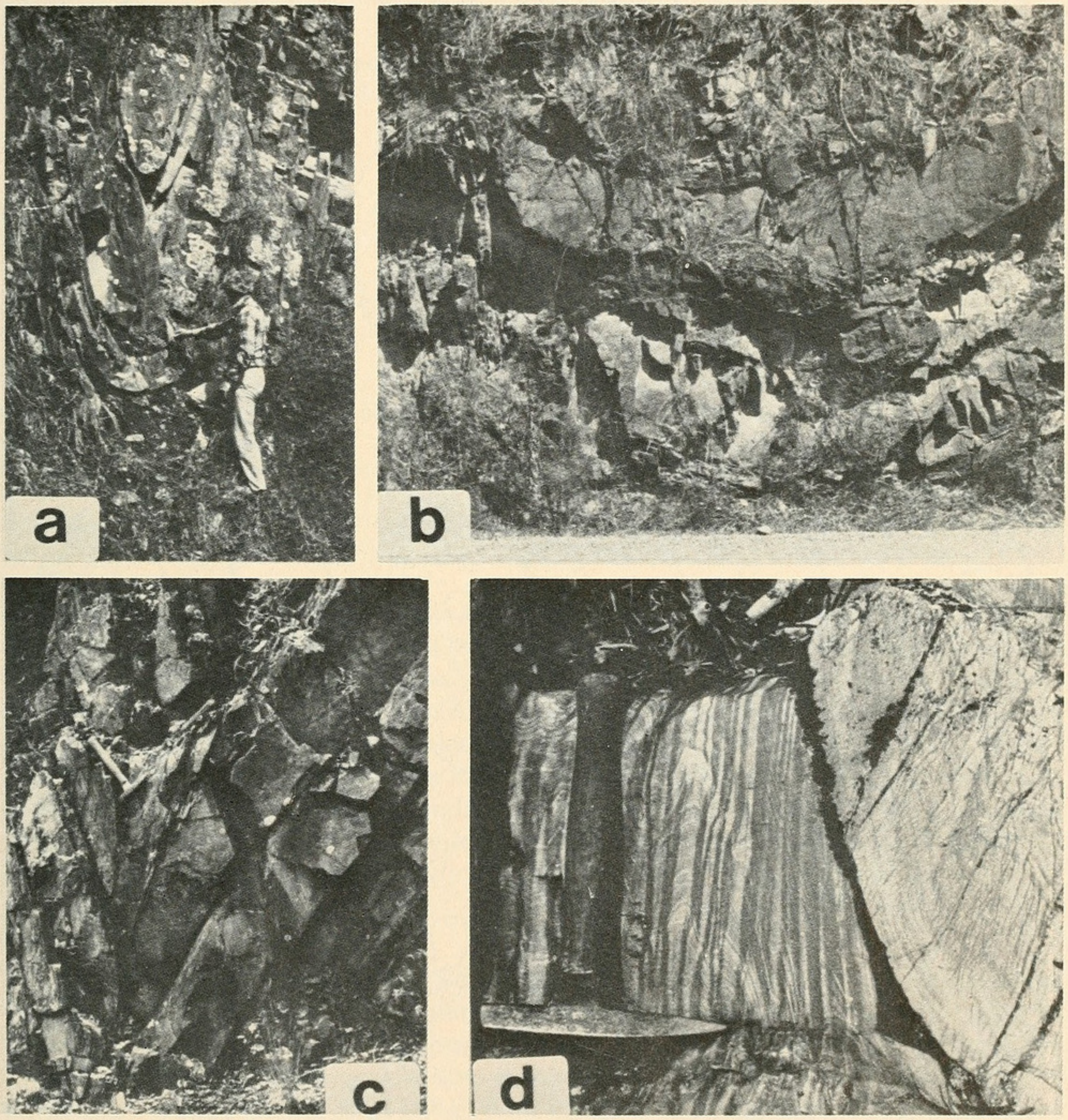

Fig. 7 **a.** — Tight F_1 syncline from domain 1, Omeo Highway (D. W. Durney for scale). Location — GR 734534 (Grid references from Omeo and Bairnsdale 1:100 000 Topographic Sheets).
b. — Downward facing F_1 synformal anticline from domain 2 (see text), Omeo Highway. Note that the southern limb of the fold is truncated by a steeply dipping fault. Width of view is 6m. Location — GR 764432.
c. — Angular upright F_1 syncline from domain 1. Hammer 33cm in length for scale. Location — GR 734538.
d. — A well-developed S_1 crenulation cleavage from the core of an upright F_1 anticline. Note the S_1 stripy cleavage in the sandstone bed and the cleavage refraction. Hammer is 33cm in length. Location — GR 809333.

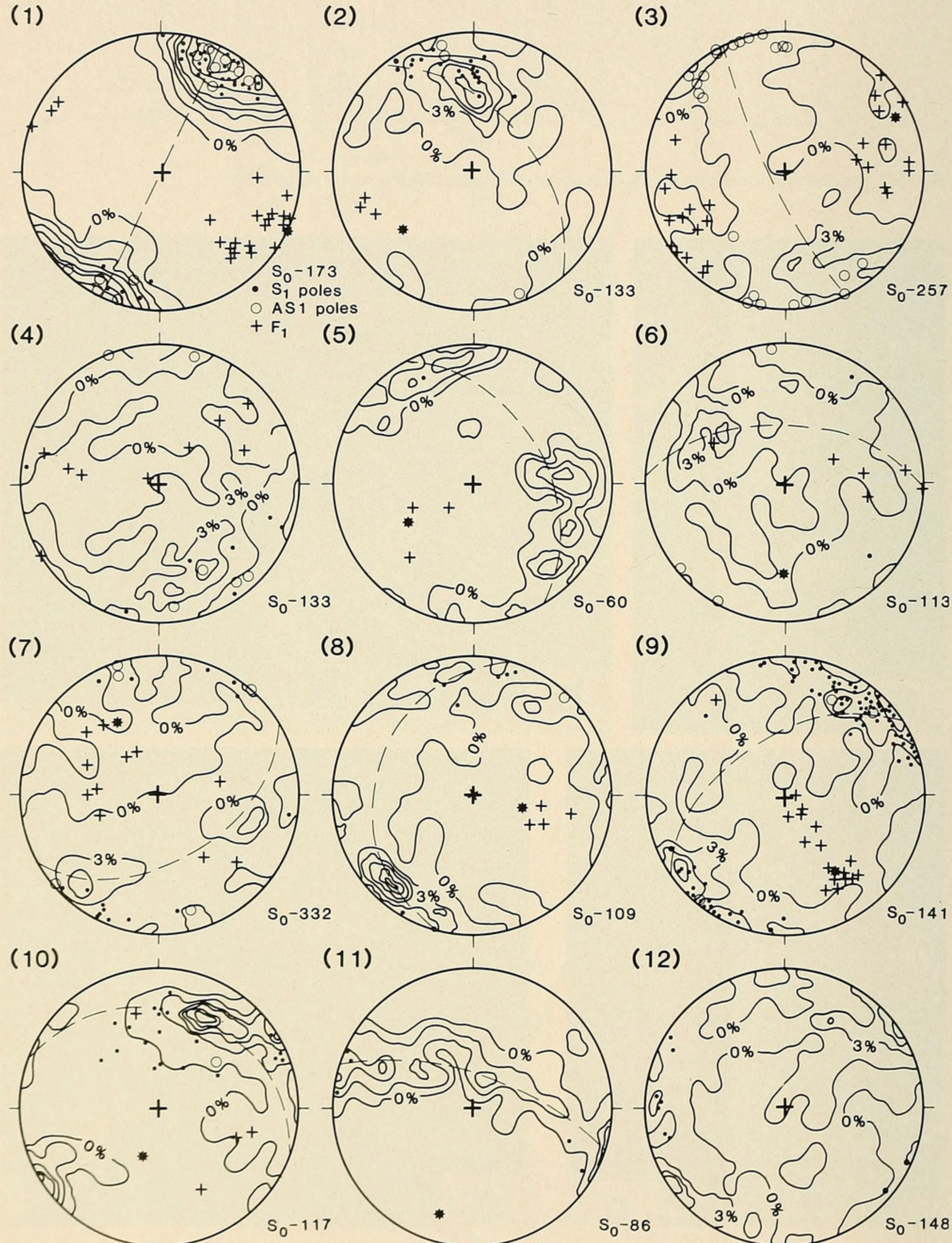

Fig. 8. Lower hemisphere equal-area stereographic projections from the Tambo River region (for domains see Fig. 1). Heavy dot is the calculated fold axis in each stereographic projection. Stereographic projections have bedding poles contoured at: 0, 3 and 6% per 1% area (nets 3, 4, 6 and 7); 0, 3, 6 and 9% per 1% area (nets 5, 9, 11 and 12); 0, 3, 6, 9 and 12% per 1% area (net 2); 0, 3, 6, 9, 12 and 15 per 1% area (nets 8 and 10); and 0, 3, 6, 9, 12, 15, 18 and 21% per 1% area (net 1).

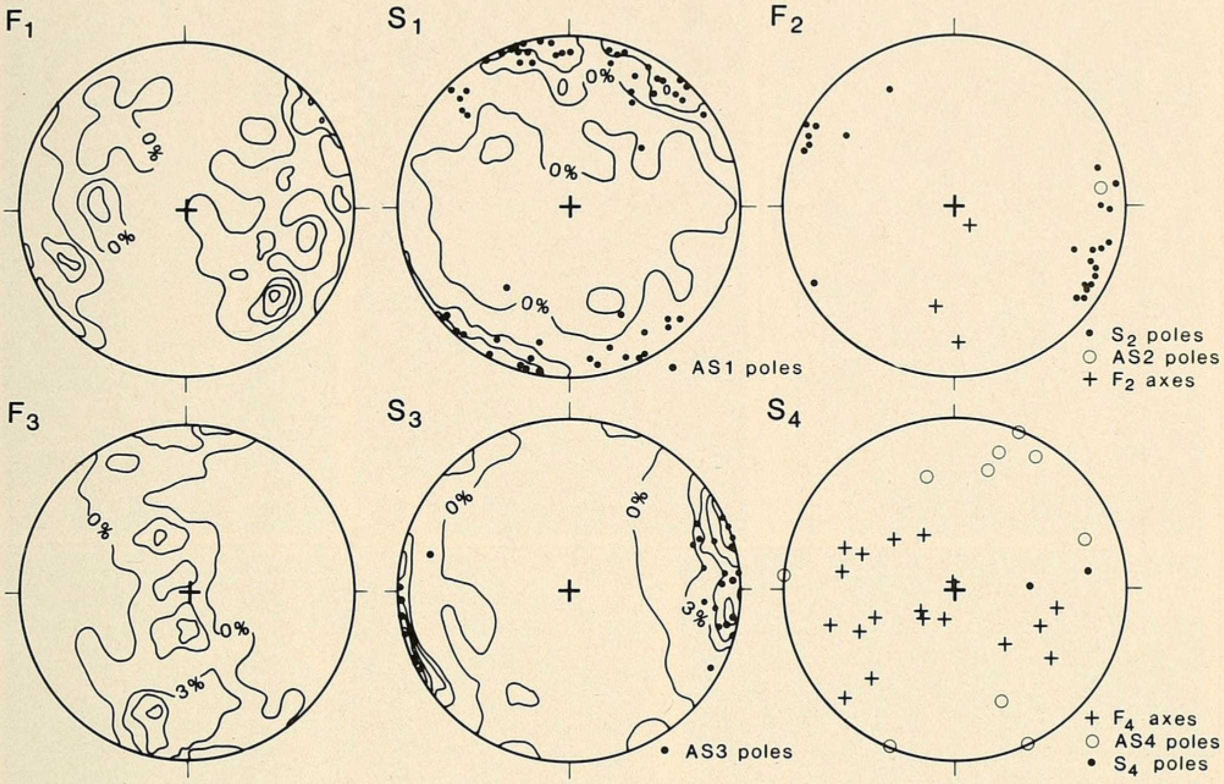

Fig. 9. Summary lower hemisphere equal-area stereographic projections for structural elements in the Tambo River region. Points are contoured at 3% intervals per 1% area. Structural elements include: F_1 fold axes (100); S_1 cleavage (212), F_1 axial surfaces (AS1); F_2 fold axes, S_2 cleavage, F_2 axial surfaces (AS2); F_3 fold axes (137), S_3 cleavage (347), F_3 axial surfaces (AS3); F_4 fold axes, S_4 cleavage and F_4 axial surfaces (AS4).

dominated by abundant F_1 parasitic folds and refolded by F_3. In domains 8 to 10 the southern limb is steeply dipping and becomes overturned farther south (Fig. 3, cross section ABCDEFG and Fig. 10). F_1 parasitic folds are largely restricted to two major Z-shaped fold pairs along cross section BCD (Fig. 3). The northern fold pair consists of F_1 minor folds plunging steeply to moderately to the east (Fig. 8, domain 8) with a faulted axial surface along the major syncline hinge. The southern fold pair (cross section BC, Fig. 3) contains a central limb with abundant upright F_1 folds in contrast to the steep limbs which only have rare Z-shaped parasitic folds. The overturned beds to the south of this fold pair in domains 11 and 12 are strongly refolded by F_2 and F_3 (Fig. 1).

F_2 FOLDING

In domain 10 this deformation formed a discrete hair-like crenulation cleavage that overprints S_1 and is in turn overprinted by S_3 (Figs 10 and 11**a**). F_2 folding is restricted to domains 11 and 12 (Figs 1 and 10). Throughout domain 11 the overturned limb of the major F_1 synclinorium is refolded by close downward facing F_2 folds with axial surfaces dipping moderately to the east (Fig. 10). The F_2 folds have relatively narrow hinge zones and are extensively refolded by the F_3 folds (Fig. 10). The inset in Fig. 10 shows the shape of the F_2 folds prior to folding by F_3.

Across the boundary between domains 11 and 12 (Fig. 1) the S_2 axial surface cleavage rapidly intensifies and bedding is transposed (with the exception of exposures along the Omeo Highway in domain 12). Throughout domain 12 S_2 is developed as a pervasive stripy cleavage in sandstones (Fig. 11**g**) and as a strong continuous cleavage in mudstones.

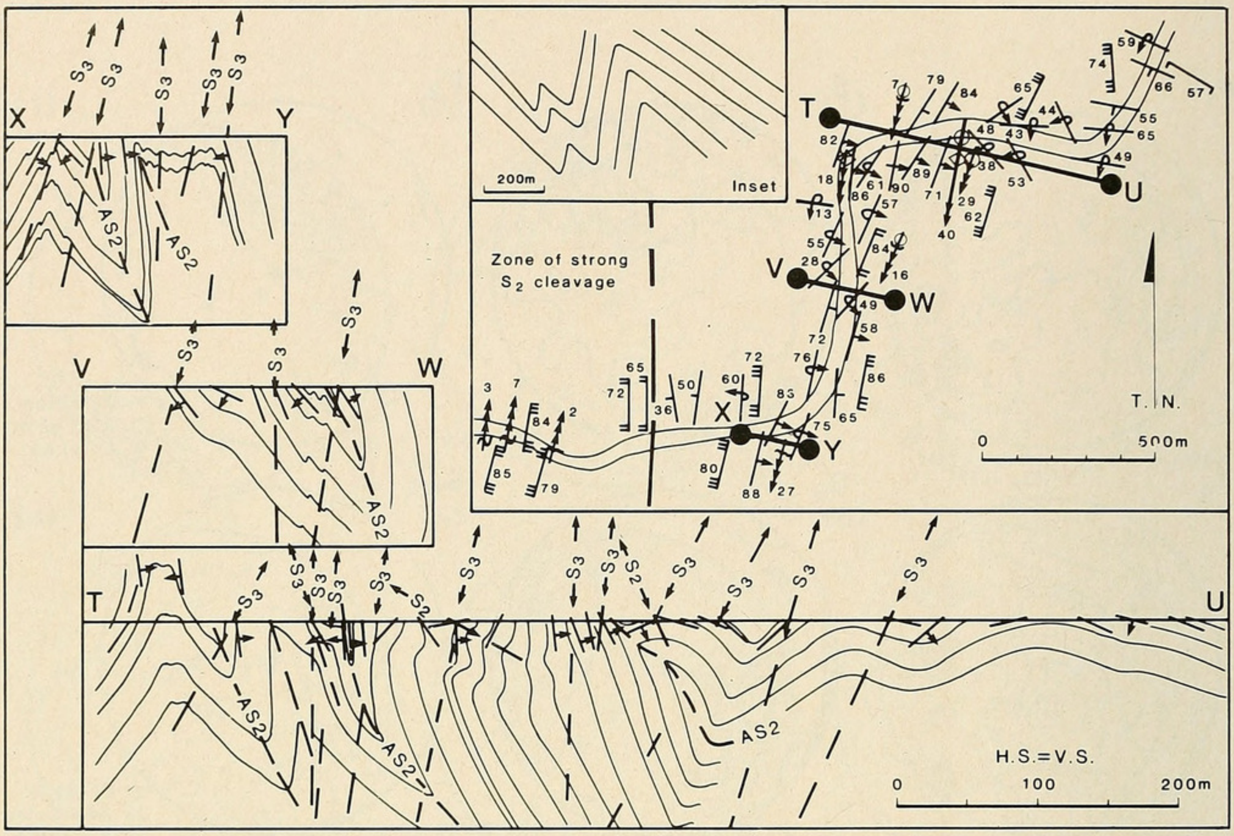

Fig. 10. Map and cross-sections of downward facing F_2 and F_3 folds in domain 11 (see Fig. 1 and Fig. 2 for location). See text for discussion. Inset shows a reconstruction of the F_2 folds in cross section prior to the F_3 folding.

The S_2 stripy cleavage is similar to S_1 cleavage in sandstones except that the former is much more pervasive. F_2 folds have not been found in domain 12 and the S_2 cleavage itself is refolded by younger structures (see below).

F_3 FOLDING

F_3 structures occur throughout the southern Tambo River region (Fig. 2). They are northerly-trending folds with steep axial surfaces and variable plunges (Figs 2, 8, 9 and 11**b-e**). F_3 folds are close to open with slightly rounded hinges and characteristic small amplitude-to-wavelength ratios (<0.5, Fig. 11**b-e**). An axial surface crenulation cleavage is developed in mudstones and occasionally a weak stripy S_3 cleavage is developed in sandstones (Fig. 11**a-d**).

Throughout most of the southern Tambo River region the F_3 folds are upward facing (Figs 2, 3 and 4). In domain 11, however, the F_3 folds are developed on the overturned limbs of the downward facing F_2 folds and are therefore downward facing (Fig. 10). Locally the combination of F_2 and F_3 folding has formed box-fold structures with the western hinge formed by an F_2 fold and the eastern hinge by an F_3 fold (e.g. cross section XY, Fig. 10). F_3 folds are abundant in domain 11 in contrast to the general scarcity of F_2 hinges.

On the map-scale the most obvious F_3 fold is the large open syncline shown in cross section DEFGH (Fig. 3). Along the Tambo River this structure has a hinge zone 800m across with an open conjugate fold style (cross section EF, Fig. 3). The hinges in the conjugate pair plunge shallowly to the north-northwest (Figs 2, 8 and 9) which indicates that they must have developed along a shallowly dipping part of the north-younging limb of the

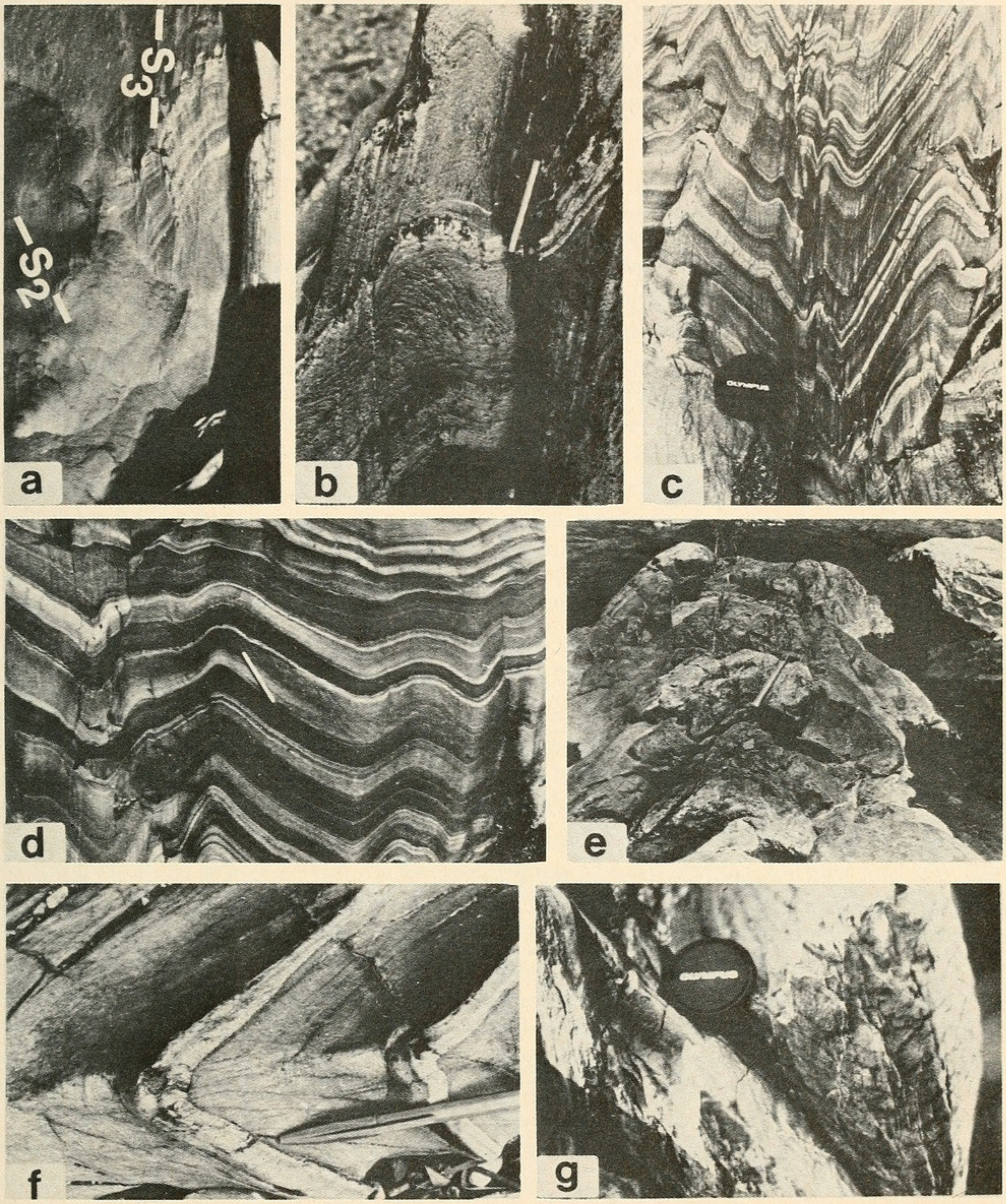

Fig. 11 **a.** — An S_3 crenulation cleavage is shown locally cross-cutting a less steeply dipping S_2 crenulation cleavage. Bedding dips steeply to the east and is overturned. Hammer for scale. Location — GR 793315.
b. — Broad F_3 fold couple with an axial surface S_3 crenulation cleavage. Note an early S_1 crenulation cleavage is folded in the core of the fold. Match stick for scale. Location — GR 808336.
c. — Close F_3 folds with a well-developed axial surface crenulation cleavage. Lens cap is 5.5cm across. Location — same as (b).
d. — Broad to open F_3 folds with S_1 crenulation cleavage oblique to bedding on the limbs and in the fold cores. Match stick for scale. Location — same as (b).
e. — Upright close F_3 fold with a box-shaped hinge. Hammer is 33cm in length. Location — GR 819362.
f. — Steeply plunging close F_3 fold with an axial surface crenulation cleavage. Pen cap is 6.5cm in length. Location — GR 809331.
g. — S_2 stripy cleavage in sandstone in the core of an upright F_3 fold with a steep S_3 axial surface cleavage (in domain 12). Location — GR 783308.

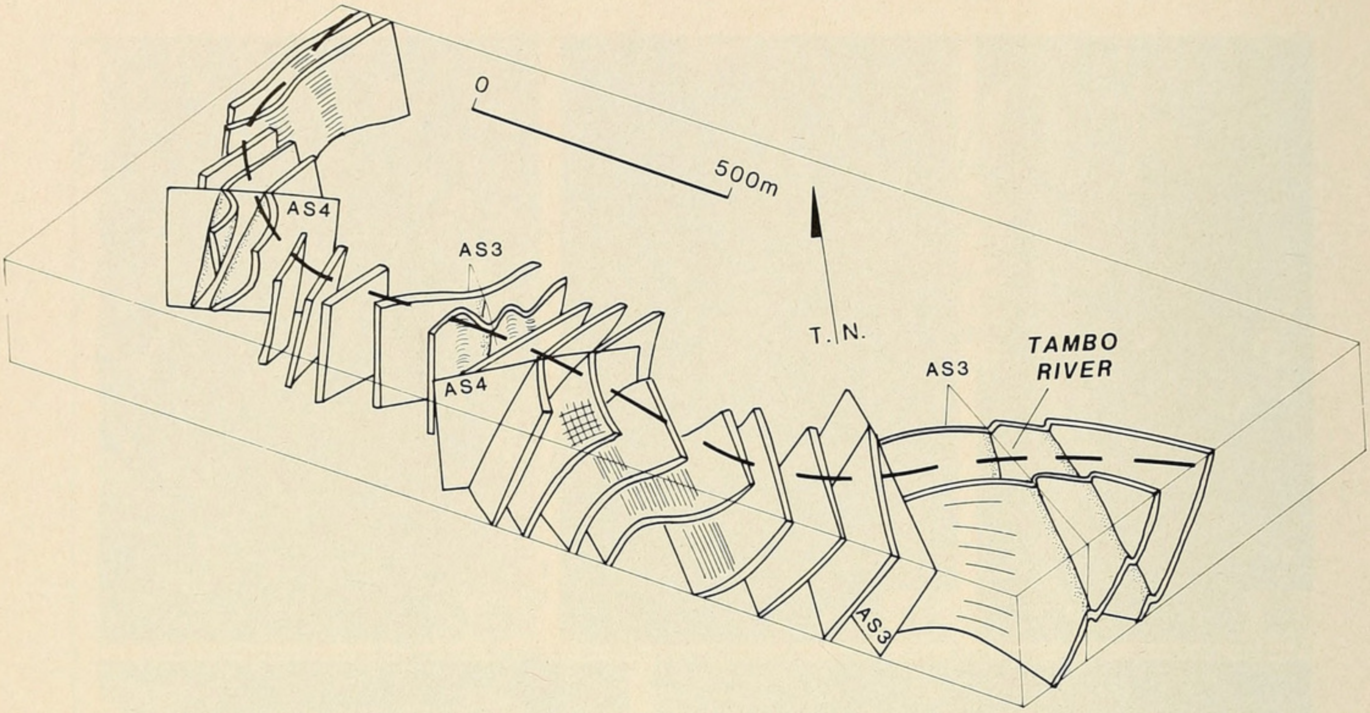

Fig. 12. Schematic block diagram of the F_4 and F_3 folds along the Tambo River in domain 5 (see Fig. 2 for location). Note that the dip of the limb of an F_3 fold has been locally decreased by post F_3 warping.

F_1 synclinorium. On the east limb of the F_3 syncline bedding dips moderately to the west whereas on the western limb it dips steeply to the northeast (Figs 2, 3 and 8, domain 7).

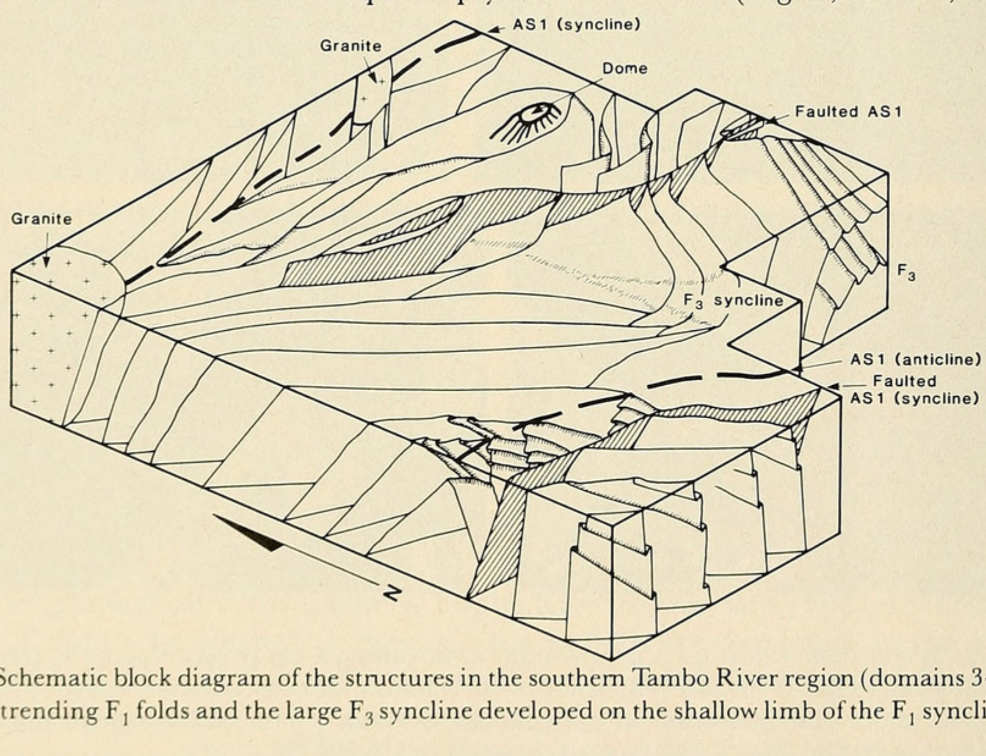

Fig. 13. Schematic block diagram of the structures in the southern Tambo River region (domains 3-10). Note the easterly trending F_1 folds and the large F_3 syncline developed on the shallow limb of the F_1 syncline.

Map-scale F_3 anticlines occur to the east and west of the major F_3 syncline (Fig. 2). The eastern F_3 anticline is partly shown on cross section GH (Fig. 3) and contains abundant M-shaped shallowly plunging F_3 folds (Figs 2 and 11**e**). Farther north the limbs of F_3 folds are extensively refolded by F_4 structures (Fig. 12). At GR 850 417 (Fig. 2) the F_3 anticline is superimposed on an F_1 anticline producing a prominent dome with bedding dipping outward from a central focus (see also Fig. 13). F_1 minor folds show significant plunge variations in this area (domain 4, Fig. 8). North of the dome the F_3 anticline causes the bending of F_1 trends from east-northeast to east-west either side of the 'granitoid' at J (Fig. 2). The western F_3 anticline caused a change in structural trends from southeasterly to easterly from domains 2 to 7 respectively (Figs 1, 2, 8 and 13). Thus the main effect of the F_3 folding on the map-scale is the bending of F_1 structures with only local development of dome and basin type interference fold patterns.

F_4 FOLDING

Local post-F_3 folds, warps and kinks occur throughout the area and these are grouped together as F_4 structures. Some of these structures may belong to different fold generations but these are not distinguished due to the lack of overprinting criteria. In domain 1 there are several moderately-plunging east-southeast trending late-stage mesoscopic folds with rounded open hinges. These late-stage structures are grouped with F_4 for convenience, as their orientations differ from the F_2 and F_3 structures.

Late-stage F_4 folds thoughout Fig. 2 are mainly easterly trending broad to open folds and/or kinks (Fig. 12). Several of these are map-scale F_2 folds (Fig. 12). Rare kink-like folds with rotated limbs up to 50m across occur at GR 806 322 (Fig. 2). In addition to the late-stage folds a number of weak crenulation cleavages and crenulation lineations are developed in the Tambo River region. These structures are not related to other deformations and they reflect only low values of shortening.

DISCUSSION

The F_1 east-west folding event extends throughout the Tabberabbera Belt (Fergusson, 1985) and the Omeo Metamorphic Belt where it is constrained between the Ordovician and Late Silurian. Bolger (1982) has emphasized that the timing of deformation and metamorphism in the Metamorphic Belt is only broadly delimited and is not confined to the Early Silurian as is sometimes implied (e.g. Crook *et al.*, 1973; Powell 1984).

Powell (1983, 1984) has proposed a tectonic model for southeastern Australia relevant to the formation of east—west folds in the Omeo Metamorphic Complex and the Tabberabbera Belt. The basis of his model is that in the Ordovician a back-arc basin (Wagga Marginal Sea) was bordered to the east by a volcanic island arc associated with a westward dipping subduction zone. In the Early and Middle Silurian Chilean-style locking of plates on the subduction zone was accompanied by dextral oblique-slip plate movement and east—west upright folds were formed at several localities in the Lachlan Fold Belt (see Cas *et al.*, 1980). The east—west folds of the Tabberabbera Belt and Omeo Metamorphic Complex are the best examples of this deformation.

The F_1 folding of the Tambo River region caused shortening of 50% or more (calculated from regional cross sections, Fig. 14). Estimates of the thickness of the Ordovician succession obtained from cross sections indicate a minimum of 4-5km. The stratigraphic thickness, fold style and shortening indicate that at least 12km and as much as 20km of the present crustal thickness consists of the folded Ordovician succession. Thus the F_1 folding represents a major episode of crustal thickening in this part of the Lachlan Fold Belt, and was probably associated with closure of the Wagga Marginal Sea.

The F_2 folding is areally restricted and is only constrained in time as post-F_1 and pre-F_3. This folding event reflects localized east-west shortening of unknown tectonic significance.

The F_3 folding is extensive throughout the southern Tambo River region but no constraints on the timing of this deformation exist within this area. Farther west at Tabberabbera, however, similar northerly trending upright folds with low amplitude-to-wavelength ratios and an axial surface crenulation cleavage affect the Ordovician succession (Fergusson, 1985). These structures have been mapped in reconnaissance between

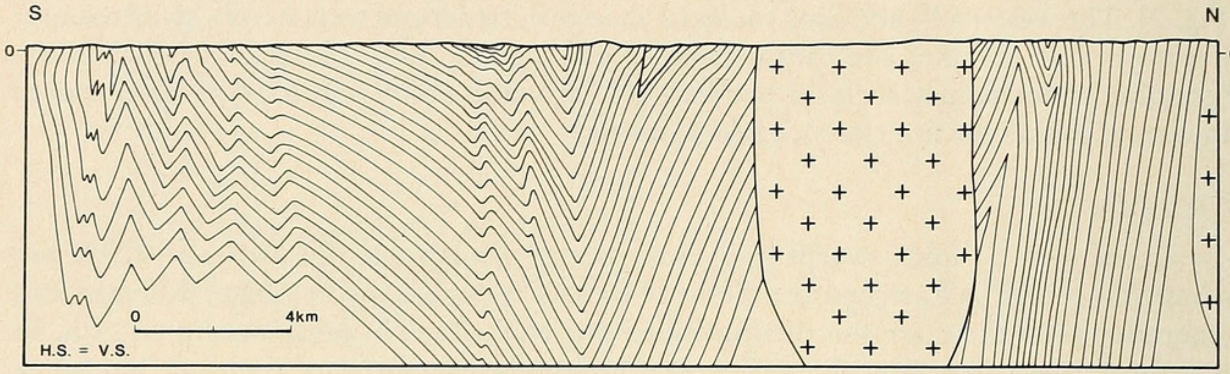

Fig. 14. Regional cross section of the main F_1 structures in the Tambo River region. Note the relatively thick-skinned style of folding.

the two areas. At Tabberabbera they are related to the deformation that strongly affected the overlying Lower Devonian Wentworth Group (Fergusson, unpub. data). Thus the F_3 folding is regarded as a consequence of the Middle Devonian Tabberabberan Orogeny. This event reflects major east—west compression and overthrusting of the Melbourne terrane over the western part of the Tabberabbera Belt (Fergusson *et al.*, 1986).

The F_4 folds must have postdated F_3 and reflect several mild compressions of differing orientations.

Conclusions

(1) F_1 folding in the Ordovician sequence of the Tambo River region involved the formation of east—west upright folds with a shortening of at least 50%. The major F_1 structures are a anticlinorium—synclinorium pair with a thick-skinned style of deformation. They may have formed due to an episode of regional dextral oblique-slip shear associated with a westward dipping subduction zone in the Early to Middle Silurian. This event was responsible for closure of the Wagga Marginal Sea and caused significant crustal thickening in the area.

(2) The F_3 folding formed due to east-west compression in the Tabberabberan Orogeny. The largest F_3 structure is a box-shaped F_3 syncline that developed on the flat-lying undeformed part of the southern limb of an F_1 synclinorium. Shortening associated with F_3 is variable and this event, though of regional significance, did not result in extensive crustal thickening in this region.

(3) The F_2 and F_4 events consist of locally developed and variably oriented folds that formed during relatively mild compressional events.

Acknowledgements

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