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ARCHEAN OCEANIC FLAKE TECTONICS

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Abstract. Assuming that the Archean mantle was hotter and the oceanic crust thicker than at present, we estimate that the Archean oceanic lithosphere had a "sandwich" rheology, with the lower crust behaving as a soft, ductile layer. Accordingly, the Archean oceanic lithosphere had a rheological structure similar to present-day continental lithosphere but unlike present-day oceanic lithosphere. The thickness of the ductile layer is a decreasing function of age, while its strength is an increasing function of age. The buoyancy problem in Archean subduction could be overcome by delamination of oceanic upper crust, but mass balance calculation indicates that most Archean oceanic crust must have been recycled. Where the right dynamic conditions existed for delamination, oceanic flake tectonics may have been an important process leading to the preservation of oceanic upper crust in "greenstone belts" that are characteristic of Archean terrains.

Introduction

The mantle in the Archean was probably a few hundred degrees hotter than at present. This is required by most thermal models and confirmed by the eruption temperature of komatiitic lavas (often quoted at 1650°C, certainly greater than 1500°C; Bickle, 1986). On the other hand, the P-T conditions in the preserved Archean continental lithosphere were similar to the present (England and Bickle, 1984; Boyd et al., 1985). This has led to the idea that the extra heat was dissipated by increased spreading activity (defined as total ridge length times average spreading rate; Bickle, 1978; Nisbet and Fowler, 1983; Hargraves, 1986).

A higher-temperature mantle must have resulted in a higher degree of partial melting and therefore a larger volume of oceanic crust (Sleep and Windley, 1982; Bickle, 1986; Vlaar, 1986). The increase in melt volume had two likely consequences: a thicker oceanic crust (usually estimated in the 25-50-km range), and an increase in the amount of heat advected by melting, which reduces but does not eliminate the need for higher spreading activity. Iceland, being underlain by anomalously hot mantle, may provide a reasonable physical analogy for Archean spreading ridges generally (Sleep, 1988a), given that hotspots may not have existed at that time (Sleep, 1988b). On the other hand, the only well-established Archean ophiolite is inferred to be less than 3 km thick (de Wit et al., 1987). However, the estimated thickness of the cumulate sequence of this ophiolite (0.3-0.5 km) is dependent on the validity of a projection across a major shear zone in the absence of a single complete profile (de Wit et al., 1987, p. 718).

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Higher spreading activity (by increased ridge length, spreading rate, or both) would result in the subduction of younger oceanic lithosphere, perhaps on average half as old as the present lithosphere at subduction (about 60 Ma). Combined with the presence of a thick basaltic crust, this implies that a part (possibly most) of oceanic lithosphere in the Archean was not capable of negative-buoyancy subduction (Baer, 1977; Oxburgh and Parmentier, 1977).

In this paper, we explore some rheological implications of a thick oceanic crust and of higher mantle temperatures for Archean tectonics. We show that, for a range of conditions, a ductile layer existed in the lower oceanic crust, imparting to the oceanic lithosphere a strong-weak-strong rheological layering similar to that existing today in the continental lithosphere (Ranalli and Murphy, 1987). It follows that the Archean oceanic lithosphere was under certain circumstances capable of delamination (Bird, 1979). In this way, the buoyancy problem in Archean subduction zones might have been overcome: the low-density oceanic crust was accreted or obducted onto the overriding plate, permitting the dense lithospheric mantle to be subducted. We suggest that many greenstone belts characteristic of Archean terrains contain relics of delaminated oceanic crust.

Archean Oceanic Geotherms and Rheology

We model oceanic geotherms by transient half-space cooling (see e.g. Turcotte and Schubert, 1982)

$$T(z,t) = T_o + (T_m - T_o)\,\mathrm{erf}\left[z/2(\kappa t)^{1/2}\right] \qquad (1)$$

where T_o, T_m are surface and upper mantle absolute temperatures respectively, z is depth, t time (age of the oceanic lithosphere), and κ the thermal diffusivity. We take $\kappa \simeq 10^{-6} m^2 s^{-1}$ and $T_m - T_o \simeq 1500$ K in the Archean, as opposed to $T_m - T_o \simeq 1300$ K at the present time. Our estimate of Archean oceanic upper mantle temperature is conservative (see discussion in Bickle, 1986), which lends credibility to our rheological inferences. Archean and present-day oceanic geotherms are shown in Figure 1.

At temperatures lower than the brittle-ductile transition, rocks fail by brittle shear fracture, independent of rock type and temperature. The brittle failure criterion can be written as (Sibson, 1974)

$$\sigma = \alpha \rho g z (1-\lambda) \qquad (2)$$

where σ is the stress difference at faulting, α a numerical coefficient which depends on the type of faulting, ρ, g, and z average density, gravity, and depth, respectively, and λ the ratio of fluid to overburden pressure. For $\alpha = 3$ (thrust faulting, which is the condition appropriate for subduction or obduction of

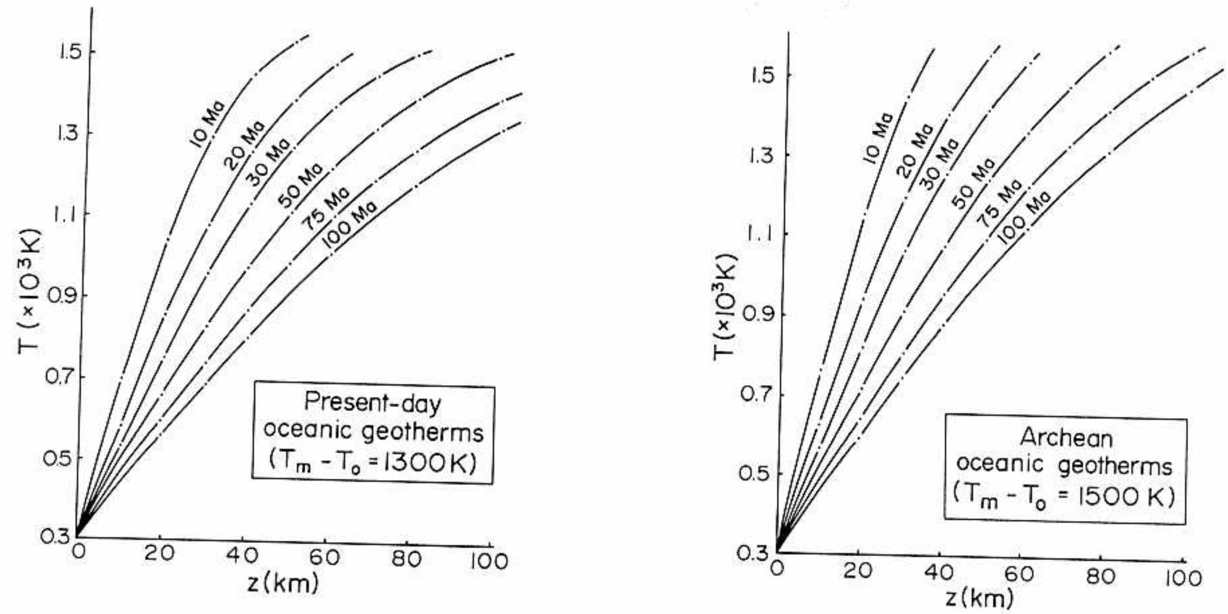

Fig. 1. Present-day (left) and Archean (right) oceanic geotherms for different lithosphere ages, and conditions discussed in the text.

young buoyant lithosphere), $\rho \simeq 3000$ kg m^{-3}, and $\lambda \simeq 0.33$ (hydrostatic fluid pressure), equation (2) reduces to

$$\sigma(\text{MPa}) \simeq 59z\ (\text{km}) \qquad (3)$$

We take equation (3) to be indicative of the brittle strength of the Archean oceanic crust. For lack of better information, we extrapolate it to the upper mantle as well; this does not affect our conclusions on the rheology of the crust.

Assuming power-law creep, the stress difference σ corresponding to a given steady-state strain rate $\dot{\epsilon}$ is (see Ranalli; 1987, for a review)

$$\sigma = (\dot{\epsilon}/A)^{1/n} \exp(E/nRT) \qquad (4)$$

where A, n, and E are creep parameters, R is the gas constant, and T absolute temperature. Equation (4) neglects the pressure-dependence of creep, which is not important in the lithosphere.

Table 1 (compiled from Carter and Tsenn, 1987; Kirby and Kronenberg, 1987) gives average values for the creep parameters of materials relevant to the Archean oceanic lithosphere. The oceanic crust was likely to consist mainly of basalt (modelled with the rheology of diabase), perhaps differentiated downward into pyroxenite or anorthosite. The lithospheric upper mantle is modelled with the rheology of peridotite.

TABLE 1. Creep Parameters for Lithospheric Rocks

Rock	$\log A$ (MPa^{-n}s^{-1})	n	E (kJ mol^{-1})
diabase	-2.5	3.3	268
pyroxenite	0.3	3.7	333
anorthosite	-3.5	3.2	238
peridotite	4.5	3.6	535

Although the error margins on creep parameters are relatively large (typically, 10% on both n and E), the rheology of diabase, pyroxenite, and anorthosite is sufficiently similar to justify modelling the Archean oceanic crust with the rheology of diabase. The creep stresses as a function of temperature for the four rock types listed in Table 1 are shown in Figure 2 for $\dot{\epsilon} = 10^{-14}$s^{-1}, taken to be a representative tectonic strain rate (increase or decrease of $\dot{\epsilon}$ by one order of magnitude changes σ by a factor of approximately 2 or 1/2 respectively).

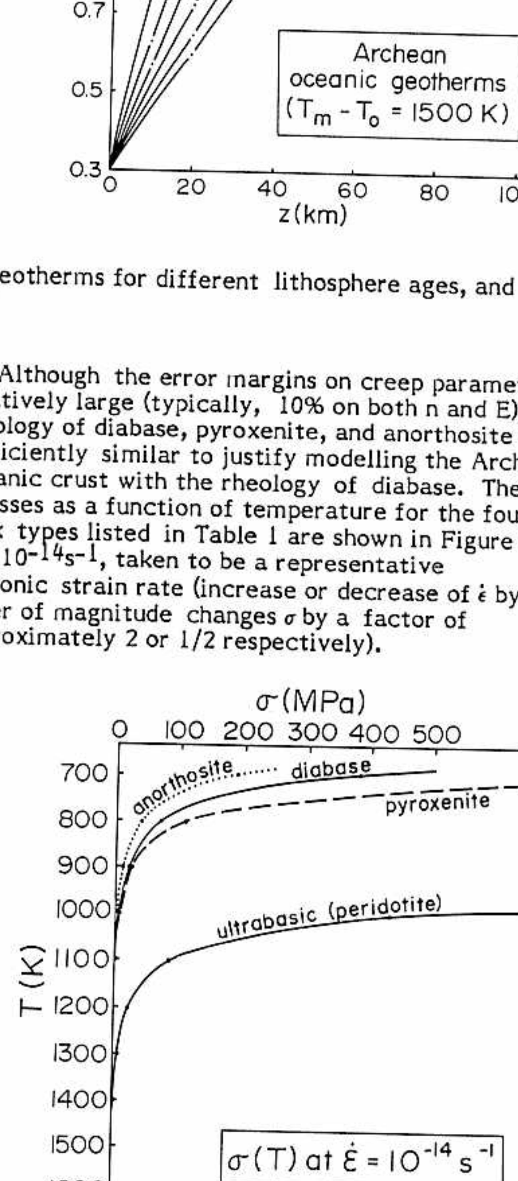

Fig. 2. Ductile rheology (power-law creep at $\dot{\epsilon} = 10^{-14}$s^{-1}) for diabase, pyroxenite, anorthosite, and peridotite as a function of temperature.

Strength Profiles and Delamination

Strength profiles are constructed by comparing the brittle and the ductile strength for a given geotherm. We show first, for comparison, the strength profiles

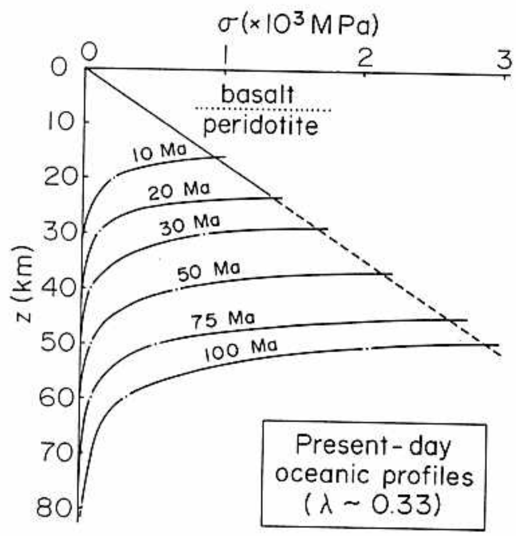

Fig. 3. Strength profiles in compression for oceanic lithosphere as a function of age with present-day structure and geotherms (λ denotes pore fluid factor).

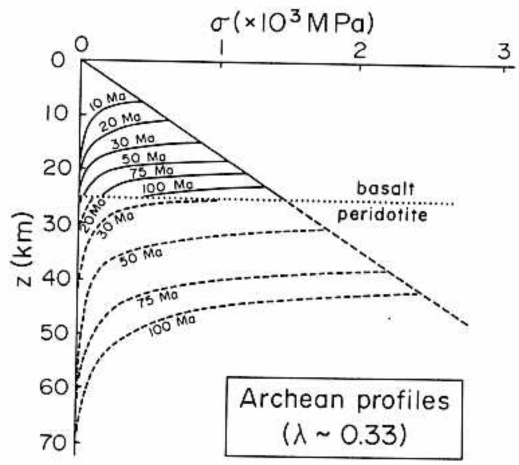

Fig. 4. Strength profiles in compression for Archean oceanic lithosphere as a function of age. The 25-km-thick crust is modelled as diabase, and the upper mantle as peridotite.

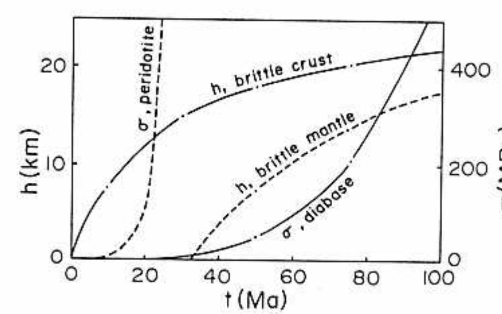

Fig. 5. Thickness h of upper crustal and upper mantle brittle layers, and ductile strength σ of the lowermost crust (diabase) and uppermost mantle (peridotite) as a function of age in Archean oceanic lithosphere.

for the present oceanic lithosphere, taken to consist of approximately 7 km of basalt overlying peridotitic subcrustal material (Figure 3). Since the crust is thin, the whole of it is brittle except for the first few million years after formation at a spreading ridge. The rheological structure of the lithosphere therefore consists of a brittle layer, comprising the crust and a part of the uppermost mantle for which thickness increases with age, overlying a ductile layer where the strength decreases rapidly with depth until it reaches values typical of the asthenosphere (1-10 MPa). This is why obducted Phanerozoic ophiolites typically include both oceanic crust and mantle, and why they can only be obducted when they are very young (Meissner and Kusznir, 1987).

We note incidentally that, where the oceanic crust is anomalously thick (e.g. seamounts and oceanic plateaus with crustal thickness of 16 km or more), a soft ductile layer in the lower crust persists to lithospheric ages of approximately 25 Ma. This may account mechanically for "accreted terranes" comprised of the upper crust of oceanic plateaus or seamounts (e.g. Barker et al., 1988). Similarly, island arcs may tend to delaminate, leading to selective accretion of their upper more felsic part and recycling of their lower more mafic part (Kay, 1987).

For the Archean lithosphere, we take the basaltic crust to be 25 km thick, which may well be an underestimate. This increased thickness is sufficient to cause a ductile layer in the lower crust which persists up to $t \simeq 100$ Ma, although decreasing in thickness and increasing in minimum strength with increasing age. The temporal evolution of the lithospheric rheological profiles is shown in Figures 4 and 5. The presence of the ductile layer is strongly determined by the thickness of the crust; such a layer would persist up to ages $t \simeq 50$ Ma even for present-day geotherms.

For $t \lesssim 50$ Ma, the lower crustal ductile layer is pronounced and soft ($\sigma \lesssim 100$ MPa), and consequently the potential existed in the Archean for the upper oceanic crust to be delaminated from the remaining lithosphere.

Mass Balance

At present, the generation rate of oceanic crust is approximately 18 km^3a^{-1} (assuming a total ridge length of 65,000 km, an average opening rate of 4 cm a^{-1}, and an oceanic crustal thickness of 7 km). It therefore takes about 400 Ma to generate a new crustal volume equivalent to the present continental volume. (This is of course a measure of sea-floor generation, not of continental growth, as practically all new oceanic crust is recycled into the mantle.) Assuming a spreading activity 2-3 times the present one and an oceanic crustal thickness of 25 km in order to satisfy the required heat loss in the Archean (Bickle, 1986), the generation rate would have been 130-195 km^3a^{-1}, resulting in equivalent times of 35-50 Ma. Obviously most of this oceanic crust was subducted. Continental crustal growth was determined in part by subduction-related magmatism, and in part by delamination and obduction of a part of the upper oceanic crust.

It is difficult to determine the amount of delamination taking place in the Archean, since neither the age-area relation in oceanic lithosphere, nor the distribution of conditions favorable to delamination are known with any confidence. (Delamination requires a suitable plate geometry in addition to favorable rheology.) Assuming that, as an order of magnitude, 1% of new crustal material was delaminated, Archean flake tectonics would produce the equivalent of slightly more than 1/4 of the present continental volume in 1.5 Ga. Delamination was therefore of subordinate importance compared with crustal recycling.

Greenstone Belts

Many Archean terrains are characterized by "greenstone belts" composed of mafic (with or without ultramafic and felsic) volcanic rocks, intruded by calc-alkaline plutons. The volcanic rocks are typically overlain and structurally interleaved with immature epiclastic sediments. Lithological and structural relations resemble those in accretionary wedges developed above active subduction zones (e.g. Lamb, 1987). Although many Archean greenstone belts probably represent island arcs or closed back-arc basins, we suggest that some may contain relics of delaminated oceanic crust.

To the extent that the upper crust was delaminated, Archean subduction zones may not have generated normal arc-type magmas. If the subducted lithosphere had been stripped of hydrated upper crust, it would have been incapable of inducing hydration melting of the overlying mantle wedge.

Proterozoic oceanic lithosphere should have been intermediate in character and behavior between Archean and present-day examples. The 2.00-Ga Purtuniq ophiolite of northern Quebec is more than 8 km thick (flows, dikes and cumulates only) and was obducted more than 40 Ma after its formation (St-Onge et al., 1988; R. Parrish, personal communication, 1988), unlike most Phanerozoic ophiolites which were obducted soon after formation.

Conclusion

If the Archean oceanic crust was as thick (25-50 km) as has been postulated, then the oceanic lithosphere would have had a "sandwich" rheology unlike that of the present day, with the lower crust behaving as a soft, ductile layer. The thickness of the ductile layer would have decreased with age, while its strength would have increased. Therefore, oceanic upper crust, especially if younger than about 50 Ma, could have been delaminated under favorable conditions. Consequently, oceanic flake tectonics may have occurred in the Archean, and may have contributed to the formation of "greenstone belts" that are often observed in Archean terrains.

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References

Baer, A. J., Speculations on the evolution of the lithosphere, Precambrian Res., 5, 249-260, 1977.

Barker, F., D. L. Jones, J. R. Budahn, and P. J. Coney, Ocean plateau-seamount origin of basaltic rocks, Angayucham Terrane, central Alaska, J. Geol., 96, 368-374, 1988.

Bickle, M. J., Heat loss from the earth: a constraint on Archaean tectonics from the relation between geothermal gradients and rate of plate production, Earth Planet. Sci. Lett., 40, 301-315, 1978.

Bickle, M. J., Implications of melting for stabilization of the lithosphere and heat loss in the Archaean, Earth Planet. Sci. Lett., 80, 314-324, 1986.

Bird, P., Continental delamination and the Colorado Plateau, J. Geophys. Res., 84, 7561-7571, 1979.

Boyd, F. R., J. J. Gurney, and S. H. Richardson, Evidence for a 150-200-km thick Archaean lithosphere from diamond inclusion thermobarometry, Nature, 315, 317-389, 1985.

Carter, N. L., and M. C. Tsenn, Flow properties of continental lithosphere, Tectonophysics, 136, 27-64, 1987.

de Wit, M. J., R. A. Hart, and R. J. Hart, The Jamestown Ophiolite Complex, Barberton mountain belt: a section through 3.5 Ga oceanic crust, J. African Earth Sci., 6, 681-730, 1987.

England, P., and M. Bickle, Continental thermal and tectonic regimes during the Archaean, J. Geol., 92, 353-367, 1984.

Hargraves, R. B., Faster spreading or greater ridge length in the Archean?, Geology, 14, 750-752, 1986.

Kay, R. W., Mass flux at convergent plate margins, Eos, 68, 1209, 1987.

Kirby, S. H., and A. K. Kronenberg, Rheology of the lithosphere: Selected topics, Rev. Geophys., 25, 1219-1244, 1987.

Lamb, S., Archean synsedimentary tectonic deformation: A comparison with the Quaternary, Geology, 15, 565-568, 1987.

Meissner, R., and N. Kusznir, Lithospheric viscosity models and their impact on tectonic structure, XIX General Assembly Int. Un. Geodesy Geophys., Vancouver, Abstracts, 1, 301, 1987.

Nisbet, E. G., and C. M. R. Fowler, Model for Archean plate tectonics, Geology, 11, 376-379, 1983.

Oxburgh, E. R., and E. M. Parmentier, Compositional density stratification in oceanic lithosphere: causes and consequences, J. Geol. Soc. London, 133, 343-355, 1977.

Ranalli, G., Rheology of the Earth, 366 pp., Allen & Unwin, London, 1987.

Ranalli, G., and D. C. Murphy, Rheological stratification of the lithosphere, Tectonophysics, 132, 281-295, 1987.

Sibson, R. H., Frictional constraints on thrust, wrench, and normal faults, Nature, 249, 542-544, 1974.

Sleep, N. H., Tapping of melt by veins and dikes, J. Geophys. Res., in press, 1988a.

Sleep, N. H., Onset of mantle plumes in the presence of pre-existing convection, J. Geophys. Res., in press, 1988b.

Sleep, N. H., and B. F. Windley, Archean plate tectonics: constraints and inferences, J. Geol., 90, 363-379, 1982.

St-Onge, M.R., S. B. Lucas, D. J. Scott, N. J. Bégin, H. Helmstaedt, and D. M. Carmichael, Thin-skinned imbrication and subsequent thick-skinned folding of rift-fill, transitional-crust, and ophiolite suites in the 1.9-Ga Cape Smith Belt, northern Quebec, in Current Research, Part C, Paper 88-1C, 1-18, Geol. Surv. Can., Ottawa, Ont., 1988.

Turcotte, D. L., and G. Schubert, Geodynamics: Applications of continuum physics to geological problems, 450 pp, John Wiley & Sons, New York, 1982.

Vlaar, N. J., 1986, Archaean global dynamics, Geologie en Mijnbouw, 65, 91-101, 1986.

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