Constraints from diffusion profiles on the duration of high-strain deformation in thickened crust

orog.

A. Camacho, P. Yang, and A. Frederiksen
Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

ABSTRACT

Diffusion profiles in garnet are used to determine the duration of movement on shear zones. In the Musgrave Block, central Australia, Grenville age granulites were overprinted at depths of ~40 km by high-strain zones during the intracratonic Petermann orogeny (ca. 550 Ma ago). In these zones, quartzofeldspathic mylonites contain garnet from the early granulite facies event that developed compositional gradients during the high-pressure overprint. The diffusion of Ca into garnet is linked with the release of Ca in plagioclase (the only calcic mineral in the rock) during neocrystallization of sodic feldspar during high-strain deformation. Available diffusion data on garnet directly define the duration of high-strain deformation at eclogite facies. Our results indicate that the integrated time scales of movement in individual high-strain zones were short lived (between 0.07 Ma and 1.4 Ma), and that wide shear zones were active longer than narrow ones. In addition, we find that relict K-feldspar in one of the narrow eclogite facies shear zones yields a ^{40}Ar-^{39}Ar age that is partially reset, indicating that the thermal event was also short lived. These short time scales support the hypothesis that shear heating was the dominant source of heat for the eclogite facies overprint.

INTRODUCTION

Understanding the dynamics of orogenic systems requires knowledge about the rates of deformation and the time scales over which deformation localizes in the lithosphere. Studies trying to quantify these parameters have until now been limited and have focused on faults developed in the middle to upper crust (Müller et al., 2000). Fault activity at the surface, however, is commonly caused by the localization of deformation at much deeper levels in the crust. Thus, the study of faults at shallow crustal levels may not yield representative data of fault conditions in the lower crust, where higher pressure and temperature may affect the mechanisms of deformation. In this study, we place limits on the duration of deformation in the lower crust by studying microscale features, such as diffusion profiles in relict minerals. We investigated relict garnets incorporated in the high-strain zones that formed in thickened crust in the Musgrave Block of central Australia. Our results indicate that individual shear zones were active over short time scales (between 0.07 and 1.4 Ma), and wide shear zones were active longer than narrow ones. In addition, relict K-feldspar in an eclogite facies shear zone yields a partially reset ^{40}Ar-^{39}Ar age, which indicates that the thermal event was also short lived, the dominant source of heat being shear heating.

GEOLOGICAL RELATIONS

The Musgrave Block, central Australia, is a Mesoproterozoic–Neoproterozoic granulite to amphibolite facies terrane that was heterogeneously overprinted by high-strain zones during the Petermann orogeny (ca. 550 Ma ago). These zones formed in an intracratonic setting under eclogite to greenschist facies conditions and trend east-west with a combined strike-slip and reverse movement (Camacho and McDougall, 2000). Detailed descriptions of the eclogite facies rocks (temperature, $T \approx 650$ °C and pressure, $P \approx 1.2$ GPa), the subject of this paper, can be found elsewhere (e.g., Camacho et al., 1997), and a brief overview of the geological history is given here.

Granulite facies metamorphism, in the range 0.6–0.9 GPa, during the Musgravian orogeny (ca. 1170 Ma ago) was followed by two pulses of mafic magmatism, ca. 1070 Ma ago (Schmidt et al., 2006) and ca. 830 Ma ago (Zhao et al., 1994). Thermodynamic crystallization modeling using MELTS (Ghiorso and Sack, 1995; a more detailed account of the exhumation history is outlined in the GSA Data Repository[1]), suggests that these dikes intruded at levels in the crust of ≤0.5 GPa, at shallower levels than those at which granulite facies metamorphism took place. Apart from these two magmatic episodes, there is no evidence for any other geological activity until the advent of the Petermann orogeny, ca. 550 Ma ago. The granulites between the north Davenport and Davenport shear zones (Fig. 1) are variably overprinted by eclogite facies deformation within high-strain bands as much as 50 m thick that truncate and fold the granulite facies foliation. The area between the Davenport shear zone and the Mann fault forms an ~10-km-wide shear zone that developed under eclogite facies conditions. The mylonites in the core of the Davenport shear zone are more thoroughly recrystallized than those in its margin or in other narrower shear zones, indicating that the core was either hotter or underwent more prolonged deformation. During the eclogite facies event, new garnet overgrew large granulite facies garnet in quartzofeldspathic

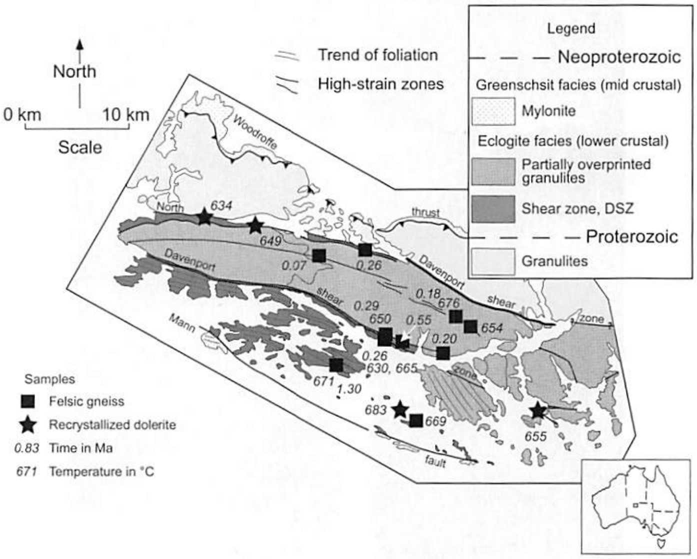

Figure 1. Simplified geological map of Mount Woodroffe region showing temperature estimates (Zr-in-rutile thermometer; Tomkins et al., 2007) and time estimates (diffusion coefficients of Perchuk et al., 2009) from compositional profiles in relict Proterozoic garnet for the block between the North Davenport shear zone and the Mann fault. Modified after Major (1973) and Camacho et al. (1997). DSZ—Davenport shear zone.

---

[1] GSA Data Repository item 2009181, Figs DR1–DR5 (thin-section photomicrographs of the same grains in Figure 2; backscattered electron images of the oxides; photomicrograph of dynamically recrystallized plagioclase, as well as compositional maps showing the distribution of Ca and Na between relict and neocrystallized plagioclase; plot of oxygen fugacity; MgO and MnO profiles for samples W-68 and W-97), and Tables DR1–DR3 (Zr concentration data and calculated temperatures; time calculated with single diffusion coefficient and multicomponent diffusion; ^{40}Ar/^{39}Ar step heating data for K-feldspar from sample W-25b), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, August 2009; v. 37; no. 8; p. 755–758; doi: 10.1130/G25753A.1; 6 figures; Data Repository item 2009181.

rocks (Fig. 2; Fig. DR1). Within the mylonitic foliation, fractured grains and pressure shadows, new garnet, ilmenite, magnetite, rutile, and small amounts of biotite and clinozoisite formed (Figs. DR1 and DR2). All rutile in these rocks is interpreted as having crystallized during eclogite facies metamorphism, because no rutile is found in the granulites outside the shear zones. Feldspar grains in the mylonites commonly show subgrain development and pass into zones of small, uniformly sized, recrystallized, strain-free grains of quartz and feldspar (Fig. DR3; cf. Fitz Gerald and Stünitz, 1993). Some feldspar grains are elongate, folded, and show strong undulatory extinction. Plagioclase primarily deformed by recrystallization-accommodated dislocation creep and to a lesser extent by climb-accommodated dislocation creep (Camacho et al., 2001).

Temperature of Eclogite Facies Metamorphism

The temperature of eclogite facies deformation in mafic rocks with well-equilibrated metamorphic textures has been estimated as ~650 °C (Ellis and Maboko, 1992; Camacho et al., 1997) using different calibrations of the garnet-clinopyroxene Fe-Mg thermometer. To further determine temperature and to establish whether the shear zones formed at the same temperature, the Zr-in-rutile thermometer (Tomkins et al., 2007; Watson et al., 2006) was used. A summary of the temperature estimates (using the Tomkins et al., 2007, calibration, which takes into account the effect of pressure on the solubility of ZrO_2 in rutile) for 11 rocks with the full buffering assemblage of zircon + rutile + quartz is presented in Table DR1. The results show that the mean Zr concentration in rutile from different rocks ranges between 210 and 402 ppm, suggesting that different mylonites formed at slightly different temperatures. However, propagation of the uncertainties in the temperature calculation yields temperature estimates that are within error (Table DR1). If all the data are pooled, the Zr-in-rutile thermometer yields a weighted mean T of 657 ± 16 °C (2σ; mean square of weighted deviates, MSWD = 0.5) and is in agreement with the previous estimate using the garnet-clinopyroxene Fe-Mg thermometer.

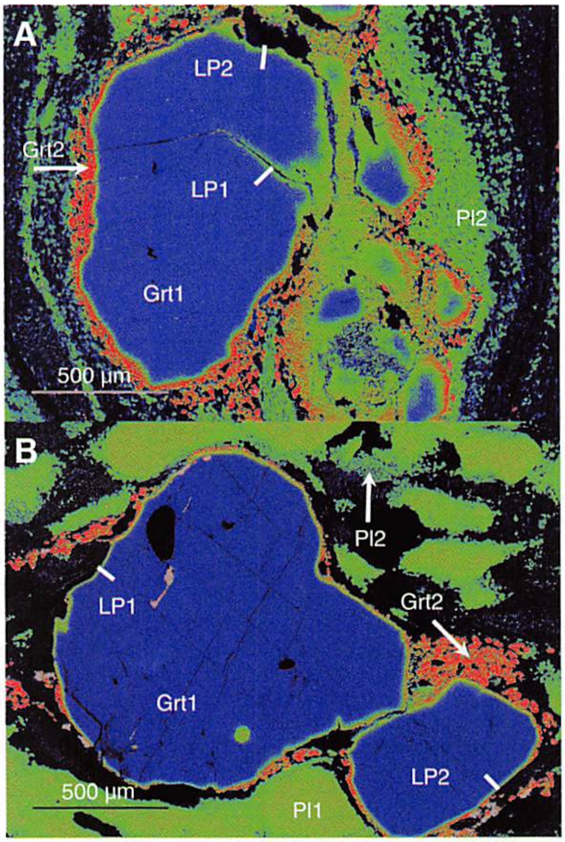

Figure 2. Maps of X-ray counts for Ca. A: Sample W-68. B: Sample W-97. Relict Proterozoic garnet (Grt1) shows enrichment of Ca along rim and across fractures. Grt2—Neoproterozoic eclogite facies garnet; LP—line profiles along which detailed electron microprobe analyses were done across garnet into the matrix. Note how plagioclase (Pl) is more recrystallized in sample W-68 than in sample W-97. Pl1—Relict plagioclase clasts. Pl2—Neoproterozoic eclogite facies plagioclase. Abbreviations after Kretz (1983). Rainbow color scheme, with red representing higher concentrations than blue.

Garnet Diffusion Modeling

To determine whether the duration of movement at eclogite facies was a function of (1) shear zone width and (2) position within the shear zone (i.e., margin versus center), eight quartzofeldspathic lithologies containing relict granulite facies garnet were studied. To minimize the possible influence of a cut effect, the extent of zoning was determined in several large garnet grains in each thin section by X-ray mapping. Detailed profiles were then measured across grain boundaries (garnet matrix) and fractures to minimize the effects of migrating grain boundaries due to resorption and recrystallization.

Modeling of the Ca, Fe, and Mg profiles of garnet yields the time of diffusion, which in this instance represents an integrated duration of movement in a shear zone while at peak temperature. Diffusion coefficients reported in the literature cover a large range, in particular for Ca (see discussion in Vielzeuf et al., 2007). We compare the results of modeling of the diffusion profiles using the diffusion coefficients of Vielzeuf et al. (2007), Carlson (2006), and Perchuk et al. (2009), because they are based on Fe-Mg garnets with compositions similar to those studied here.

Using a thermal spike of T = 657 °C (pooled weighted mean temperature obtained from rutiles), P = 1.2 Gpa, and log fO_2 = −14.9 (Fig. DR4; Berman, 2007), we calculated the diffusion coefficients for garnet and used a concentration-dependent formulation of Fick's second law for the diffusion data (for method, see the Data Repository).

RESULTS AND DISCUSSION

Time Scales of Slip in Shear Zones

Compositional variations in relict garnet occur across grain boundaries with the matrix and away from some closely spaced fractures (Fig. 2). The rims of these garnets have a slightly different chemistry (Alm_{49-56} Prp_{24-31} Grs_{10-23} Sps_{2-3}) than neocrystalline garnet (Alm_{47-53} Prp_{21-30} Grs_{17-29} Sps_{1-2}) in the matrix. Volume diffusion is interpreted to be the dominant process that caused the observed enrichment of Ca and depletions of Fe and Mg (Fig. 3; Fig. DR5), since gradients are regular and concentric and diffusion models reproduce nicely the observed profiles (Fig. 3). In contrast to garnet, we consider that volume diffusion was not the diffusing mechanism in the matrix, even though the rocks are relatively dry. The migrating grain boundaries, forming during dislocation creep of granulite facies plagioclase (Ab_{70}) and the neocrystallization of more sodic plagioclase (Ab_{80}) (Fig. DR3), provided faster diffusion pathways than volume diffusion, and enhanced the mobility of Ca in the rock (e.g., Yund and Tullis, 1991). Dislocation creep accommodated by recrystallization is characteristic of temperatures of ~500 °C or greater (e.g., Tullis and Yund, 1991). In addition, recrystallization and deformation textures in quartz and feldspar from the eclogite facies shear zones are similar, which is more typical at high temperatures than at low temperatures (~400 °C). Thus, the deformation behavior of feldspar in quartzofeldspathic lithologies in the eclogite facies shear zones is consistent with the temperature estimates of ~650 °C. Fe and Mg diffused out of garnet in response to the uptake of Ca and combined to form the opaque oxides in the matrix (Fig. DR2). Mn profiles are generally flat (Fig. DR4), and Mn was treated as the dependent component when calculating the interdiffusion coefficients for multicomponent diffusion. Calcium profiles are the most marked (variations between initial and

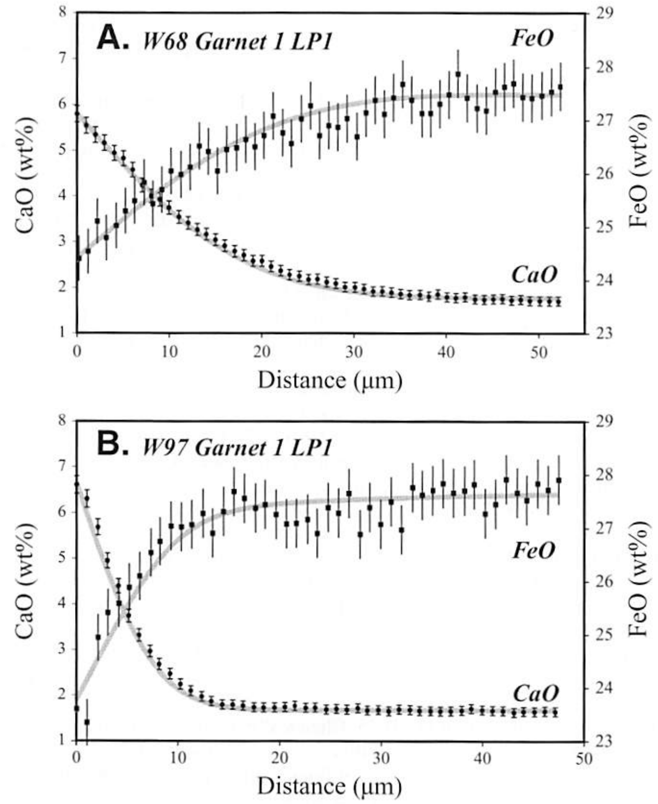

Figure 3. FeO and CaO (wt%) profiles across relict granulite facies garnet and multicomponent (FeO-MgO-CaO) diffusion modeling results. A: Sample W-68 from center of Davenport shear zone. Garnet composition: x = 0 (Alm$_{53}$ Prp$_{29}$ Grs$_{16}$ Sps$_{2}$); x = 50 (Alm$_{59}$ Prp$_{34}$ Grs$_{5}$ Sps$_{2}$). B: Sample W-97 from edge of Davenport shear zone. Garnet composition: x = 0 (Alm$_{52}$ Prp$_{28}$ Grs$_{28}$ Sps$_{1}$); x = 49 (Alm$_{59}$ Prp$_{35}$ Grs$_{5}$ Sps$_{1}$). Gray solid lines represent best-fit solution of 1.30 Ma and 0.26 Ma, respectively. Calculations were done using garnet diffusion coefficients of Perchuk et al. (2009). Error bars are 2σ.

final composition of as much as 400%), and thus provide the most reliable time scales of diffusion. Time scales using the parameters of Perchuk et al. (2009) yield comparable estimates for the Mg, Fe, and Ca profiles (Fig. 3; Fig. DR5), and are considerably longer than those using the coefficients of Carlson (2006) (Table DR2). Equal weighting of the individual element times favor the Ca profiles because the errors on the CaO analyses are smaller (Fig. 3). The diffusion data of Vielzeuf et al. (2007) yield times that are intermediate between the other two diffusion data sets. Nevertheless, regardless of the diffusion coefficients used, the calculated time-integrated durations for shearing are short; all are <1.5 Ma (Fig. 4). In addition, we find that movement in the center of the wide Davenport shear zone is more protracted compared to its margin and in other narrower shear zones (Fig. 1).

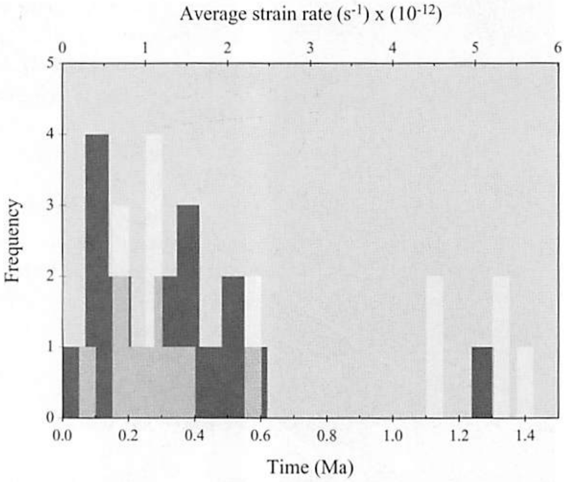

Figure 4. Histogram of time calculated (in white) using multicomponent diffusion approach (diffusion data of Perchuk et al., 2009) for development of compositional profiles that formed ca. 550 Ma ago during high-strain deformation at eclogite facies in relict Proterozoic granulite facies garnet. Strain rates (in dark gray) calculated using time derived from diffusion data of Perchuk et al. (2009). Table DR2 (see footnote 1) contains data used to produce this figure.

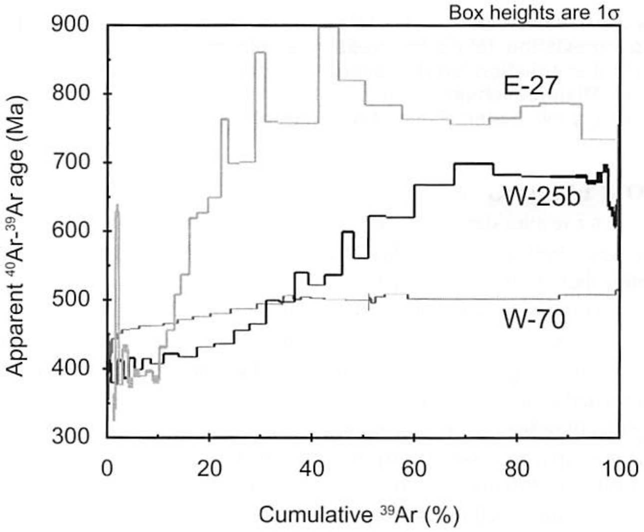

Figure 5. Recrystallized K-feldspar from center of Davenport shear zone (sample W-70) shows relatively flat ^{40}Ar-^{39}Ar age spectrum and does not preserve ages older than ~530 Ma (Camacho et al., 1997), while K-feldspar from undeformed country rock yield much older ages of ~750 Ma (Camacho and McDougall, 2000).

Time Scale of the Thermal Event

Isotopic methods can also provide data on the duration of a thermal event by revealing whether the ages of relict minerals have been completely or partially reset. Thus, relict K-feldspar from a Proterozoic granitic gneiss in the eclogite facies North Davenport (W-25b) was analyzed by the ^{40}Ar-^{39}Ar method. The low-temperature steps show varying degrees of excess argon, as indicated by the anomalous old ages for the first step of a pair of isothermal steps. Disregarding these higher ages, the age spectrum rises more or less monotonically from ~380 Ma old in the relatively low-temperature steps to a plateau-like segment ~680 Ma old (Fig. 5; Table DR3). This flat segment in the higher-temperature steps suggests that the K-feldspar relicts were only partially reset, indicating that the thermal pulse associated with high-strain deformation was also short lived.

Calculation of Strain Rate

The orientation of the deflected fabric can be used to estimate shear strain (Ramsay and Graham, 1970). An average strain rate can then be calculated by accommodating the shear strain value over the calculated time scales of slip (strain rate = shear strain/time). A minimum value of 11.3 (Fig. 6) for shear strain is calculated, yielding time-averaged slip rates ranging between 5.1×10^{-12} s^{-1} and 9.2×10^{-13} s^{-1} (Fig. 4), which is within the reported range of strain rates (10^{-12} s^{-1} to 10^{-16} s^{-1}) for convergent margins (Campbell-Stone, 2002).

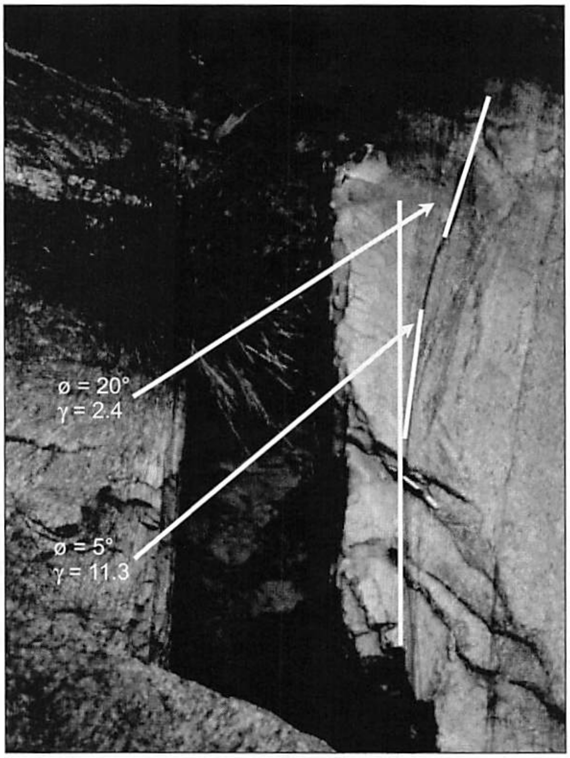

Figure 6. View toward west of Davenport shear zone mylonites showing preexisting fabric progressively rotating into parallelism with mylonitic foliation until it eventually becomes parallel with shear zone. Minimum shear strain ($\gamma = 2/\tan 2ø$; Ramsay and Graham, 1970) of 11.3 is calculated. Base of photograph is 60 cm.

CONCLUSIONS

Our results show that shear zones developed in crust buried to ~40 km were short lived (<1.5 Ma). The diffusion profiles in garnet yield time scales that are much shorter than can be determined by most chronometers. Thus, we cannot yet resolve whether (1) the shear zones developed at the same time or (2) strain was partitioned across the terrane with time. In addition, slip in the center of the wide Davenport shear zone is more protracted than in its margin and in narrower shear zones (Fig. 1), indicating that the edges of shear zones migrate laterally with time, or that subsequent reactivation along the shear zone boundary causes broadening of the fault system. Strain rates in the eclogites, developed in an intracratonic setting, are similar to those reported in convergent margins around the world. Such high strain rates can explain the large volumes of pseudotachylytes found in the mid-crustal shear zones such as the nearby Woodroffe thrust (Fig. 1; Camacho et al., 1995). Moreover, Camacho et al. (2001) suggested that a combination of relatively high shear stresses (100 MPa) and high strain rates of $\sim10^{-11}\ \mathrm{s}^{-1}$ for short durations (<1 Ma) can account for the observed temperature variations in the undeformed rock, indicating that shear heating is the dominant mechanism for localized temperature increases in the shear zones. The results presented here show that the durations of heating and high-strain deformation in the lower crust were short lived, which is consistent with the proposal that shear heating was the primary source of heat during the Petermann orogeny in central Australia.

ACKNOWLEDGMENTS

We thank the Anangu Pitjantjatjara for permission to carry out field work and collect samples in the Amata region, central Australia. We also thank Neville and Ann Nicolle of Mulga Park for logistical help in the field and N. Halden for access to the electron microprobe at the University of Manitoba. We are grateful to J. Ganguly, D. Vielzeuf, and J. Ague for assistance and guidance on many aspects of garnet diffusion. Thoughtful comments by S. Chakraborty, R. Berman, B. Hensen and N. Mancktelow on earlier versions of the manuscript are appreciated. E.F. Baxter, P.J. O'Brien, and F. Costa provided perceptive and helpful reviews.

REFERENCES CITED

Berman, R.G., 2007, winTWQ (version 2.32): A software package for performing internally-consistent thermobarometric calculations: Geological Survey of Canada Open File 5462, 41 p.

Camacho, A., and McDougall, I., 2000, Intracratonic, strike-slip partitioned transpression and the formation and exhumation of eclogite facies rocks: An example from the Musgrave Block, central Australia: Tectonics, v. 19, p. 978–996, doi: 10.1029/1999TC001151.

Camacho, A., Vernon, R.H., and Fitz Gerald, J.D., 1995, Large volumes of anhydrous pseudotachylyte in the Woodroffe Thrust, eastern Musgrave Ranges, Australia: Journal of Structural Geology, v. 17, p. 371–383, doi: 10.1016/0191-8141(94)00069-C.

Camacho, A., Compston, W., McCulloch, M., and McDougall, I., 1997, Timing and exhumation of eclogite facies shear zones, Musgrave Block, central Australia: Journal of Metamorphic Geology, v. 15, p. 735–751, doi: 10.1111/j.1525-1314.1997.00053.x.

Camacho, A., McDougall, I., Armstrong, R., and Braun, J., 2001, Evidence for shear heating, Musgrave Block, central Australia: Journal of Structural Geology, v. 23, p. 1007–1013, doi: 10.1016/S0191-8141(00)00172-3.

Campbell-Stone, E., 2002, Realistic geology strain rates: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 374.

Carlson, W.D., 2006, Rates of Fe, Mg, Mn and Ca diffusion in garnet: American Mineralogist, v. 91, p. 1–11, doi: 10.2138/am.2006.2043.

Ellis, D.J., and Maboko, M.A.H., 1992, Precambrian tectonics and physicochemical evolution of the continental crust: I—The gabbro-eclogite transition: Precambrian Research, v. 55, p. 491–506, doi: 10.1016/0301-9268(92)90041-L.

Fitz Gerald, J.D., and Stünitz, H., 1993, Deformation of granitoids at low metamorphic grade; I, Reactions and grain size reduction: Tectonophysics, v. 221, p. 269–297, doi: 10.1016/0040-1951(93)90163-E.

Ghiorso, M.S., and Sack, R.O., 1995, Chemical mass transfer in magmatic process IV: A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures: Contributions to Mineralogy and Petrology, v. 119, p. 197–212.

Kretz, R., 1983, Symbols for rock-forming minerals: American Mineralogist, v. 68, p. 277–279.

Major, R.B., 1973, Woodroffe, South Australia, 1:250 000 Geological Series: South Australian Department of Mines and Energy Explanatory Notes, v. SG52–12.

Müller, W., Aerden, D., and Halliday, A.N., 2000, Isotopic dating of strain fringe increments: Duration and rates of deformation in shear zones: Science, v. 288, p. 2195–2198, doi: 10.1126/science.288.5474.2195.

Perchuk, A.L., Burchard, M., Schertl, H.-P., Maresch, W.V., Gerya, T.V., Bernhardt, H.-J., and Vidal, O., 2009, Diffusion of divalent cations in garnet: Multi-couple experiments: Contributions to Mineralogy and Petrology, v. 157, p. 573–592, doi: doi: 10.1007/s00410-008-0353-6.

Ramsay, J.G., and Graham, R.H., 1970, Strain variation in shear belts: Canadian Journal of Earth Sciences, v. 7, p. 786–813.

Schmidt, P.W., Williams, G.E., Camacho, A., and Lee, J.K.W., 2006, Assembly of Proterozoic Australia: Implications of a revised pole for the ~1070 Ma Alcurra Dyke Swarm, central Australia: Geophysical Journal International, v. 167, p. 626–634.

Tomkins, H.S., Powell, R., and Ellis, D.J., 2007, The pressure dependence of the zirconium-in-rutile thermometer: Journal of Metamorphic Geology, v. 25, p. 703–713, doi: 10.1111/j.1525-1314.2007.00724.x.

Tullis, J., and Yund, R., 1991, Diffusion creep in feldspar aggregates: Experimental evidence: Journal of Structural Geology, v. 13, p. 987–1000.

Vielzeuf, D., Baronnet, A., Perchuck, A.L., Laporte, D., and Baker, M.B., 2007, Calcium diffusivity in alumino-silicate garnets: An experimental and ATEM study: Contributions to Mineralogy and Petrology, v. 154, p. 153–170, doi: 10.1007/s00410-007-0184-x.

Watson, E.B., Wark, D.A., and Thomas, J.B., 2006, Crystallization thermometers for zircon and rutile: Contributions to Mineralogy and Petrology, v. 151, p. 413–433, doi: 10.1007/s00410-006-0068-5.

Yund, R., and Tullis, J., 1991, Compositional changes of minerals associated with dynamic recrystallization: Contributions to Mineralogy and Petrology, v. 108, p. 346–355.

Zhao, J.X., McCulloch, M.T., and Korsch, R.J., 1994, Characterisation of a plume-related ~800 Ma magmatic event and its implications for basin formation in central-southern Australia: Earth and Planetary Science Letters, v. 121, p. 349–367.

Manuscript received 25 December 2008
Revised manuscript received 1 April 2009
Manuscript accepted 2 April 2009

Printed in USA