Tempo of burial and exhumation within the deep roots of a magmatic arc, Fiordland, New Zealand

R.M. Flowers*
S.A. Bowring
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
A.J. Tulloch Geological and Nuclear Sciences, Private Bag 1930, Dunedin, New Zealand
K.A. Klepeis Department of Geology, University of Vermont, Burlington, Vermont 05405, USA

ABSTRACT

The U-Pb thermochronology of titanite, apatite, and rutile from a crustal profile through a Mesozoic magmatic arc in Fiordland, New Zealand, is used to constrain the timing and duration of significant vertical movements during arc construction and evolution. Titanite data from deep-crustal (12–13 kbar) basement and cover rocks of central Fiordland imply that contractional arc thickening ($\sim$25 km) occurred by 111.1–113.4 Ma, within a few million years of a major phase of mid- to deep-crustal magmatism. This finding suggests that this cycle of magmatism, arc thickening, and high-grade metamorphism occurred in $\leq$6.2 m.y. In contrast to rapid burial, significant unroofing of the central Fiordland granulites was more protracted, requiring an additional 40–45 m.y. These new data are consistent with continued residence of the granulites in thickened arc crust for 15–20 m.y., with subsequent major unroofing recorded by rutile cooling to $<$450 °C by ca. 70 Ma. Such temporal constraints are essential for comprehensive models of the growth, modification, and unroofing of magmatic arc systems.

Keywords: magmatic arc, U-Pb, thermochronology, burial, exhumation, lower crust.

INTRODUCTION

Characterizing the timing and magnitude of vertical motions of rocks within continental arcs is critical for understanding arc development and evolution. Although structural and metamorphic studies have begun to address these fundamental issues (e.g., Miller et al., 1993; Whitney et al., 1999; Klepeis et al., 2004), remarkably little is known of the timing, duration, and rates of arc construction, thickening, and unroofing. Deciphering thermal histories in shallow through deep crust can provide vital information about these processes. Modern high-precision U-Pb thermochronology of accessory minerals with a range of closure temperatures (T_c), including zircon and monazite ($T_c > 1000$ °C), titanite ($T_c \approx 600$–650 °C), apatite ($T_c \approx 450$–500 °C), and rutile ($T_c \approx 400$–450 °C), in conjunction with ^{40}Ar/^{39}Ar hornblende and mica data, can be used to reconstruct cooling records with unprecedented resolution (see Data Repository[1]). These data, when linked with the structural and metamorphic record, can provide critical temporal constraints on pressure-temperature (*P-T*) paths that are necessary for a more complete understanding of magmatic arc dynamics.

Fiordland, New Zealand, provides a superb opportunity to develop a cooling history through a rare vertical profile of a magmatic arc. This region not only contains one of the world's largest ($>$5000 km^2) and best exposures of the deep roots (50 km deep) of a thickened Mesozoic arc, but also preserves the mid- to upper-crustal levels of this same arc system. Because of little overprinting by later arc activity, Fiordland preserves a rare snapshot of deep arc-crust burial and exhumation. We use U-Pb titanite, apatite, and rutile systematics from eight samples to provide constraints on the *P-T* evolution of the Fiordland crustal profile. Our data reveal that arc thickening was more rapid, and major exhumation was more protracted, than resolved in previous geochronological studies.

REGIONAL GEOLOGIC SETTING

Central and eastern Fiordland comprise parts of a Late Jurassic–Early Cretaceous magmatic arc (Fig. 1). North of the Alpine fault, displaced by Neogene dextral strike-slip movement, the arc continues in Westland-Nelson (Mortimer et al., 1999). The arc—the site of semicontinuous convergent-margin magmatism from 165 to 105 Ma—comprises paired older outboard and younger inboard belts of contrasted low and high Sr/Y ratios, respectively (LoSY and HiSY; Tulloch and Kimbrough, 2003). In the Fiordland segment, the inboard plutonic belt and country rock are deeply exhumed. Here, Paleozoic schists and gneisses of the Tuhua sequence structurally overlie Mesozoic arc-related plutons (e.g., Oliver, 1980; Bradshaw, 1990). Within this basement in northern Fiordland, the Arthur River Complex is a heterogeneous orthogneiss package that yields sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon dates of 136–129 Ma, with both Mesozoic and Paleozoic zircon cores and ca. 120 Ma metamorphic zircon rims (Tulloch et al., 2000; Hollis et al., 2003; Klepeis et al., 2004). These rocks have a partly faulted eastern contact with diorites of the essentially unmetamorphosed, shallower level, 141–137 Ma Darran Complex to the east (Blattner, 1978; Mattinson et al., 1986; Kimbrough et al., 1994; Wandres et al., 1997; Clarke et al., 2000). The Arthur River Complex is intruded by the $>$10-km-thick granulite facies Western Fiordland Orthogneiss, a younger belt of plutons dominated by dioritic rocks. The U-Pb thermal ionization mass spectrometry and ion-probe zircon crystallization dates for the Western Fiordland Orthogneiss range from 126 to 116 Ma, with a distribution of older dates in northern Fiordland ($>$120 Ma) that is apparently distinct from younger dates (ca. 116 Ma) in central Fiordland (Mattinson et al., 1986; Muir et al., 1998; Tulloch and Kimbrough, 2003; Hollis et al., 2004). A population of orthogneiss zircons that yielded an ion-probe date of ca. 108 Ma has been interpreted to indicate a younger phase of granulite facies metamorphism (Gibson and Ireland, 1995), but this date has not been reproduced in other studies.

The Western Fiordland Orthogneiss and Arthur River Complex granulites preserve an early, relatively low-*P*, high-*T* metamorphic event ($P < 8$ kbar, $T > 700$ °C), followed by high-*P* metamorphism and the attainment of peak conditions ($P \leq 16$ kbar, $T > 750$ °C) that vary with exposure level (Bradshaw, 1989; Brown, 1996; Clarke et al., 2000; Daczko et al., 2001, 2002a). Structural studies attribute the up-pressure metamorphic record of the Mesozoic arc rocks to burial by $\sim$25 km of continental crust due to contraction following pluton intrusion (Clarke et al., 2000; Daczko et al., 2001, 2002a). Klepeis et al. (2003) proposed three major phases in Fiordland's tectonic evolution: (1) significant mafic to intermediate-composition magmatism during emplacement of the Western Fiordland Orthogneiss, (2) contractional deformation leading to magmatic arc thickening, and (3)

---

*E-mail: rflowers@mit.edu.

[1] GSA Data Repository item 2005002, Table DR1, U-Pb isotopic data for titanite, apatite, and rutile; Table DR2, Pb isotopic composition of leached feldspar separates; Figure DR1, U-Pb concordia diagrams; and Appendix, closure temperatures of accessory minerals and analytical methods, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Geology; January 2005; v. 33; no. 1; p. 17–20; doi: 10.1130/G21010.1; 2 figures; Data Repository item 2005002.

extensional exhumation prior to opening of the Tasman Sea. Previous constraints on the cooling history of the Western Fiordland Orthogneiss are provided by a K-Ar hornblende ($T_c \sim 500$–550 °C) date of 92.6 $\pm$ 0.9 Ma (1σ), a K-Ar biotite ($T_c \sim 300$–400 °C) date of 76.9 $\pm$ 0.8 Ma (1σ), and U-Pb apatite (T_c 450–500 °C) dates from 92.6 $\pm$ 2.0 Ma to 57.9 $\pm$ 0.4 Ma (2σ) (Mattinson et al., 1986; Gibson et al., 1988). At shallower crustal levels, K-Ar hornblende and biotite dates in the Tuhua cover sequence are older with increasing distance from the Western Fiordland Orthogneiss, suggesting less Cretaceous isotopic disturbance (Gibson et al., 1988). U-Pb apatite dates for the Darran Complex range from 113.0 $\pm$ 0.4 to 135.6 $\pm$ 0.4 Ma (2σ) (Mattinson et al., 1986).

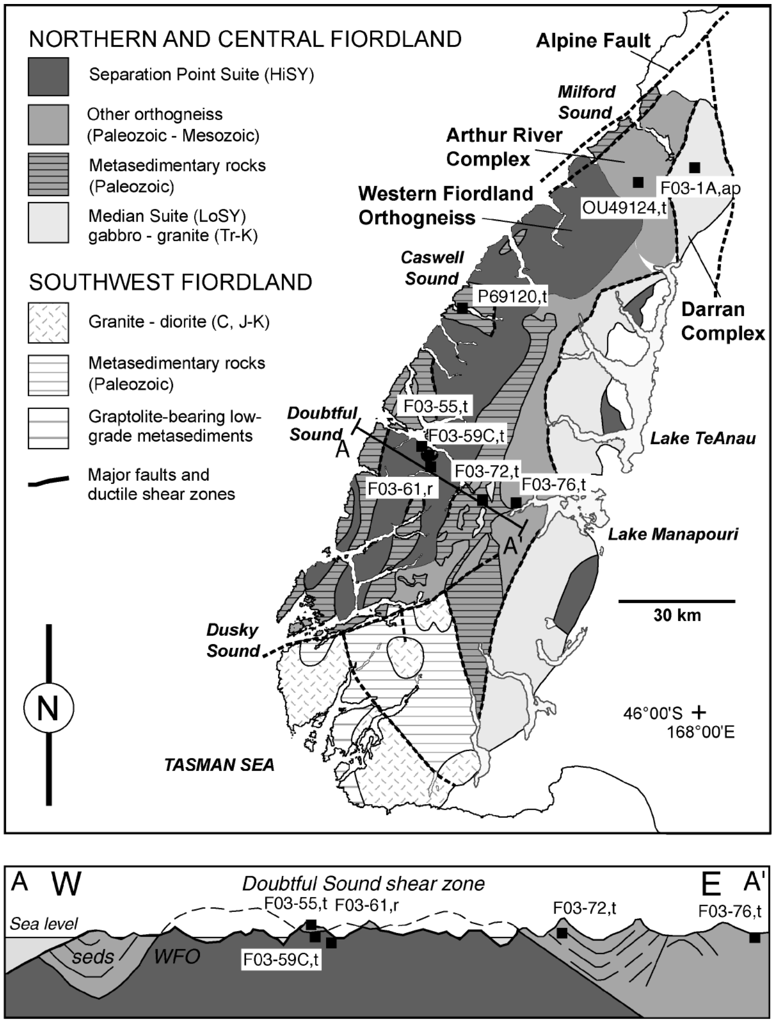

Figure 1. Regional map of basement geology of Fiordland, New Zealand (after Bradshaw, 1990), with associated geologic cross section through central Fiordland (after Oliver, 1980; Gibson et al., 1988). Squares show sample locations. Letter after sample name indicates mineral analyzed: t—titanite, ap—apatite, r—rutile. LoSY and HiSY—paired older outboard and younger inboard belts of contrasted low and high Sr/Y ratios, respectively. In legend, C—Carboniferous, J—Jurassic, K—Cretaceous, Tr—Triassic.

U-Pb THERMOCHRONOLOGICAL RESULTS

In order to place constraints on the burial and exhumation history of the Fiordland sector of the magmatic arc, we selected eight samples for U-Pb accessory mineral analysis (Fig. 1). Mineral separation and U-Pb analytical methods are described in the Data Repository (see footnote 1). Isotopic data and isotopic ratio corrections are included in Tables DR1 and DR2 (see footnote 1). The best thermochronological constraints in this study are provided by five samples from the Doubtful Sound region in central Fiordland (Fig. 1). Here, the granulite Western Fiordland Orthogneiss basement is separated from high-grade schists and gneisses of the Tuhua cover sequence by the extensional Doubtful Sound shear zone (Oliver, 1980; Gibson et al., 1988). Titanite grains from a calc-silicate (F03-55) several meters above the shear zone and from a gneissic inclusion within the Western Fiordland Orthogneiss basement (F03-59C) were analyzed to constrain the timing of peak metamorphic conditions associated with magmatic arc thickening. Six titanite fractions from F03-55 yielded ^{206}Pb-^{238}U dates from 112.5 $\pm$ 0.1 Ma to 111.1 $\pm$ 0.5 Ma to (Fig. 2A). Four titanite fractions from F03-59C yielded ^{206}Pb/^{238}U dates from 113.4 $\pm$ 0.4 Ma to 112.1 $\pm$ 0.3 Ma (Fig. 2A). Four rutile fractions from a nearby Western Fiordland Orthogneiss granulite (F03-61), intended to constrain the subsequent cooling history, yielded ^{206}Pb/^{238}U dates from 73.9 $\pm$ 0.5 Ma to 65.8 $\pm$ 0.5 Ma (Fig. 2A). In contrast with these deeper-level samples, titanite data from a calc-silicate of the Tuhua sequence (F03-72) 4–5 km structurally above the Western Fiordland Orthogneiss, and a biotite granite (F03-76) 9–10 km east of Doubtful Sound, yielded information regarding the thermal histories of shallower rocks. Four titanite fractions from F03-72 yielded only Paleozoic ^{206}Pb/^{238}U dates from 314.0 $\pm$ 0.5 Ma to 310.6 $\pm$ 0.2 Ma (Fig. DR1A; see footnote 1). Five titanite fractions from F03-76 yielded ^{206}Pb/^{238}U dates from 123.7 $\pm$ 0.2 Ma to 118.6 $\pm$ 0.6 Ma and define a linear array with an upper intercept of 128.1 $\pm$ 8.1 Ma (mean square of weighted deviates [MSWD] = 0.57) (Fig. DR1B; see footnote 1).

In an effort to compare thermal histories in different parts of Fiordland, three additional samples were analyzed from Caswell and Milford Sounds (Fig. 1). Four titanite fractions from an Arthur River Complex granulite (OU49124) of Milford Sound had low ratios of radiogenic Pb to common Pb and yielded ^{206}Pb/^{238}U dates of ca. 120 Ma. Four titanite fractions from a Caswell Sound calc-silicate (P69120) yielded a linear array with Paleozoic and Mesozoic intercepts, suggesting either partial resetting of Paleozoic titanite or new Mesozoic titanite growth (Fig. DR1C; see footnote 1). Five multigrain fractions of apatite from a Darran diorite sample (F03-1A) from east of Milford Sound yielded ^{206}Pb/^{238}U dates from 129.8 $\pm$ 0.6 Ma to 124.4 $\pm$ 0.4 Ma.

IMPLICATIONS FOR THE TEMPO OF BURIAL AND EXHUMATION IN MAGMATIC ARCS

Magmatic Arc Burial

Our thermochronological data indicate that burial of the magmatic arc in Fiordland occurred within a few million years of a significant pulse of mid- to deep-crustal magmatism. Intrusion of the Western Fiordland Orthogneiss at $P < 8$ kbar, $T > 700$ °C, followed by peak metamorphism at $P \leq 16$ kbar and $T > 750$ °C, is ascribed to burial of the orthogneiss and Arthur River Complex by $\sim$25 km of crust (e.g., Bradshaw, 1990; Klepeis et al., 2004). In central Fiordland (12–13

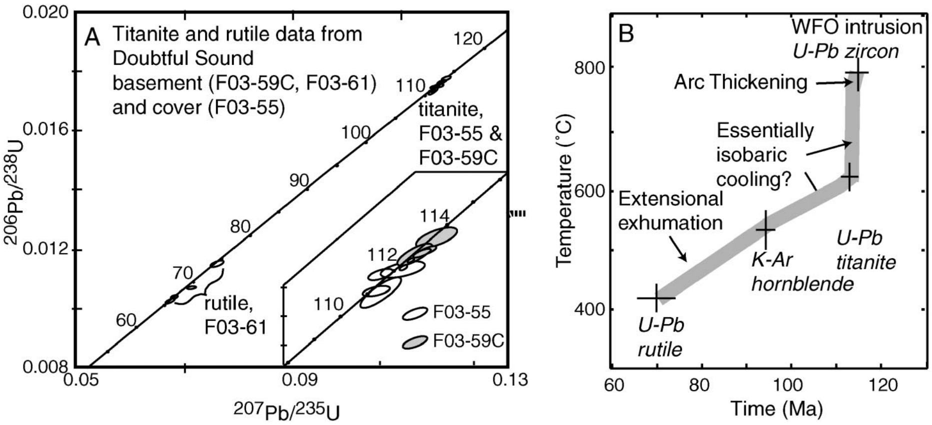

Figure 2. A: U-Pb concordia diagram, showing F03-55 titanite, F03-59C titanite, and F03-61 rutile data. Inset is detail of titanite data. B: Temperature vs. time diagram for central Fiordland granulites from Doubtful Sound. Western Fiordland Orthogneiss (WFO) U-Pb zircon data error (cross) depicts crystallization dates with approximate errors for central Fiordland (Mattinson et al., 1986; Hollis et al., 2004). K-Ar hornblende data are from Gibson et al. (1988). Titanite and rutile data show range of dates obtained in this study. Temperature errors for zircon data approximate peak metamorphic conditions associated with WFO intrusion; those for other minerals represent conventionally accepted closure-temperature ranges.

kbar), titanite grains from basement and cover-sequence samples record cooling through 600–650 °C by 113.4–111.1 Ma, following either new titanite growth or resetting associated with peak metamorphism. The most precise constraint on the duration of major crustal loading is provided by comparison of basement samples within Crooked Arm of Doubtful Sound. Our U-Pb basement titanite dates from 113.4 ± 0.4 Ma to 112.1 ± 0.3 Ma, combined with a recent U-Pb zircon crystallization date of 115.6 ± 2.4 Ma (2σ) for a Western Fiordland Orthogneiss sample within several kilometers of our analyzed titanite (Hollis et al., 2004), impose a maximum 6.2 m.y. interval for an episode of major magmatism, arc contraction, and peak metamorphism in the central Fiordland arc. The oldest titanite date and the zircon date are within error, suggesting that the duration may have been much shorter.

The brevity of burial and metamorphism indicated by our data is consistent with sharp growth zoning of Fiordland garnets suggesting a duration at high temperatures of <6.2 m.y. (Bradshaw, 1989; Brown, 1996), and is compatible with the inference of rapid decoupling and coupling within the orogen during and following emplacement of the Western Fiordland Othogneiss (Klepeis et al., 2004). Similarly, our results support the suggestion by Hollis et al. (2004) that magmatism and contraction were sufficiently close in time such that heat associated with Western Fiordland Orthogneiss intrusion contributed to high temperatures during arc burial. These data are inconsistent with a second episode of granulite facies metamorphism at 108 Ma (Gibson et al., 1988; Gibson and Ireland, 1995). The precise timing of tectonic loading in northern Fiordland remains equivocal, owing to the scarcity of radiogenic titanite from rocks in this area. Although it is reasonable to suspect that our rapid burial constraints for Doubtful Sound also apply to northern Fiordland, additional work is required to confirm a synchronous burial history throughout the region.

In contrast to the high temperatures achieved in the granulites during arc thickening, analyses of titanite and apatite from mid-crustal samples suggest that these rocks were not significantly affected by the thermal event. Titanite grains from a calc-silicate (F03-72) record Paleozoic dates of ca. 330 Ma. Titanite grains from a biotite granite (F03-76) yield dates of ca. 128 Ma, which may represent cooling following the crystallization of this granite at shallow crustal levels. Apatite grains from the 141–137 Ma mid to upper-crustal Darran Complex in northern Fiordland (F03-1A) yield U-Pb dates of ca. 128 Ma. This is consistent with previous analyses (Mattinson et al., 1986) and indicates cooling following intrusion without subsequent reheating above ~450–500 °C during Western Fiordland Orthogneiss magmatism and burial. Although the magnitude of displacement between the amphibolite facies Darran Complex and the granulite facies Arthur River Complex is uncertain, the apparent generation and emplacement of the Darran Complex within the same arc implies that it was proximal to western Fiordland during subsequent arc events. All of the evidence here for a relatively cool middle to upper crust is consistent with the brief duration of lower-crustal magmatism and metamorphism implied by our titanite data.

Magmatic Arc Exhumation

Following rapid burial, our data indicate that major exhumation of the central Fiordland magmatic arc was significantly more protracted, requiring 40–45 m.y. U-Pb rutile data from a Western Fiordland Orthogneiss granulite from Crooked Arm of Doubtful Sound (F03-61) indicate that exhumation and cooling below 400–450 °C did not occur until ca. 70 Ma. This date indicates a more extended interval than implied by previous studies (Mattinson et al., 1986; Gibson et al., 1988). The distribution of samples dated previously includes northern and southern Fiordland, and age discrepancies may in part reflect dissection, differential uplift, and variable cooling of blocks due to heterogeneous exhumation and/or deformation along the Alpine fault.

These first U-Pb titanite and rutile data from Fiordland also permit a more detailed analysis of the tempo of unroofing during this 40–45 m.y. period (Fig. 2B). We suggest that the titanite dates of 113.4–111.1 Ma represent essentially isobaric cooling through 600–650 °C, without significant exhumation. In northern Fiordland, kyanite-quartz-plagioclase pseudomorphs are interpreted to record high-*P* cooling by 200 °C prior to decompression (Daczko et al., 2002b). A K-Ar hornblende date does not indicate cooling through ~500 °C until 93 Ma (Gibson et al., 1988), perhaps marking the onset of unroofing at that time. This is compatible with continued residence of Western Fiordland Orthogneiss rocks in deep crust of the thickened arc for at least 15–20 m.y. Our temporal constraints that suggest a delay in significant cooling and unroofing are consistent with continued arc-related magmatism at shallower levels until at least 105 Ma, the youngest dated pluton from the inboard plutonic belt (Tulloch and Kimbrough, 2003). Widespread latest Early Cretaceous and Late Cretaceous extension recorded by structures in both the deep and shallow crust, due to breakup of the Pacific margin of Gondwana, has been correlated with exhumation of the deep roots of the Fiordland arc (e.g., Gibson et al., 1988; Tulloch and Kimbrough, 1989; Klepeis et al., 2003, 2004).

Burial and Exhumation in Other Magmatic Arcs

In general, the nature and rates of vertical arc motions are poorly constrained because of overprinting by later arc activity, inadequate exposure levels, or retrograde metamorphism. Rocks within the Sierra Nevada batholith are typically characterized by relatively shallow exposure levels of <5 kbar, contain deepest exposures of 8–9 kbar, and appear to lack a significant loading history following voluminous magmatism (e.g., Bateman, 1992; Ague, 1997; Wood and Saleeby, 1997). The early exhumation history of the Sierran arc is poorly understood, but was followed by a more recent Pliocene to Holocene phase of uplift attributed to lithospheric delamination (e.g., Saleeby et al., 2003; Saleeby and Foster, 2004). In contrast, rocks within part of the crystalline core of the Cretaceous Cascades arc record intrusion at <4 kbar and subsequent tectonic loading to pressures of 9–12 kbar within a few million years of emplacement, a shallower level burial history that is similar in magnitude to that preserved in Fiordland (e.g., Miller et al., 1993; Whitney et al., 1999; Valley et al., 2003). Exhumation of the Cascades core was heterogeneous and has been attributed to contractional and extensional processes directly associated with arc construction (Matzel, 2004; Paterson et al., 2004). Identifying the universal or distinct processes associated with individual magmatic arcs is central to understanding the growth and modification of continental margins. The exceptional snapshot of deep crustal burial and exhumation preserved in Fiordland provides a valuable perspective, and yields some of the best temporal constraints, on a critical aspect of magmatic arc dynamics.

ACKNOWLEDGMENTS

Discussion and constructive review of this manuscript by Bob Miller and field assistance and discussion with Jenny Matzel are greatly appreciated. We thank John Bradshaw and Simon Cox for thoughtful reviews. A National Science Foundation (NSF) graduate fellowship to R. Flowers, NSF grant EAR-9980623 to S. Bowring, and NSF grant EAR-0337111 to K. Klepeis in part supported this work.

REFERENCES CITED

Ague, J.J., 1997, Thermodynamic calculation of emplacement pressures for batholithic rocks, California: Implications for the aluminum-in-hornblende barometer: Geology, v. 25, p. 563–566.

Bateman, P.C., 1992, Plutonism in the central part of the Sierra Nevada batholith, California: U.S. Geological Survey Professional Paper 1483, 186 p.

Blattner, P., 1978, Geology of the crystalline basement between Milford Sound and the Hollyford Valley, New Zealand: New Zealand Journal of Geology and Geophysics, v. 21, p. 33–47.

Bradshaw, J.Y., 1989, Origin and metamorphic history of an Early Cretaceous polybaric granulite terrain, Fiordland, southwest New Zealand: Contributions to Mineralogy and Petrology, v. 103, p. 346–360.

Bradshaw, J.Y., 1990, Geology of crystalline rocks of northern Fiordland: Details of the granulite facies Western Fiordland Orthogneiss and associated rock units: New Zealand Journal of Geology and Geophysics, v. 33, p. 465–484.

Brown, E.H., 1996, High-pressure metamorphism caused by magma loading in Fiordland, New Zealand: Journal of Metamorphic Geology, v. 14, p. 441–452.

Clarke, G.L., Klepeis, K.A., and Daczko, N.R., 2000, Cretaceous high-*P* granulites at Milford Sound, New Zealand: Metamorphic history and emplacement in a convergent margin setting: Journal of Metamorphic Geology, v. 18, p. 359–374.

Daczko, N.R., Clarke, G.L., and Klepeis, K.A., 2001, Transformation of two-pyroxene hornblende granulite to garnet granulite involving simultaneous melting and fracturing of the lower crust, Fiordland, New Zealand: Journal of Metamorphic Geology, v. 19, p. 547–560.

Daczko, N.R., Klepeis, K.A., and Clarke, G.L., 2002a, Thermomechanical evolution of the crust during convergence and deep crustal pluton emplacement in the Western Province of Fiordland, New Zealand: Tectonics, v. 21, p. 1–18.

Daczko, N.R., Stevenson, J.A., Clarke, G.L., and Klepeis, K.A., 2002b, Kyanite-paragonite–bearing assemblages, northern Fiordland, New Zealand: Rapid cooling in the lower crustal roots of a Cretaceous magmatic arc: Journal of Metamorphic Geology, v. 20, p. 887–902.

Gibson, G.M., and Ireland, T.R., 1995, Granulite formation during continental extension in Fiordland: Nature, v. 375, p. 479–482.

Gibson, G.M., McDougall, I., and Ireland, R.R., 1988, Age constraints on metamorphism and the development of a metamorphic core complex in Fiordland, southern New Zealand: Geology, v. 16, p. 405–408.

Hollis, J.A., Clarke, G.L., Klepeis, K.A., Daczko, N.R., and Ireland, T.R., 2003, Geochronology and geochemistry of high-pressure granulites of the Arthur River Complex, Fiordland, New Zealand: Cretaceous magmatism and metamorphism on the palaeo-Pacific margin: Journal of Metamorphic Geology, v. 21, p. 299–313.

Hollis, J.A., Clarke, G.L., Klepeis, K.A., Daczko, N.R., and Ireland, T.R., 2004, The regional significance of Cretaceous magmatism and metamorphism in Fiordland, New Zealand, from U-Pb zircon geochronology: Journal of Metamorphic Geology, v. 22, p. 604–627.

Kimbrough, D.L., Tulloch, A.J., Coombs, D.S., Landis, C.A., Johnston, M.R., and Mattinson, J.M., 1994, Uranium-lead zircon ages from the Median Tectonic Zone, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 393–419.

Klepeis, K.A., Clarke, G.L., and Rushmer, T.R., 2003, Magma transport and coupling between deformation and magmatism in the continental lithosphere: GSA Today, v. 13, no. 1, p. 4–11.

Klepeis, K.A., Clarke, G.L., Gehrels, G., and Vervoort, J., 2004, Processes controlling vertical coupling and decoupling between the upper and lower crust of orogens: Results from Fiordland, New Zealand: Journal of Structural Geology, v. 26, p. 765–791.

Mattinson, J.L., Kimbrough, D.L., and Bradshaw, J.Y., 1986, Western Fiordland orthogneiss: Early Cretaceous arc magmatism and granulite facies metamorphism, New Zealand: Contributions to Mineralogy and Petrology, v. 92, p. 383–392.

Matzel, J.P., 2004, Rates of tectonic and magmatic processes in the North Cascades continental magmatic arc [Ph.D. thesis]: Cambridge, Massachusetts Institute of Technology, 249 p.

Miller, R.B., Brown, E.H., McShane, D.P., and Whitney, D.L., 1993, Intra-arc crustal loading and its tectonic implications, North Cascades crystalline core, Washington and British Columbia: Geology, v. 21, p. 255–258.

Mortimer, N., Tulloch, A.J., Spark, R.N., Walker, N.W., Ladley, E., Allibone, A., and Kimbrough, D.L., 1999, Overview of the Median Batholith, New Zealand: A new interpretation of the geology of the Median Tectonic Zone: Journal of African Earth Sciences, v. 29, p. 257–268.

Muir, R.J., Ireland, T.R., Weaver, S.D., Bradshaw, J.D., Evans, J.A., Eby, G.N., and Shelley, D., 1998, Geochronology and geochemistry of a Mesozoic magmatic arc system, Fiordland, New Zealand: Geological Society [London] Journal, v. 155, p. 1037–1053.

Oliver, G.J.H., 1980, Geology of the granulite and amphibolite facies gneisses of Doubtful Sound, Fiordland, New Zealand: New Zealand Journal of Geology and Geophysics, v. 1, p. 27–41.

Paterson, S.R., Miller, R.B., Alsleben, H., Whitney, D.L., Valley, P.M., and Hurlow, H., 2004, Driving mechanisms for ≥40 km of exhumation during contraction and extension in a continental arc, Cascades core, Washington: Tectonics, v. 23, no. 3, TC3005, doi: 10.1029/2002TC001440.

Saleeby, J., and Foster, Z., 2004, Topographic response to mantle lithosphere removal in the southern Sierra Nevada region, California: Geology, v. 32, p. 245–248.

Saleeby, J., Ducea, M., and Clemens-Knott, D., 2003, Production and loss of high-density batholithic root, southern Sierra Nevada, California: Tectonics, v. 22, no. 6, 1064, doi: 10.1029/2002TC001374.

Tulloch, A.J., and Kimbrough, D.L., 1989, The Paparoa metamorphic core complex, New Zealand: Cretaceous extension associated with fragmentation of the Pacific margin of Gondwana: Tectonics, v. 8, p. 1217–1234.

Tulloch, A.J., and Kimbrough, D.L., 2003, Paired plutonic belts in convergent margins and the development of high Sr/Y magmatism: The Peninsular Ranges batholith of California and the Median batholith of New Zealand, *in* Johnson, S.E., et al., eds., Tectonic evolution of northwestern México and southwestern USA: Geological Society of America Special Paper 374, p. 275–295.

Tulloch, A.J., Ireland, T.R., Walker, N.W., and Kimbrough, D.L., 2000, U-Pb zircon ages from the Milford Orthogneiss, Milford Sound, northern Fiordland: Paleozoic igneous emplacement and Early Cretaceous metamorphism: Institute of Geology and Nuclear Sciences (New Zealand) Report 2000/6, 23 p.

Valley, P.M., Whitney, D.L., Paterson, S.R., Miller, R.B., and Alsleben, H., 2003, Metamorphism of the deepest exposed arc rocks in the Cretaceous to Paleogene Cascades belt, Washington: Evidence for large-scale vertical motion in a continental arc: Journal of Metamorphic Geology, v. 21, p. 203–220.

Wandres, A.M., Weaver, S.D., Shelley, D., and Bradshaw, J.D., 1997, Change from calc-alkaline to adakitic magmatism recorded in the Early Cretaceous Darran Complex, Fiordland, New Zealand: New Zealand Journal of Geology and Geophysics, v. 41, p. 1–14.

Whitney, D.L., Miller, R.B., and Paterson, S.R., 1999, *P-T-t* evidence for mechanisms of vertical tectonic motion in a contractional orogen: Northwestern US and Canadian Cordillera: Journal of Metamorphic Geology, v. 17, p. 75–90.

Wood, D.J., and Saleeby, J.B., 1997, Late Cretaceous–Paleocene extensional collapse and disaggregation of the southernmost Sierra Nevada batholith: International Geology Review, v. 39, p. 973–1009.

Manuscript received 11 July 2004
Revised manuscript received 27 September 2004
Manuscript accepted 28 September 2004

Printed in USA