SECULAR COOLING OF EARTH AS A SOURCE OF INTRAPLATE STRESS

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Introduction. The once popular idea that changes in planetary volume play an important role in terrestrial orogeny and tectonics [1,2] was generally discarded with the acceptance of plate tectonics. It is nonetheless likely that the Earth has been steadily cooling over the last 3-4 billion years [e.g., 3,4], and the global contraction that accompanied such cooling would have led to a secular decrease in the radius of curvature of the plates. We explore here the implications of this global cooling and contraction for the intraplate stress field and the evolution of continental plates.

Procedure. We make used of the formulation of Turcotte [5] and McKinnon [6] for stress in a thin, spherical, elastic cap on an expanding or contracting planetary body. The formulation is based on conservation of cap area and the assumption that the radial or polar ($\sigma_{\theta\theta}$) horizontal stress is zero at the cap boundary. The latter assumption is quite reasonable for lithospheric plates subjected to episodic stress release by earthquakes at their boundaries. Extensional stress is predicted in the interior of a plate on a contracting Earth (opposite to the effect of contraction on a body with a globally continuous lithosphere), with a time rate of stress accumulation approximately proportional to the plate area and to the rate dR/dt of global contraction [5,6]. The quantity dR/dt may be obtained from a thermal history model and an estimate of the radial dependence of the coefficient of volumetric thermal expansion. The effects of radial migrations of phase boundaries involving changes in specific volume can also be incorporated.

Rate of Global Contraction. As a simple first approximation, consider that $dR/dt \cong R\,\alpha/3\; dT/dt$ where α is the mean coefficient of thermal expansion in the Earth and T is a characteristic temperature. From the estimated eruption temperatures of Archaean komatiites, Sleep [7] has estimated that $dT/dt \cong -100$ K/b.y. for the last 3 b.y. With $\alpha = 3 \times 10^{-5}\ K^{-1}$, this gives $dR/dt \cong -6$ km/b.y. (Table 1). Comparable results are given by thermal history models, making use of the approximation $q - q_{ss} \cong 4/3\, \pi R^3 \rho C_p\, dT/dt$, where q is the mean global heat flux, q_{ss} is the steady-state value of q (if heat loss equaled heat production), and ρ and C_p are density and specific heat, respectively. Thermal history models differ in how mantle convective heat transport is parameterized, principally in whether whole-mantle or layered convection systems predominate [e.g., 3,4]. These differences yield variations in q/q_{ss} ranging from about 1.1 to 2, with values toward the upper end of this range yielding estimates for dT/dt most consistent with the estimate from the eruption temperatures of mantle-derived magmas [7].

Effects of Phase Boundary Migrations. As the mantle cools, temperature dependent phase boundaries will move radially outward or inward, depending on whether the Clapeyron slope dP/dT is respectively positive or negative. The resulting change in the volume of mantle changing phase is equivalent to a change in R. We show in Table 1 estimates for dR/dt due to a rate of global cooling dT/dt of 100 K/b.y. and consequent migration of the olivine-β phase boundary, the β–γ (spinel) phase boundary, and the reaction γ-(Mg, Fe)$_2$SiO$_4$ $\rightarrow$ (Mg, Fe)SiO$_3$ (perovskite) + (Mg, Fe)O. The specific volumes are from Lees et al. [8], and the Clapeyron slopes are taken to be 35 bar/K [9], 55 bar/K [9], and -20 bar/K [10], respectively. The effect on the rate of global contraction may be seen to be an order of magnitude less than for whole-Earth cooling, and the contributions of these phaase boundaries partially concel each other because of the mix of signs of the Clapeyron slopes.

Also shown in Table 1 is an estimate of the contribution to dR/dt from inner core solidification, under the assumption that solid Fe at inner core pressures is in the ε phase [11] and that the rate of increase in inner core volume has been constant for 4 b.y. This effect is much smaller than the others considered and may be neglected.

Rates of Stress and Strain. For the overall rate of global contraction given in Table 1, a circular plate of radius R would experience a secular increase in the rate of extensional membrane stress and strain in the plate interior [5,6] of 120 bar/b.y. and 3×10^{-21} s^{-1}, respectively. Neither one of these rates is particularly large, but it is of interest to compare them with other sources of steady change in membrane stress and to consider the conditions under which these estimates might be raised.

Another source of membrane stress is the change in the ellipticity e of the Earth's figure accompanying tidal despinning. From first order hydrostatic theory, $\dot{e}/e = 2\dot{\Omega}/\Omega$, where Ω is the spin rate. From the paleontological record of growth in corals and bivalves, Lambeck [12] gives $\dot{\Omega} = -5 \times 10^{-22}$ s^{-2} since the mid-Paleozoic, which yields $\dot{e} = -1.4 \times 10^{-3}$/b.y., equivalent to changes in mean radius of curvature dR/dt of -9 km/b.y. at the poles and +9 km/b.y. at the equator. The rate of change of radius of curvature of a large plate due to change in spin rate is thus comparable to that due to global cooling.

Membrane stress also accumulates as plates change latitude on an ellipsoidal Earth [5]. For a circular plate with radius R moving from the pole to the equator at 1 cm/yr latitudinal velocity, the central interior is subjected to increasing extension at the rate 1 kbar/b.y. [5]. This effect can thus yield locally larger stress than the stress due to global contraction or despinning, but only if the poleward component of plate motions are rapid or are sustained for a long interval of geological time.

Several effects might increase the importance of global cooling and contraction for the intraplate stress field. The stress level increases with the area of a plate and with its longevity, and thus would be maximum for a long-lived "supercontinent" plate such as Pangaea. The rate of stress build-up would also be increased during periods of accelerated plate cooling; such periods have been suggested on the basis of documented intervals of rapid seafloor spreading [13] and convective thermal history models.

Conclusions. Global cooling of the Earth can be an important contributor to the state of stress in the interiors of large continental plates. Global contraction in the geologic past should have led to extension in plate interiors, and may have contributed to the formation of intracontinental rifts and to the break-up of supercontinents.

Table 1. Contributions to Global Contraction

Whole Earth Cooling	dR/dt
$dT/dt = -100$ K/b.y.	-6 km/b.y.
Mantle Phase Changes (assuming same cooling rate)	
$\alpha \rightarrow \beta$-$(Mg, Fe)_2SiO_4$	-0.5 km/b.y.
$\beta \rightarrow \gamma$-$(Mg, Fe)_2SiO_4$	-0.3 km/b.y.
$\gamma \rightarrow$ pv + mw	0.4 km/b.y.
Inner Core Solidification	-0.05 km/b.y.

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