# Magma transport and coupling between deformation and magmatism in the continental lithosphere


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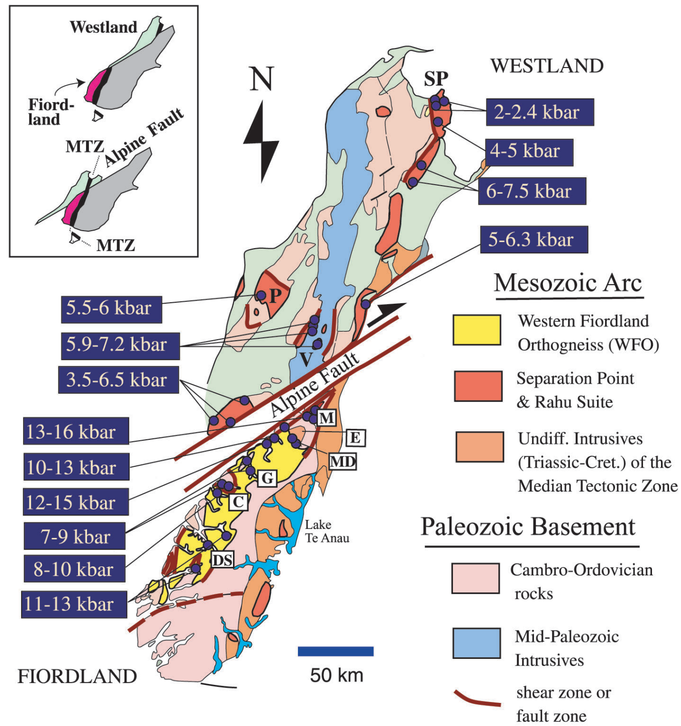


**Figure 1.** Inset shows present configuration (top) and Cretaceous reconstruction (bottom) of western New Zealand assembled by restoring the Median Tectonic Zone (MTZ) to its pre-late Cenozoic position. Main diagram shows Cretaceous reconstruction. Metamorphic pressures from Fiordland (7–16 kbar) represent the peak of Early Cretaceous metamorphism at ca. 120 Ma. Data show a south-tilted lower crustal section and are from J.Y. Bradshaw (1985, 1989), Clarke et al. (2000), Daczko et al. (2001a, 2001b), and Daczko et al. (2002a). Pressures from Westland show shallower Early-mid-Cretaceous (125–105 Ma) pluton emplacement depths (after Tulloch and Challis, 2000). Abbreviations show key locations or features: SP—Separation Point, P—Paparoa Range, V—Victoria Range, M—Milford Sound, E—Mount Edgar, MD—Mount Daniel, G—George Sound, C—Caswell Sound, DS—Doubtful Sound, WFO—Western Fiordland Orthogneiss.


## ABSTRACT

The mechanisms by which magma is generated and transported through continental crust and how these processes affect the chemical and mechanical evolution of the lithosphere are some of the least understood issues of continental dynamics. We report here on the evolution of an unusually well-exposed early Mesozoic arc that originally formed along the ancient margin of Gondwana and is now located in western New Zealand. The pre-Cenozoic configuration and deeply eroded character of this arc lead us to the following conclusions about magmatism and deformation at 10–50 km paleodepths: (1) The mafic-intermediate composition of the lower crust and the mineral reactions controlling melt production strongly influenced pathways of melt transfer and controlled the mechanical behavior of the lithosphere during orogenesis. (2) Evolving lithospheric strength profiles during magmatism and convergence produced transient periods of vertical coupling and decoupling of crustal layers. (3) Late orogenic extension was driven by plate interactions rather than by gravitational forces and a weak lower crust.


## INTRODUCTION

Many of the Mesozoic Cordilleran plutonic complexes located in western North America (Tepper et al., 1993), the Andes (Petford and Atherton, 1996), Antarctica (Wareham et al., 1997), and New Zealand (Muir et al., 1995) contain tonalite to granodiorite batholiths that are thought to originate from the partial melting of mafic lower crust. However, considerable uncertainty surrounds how these magmas are produced and move through the lower crust, and how these processes influence crustal evolution. Much of this uncertainty arises because Phanerozoic arc systems that allow direct examination of mafic lower crust are rare. There are even fewer field sites where exposures of tilted crustal sections allow us to examine structural and magmatic features that evolved simultaneously at lower, middle, and upper crustal levels.

Exposures of early Mesozoic arc crust in western New Zealand allow us to examine directly how deformation interacted with magma generation and transport processes at outcrop to lithospheric scales. The Fiordland part of this belt (Fig. 1) contains >5000 km2 of high-pressure (P = 14–16 kbar) migmatites, granulite facies mineral assemblages, and layered mafic-intermediate intrusions that formed in the lower and middle crust of the arc (25–50 km paleodepths) during the Early Cretaceous. The Westland part (Fig. 1) preserves the middle to upper crustal levels of this same arc (10–27 km paleodepths) where sodic, high Sr/Y granitoids were emplaced following partial melting of mafic-intermediate lower crust (Muir et al., 1998; Tulloch and Challis, 2000). This unusual degree of exposure allowed us to examine the evolution of a 50 km thick column of deforming continental crust over a 35 Ma cycle of orogenesis (Fig. 2). Reconstructing this type of composite crustal column is based on metamorphic pressure data and on inferences about how outcrops can be restored to their original depth-stratified paleogeometry (see also Karlstrom and Williams, 1998, 2002; Miller and Paterson, 2001).

## RECONSTRUCTING THE FIORDLAND-WESTLAND OROGEN

On the South Island of New Zealand, a segment of the present-day boundary between the Australian and Pacific plates occurs along an 800-km-long transform called the Alpine fault (Fig. 1). This fault has accommodated ~460 km of dextral strike-slip displacement since the Miocene (Wellman, 1953). By removing this amount of slip, the pre-Cenozoic configuration of western New Zealand can be reconstructed (Tulloch and Challis, 2000). Cretaceous reconstructions (Fig. 1) show a continuous NE-trending belt of calc-alkaline granitoids, layered mafic igneous complexes, and volcano-sedimentary terranes that define an early Mesozoic (247–105 Ma) composite arc (Kimbrough et al., 1994; Mortimer et al., 1999).

Near continuous exposure along coastlines and in the mountainous terrain of Fiordland reveal the three-dimensional structure of the deepest parts of the arc. Fiordland (Fig. 1) contains a layered, dome-shaped mid-lower crustal section where the shallowest paleodepths (~25 km) occur in the center at Caswell Sound (C, Figs. 1, 2A, 2B) and the deepest paleodepths (45–50 km) occur at Milford Sound (M, Figs. 1, 2A, 2B) and Doubtful Sound (DS, Figs. 1, 2C). In Westland, high Sr/Y sodic granitoids of the 125–105 Ma Separation Point Suite (Fig. 1) record Early Cretaceous emplacement depths of 8–27 km (Tulloch and Challis, 2000).

The ages of major intrusive features and of Cretaceous deformation and metamorphism are well constrained by published geochronology (Mattinson et al., 1986; McCulloch et al., 1987; Gibson and Ireland, 1995; Muir et al., 1998; Ireland and Gibson, 1998; Nathan et al., 2000; Tulloch et al., 2000). Published dates and new analyses of zircon (Klepeis et al., 2001; Hollis et al., 2002; G. Gehrels, 2002, personal comm.) from within the section reveal three tectonic phases (Fig 2): (1) the addition of mafic-intermediate magma into the lower crust (126–116 Ma) and the partial melting of lower crustal host gneisses; (2) contractional deformation and the emplacement of sodic, high Sr/Y granitoids in the middle and upper crust (116–105 Ma); and (3) late orogenic extension, cooling and exhumation (105–90 Ma). This last phase preceded inception of seafloor spreading in the Tasman Sea (ca. 84 Ma) by ca. 15 Ma (Gaina et al., 1998) and was accompanied by the formation of extensional metamorphic core complexes in Westland, New Zealand (Tulloch and Kimbrough, 1989).

## MAGMA EMPLACEMENT AND PARTIAL MELTING IN THE LOWER CRUST

During the period 126–116 Ma (Fig. 2A), the lower crust of the Fiordland belt accumulated at least 10 km (thickness) of mafic-intermediate magma (Mattinson et al., 1986). The first phases were gabbroic with minor ultramafic compositions; later phases were dominated by diorite. This intrusion formed a >3000 km² tabular batholith called the Western Fiordland Orthogneiss (WFO, Figs. 1, 2A) and has been interpreted to have added sufficient heat to the lower crust to partially melt

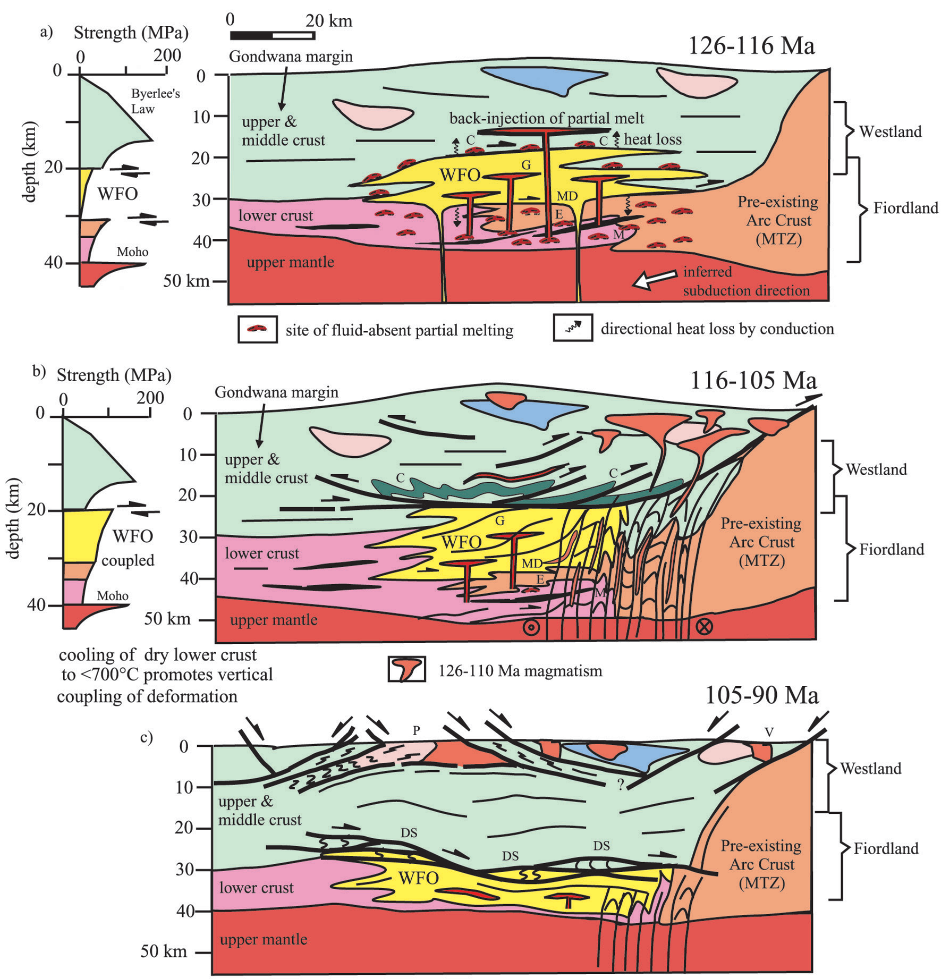


**Figure 2.** Cartoons illustrating the tectonic evolution of the Fiordland-Westland belt. Abbreviations and color scheme are as in Figure 1. **A:** During interval 126–116 Ma, mafic-intermediate magma (WFO, yellow) was added to the middle (bottom part of green color) and lower (dark pink and tan) crust. Upper crust was composed mostly of Paleozoic Gondwana margin rocks (green) and granitoid plutons (light blue and light pink). Lower crust was composed of older (>126 Ma) arc-related rocks, including parts of the Median Tectonic Zone (MTZ) and Mount Edgar diorite (E) in tan and Paleozoic gneisses of Gondwana in dark pink. **B:** Contractional deformation (116–105 Ma) followed magmatism and melt production. C: Late orogenic extension (105–90 Ma) formed metamorphic core complexes (P and V) in mid-upper crust and the Doubtful Sound shear zone (DS) in the lower crust. Schematic strength profiles illustrate variations in the strength of the lower crust during two stages of orogenesis. Lower crust in A was weakened by magmatism. Lower crust in B was strengthened by dehydration and the cooling of the Western Fiordland Orthogneiss (WFO) to T < 700 °C following data presented in Daczko et al. (2002b).

host gneisses (Daczko et al., 2001b). At the time of this intrusion, the lower crust was composed of older (>126 Ma) vertically stratified mafic-intermediate intrusive phases of the early Mesozoic arc, including the western Median Tectonic Zone (MTZ) and Mount Edgar (E) diorite (Figs. 1, 2; Hollis et al., 2002), and Paleozoic gneisses of Gondwana margin affinity (Tulloch et al., 2000).

Field data show that the spatial distribution of rocks that partially melted following magma emplacement was highly heterogeneous. Above and near the top of the batholith, at the Caswell (C, Figs. 1, 2A) and George Sounds (G, Figs. 1, 2A), migmatites formed in a narrow zone 200–500 m thick near the batholith-country rock contact. In contrast, below the batholith a region of lower crust at least 10 km thick partially melted (Fig. 2A). Petrologic analyses suggest that the partial melting of mafic-intermediate gneisses below the batholith was patchy and mostly involved hornblende breakdown to form garnet surrounded by leucosome (Daczko et al., 2001b).

To test possible mechanisms of melt generation in gneisses below the batholith, piston-cylinder experiments were performed on an unmelted sample of dioritic gneiss at P = 14 kbar and T = 800–975 °C (Antignano et al., 2001). The mineral assemblage consisted of plagioclase + quartz with hornblende, clinozoisite, and biotite as the hydrous phases. At T = 825 °C, biotite undergoes melting in the absence of free water (fluid-absent), followed by the reaction of hornblende and clinozoisite resulting in garnet + melt as reaction products. Melt compositions initially are granitic due to the influence of biotite but become granodioritic to tonalitic with increasing temperature as the main reaction shifts to fluid-absent melting of hornblende ± clinozoisite (Fig. 3A). Calculated water activities of the melts are low (0.39 to 0.12) and trace element data from experimentally produced glasses show high Sr/Y ratios. Melt fractions remained low (<10 vol%) at all temperatures up to T = 975 °C. This suggests that although partial melting occurred in large parts of the section below the batholith (Fig. 2A), the volume of melt produced probably remained low. These results may explain the low percentage of leucosome observed in mafic lower crust in the field and contrasts with the much higher melt fractions observed in migmatitic paragneiss above the batholith.

## MELT SEGREGATION AND TRANSPORT

In migmatite formed at paleodepths of 45–50 km (Fig. 3D), diffuse patches of leucosome parallel gneissic layering and feed laterally into vertical (layer-perpendicular), vein-filled extension fractures (Figs. 3E, 3F, 3G). The sharp, straight edges of the veins and curved vein tips are typical of brittle extension fractures. The fracture sets cut across all lithologic boundaries and occur within hundreds of square kilometers of the lower crustal section, including the batholith. These features provide strong geological evidence that melt segregation and transport were aided by diking and fracture propagation following batholith emplacement.

The physical links that occur between leucosome in migmatitic gneiss and the vein-filled fractures and dikes suggest that positive volume changes and the development of high melt fluid pressures during melt production induced brittle failure by lowering effective normal stresses in the lower crust (e.g., Clemens and Mawer, 1992; Davidson et al., 1994). In this scenario, the leucosome observed in the field reflects melt migration along fractures. We tested this hypothesis in the field and laboratory using metamorphic and geochemical relationships that record how partial melts interacted chemically with gabbroic gneiss during their migration. Adjacent to leucosome in gabbroic gneiss, hornblende-bearing assemblages recrystallized to garnet granulite (Figs. 3E, 3F) at conditions of T > 750 °C and P = 14 kbar (Clarke et al., 2000). Early theories (e.g., Blattner, 1976; Bradshaw and Kimbrough, 1989) suggested that these recrystallized zones formed by dehydration as CO2-rich fluids were introduced along fractures. However, the garnet-bearing dehydration zones only occur in gabbroic gneiss and are physically continuous with leucosome formed in migmatitic diorite. These relationships led Daczko et al. (2001b) to infer that dehydration of the gabbroic gneiss reflected the scavenging of water by migrating, water-poor partial melt sourced from the melted diorite gneiss.

Distinctive trace and rare earth element (REE) patterns in the dioritic and gabbroic gneisses provided another means of testing the interconnectivity and chemical communication between the partial melt produced in the diorite and the dehydration zones in the gabbroic gneiss. Hornblende in partially melted dioritic gneiss displayed a progressively increasing heavy REE content relative to that of chondrite. In contrast, hornblende in the fractured gabbroic gneiss showed a progressively decreasing heavy REE content. These distinctive patterns were inherited by garnet that formed in both the migmatitic structures in diorite (Fig. 3D) and in veins where partial melts invaded the gabbroic gneiss (Fig. 3E). This result is important because it supports the interpretation that hornblende ± clinozoisite produced garnet + melt in the dioritic gneiss and that these melts migrated into the dehydrated gabbroic gneiss along fracture networks.

To further test the hypothesis that fractures can be produced by the fluid-absent melting of horndblende + clinozoisite, we established experimentally that this reaction involves a positive volume change. Partial melting experiments on solid rock cores show that the dilational strain associated with the hornblende + clinozoisite reaction is high enough to induce fracture in matrix feldspar and quartz (Fig. 3B) and confirms the low water activity of these melts (Antignano, 2002). These results support the interpretation that fluid-absent melting reactions with high dilational strain can produce fracture networks that allow for interconnectivity and melt transfer. These data combined with the development of vein arrays within large parts of the Fiordland section suggest that fracture networks aided melt segregation and that melt migration was linked to dehydration in the surrounding gabbroic rocks.

Field relationships also show that fracture propagation and diking were not the only mechanisms of melt transfer following intrusion of the batholith. Foliation planes, lithologic contacts, boudin necks, and fold hinges in ductile shear zones that developed after batholith emplacement also contain leucosome. These observations suggest that a combination of fracture networks and deformation in shear zones moved partial melt horizontally and vertically through the crustal column.

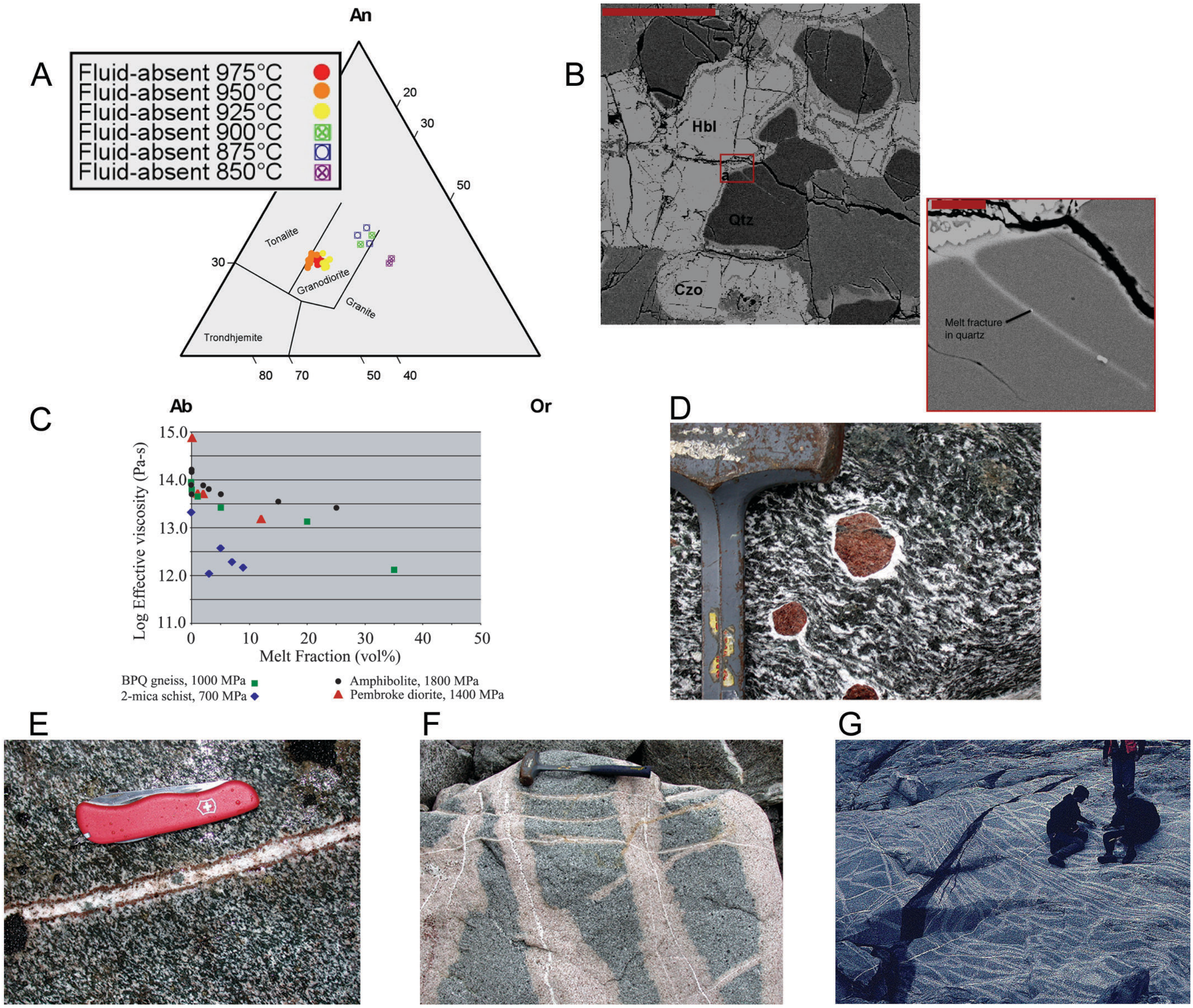


**Figure 3. A:** Compositions of partial melts in metadiorite plotted on an Ab-An-Or diagram. **B:** Backscatter image showing textural evidence of the melting reaction: hornblende + clinozoisite + quartz + plagioclase ≥ clinopyroxene + garnet + melt + plagioclase ± Fe-oxides in solid diorite core experiment. Reaction products surround quartz grain and melt is observed in a fracture (red box). Scale is 200 microns. Inset shows close-up of melt fracture in quartz grain, product clinopyroxene is shown in top left corner. Black crack is due to unloading of experiment. Scale is 20 microns. **C:** Effective viscosity vs. melt fraction plot showing results from solid-media deformation experiments. Metadiorite sample displayed a high effective viscosity compared to pelite under subsolidus conditions and is similar to amphibolite (Rushmer, 1995) and biotite-plagioclase-quartz (BPQ) gneiss (Holyoke and Rushmer, 2002) with partial melt present (Antignano, 2002). **D:** Migmatitic dioritic gneiss showing leucosome surrounding peritectic garnet. **E:** Garnet-bearing leucosome filling extension fracture in gabbroic gneiss. **F:** Granulite facies dehydration haloes surrounding leucosome and fracture networks. Haloes contain clinopyroxene + garnet assemblage that replaces hornblende-bearing assemblage in gabbroic gneiss. **G:** Reorientation of extension fractures record ductile deformation following brittle failure of the lower crust.

## CHANGES IN LOWER CRUSTAL STRENGTH AND RHEOLOGY

In Fiordland, magma compositions and the liquidus temperature of basalt indicate that the initial intrusion temperatures of the WFO were likely ≥1200 °C following the estimates of Petford and Gallagher (2001). Mineral assemblages that formed in the batholith and its host rocks following its emplacement record progressive changes in temperature and fluid activities. Partial melting and granulite facies metamorphism occurred at 750 °C < T < 850 °C (Daczko et al., 2001b). With time, kyanite- and paragonite-bearing assemblages replaced older garnet-clinopyroxene-plagioclase assemblages reflecting isobaric cooling of the lower crust to ~650 °C prior to 108–105 Ma (Daczko et al., 2002b). These observations and the well-known dependence of lower crustal strength and rheology on melt fraction, temperature, and fluid activity imply that the lower crust must have had a different mechanical strength at different times between 126 and 105 Ma. These results are consistent with evidence of complex rheological stratifications in sections of arc crust exposed in the U.S. Cordillera (Miller and Paterson, 2001).

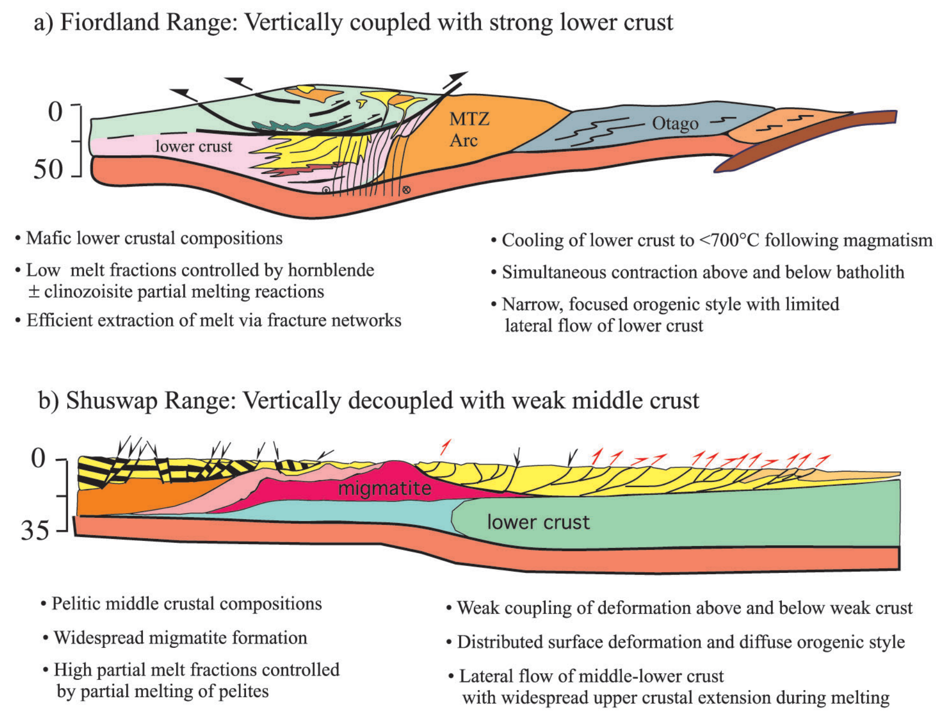


**Figure 4.** Cartoons showing the different possible mechanical responses of continental lithosphere following partial melting of the deep crust. **A:** The Fiordland-Westland belt reflects a strong lower crust during the period 116–105 Ma that promoted vertical coupling of deformation. **B:** The Shuswap range of southern British Columbia, Canada is characterized by a weak middle crust (after Vanderhaege and Teyssier, 1997; 2001). Text below diagrams highlights differences in the characteristics and boundary conditions that influence orogenic styles.

During the earliest stages of magmatism (126–116 Ma) suprasolidus shear zones formed at the upper and lower boundaries of the batholith. At Mount Daniel (MD, Figs. 1, 2A) these shear zones contain tightly folded tonalite sheets that are cut by less deformed sheets, indicating that deformation coincided with the periodic emplacement of magma. Coarse biotite in tightly folded layers exhibits radial patterns and tabular plagioclase lacks evidence of subsolidus recrystallization. These features reflect deformation under magmatic conditions and suggest that the flow of magma participated in, and may have facilitated, the imbrication of crustal slices during crustal thickening.

Inside the batholith all magmatic features are cut by the fracture arrays that have been linked physically and chemically to sites of partially melted host rock (Fig. 3). The fact that these fractures cut the lower contact of the batholith (MD, Fig. 2A) provides direct evidence that by ca. 116 Ma the batholith had mostly crystallized and was strong as it deformed together with its host rocks at high effective viscosities. Finally, ductile shear zones that record subsolidus temperatures of 650 °C < T < 800 °C deform many of the fractures and dikes inside and below the batholith (Daczko et al., 2001a). These transitions suggest that during the period ca. 116–105 Ma, the lower crust initially was weakened by the addition of heat and magma and later strengthened as melt moved out of the lower crust and the lower crust cooled. Experimental data confirmed the relatively high strengths of lower crustal mafic rocks even as they underwent mineral reactions involving partial melting (Fig. 3C). These changes are illustrated qualitatively in the strength-depth profiles showing a weak lower crust in Figure 2A and a stronger lower crust in 2b.

## CHANGING PATTERNS OF DEFORMATION IN THE LOWER CRUST

One of the most useful features in the study of deformation in Fiordland was the penetrative arrays of extension fractures surrounded by garnet granulite dehydration zones that formed over hundreds of square kilometers of the section, including the batholith. Changes in the angular relationships among these and other vein sets provided a means of defining strain gradients and the kinematic evolution of shear zones from the outcrop to the regional scale (Fig. 3G). Within the westernmost part of the section, a penetrative, SW-dipping gneissic layering also provided a reference frame that facilitated a comparison of structural styles across the belt. In the west, where Early Cretaceous deformation was weakest, thermobarometric data indicate that this layering was oriented close to horizontal during and after batholith intrusion and fracture sets cut across layering at high angles approaching 90°.

Following partial melting of the lower crust, swarms of vertical, ≤1 m thick, E- and NW-striking shear zones formed at the margins of dikes below the batholith. These shear zones form antithetic (dextral) and synthetic (sinistral) pairs that record arc-parallel (NE-SW) displacements and subhorizontal (layer-parallel) arc-normal (NW-SE) shortening within a dominantly sinistral flow regime (Daczko et al., 2001a). Subsequently, these shear zones were deformed by a series of SE-dipping (avg. 27°), vertically stacked (100 m spacing) shear zones that contain imbricated, asymmetric pods of mylonite. These pods form antiformal stacks that are typical of thrust duplexes and record layer-parallel (subhorizontal) shortening and layer-perpendicular (subvertical) thickening during arc-normal contraction (Daczko et al., 2001a). Mineral assemblages that define foliation planes in these thrusts record metamorphic conditions of P = 14 ± 1.2 kbar and T = 674 ± 36° C (Daczko et al., 2001a). This style of duplex involving simultaneous deformation along steeply and shallowly dipping foliations was also noted by Karlstrom and Williams (2002) as an important mechanism in the middle crust for accommodating strain during synchronous thickening of crust and migration of melt.

As the batholith cooled further and contraction continued, the style of deformation in the lower crust changed. Along the western boundary of the MTZ (below letter M in Figs. 1, 2B), shortening resulted in a vertical, 10–15 km wide, N-striking transpressional shear zone that cuts across the entire lower crustal section, including the lower and eastern contact of the batholith. This shear zone records an oblique-sinistral sense of shear.

Near vertical foliations that define the shear zone at deep levels (14–16 kbar) gradually flatten upward and merge into a horizontal décollement zone underlying a mid-crustal fold-thrust belt (7–9 kbar) at the top of the batholith (Fig. 2B). On the basis of thermobarometry, this shear zone transects a crustal thickness of at least 20 km (Fig. 2B). The mid-crustal fold-thrust belt is well exposed at Caswell Sound (C, Figs, 1, 2B) and exhibits features that are common in many upper crustal settings including imbricated thrust splays that sole into flat detachments, fault propagation folds, and conjugate thrusts and back thrusts (Daczko et al., 2002a).

Both the mid-crustal fold-thrust belt and the steep lower crustal shear zone below it cut the 126–116 Ma Western Fiordland Orthogneiss and are deformed by a younger set of upper amphibolite facies shear zones, including the Doubtful Sound shear zone (DS, Figs. 1, 2C). These shear zones cut all contractional structures in Fiordland and record decompression and cooling of the granulite belt through the closure temperature of hornblende (~550 °C) by ca. 108–105 Ma and to ≤400 °C by 90 Ma (Gibson et al., 1988; Gibson and Ireland, 1995; Klepeis et al., 1999; Nathan et al., 2000). These relationships and U-Pb geochronology (Tulloch et al., 2000; Hollis et al., 2002) indicate that as the batholith cooled during the period 116–105 Ma, contraction was coupled at different levels of the crust through an interconnected network of steeply and gently dipping shear zones.

## DISCUSSION AND CONCLUSIONS

### Lithospheric-Scale Interactions Among Deformation and Melt Transfer Processes

The Fiordland-Westland example provides strong geological evidence that diking and melt-enhanced fracturing was an important mechanism for the segregation and initial ascent of melt out of the lower crust. Similar melt-enhanced fracture systems have been observed in other orogenic belts (Davidson et al., 1994; Roering et al., 1995; Yamamoto and Yoshino, 1998) but to our knowledge none show this behavior on such large scales as in the Fiordland belt.

Once the batholith and its host rocks had cooled to subsolidus temperatures (T < 820 °C), structural elements in large vertical shear zones were exploited as pathways for melt transport horizontally and vertically through the crustal column. These observations agree with models that predict the buoyancy of hot felsic magma and the dynamics of transpression can create pressure gradients that help force magma through the crust (e.g., Robin and Cruden, 1994; de Saint Blanquat et al., 1998).

As transpressional shear zones evolved in the lower crust, granitoids were emplaced into the upper crust until ca. 105 Ma (Muir et al., 1995; Waight et al., 1998). The Separation Point batholith represents the final stages of this process. This batholith consists of sodic, alkali-calcic diorite to biotite-hornblende monzogranite that is similar in composition to Cordilleran adakite suites (Muir et al., 1995). The geochemical and isotopic signatures of these granitoids suggest that they were derived either from young, hot subducted oceanic crust or from mafic crust at the root of a thickened (>40 km paleodepths) magmatic arc (Muir et al., 1995, 1998). Our observations support the latter interpretation.

The isotopic (Sr, Nd) composition of the Separation Point suites also suggests that rising magmas experienced little to no interaction with felsic arc crust (Muir et al., 1995, 1998). This implies that the mixing of mantle and crustal components to form shallow-level plutons occurred in the mafic lower crust. Fiordland provides an example where the mixing of mantle and crust components may have occurred beneath a mafic intrusion (e.g., Petford and Gallagher, 2001), and where the rapid ascent of hybrid magmas through fracture networks and shear zones inhibited crustal contamination at shallower levels. Finally, data from Fiordland reconcile the previously tenuous relationship between crustal melting and high-pressure granulite facies metamorphism. The data show that this metamorphism was related directly to the migration of water-poor partial melts through the lower crust.

### Transient Coupling and Decoupling Within the Lithosphere

High melt volumes (>30%) associated with the emplacement of the WFO and the virtual absence of any Cretaceous deformation outside the batholith and its contact aureoles during emplacement indicate that the lower crust probably was decoupled from the upper and middle crust during the interval 126–116 Ma. Structural patterns indicate that subhorizontal (layer-parallel) flow between layers of colder, less deformed host rock characterized this period and reflected the localization of deformation into areas weakened by melt and heat. However, this period of vertical decoupling was transient, occurring only during the ~10 m.y. period before the batholith cooled and crystallized.

By ca. 116 Ma, the melt enhanced shear zones at the base of the batholith were abandoned. The development of granulite facies fracture arrays inside the batholith and its host indicate that decoupling had ended by this time and that these crustal layers were deforming together at similar high effective viscosities. Evidence that a 10–15 km wide transpressional shear zone in the lower crust evolved simultaneously with, and was connected physically to, a mid-crustal thrust system following batholith emplacement and crustal melting also indicates that deformation at these levels was coupled during the interval 116–105 Ma (Fig. 2B). Metamorphic data suggest that strengthening of the lower crust promoted vertical coupling during this phase and was aided by efficient melt extraction, dehydration, and cooling as the batholith crystallized and melt escaped.

Structural features in the upper crust of the arc exposed in Westland also are consistent with a relatively strong, cooling viscous lower crust after ~116 Ma. At shallow levels of the crust contractional deformation occurred within a narrow (50–75 km wide) zone focused along the western side of the MTZ (SP, Fig. 1; Tulloch and Challis, 2000). This narrow, focused structural style (Fig. 4A) supports the predictions of numerical models of orogens where a highly viscous lower crust preferentially transmits stresses vertically through the lithosphere (Royden, 1996; Ellis et al., 1998). The style also contrasts with the distributed style of near surface deformation in orogens characterized by a weak middle or lower crust (Fig. 4B).

### Magmatism and Late Orogenic Extension

In some Cordilleran settings, late orogenic extension has been linked to a thermal weakening of the middle or lower crust (Vanderhaeghe and Teyssier, 1997;

Ellis et al., 1998). For example, in the Shuswap Ranges of southern British Columbia, crustal melting and magma intrusion decreased crustal viscosity by several orders of magnitude and appear to have aided the development of extensional structures within previously thickened crust (Vanderhaeghe and Teyssier, 2001). However, in Fiordland, the discovery of a vertical transpressional shear zone that formed after batholith emplacement, and evidence for a relatively strong lower crust that promoted vertical coupling prior to the onset of extension suggest an alternative mechanism at work. Late orogenic extension in western New Zealand appears to be linked to changes in plate boundary dynamics rather than a change in lower crustal rheology. The shift in structural style in Fiordland from contraction and crustal thickening to crustal thinning and decompression ca. 105 Ma corresponds to the end of subduction and a reorganization of plate boundaries outboard of Gondwana (J.D. Bradshaw, 1989). This implies that the development of a regional tensile stress field at this time resulted in the extensional failure of the lithosphere rather than a weakening of the lower crust by melt and heat.

These relationships suggest a different type of response to magmatism and melting of the lower crust in Fiordland (Fig. 4A) compared to other orogens that experienced deep crustal melting such as the Shuswap Range (Fig. 4B). One important reason for the mechanical response of the Fiordland-Westland orogen appears to be the mafic composition of the lower crust and the mineral reactions controlling melt production. In Fiordland, melt production was mostly controlled by hornblende-breakdown, which produced relatively low volumes of partial melt that were extracted from the lower crust via fracture networks and ductile shear zones. This situation contrasts with the high melt volumes and widespread development of diatexite in the Shuswap Range, where melt production in metapelitic protoliths was controlled by biotite and/or muscovite breakdown. These relationships imply that the hornblende-rich, mafic composition of the lower crust and the mineral reactions controlling melt production strongly influenced the mechanical behavior of the belt following magma emplacement.

In summary, the Fiordland setting provides a natural laboratory within which we can test our understanding of the feedbacks that develop among magmatism, metamorphism, and deformation during cycles of orogenesis. In addition, the approach of using parallel field, laboratory, and experimental studies may be one of the most important tools we have to develop a complete picture of coupled processes in the continental lithosphere. In Fiordland, this approach has revealed the mechanisms by which magma was generated and transported through lower continental crust and how these processes affected the evolution of the lithosphere over a 35 m.y. cycle.

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