The evolution of an exposed mid-lower crustal attachment zone in Fiordland, New Zealand

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Abstract. Studies of convergent margins suggest that large subhorizontal shear zones in the lower crust help regulate how displacements are transferred horizontally and vertically through the lithosphere. We present structural data from the Fiordland belt of southwest New Zealand that illustrate the progressive evolution of a 25 km thick section of exhumed, Early Cretaceous middle and lower crust. The data show that the mechanisms by which displacements were relayed through the crust during a 25 Ma cycle of arc-related magmatism, high-grade metamorphism and contraction changed repeatedly. During the period 126-116 Ma, a ≥10 km batholith composed of gabbroic-dioritic magma was emplaced into the lower crust. Melt-enhanced shear zones evolved at the upper and lower contacts of the batholith where magma and steep temperature gradients created strength contrasts. By ~120 Ma, partial melting of mafic-intermediate lower crust resulted in the formation of high-pressure (14-16 kbar) migmatite and steep, regionally extensive vein networks up to 10 km below the batholith. Melt segregation and transfer through and out of the lower crust was aided by melt-induced fracture arrays and in ductile deformation in shear zones. During the period 116-108 Ma, differential shortening of the crust produced a network of subhorizontal and subvertical shear zones at different crustal depths. Near vertical shear zones up to 15 km wide formed at the deepest part of the section. These shear zones cut upwards across the entire lower crust to merge with a gently dipping upper amphibolite facies fold-thrust zone that formed in the middle crust. A 1 km thick,subhorizontal shear zone underlies this mid-crustal fold-thrust zone and physically connected shear zones that formed at different crustal depths. Our data suggest that deformation above and below this mid-lower crustal attachment zone was coupled kinematically and accommodated subhorizontal arc-normal displacements in the middle crust and oblique sinistral displacements on steep shear zones in the lower crust. The steep lower crustal shear zones also record components of subhorizontal arc-normal shortening and vertical thickening. These results strongly suggest that large, kinematically coupled networks of flat and steep shear zones separated the Fiordland crust into distinctive structural domains and relayed displacements vertically and horizontally through the lithosphere during Early Cretaceous oblique convergence.

Introduction

The degree and mechanisms by which deformation in the upper crust is coupled to deformation in the lower crust and mantle are two of the least understood issues of continental dynamics. In convergent regimes, the middle and lower crust typically contain large flat or dipping shear zones that separate the lithosphere into distinctive structural domains (Fuis & Clowes 1993; Mayer et al. 1997; Oldow et al. 1990; Axen et al. 1998; Miller et al. 2002; Karlstrom & Williams 2002). Physical and numerical models of convergence (Harry et al. 1995; Royden 1996; Teyssier & Tikoff 1998; Ellis et al. 1998; Beaumont et al. 2002) suggest that some of these shear zones act as transfer zones that help relay displacements vertically and horizontally through the lithosphere. However, exactly how these zones form and evolve through time are unresolved problems in lithospheric dynamics.

The application of simple steady-state numerical models of lower crustal deformation to natural settings is complicated by the extremely heterogeneous and transient nature of lower crustal rheology and structure. Some studies (e.g. Karlstrom & Williams 2002; Miller et al. 2002) have shown that discrete, layered subdivisions at the deepest levels of the crust are unlikely to persist for very long as the rheological profile of the crust responds to changes in temperature, fluid activity, magmatism, and composition. This extreme variability implies that the manner in which mantle and lower crustal displacements are transferred through the lithosphere is also highly variable and reflects changing ambient conditions. Further complicating the picture, our understanding of the kinematic and mechanical behavior of the lower crust for different scenarios has been hindered by a lack of natural examples. Inadequate exposure of the lower crust and the inherent difficulty in studying deformation evolving simultaneously within large sections of ancient lower crust has inhibited our understanding of lithospheric-scale processes. In addition, the insensitivity of most geophysical imaging techniques to the age and kinematic significance of lower crustal structures complicates the interpretation of deformation at the lithospheric scale.

In this paper, we describe the structural evolution of a 25 km thick, exhumed section of mafic lower crust in Fiordland, New Zealand that formed at the roots of an Early Cretaceous magmatic arc (Fig. 1). Fiordland contains the Earth's largest belt (>5,000 km²) of exhumed Mesozoic lower crustal granulites. These exposures not only provide us with an important natural example of the variability of lower

Klepeis, K.A. and Clarke, G. L., 2003, Evolution of an exposed lower crustal attachment zone in Fiordland, New Zealand, *In*: Vertical coupling and decoupling in the lithosphere, Grocott, J., McCaffrey, K., Taylor, G., Tikoff, B. (eds), *Geological Society Special Publications*, in press.

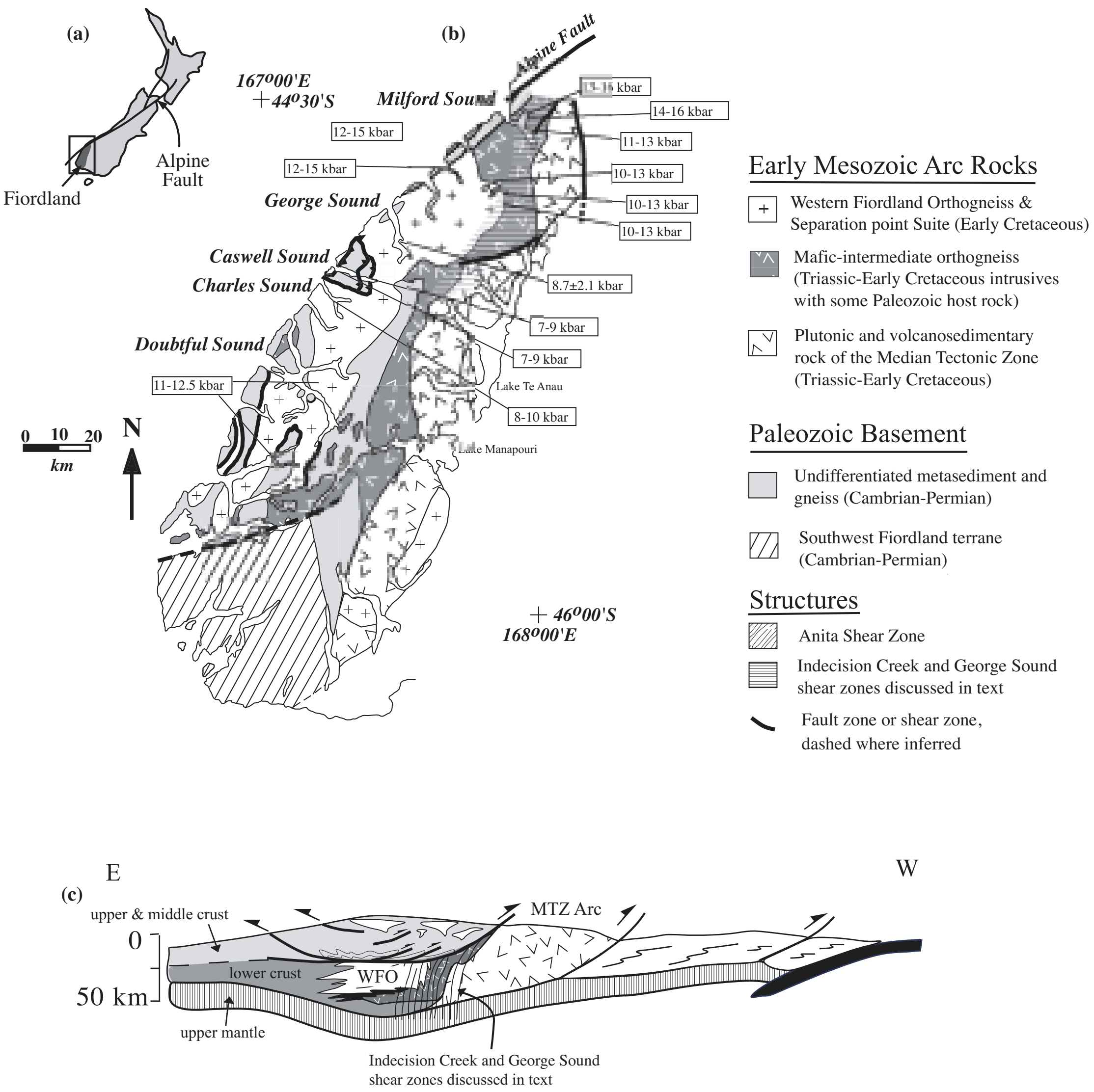


Fig. 1 (a) Inset shows location of Fiordland on the South Island of New Zealand. (b) Geologic map of Fiordland showing regional subdivisions. Pressures representing the peak of Early Cretaceous granulite facies metamorphism at ~120 Ma show tilted lower crustal section constructed using metamorphic data in Table 1 and, for the Doubtful Sound area, in Gibson & Ireland (1995). (c) Schematic cross-section showing a convergent setting between the Gondwana continental margin and an early Mesozoic arc (MTZ). WFO is the Western Fiordland Orthogneiss batholith.

crustal strength profiles, but they also allow us to examine directly the effects of this variability on the evolution of lower crustal fabrics and shear zones. Through work related to this and our previous studies (Klepeis et al. 1999; Clarke et al. 2000; Daczko et al. 2001a, b; 2002; Klepeis et al. 2001; 2003), we identified a continuous lower crustal section in Fiordland representing Early Cretaceous paleodepths of 25 km to 50 km. This exposure, excellent geochronologic control, and regional-scale crosscutting relationships enabled us to determine how the lower crustal section evolved structurally within a well constrained, ~25 Ma period of time (130-105 Ma).

Geologic Setting

The geology of southwest New Zealand records a history of magmatism, high-grade metamorphism and convergence that accompanied the evolution of an early Mesozoic magmatic arc along the ancient margin of Gondwana (J.D. Bradshaw 1989; Muir et al. 1994; Daczko et al. 2001a). Part of this arc is thought to have formed initially outboard of the Gondwana margin during Early Triassic-Early Cretaceous (247-131 Ma) subduction-related magmatism (Kimbrough et al. 1994; Muir et al. 1998; Tulloch and Kimbrough, 2003). In Fiordland (Fig 1b), a N- and NNE-striking belt of plutonic, volcanic and sedimentary rocks called the Median Tectonic Zone (Tulloch & Kimbrough

1989; Muir et al. 1994) or the Median Batholith (Mortimer 1999) represents this outboard part of the arc. On the eastern side of the Median Tectonic Zone (MTZ), Triassic plutons intruded Permo-Triassic volcanoclastic rocks of the Brook Street volcanics and the Maitai Terrane (Fig. 2). These latter units represent arc-derived sedimentary rocks and accretionary complexes that also lay outboard of Gondwana during the early Mesozoic (J.D. Bradshaw 1989; Mortimer 1999).

Following its initial construction, the outboard part of the Mesozoic arc (the MTZ) accreted onto the Gondwana margin during convergence. This stage of arc evolution resulted in the emplacement of 126-105 Ma intrusive rocks (ages from Kimbrough et al. 1984; Mattinson et al. 1986; McCullough et al. 1987; J.Y. Bradshaw 1989) into crust composed of both MTZ and Gondwana margin rocks (Mortimer 1999). Mafic-felsic rocks of the Western Fiordland Orthogneiss and the Separation Point Suite are included in this event (Fig. 1b). In addition, the ages of mafic dykes that intrude Lower Paleozoic host gneiss in the Arthur River Complex (Fig. 2) suggest that the amalgamation of the outboard arc with Gondwana may have occurred as early as ~136 Ma and probably by ~129 Ma (Hollis et al. 2002). In Fiordland, rocks of the Gondwana margin are represented by metasedimentary rock and granitic orthogneiss of Cambrian-Permian age (Fig. 1b).

Intense contractional deformation and crustal thickening accompanied and followed magmatism that resulted in the emplacement of the Western Fiordland Orthogneiss (Bradshaw 1990; Muir et al. 1995; 1998; Daczko et al. 2001a, Daczko et al. 2002). On the basis of geochronologic and geochemical data, Muir et al. (1995; 1998) suggested that the sudden appearance of large volumes of Na-rich magma within the arc at ~126 Ma, including the Western Fiordland Orthogneiss, was triggered tectonically by the underthrusting and subsequent melting of MTZ rocks beneath western Fiordland. Daczko et al. (2001a; 2002) presented structural data that support this interpretation. However, the origin of this contraction is controversial. The deformation may reflect the collision of the outboard part of the arc (the MTZ) with Gondwana following emplacement of the Western Fiordland Orthogneiss (Bradshaw, 1990; Bradshaw and Kimbrough, 1989; Daczko et al. 2001a; 2002). Alternatively, the deformation could reflect the collision of a basaltic plateau with the subduction zone on the outboard side of the arc (Sutherland and Hollis, 2001; Tulloch and Kimbrough, 2003).

In addition to the deformation, crustal thickening is reflected in the formation of high-pressure granulite facies and upper amphibolite facies metamorphism that recrystallised the Western Fiordland Orthogneiss and its host rock (Blattner 1978; J.Y. Bradshaw 1989; Clarke et al. 2000; Daczko et al. 2001b). Garnet-pyroxene-plagioclase-bearing assemblages have yielded peal metamorphic pressures of P=12-16 kbar and temperatures of T>750°C (Table 1). These assemblages occur with the Western Fiordland Orthogneiss and its host rocks between Doubtful Sound and Milford Sound (Fig. 1). The Early Cretaceous age of this metamorphism is constrained by three relationships: 1) crystallisation ages (126-116 Ma) of the Western Fiordland Orthogneiss (Table 2), 2) metamorphic ages from the Arthur River Complex (Fig. 2) and adjacent units, and 3) crosscutting relationships between high grade fabrics and dykes of known age (Mattinson et al. 1986; McCulloch et al. 1987; Gibson & Ireland, 1995; Tulloch et al. 2000; Hollis et al. 2002). The ages of specific fabrics and rock units discussed in this paper are discussed in more detail below.

By ~105 Ma, widespread extension affected parts of the Fiordland belt and adjacent areas (J.D. Bradshaw 1989; Tulloch & Kimbrough 1989; Gibson & Ireland, 1995). The Doubtful Sound shear zone (Fig. 1b) is the dominant structural expression of this extension in Fiordland. This shear zone is composed of granulite facies and upper amphibolite facies fabrics that cut the Western Fiordland Orthogneiss. Kinematic data reported by Gibson et al. (1988) and Claypool (2002) indicate that this shear zone records NE-SW stretching and a dominantly NE-directed sense of shear that is consistent with extension directions in other parts of New Zealand during the mid-Cretaceous (Tulloch and Kimbrough 1989). The crystallisation age of the Western Fiordland Orthogneiss and K-Ar cooling ages on hornblende from the upper amphibolite facies fabrics indicate a mid-Cretaceous (~108 Ma) age for this deformation (Gibson et al., 1988). The Anita Shear Zone (Figs. 1b, 2) in northern Fiordland also formed during or after this period (Hill 1995; Klepeis et al. 1999). Both of the Doubtful Sound and Anita shear zones record cooling, decompression, and exhumation of the granulite belt following crustal thickening and arc-related magmatism (Gibson & Ireland 1995; Klepeis et al. 1999).

Crustal Structure and Geochronology

In this section we define the boundaries and main lithologic divisions of Fiordland's high-pressure metamorphic belt (7-16 kbar, Fig. 1b, Table 1). These rocks represent the deformed and metamorphosed roots of the early Mesozoic arc. We also review the ages of the major rock units that make up the section (Fig. 2, Table 2) and describe structural relationships (Figs. 3, 4) that reflect a heterogeneous history of Early Cretaceous magmatism and convergence.

Boundaries of the High-Grade Metamorphic Belt

Rocks of contrasting tectonic affinity surround Fiordland's high-pressure granulite and upper amphibolite facies gneisses. To the east of the high-grade rocks, the Darran Suite is composed of unmetamorphosed gabbro and diorite that represent the upper crustal part of the early Mesozoic arc (the MTZ). Most of the Darran Suite is only weakly deformed. However, its western margin is highly deformed and shares a steep, upper amphibolite facies foliation that forms the dominant structural grain north and northeast of Milford Sound (Figs. 3b, 4). This foliation represents part of a steep, 10-15 km wide shear zone (Figs. 3b, 4) defined and discussed in detail later in this chapter. Southwest of the Darran Suite, weakly foliated tonalite and quartz diorite of the Roxburgh Suite (Fig. 2) form the boundary between the high-grade gneisses to the west and low-grade plutonic rocks and Tertiary sedimentary rocks of the MTZ to the east. The Roxburgh Suite is thought to be mostly Paleozoic in age (Turnbull, 2000).

The western boundary of the high-grade gneisses coincides with the 4-5 km wide, near vertical Anita Shear Zone (Fig. 2). The Anita Shear Zone separates intensely deformed granulite and upper amphibolite facies rocks of the Arthur River Complex from weakly deformed Lower Paleozoic metasedimentary rocks and granite of the Gondwana margin. The Greenland Group, the Thurso Gneiss, and the Saint Anne Gneiss (Fig. 2) represent parts of this Lower Paleozoic succession. Upper amphibolite and greenschist facies mineral assemblages within the Anita Shear Zone record peak metamorphic pressures of ~12 kbar and decompression that accompanied exhumation of the Fiordland granulites after ~108-105 Ma (Hill, 1995; Klepeis et al. 1999). The Alpine Fault and other late Cenozoic faults (Fig. 2) reactivate the steep margins of Anita Shear Zone and truncate the exposures of high-grade gneisses north of Milford Sound (Claypool et al. 2002). The southern boundary of the metamorphic belt occurs south of Doubtful Sound (Fig. 1b) and coincides with a large Tertiary fault that forms the northern margin of the Cambrian-Permian Southwest Fiordland terrane (Fig. 1b).

Lithologic Divisions of the Magmatic Arc

West of the Darran Suite near Milford Sound, the Arthur River Complex (ARC, Fig. 2) is composed of gabbroic and dioritic gneiss that is subdivided into four lithologically distinctive units (Fig. 2). The Milford Gneiss is composed mostly of garnet-, hornblende-bearing metagabbro with minor migmatitic metadiorite (m, Fig. 2). Mafic dykes of the Milford Gneiss intrude rafts of Paleozoic rock at Camp Oven Creek south of Milford Sound (CO, Fig. 2). The Mount Edgar Diorite (Fig. 2) is a pile of dioritic sheets that intruded into the Milford Gneiss, cutting across older gneissic layering at low angles. Structural relationships within these units are described in more detail in the next section. North of Milford Sound, the Pembroke Granulite forms a large pod that is aligned parallel to the NNE-strike of the dominant foliation near Milford Sound (Fig. 4). This unit includes two pyroxene-, hornblende-bearing metagabbro and migmatitic metadiorite. East of the Pembroke Granulite, the Harrison Gneiss is composed of banded metadiorite with discontinuous sheets of mafic to felsic compositions in gradational contact with the more mafic Milford Gneiss.

The zone located between the Arthur River Complex and the Darran Suite is composed of discontinuous gabbroic units intruded by variably deformed quartz diorite gneiss and felsic dykes. Bradshaw (1990) divided this zone into the Indecision Creek and Mount Anau igneous complexes. For simplicity, we refer to all of the rocks in this area as the Indecision Creek Complex (Fig. 2). The northern contact of the Indecision Creek Complex is gradational with the Harrison Gneiss; its eastern and wester contacts are gradational with dioritic rocks of the weakly deformed Darran Suite and the highly deformed Western Fiordland Orthogneiss,respectively. This unit is chemically similar to the Western Fiordland Orthogneiss (Fig. 2) and may contain less Paleozoic inheritance than the subunits of the Arthur River Complex (Turnbull, 2000).

In the central part of the high-grade metamorphic belt, the Western Fiordland Orthogneiss is a major batholith that intruded the Arthur River Complex. The batholith is composed mostly of layered sequences of gabbro and diorite with some ultramafic dykes and pods. The lower (northern) contact of this unit is well exposed at Mount Daniel (MD, Fig. 2); its upper (southern) contact with Paleozoic metasedimentary rocks is well exposed at Caswell Sound. Some areas of this batholith preserve primary igneous layering that escaped the intense recrystallisation observed in most of the rock units of northern Fiordland (described below). However, in areas such as the eastern end of George Sound and along its eastern contact these rocks were intensely deformed and recrystallised. Rafts of Paleozoic metasedimentary rocks occur within and near the contacts of the intrusion east of Mount Daniel and at George Sound. These metasedimentary rocks are migmatitic (m, Fig. 2) near the contacts with the batholith.

The Ages of Magmatism, Crustal Melting, and High-Grade Metamorphism

Published U-Pb ages from northern Fiordland (Fig. 2, Table 2) reflect a history of Early Cretaceous magmatism and Early Cretaceous metamorphism and melting. Tulloch et al. (2000) analysed zircon cores from the Arthur River Complex near Milford Sound and obtained both Early Carboniferous (~360 Ma) and Early Cretaceous (~134 Ma) U-Pb ages. Hollis et al. (2002) obtained 136-129 Ma U-Pb ages from the cores of magmatic zircon in the Arthur River Complex and showed that these ages most likely reflect the crystallisation of Early Cretaceous dykes and plutons. These data combined with evidence of an intrusive relationship between the mafic dykes of the Milford Gneiss and migmatitic Paleozoic host rocks at Camp Oven Creek (CO, Fig. 2) suggest that the Arthur River Complex was emplaced into crust composed of a mixture of MTZ arc rocks and Paleozoic rocks of Gondwana. A crystallisation age of ~154 Ma for the main dioritic part of the Selwyn Creek Gneiss (Fig. 2; Table 2) suggests that these rocks also were emplaced during an early phase of MTZ magmatism (Hollis et al. 2002) and likely represent deformed parts of the Darran Suite.

Following emplacement of the Arthur River

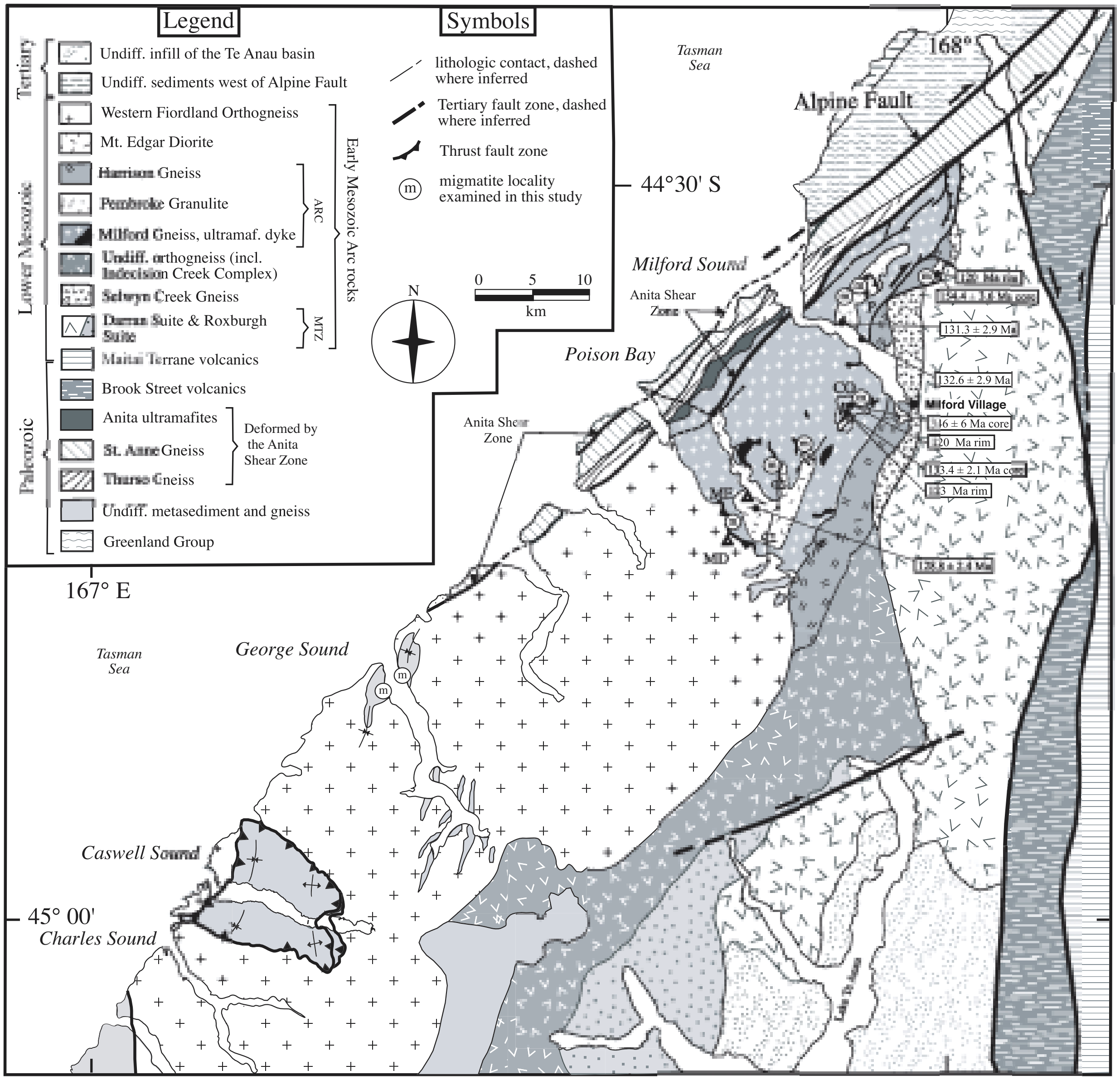


Fig. 2. Geologic map of north-central Fiordland showing the major lithologic subdivisions. Map was constructed using data from this study and from Bradshaw (1989; 1990), Blattner (1991), Turnbull (2000), Daczko et al. (2002), and Claypool et al. (2002). Plotted dates (see also Table 2) are from U-Pb analyses of zircon cores and rims reported by Hollis et al. (2002). Data show the distribution of Early Cretaceous crystallisation (zircon cores) ages and ~120 Ma metamorphic (rim) ages from the Arthur River complex. Also note distribution of migmatite (m) below the batholith. MD is Mount Daniel, ME is Mount Edgar, P is Pembroke Valley, CO is Camp Oven Creek, ARC is the Arthur River Complex, MTZ is the Median Tectonic Zone. Profiles A-A', B-B', C-C', D-D', E-E' and F-F' are shown in Fig. 3.

Complex, the Mount Edgar Diorite (Fig. 2) was emplaced at ~129 Ma (Hollis et al. 2002). This age is consistent with field relationships indicating that the Mount Edgar Diorite intruded and cuts across gneissic layering in the Milford Gneiss at low angles. The dioritic parts of the Indecision Creek Complex also intruded older metagabbroic crust. However, the exact age of the Indecision Creek Complex is uncertain. A few unpublished U-Pb dates suggest that parts of it intruded between ~135 Ma and ~122 Ma (reported in Bradshaw, 1985, 1990). These ages combined with a history of some Paleozoic inheritance (although less than the Arthur River Complex) indicate that it was emplaced following the amalgamation of the MTZ with the Gondwana margin. This relationship suggests that it probably has a similar origin as the Mount Edgar Diorite and the Western Fiordland Orthogneiss.

U-Pb geochronologic data also indicate that high-grade metamorphism accompanied Early Cretaceous magmatism and crustal melting. Thin, high-U metamorphic rims around magmatic zircon cores of both Paleozoic and Early Cretaceous occur in the Milford Gneiss,the Harrison Gneiss, the Selwyn Creek Gneiss, and Paleozoic gneiss at Camp Oven Creek (Tulloch et al. 2001; Hollis et al. 2002). These ages are interpreted to reflect the influx of heat that accompanied the emplacement of the mafic-intermediate Western Fiordland Orthogneiss (Tulloch et al. 2001; Hollis et al. 2002). This interpretation is consistent with the range of crystallisation ages from the Western Fiordland Orthogneiss (126-116 Ma, Table 2) and with the spatial distribution of zircon displaying metamorphic rims in migmatite and granulite facies rocks below the batholith. The age of lower crustal melting (migmatite localities shown in Fig. 2) also is interpreted to have coincided with this widespread thermal pulse.

Zircon ages (81.8 ± 1.8 Ma) from a post-tectonic dyke located in the Pembroke Valley (P, Fig. 2) north of Milford Sound indicate that high-grade granulite and upper amphibolite facies metamorphism in the Arthur River Complex terminated in the mid-Cretaceous (Hollis et al. 2002). In addition, K-Ar ages on hornblende (Gibson et al. 1988; Nathan et al. 2000) and U-Pb dates on apatite (Mattinson et al. 1986) indicate that the Western Fiordland Orthogneiss and Arthur River Complex had cooled to 300-400°C by ~90 Ma (Table 2). K-Ar amphibole and biotite cooling ages of ~93 Ma and ~77 Ma respectively also support a mid-Cretaceous age for the extensional Doubtful Sound Shear Zone (Gibson et al. 1988).

Structural Relationships

Two distinctive structural domains characterise the zone between the Anita Shear Zone and the Darran Suite (Figs. 4a, 4b, 4c). The western part of this zone is dominated by layered intrusions (e.g. the Mount Edgar Diorite) and gneissic foliations that mostly dip moderately to the south, southwest, and west (Fig. 4b). Hornblende and biotite mineral lineations on foliation planes plunge moderately to the west and southwest. This western domain is narrowest (>10 km) near Milford Sound and widest (>30 km) near Caswell Sound. The eastern domain contains penetrative upper amphibolite facies foliations that are mostly steep to subvertical and strike to the north-northeast (Figs. 3b, 4c). These latter foliations define a 10-15 km wide zone of penetrative ductile deformation that we define in this paper

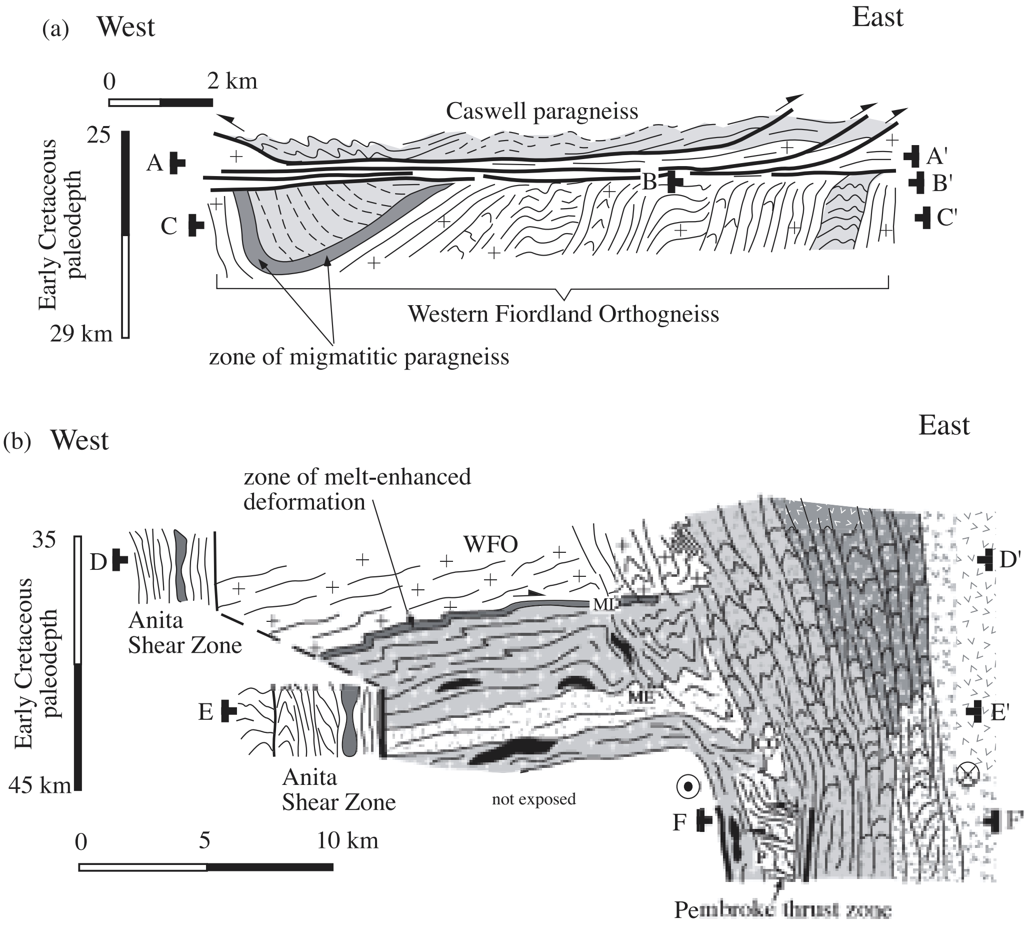


Fig. 3. (a) Composite cross section constructed using structural data from Caswell, Charles, and George sounds (locations shown in Figure 2). Profile shows the geometry of structures above and below the upper contact of the Western Fiordland Orthogneiss batholith. Shaded areas represent Paleozoic paragneiss representative of the ancient Gondwana margin. Dashed lines represent gneissic layering that predated batholith emplacement. (b) Composite cross section constructed using data from the region between the Pembroke Valley and Mount Daniel (for locations see Fig. 2). Sections show the geometry of structures above and below the lowermost contact of the Western Fiordland Orthogneiss. Patterns are the same as in Figure 2.

as a steep shear zone. Hornblende and biotite mineral lineations in this domain mostly plunge moderately to the south and southwest with some localities also displaying near vertical plunges (Fig. 4c). We introduce the new name Indecision Creek Shear Zone for this zone of intense deformation. All foliations and lithologic contacts in both domains are cut by mylonitic foliations of the Anita Shear Zone (Fig. 4a).

The structure of the western domain constitutes a tilted middle and lower crustal section with the deepest paleodepths occurring in the north near Milford Sound and the shallowest paleodepths occurring in the south near Caswell and George sounds (Fig. 1b; Table 1). The dominant features in this section include the diorite intrusions that make up the Mount Edgar Diorite and the Western Fiordland Orthogneiss (Figs. 2 and 3c). At Mount Daniel (MD, Fig. 2) the lower contact of the Western Fiordland Orthogneiss is mostly concordant with gneissic foliations in the Milford Gneiss. This relationship suggests that at magma exploited gneissic layering in the older rocks during batholith emplacement. Elsewhere, such as at the northwestern end of George Sound, the contacts of the Western Fiordland Orthogneiss cuts obliquely across gneissic layering in host rocks (Fig. 3a).

In some areas, rocks of the Western Fiordland Orthogneiss and Mount Edgar Diorite record a heterogeneous, tectonic overprint. The eastern side of the Mount Edgar Diorite is folded (Fig. 2). At Mount Daniel the lower contact of the WFO is dips to the west and southwest and also is folded (Fig. 3b). However, most of the original intrusive relationships between different phases of the batholith are well preserved at this locality. In areas where this deformation is intense, such as at the southeast end of George Sound and near the upper and eastern contacts of the Western Fiordland Orthogneiss, these rocks contain a strong upper amphibolite facies tectonic foliation that transposes all primary igneous layering in the batholith.

Thermobarometric data (Table 1) derived from garnet granulite and upper amphibolite facies mineral assemblages from the Western Fiordland Orthogneiss and its contact aureoles constrain the range of paleodepths represented in the tilted section. Pressures reflecting the peak of Early Cretaceous metamorphism range from 7-9 kbar at Caswell and George sounds, to 10-13 kbar near the base of the Western Fiordland Orthogneiss, and 13-16 kbar in the deepest part of the section north of Milford Sound (Fig. 1a). These data indicate paleodepths of 25-50 km from south to north (Figs. 3a, 3b).

The dominant north-northeast-striking foliations of the eastern domain everywhere cut and transpose the west- and southwest-dipping foliations and igneous layering of the western domain. Crosscutting relationships between these two groups of foliations are best preserved inside a ~1-5 km wide transitional zone that includes the eastern contacts of the Milford Gneiss (from east of Mount Edgar, ME, to the Pembroke Valley, P, Fig. 2) and the Western Fiordland Orthogneiss. In this transitional zone the dominant southwest-, and west-dipping foliations of the western domain are tightly folded into a series of overturned south-plunging folds (Figs. 3b, 4a). Fold tightness (interlimb angle) increases from northwest to southeast across this zone and fold axial planes progressively steepen toward the southeast. Where these folds are tight to isoclinal and upright, such as occurs inside the Indecision Creek Complex, the north-northeast-striking foliation of the eastern domain parallels the axial planes of the folds. In zones of the highest strain, the steep north-northeast-striking foliations transpose all folds and intrusive contacts, including the eastern contacts of the Western Fiordland Orthogneiss and Mount Edgar Diorite. Mylonitic foliations also occur locally. These crosscutting relationships and variations in the intensity of folding and transposition form the basis of our interpretation that this eastern domain represents a zone of high strain. The kinematic significance of this zone is discussed in a later section (Stage 3).

Between Caswell Sound and Mount Daniel, a third structural domain occurs near the southern end of George Sound (Fig. 4a). This domain exhibits structural relationships that are similar to those of the eastern domain. At George Sound, steep upper amphibolite facies foliations that strike to the north-northeast transpose older west- and southwest-dipping gneissic foliations and dykes (Fig. 4d) inside the Western Fiordland Orthogneiss. These steep foliations parallel the axial planes of tight, upright folds of the dykes and the older gneiss. The boundaries of this zone approximately parallel those of the eastern domain (Fig. 4a). These relationships indicate that the structures of this third area, like those of the eastern domain, are younger than the dominant gneissic foliations of the titled section in western Fiordland. The tightness of folding and degree of transposition also indicate that this area represents a zone of high strain. We introduce the name George Sound Shear zone to describe this zone of high strain.

Finally, the fourth structural domain occurs at Caswell Sound (Figs. 4a, 4e). Here, a series of upper amphibolite and garnet granulite facies thrust zones cut and transpose the upper contact of the Western Fiordland Orthogneiss. The zone consists of both west- and east-verging ductile thrusts that separate a central domain that contains open to tight folds of gneissic foliation in Paleozoic metasedimentary rocks (Fig. 3a). Fold tightness increases towards the contacts of the Western Fiordland Orthogneiss. The most intense zone of thrusts occurs at the eastern end of the sound. Here, thrust splays and fold axial surfaces curve downward to sole into a 1 km thick basal shear zone that occurs within the Western Fiordland Orthogneiss (Fig. 4e). Hornblende, clinozoisite and biotite mineral lineations on foliation surfaces in the dipping thrust zones plunge moderately and gently to the west (Fig. 4e). This basal shear zone is exposed at Charles Sound and at the eastern end of Caswell Sound. The steep upper amphibolite facies fabric of the George Sound shear zone merges into parallelism with this gently dipping basal shear zone (Figs. 3a, 4a).

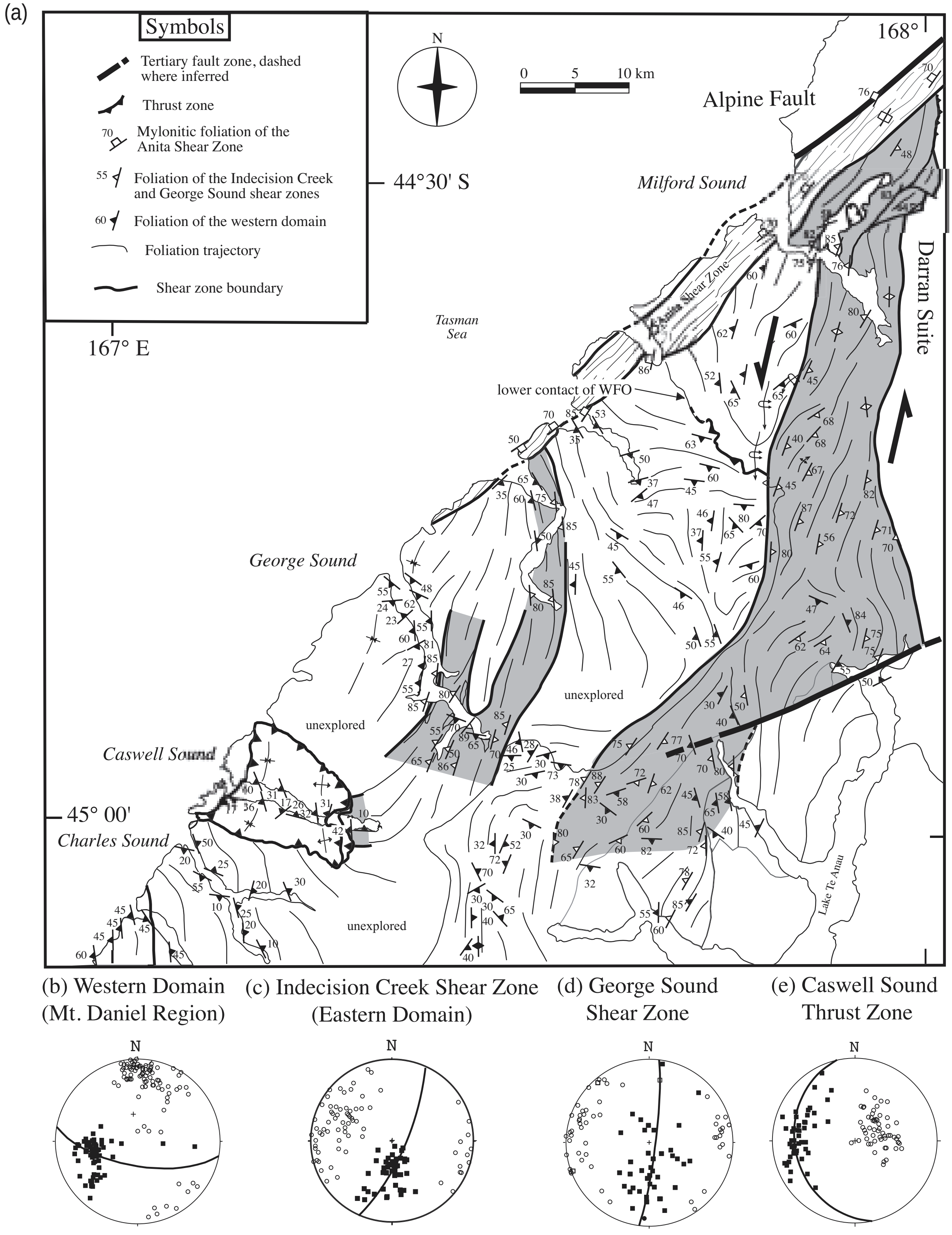


Fig. 4. (a) Map showing structural data from northern Fiordland. Structural data are from this study and data from Bradshaw (1989; 1990), Blattner (1991), Klepeis et al. (1999), Daczko et al. (2002), and Claypool et al. (2002). Foliation trajectories represent the interpolation of structural trends constructed using plotted data and reconnaissance mapping. Shaded areas show the Indecision Creek Shear Zone (eastern side) and the George Sound Shear Zone (western side). Equal-area stereoplots in (b), (c), (d), and (e) show poles to foliations (open circles) and mineral lineations (black squares) for the four structural domains discussed in the text. Black lines in stereoplots represent best-fit planes to foliation clusters.

Space-Time Correlation of High-Grade Fabrics

Crosscutting relationships, published U-Pb ages, and similarities in metamorphic grade and structural style allowed us to correlate magmatic, metamorphic and deformational events across northern Fiordland. These correlations helped us to reconstruct the Cretaceous structural and magmatic evolution of the middle and lower crustal section.

A key marker horizon in the section is the 126-116 Ma Western Fiordland Orthogneiss. The well documented age and regional extent of this unit allowed us to divide the evolution of rock fabrics in the section into three time intervals corresponding to events that occurred before (>126 Ma), during (126-116 Ma) and after (<116 Ma) its emplacement. Rock fabrics that predate emplacement of the Western Fiordland Orthogneiss occur mostly in gneiss of the Arthur River Complex and in Paleozoic host rock near the margins of the batholith. Rock fabrics that formed during emplacement of the batholith occur within 1-2 km of the batholith contacts (e.g., at Mount Daniel and in the Paleozoic rafts George Sound, Fig. 2). Rock fabrics in these latter areas display textures that indicate deformation occurred while the batholith was still partially molten. We describe these features in a later section.

Another key relationship involves the Anita Shear Zone, which cuts all structures of the high-grade gneiss belt at its northern and western ends (Fig. 4a). Because the Anita Shear Zone records decompression that began during regional extension at ~108-105 Ma, the Indecision Creek and George Sound shear zones must have evolved before this ~108-105 Ma interval. Finally, deformation in both the Indecision Creek Shear Zone and George Sound Shear Zone transposed all fabrics that formed during or before emplacement of the Western Fiordland Orthogneiss (Figs. 3b, 4a). The subsolidus style and upper amphibolite facies mineral assemblages that characterize these shear zones indicate that they must have evolved after the Western Fiordland Orthogneiss had cooled and crystallized.

To highlight the sequential evolution of the different structural zones, we grouped all foliations in the high-grade gneisses and plotted them (Fig. 4a) according to their relative age with respect to the dominant foliations of the Indecision Creek Shear Zone. On the basis of similar orientations of structures, similar metamorphic grade, and identical crosscutting relationships with respect to the Western Fiordland Orthogneiss and the Anita Shear Zone, we correlated the steep foliations of the Indecision Creek and George Sound shear zones. Foliations that formed during the deformation that produced the shear zones are plotted with white triangles; those that predate the shear zone are plotted with black triangles (Fig. 4a). The mylonitic foliations of the Anita Shear Zone are plotted using white squares (Fig. 4a). Although the plotting scheme we employed (Fig. 4a) does not distinguish between foliations that predate and accompanied emplacement of the Western Fiordland Orthogneiss, the scheme illustrates that the western domain preserves the oldest structures in the section.

The ages of structures that define the fold-thrust zone at Caswell Sound are constrained by several structural and metamorphic relationships in the contact aureole of the Western Fiordland Orthogneiss. The foliations that define the thrust zones all display subsolidus textures and cut the uppermost contact of the batholith. These characteristics indicate that the thrusts and the basal shear zone evolved after the batholith had cooled and crystallized. However, the thrust zones within 500 meters of the Western Fiordland Orthogneiss also contact contain high-grade garnet-biotite-potassium feldspar granulite facies assemblages whereas farther from the contact (>500 m) they contain chlorite-epidote amphibolite facies assemblages. Daczko et al. (2002) described these mineral assemblages in detail and showed that they reflect a temperature gradient of 700-800°C within the contact aureole and 550-600°C outside it. These observations suggest that the thrust zones initially formed within the thermally softened aureole of the batholith and continued to evolve as batholith cooled.

The high pressures (7-9 kbar, Fig. 1b) and temperatures recorded by the mineral assemblages of the Caswell thrust zone and their contractional style indicate they formed prior to the onset of regional extension at ~108-105 Ma (Daczko et al. 2002). Using this relationship and the fact that the thrust zone deforms the margins of the Western Fiordland Orthogneiss the Caswell thrust zone must have evolved during the same time interval (116-108 Ma) as the George Sound Shear Zone and the Indecision Creek Complex shear zones. These features exhibit identical metamorphic grade and identical crosscutting relationships with respect to the Western Fiordland Orthogneiss. This interpretation also is consistent with the gradually merging of the George Sound Shear Zone with the basal shear zone of the Caswell thrust zone.

The structural relationships we have outlined show a remarkable variability with depth in the crustal section (Fig. 3a, b). These relationships combined with good age control at the regional scale allowed us to investigate variations in the style of strain partitioning with depth for different time periods. Here, we define three stages in the magmatic and structural evolution of the Fiordland section: (1) The injection of mafic-intermediate magma of the Western Fiordland Orthogneiss batholith into a lower crust during the interval 126-116 Ma. The partial melting of mafic host rocks below the batholith and it its aureole (m, Fig. 2) accompanied this magmatism. (2) The mobilization and extraction of lower crustal melts during deformation that occurred as the batholith cooled to subsolidus temperatures. (3) The development of the steep upper amphibolite facies fabrics that define the Indecision Creek and George Sound shear zones and the Caswell thrust zone. These second and third stages are bracketed by the age of the Western Fiordland Orthogneiss and the youngest age of lower crustal fabrics that formed prior to the mid-Cretaceous exhumation of the belt (~108-105 Ma). These age intervals allow for diachronous activity within the belt.

Stage 1: Mafic-Intermediate Magmatism & the Partial Melting of Lower Crust

During the interval 126-116 Ma the Western Fiordland Orthogneiss was emplaced into lower crust composed of older (>126 Ma) rocks of the Median Tectonic Zone and Paleozoic margin of Gondwana. This magmatism resulted in a >3000 km^2 batholith that was at least 10 km thick. The first phases of the batholith were gabbroic with minor ultramafic compositions; later phases were dominated by coarse-grained diorite. In some places, diffuse, undulate contacts between the gabbro and slightly younger diorite dykes suggests that these two phases mingled while still in a semi-molten state (Fig. 5a).

The lower contact of the batholith at Mount Daniel (MD, Fig. 2) preserves a 200-500 meter-thick banded igneous complex. In this zone sheets of tonalite, trondhjemite, and hornblende gabbro display mutually crosscutting relationships and are complexly interfolded (Fig. 5b). Thin (<0.5 m) tonalite sheets display undulate contacts with slightly more mafic sheets reflecting injection into an incompletely crystallised host. Discordant amphibolite dykes with sharp, straight contacts cut some of these tonalite sheets but also are cut by veins and dyke apophases that originate from the surrounding tonalite host. These mutually crosscutting relationships indicate the simultaneous injection of tonalitic and more mafic phases.

Many of the folds that occur within the banded igneous complex at the base of the Western Fiordland Orthogneiss preserves relationships that suggest deformation occurred while the rocks were still in a partially molten state. Discordant patches of leucosome occur within the hinges of folded intrusions and are slightly folded (Fig. 5c). This texture suggests that the migration of melt, now represented by leucosome, occurred during folding of a partially molten tonalite host. Tightly folded and highly attenuated tonalite intrusions also are interfolded with slightly younger, less deformed tonalite sheets that cut them (Fig. 5d). The highly attenuated, stretched limbs of these folded layers are surrounded by leucosome that is unfoliated despite the evidence of high strains (Fig. 5d). Coarse biotite in the mafic parts of these layers forms radial and misaligned patterns. These relationships indicate that folding coincided with the periodic emplacement of the sheeted intrusions and suggest that the deformation occurred prior to full crystallisation of the tonalite.

In some areas near the base of the Western Fiordland Orthogneiss the surfaces of folded layers display southwest-plunging hornblende and biotite mineral lineations that parallel the axes of the folds. These strucures also parallel southwest-plunging hornblende mineral lineations observed elsewhere in the western domain (Fig. 4b). The sense of asymmetry displayed by the crosscutting sheets and the sheared out limbs of folds at Mount Daniel (MD, Fig.2) suggests a top-to-the-northeast shear sense parallel to this southwest-plunging lineation. This asymmetry, the evidence of high strains, and evidence of deformation while in a partially molten state suggests that this zone represents a melt-enhanced shear zone that accompanied emplacement of the Western Fiordland Orthogneiss (Fig. 3b).

We recognized two generations of folds at the base of the Western Fiordland Orthogneiss at Mount Daniel. The first generation includes the melt-enhanced folds that only occur within the 200-500 m thick basal shear zone. The second generation produced recumbent folds that refold the first generation. However, unlike the first generation, these second folds deform all units within the Western Fiordland Orthogneiss and underlying Milford Gneiss. These second generation folds also display similar orientations and styles as those that formed within the western margin of the Indecision Creek Shear Zone near Mount Edgar (ME, Fig. 2). The deformation that produced these folds reoriented the sheeted intrusions but did not transpose the older fabrics. A penetrative axial planar foliation is lacking in most areas. This lack of penetrative deformation during folding preserved the migmatitic textures we describe in this section.

Lastly, a few thin (<10 m wide), mylonitic shear zones (Fig. 7d) parallel the axial planes of the second generation folds. These shear zones display microstructural evidence that plagioclase grain sizes were reduced during subsolidus dynamic recrystallisation. Some coarse plagioclase displays core-mantle structures and deformation bands composed of subgrains inside larger grains. On the basis of these relationships and similarities in structural style we interpret these features as having formed during evolution of the Indecision Creek Shear Zone.

Below and near the contacts of the Western Fiordland Orthogneiss, Paleozoic gneiss and mafic rocks of the Arthur River Complex preserve evidence of partial melting. Migmatite (m, Fig. 2) is best preserved in western domain where delicate leucosome structures and granulite facies metamorphic mineral assemblages avoided most of the recrystallisation and transposition that accompanied development of the Indecision Creek Shear Zone. The ~120 Ma metamorphic rims on zircons from migmatite and granulite facies mineral assemblages below the Western Fiordland Orthogneiss also support the interpretation that partial melting coincided with a thermal pulse that accompanied batholith intrusion.

Field data show that the spatial distribution of rocks that partially melted was heterogeneous. Near the top of the batholith at George Sound giant rafts of metapelitic host rock up to 4 km wide are enclosed by diorite (Figs. 2 & 3a). These rafts preserve diatexite within 200-500 m of the Western Fiordland Orthogneiss. Mineral assemblages in the diatexite, including garnet, biotite, hornblende and plagioclase that replace older staurolite- and kyanite-bearing assemblages, record the depth (25-30 km) of magma emplacement and partial melting at this locality (Table 1). At Caswell Sound migmatite was deformed and recrystallised by the deformation that produced the Caswell thrust zone (see also

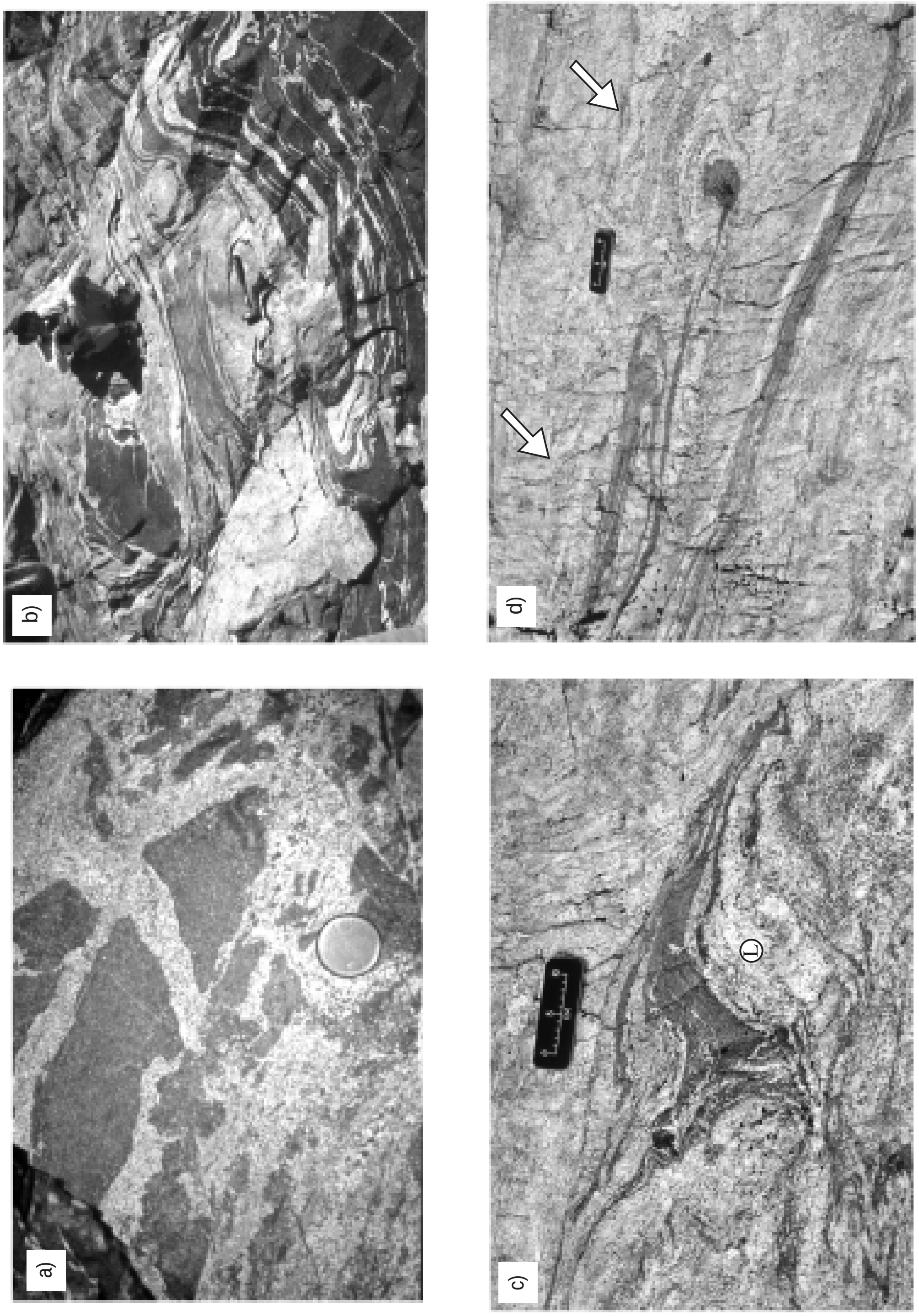


Fig. 5. (a) Photograph showing the main gabbroic and dioritic phases of the Western Fiordland Orthogneiss batholith. Gabbro (dark color) was invaded by slightly younger diorite (light color). Note diffuse, undulate contacts suggesting magma mingling in a semi-molten state. (b) Photograph of a 200-500 m thick, banded igneous complex located at the base of the Western Fiordland Orthogneiss at Mount Daniel (location shown in Figure 2). Sectional view to the southwest. Note the interfolding of tonalite, trondhjemite, and gabbroic sheets. See text for discussion. (c) Discordant leucosome patches (L) in an incompletely crystallized tonalite host. Leucosome is located within the hinge of a complexly folded and stretched mafic amphibolite dyke (dark layers). The leucosome is unfoliated and slightly folded. Texture is interpreted to reflect the migration of melt now represented by leucosome during deformation of a partially molten tonalite host. (d) Sectional view to the southwest. Tightly folded mafic (dark color) layer in a tonalite host at the base of the Western Fiordland Orthogneiss at Mount Daniel. The folded layer is surrounded by leucosome (white). Despite the evidence for isoclinal folding, the tonalite host displays no microstructural evidence of subsolidus recrystallisation near the stretched lower limb. Note that the folded layer and its tonalite host are truncated by a younger, less deformed banded tonalite intrusion at the top of the photograph (arrows). Texture is interpreted to reflect deformation while the tonalite host was in a partially molten state. See text for discussion.

Daczko et al., 2002).

In contrast to the narrow zones of partially melted rock near the top of the Western Fiordland Orthogneiss, migmatite formed in the Arthur River Complex up to 10 km below the batholith north of Mt. Daniel (m, Fig., 2). Daczko et al. (2001b) recognized that fluid-absent partial melting in the mafic parts of the Arthur River Complex was patchy and involved the decomposition of hornblende at T>750°C. Piston-cylinder experiments conducted at the University of Vermont (Antignano et al., 2001; Antignano 2002) on a natural unmelted sample of metadiorite from the Pembroke Granulite confirmed this relationship. These experiments produced two results that are of importance to the study of partial melting in the Arthur River Complex during batholith emplacement. First, in accordance with field observations, they showed that at T=850°C biotite undergoes melting in the absence of free water followed by the reaction of hornblende and clinozoisite to form garnet plus melt as reaction products (Antignano et al. 2001; Antignano 2002). Second, they showed that the melt fractions produced during melting remained low (≤10%) at all temperatures up to T=975°C. This latter result may explain the low percentage of leucosome we observed in mafic orthogneiss below the Western Fiordland Orthogneiss compared to the much higher melt fractions observed in migmatitic paragneiss near the top of the batholith (see also Klepeis et al. 2003).

Unlike the relationships we described for the basal shear zone at Mt. Daniel, many areas that preserve migmatite below the Western Fiordland Orthogneiss do not display evidence of high-temperature ductile deformation during partial melting. This suggests that during the early stages of magmatism most of the deformation was partitioned along the basal contact of the batholith where a strength contrast occurred between partially molten rock and the older gneisses of the Arthur River Complex.

Stage 2: Melt segregation and transfer mechanisms

Migmatitic rocks located structurally below the Western Fiordland Orthogneiss contain features that suggest several different mechanisms helped segregate and transport partial melts through the lower crust. In this section we describe two examples that illustrate how combinations of melt-induced fracture networks and ductile deformation in the Indecision Creek Shear Zone aided melt transfer during and after batholith emplacement.

Melt-Induced Fracture Propagation

One of the best-exposed examples of migmatite in northern Fiordland is located in the Pembroke Granulite north of Milford Sound (P, Fig. 2). Here, dioritic gneiss displays a penetrative foliation composed of aggregates of hornblende, clinopyroxene, orthopyroxene, clinozoisite, plagioclase and small amounts of biotite and quartz. Leucosome in these rocks occurs as trains or patches of euhedral garnet partially surrounded by aggregates of equidimensional plagioclase. The leucosome forms discontinuous lenses that are drawn out parallel to the foliation. However, there is no evidence of ductile deformation accompanying partial melting at this locality. These textures provide evidence that some of the original melt exploited and migrated along foliation planes following partial melting of the lower crust.

In all areas of the Pembroke Granulite, the percentage of leucosome is low (≤10%) and there is no disruption of stromatic layering. These observations support our interpretation that the volume of melt produced during partial melting of hornblende-bearing gneiss remained relatively low (≤10%). They also suggest that the segregation of melt from migmatitic source rocks was efficient. We observed stromatic leucosome feeding laterally into larger discordant veins that cut the foliation at high angles (arrow in Fig. 6a). Garnet trains in these discordant veins are more extensively developed than in other areas of leucosome and are linked together into a continuous septum that is completely enclosed by coarse plagioclase (Fig. 6a). These features suggest that original partial melt was efficiently extracted from the migmatite by arrays of discordant veins.

The veins that cut discordantly across foliation in the Pembroke Granulite are some of the most striking and penetrative features of these exposures. A regular lattice pattern consisting of steep orthogonal veins cuts across all rock contacts regardless of lithologic composition (Figs. 6b, 6c). Some of these veins display en echelon patterns and curved, tapered tips (Fig. 6d). None of the veins display sigmoid shapes, sheared boundaries, or other features that typically indicate opening during deformation in shear zones. The curvature of some vein tips in the bridge between parallel but offset veins (Fig. 6d) is characteristic of a stress field modified by the internal fluid pressure of opening veins (p. 766-767, Ramsay and Lisle, 2000). These features are typical of en echelon tension gashes that form in regions of brittle deformation and high strain rates and provide strong field evidence that fracture propagation and dyking aided melt transfer through parts of the lower crust.

Across contacts between the migmatitic diorite gneiss and adjacent, non-migmatitic gabbroic gneiss, a physical connectivity exists between leucosome in the migmatite and veins in the metagabbro (Fig. 6b). This physical connectivity revealed how migrating partial melts interacted chemically with gabbroic gneiss during their migration. Over distances of a few centimeters, leucosome in stromatic migmatite changes into thin (2-5 cm) planar veins that are surrounded by dehydration zones in adjacent gabbroic gneiss (Figs. 6b, 6c, 6d, see also Daczko et al. 2001b; and Fig. 3 of Klepeis et al. 2003). These dehydration zones record the recrystallisation of hornblende-bearing assemblages to garnet granulite at conditions of T>750°C and P=13-16 kbar (Table 1; Clarke et al. 2000). Early theories suggested that the streaming of a CO_2-rich fluid through fracture and vein networks caused the dehydration (Blattner 1976; Bradshaw & Kimbrough 1989). However, the garnet granulite dehydration zones only occur in the gabbroic gneiss and are

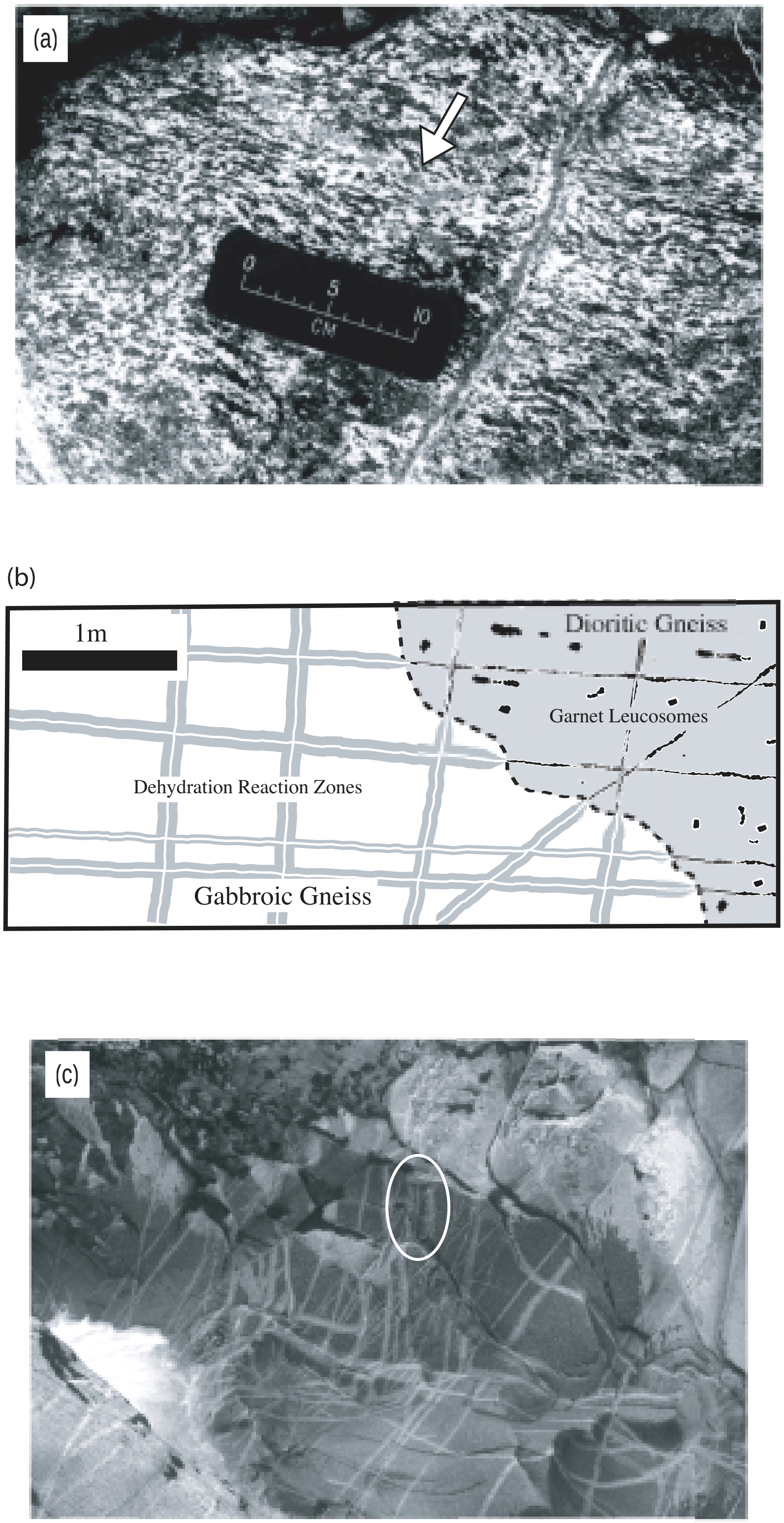


Fig. 6. (a) Stromatic migmatite in metadioritic host gneiss of the Pembroke Granulite (location shown in Figure 2). Note foliation-parallel leucosome (arrow) that feeds a steep, discordant vein containing a continuous train of euhedral garnet to the right of the scale. (b) Structural form map showing the physical links that occur between garnet-bearing leucosomes in migmatitic dioritic gneiss and garnet-, clinopyroxene-bearing dehydration zones that surround tensile fractures in gabbroic gneiss (see also Daczko et al., 2001b). (c) Tensile fracture arrays surrounded by dehydration zones form steep orthogonal arrays that cut all lithologic contacts in the Pembroke Granulite. Host is gabbroic gneiss. Circle shows hammer for scale. View shows a bench-like surface where hammer is perched on a vertical wall above a horizontal surface. These veins and dehydration zones are defined by a central garnet-bearing leucosome surrounded by a halo (light gray lines) composed of garnet-clinopyroxene symplectite.

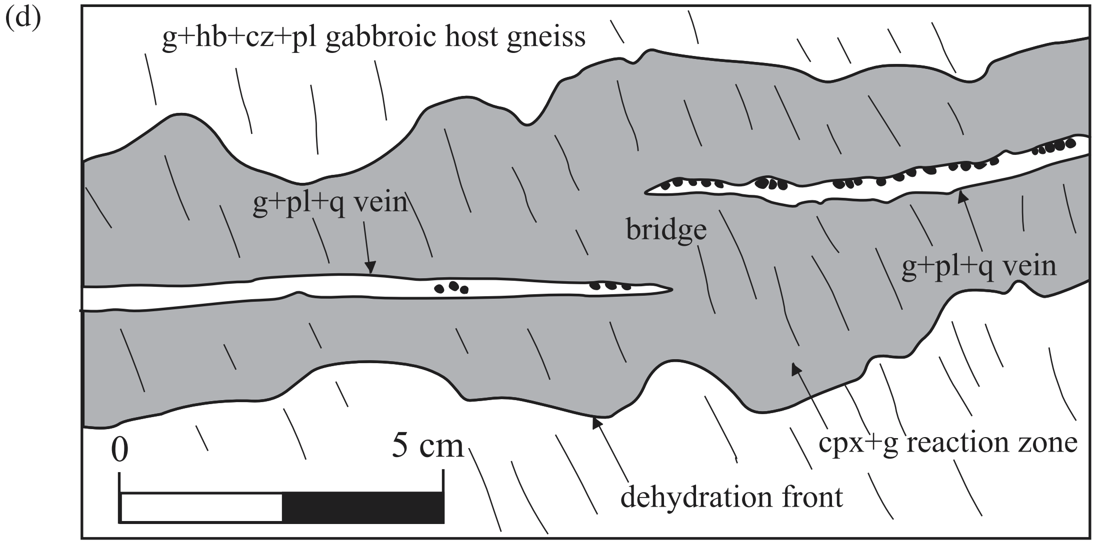


Fig. 6 (continued). (d) Tracing of a photograph showing the geometry of en echelon veins in metagabbroic host in the Pembroke Granulite. The veins show stepped tapered tips with a slight degree of curvature that are characteristic of tension fractures. Irregular vein boundaries probably reflect recrystallisation during granulite facies metamorphism that accompanied vein formation. Black dots inside veins represent garnet formed as a product of melting involving the decomposition of hornblende and clinozoisite. Shaded areas represent garnet-, clinopyroxene-bearing dehydration fronts surrounding the veins. See text for discussion.

physically continuous with leucosome in the migmatitic diorite gneiss. These observations suggest that the dehydration of the metagabbro reflected migrating water-poor melt sourced from the migmatitic dioritic gneiss.

On the basis of vein morphology, physical connectivity with migmatite, and trace element data, Daczko et al. (2001b) concluded that the veins and leucosome were produced by fracturing induced by a positive volume change during fluid-absent melting of the dioritic gneiss. The partial melting was inferred to have been controlled by the decomposition of hornblende and clinozoisite (Daczko et al. 2001b). This mechanism of fracturing is similar to that proposed by Clemens & Mawer (1992) and Roering et al. (1995) where high volumetric strain rates and a solid framework in host rock leads to the development of high pore fluid pressures in melt pockets due to local reaction. The elevated pressures lower effective normal stresses and eventually induce microfractures that propagate until fluid pressure drops below rock strength. The progressive migration of the melt maintains high fluid pressures and promotes continued microcrack propagation (Barker, 1990).

The hypotheses of melt-induced fracturing and the dehydration of host gneiss as a result of melt migration were tested for the Pembroke Granulite locality using partial melting experiments. Using a natural, unmelted sample of the dioritic gneiss these experiments (Antignano et al. 2001; Antignano 2002) established that the dilatational strains associated with melting involving the reaction of hornblende and clinozoisite were high enough to fracture matrix feldspar and quartz (see also Fig. 3B in Klepeis et al. 2003). In addition, the experiments showed that calculated water activities for these melts are low enough (0.39 to 0.12) to cause dehydration (Antignano et al. 2001; Antignano 2002). The combined field, petrologic and experimental data support the interpretation that fracture networks aided melt segregation in the Pembroke Granulite and that melt migration was linked to dehydration in the surrounding gabbroic rocks.

An alternative mechanism to the fracture propagation hypothesis is focused flow in zones of low fluid pressure without creating microfractures. Such a mechanism has been observed in migmatite located elsewhere in Fiordland (described below). The migration of melt along grain boundaries could explain the diffuse boundaries of leucosome in the stromatic migmatite and some veins, and the collection of leucosome around garnet along foliation planes. However, focused flow alone does not explain the observed vein geometries. The orthogonal vein arrays and the tapered tips of en echelon tension gashes are characteristic of fractures forming under conditions of high fluid pressure and low differential stress. In addition, the irregular boundaries of some veins could reflect high temperature recrystallisation or alteration during the garnet granulite facies metamorphism that accompanied vein formation. The lack of any evidence of ductile deformation during the formation of the orthogonal vein sets and dehydration zones suggests that the migration of melt into areas of low fluid pressure (e.g., boudin necks) during such deformation can be ruled out for this site.

The distinctive vein networks with planar garnet granulite dehydration zones occur within a huge area of the western domain. We traced these features from the Pembroke Granulite into the lower part of the Western Fiordland Orthogneiss. This pervasive development suggests that melt-

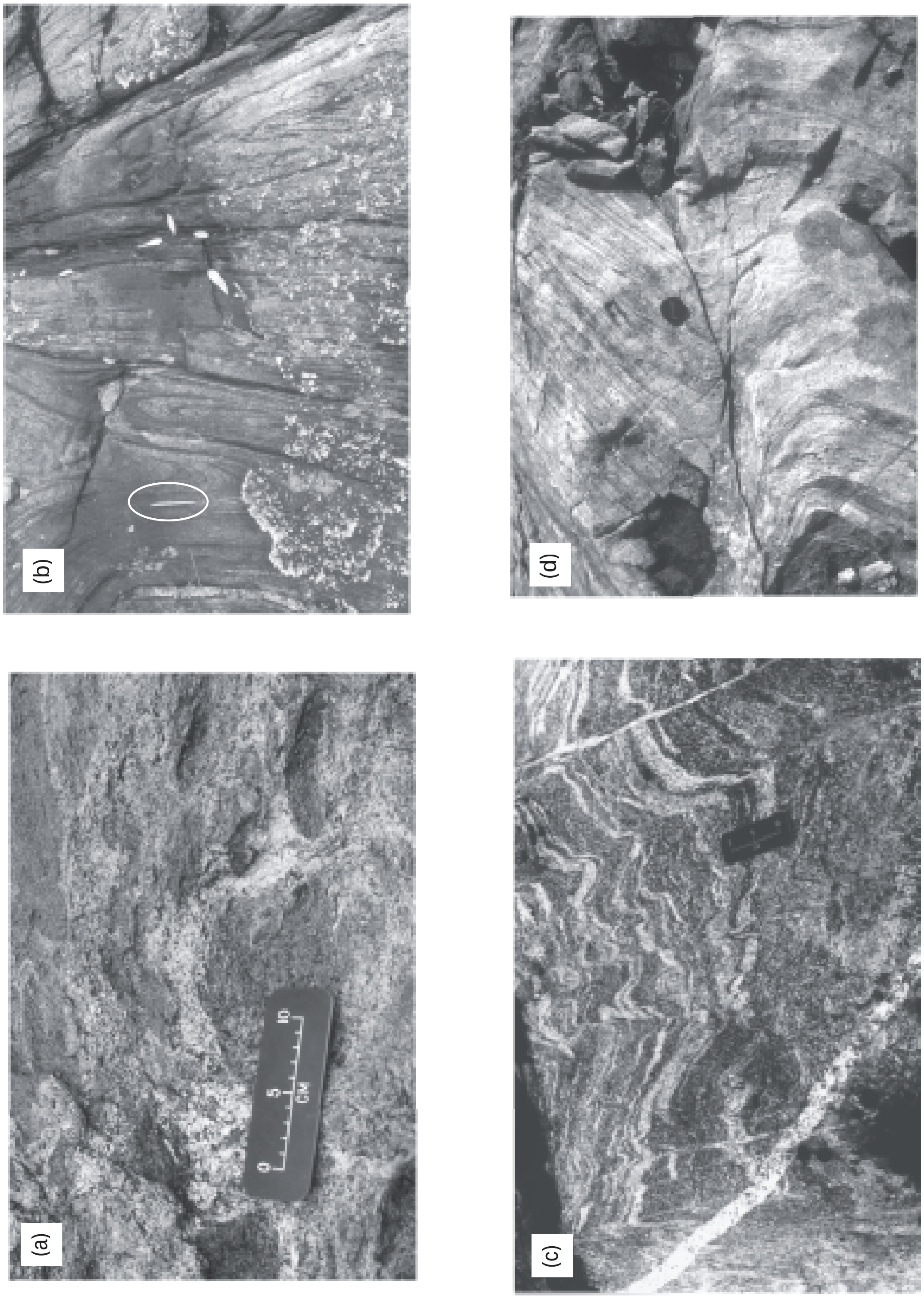


Fig. 7. (a) Photograph of a diatexite formed within 200 m of the contact between pelitic schist and the Western Fiordland Orthogneiss at the northwestern end of George Sound (Figure 2 shows location). Diatexite occurs within a pelitic raft enclosed by the main dioritic phase of the batholith. (b) Photograph showing the steep subsolidus fabric that forms part of the George Sound Shear Zone inside the Western Fiordland Orthogneiss at George Sound (white circle shows pencil for scale). Sectional view of a vertical face. Southeast is to the left. (c) Stromatic migmatite in dioritic gneiss at Camp Oven Creek (CO, Fig. 2). Note folded foliation-parallel leucosome cut by discordant leucosome that parallel the axial planes of folds. Texture is interpreted to represent the migration of melt, now represented by the axial planar leucosome, during folding. See text for discussion. View is of a horizontal surface. Southeast is to the left. (d) Photograph of gently dipping mylonitic shear zone that formed within the Western Fiordland Orthogneiss near Mount Daniel (MD, Fig. 2).

enhanced fracture propagation and the development of steep, regionally extensive fracture networks were important mechanisms of melt transfer during and immediately after emplacement of the Western Fiordland Orthogneiss. However, melt migration in propagating fractures was not the only mechanism of melt segregation and transport. Below we contrast the characteristics of migmatite in the Pembroke Valley locality with those that record ductile deformation during partial melting within the Indecision Creek Shear Zone and the contact aureole of the Western Fiordland Orthogneiss.

Melt Accumulation in Ductile Shear Zones

Migmatite that formed in the metapelitic rafts exposed at George Sound contain an abundance of leucosome that suggests high melt fractions (>30%) were produced and controlled by the reaction of biotite and muscovite during melting. An inhomogeneous diatexite in a metapelitic host near the contact aureole of the Western Fiordland Orthogneiss contains interconnected pockets of leucosome between irregular, joined paleosome (Fig. 7a). The size and abundance of leucosome increases toward the contact between the batholith and its host where leucosome feeds discordant dykes that were injected back into the dioritic parts of the Western Fiordland Orthogneiss.

Within a few tens of meters of the batholith contact, disconnected rafts of host rock are surrounded by leucosome that infill boudin necks. Differential movement between the rafts relative to gneissic layering in host rock is evident by the discordant pattern of foliations preserved inside them. These relationships suggest that melt, now represented by leucosome, migrated along foliation planes to low-pressure sites. However, apart from the localized boudinage and rotated blocks, this site does not record pervasive ductile deformation such as that which produced the Indecision Creek and George Sound shear zones.

At Camp Oven Creek (CO, Fig. 2), stromatic migmatite in a dioritic host contains folded leucosome that parallels a folded foliation (Fig. 7c). This foliation contains the assemblage biotite, hornblende, clinozoisite, plagioclase, and quartz. A second set of leucosomes that is not folded forms spaced arrays that parallel the axial surfaces of the folds (Figs. 7c, 9a). The folds plunge gently to the south and their axial surfaces parallel the steep north-northeast-striking foliation of the Indecision Creek Shear Zone that occurs farther east. However, at this locality the folds lack an axial planar foliation.

In some parts of the Camp Oven Creek exposures the steep axial planar leucosomes truncate and offset the folded leucosomes (Figs. 7c, 9a). This relationship suggests that melt represented by the folded leucosome did not feed the second set of leucosomes but were below the solidus during deformation. However, the occurrence of leucosome parallel to the axial planes of folds suggests that these younger structures reflect melt migration during deformation in the shear zone. East of Camp Oven Creek, the abundance of leucosome decreases, most likely reflecting an increase in strain from the margin toward the central parts of the Indecision Creek Shear Zone. This strain gradient and the steep fabrics of the Indecision Creek Shear Zone are described in the next section.

Stage 3: Evolving Styles of Deformation following Magmatism and Crustal Melting

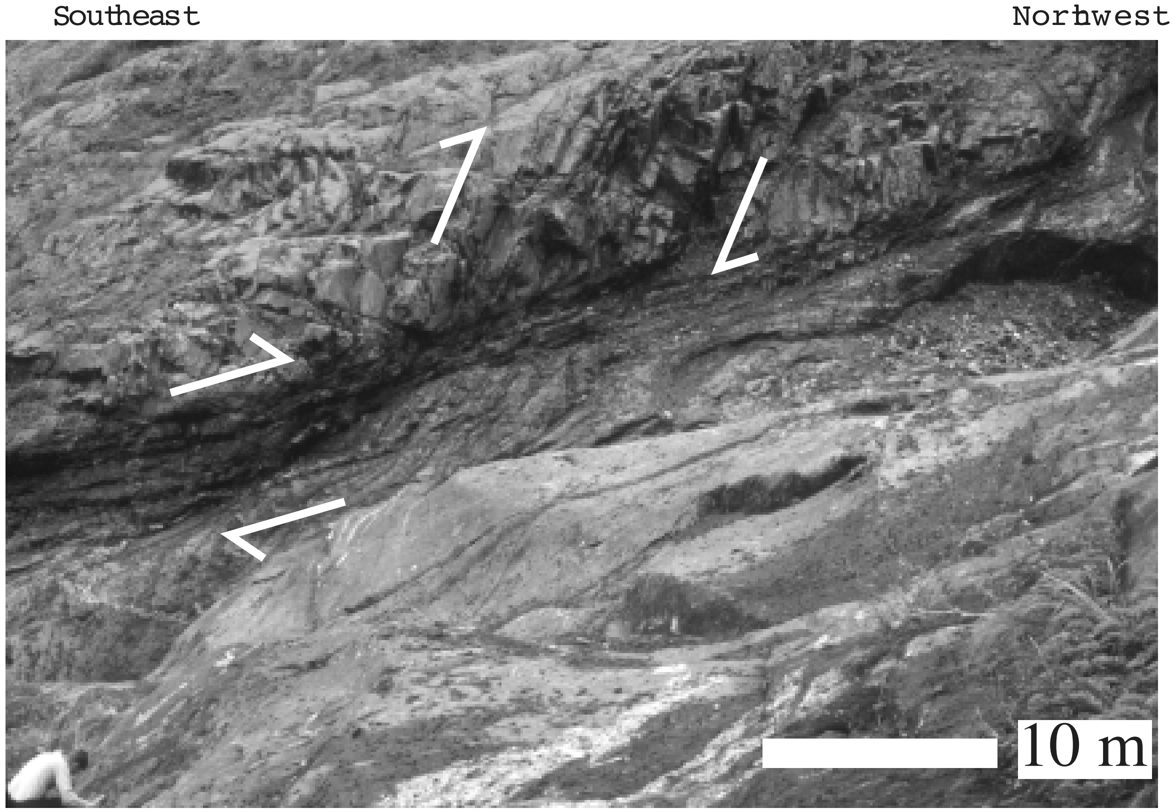
In this section we use outcrop-scale data to define the sequential evolution of ductile structures within and below the Western Fiordland Orthogneiss following partial melting of the lower crust. The relationships we describe illustrate the evolution of a network of steeply and gently dipping shear zones that culminated in formation of the steep Indecision Creek and George Sound shear zones (Fig. 4a).

Steeply Dipping Sinistral and Dextral Shear Zones

In the Pembroke Valley north of Milford Sound (P, Fig. 2), a series of nearly vertical 1-3 meter-wide dextral and sinistral shear zones deform all vein arrays and garnet-bearing dehydration zones in metagabbro and metadiorite. These shear zones, and the migmatite and garnet dehydration zones at this locality, escaped the intense deformation and recrystallisation accompanying development of the Indecision Creek Complex (Fig. 4a). Bradshaw (1990) reported similar narrow and steep shear zones along the eastern side of the Western Fiordland Orthogneiss east of Mount Daniel.

The shear zones display two orientations. The sinistral set contains a mylonitic foliation that strikes to the east and dips steeply to the south. A penetrative, gently southwest-plunging mineral lineation defined by attenuated clusters of amphibole and clinozoisite occurs on these foliation planes. Sense of shear indicators within this set include oblique foliations, asymmetric recrystallised tails on feldspar porphyroclasts, and microfaulted garnet. These structures all record sinistral displacements parallel to the mineral lineation. The second set of minor shear zones is subordinate in size and abundance to the first set. This second set contains mylonitic foliation that strikes to the northwest and displays shallow to moderate dips to the southwest. A gently west- and northwest-plunging amphibole and clinozoisite mineral lineation occurs on foliation planes. Sense of shear indicators within this subordinate set all show dextral displacements.

The kinematic evolution of these sinistral-dextral shear zones are described in detail by Daczko et al. (2001a). Many of the shear zones appear to have nucleated on the margins of steep veins and the garnet-bearing dehydration zones where grain size and compositional differences produced strength contrasts. The results of using deformed vein sets as strain markers suggests that they record subhorizontal arc-normal (northwest-southeast) shortening and arc-parallel (northeast-southwest) stretching at the deepest levels of the section. Analyses of the mineral a)



b)

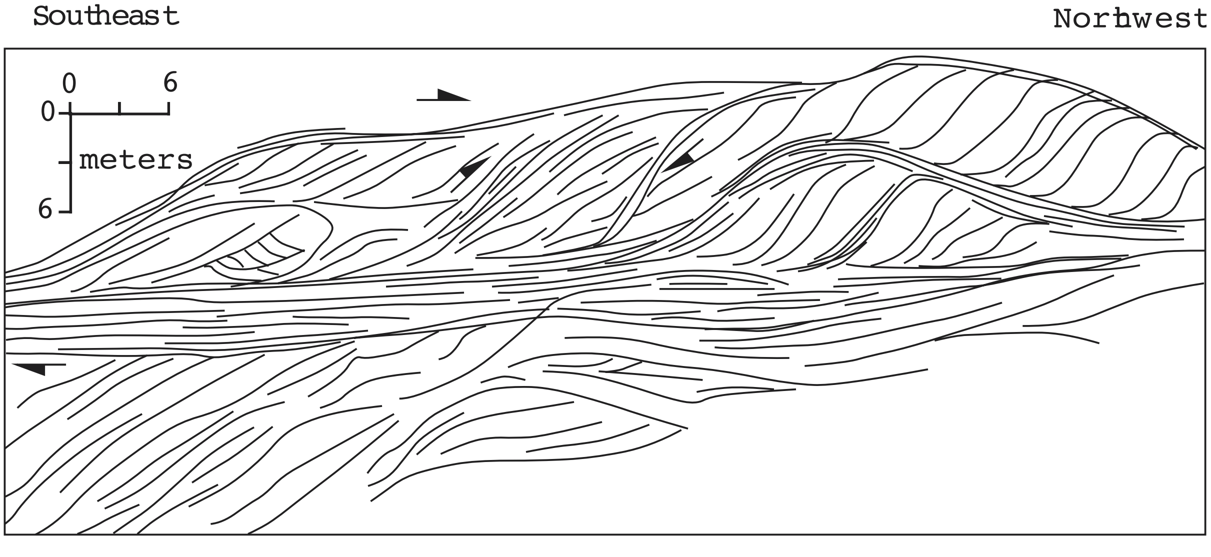


Fig. 8. (a) Sectional view of an outcrop-scale thrust duplex that deforms the Pembroke Granulite. Arrows show relative senses of displacement on mylonitic shear zones. Southeast is to the left. (b) Cross sectional sketch of the shear zone forming the part of the duplex in (a). Black lines are foliation traces. Note imbricated asymmetric pods surrounded by mylonitic foliations that define a vertically thickening shear zone.

assemblages that define foliation in both sets of shear zones, including garnet, pyroxene, hornblende, plagioclase, rutile and quartz, suggest that they equilibrated a peak conditions of P=14.0 ±1.3 kbar and T=676 ±34°C (Daczko et al. 2001a).

Gently Dipping, Layer-Parallel Shear Zones

The steep shear zones of the Pembroke Valley are all deformed and transposed by a series of gently southeast-dipping shear zones that approximately parallel the dominant gneissic foliations of the western domain. Each shear zone displays a mylonitic foliation consisting of the assemblage hornblende, clinozoisite, garnet and biotite. Stretched aggregates of garnet and plagioclase and aligned hornblende form down-dip, southeast-plunging mineral lineations on foliation planes. Daczko et al. (2001a) inferred that the metamorphic mineral assemblages within these shear zones equilibrated at peak conditions of P=14.1 ±1.2 kbar and T=674 ±36°C.

The zone of mylonite that occurs in the central part of each of the gently dipping shear zones is approximately 7-10 meter thick (Fig. 8a). These central mylonite zones, all of which are approximately parallel, are vertically stacked on top of one another at a spacing of approximately 50-100 meters. The total thickness of this shear zone stack is unknown but available exposure indicates that it is at least 1 km thick. Between the stacked shear zones thin (<1 meter thick) mylonitic shear bands dip to the southeast and northwest and sweep into parallelism with the central mylonite zones located above and below them (Figs. 3b, 8b). These shear bands envelop asymmetric pods of coarse-grained metagabbro and metadiorite that form imbricated, antiformal stacks that also dip to the southeast and northwest (Fig. 8). The displaced pods display an older, recrystallised gneissic foliation that is truncated by the margins of the shear bands. Lineations on foliation planes within the shear bands display similar trends but steeper plunges than the lineations that occur in the central mylonite zones. The sense of shear in all of these mylonite zones and shear bands is top-to-the-northwest regardless of the dip of mylonitic foliations (Fig. 8).

The style of displaced, imbricated pods that override one another in these shear zones is diagnostic of layer-parallel shortening and thickening in zones of contraction. Forward models of these geometries suggests that the antiformal style results when the successive stacking of displaced wedges during progressive deformation uplifts earlier formed wedges and causes them to rotate (p. 527, Ramsey and Huber, 1987). On the basis of these geometries and kinematics, we interpret these shear zones as a lower crustal duplex that records arc-normal or oblique (northwest-southeast) shortening and vertical (layer-perpendicular) thickening of the crust below the Western Fiordland Orthogneiss. Daczko et al. (2001a) suggested that because the thrust zones and the sinistral shear zones described earlier both involved subhorizontal shortening at high angles to the MTZ arc, these structures reflect a partitioning of arc-parallel and arc-normal components of oblique convergence onto sinistral strike-slip shear zones and ductile thrusts, respectively.

The Steep Indecision Creek and George Sound Shear Zones

The steep foliation of the Indecision Creek Shear Zone is defined by flattened aggregates of garnet, hornblende, paragonite, biotite, clinozoisite, plagioclase and quartz. Hornblende and biotite mineral lineations on foliation planes display variable plunges to the south and southwest (Fig. 4c). Stretched garnet and boudinage of amphibolite layers indicate that these mineral lineations represent a true stretching direction. Daczko et al. (2001c) showed that metamorphic conditions accompanying this deformation involved cooling from 750-800°C to 650-700°C with no corresponding change in pressure (stage 3 cooling, Table 1). This result is consistent with our results indicating that the Indecision Creek Shear Zone cuts across and transposes all suprasolidus fabrics on the eastern side of the Western Fiordland Orthogneiss (Fig. 4a).

Along western boundary of the shear zone, foliations of western domain are deformed into a series of overturned, west-verging folds (Figs. 3b, 4a) that plunge gently to moderately to the south and southwest. We described earlier in this chapter how the geometry of these folds helps to define a regional strain gradient that increases from northwest to southeast into the Indecision Creek Shear Zone. Fold tightness (interlimb angle) and the dip of axial surfaces increase from northwest to southeast. Zones of high strain display tight to isoclinal, steeply plunging folds. In these areas, fold hinges and isolated pods that contain older foliations are enveloped and transposed parallel to a steep north-northeast-striking foliation (Figs. 9b, 10b). The pods that are enveloped by the steep foliation occur at all scales. The largest of them preserves the thrust zones, migmatite and garnet dehydration zones of the Pembroke Granulite. This steep foliation is locally mylonitic (Fig. 10a) and parallels the boundaries of the Indecision Creek Shear Zone (Fig. 4a).

Outcrop-scale sense of shear indicators occur mostly in zones of intermediate or low strain where the degree of transposition is less than in the high strain areas. These low-intermediate strain zones occur mainly along the western boundary of the shear zone. Exceptions to this relationship occur in zones of mylonite, where sense of shear indicators are abundant (e.g. Fig. 10b). Sense of shear indicators include asymmetric hornblende and clinozoisite fish, asymmetric tails of biotite and hornblende on garnet porphyroblasts, asymmetric boudinage and minor shear zones. These indicators provide evidence of oblique sinistral displacements parallel to the moderately south- and southwest-plunging mineral lineations that occur on the western side of the shear zone (Fig. 4a, 10b). This sense of shear is consistent with the arc-parallel sinistral displacements recorded by steep minor shear zones of the Pembroke Valley.

In addition to a dominantly sinistral shear sense, the involvement of folds at all scales and their change in

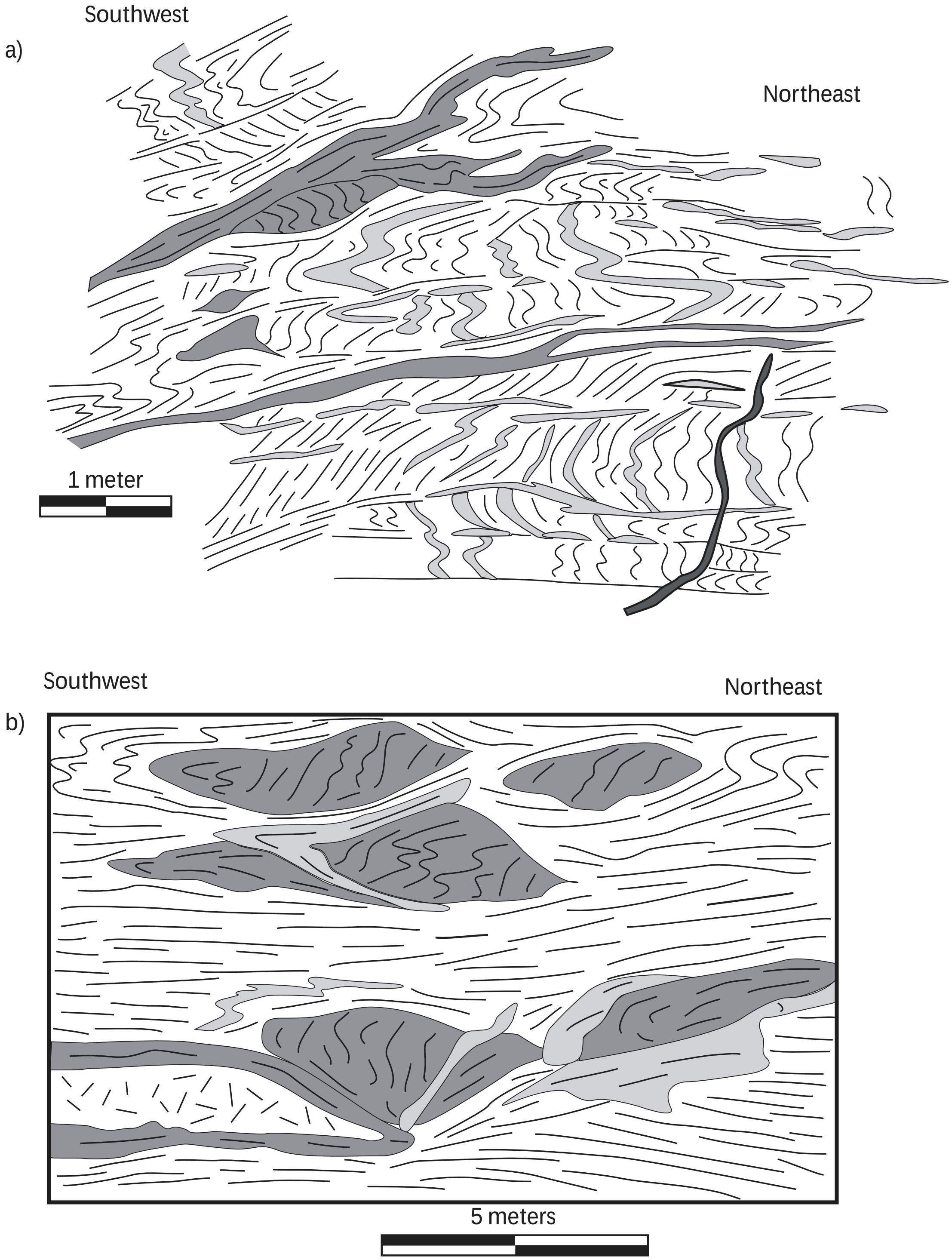


Fig. 9. Structural form maps illustrating variations in the degree of transposition in the Indecision Creek Shear Zone. (a) Sketch is of the same migmatitic metadiorite shown in Fig.7c. Lightly shaded areas represent leucosome in stromatic migmatite. Darkly shaded areas represent deformed mafic dykes of the Milford Gneiss that intrude Paleozoic host gneiss. Sketch location is at Camp Oven Creek (CO, Fig. 2) and lies within the transitional zone between the western domain and the Indecision Creek Shear Zone. Note folded, foliation-parallel leucosome cut by leucosome that parallels the axial planes of the folds. Axial planar leucosome parallels mylonitic foliation in the Indecision Creek Shear Zone. (b) Structural form map of a zone of high strain within the Indecision Creek Shear Zone located at in Selwyn Creek Gneiss (Fig. 2). Foliation exhibits same orientation as axial planar leucosome shown in (a). See Figure 4c for orientation data. Note that the dominant foliation of the shear zone envelops gabbroic pods (darkly shaded) that preserve folds of an older foliation. Outside the pods the older foliation is completely transposed. Pods are surrounded by leucosome interpreted to reflect partial melt (lightly shaded). Stippled pattern represents a diorite dyke. See text for discussion.

geometry from northwest to southeast into the Indecision Creek Shear Zone provide evidence of a component of shortening across the shear zone. The steepening of fold axial surfaces that parallel the shear zone boundaries with increasing strain is consistent with arc-normal contraction. This interpretation also is in good agreement with data from both the sinistral and dextral shear zones and the ductile thrust zones exposed in the Pembroke Valley.

Finally, changes in the plunge of hornblende mineral lineations on steep foliation surfaces with increasing strain (i.e. from northwest to southeast across the 1-5 km wide transitional zone) provide additional kinematic information. The plunges of these mineral lineations gradually steepen from gently and moderately southwest-plunging to near vertical in high strain zones (Fig. 4c). The migration of these lineations toward the dip-line of a vertical shear zone with increasing strain indicates that the shear zone was stretching or thickening in this down-dip direction. The results of forward modeling of lineation and foliation trends in three-dimensional shear zones by Lin et al. (1998) and Jiang and Williams (1998) illustrate this relationship. In the reference frames provided by both the older gneisic foliations of the western domain and the steep boundaries of the shear zone, this result indicates that the Indecision Creek Shear Zone involved a component of vertically thickening. This interpretation is compatible with both a sinistral shear sense and subhorizontal shortening at high angles to the shear zone boundaries. Therefore, we conclude that this shear zone records subhorizontal northwest to southeast arc-normal shortening and sinistral arc-parallel displacements.

The kinematic evolution of the George Sound Shear Zone is less well known than the Indecision Creek Shear Zone. However, numerous similarities exist between these two shea zones. Tight, upright, south-plunging folds of dykes (Fig. 5b) display geometries that are similar in style and orientation to the folds of the Indecision Creek Shear Zone (Fig. 7b). Like in the Pembroke thrust zone near Milford Sound (Fig. 3b), gently dipping mylonitic shear zones deform older gently dipping fabrics inside the Western Fiordland Orthogneiss. The steep upper amphibolite facies fabrics of the George Sound Shear Zone also cut and transpose all older fabrics inside the Western Fiordland Orthogneiss. These steep foliations envelop lenses of diorite that preserve undeformed dykes and unrecrystallised magmatic textures. On the basis of similar structural styles, age and metamorphic grade, we suggested that the Indecision Creek Shear Zone formed during the same contractional event as the George Sound Shear Zone (see also section of *Space-Time Correlation of High Grade Fabrics*).

Discussion: Strucural evolution of a mid-lower crustal attachment zone

The relationships we describe in this chapter show that contractional deformation following Early Cretaceous batholith emplacement and crustal melting produced a heterogeneous network of steep and flat shear zones between 25 km and 50 km depth. In this section we show how this crustal structure and the kinematic relationships that developed during the contraction define a mid-lower crustal *attachment zone* that linked arc-normal displacements in a mid-crustal fold-thrust belt to complexly deforming subvertical shear zones in the lowermost crust.

During the period 126-116 Ma melt-enhanced shear zones formed in narrow zones at the upper and lower contacts of the Western Fiordland Orthogneiss (Stage 1, Fig. 11a). Below the batholith, metamorphic data indicate that the thermal pulse accompanying this magmatism affected up to 10 km of crust below the batholith. However, little penetrative ductile deformation appears to have accompanied the earliest stages of migmatite formation and melt-induced fracturing in most areas of the Arthur River Complex. These observations suggests that magma and steep temperature gradients associated with emplacement of the Western Fiordland Orthogneiss created large strength contrasts that focused deformation inside and at the margins of the batholith during this period.

As the batholith cooled and partial melts were extracted efficiently from beneath it (Stage 2, Fig. 11b), the style of deformation at the deepest levels of the section changed. The melt-enhanced shear zone that localized at the base of the Western Fiordland Orthogneiss was abandoned and a series of deformations evolved below it during the period 116-108 Ma (Stage 3, Fig. 11c). The largest of the shear zones that formed during this period cut across the lower and central parts of the batholith and at least the ~10 km of crust beneath it (Figs. 3b, 4a).

The Indecision Creek and George Sound shear zones represent the last phases in this series of contractional deformations affecting the lower crust following batholith emplacement. The earliest stages of this contraction produced a lower crustal thrust system characterized by simultaneous or nearly simultaneous motion on a series of interconnected steep and flat shear zones. Similar networks of flat and steep shear zones have been described by Karlstrom and Williams (2002). In addition, the Fiordland exposures illustrate a cyclic alternation between the development of steep sinistral shear zones at different times and the formation of flat ductile thrust zones at different depths in the crust (Fig. 11c). However, despite the crosscutting relationships, there are numerous kinematic similarities between these different phases of deformation. All of the deformations are consistent with subhorizontal shortening at high angles to the north-northeast trend of the arc (MTZ). The last two phases of deformation, represented by the Pembroke thrust zone and the Indecision Creek Shear Zone, both record vertical (layer-perpendicular) thickening as well as subhorizontal shortening. Finally, the steep minor shear zones of the Pembroke Valley and the Indecision Creek Shear Zone both record sinistral arc-parallel displacements at slightly different times.

An entirely different structural style and evolution than that which occurred below the batholith characterizes the region of the crust located at the upper margin and above

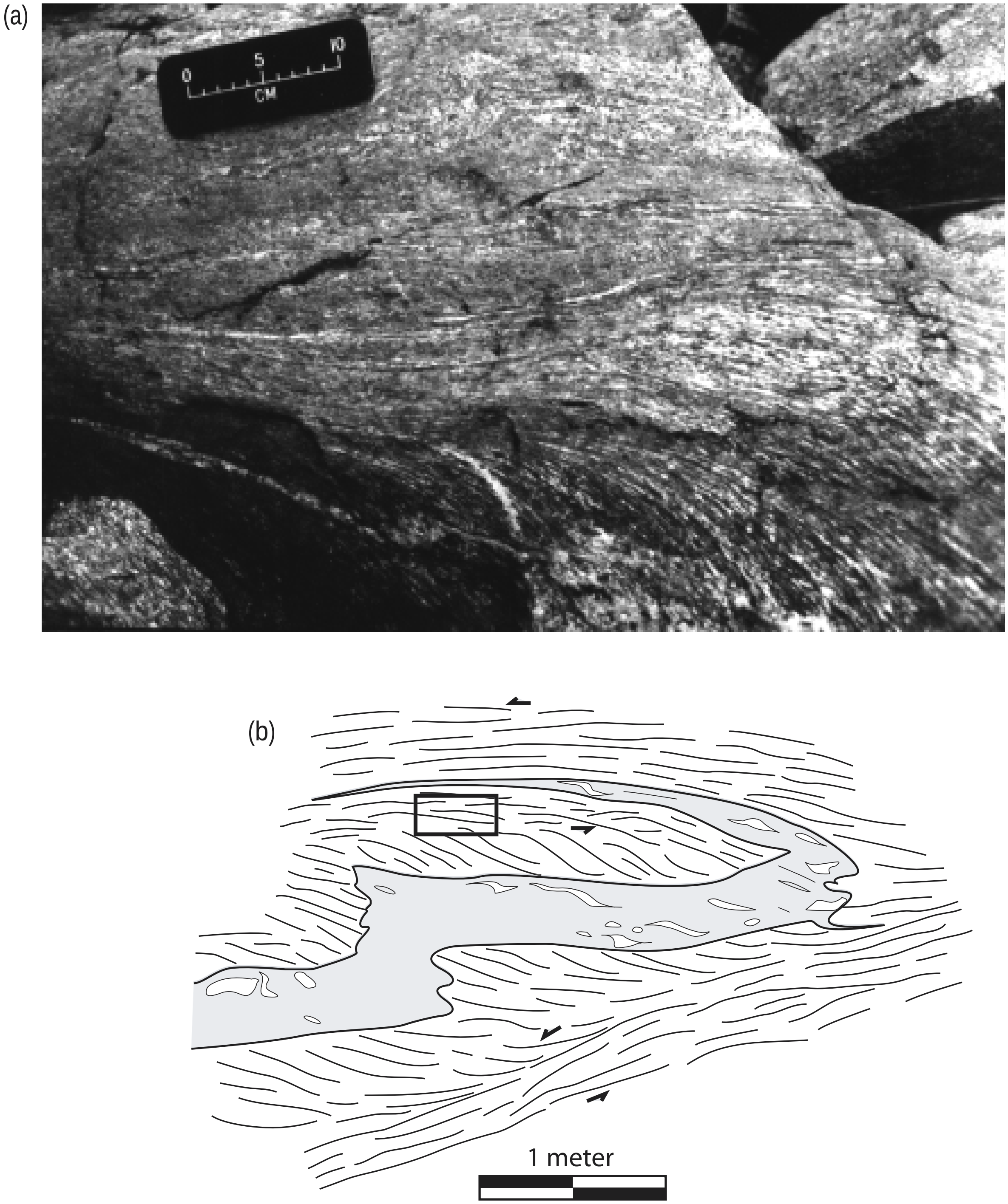
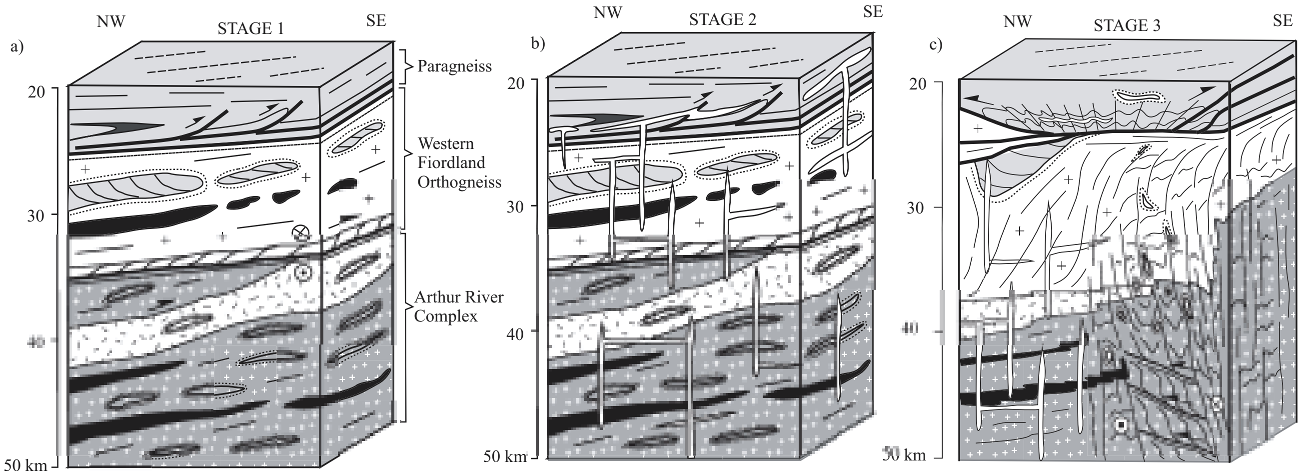


Fig. 10. (a) Photograph showing the deflection and transposition of a gneissic foliation (lower part of photograph) parallel to a steep mylonitic foliation (upper part of photograph) in the Indecision Creek Shear Zone. (b) Sketch of an isoclinal fold of a pegmatite that cuts an older gneissic foliation. Box shows location of photograph in (a). This style of gneissic foliation in lenses that are enveloped by mylonitic foliation occurs at all scales within the Indecision Creek Shear Zone. Sketch and photograph are from a dislodged exposure so that foliations are not in their true orientation.



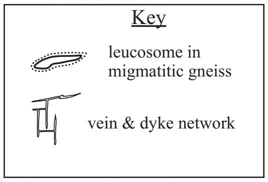


Fig. 11. Cartoons illustrating three stages in the evolution of the Fiordland crustal section. (a) Stage 1 (126-116 Ma): The injection of mafic-intermediate magma of the Western Fiordland Orthogneiss batholith into a layered lower crust. (b) Stage 2: The extraction of partial melts from below the batholith via regional networks of veins and dykes. (c) Stage 3 (116-108 Ma): Contractional deformation followed batholith emplacement and partial melting of the lower crust. Contraction culminated in development of the Indecision Creek and George Sound shear zones that cut across the batholith and merge with a mid-crustal fold-thrust zone located at the top of the batholith. The thrusts root into a 1km thick shear zone that is defined in the text as an attachment zone. This attachment zone links the ductile thrust zone above (bold black lines) to the steep foliations of the Indecision Creek Shear Zone below. Data presented in the text indicate that these features evolved during the same time period after the batholith cooled and crystallised. See text for discussion.

the batholith (Figs. 3, 11c). At Caswell Sound, the ductile thrust system that localized at the upper contact of the Western Fiordland Orthogneiss was not abandoned but continued to evolve as the batholith cooled below the solidus to temperatures of T<800°C after 116 Ma. Our analysis of exposure below the Caswell thrust zone also indicate that the steep foliations of the George Sound Shear Zone flatten and merge with the 1 km thick shear zone that forms the base of the Caswell thrust zone (Figs. 3, 4a). Yet despite their different styles and orientations, both the Caswell thrust zone and the steep shear zones located structurally below it also record subhorizontal shortening at high angles to the arc and vertical thickening. These relationships suggest that, despite the variability in size, style and orientation of the shear zones located above and below the batholith, all phases of deformation during the period 116-108 Ma are consistent with arc-normal shortening, vertical thickening and a preferential partitioning of arc-parallel displacements on steep NNE-striking surfaces.

These kinematic links between different crustal levels define a transfer zone between west-directed shortening in the Caswell fold-thrust zone and oblique sinistral displacements with a component of arc-normal shortening in the Indecision Creek Shear Zone. Fabric correlations based on regional-scale crosscutting relationships and U-Pb data outline earlier in this chapter suggest that these systems evolved during the same 116-108 Ma interval. Although different mechanisms apply, simultaneous movement above and below the Caswell thrust zone is required to accommodate shortening at different crustal depths.

We define the basal shear zone that underlies the Caswell thrust zone as an attachment zone that linked simultaneous deformation on an interconnected network of flat and steep shear zones. The 1 km thick shear zone that underlies the Caswell belt divided the crust into domains exhibiting widely different styles and physically attached the thrusts to the steep, complexly deforming shear zones below it. The middle-crust above the attachment zone is more partitioned and segmented than the penetrative 10-15 km wide zones of ductile deformation that define the shear zonesbelow it. Nevertheless, despite the different styles of deformation, structures above and below the attachment zone are compatible with arc-normal shortening that was accommodated on surfaces of different orientation. In addion, the steep shear zones that formed at the deepest levels of the section accommodated a component on arc-parallel displacements on steep NNE-striking surfaces. This later relationship leads to the prediction that steep, arc-parallel strike slip faults probably formed west of the MTZ at upper crustal levels at this time.

Conclusions

The Fiordland belt records an Early Cretaceous history of mid-lower crustal magmatism, high-grade metamorphism and intense contractional deformation that occurred at paleodepths of 25-50 km. From 126-116 Ma, a ≥10 km thick batholith composed of mafic-intermediate magma was emplaced into the lower crust section. During magma emplacement layer-parallel, melt-enhanced shear zones formed at the upper and lower boundaries of the batholith where strength contrasts were produced by magma and steep temperature gradients. Magmatism was accompanied by granulite facies metamorphism and the formation of migmatite up to 10 km below the intruding batholith. Fluid absent melting of mafic-intermediate gneiss was controlled mostly by the decomposition of hornblende ± clinozoisite. Positive volume changes and high melt fluid pressures during melt production produced fracture networks that aided the segregation and transfer of melt through and out of the lower crust. Ductile deformation in steep shear zones also was important for moving partial melts vertically and horizontally through the lower crust.

During the period 116-108 Ma, the batholith and rocks located below it cooled to temperatures of T<800°C, differential shortening of the crust created a heterogeneous network of subvertical and subhorizontal shear zones. During the earliest stages of this deformation, these shear zones exploited the layered architecture of the middle and lower crust and separated it into structural domains exhibiting widely different structural styles. A ductile fold-thrust system formed in the middle crust (25-30 km paleodepths), with garnet granulite and upper amphibolite facies thrust splays rooting down into a 1 km thick, nearly horizontal shear zone that localized at the uppermost contact of the batholith. This flat shear zone physically connected the mid-crustal fold-thrust zone to subvertical shear zones in the lower crust that are up to 15 km wide. The subvertical foliations in these steep shear zones cut across the lower contact of the batholith and merge smoothly with the subhorizontal shear zone in the middle crust. Fabric correlations based on regional-scale crosscutting relationships and U-Pb data strongly suggest that these systems evolved simultaneously or nearly so during the same 116-108 Ma interval. Simultaneous movement above and below the mid-crustal fold-thrust zone also is required to accommodate shortening at different crustal depths.

This crustal structure and evidence of kinematic links above and below the flat shear zone at the top of the batholith define a mid-lower crustal *attachment zone* that accommodated differential displacements at different crustal depths. Together this network of flat and steep shear zones accommodated mostly subhorizontal east-west, arc-normal shortening in the fold-thrust zone at mid-crustal depths and oblique sinistral displacements on steep, complexly deforming shear zones at lower crustal depths. The oblique-sinistral displacements also were accompanied by a component of vertical thickening and subhorizontal arc-parallel displacements on north-northeast striking surfaces. These displacement patterns are consistent with oblique convergence along an Early Cretacous plate boundary located outboard of the early Mesozoic arc.

Acknowledgments. We are grateful to Cheryl Waters, Olivier Vanderhaeghe and Basil Tikoff for suggestions on ways to improve the original manuscript. We also thank N. Daczko, I. Turnbull, N. Mortimer, and A. Tulloch for helpful discussions during this study. J. Hollis, A. Claypool, S. Marcotte, W.C. Simonson, G. Mora-Klepeis also provided valuable assistance. We thank the Department of Land Conservation in Te Anau for permission to visit and sample localities mentioned in the text. This study was funded by a National Science Foundation grant to K.A.K. (EAR-0087323), an Australian Research Council grant to K.A.K. and G.L.C. (ARC-A10009053), and grants from the Geological Society of America and the University of Vermont.

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