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Ophiolite accretion in the Lachlan Orogen, Southeastern Australia

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Abstract

Slivers of dismembered Cambrian ophiolites are preserved in major fault zones of the turbidite-dominated, western and central Lachlan Orogen of southeastern Australia. Geometrical, chronological, and metamorphic constraints indicate that these slivers did not undergo classic Tethyan-style obduction but were incorporated into evolving turbidite wedges as offscraped slices, imbricated fault slivers or duplexes, and as blocks in mélange. The processes involved include decoupling of the oceanic crustal stratigraphy predominantly above the moho, formation and metamorphism of serpentinite/talc matrix mélange up to blueschist conditions, and accretion via underplating or offscraping during underthrusting. These processes have produced major, large-scale fault zones within the chevron folded turbidites that show marked along-strike variation in structural complexity that relate to magnitude of displacement. The fault zones may have formed preferentially where topographic highs occurred in the oceanic crust, promoting fold and fault nucleation within irregularities in the layering. These fault zones have predominantly brittle character due to their formation under a low geothermal gradient. Duplex-like structures in the fault zones and the inferred development through buckling of, then faulting of, the oceanic lithosphere, have analogues in modern oceanic environments (e.g. Indian Ocean) and young subduction systems (e.g. Sulu Sea, southeast Asia). They are interpreted to have formed due to convergence in a non-collisional, intra-oceanic setting during closure of a Cambrian backarc basin.

Keywords: Ophiolitic fault slices; Mélange; Underplating; Accretion; Oceanic setting; Lachlan Orogen

1. Introduction

Obduction relates to the emplacement of oceanic crust as a sheet onto a continental margin, enabling relatively complete sections of oceanic stratigraphy to be preserved (e.g. Semail ophiolite, Oman; Coleman, 1971; Dewey and Bird, 1971). This process is thought to be initiated by intra-oceanic thrusting, where contact and friction with young, hot oceanic crust produces a strongly deformed, metamorphic sole (e.g. Hacker et al., 1996). The resulting nappe is commonly modified by deformation, particularly during terminal continent–continent collision (e.g. the European Alps; Dewey, 1976). Where clear relationships to continental basement exist, such ophiolites have been termed 'Tethyan-type' (Moores, 1982; Moores et al., 2000). Many ophiolites are not sheet-like, do not have well-preserved oceanic stratigraphies, lack a metamorphic sole, and consist of fault-bounded, dismembered fragments that have ambiguous relationships to continental basement and may be emplaced over or incorporated into accretionary complexes (termed 'Cordilleran-type'; Moores, 1982; Moores et al., 2000). Many Pacific-rim ophiolites are Cordilleran-type and occur within accreted oceanic terranes and/or trench–forearc settings, and may be the products of accretion and underplating (or 'tectonic wedging'), rather than obduction in the classic sense (e.g. Kimura et al., 1996; Coleman, 2000). In this paper we describe dismembered ophiolites preserved in large-scale fault zones in the Lachlan Orogen, southeastern Australia, and argue that their emplacement was largely the product of forearc accretion in a predominantly intra-oceanic setting, not unlike parts of the present-day SW-Pacific.

The processes involved in dismembering and accretion versus obduction of ophiolites as sheets may depend on factors such as the age and temperature of the oceanic crust (old cold versus young hot; e.g. Hacker et al., 1996), the

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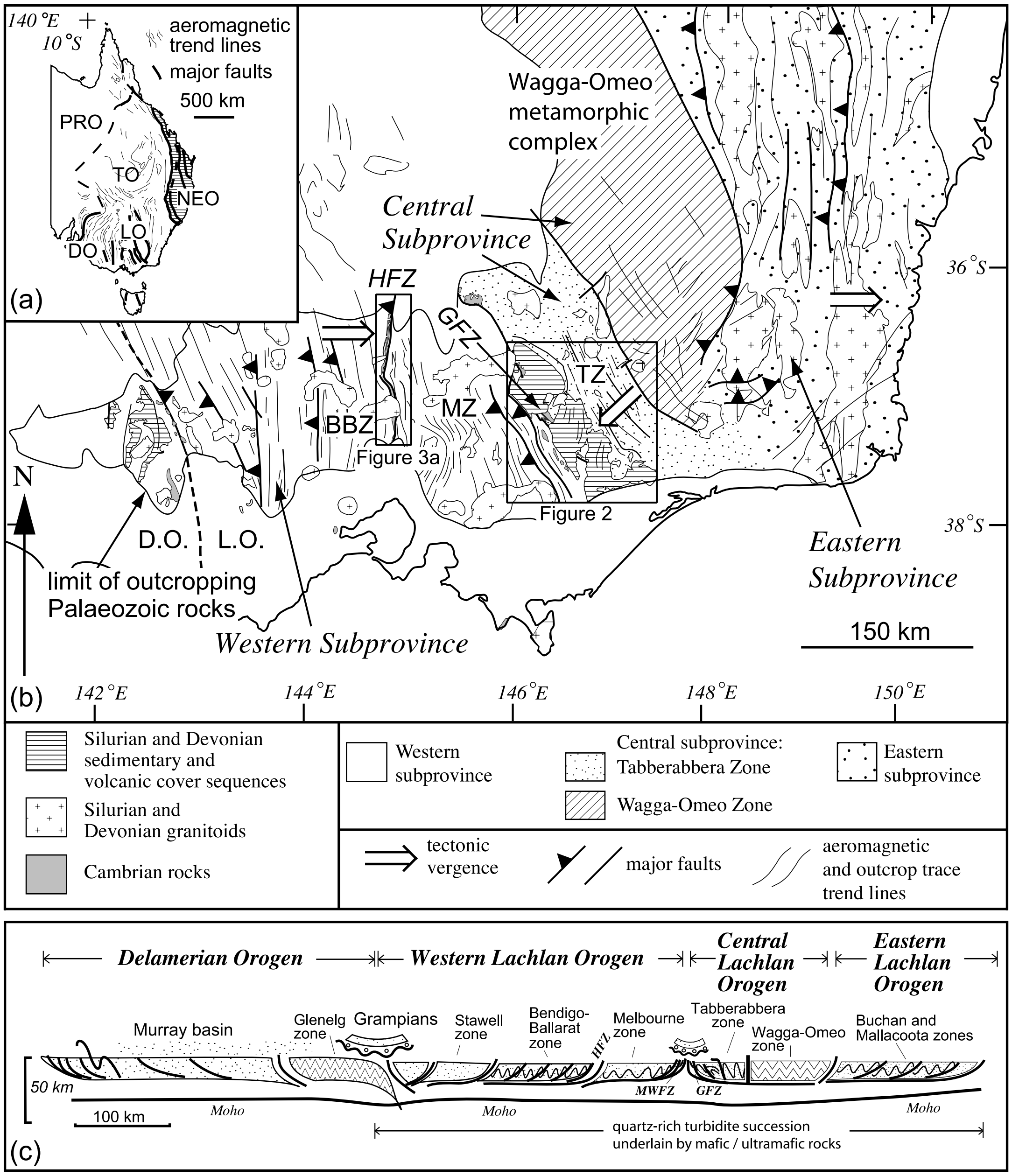


Fig. 1. (a) Map of eastern Australia showing orogenic belts of the Tasmanides. PRO: Proterozoic crust; TO: Thomson Orogen; NEO: New England Orogen; DO: Delamerian Orogen; LO: Lachlan Orogen. (b) Structural map of southeastern Australia showing the western, central, and eastern subprovinces of the Lachlan Orogen, Wagga-Omeo metamorphic complex, and tectonic vergence directions. GFZ, Governor Fault Zone; HFZ, Heathcote Fault Zone; BBZ, Bendigo-Ballarat Zone; MZ, Melbourne Zone; TZ, Tabberabbera Zone (modified from Gray and Foster, 1998). (c) Schematic crustal architecture profile at 37.5°S latitude illustrating thrust system geometry. Chevron pattern = metamorphic complexes, stipple pattern = predominantly turbidites. MWFZ, Mount Wellington Fault Zone (modified from Gray, 1997).

nature of the oceanic crust (suprasubduction zone versus mid-ocean ridge type), the presence of topographic highs such as oceanic plateaux or seamounts, the nature, thickness and effect of the overlying sediment pile, and whether the oceanic crust is deformed prior to obduction or accretion (e.g. intraplate buckling (Royer and Gordon, 1997); presence of transform faults (Coleman, 2000)). These factors are dependent on tectonic setting, which in turn influences the types of lithologies involved and the structures produced.

This paper builds on a model of intra-oceanic, accretionary wedge deformation in the Lachlan Orogen given by Gray and Foster (1998), but with emphasis on the character and emplacement mechanisms of the oceanic crustal sections and mélange. It incorporates new data from two major fault zones (the Heathcote and Governor Fault Zones) that defines their geometry, foliation type and chronology, kinematic evolution, and lithological associations. These elements have been determined from detailed field mapping coupled with interpretation of aeromagnetic and radiometric

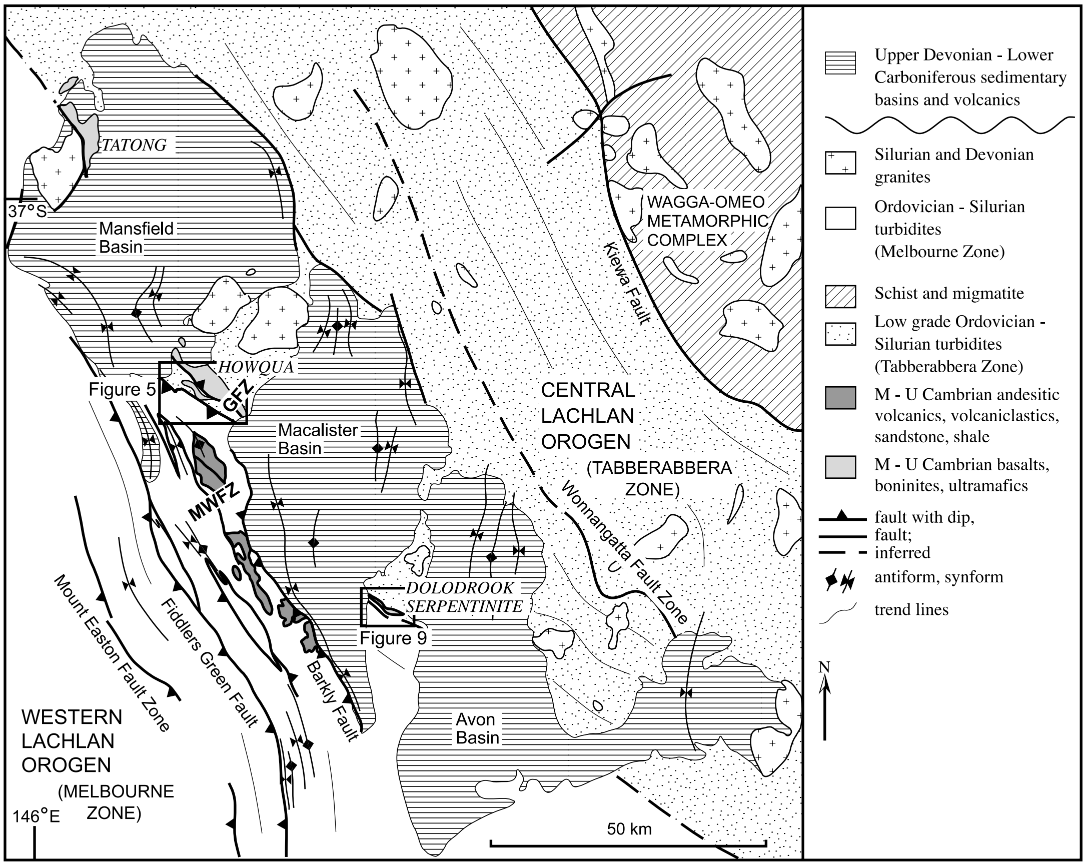


Fig. 2. Map of the eastern Melbourne zone and Tabberabbera zone, showing the locations of the Mount Wellington Fault Zone (MWFZ), Governor Fault Zone (GFZ), and Late Devonian cover sequences (modified from VandenBerg et al., 1995, 2000; Gray and Foster, 1998).

data, and microstructural analysis. Detailed metamorphic analyses are provided in Spaggiari et al. (2002a). The results have implications for understanding the processes involved in formation of large-scale fault zones in predominantly intra-oceanic settings, where slices of suprasubduction zone oceanic (backarc and forearc) crust are incorporated into an evolving orogen during formation of crust of continental character. In contrast to passive margin obduction, these processes have led to the preservation of ophiolites within thick, turbidite-dominated, accretionary wedges.

2. Geological overview

The Lachlan Orogen is part of the Tasman orogenic system, which formed along the eastern margin of Gondwana during late Neoproterozoic through Palaeozoic times (Fig. 1; Coney et al., 1990; Fergusson and Coney, 1992; Foster and Gray, 2000). It is dominated by voluminous and extensive, low grade turbidites of mostly Ordovician to Silurian age that are intruded by Silurian to Devonian granitoids (Gray, 1997; Collins, 1998). The thick turbidite pile was deposited on Middle to Late Cambrian backarc/forearc crust consisting of predominantly low-K, MORB to arc-tholeiite basalts, dolerites and gabbros, high-Mg low-Ti boninites, ultramafics, and calc-alkaline, andesitic to rhyodacitic arc rocks. These rocks are interpreted to have formed in an intra-oceanic, suprasubduction zone setting (Crawford et al., 1984; Nelson et al., 1984; Crawford and Cameron, 1985; Crawford and Keays, 1987).

Based on differences in tectonic vergence and geological evolution, the Lachlan Orogen has been divided into western, central, and eastern subprovinces (Fig. 1; Gray, 1997; Gray and Foster, 1998). These differences are related to a history of complex microplate interaction during closure of the backarc basin in Late Ordovician through Silurian times (Gray and Foster, 1998; Foster et al., 1999). The subprovinces are further divided into structural zones bound by major faults (Gray, 1997). Major inter-zone fault zones, such as the Heathcote and Governor Fault Zones (Figs. 1 and 2) are interpreted to have formed by underthrusting of the oceanic crust beneath thick, turbidite wedges, producing leading-imbricate fan geometries (Fig. 1c; Gray and Foster, 1998). Remnants of the oceanic crust are preserved predominantly in the frontal portions of the wedges where maximum displacement has occurred. This has led to massive shortening and structural thickening of the overlying turbidite pile by chevron-folding and thrust-faulting (Gray and Willman, 1991; Gray and Foster, 1998).

The boundary between east-directed tectonic vergence in

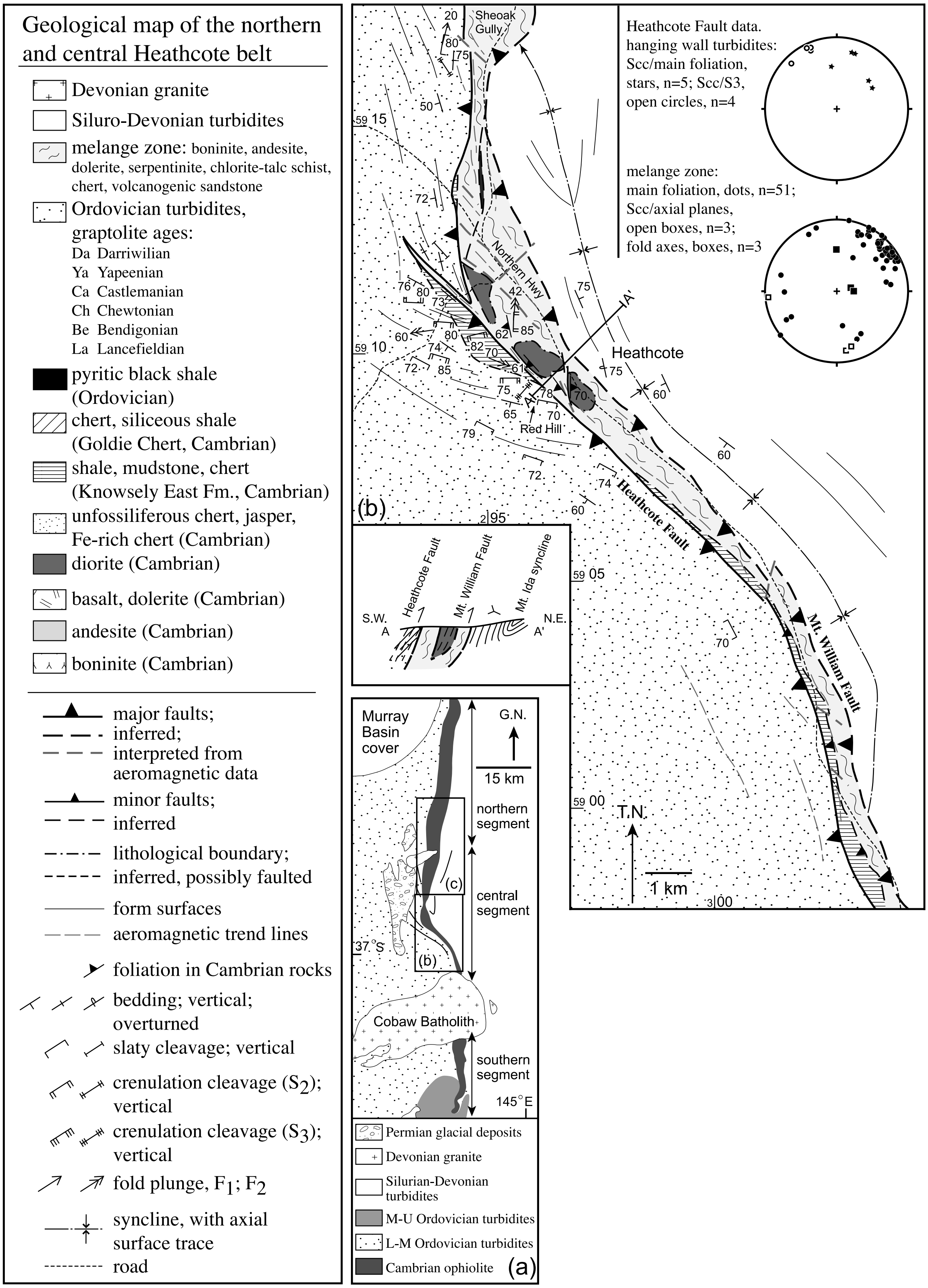


Fig. 3. Maps of the Heathcote Fault Zone. (a) Simplified map of the northern, central, and southern segments, showing outcrop extent of the Cambrian rocks. (b) Map and profile of the lower portion of the central segment, including structural data for the mélange zone and turbidites from the Red Hill area. All planes are plotted as poles. (c) Map and profiles of the northern part of the central segment and southern part of the northern segment. Structural data on equal angle stereonet is from the northern segment. All planes are plotted as poles (maps modified from Gray and Willman, 1991; Wohlt and Edwards, 1999).

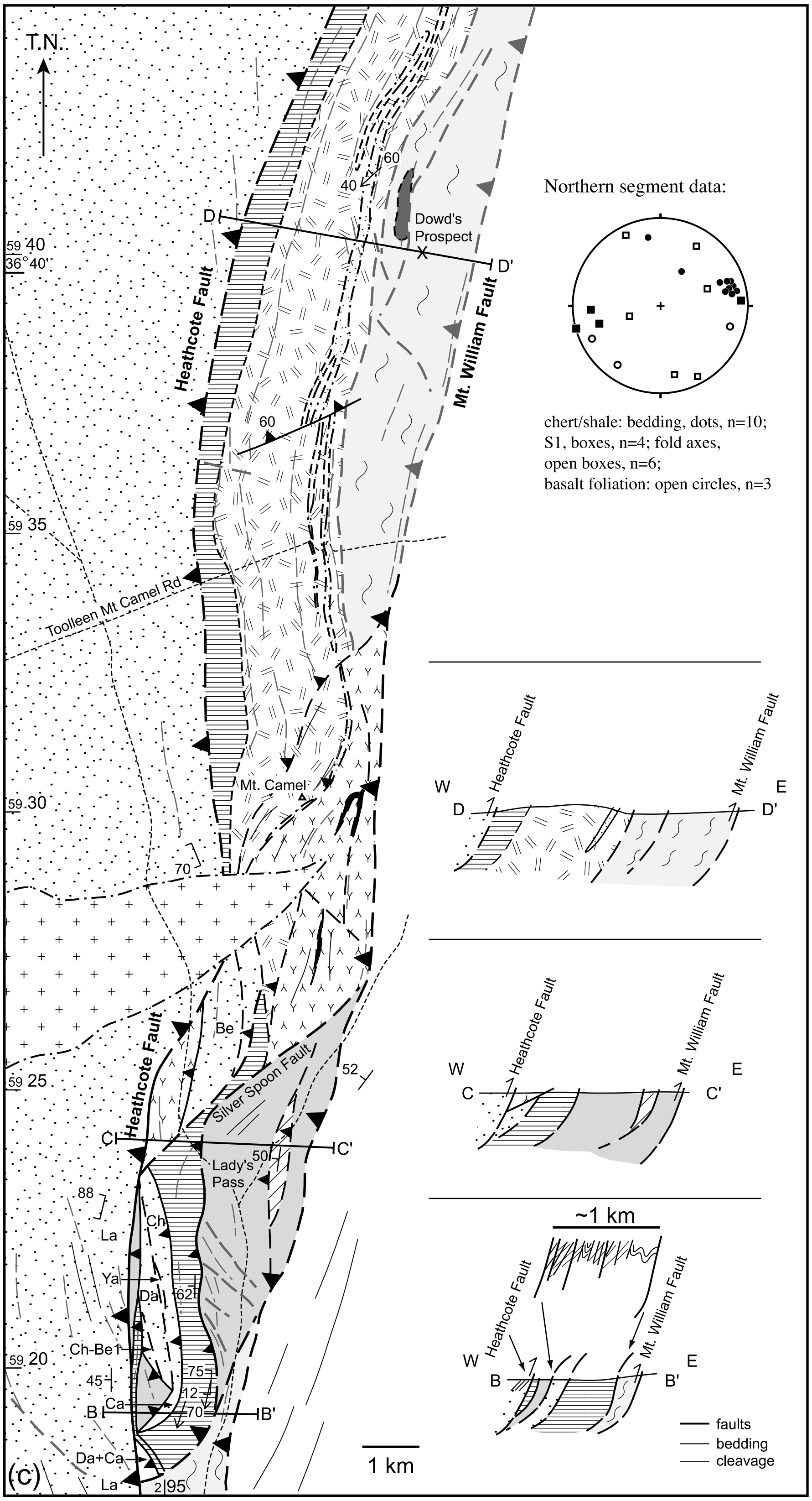
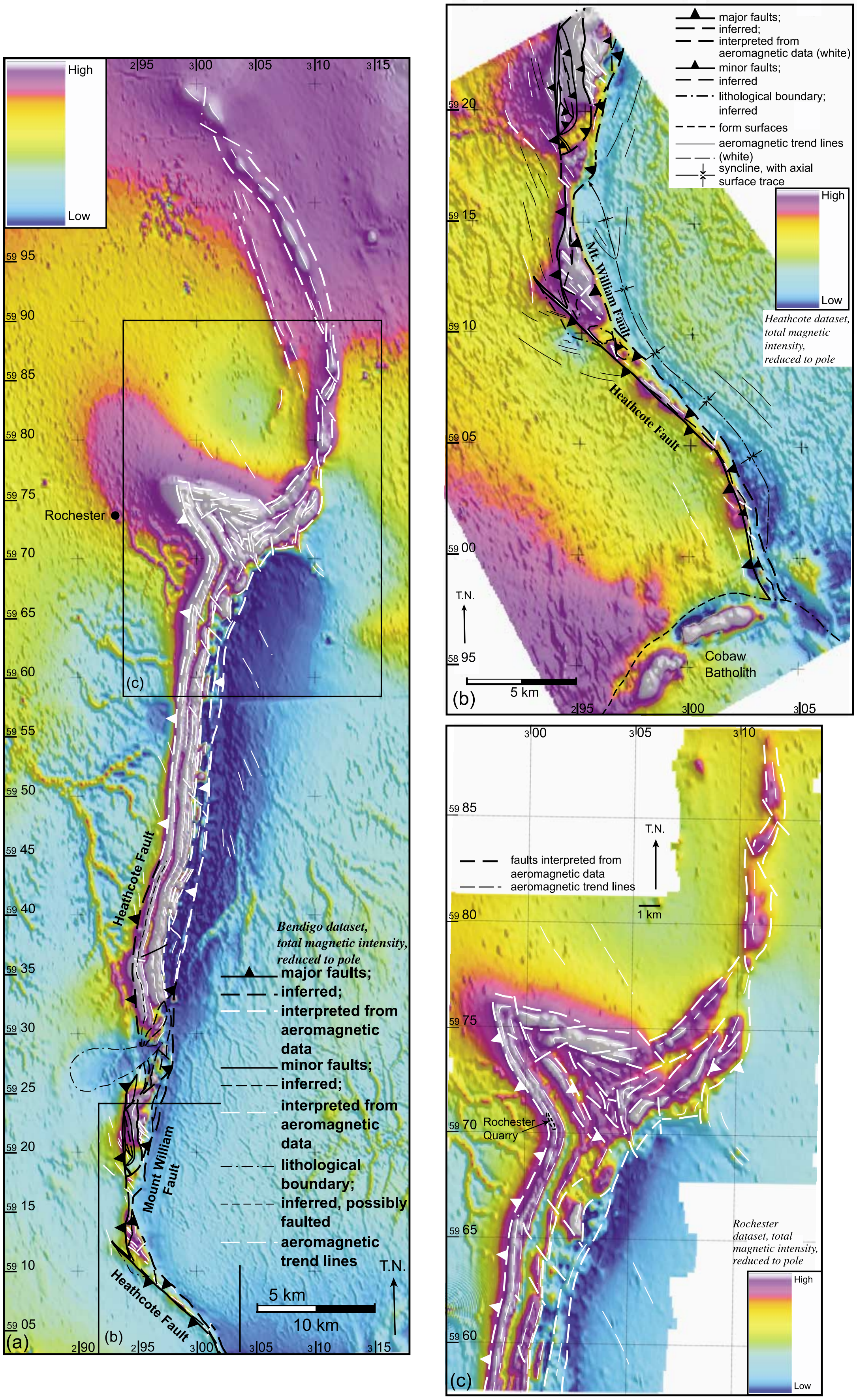


Fig. 3 (*continued*)


(a)
High
Low
Rochester
Heathcote Fault
Mount William Fault
Bendigo dataset, total magnetic intensity, reduced to pole
major faults;
inferred;
interpreted from aeromagnetic data
minor faults;
inferred;
interpreted from aeromagnetic data
lithological boundary;
inferred, possibly faulted
aeromagnetic trend lines
T.N.
5 km
10 km
(b)
(c)
major faults;
inferred;
interpreted from aeromagnetic data (white)
minor faults;
inferred
lithological boundary;
inferred
form surfaces
aeromagnetic trend lines
(white)
syncline, with axial surface trace
Heathcote dataset, total magnetic intensity, reduced to pole
Mt. William Fault
Heathcote Fault
Cobaw Batholith
faults interpreted from aeromagnetic data
aeromagnetic trend lines
1 km
Rochester Quarry
Rochester dataset, total magnetic intensity, reduced to pole

the western subprovince and southwest-directed tectonic vergence in the central subprovince is defined as the Governor Fault Zone (Figs. 1 and 2; VandenBerg et al., 1995, Spaggiari et al., in press). The fault zone crops out as structural highs lying unconformably beneath an en-échelon sequence of three, Late Devonian, transtensional basins that mark the transition from a marine to a continental setting (Fig. 2; VandenBerg et al., 2000). It is at least partially overridden by the Mount Wellington Fault Zone, which defines the eastern margin of the western subprovince (Fig. 2). The Heathcote Fault Zone, which marks a major boundary between two structural zones within the western subprovince, separates chevron-folded Ordovician turbidites linked to high strain zones adjacent to inter- and intra-zone faults, from gently folded, predominantly Silurian–Devonian turbidites to the east (Fig. 1; Gray and Willman, 1991; Gray, 1997).

3. Geometry and fabric character of the fault zones

3.1. Heathcote Fault Zone

Cambrian ophiolitic rocks are exposed in the northern, central, and southern segments of the Heathcote Fault Zone (HFZ; Fig. 3). They are bound by major west- or southwest-dipping thrust faults that are interpreted to have listric form and flatten at approximately 17 km depth (Gray and Willman, 1991; Gray et al., 1991). The fault zone shows marked lateral variation in exposed structural levels and lithology that relate to differences in displacement along faults within and bounding the zone (Gray and Willman, 1991). Differences in structural levels are largely defined by differences in metamorphic grade, structural complexity, and foliation intensity, and in places coincide with strike changes. The fault zone completely loses displacement within the southern segment, where the Mount William Fault steepens and steps east into rocks of similar age on either side (Fig. 3a; Gray and Willman, 1991). A conformable sequence of Cambrian, homoclinally west-dipping, prehnite-pumpellyite facies, tholeiitic basalt, volcaniclastics, chert and shale overlain by early Ordovician turbidites comprise the western margin of this segment (VandenBerg, 1991).

The northern segment is dominated by north-trending ridges of homoclinally west-dipping, prehnite-pumpellyite facies, tholeiitic basalt, dolerite and volcaniclastics with interbedded and overlying chert and silicified shale (cf. Crawford et al., 1984; Edwards et al., 1998). These structurally overlie fault slivers of boninite, andesite, basalt, chert, and turbidite in the northern part of the central segment (Figs. 3a and c and 4a and c). The basalt and dolerite are weakly foliated, and locally cut by fine bands of cataclasite. Chert and silicified shale sequences have a spaced cleavage axial planar to open to tight folds. The ridges coincide with strong linear features on aeromagnetic imagery, some of which correlate with Fe-rich and highly magnetic pelagic rocks (Fig. 4a and c). This highlights a pronounced curvature of the belt to the northwest where a structurally complex area of chevron folds is cut by numerous faults (Fig. 4c). This area is completely under cover but comparisons of total magnetic intensity, first vertical derivative images, and magnetic gradients suggest most faults in this area are steeply dipping, and that the western margin consistently dips to the west. Strongly deformed chert and silicified shale (Rochester Quarry; Fig. 4c) coincide with a strong magnetic high on the western margin. Tight to isoclinal folds in these rocks plunge moderately to steeply northwest and southeast, are upright or inclined to the northeast, and cut by steeply southwest-dipping reverse faults (Edwards et al., 1998). A sharp drop in magnetic signature to the east along the north–south section of the northern segment coincides with a change in lithology and flat topography (Figs. 3c and 4a; section D–D′). This correlates with weakly deformed tholeiitic rocks underlain by mélange similar to that in the central segment (Fig. 3c; drill core analysis, Dowd's Prospect; Spaggiari, 2002).

Where the mélange is exposed in the central segment the belt narrows markedly and changes strike from north–south to northwest–southeast (Figs. 3a and b and 4a and b; section A–A′). Here strongly deformed Ordovician turbidites are in direct fault contact with the mélange. The main foliation in the turbidites has a moderate to subvertical dip, trends east–southeast, and is locally folded into steeply southwest-plunging folds (Gray and Willman, 1991). The mélange contains blocks of variably deformed boninite, andesite, dolerite, ultramafics, chert, and volcanogenic sandstone, metamorphosed up to greenschist or blueschist conditions (Spaggiari et al., 2002a). The serpentinite/talc-chlorite matrix has a well-developed scaly foliation with a predominant southwest dip, folded into moderately north-west plunging, tight to isoclinal folds that are cut by small brittle faults and carbonate veins (Spaggiari et al., 2002b). Small blocks have pervasive foliations and are overprinted by well-developed crenulation cleavages, and silica and carbonate alteration. Blocks in the mélange greater than approximately 30 cm diameter have foliated margins and less deformed interiors, but rarely show any development of crenulation cleavage except on their margins. Diorite and

Fig. 4. Aeromagnetic images and interpretation of the Heathcote Fault Zone, showing large-scale geometry. Dashed lines are inferred whereas solid lines are based on field data. (a) Central and northern segments of the Heathcote Fault Zone. Data source: Bendigo dataset, Australian Geological Survey Organisation–Geoscience Australia. (b) Lower portion of the central segment. Data source: Heathcote dataset, Geological Survey of Victoria. (c) Rochester area of the northern segment. Data source: Rochester dataset, Geological Survey of Victoria.

microgranodiorite bodies within the mélange also have foliated margins and where exposed, faulted contacts with mafic mélange rocks (Fig. 3b).

West to northwest-dipping, elongate fault slices of Cambrian sedimentary rocks, high-Mg andesite, boninite, Ordovician turbidite and black shale are interpreted to form a series of stacked and disrupted duplexes, structurally above the mélange (Fig. 3c; section B–B′; cf. Gray and Willman, 1991). The main foliation in these fault slices is mostly west-dipping or subvertical, and more intense close to the fault slice margins. The most intensely deformed zones contain steep to moderately south-plunging, rootless fold hinges refolded by northwest-striking and plunging folds (Gray and Willman, 1991). Northeast-trending faults (e.g. the Silver Spoon Fault) appear to link with the Mount William Fault and may be 'roof thrusts' to the inferred duplex packages. The Mount William Fault can be traced on aeromagnetic imagery to the east, and appears to have cut up sequence through the mélange rocks (Fig. 4). Aeromagnetic imagery shows small, northeast- and northwest-trending faults with both sinistral and dextral apparent offset that disrupt belt-parallel faults and stratigraphy, but do not always offset the major bounding faults.

Major deformation and metamorphism in the HFZ occurred between ~455 and 440 Ma, coinciding with ongoing sedimentation further outboard (Melbourne zone; Foster et al., 1999). This is constrained by Ar/Ar ages of white mica from the main (S1) thrust-related fabric in Early Ordovician phyllite from the hanging wall of the Heathcote Fault, metamorphic biotite in diorite within the mélange, detrital mica ages in Melbourne zone rocks similar to fault zone fabric ages (~440 Ma; Foster et al., 1999), presence of slivers of early to middle Ordovician turbidites within the fault zone (Fig. 3), and fossil ages in the footwall turbidites (Melbourne zone; VandenBerg et al., 2000). Steeply plunging folds that are oblique to major bounding faults and occur within the hanging wall turbidites have been interpreted to relate to reactivation with a strike-slip component, but without significant displacement (Gray and Willman, 1991). Based on Ar/Ar data, this has been inferred to have occurred at ~425–420 Ma, followed by further reactivation at ~380 Ma (Foster et al., 1999). The youngest deformational events have clearly involved a component of thrusting on both the Heathcote Fault and particularly the Mount William Fault as they clearly truncate most of the small, northeast- and northwest-trending faults throughout the HFZ, as well as folds in the Siluro–Devonian rocks of the Melbourne zone (cf. VandenBerg et al., 2000).

3.2. Governor Fault Zone—Howqua

Cambrian ophiolitic rocks in the Governor Fault Zone (GFZ) at Howqua (Fig. 2) are preserved in two, elongate, northwest-trending fault slices, and as blocks and smaller fault slices in mélange (Fig. 5). From northeast to southwest (and structurally highest to lowest) the sequence consists of folded and faulted turbidites, folded bedded cherts and silicified shale, imbricated tholeiitic pillow basalts, dolerite, gabbro, volcaniclastics and chert, and imbricated mafic and ultramafic rocks including boninites (Fig. 6). These overlie an approximately 2.5-km-wide, folded and faulted mélange zone (see also Spaggiari et al., 2002a,b). As in the HFZ, foliation intensity increases with metamorphic grade and is indicative of the structural level exposed. Whereas the upper structural levels are dominated by brittle structures, mélange from the deeper levels is largely polydeformed. A magnetic model constructed along approximately the same line of section as Fig. 6 provided an independent test of the interpreted geometry, and showed a good correlation (Spaggiari, 2002).

The turbidite sequence is dominated by upright, gently southeast plunging chevron folds with a closely spaced, axial planar cleavage cut by small brittle faults (Figs. 5 and 6a). Crenulation cleavages and small kink-folds occur sporadically in the vicinity of brittle faults, and are probably fault-related. A subvertical, northwest-trending fault within the turbidite sequence separates Lower Ordovician (Lancefieldian), quartz–lithic–feldspathic sandstone and mudstone from Lower to Middle Ordovician (Bendigonian–Darriwilian), quartz-rich sandstone, mudstone and shale (Fig. 6a; cf. Fergusson, 1998). Structures in these rocks are truncated to the east by a subvertical, approximately north-trending, dextral strike-slip fault (Fig. 5). The contact between the turbidites and chert/silicified shale is also folded into gently southeast plunging folds, but is locally disrupted by brittle faults with minor displacement. The map pattern of the chert/silicified shale sequence is suggestive of a tapered sliver that thickens to the northwest where it passes underneath Late Devonian volcanics, and disappears completely to the southeast where turbidites are in direct contact with pillow basalt. Fold plunges within the sequence vary from steep to gentle, and north to southeast directions. Axial plane orientations are also variable but bedding dips are mostly to the northeast (Figs. 5 and 6a). Cleavage development is weak and mostly restricted to hinge zones.

The contact between the chert/shale and underlying pillow basalts is conformable, but locally offset by small faults. The map pattern indicates the tholeiitic mafic sequence is an elongate, tapered body that thins both to the northwest and southeast. It appears to be structurally thickened by imbrication as indicated by repetition of bedded chert and volcanic breccia within the pile that coincide with interpreted faults in the aeromagnetic data (Figs. 5–7). A steeply northeast-dipping fault (Mai Fault) separates the weakly deformed, tholeiitic mafic rocks from tholeiitic and boninitic, mafic and ultramafic rocks in the footwall sequence. Pillow basalts in the immediate hanging wall show marked carbonate alteration and moderate foliation development whereas serpentinised ultramafics in the footwall have a strong, 'scaly' anastomosing foliation

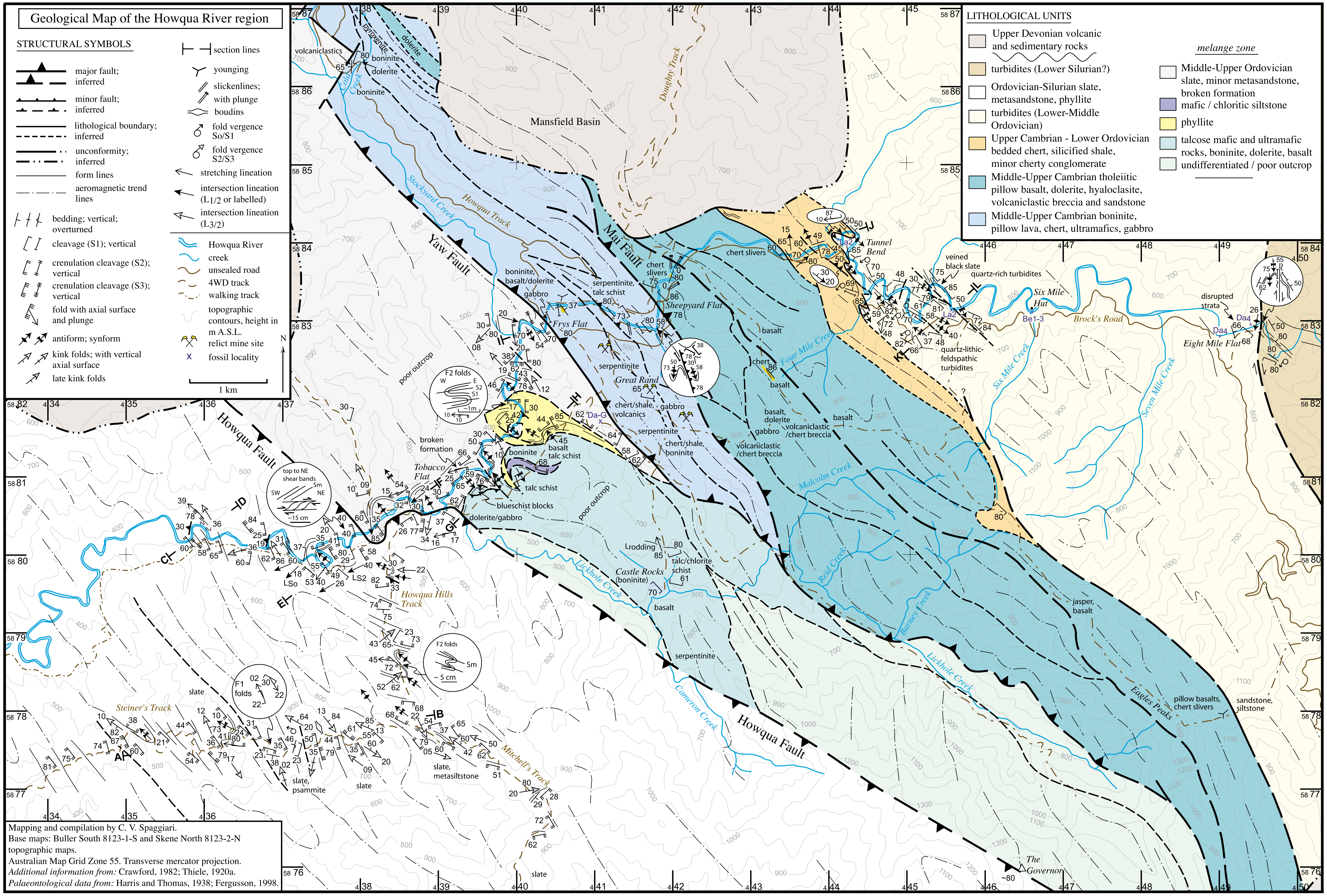


Fig. 5. Geological map of the Governor Fault Zone and part of the Mount Wellington Fault Zone in the Howqua River region.

occasionally cut by small mesoscopic or microscopic faults (Fig. 8a). Drag folds in splays in the footwall indicate a top to the southwest thrust sense. The mafic–ultramafic sequence forms a second elongate tapered body, bound to the west by the steeply northeast-dipping Yaw Fault. Mai Fault is interpreted to link into Yaw Fault to the southeast. The scaly foliation in the serpentinite is subparallel to a foliation in small mafic–ultramafic pods defined by blue–green sodic–calcic amphiboles and chlorite, indicative of intermediate pressure conditions (~4 kbars; Spaggiari et al., 2002a). Strongly deformed, gabbroic and ultramafic rocks are in fault contact with relatively undeformed pillow lavas and cherts that show consistent northeast-younging, indicative of imbrication. Neither this nor the overlying tholeiitic sequence show any evidence of folding.

Structurally underlying the mafic–ultramafic sequence is a mélange zone that consists of fault slices of basalt, dolerite, boninite, talc schist, phyllite, and slate (Figs. 5 and 6b; see also Spaggiari et al., 2002a,b). Unlike the overlying mafic sequences at least two phases of folding are evident resulting in a fold interference pattern. The first phase folds are predominantly tight to isoclinal, gently southwest plunging with variably dipping axial surfaces, and occur predominantly in the talc schist, phyllite, and slate. The second set can be traced across the mélange zone and the Howqua Fault into the Mount Wellington Fault Zone (Fig. 5). These have open, sinusoidal, rounded to kink-like form, plunge gently to moderately steeply both to the northwest and southeast, and have subvertical axial surfaces. The mélange zone is truncated to the southwest by the southwest-dipping Howqua Fault, where Mount Wellington Fault Zone rocks have been thrust over GFZ rocks in the footwall.

Mafic slivers and blocks in the mélange show heterogeneous foliation development, whereas talc schist, slate, and phyllite have three foliations of which the second is the most dominant. The talc schists form a matrix to mostly less deformed, more competent blocks or slices of basalt, dolerite or boninite, some of which, along with the matrix, have been metamorphosed to blueschist conditions (Spaggiari et al., 2002a). The main foliation is axial planar to tight to isoclinal folds that in places have been stretched to form a rodding lineation, indicative of high strain (Fig. 8b). No folding related to the first foliation has been identified.

The dominant foliation throughout the slate and phyllite is a crenulation cleavage (*S2*) defined by zones of recrystallised white mica and/or dark dissolution seams due to pressure solution (Fig. 8c). It is axial planar to tight to isoclinal folds, which fold bedding, an earlier foliation, zones of broken formation, and quartz veins. Because both foliations are mostly subparallel, the crenulation cleavage often has the appearance of a slaty cleavage except where the earlier foliation is preserved in hinges and some pressure shadows. Quartz-rich lithologies show development of mica beards off the ends of slightly elongate quartz grains. The earlier foliation (*S1*) is a closely spaced cleavage mostly subparallel to bedding, defined by both dark dissolution seams due to pressure solution and small white micas. Large quartz veins are boudinaged approximately parallel to the main foliation, whereas smaller quartz veins locally cross-cut it. Open folding of the mélange zone has produced small parasitic kink folds, and a discrete, second crenulation cleavage (*S3*), mostly due to pressure solution, in talc schist, slate and phyllite.

Zones of broken formation within the sedimentary sequence are indicative of tectonic stratal disruption early in the deformation history, and may relate to formation of the first foliation. Within these zones bedding has been fractured, pulled apart and is cut by small normal faults and fine, perpendicular veins. Cataclasis is evident in the necks of some blocks (see also Spaggiari et al., 2002b). This has produced a black mud-matrix enclosing rhomboidal blocks of sandstone, siltstone, and minor chert ranging in size from centimetre-scale to approximately 0.5 m (Fig. 8d), and chaotically veined and disrupted sequences (Fig. 8e). Larger sandstone blocks are mostly unfoliated except on their margins where the main foliation (*S2*) wraps around them. Some have quartz veins that terminate at the block margins, indicating that disruption took place in lithified rocks prior to the main deformation.

The timing of mélange formation is constrained by Ar/Ar dating of the main fabric (*S2*) forming white mica at 446 ± 2 Ma, and blueschist metamorphism (~450 Ma, U–Pb in titanite; Spaggiari et al., 2002b). These ages are consistent with the presence of graptolite fauna in slates in the mélange indicative of Middle to early Late Ordovician (~467–455 Ma) depositional ages (Teale, 1920a; Harris and Thomas, 1938). Turbidites above the pelagic section have fauna indicative of Lower Ordovician to Middle to early Late Ordovician depositional ages (~490–455 Ma; e.g. Fergusson, 1998). Turbidites east of the strike-slip fault at 8-mile Flat and west of the Howqua Fault (Fig. 5) have an inferred early Silurian age (~440 Ma; Fergusson, 1998; VandenBerg et al., 2000). Late Ordovician chert/shale sequences with interbedded sandstone and mudstone occur throughout the Tabberabbera zone, and together with the turbidites indicate that sedimentation continued during fault zone formation (cf. Foster et al., 1999).

3.3. Governor Fault Zone—Dolodrook

Cambrian ophiolitic rocks exposed in the GFZ at Dolodrook (Fig. 2) consist of serpentinised ultramafics (dunite, harzburgite, orthopyroxenite, podiform chromitite, and clinopyroxenite; Crawford, 1982) and mafic–ultramafic breccia, which together constitute an approximately 5-km-long, 1-km-wide body (Fig. 9). This is flanked by lenses of mafic mudstone and sandstone with minor conglomerates that include olistostromes of Cambrian limestone. Middle to Late Ordovician chert, silicified shale, and interbedded sandstone and mudstone are in fault contact with and surround the serpentinite body and mafic rocks. The Ordovician rocks are flanked by weakly deformed turbidites

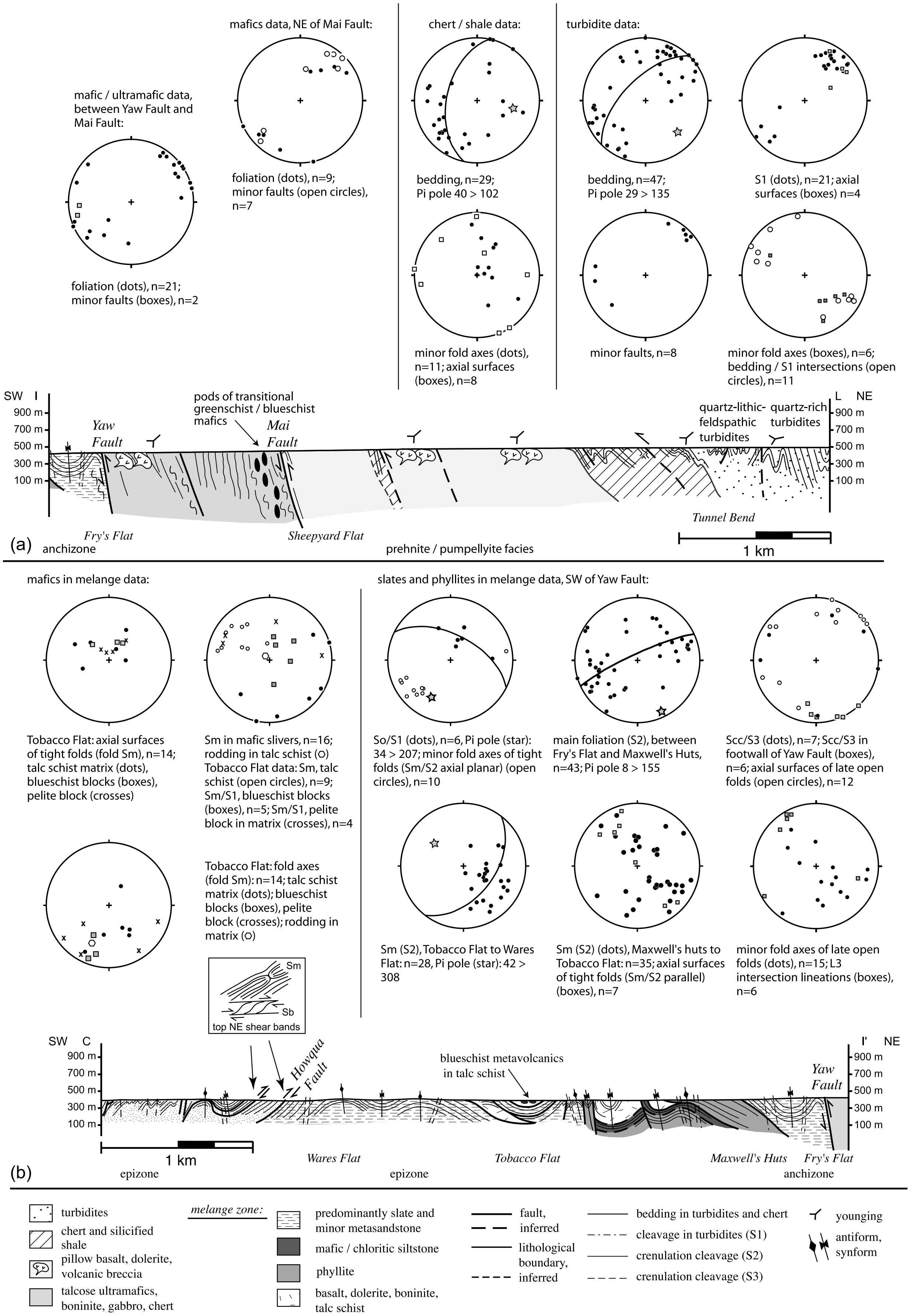


Fig. 6. (a) and (b) Composite profile of the Howqua River region. See Fig. 5 for section line locations. All equal angle stereonet data are from the Governor Fault Zone, and all planes are plotted as poles.

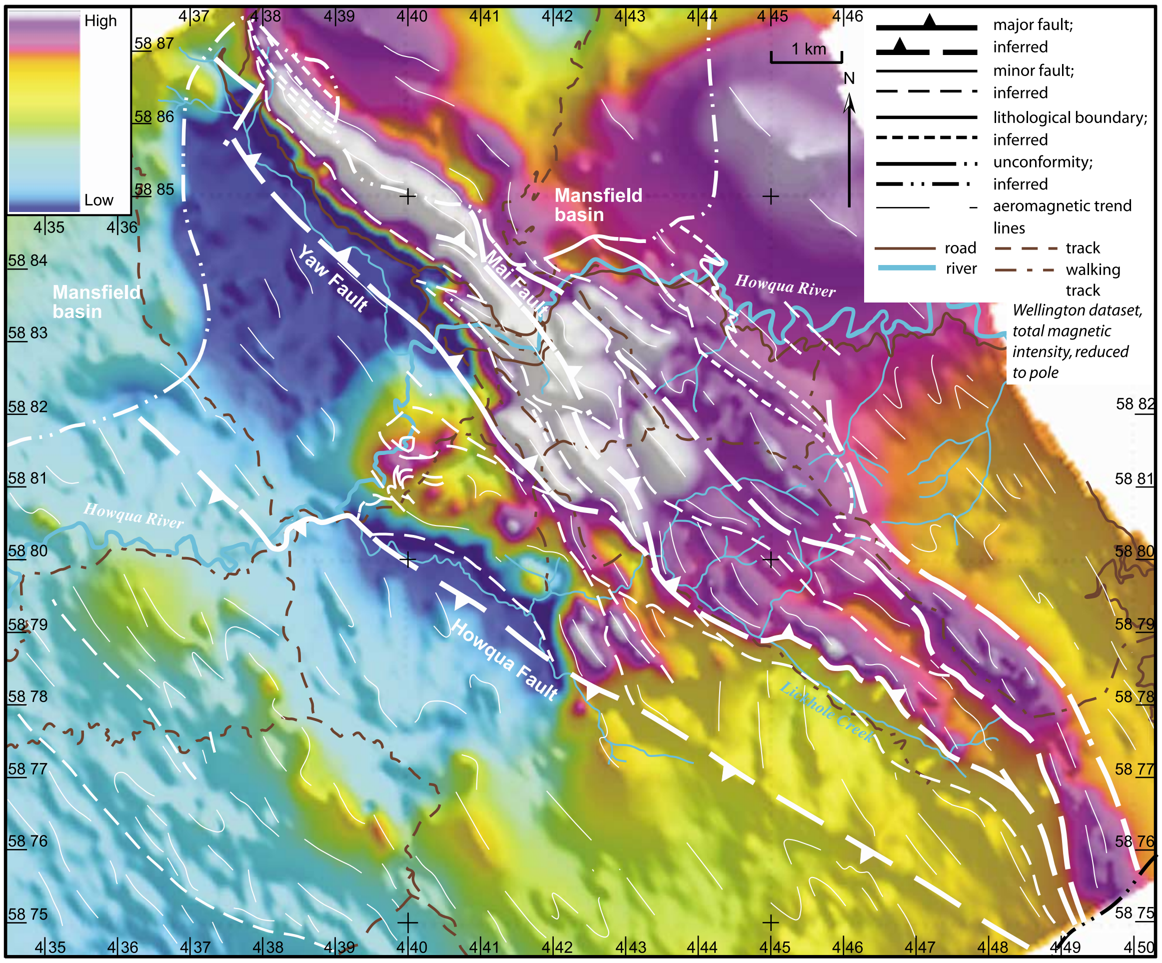


Fig. 7. Aeromagnetic image and interpretation showing large-scale geometry of the Howqua River region. Dashed lines are inferred whereas solid lines are based on field data. Radiometric data (not shown) were used to help determine contacts where magnetic signatures overlapped (e.g. Late Devonian basin volcanics and Cambrian mafics) and the extent of mafic–ultramafic rocks. Data source: Wellington dataset, Geological Survey of Victoria.

of probable Early Silurian age (Harris and Thomas, 1954). There is no indication of metamorphic grades higher than anchizonal or prehnite–pumpellyite facies in any of the rocks in this fault zone.

The serpentinite body trends northwest–southeast in the northwest, and east–west in the southeast and has a predominantly asymmetric, antiformal geometry with steeper dips on its northeastern and northern margins (Figs. 10 and 11). Towards the centre its margins steepen to subvertical dip, and it appears to narrow giving it a slightly curved geometry (Fig. 10). The antiformal geometry suggests that only the top of the body is currently exposed. Gradients in the aeromagnetic data indicate that the serpentinite body plunges gently to the southeast. A well-developed foliation within the serpentinite body has the same trend as its outline. It is mostly steeply dipping and anastomosing, but is locally folded into small-scale, tight folds. In the southeast the foliation appears to be folded into east-trending, upright open folds that have minor axial planar cleavage. The serpentinite is dominated by phacoidal texture defined by anastomosing foliations that enclose small lenticular pods of less foliated serpentinite, morphologically similar to S–C foliations. These lenses have shiny, striated fracture surfaces. The serpentine minerals are lizardite and chrysotile (XRD powder analyses; Spaggiari, 2002) and primary serpentinisation textures are mostly overprinted by serpentine, carbonate, and talc foliations, and carbonate veins.

In the northwest, Cambrian mafic sandstone and mudstone is interleaved with the Ordovician sequence forming a series of tapered fault slivers. Both bedding and cleavages are mostly steeply northeast- or southwest-dipping, and folds have gentle to steep, mostly southeasterly plunges (Figs. 9 and 10a). Open chevron folds predominate in these rocks but tight to isoclinal folds also occur in the Ordovician sequence, particularly close to fault contacts. The closely spaced, marked spread in ages of graptolite fauna in these rocks is also suggestive of tight folding and/or faulting (cf. Andrews, 1988). The strongest foliation throughout the Ordovician rocks is a locally developed, spaced cleavage defined by a combination of mica (mostly due to rotation) and dark dissolution seams due to pressure solution. This foliation is in places folded into tight to isoclinal folds that have little axial planar crenulation

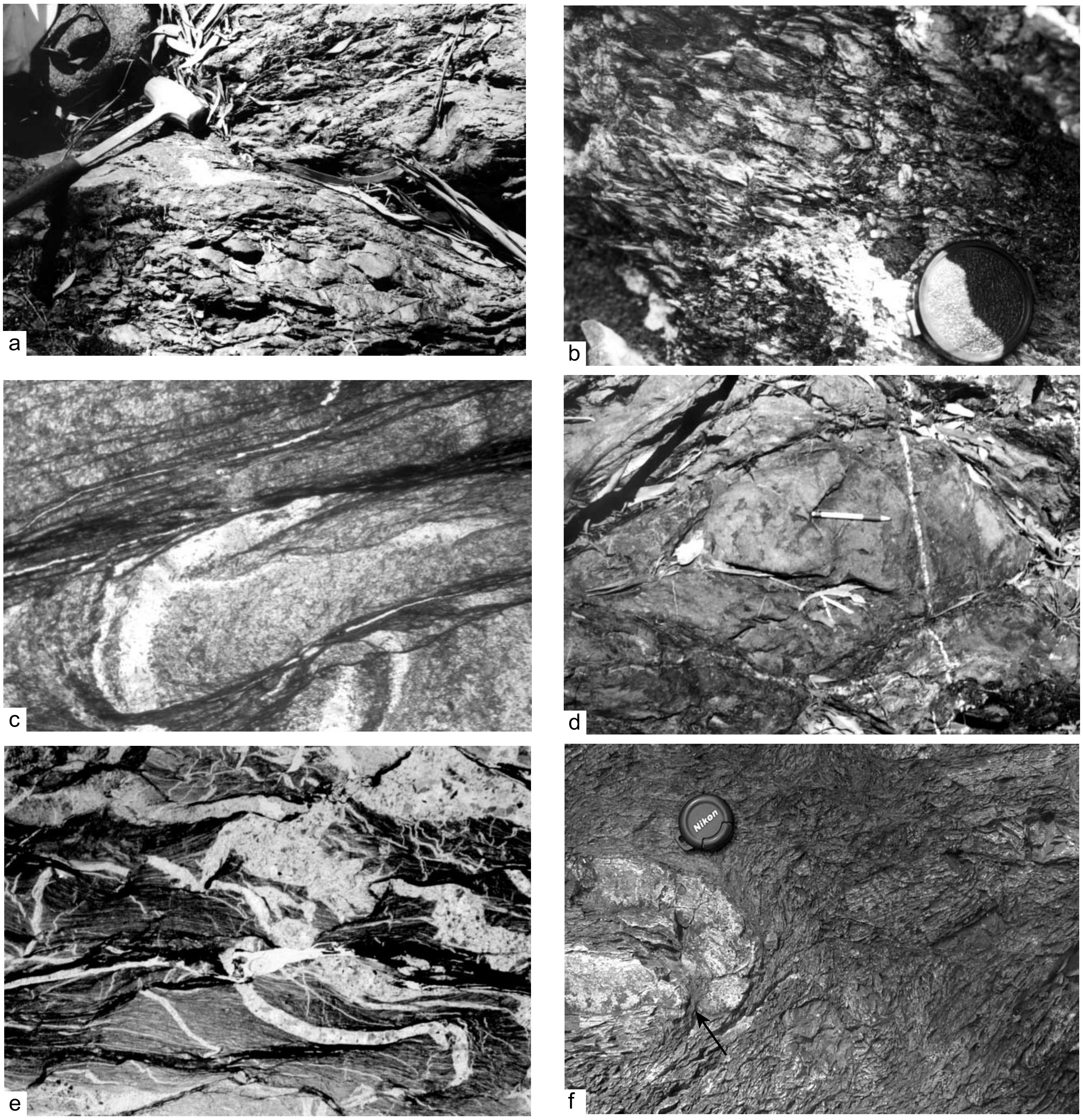


Fig. 8. Photos and photomicrographs from the Governor Fault Zone. (a) Photo of scaly foliation in talcose, serpentinised mafic–ultramafic section, Howqua. Sledge hammer is approximately 40 cm long. (b) Rodding in talc schist mélange matrix, Tobacco Flat, Howqua. Lens cap is approximately 4 cm. (c) Photomicrograph of phyllite from the mélange zone, Howqua. The dominant foliation (S2) is a crenulation cleavage, diagonal from upper right to lower left in the image. The earlier foliation (S1) and bedding are approximately vertical in the image. PPL. Base of photomicrograph is approximately 4 mm. (d) Photo of rhomboidal sandstone block in slaty mud-matrix, footwall of Yaw Fault, Fry's Flat, Howqua. Pencil is approximately 15 cm long. (e) Photomicrograph of chaotically disrupted and veined black late and minor sandstone from the mélange zone, Howqua. The main foliation (S2) is subhorizontal in the image and is overprinted by a weak crenulation cleavage (S3), diagonal from upper right to lower left. XPL. Base of photomicrograph is approximately 2 cm. (f) Scaly fabric in Ordovician mudstone, eastern Dolodrook River. Note the intrusion of mud into the disrupted sandstone layering (arrow, lower left), prior to folding. Lens cap is approximately 3 cm wide.

cleavage development. These folds sometimes have unusual morphologies, such as changing interlimb angles along their length, and plunge variation. The foliation in the hinges is at a low angle to bedding, and is mostly subparallel elsewhere. In the southeast, two generations of tight to isoclinal folds with minor development of axial planar crenulation cleavage are locally present. This correlates with exposure of slightly deeper levels adjacent to the gently southeast-plunging serpentinite body. Both fold sets have gentle to steep, mostly east-plunging fold axes and steep north or

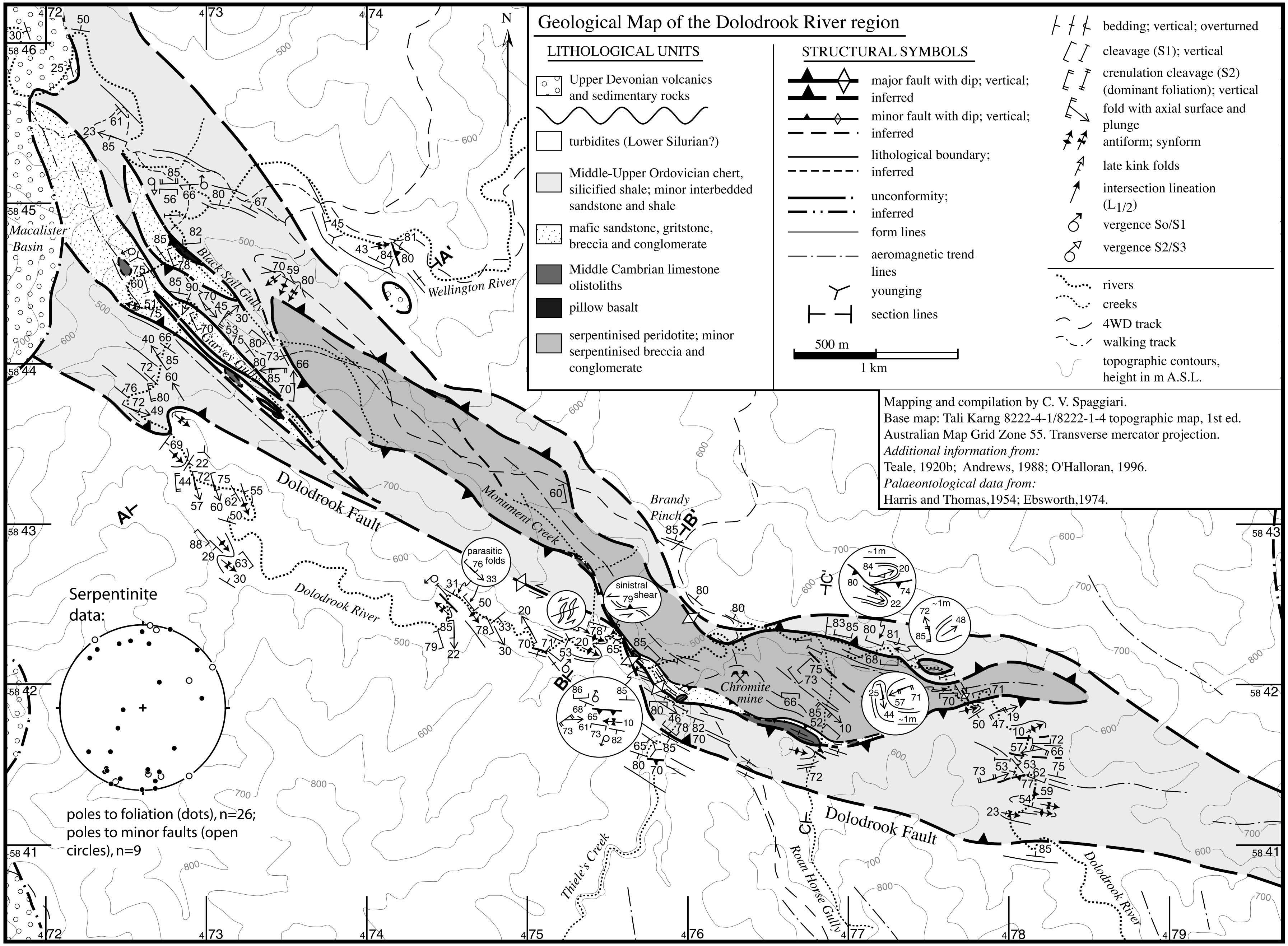


Fig. 9. Geological map of the Governor Fault Zone, Dolodrook River region.

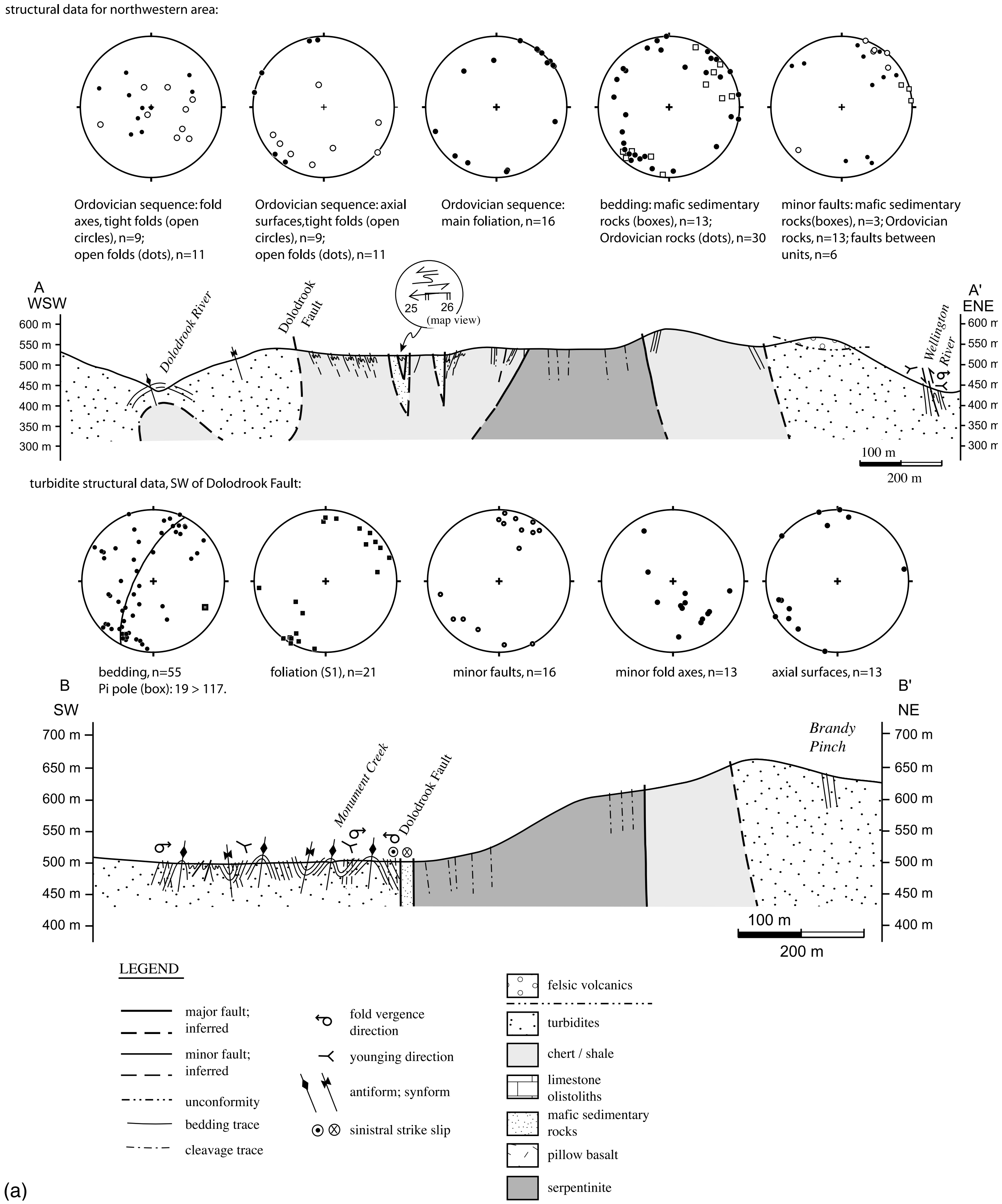


Fig. 10. Profiles and structural data from the Governor Fault Zone, Dolodrook River region. See Fig. 9 for section line locations. All planes on equal area stereonets are plotted as poles. (a) Northwestern part (section A–A′) and central part (section B–B′) of the map area. (b) Eastern part of the map area.

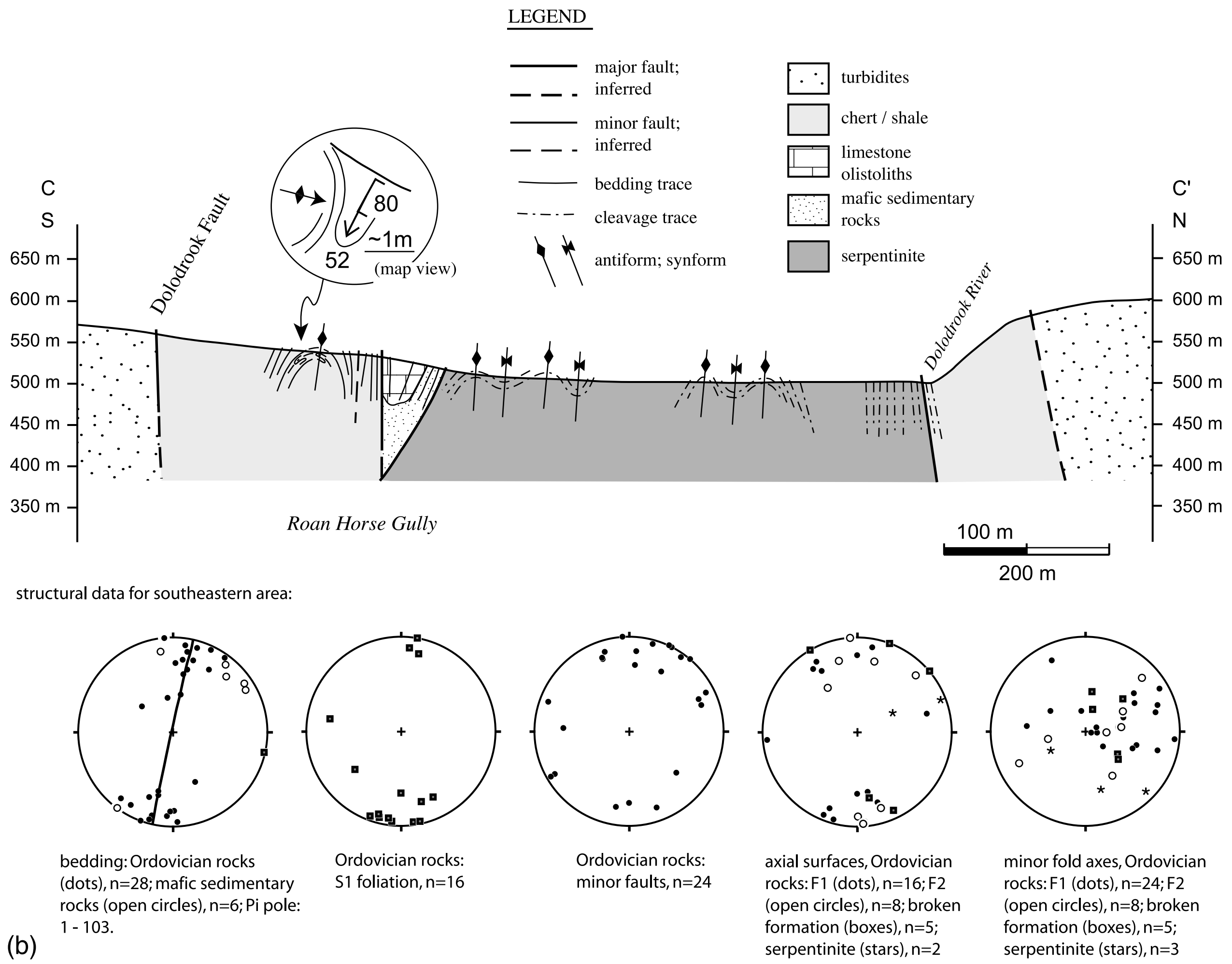


Fig. 10 (*continued*)

south dipping axial surfaces (Figs. 9 and 10b). In places these folds are refolded by small-scale open folds. Localised, late open folds in the Ordovician sequence have mostly steep plunges and variably orientated axial surfaces, some of which are oriented almost perpendicular to the main strike of the belt. The Ordovician sequence and the mafic/ultramafic rocks are cut by numerous, mostly northwest-trending and steeply dipping brittle faults associated with zones of cataclasite.

Zones of stratal disruption (broken formation) up to several metres wide occur in mudstone and sandstone within the Ordovician sequence. Folds within these zones have similar orientations to those outside the zones, and are cross-cut by late brittle faults (Figs. 9 and 10b). The broken formation is in part interleaved with the serpentinite along the northern margin of the body. Stratal disruption in these rocks is characterised by pulled apart sandstone beds resulting in isolated blocks in mudstone, some of which show rotation, and a strong bedding-parallel, scaly foliation in the mudstone matrix (Fig. 8f). The foliation is a spaced cleavage defined by rotated micas and dark seams due to pressure solution, and where incipiently developed consists of a fracture network with small polished and striated surfaces with mineral steps. Fine sand dykes predate foliation formation, and are subperpendicular to bedding. Both the scaly foliation and isolated fragments of sandstone layering are locally folded into isoclinal folds, and sometimes refolded into open folds. There is no development of axial planar cleavage, or cataclasis. Some of the folded sandstone layers are intruded by mud injections (Fig. 8f).

Turbidites in fault contact with Ordovician rocks on both sides of the serpentinite body are simply folded into predominantly gently southeast plunging, chevron or rounded open folds with steeply dipping axial surfaces, occasionally cut by small, northwest-trending, steeply dipping brittle faults (Figs. 9 and 10a). Folds on the north and northeastern side have a slight asymmetry indicative of southwest transport (Andrews, 1988). Where developed, axial planar cleavage is disjunctive and defined by rotated mica and chlorite, or due to pressure solution. The southwestern boundary between the turbidites and the Ordovician sequence is marked by the Dolodrook Fault, which is locally folded and has a mostly subvertical or steep northeasterly dip. En échelon vein sets on steeply dipping

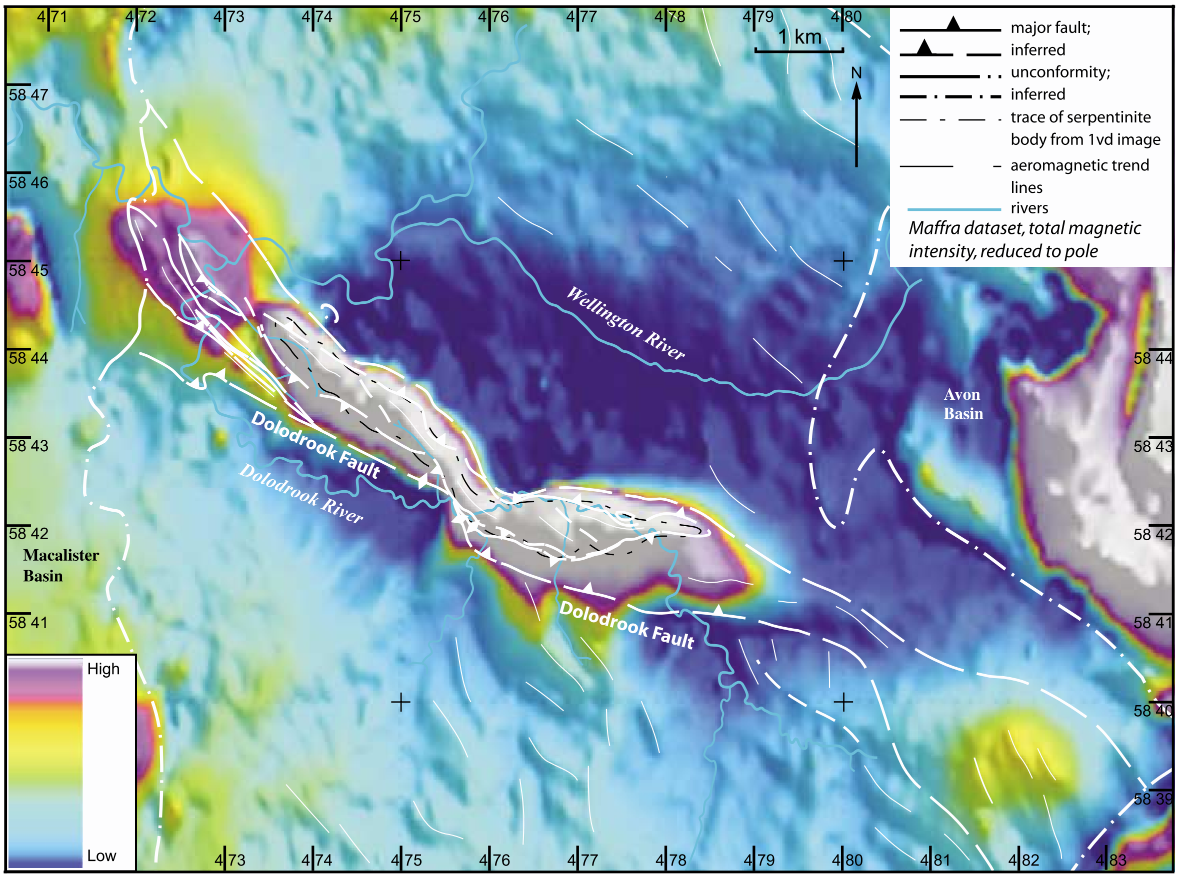


Fig. 11. Aeromagnetic image and interpretation showing large-scale geometry of the Dolodrook River region. Dashed lines are inferred whereas solid lines are based on field data. The total magnetic intensity outline shows deep level contacts of the serpentinite body, whereas the black dashed line is the trace of the serpentinite body from a first vertical derivative image and shows shallower level contacts. Airphoto interpretation and ground mapping show the ground level contacts. These allow determination of the 3-D geometry of the serpentinite body. Data source: Maffra dataset, Geological Survey of Victoria.

planes of adjacent minor faults are indicative of a component of sinistral strike-slip displacement.

4. Fault zone evolution

4.1. Heathcote Fault Zone

Formation of the HFZ involved emplacement of ophiolitic slivers into the deforming turbidite wedge, resulting in a complex zone of largely west-dipping fault slices of variable lithologies and grade that have marked lateral variation and strike changes. The timing of thrusting and emplacement is constrained by Ar/Ar dating of the main foliation in the hanging wall turbidites, and metamorphic biotite in metadiorite within the mélange, synchronous with turbidite deposition further outboard (~455–440 Ma; Foster et al., 1999; Spaggiari et al., 2002b). Exposure of different crustal levels along strike links to variation in magnitude of displacement along the fault zone, with minimal displacement at the terminations where shallower stratigraphic levels are exposed. This is exemplified by folded Fe-rich pelagic rocks in the northern segment (Fig. 4c) and at the tip of the southern segment where Ordovician–Silurian turbidites straddle the fault zone (Fig. 3a). Maximum displacement is indicated in the central segment where deeper levels are exposed, represented by rocks with greater structural complexity, more pervasive foliation, and higher estimated metamorphic pressure and temperature. The presence of blueschist metavolcanic blocks in the mélange, and increased deformation intensity, has been interpreted to relate to underplating beneath imbricated or duplexed upper oceanic crust within the turbidite wedge (Spaggiari et al., 2002a).

4.2. Governor Fault Zone, Howqua

The geometry and chronology of structures preserved at Howqua can be interpreted in terms of disruption of oceanic crust during underthrusting, imbrication, accretion, and underplating. Faulting within the turbidites at the top of the fault zone suggests the possibility of a ‘roof thrust zone’ and duplexing of the ophiolitic rocks as they were decoupled. Examples of this include locations where turbidites are in direct fault contact with pillow basalts to the southeast, and where quartz–lithic–feldspathic turbidites are in fault contact with more quartz-rich turbidites (Figs. 5 and 6a). Strongly deformed mafic–ultramafic rocks at the base of the fault slice (section between Yaw Fault and Mai Fault) may represent a ‘floor thrust zone’, as they partially consist of the deepest parts of the oceanic crustal stratigraphy, show the most pronounced foliation development, and have slightly higher estimated metamorphic pressure and temperature (Fig. 6; Spaggiari et al., 2002a). These ‘floor and roof’ zones most likely did not develop as smooth breaks, but involved disruption and variation of the initiation point and level of structural break over a period of time. This may have been in part due to the lack of a significant slip horizon within the turbidite section, and a non-layer-cake stratigraphy in the floor thrust zone.

The higher metamorphic pressure and temperature, and greater structural complexity of the mélange zone below Yaw Fault are indicative of maximum disruption to produce block-in-matrix type mélange, and underplating beneath oceanic crustal slivers. Ophiolitic rocks within the mélange are predominantly volcanic or doleritic, and indicate that it is the upper stratigraphic levels of the oceanic crust that are disrupted during underthrusting. Partial exhumation of the blueschist rocks resulted in interleaving with underplated slate, phyllite, and slices of basalt and dolerite, followed by tight to isoclinal folding of the now complete mélange. Rodding in the talc–schist matrix that hosts the blueschists is indicative of rotation of fold axes into the transport direction (to the southwest), and matches the orientation of fold axes of tight to isoclinal folds within the slate and phyllite, and stretching (boudinage) of large quartz veins (Fig. 6b).

Estimated P–T conditions in the mélange range from 7–9 kbars and $<450\,^{\circ}C$ (blueschists; Spaggiari et al., 2002a) to anchizonal/subgreenschist and intermediate P (~4 kbars, micas from the dominant S2 foliation in the slates; average illite crystallinity = 0.25 and $b_o = 9.026$; Spaggiari, et al., in press). This indicates that the blueschists did not require more than approximately 12 km of partial exhumation prior to interleaving, and not more than approximately 25 km in total. The illite crystallinity and b_o data indicate removal of approximately 10–12 km of overburden following Late Ordovician interleaving and prior to deposition of unconformably overlying Late Devonian volcanics and sedimentary rocks. This suggests that wedge thickening by underplating may have been balanced by significant erosion. Subsequent collision of the Tabberabbera zone with the eastern Melbourne zone (Figs. 1 and 2), and formation of the Howqua Fault, produced the open folds in the mélange, and most likely reactivated and possibly steepened the major faults such as Yaw Fault and Mai Fault. Sections above Yaw Fault appear to have also been affected as indicated by small back-thrusts, offsets of contacts, slickensides in the mafic sections, and steepening of northwest–southeast trending axial planes in the turbidite section.

4.3. Governor Fault Zone, Dolodrook

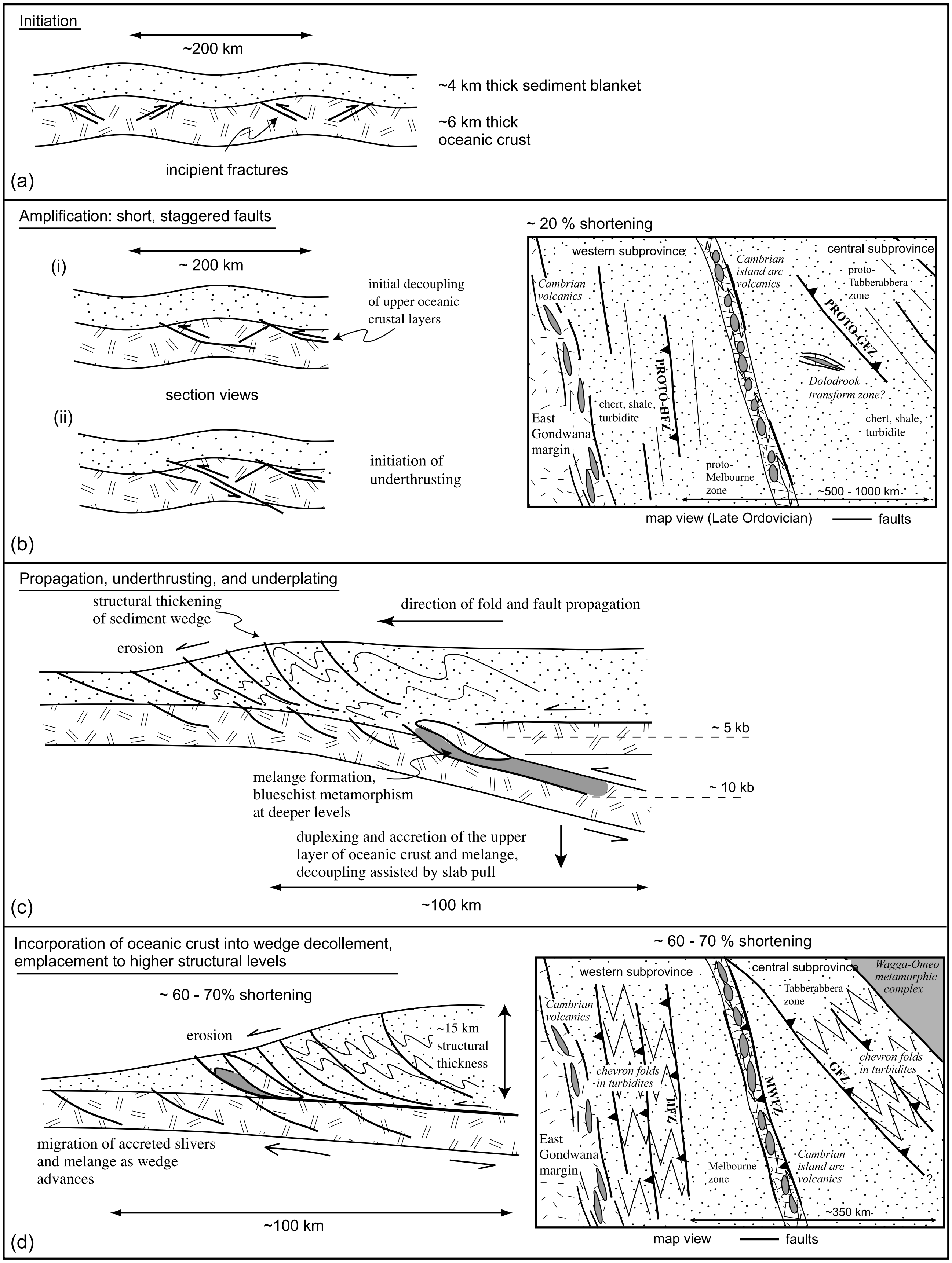
Structural evolution of the GFZ at Dolodrook has taken place at relatively shallow crustal depths, and is interpreted to have involved offscraping of a Cambrian topographic high on the seafloor (Spaggiari et al., 2003), followed by disruption and compression during accretion. Faulting processes during suprasubduction zone crustal formation may have led to emplacement of the serpentinite body within a transform or normal fault, leaving it in an elevated position with respect to the surrounding ocean basin. Alternatively, the serpentinite body may represent a fault slice only related to the surrounding younger sedimentary rocks by post-Ordovician faulting.

The early deformation history within the Ordovician sequence has involved stratal disruption, and folding of partly lithified rocks. Partial lithification may have affected mechanical behaviour, resulting in variable plunges of isoclinal fold axes and localised refolding, and allowing these rocks to behave in a ‘ductile’ manner with little development of axial planar cleavage. Apparent fold axis rotation is unlikely to be due to thrusting as the lack of downdip stretching lineations, rodding, or development of pressure shadows suggests these rocks did not undergo high strain or recrystallisation during faulting. Stratal disruption is interpreted to have taken place in partly lithified rocks as both ductile and brittle behaviour appear to have occurred simultaneously. Pulled apart sandstone layering and development of scaly foliation has semi-brittle characteristics whereas tight folding of the foliation and sandstone layering, and intrusion of mud into semi-soft sandstone during folding has semi-ductile characteristics (Fig. 8f). Brittle faulting and cataclasite zones have mostly occurred late in the deformation history as they truncate foliations at contacts, cross-cut folds, and mark a transition to fully lithified rocks.

The main foliation in the Ordovician sequence and mafic sedimentary rocks is interpreted to relate to subhorizontal stresses as the serpentinite body and overlying sedimentary rocks were offscraped and accreted to the turbidite wedge. The very low metamorphic grade, and the characteristics of the folds and foliations are consistent with well-documented examples of offscraped and accreted rocks from elsewhere (e.g. Barbados and the Middle America trench, southern Mexico; Lucas and Moore, 1986; Moore et al., 1986; see also Sample and Moore, 1987).

5. Thrusting and underthrusting in intra-oceanic environments

The geometrical relationships of the ophiolitic slices within the turbidite wedges is similar to observations of accreted oceanic crustal slices in modern accretionary environments. Seismic imaging has shown the presence of large-scale duplex-like structures in the New Britain


Initiation
~200 km
~4 km thick sediment blanket
~6 km thick
oceanic crust
incipient fractures
(a)
Amplification: short, staggered faults
~ 200 km
(i)
initial decoupling
of upper oceanic
crustal layers
section views
(ii)
initiation of
underthrusting
~ 20 % shortening
western subprovince
central subprovince
Cambrian
volcanics
Cambrian
island arc
volcanics
proto-
Tabberabbera
zone
PROTO-GEZ
PROTO-HFZ
Dolodrook
transform zone?
chert, shale,
turbidite
East
Gondwana
margin
chert, shale,
turbidite
proto-
Melbourne
zone
~500 - 1000 km
map view (Late Ordovician)
faults
(b)
Propagation, underthrusting, and underplating
structural thickening
of sediment wedge
direction of fold and fault propagation
erosion
~ 5 kb
~ 10 kb
melange formation,
blueschist metamorphism
at deeper levels
duplexing and accretion of the upper
layer of oceanic crust and melange,
decoupling assisted by slab pull
~100 km
(c)
Incorporation of oceanic crust into wedge decollement,
emplacement to higher structural levels
~ 60 - 70 % shortening
~ 60 - 70% shortening
erosion
~15 km
structural
thickness
migration of accreted slivers
and melange as wedge
advances
~100 km
western subprovince
central subprovince
Wagga-Omeo
metamorphic
complex
Cambrian
volcanics
Tabberabbera
zone
chevron folds
in turbidites
HFZ
MWFZ
GFZ
chevron folds
in turbidites
East
Gondwana
margin
Melbourne
zone
Cambrian
island arc
volcanics
~350 km
map view
faults
(d)

accretionary wedge in the Solomon Sea, which, in conjunction with magnetic data, are interpreted as accreted ophiolitic slivers (Bernstein-Taylor et al., 1992). Similar observations have been made and tested by deep sea drilling or observed on land in the Sulu Sea and South China Sea (Rangin et al., 1995). It is clear that ophiolite accretion does take place within forearcs, but the mechanics of emplacement, and particularly how this may occur at deeper levels, are not well understood.

Major fault zones such as the HFZ and GFZ have been interpreted as having formed by underthrusting of oceanic, suprasubduction zone crust during basin closure, with the Delamerian (Gondwana) margin acting as a backstop relative to the western subprovince (Fig. 1; Gray and Foster, 1998). On a larger scale, marginal basin closure may have been initiated and driven by a change in convergence relative directions and rates between Australia and the palaeo-Pacific plate in the Late Ordovician, because of plate reorganisations suggested by clockwise rotation of the Gondwana apparent polar wander path in the Late Ordovician and Early Silurian (Li et al., 1990). Significant counterclockwise rotation of Australia in the Late Silurian–Early Devonian (Li et al., 1990) coincides with ~420 Ma Ar/Ar ages of reactivation in the HFZ and deformation in the Tabberabbera and Wagga-Omeo structural zones (Fig. 1; Foster et al., 1999).

The structural and metamorphic data from the fault zones are indicative of thrusting in relatively cool conditions, but it is unclear why they form linear belts with distinct along-strike variation. It has been noted that major faults containing Cambrian oceanic crust within the western subprovince are regularly spaced across strike at intervals of approximately 100–150 km (Gray and Foster, 1998). This has been attributed to the horizontal strength of the oceanic crust (beam strength), and is also probably influenced by the 'overburden' effect of the large turbidite pile (Gray and Foster, 1998). The presence of upper stratigraphic levels of oceanic crust in the hanging walls of these faults requires a break within that crust, while the consistent presence of Lower Ordovician (Lancefieldian) turbidites in the hanging walls of intra-zone faults within the western subprovince requires a higher break between the oceanic crust and the turbidite pile (Gray and Willman, 1991). These features are indicative of two décollement horizons, but do not explain the along-strike variation and non-uniform exposure of crustal levels within the major fault zones.

5.1. Proposed model of oceanic thrusting

Fig. 12 is a series of schematic diagrams illustrating how these fault zones may develop by underthrusting of oceanic, suprasubduction zone-type crust during convergence. Deformation of the oceanic crust may be initiated by long wavelength buckling at the onset of convergence (Fig. 12a). In the central Indian Basin of the Indian Ocean observations of undulating topography with ~1 km amplitude and 100–300 km wavelengths, east–west-trending thrust faults, and intraplate seismicity over distances greater than 1000 km indicate north–south shortening of the oceanic lithosphere by buckling and faulting (Royer and Gordon, 1997; see also Gerbault (2000) for numerical modelling of these data for required stresses). Similar observations have been made along the eastern margin of the Japan Sea, and interpreted to relate to incipient subduction due to convergence (Tamaki and Honza, 1985; Rangin et al., 1995). Pre-existing irregularities such as topographic highs associated with variable lithologies in the oceanic crust may help fold nucleation, which may in turn lead to fault activation. Inversion of normal faults formed during development of the oceanic crust may also contribute to fault zone initiation. At approximately 20% shortening, these faults may either begin to decouple the oceanic crust, perhaps along hydrothermally altered sections (e.g. Kimura and Ludden, 1995), and/or cut through the entire crust and therefore initiate underthrusting (Fig. 12b). This may be assisted where variable density in the oceanic crust occurs (e.g. serpentinised sections) or where transform faults are located (e.g. Casey and Dewey, 1984). In plan view these faults are likely to have a staggered morphology, as would be expected where the overall amount of shortening is low. Once underthrusting is underway, the faults may merge and grow laterally as deeper levels within the oceanic crust fail (Fig. 12c). In this scenario the oceanic crust is already partly disrupted prior to underthrusting, but significant disruption takes place during underthrusting to form fault slivers and eventually, mélange. As the system matures and flexural rigidity of the plate is overcome, decoupling of the oceanic crust may also be assisted by the downward pull of the slab, which may also help continue to drive underthrusting. Episodic thrusting within the wedge and tiered decollements

Fig. 12. Schematic diagrams illustrating deformation of oceanic crust under compression and incorporation of fault slivers and mélange into a turbidite wedge. (a) Large-scale buckling and incipient fractures form in the oceanic crust of the marginal basin at the onset of convergence. (b) At approximately 20% shortening fractures in the oceanic crust begin to increase in number and magnitude. The faults are short and staggered, and are overlain by a thick turbidite blanket. The length and position of the Cambrian island arc, relicts of which are now preserved in the Mount Wellington Fault Zone, are inferred. (c) Convergence during basin closure leads to underthrusting, possibly initiated at a transform fault, or as the initial fractures cut through irregularities in the oceanic crust. This leads to disruption of the upper oceanic crust, and formation of mélange. Decoupling and underplating may be assisted by slab pull as the system matures. Accreted units are propagated forwards and upwards by lateral wedge migration and underplating during underthrusting. (d) The oceanic crustal slivers and mélange are incorporated into the basal décollement of the wedge and thrust to higher crustal levels. The major faults have grown laterally but do not cover the full length of the basin.

may help transfer the fault slivers and mélange to the hanging wall, and propagate them trenchwards. As the amount of shortening of the wedge increases, propagation along the basal décollement brings the accreted oceanic slivers and mélange to higher crustal levels, now exposed in the hanging walls of the major faults (Fig. 12d; cf. Gray and Foster, 1998).

The non-uniform development of this basal décollement reflects the accretion of oceanic materials from different crustal levels, and lateral growth of the fault zones during deformation of the oceanic substrate prior to propagation along the décollement. The metamorphic assemblages and the predominantly brittle character of these fault zones are indicative of relatively cool conditions. The presence of low grade blueschists in mélange are perhaps indicative of the deepest levels at which these types of fault zones may develop, that is, at depths not greater than 25–30 km. High fluid activity is indicated by prolific vein development at all structural levels observed, and by alteration rinds on blocks in the mélange (see also Spaggiari et al., 2002a). These features support an interpretation of thrusting or underthrusting of oceanic crust during periods of convergence (cf. Gray and Foster, 1998; Foster et al., 1999).

5.2. Problems of footwall versus hanging wall accretion

Accretion in the thrust wedge is defined as transfer from the footwall to the hanging wall, but because discrete footwall and hanging wall lithologies cannot be defined, the resultant geometry makes it impossible to determine whether emplacement of the ophiolite slices is purely by accretion, or a combination of accretion and wedge collapse (Fig. 13). It is evident that what is preserved in the Heathcote and Governor Fault Zones is predominantly upper rather than lower oceanic crustal stratigraphies but, apart from offscraped slices such as topographic highs (e.g. Dolodrook), these may have originated from either the footwall or hanging wall (Fig. 13). Pillow lavas metamorphosed to blueschist facies in mélange (Spaggiari et al., 2002a) are perhaps more likely to have been derived from the footwall (lower plate) as they would require underthrusting to depths possibly beyond where the hanging wall breaks. The matrix to the blocks may have formed by mixing with ultramafics from deeper parts of the hanging wall (upper plate). Fault slivers structurally above the mélange, however, may have been derived from either the footwall or hanging wall, or both (Fig. 13).

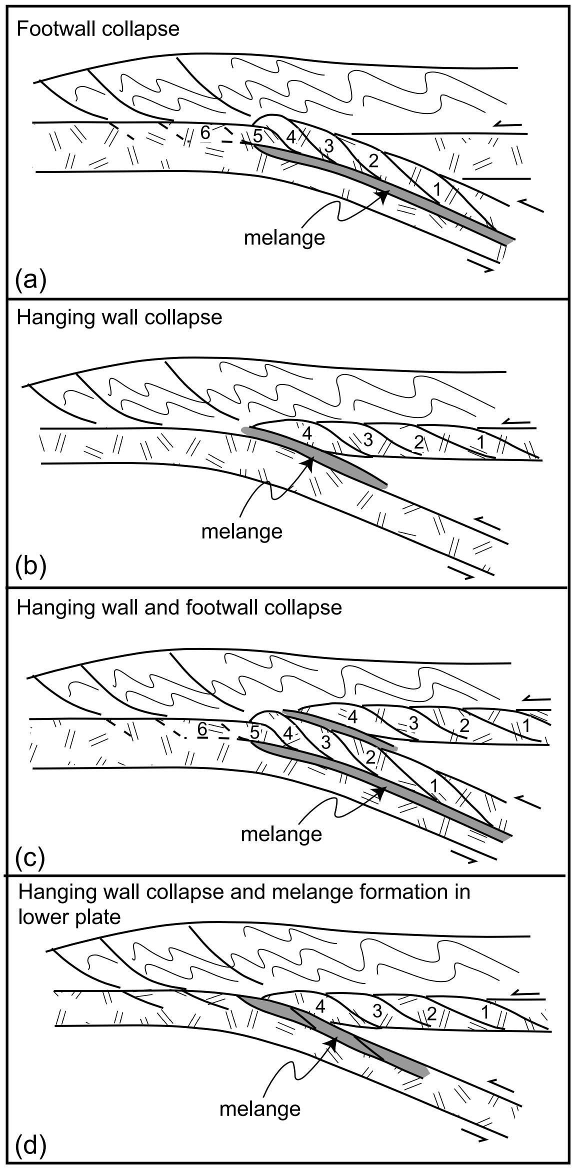


Fig. 13. Possibilities of ophiolite emplacement by footwall collapse, wedge collapse, or both, with duplexing of the oceanic crust (see also fig. 19 of Boyer and Elliot, 1982). (a) Underthrusting with progressive footwall collapse, and rearwards propagating duplexes indicated by numbering of duplexes. Mélange may form beneath the duplexes where maximum disruption occurs. Forward propagation of the wedge would occur along the basalt/turbidite interface, without deforming the underlying oceanic crust in the upper plate. (b) Underthrusting with hanging wall collapse, and rearwards propagating duplexes. Mélange would probably form in the decoupled zone between the duplexes and underthrusting plate. The lower plate is not deformed during underthrusting. (c) Underthrusting with duplexing in both plates, and mélange formation either between the plates or beneath duplexes in the lower plate as in (a). (d) Underthrusting with duplexing in the upper plate, and mélange formation in the underthrust plate.

6. Conclusions

Oceanic crustal rocks are preserved in major fault zones of the Lachlan Orogen as fault slivers, offscraped wedges, or mélange, and are examples of Cordilleran-type ophiolites. They are typified by their fragmentation, lack of thick mantle sections, pervasive low temperature metamorphism, and brittle character. Unlike most Tethyan-types, these ophiolites are dismembered, occur as fault slices with elongate, tapered geometries, and lack high temperature, strongly deformed, metamorphic soles. These features, and their position within turbidite wedges rather than overlying continental basement, are consistent with the interpretation that they were emplaced as fault slices and mélange during underthrusting of cool, ~50 m.y. old, suprasubduction zone-type oceanic crust.

In both the HFZ and GFZ, differences in along-strike exposure of different crustal levels is interpreted to relate to non-uniform displacement during lateral growth of major faults. Accretion takes place by either offscraping or underplating, but hanging wall (wedge) collapse may also occur. Décollement formation within the oceanic crust is not uniformly extensive in the initial stages, but is a clear requirement in the final stages of transfer of oceanic crustal slices to higher crustal levels, where they occur in the hanging walls of major faults.

The formation of Cordilleran-type ophiolites such as those of the Lachlan Orogen is a function of a non-collisional, intra-oceanic tectonic setting, where closure of a backarc marginal basin has produced large-scale fault zones incorporating suprasubduction zone-type oceanic crust. The nature of this oceanic crust, with its topographic highs and presumably complex primary structure may have enhanced nucleation of the host fault zones, leading to underthrusting. Thus, the tectonic setting, presence of cool, old, complex crust, and low geothermal gradient are perhaps all features that lead to the production of Cordilleran-type ophiolites.

Acknowledgements

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