Episodic metamorphism and deformation in low-pressure, high-temperature terranes

Kurt Stüwe
Michael Sandiford
Department of Geology and Geophysics, University of Adelaide, GPO Box 498, Adelaide, South Australia 5001, Australia
Roger Powell
Department of Geology, University of Melbourne, Parkville, Victoria 3052, Australia

ABSTRACT

In many cases, low-pressure, high-temperature metamorphism must be the consequence of advective heat transfer, e.g., the ascent of granitic magma. Whereas such heating mechanisms are necessarily short-lived, the lifetime of the underlying orogenic processes is likely to be much longer, and it is conceivable that, during the evolution of an orogen, repeated transient heating at shallow crustal levels is caused by episodes of segregation and upward passage of melts generated at deep crustal levels. The number and timing of these events would depend on such factors as critical melt segregation volume, Moho temperature, and strain-rate evolution. We investigate some of the controls on this multiple-event superposition using a simple thermomechanical model designed to predict, simultaneously, the strain-rate and the isostatic and thermal evolution of convergent orogenesis, subject to a constant driving force. An appealing aspect of this formulation is that, in contrast to models that have attempted to explain event cyclicity through episodic processes acting on the orogenic boundaries, it accounts for the repeated occurrence of events through processes inherent to the orogenic system itself.

INTRODUCTION

Many low-pressure (P), high-temperature (T) terranes show evidence of repeated deformation, metamorphism and granitic magmatism (e.g., Kröner, 1982, 1983; Miller and Gans, 1989; Hand et al., 1992). Clearly, it is important to determine whether this episodicity is caused by processes operating beyond, and therefore imposed on, the orogen, or whether the episodicity is intrinsic to the orogenic process itself. Episodicity of plutonic activity in modern-day orogens is well established (Pitcher, 1979). There, it has been interpreted as a reflection of changes in the plate-tectonic driving forces imposed at the boundary of the orogen (Noble et al., 1974; Lanphere and Reed, 1973). In contrast, the notion that episodicity of events may arise as a natural consequence of continuous orogenic processes has received very little attention.

Inspired by the common association of convergent deformation with granitic magmatism in many low-P, high-T metamorphic terranes, Sandiford et al. (1991, 1992) have used a simple thermomechanical model based on the thin-sheet approximation (e.g., Bird and Piper, 1980) and a temperature-sensitive lithosphere rheology to show that the heat transferred by advection in discrete magmatic episodes may induce discrete deformation events at temperatures appropriate to low-P, high-T metamorphism without any changes in the tectonic driving forces. Here, we extend their model and show that ongoing deformation may provide the feedback mechanism that causes episodicity in magmatic events and, thus, metamorphism. The critical control on this feedback is a critical melt fraction that determines the timing of segregation and ascent of melts from a distributed, partially melted region (e.g., Wickham, 1987). A brief summary of the thin-sheet model and other computational aspects of the modeling undertaken in this paper is presented in Appendix 1.

CRITICAL MELT FRACTION AND FORMATION OF PLUTONS

The segregation of melt into rising plutons from a partially melted source region is controlled by a critical melt fraction (Arzi, 1978; Van der Molen and Paterson, 1979; Wickham, 1987). Following Wickham (1987), we assume that the formation of plutons from a distributed, partially melted source region requires the generation of a convective instability. Such an instability requires the effective shear viscosity of the source to fall beneath a critical value over an appropriate length scale. For a scenario where heating is imposed on the lower crust, e.g., as a consequence of prior crustal thickening, the requirement that a critical melt fraction be achieved over a critical length scale suggests that pluton formation is likely to be episodic (Fig. 1). Our aim here is to show how such a simple model for granite formation and ascent may influence the deformation and metamorphic history of an orogen subject to a constant driving force in the manner described by Sandiford et al. (1991).

A value of the critical melt fraction of 30% melt per volume has been commonly accepted for geologically slow strain rates and for kilometre-sized plutons (e.g., Wickham, 1987). Following Miller et al. (1988), we assume a weak exponential dependence of the critical melt fraction with strain rate (Appendix 1). We assume a very simplified form for the melting of the lower crust, with a melting interval between a solidus temperature $T_{sol} = 700\ °C$ and a liquidus temperature $T_{liq} = 1300\ °C$, with a linear relation between melt volume and temperature in this interval. Although such a relation is not likely to hold for any specific bulk composition, in which the melt-producing reactions will be a discontinuous function of temperature, this approach is likely to provide an acceptable approximation for the melting behavior of a compositionally heterogeneous source region appropriate to the continental crust. Following Wickham (1987), we suggest that the critical length scale, l, for the onset of convective instability is of the order of several kilometres. Therefore, we assume plutons between 1 and 5 km thick and explore the consequences of their emplacement at mid-crustal levels for the strain-rate evolution of the orogen. We assume that the melt proportion is extracted efficiently, leaving behind a residue largely depleted in melt but having the possibility of generating more melt upon further heating. In the one-dimensional model used here, we consider melt transfer only in the thermal sense. Thus, the temperature distribution and melt proportion are updated
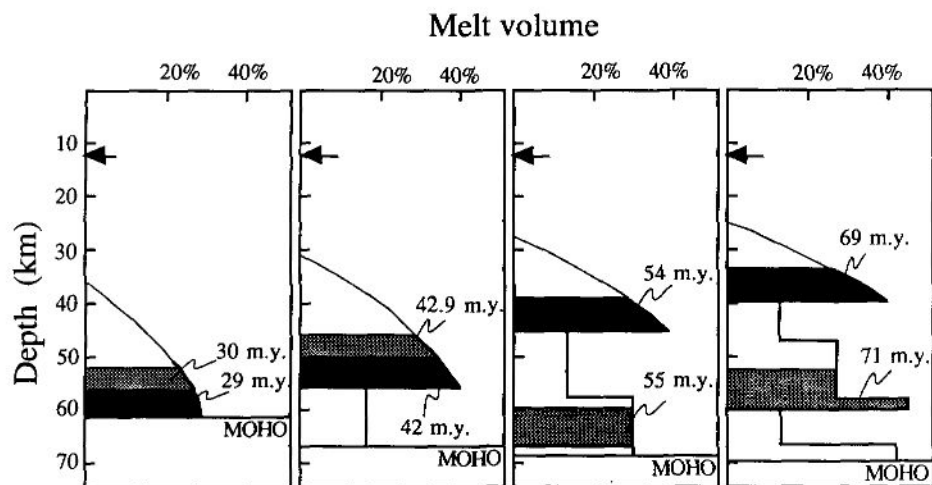
Melt volume

Figure 1. Evolution of melt volume with depth for first four segregation periods in crustal model evolution. Because of fast strain rates after intrusion and strain-rate dependence of critical melt fraction (CMF), at least two melt bodies are segregated in short time interval during each period. All plots are calculated at time step of first melt segregation and loss during each such period. Black indicates melt bodies segregated during this time step. Lighter pattern indicates melt bodies that will exceed CMF briefly later. In addition, because of strain-rate dependence, segregating plutons increase in size through evolution of run. Absolute times of individual segregation events are marked, and crustal thickness at start of each segregation period is also indicated through Moho location. Arrow marks top of intrusion location.

Figure 2. Strain-rate $\dot{\varepsilon}$ (A) and temperature (B) evolutions for model orogenesis corresponding to melt evolution of Figure 1. Assumed intrusion depth is 12 km, pluton thickness is $l = 3$ km. Strain rate in A is for whole crust. Horizontal line indicates limit of geologically significant strain rates. Dashed line indicates melt-free strain-rate evolution for comparison. Note that melt-free evolution drops below geologically significant strain rates after ~50 m.y., whereas evolution involving melting includes transient deformation events for total time of nearly 150 m.y. In B, temperature evolution is for depth of 10 km and, like strain rate, shows episodicity. T_{sol} is solidus temperature.

according to emplacement and extraction of plutons, but no actual mass transfer is modeled.

EPISODIC DEFORMATION AND METAMORPHISM

The evolution of melt volume during crustal thickening is shown in Figure 1. Segregation of plutons occurs according to the assumption of the critical melt fraction outlined in Appendix 1. There is an overall but not systematic decrease in crustal level from which melt is extracted. This is because after an extraction event from a given crustal depth, the maximum melt percentage is located at shallower levels, which therefore provide the next likely location for melt extraction. For more complicated compositional variations, the locus of melt production will obviously vary. However, critical to our model is only the fact that melt production and pluton segregation occur at crustal levels that are rheologically weak compared to the region of their emplacement. In fact, our model is supported by Hawkesworth et al. (1983), who argued that intrusions in the Damara belt of Namibia, associated with a multievent history there, are derived from successively higher levels as shortening proceeds.

In our model calculation (Fig. 2A), we show the effect on the crustal thickening rate $(\dot{\varepsilon}_z)$ when the lithosphere is subjected to a constant driving force $(1 \times 10^{13}$ N/m) when (1) no melting occurs (dashed line) and (2) when melt is segregated according to the critical melt fraction model as outlined

above and shown in Figure 1 (solid line). In the case of granite segregation, the granitic body is considered to rise instantaneously and is intruded as a 3-km-thick sill at a depth of 12 km for the top of the pluton. The episodic heating and strain-rate fluctuations occur in response to the nature of the magma-segregation process in the lower crust. In the case where there is no granite segregation, and thus no advection of heat, the strain rates over the life of the orogen decline more gradually as the gravitational potential energy gained by the deformed lithosphere approaches the magnitude of the forces driving deformation. For this driving force, a natural limit to convergence is provided when the crustal thickness reaches 70 km, double the initial crustal thickness at which the driving force is balanced by the horizontal buoyancy force for this choice of parameters. Note that crustal-thickening rates decline to geologically insignificant values $(\dot{\varepsilon}_z < 10^{-16}/\text{s})$ after about 50 m.y.

Crustal evolution in which melting of the lower crust is considered can be viewed as follows. Heating of the lower crust causes partial melting of the rocks until the melt proportion in the rock exceeds the critical melt fraction and the magma segregates as a pluton. The emplacement of the hot pluton at shallow levels destroys the temperature-sensitive, high-strength region in the upper crustal locus of emplacement, thus allowing a transient rapid increase in the overall strain rate for a period comparable to the time constant of the intrusion. During this time, the increased strain rate causes rapid crustal
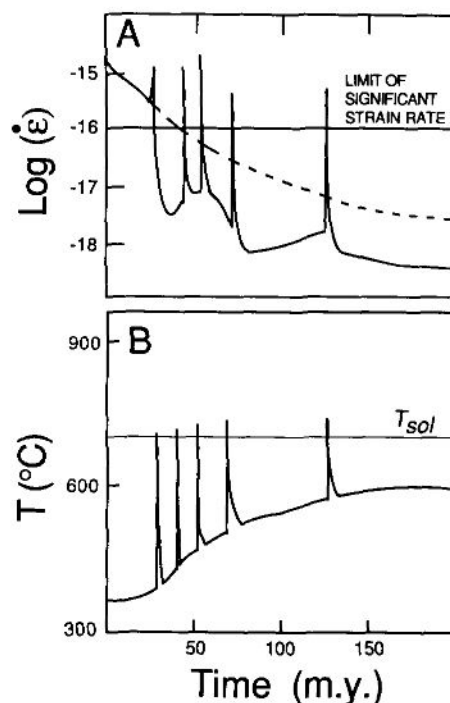
thickening, a gain of potential energy of the orogen, and a transient drop of the strain-rate–dependent critical melt fraction, which allows several pluton segregations to occur within a short period (Fig. 1). The subsequent cooling of the pluton causes the strain rates to drop, generally to below the pre-deformation value. Continued thermal equilibration and thickening cause further heating, and the event may thus repeat itself. As an ultimate consequence, the overall lifetime of the orogen is shortened compared with the melt-free evolution, but the time span over which geologically significant strains and strain rates may occur in the form of discrete deformation events may be prolonged compared to melt-free evolutions.

VARYING MODEL PARAMETERS

The overall time span of the multiple-event history is a strong function of the Moho temperature and is thus dependent on the assumptions of original surface heat flow
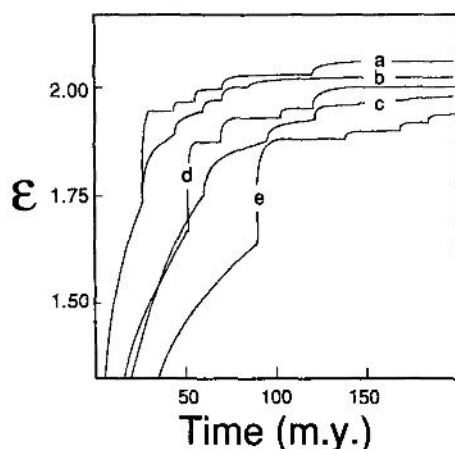
Figure 3. Total crustal thickening strain, ε, over time for several numerical experiments exploring range of thermal and mechanical parameters. Note that strains are for total crustal thickening and may therefore substantially underestimate finite strains observed at given crustal level, in particular near heat source. Note also that total strain decreases through time, a result well matched by observations in many low-P, high-T terranes. Line a corresponds to run of Figures 1 and 2 with surface heat flow $q_s = 90$ mW/m^2, $Q_q = 1.9 \times 10^5$ J/mol, $Q_o = 5.2 \times 10^5$ J/mol, $z_o = 12$ km, $l = 3$ km, where Q_q and Q_o are the activation energies of power law creep for quartz and olivine, respectively. Line b uses same parameters except for smaller pluton size and larger emplacement depth: $z_o = 15$ km, $l = 1$ km. Line c is same as b but with colder temperature distribution; $q_s = 80$ mW/m^2. Line d uses stronger partitioning of strength into crust; $q_s = 90$ mW/m^2, $Q_q = 2.1 \times 10^5$ J/mol, $Q_o = 5.2 \times 10^5$ J/mol, $l = 4$ km; $z_o = 14$ km. Line e uses stronger partitioning of strength into crust and smaller plutons; $q_s = 80$ mW/m^2, $Q_q = 2.1 \times 10^5$ J/mol, $Q_o = 4.9 \times 10^5$ J/mol, $l = 1$ km, $z_o = 14$ km.

as well as the behavior of the subcrustal lithosphere. The wavelength of cyclicity of these events is a function of the critical length scale for pluton segregation, the critical segregation volume, the depth of emplacement, and the temperature distribution in the crust, which ultimately controls the rheology. For the assumptions used in Figure 2, the wavelength is of the order of tens of million years, and deformation events occur over nearly 150 m.y.

Smaller pluton sizes and smaller critical melt fractions result in shorter wavelengths for the same rate of temperature change at the Moho. A shallower emplacement depth nearer the strength maximum of the crust results in a relative shortening of the overall interval compared to the model run shown. Smaller driving forces, on the other hand, may prolong the time interval dramatically. The choice of the bottom boundary prescribes the deformation geometry of the mantle lithosphere directly. A boundary

condition of constant heat flow would result in a shortening of the overall interval because it would imply a stronger partitioning of the strength into the upper crust. If the strength of the lithosphere is more partitioned into the crust, then the magma emplacement effect will be more dramatic and is largely equivalent to increasing the pluton size.

For no strain-rate dependence of the critical melt fraction, individual periods of magma segregation are shorter and much more frequent. For stronger strain-rate dependencies, the intervals between periods of magma intrusion increase because of more effective removal of melt. The segregation and upward emplacement of a pluton will result in weakening of the upper crust and a sudden transient increase in strain rate. This increase results in a sudden reduction of the critical melt fraction, which ultimately results in the drainage of regions of smaller melt volume in the lower crust. A period of segregation and emplacement of several plutons in a short time interval (Fig. 1) is, therefore, followed by a period of quiescence during which continued heating of the lower crust reestablishes the presence of low melt fractions.

Significant uncertainties in such modeling arise from the large uncertainties about the thermal and rheological properties of the lithosphere, particularly the way strength varies with depth and temperature, and the magnitude of the forces driving convergence. Because of such uncertainties, it is unreasonable to attach any significance to the absolute time scales for granite generation shown in the models here, expect perhaps for the possibility of generating granites within the time scales appropriate to crustal deformation. Clearly, the scenario outlined here is only appropriate if much of the lithospheric rheology is sensitive to temperature and if a significant proportion of the strength of the lithosphere resides at the middle or shallow levels of the crust, corresponding to the emplacement levels of granites and to the levels appropriate to low-P, high-T metamorphism. The consequences of stronger and weaker crustal rheology are shown in Figure 3. However, one important result for all model evolutions is that earlier thickening events cause larger finite strains than do later events.

DISCUSSION

The modeling described above shows that the superposition of multiple events at shallower levels in Earth's crust may be a natural consequence of (1) episodic melt segregation and pluton intrusion and (2) T-sensitive upper crustal rheology control-

ling the strength of the lithosphere. The model relies therefore, in part, on the assumption that granites may form as the consequence of conductive heating of the lower crust. Although such a model represents only one of several plausible mechanisms for granite generation, it is likely to be appropriate to at least some orogens (e.g., Miller and Gans, 1989). Indeed, Miller and Gans (1989) suggested that such a mechanism may be appropriate to the formation of low-P, high-T terranes. However, it is important to note that this mechanism is generally closely associated with the evolution of the thickness of the mantle lithosphere, which, along with changes in the tectonic driving forces, may substantially prolong or shorten the evolutions described here. The results discussed above correlate well with plutonic episodicity in some modern-day mountain belts. For example, Clark et al. (1976) recognized five major episodes of plutonism and uplift in Chile between 107 and 7 Ma, and distinct groupings of radiometric ages between 95 and 35 Ma can be recognized in the intrusive ages of the coastal batholith of Peru (Cobbing and Pitcher, 1972). Episodicity in the plutonic activity has also been discussed for the Sierra Nevada batholith, where coalescence of contact metamorphic aureoles has been suggested as a mechanism for the generation of low-P, high-T terranes (Barton and Hanson, 1989).

A more apposite comparison with our results is with the episodicity in some ancient low-P, high-T terranes such as the Damaran belt of Namibia (Kröner, 1982, 1983) or the terranes of the Arunta block in central Australia (e.g., James and Ding, 1988; Hand et al., 1992). Also note that an increasing number of terranes in which overprinted textures have previously been interpreted as the consequence of one P-T path are now being recognized as the consequence of multiple-event superposition (e.g., Hand et al., 1992). Our results may, therefore, form a welcome interpretation for a range of low-P, high-T terranes in which the episodicity of deformation and metamorphic events is recognized in a corresponding framework in time.

APPENDIX 1. MODELING

In the modeling, we adopt the thin-sheet approximation for the lithosphere, in which components of strain rate $\dot{\varepsilon}$ and horizontal velocity are independent of depth; therefore, the vertically integrated strength of the lithosphere, F_l, is given by (e.g., Sonder and England, 1986)

$$F_l = \int_0^{z_l} (\sigma_1 - \sigma_3) dz, \qquad (1)$$

which is uniquely defined only when the thermal structure and strain rate are specified (Fig. 1). We

define thermal structure in terms of the surface heat flow and a heat-source distribution; initial strain rate is defined by the force balance of driving force for continental plate convergence and mechanical strength. Moreover, we assume a strain-rate regime appropriate to horizontal biaxial compression where the principal stresses act in the horizontal and vertical direction, respectively:

$$\sigma_1 = \sigma_{xx}, \sigma_3 = \sigma_{zz},$$

$$\dot{\epsilon}_{zz} = \dot{\epsilon}_{xx} = \dot{\epsilon},$$

$$\dot{\epsilon}_{yy} = 0.$$

Thus, equation 1 becomes

$$F_1 = \int_0^{z_1} (\sigma_{xx} - \sigma_{zz}) dz. \tag{2}$$

We assume a simple rheological model lithosphere with crustal thickness $z_c = 35$ km, and lithosphere thickness $z_1 = 100$ km, consisting of a crust and mantle lithosphere the behavior of which is governed by the rheology of quartz and olivine, respectively. For biaxial horizontal compression, failure is modeled as either frictional sliding or power law creep for all $(\sigma_1 - \sigma_3)$ in the crust and as Dorn Law creep for $(\sigma_1 - \sigma_3) < 200$ MPa in the mantle. The model lithosphere is subjected to a constant driving force of 1×10^{13} N/m. Thickening strain is assumed to be homogeneous in the crust; the mantle lithosphere is assumed to be at constant thickness during the evolution.

Strength is calculated by numerical integration under the failure envelope with strain rate adjusted to balance the effective driving force. The orogenic force balance is calculated assuming that the effective driving force of orogenesis can be described as the difference between the convergent tectonic driving force and the extensional horizontal buoyancy force (Sandiford and Powell, 1991).

Temperature profiles were calculated by solving the one-dimensional thermal energy balance equation

$$\rho \frac{\partial H}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + S + L \rho \frac{\partial V}{\partial t}, \tag{3}$$

with initial and boundary conditions imposed by the mechanical model. H is the heat in J/kg, t is time, k is the thermal conductivity (3 $W \cdot m^{-1} \cdot K^{-1}$), ρ is the density, T is the temperature, S is the volumetric heat source contribution (zero in the mantle and constant in the crust: 1.4×10^{-6} W/m^3 as uniquely defined through the surface heat flow, $q_s = 80$ mW/m^2 or $S = 1.8 \times 10^{-6}$ W/m^3 at $q_s = 90$ mW/m^2), L is the latent heat of fusion (3.2×10^5 J/kg), and $\partial V/\partial t$ describes the change of melt volume with time (Wells, 1980). Equation 3 was solved with a Crank-Nicholson finite-difference scheme as well as with an explicit method updating temperature through the heat budget, with $\Delta T = \Delta H/c_p$, where c_p is the heat capacity, in order to account for the latent heat of fusion. Comparison of these two methods showed that the effect of the latent heat of fusion is negligible compared with the effects of changing the mechanical and melting model parameters; the results are thus only given for the implicit calculations.

The strain-rate dependence of the critical melt fraction (CMF) is given by

$$CMF = (CMF_0) \exp \left(- \frac{\log(\dot{\epsilon}) + 16}{6} \right) \tag{4}$$

with $CMF_0 = 30\%$, so that CMF = 30% applies at geologically insignificant strain rates of 10^{-16}/s and drops to e^{-1} of this at 10^{-10}/s, a strain rate appropriate to the ascent velocity of plutons.

REFERENCES CITED

Arzi, A.A., 1978, Critical phenomena in the rheology of partially melted rocks: Tectonophysics, v. 44, p. 397–411.

Barton, M.D., and Hanson, R.B., 1989, Magmatism and the development of low-pressure metamorphic belts: Implications from the western United States and thermal modeling: Geological Society of America Bulletin, v. 101, p. 1051–1065.

Bird, P., and Piper, K., 1980, Plane stress finite element modes of tectonic flow in southern California: Physics of the Earth and Planetary Interiors, v. 21, p. 158–175.

Clark, A.H., Farraf, E., Caelles, J.C., Haynes, S.J., Lortie, R.B., and Zentilli, M., 1976, Longitudinal variations in the metallogenetic evolution of the Central Andes, in Strong, D.F., ed., Metallogeny and plate tectonics: Geological Association of Canada Special Paper 14, p. 24–58.

Cobbing, E.J., and Pitcher, W.S., 1972, The coastal batholith of Central Peru: Geological Society of London Journal, v. 128, p. 421–460.

Hand, M., Dirks, P.H.G.M., Powell, R., and Buick, I.S., 1992, How well established is isobaric cooling in Proterozoic orogenic belts? An example from the Arunta inlier, central Australia: Geology, v. 20, p. 649–652.

Hawkesworth, C.J., Gledhill, A.R., Roddick, J.C., Miller, R.McG., and Kröner, A., 1983, Rb/Sr and ^{40}Ar/^{39}Ar studies bearing on model for the thermal evolution of the Damara belt, Namibia, in Miller, R.McG., ed., Geodynamic evolution of the Damara orogen: Geological Society of South Africa Special Volume.

James, P.R., and Ding, P., 1988, 'Caterpillar tectonics' in the Harts Range area: A kinship between two sequential Proterozoic extension-collision orogenic belts within the eastern Arunta inlier of Central Australia: Precambrian Research, v. 40, p. 199–216.

Kröner, A., 1982, Rb-Sr geochronology and tectonic evolution of the Pan-African Damara belt of Namibia, southwestern Africa: American Journal of Science, v. 282, p. 1471–1507.

Kröner, A., 1983, Proterozoic mobile belts compatible with the plate tectonic concept, in Medaris, L.G., Jr., et al., eds., Proterozoic geology: Selected papers from an international Proterozoic symposium: Geological Society of America Memoir 161, p. 59–74.

Lanphere, M.A., and Reed, B.L., 1973, Timing of Mesozoic and Cenozoic plutonic events in circum-Pacific North America: Geological Society of America Bulletin, v. 84, p. 3773–3782.

Miller, C.F., Watson, E.B., and Harrison, T.M., 1988, Perspectives on the source, segregation and transport of granitoid magmas: Royal Society of Edinburgh Transactions, v. 79, p. 135–156.

Miller, E.L., and Gans, P.B., 1989, Cretaceous crustal structure and metamorphism in the hinterland of the Sevier thrust belt, western U.S. Cordillera: Geology, v. 17, p. 59–63.

Noble, D.C., McKee, E.H., Farrar, E., and Petersen, U., 1974, Episodic Cenozoic volcanism and tectonism in the Andes of Peru: Earth and Planetary Science Letters, v. 21, p. 213–221.

Pitcher, W., 1979, The nature of ascent and emplacement of granitic magmas: Geological Society of London Journal, v. 136, p. 627–662.

Sandiford, M., and Powell, R., 1991, Some remarks on high temperature–low pressure metamorphism in convergent orogens: Journal of Metamorphic Geology, v. 9, p. 333–340.

Sandiford, M., Martin, N., Zhou, S., and Fraser, G., 1991, Mechanical consequences of granite emplacement during high-T, low-P metamorphism and the origin of "anticlockwise" PT paths: Earth and Planetary Science Letters, v. 107, p. 164–172.

Sandiford, M., Foden, J., Zhou, S., and Turner, S., 1992, Granite genesis and the mechanism of convergent orogenic belts with application to the southern Adelaide fold belt: Royal Society of Edinburgh Transactions, v. 83, p. 83–93.

Sonder, L.J., and England, P., 1986, Vertical averages of rheology of the continental lithosphere: Relation to thin sheet parameters: Earth and Planetary Science Letters, v. 77, p. 81–90.

Van der Molen, I., and Paterson, M.S., 1979, Experimental deformation of partially-melted granite: Contributions to Mineralogy and Petrology, v. 70, p. 275–295.

Wells, P.R.A., 1980, Thermal models for the magmatic accretion and subsequent metamorphism of continental crust: Earth and Planetary Science Letters, v. 46, p. 253–265.

Wickham, S.M., 1987, The segregation and emplacement of granitic magmas: Geological Society of London Journal, v. 144, p. 281–297.