MATTERS ARISING

Thermomechanical inferences from deep seismic sounding sections

CHOWDHURY AND HARGRAVES[1] recently interpreted a deep seismic sounding section, between Kavali and Udipi in India, which appears to show deep faults offsetting an essentially horizontal Mohorovičić discontinuity. Reflectors below the Moho seem to have lower and more uniform apparent dips than those above it, leading these authors to suggest that "at the time of its formation [before faulting] the Moho constituted a thermomechanical boundary between rigid [folding] crust and plastic [ductilely flowing] mantle"[1]. Although elements of this interpretation are questionable (notably that folding constitutes rigid behaviour), their subsequent conclusions ignore even more fundamental considerations regarding the rheology of solids: "Ductile flow requires that the then Moho level temperatures were close to the crustal solidus [of 1,000 °C for anhydrous granulite[3]]. Consequently, mean geothermal gradients must have been in the range 20–30 °C km^{-1}, two or three times those inferred for present day shields[4]"[1].

The mere fact that a rock has been plastically deformed does not uniquely determine the temperature at which that deformation took place. Steady homogeneous flow in a solid is governed by a constitutive equation relating temperature, strain rate, and stress. For a rock subjected to uniaxial compression the equation relating the shortening rate $\dot{\varepsilon}$ to the differential stress σ and absolute temperature T is typically of the form

$$\dot{\varepsilon} = A \exp(-Q/RT) f(\sigma) \qquad (1)$$

where Q is an activation energy, R is the universal gas constant and A is a constant. The form of the function f depends on the dominant deformation mechanism(s), whereas the constants A and Q are determined by the minerals present, their grain size and geometry, and the activities of any volatile phases.

Solving equation (1) for the temperature gives

$$T = Q\{R \ln [Af(\sigma)/\dot{\varepsilon}]\}^{-1} \qquad (2)$$

from which it is evident that the temperature required for flow can be reduced either by decreasing the strain rate or by increasing the stress. The validity of this conclusion is not limited to the case of uniaxial deformation; equations (1) and (2) can be extended to more general states of deformation, although the measures of strain rate and stress must be appropriately generalized and the function $f(\sigma)$ may take a different form.

Table 1 Temperature limits calculated using experimental flow laws

	Minimum temperature* (°C) [Range of mean geothermal gradients (°C km^{-1})]	Maximum temperature† (°C) [Range of mean geothermal gradients (°C km^{-1})]
Quartz	175 [3–6]	710 [10–24]
Diopside	440 [6–15]	975 [14–33]
Olivine	490 [7–16]	1,040 [15–35]

* $\sigma = 2.5$ kbar, $\dot{\varepsilon} = 10^{-17}\ s^{-1}$.
† $\sigma = 20$ bar, $\dot{\varepsilon} = 10^{-12}\ s^{-1}$.

To determine unambiguously the temperature at which plastic deformation ceased (and at which the Moho formed in the Chowdhury–Hargraves model) we would need to know: (1) whether the deformation was homogeneous and steady; (2) what was the appropriate constitutive relation; and (3) what were the values of $\dot{\varepsilon}$ and σ just below the Moho when it formed. Condition (1) may be approximately satisfied for deep processes and geological time scales but requirements (2) and (3) cannot easily be met. If simplifying assumptions could be made about sub-Moho mineralogy and deformation mechanisms, an empirical flow law[5–9] might be used. Similarly it could be assumed that currently estimated deep crustal or mantle flow stresses (several tens of bars to several kilobars)[10] and strain rates (10^{-17}–$10^{-12}\ s^{-1}$)[11,12] were applicable to the process of Moho formation. Using flow laws for quartz (ref. 6 and unpublished data), diopside[8] and olivine[9] aggregates along with the extreme values of stress and strain rate noted above, upper and lower bounds may be placed on flow temperature from equation (2). Table 1 shows these values together with their respective mean geothermal gradients for crustal thicknesses of 30–70 km.

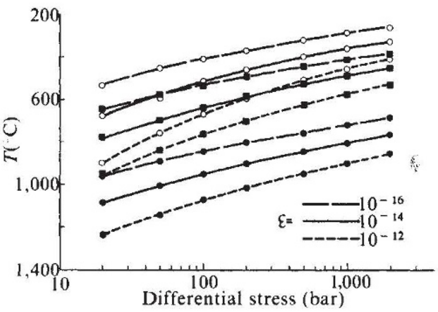

Fig. 1 Flow temperature as a function of differential stress for three strain rates. ○, Quartz[6]; □, diabase[7]; ●, olivine[5].

Evidently Chowdhury and Hargraves' model places no real constraints on crustal thermal structure; in fact their near crustal solidus Moho formation temperature and corresponding geothermal gradients are nearly maximal values in a broad spectrum of possibilities. Unique determination of thermal structure by this method requires petrological and rheological constraints which are not generally available and cannot be assumed without prejudicing the results.

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P. S. KOCH

Department of Earth and Space Sciences, University of California, Los Angeles, California 90024, USA

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ROY CHOWDHURY AND HARGRAVES REPLY—Koch's argument pertains to the validity of an indirect consequence of our conclusion—the inferred geothermal gradient in Archaean times—without disputing the seismic evidence which prompted our overall speculation: that in Archaean times, the base of the crust was the base of the lithosphere[1]. Nevertheless his point is well taken, because we had not considered rheology in our paper.

In essence, Koch is stating that if one takes the extreme estimates of the relevant rheological variables, one gets a wider range in the resulting geothermal gradient for our model than the 20–30 °C km^{-1} we had inferred. These variables are (1) crustal composition and thickness, (2) stress and strain rate, (3) flow law. We do not dispute this, but would rather ask: what physical conditions are required to permit our interpre-

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