Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs

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ABSTRACT

This paper explores the secular evolution of the height of an isostatically balanced collisional mountain belt in the context of ongoing convergence. We show that until the Neoarchean, continents were unable to sustain topography >2500 m. During the Neoarchean the continental lithosphere evolved through a rheological threshold, allowing for the development of significant topography. The consequence of the strengthening of the continental lithosphere is fundamental for the coupling of the Earth's geochemical reservoirs. The Neoarchean was a period of global changes during which exogenic envelopes recorded major shifts in composition toward modern values. We propose that during the Neoarchean the exogenic envelopes, which were until then coupled to the mantle through hydrothermal processes and volcanism, also became coupled to the continental crust through relief-generating tectonics processes and erosion, hence changing the balance between mantle versus crustal interaction with the exogenic Earth.

Keywords: Archean, tectonics, geochemistry, erosion, Earth evolution, modeling.

INTRODUCTION

Through the recycling of the continental crust into the mantle, erosion bridges atmospheric, hydrospheric, crustal, and mantle geochemical reservoirs while delivering vital nutrients to the biosphere and buffering the atmospheric CO_2 level (Garrels and Mackenzie, 1971; Berner et al., 1983). On the modern Earth, erosion is both the direct consequence of plate tectonic processes, creating vigorous topographic heights and steep slopes, and a driving mechanism for mountain growth (e.g., Avouac and Burov, 1996). Consequently, major orogenic episodes are known to leave behind fingerprints in the form of short-term excursions (<20 m.y.) of biogeochemical and environmental markers (Gaillardet et al., 1999). Emerged topographic heights and strong elevation gradients are critical to erosion (e.g., Koons, 1989). The ability of the continental lithosphere to sustain topographic heights and steep slopes is controlled by its rheology and therefore its geotherm, since rocks are exponentially weaker with increasing temperature. Because of the decay of the radiogenic elements and the decrease of the mantle potential temperature through time, one can assume that the continental geotherm was hotter in the past (e.g., Turcotte, 1980). This suggests that early in Earth's history, the continental lithosphere was weaker, its surface smoother, and erosion less efficient to couple the Earth's geochemical reservoirs.

Using a thin sheet model of continental lithosphere under a triaxial state of stress, this paper explores the secular evolution of the height of an isostatically balanced collisional mountain belt in the context of ongoing convergence. Our numerical experiments show that during the Neoarchean (2800–2500 Ma), the continental lithosphere evolved through a rheological threshold allowing for the development of topography >2500 m. We relate this evolution to the cooling and strengthening of the upper lithospheric mantle. The consequence of the strengthening of the continental lithosphere is fundamental for the geochemical coupling between Earth's exogenic and endogenic envelopes. The Neoarchean was a period of global changes during which exogenic envelopes recorded major shifts in composition. Here we propose that during the Neoarchean the exogenic envelopes, that were until then coupled to the mantle through hydrothermal processes and volcanism, also became coupled to the continental crust through relief-generating tectonics processes and erosion, hence changing the balance between mantle versus crustal interaction with the exogenic Earth.

CONTINENTAL REFERENCE AND NUMERICAL EXPERIMENTS SETUP

Some have cautioned the use of present-day Archean cratons as representative of the continental lithosphere in the Archean, because they may only represent the stronger segments of otherwise weaker continental lithosphere that could have been easily recycled (e.g., Gurnis and Davies, 1986). In our numerical experiments, thinner and weaker Archean continental lithosphere would only lower the capacity of the crust to sustain significant topography. Choosing the present-day average Archean lithosphere for reference is therefore a conservative approach. The thermal state of this lithosphere is adjusted to explore the secular evolution of its mechanical response to ongoing convergence, in particular its capacity to sustain orogenic plateaus. Our reference lithosphere includes a 40-km-thick continental crust, the density of which at room temperature increases toward the Moho, from 2700 to 2900 kg m^{-3}, but decreases with temperature following a coefficient of thermal expansion of 3×10^{-5}. The density at room temperature of the lithospheric mantle under cratonic area is 3310 kg m^{-3} and that of the asthenospheric mantle is 3395 kg m^{-3} (Griffin et al., 1998). Disregarding the heat production in the lithospheric mantle, we use the U, Th, and K concentrations of present-day average Archean crust determined by Taylor and McLennan (1995), and get a depth-independent heat production of 4.84×10^{-6} W m^{-3}. The mantle heat flow under the cratonic area is ~12×10^{-3} W m^{-2} (Mareschal et al., 2000). Therefore, assuming a conductivity of 2.535 W m^{-1} K^{-1}, one can calculate that the Moho temperature in the present-day craton is 342 °C, while the 1330 °C isotherm is met at a depth of 250 km. This continental geotherm changes over time in response to the decay of radiogenic elements and the decrease in mantle heat flow, for which we use the parameterization of Grigné et al. (2005), assuming a 200 °C drop in mean mantle temperature since 3.5 Ga. To evaluate the evolution of the integrated strength of the continental lithosphere in response to secular cooling (Fig. 1), we use the triaxial constitutive relationships derived by Rey and Houseman (2006) with the dislocation creep parameters for dry quartz-rich rock and olivine from Brace and Kohlstedt (1980). Figure 1 shows that the integrated strength increases tenfold from 3.5 to 1.5 Ga with a sudden increase near the end of the Archean. We do not investigate the reference lithosphere for the times younger than 1.2 Ga, because by then its strength exceeds realistic tectonic forces.

We use thin viscous sheet equations in a triaxial situation (see Rey and Houseman 2006, for details) in which we specify that the horizontal principal stresses (σ_{xx} and σ_{yy}) are externally specified, while the vertical stress component (σ_{zz}) is determined simply by gravity assuming local isostasy. The tectonic effect of in-plane stress in the x direction is then simulated by adding, to σ_{xx}, an increment large enough to drive convergence at a specified initial strain rate. We assume that the stress component driving deformation remains constant during convergence, which implies that the contractional strain rate is free to depart from its initial value. As thin sheet deformation (England and McKenzie 1982) occurs, the tectonic stress balance changes with the thickness of the deforming lithosphere. Disregarding erosion and sedimentation, the thickness of the lithospheric column changes under the action of (1) a tectonic and gravity driven triaxial flow, (2) local isostasy, and (3) thermal relaxation. These processes are integrated forward in time using time increments small enough to maintain incremental change in lithospheric thickness below 500 m. Calculation of transient geotherms uses a Crank-Nicholson finite differences scheme with a constant heat flow at the base of the lithosphere and no lateral heat transfer. The vertically averaged stress difference is related to the strain rates by the constitutive equations. The vertical stress component is always evaluated directly from the current density profile. The two horizontal stress components are set up as described above: σ_{yy} is constant throughout the experiments, and σ_{xx} results from maintaining a constant plate boundary force against the vertical section of the deforming lithosphere normal to the x direction. Therefore, σ_{xx} is inversely proportional to the current thickness of the deforming lithosphere on which the force is applied. Note that between 1.8 and 2 Ga our reference cratonic lithosphere has a thermal state similar to that of Phanerozoic lithosphere. Therefore, if our flow laws and boundary conditions are reasonable, the cratonic lithosphere at 1.8–2 Ga should be able to sustain a Tibet-like plateau.

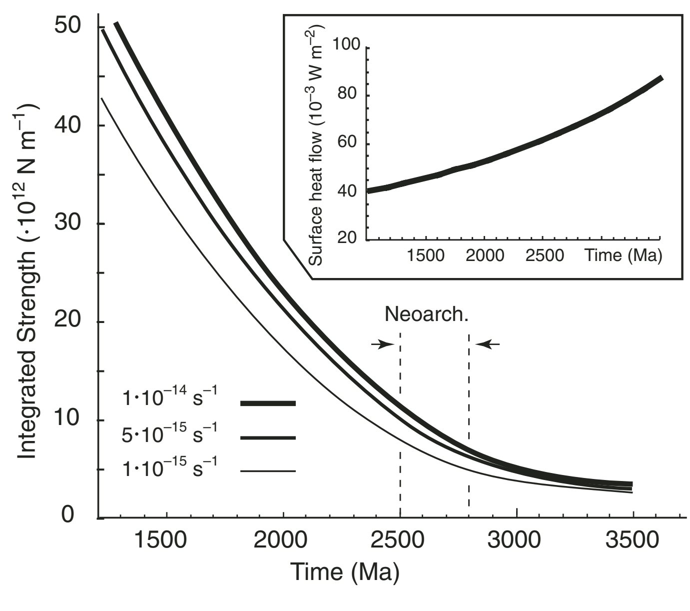

Figure 1. Secular evolution of surface heat flow (inset) and that of the integrated strength in compression of the reference continental lithosphere at various nominal strain rates.

RESULTS

Figure 2A summarizes the evolution of the elevation of the deforming lithospheres through time, assuming that convergence initiates at a strain rate of 5×10^{-15} s^{-1}. In each case, the elevation increases up to a near steady-state value, which results from the balance between the tectonic force, the viscous force, and the body force. From that point onward, the lithospheric thickness and its elevation vary little during ongoing convergence and the orogenic plateau grows laterally. The time required to reach the steady-state plateau elevation is at most 10 m.y. before 2.7 Ga, and increases with the strengthening of the lithosphere. This suggests that ongoing convergence in the Archean resulted in broad but low-elevation plateaus, rather than narrow mountain belts. In our numerical experiments, convergence is driven by a tectonic force that is adjusted to initiate convergence at specified strain rates (10^{-15} s^{-1}, 5×10^{-15} s^{-1}, 10^{-14} s^{-1}). Because of the strengthening of the lithosphere through time, the driving tectonic force had to be increased from ~4×10^{12} N·m^{-1} for the model at 3.4 Ga to ~40×10^{12} N·m^{1} for the model at 1.5 Ga. The latter value is closer to the present-day upper limit for the effective tectonic driving force, while the former is consistent with the expected weaker ridge-push and slab pull due to thicker and buoyant oceanic crust for a hotter mantle (Sleep and Windley, 1982; Vlaar, 2000).

A plot of the plateau elevation versus time (Fig. 2B) shows a nonlinear trend. For most of the Archean, the elevation of the orogenic plateau is <2000 m. During the Neoarchean, the steady-state plateau elevation rapidly increases over geological time. Figure 2B shows also that the cratonic lithosphere at 1.8–2 Ga (thermally equivalent to Phanerozoic lithospheres) develops, under ongoing compression, a 4700–5400-m-high plateau con-

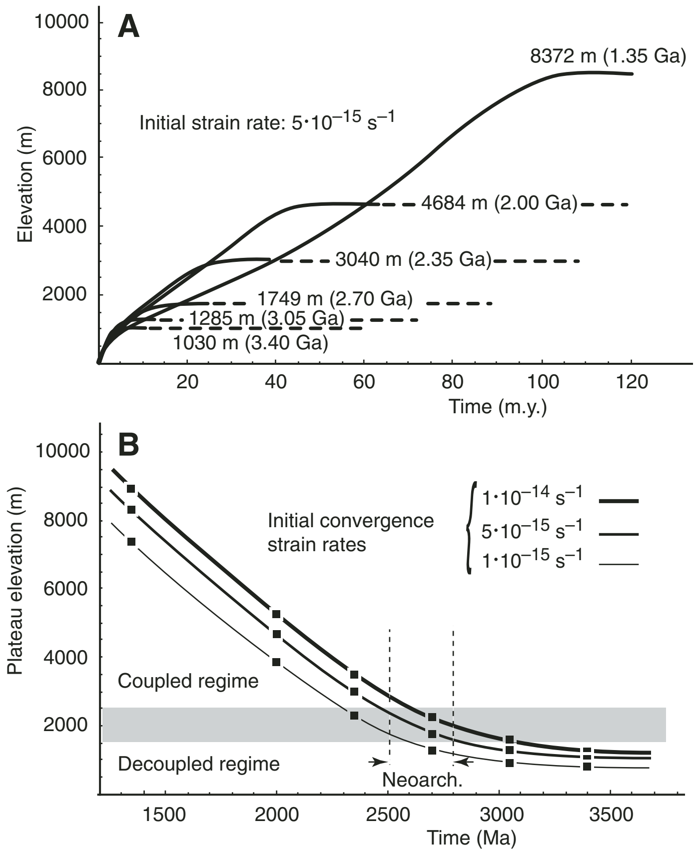

Figure 2. A: Synconvergence elevation of collisional orogen at various times in Earth's history. B: Synconvergence steady-state plateau elevation through times and for various initial convergence strain rates. Note sudden increase of plateau elevation in Neoarchean.

sistent with Tibet's elevation. The ability of the continental lithosphere to support topography is strongly dependent upon its geotherm, a point that Figure 3 illustrates. As the temperature at the Moho decreases from 720 °C to 680 °C, the strength of the lithosphere increases sharply. This increase is directly related to the strengthening of the upper mantle, as seen in the inset in Figure 3B.

DISCUSSION

Flat Earth Hypothesis for the Pre-Neoarchean Earth

Geological records for the Archean cratons point toward low surface elevation. The low erosion level (5 ± 2 km) across most Archean cratons (Galer and Mezger, 1998) does not expose deep orogenic zones, but instead low- to medium-grade metasedimentary and metavolcanic rocks wrapping around granitic domes. Archean high-grade gneisses with subhorizontal flow structures, sometimes interpreted as deeply eroded overthrust belts (e.g., Myers, 1976; Bickle et al., 1980; England and Bickle, 1984), are also compatible with gravity-driven processes involving limited crustal thickening (Delor et al., 1991; Cagnard et al., 2006; Duclaux et al., 2007). The maintenance of shallow subaqueous surface topography during the accumulation of volcano-sedimentary sequences, some as thick as 20 km, above mainly felsic basement (Arndt, 1999; DeWitt and Ashwal, 1997; Kump and Barley, 2007), suggests that thickening of the continental crust due to the emplacement of continental flood basalts failed to significantly raise the crust above sea level. Our experiments suggest that the gravitational flow of the hot and weak lower continental crust during the loading of crust could explain why the accumulation of thick volcano-sedimentary sequences did not translate into significant crustal thickening.

Lithospheric Strengthening and the Onset of Geochemical Coupling

In the Archean, a flatter, largely flooded continental crust covered by continental flood basalt would have been isolated from other geochemical reservoirs. This would impose significant constraints on the global biogeochemical cycling between the Earth's geochemical reservoirs. Our numerical experiments suggest that the relative isolation of the felsic continental crust may have ended during the Neoarchean, when the strengthening of the continental lithosphere allowed for the buildup of significant and sustainable topographic gradients. The erosion of these relief and the exhumation of the felsic crust from under the greenstone covers would have led to a coupling between the continental reservoir with the hydrosphere, the atmosphere, and the mantle reservoirs. Therefore, our numerical experiments point toward a transition from low erosion and weakly coupled geochemical regime in the primitive Earth, to stronger erosion and largely coupled geochemical regime in the Proterozoic and Phanerozoic.

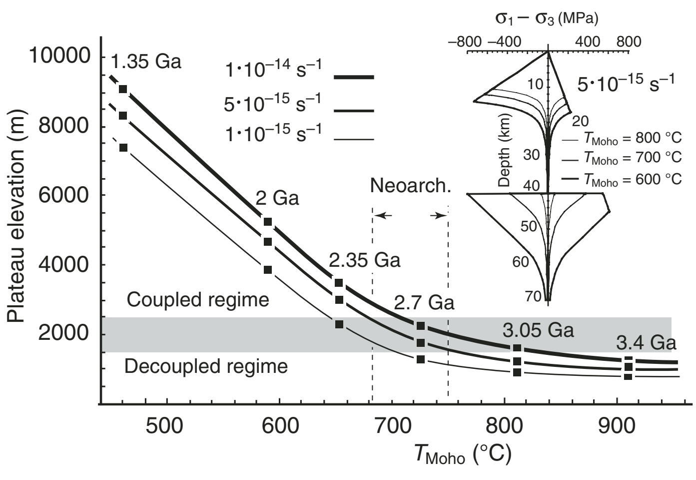

Figure 3. Synconvergence steady-state plateau elevation as a function of Moho temperature (*T*). Continental lithospheres with Moho temperature >700 °C cannot sustain large topographic gradients (Sonder et al., 1987). Inset: Rheological profiles of the reference lithosphere in three contrasting thermal states.

Geological Records and the Transition Toward a Strongly Coupled Geochemical Regime

In the Archean, >80% of continental flood basalts were emplaced on flooded continents, compared to 20% for post-Archean continental flood basalts (Arndt, 1999; Kump and Barley, 2007). This strongly suggests that continental emergence occurred at the transition between the Archean and Proterozoic Eons. In the Neoarchean, exogenic envelopes recorded major shifts in composition that are consistent with the progressive exposure of large areas of felsic crust at the Earth's surface. The change of the average composition of the surface of emerged land is recorded on continents by the composition of black shales, and in the ocean by the strontium isotopic composition of carbonates and the phosphorus concentration of banded iron formations. Neoarchean black shales and carbonates record a shift from compositions buffered by mafic lithologies to compositions buffered by felsic lithologies (Taylor and McLennan, 1985; Veizer and Compston, 1976; Shields and Veizer, 2002), whereas banded iron formations indicate that the pre–2 Ga ocean was strongly depleted in phosphorus, an element strongly partitioned into the felsic continental crust (Bjerrum and Canfield, 2002). In addition, oxygen isotopic data on detrital magmatic zircons show that the incorporation of crustal sediments in silicic magma, an indication of intracrustal recycling, did not appear before the Neoarchean (Valley et al., 2005; Kemp et al., 2006). Oxygen and silica isotopes in cherts point toward a drop in the Earth's surface temperature in the Neoarchean, at a time when oxygenation reached a critical level (Robert and Chaussidon, 2006). Silicate weathering and erosion being a very efficient sink for atmospheric CO_2, we propose that the strengthening and emergence of the continental lithosphere in the Neoarchean was a very important factor contributing to both the cooling of the Earth's surface and oxygenation of the Earth's atmosphere.

This Neoarchean transition from primitive to modern Earth has often been presented in the context of a major pulse of crustal growth and differentiation (Taylor and McLennan, 1985, 1995), superplume activity (Condie, 2004), and/or mantle overturn and orogenic crisis (Stein and Hofman, 1994; Breuer and Spohn, 1995). However, in the context of continental strengthening, we propose that the Earth's exogenic and endogenic geochemical reservoirs became strongly coupled when a significant portion of the felsic crust, hitherto hidden under greenstone covers and/or under sea level, permanently reached the Earth's surface and when sharper mountain belts and high orogenic plateaus were able to sustain higher erosion rates and fluxes toward the oceans.

CONCLUSIONS

The pre–Neoarchean geological record points toward a minor role of continental weathering and erosion in the cycling of atmospheric carbon and that of incompatible elements trapped in the continental crust. A large number of global anomalies in the Neoarchean point toward a major period of reorganization in the Earth's endogenic and exogenic envelopes. To understand this critical period of the Earth's history, the long-term evolution related to the progressive cooling and differentiation of the Earth's envelopes must be considered separately from shorter pulses related to superplume events (Condie, 2004; Eriksson, 1999) and mantle instabilities (Stein and Hofmann, 1994; Breuer and Spohn, 1995). As the rheology of rocks is exponentially sensitive to temperature, we argue that the secular cooling of the Earth was associated with a rapid strengthening and emergence of its continental lithosphere. Our numerical experiments show that the strengthening of the continental lithosphere went through a rheological threshold in the Neoarchean. At that time, the strength of the continents reached a level enabling significant crustal thickening and topographic heights. This in turn increased drastically erosion and the geochemical coupling between the felsic crust, the atmosphere, the hydrosphere, and the mantle.

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