Orogen-parallel flow during continental convergence: Numerical experiments and Archean field examples

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ABSTRACT

Using triaxial numerical experiments, we investigated the evolution of the state of stress and that of the bulk instantaneous and finite strain during ongoing convergence and subsequent progressive tectonic unloading of a warm and buoyant continental lithosphere. Various unloading histories of the driving tectonic force were considered. As the tectonic force progressively declines, the instantaneous strain evolves from plane strain to horizontal constriction in a direction perpendicular to that of convergence, and finally to horizontal flattening. During the progressive unloading of the tectonic force driving convergence, bulk constrictional strain accommodates the release of accumulated gravitational stress. The decline of the triaxial strain rates to low values reduces the potential for the orogen-parallel linear fabric to be erased by horizontal flattening. This is confirmed by the finite strain ellipsoid that evolves toward plane strain with a long axis parallel to the orogen. In the ca. 2.5 Ga Gawler and Terre Adélie cratons, we have identified a well-preserved and widespread horizontal linear fabric. As suggested by our numerical experiments, we associate the development of this linear fabric with the waning stages of late Archean convergence.

Keywords: Bulk constriction, ductile flow, warm lithosphere, Archean geodynamics.

INTRODUCTION

Cooler, stronger plates accommodate convergence through a combination of crustal underthrusting along narrow mountain belts and lateral escape of continental blocks along lithosphere-scale strike-slip faults (Tapponnier et al., 1982). In contrast, warm lithospheres accommodate convergence through homogeneous thickening and lateral ductile flow (Cagnard et al., 2006; Rey and Houseman, 2006; Cruden et al., 2006). The latter mode of deformation was particularly well represented in Archean times (Choukroune et al., 1995; Davis and Maidens, 2003) when the continental geotherm and density profile conspired to make the continental lithosphere weaker and more buoyant (Jordan, 1978; Griffin et al., 1998). Upon ongoing convergence, the evolution of the bulk triaxial strain in a warm and buoyant lithosphere follows a path where vertical flattening, $\sigma_{zz} = \sigma_3$, is followed by a phase of vertical plane strain when $\sigma_{zz} = \sigma_2$. This evolution accounts for ubiquitous upright folds, strike-slip faults, and homogeneous vertical foliation described in many Archean crusts (Choukroune et al., 1995; Davis and Maidens, 2003; Rey and Houseman, 2006; Cruden et al., 2006; Cagnard et al., 2006), as well as the limited crustal thickening recorded by Archean continental crust (Rey and Houseman, 2006). We examined the evolution of the instantaneous and finite bulk triaxial strain regime in a warm and buoyant Archean continental lithosphere during a tectonic history where the tectonic force is progressively relaxed following a period of ongoing convergence. We show that, as the tectonic force progressively decreases, most of the excess in gravitational potential energy is released during a phase of instantaneous constrictional flow. Examples of such strain regime can be found in the Terre Adélie craton (East Antarctica) and Gawler craton (South Australia). Our structural analysis reveals a crustal-scale horizontal linear fabric parallel to the orogen. On the basis of our numerical experiments, we interpret this fabric as the response of a warm and buoyant lithosphere to the decline of the tectonic driving force during a period of continental convergence.

NUMERICAL EXPERIMENTS

Physical Model

Although deformation in the continental crust is strongly heterogeneous, variably partitioned into fractures, faults, shear zones, folds, and zones of homogeneous deformation, it is still possible to consider lithospheric-scale deformation as a continuum. This has led to the thin-sheet approximation (England and McKenzie, 1982, 1983; Nanjo et al., 2005). Under this approximation, we investigated the evolution of the triaxial instantaneous and finite bulk strain during a tectonic history where a phase of continental convergence is followed by a progressive unloading of the tectonic force.

Our reference lithosphere was 120 km thick and included a 40-km-thick crust. Its geotherm was calculated at 2.7 Ga from knowledge of the average composition of present-day Archean crust (see Rey et al., 2003, for details), which led to a Moho temperature of 650 °C. The pressure- and temperature-dependent densities for the lithospheric mantle and asthenosphere (3310 and 3395 kg m^{-3}, respectively) were those proposed by Griffin et al. (1998) for Archean cratons. At time t_0, a tectonic force (Fd_0) of 9.7×10^{12} N m^{-1} initiated convergence in direction x to promote triaxial flow, where z represented the vertical and y represented the horizontal direction perpendicular to the direction of convergence. The magnitude of the tectonic force was such that it triggered an initial strain rate in the direction x of ~5×10^{-15} s^{-1}. Disregarding erosion and sedimentation, the lithospheric column changed under the action of (1) a triaxial state of stress, (2) local isostasy, and (3) thermal relaxation. These processes were integrated forward in time, using small increments of time. Calculation of transient geotherms used a Crank-Nicholson finite difference scheme with a constant heat flow at the base of the lithosphere and no lateral heat transfer. Deformation strain rates along the directions x, y, and z were calculated using the thin-sheet approximation (England and McKenzie, 1982, 1983), in which the vertically averaged differential stresses are related to the strain rates through the triaxial constitutive equations (see Rey and Houseman, 2006, for details).

We assumed the same constitutive equations and rheological parameters used for Archean continental lithosphere used by Rey and Houseman (2006) to define the effective viscosity for the whole system. Throughout the experiment, the vertical stress component σ_{zz} was evaluated from the current density profile. The horizontal stresses, σ_{xx} and σ_{yy}, were determined from the initial density profile and the current thickness of the deforming lithosphere, adding a tectonic stress to σ_{xx} that derived from application of a constant tectonic force for the first 20 m.y. before declining to zero at 40 m.y., following $Fd(t) = Fd_0(1 - [(t-20) / 20]^n)$, where t is time in m.y. Three cases were investigated (Fig. 1): instantaneous unloading ($n = 0$), unloading with a decreasing rate ($n = 0.25$), and unloading with a constant rate ($n = 1$).

Results

The evolution of the instantaneous strain at the crustal scale can be mapped as a path in a space σ_{zz}-σ_{xx} versus σ_{zz}-σ_{yy}, where plane strain

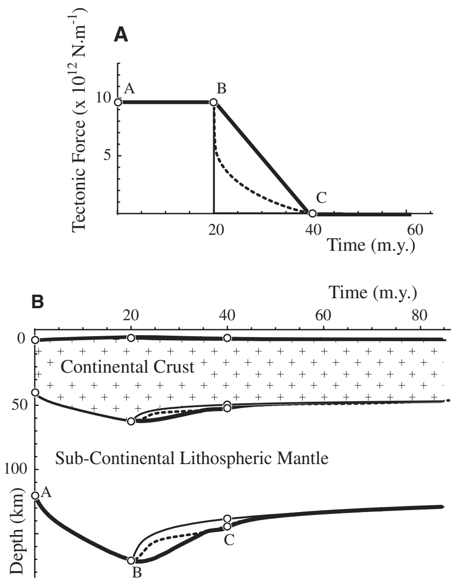

Figure 1. Warm and buoyant continental lithosphere is submitted to a tectonic force that drives convergence at initial strain rate of 5 × 10^{-15} s^{-1}. A: Driving force is constant for 20 m.y. before it decreases progressively to zero over a 20 m.y. period. Three unloading histories are considered. B: Each tectonic history results in slightly different evolution of vertical geometry of continental lithosphere.

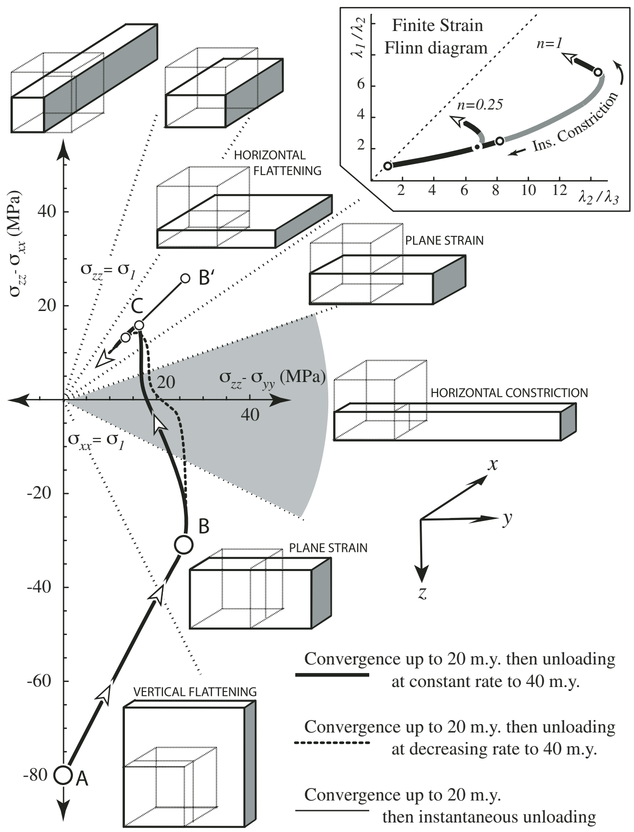

Figure 2. Triaxial stress trajectories in graph σ_{zz}-σ_{xx} vs. σ_{zz}-σ_{yy}, where dotted straight lines separate various instantaneous bulk strain regimes. Trajectories show evolution of triaxial state of stress during tectonic evolution involving 20 m.y. of convergence and thickening (A to B) followed by unloading of driving tectonic force (B to C). Instantaneous unloading (thin solid line) led to switch from plane strain (B) to horizontal flattening (B′). In contrast, trajectories involving 20-m.y.-long progressive unloading of tectonic force, at constant or decreasing rate (A, B, C), go through strain regime for horizontal constriction (shaded area) before ending in horizontal flattening field. Evolution of finite strain (λ) is portrayed as a path in Flinn diagram (inset) and shows progressive strengthening of linear fabric.

regions separate regions where bulk constriction or flattening dominates. Results are presented in Figures 2 and 3, and the evolution of the finite strain is portrayed as a path in the Flinn diagram. Over the first 20 m.y. of ongoing convergence and thickening, the gravitational force—and therefore the vertical stress—progressively increases. This leads σ_{zz}-σ_{xx} to converge toward σ_{zz}-σ_{yy} (path A to B in Fig. 2) and to the establishment of a bulk instantaneous plane strain regime. At that stage, upon instantaneous removal of the tectonic force, the instantaneous strain regime switches from plane strain (point B in Fig. 2) to horizontal flattening (point B′ and beyond in Fig. 2) as σ_1 switches from σ_{xx} to σ_{zz}. In such a case, the bulk instantaneous strain evolves from vertical flattening to plane strain and finally to horizontal flattening. A protracted phase of divergent gravitational collapse (Rey et al., 2001) with horizontal flattening controls the postconvergence evolution of the continental lithosphere. In the Flinn diagram, the finite strain path (n = 0.25 in Fig. 2) marks a sudden departure from S > L toward L = S fabrics; this change is correlated with the instantaneous bulk constriction.

The bulk strain evolution is significantly different when one considers a progressive unloading of the tectonic force. For a progressive unloading, the evolution of the instantaneous bulk strain regime passes through a phase of horizontal constriction followed by a phase of plane strain before ending in the field of horizontal flattening (paths B to C and beyond in Fig. 2). In this case, a significant portion of the gravitational collapse occurs while σ_1 corresponds to σ_{xx}. This is a case of synconvergent gravitational collapse unfolding during a phase of bulk instantaneous horizontal constriction. In the Flinn diagram, the finite strain path (n = 1 in Fig. 2) evolves toward L = S fabrics, and the instantaneous constrictional strain strengthens the orogen-parallel linear fabric.

Both progressive tectonic unloading histories (n = 1 and n = 0.25) reveal similar instantaneous and finite strain paths. However, their respective evolutions show significant differences. When the tectonic unloading unfolds at a constant rate, the instantaneous horizontal constriction strain regime develops in the final stage of the unloading (Fig. 3A). In contrast, when the unloading occurs at a decreasing rate, the constriction strain regime unfolds earlier and is followed by a longer phase of plane strain then flattening strain (Fig. 3A). In this last case, the constriction could be erased by later fabrics. To evaluate the chances that the constrictional fabric is preserved, one can consider the evolution of the triaxial strain rates (Fig. 3B). Figure 3B documents a rather complex evolution of the triaxial strain rates. During the first 20 m.y., we observe a strong decrease then increase of $\dot{\varepsilon}_{xx}$ and $\dot{\varepsilon}_{yy}$, whereas $\dot{\varepsilon}_{zz}$ shows a monotonous decrease. The decreasing $\dot{\varepsilon}_{xx}$ and $\dot{\varepsilon}_{yy}$ correspond to the thickening and strengthening of the continental lithosphere. As thermal relaxation proceeds, the thermal softening of the lithosphere promotes increasing strain rates in the directions x and y. In both cases of progressive unloading, strain rates decrease up to one order of magnitude during the constrictional phase, down to a few 10^{-16} s^{-1}, making possible the preservation of the bulk constrictional strain.

On the basis of these results, one can expect to find orogen-parallel horizontal linear fabric preserved in hot orogens in general and in Archean cratons in particular. In what follows, we describe examples of this crustal-scale constrictional strain regime preserved in Neoarchean cratons.

ARCHEAN EXAMPLES OF OROGEN-PARALLEL FLOW

Palinspastic reconstructions by Oliver and Fanning (1997) and Fanning et al. (1999) allow a precise correlation between the Gawler craton (South Australia) and the Terre Adélie craton (East Antarctica), supporting the notion of a Neoarchean Mawson continent. In both cratons, 2530–2440 Ma granulite to amphibolite facies metasediments associated with felsic to mafic gneisses represent a deep crust under an intermediate to upper crust consisting of amphibolite

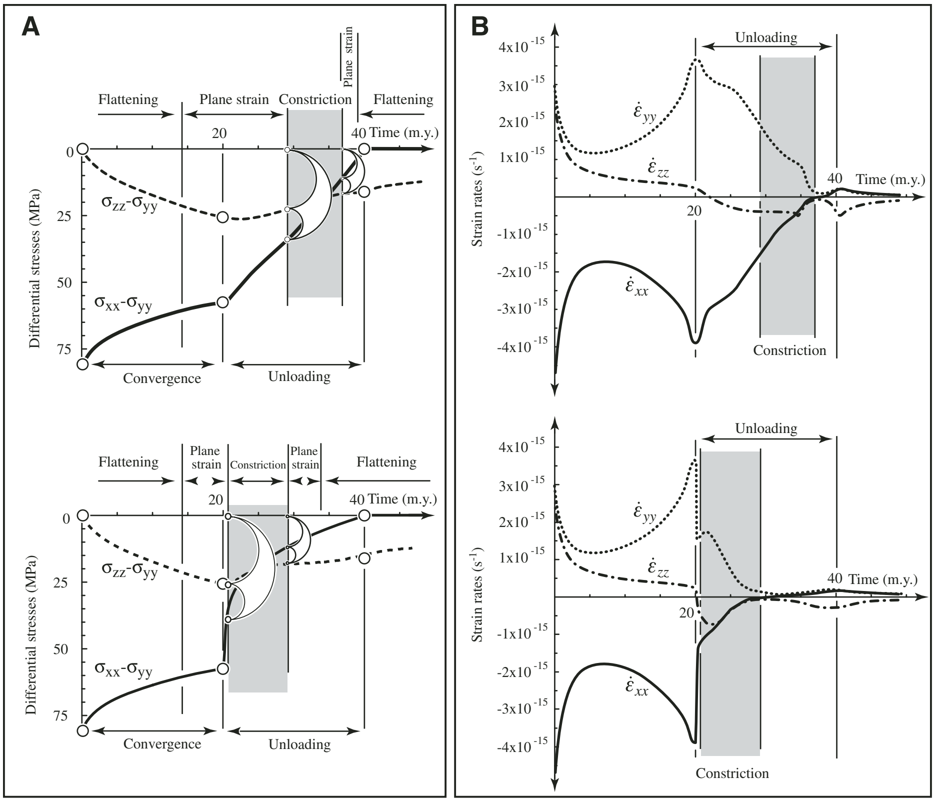

Figure 3. A: Evolution of differential stresses σ_{zz}-σ_{yy} and σ_{xx}-σ_{yy} during a tectonic history involving 20 m.y. of convergence and thickening followed by unloading of tectonic force over 20 m.y. at a constant rate (top) and decreasing rate (bottom). Constrictional strain regime develops during later stage of tectonic unloading when unloading occurs at a constant rate. In contrast, it develops at an earlier stage when unloading rate decreases through time. B: Evolution of strain rates in *x*, *y*, and *z* directions for a constant unloading rate (top) and decreasing unloading rate (bottom). In both cases, strain rates decrease by about an order of magnitude during unloading. Most of that decrease is reached by end of constrictional deformation, allowing for preservation of constrictional fabric.

facies gray gneisses (map in Fig. 4). This higher structural level is intruded by 2520–2440 Ma synkinematic meta-granodiorites (Swain et al., 2005; Stüwe and Oliver, 1989; Ménot et al., 2005). Parallel to the eastern margin of the Gawler craton, the deeper domain trends N-S for over 250 km (shaded domain on the map in Fig. 4) and crops out under an extensive Proterozoic and younger cover. Exposures reveal anatectic orthogneisses and garnet-bearing aluminous migmatites associated with mafic rocks that equilibrated at 800–1000 MPa and 800–900 °C. We dated monazites included in garnet crystals from anatectic leucosome pods that formed along melt-filled dilatant conjugate shear zones. They were dated with the Cameca SX100 electron microprobe in Clermont Ferrand (Fr) using the method described in Goncalves et al. (2004). An age of 2479 ± 20 Ma was calculated following the method of Montel et al. (1996). In the same area, a postkinematic isotropic cordierite-bearing granite dike records monazites age of 1827 ± 10 Ma. These results suggest that the main high-temperature structural architecture developed during the 2500–2430 Ga Sleaford orogeny (Swain et al., 2005).

In these high-grade rocks, the foliation is weak, subhorizontal or subvertical, and carries a prominent subhorizontal mineral and stretching lineation (Fig. 4A) oriented NNW in the north of the domain to NNE in the south. Quartz-feldspar-garnet aggregates and aligned biotites define the lineation. Other important structures include centimeter- to meter-scale leucosome-filled conjugate shear, as well as fold hinges that have been boudinaged along their axes, which are parallel to the subhorizontal stretching lineation. Synkinematic granites display spectacular magmatic fabric marked by feldspar preferred orientation (Fig. 4C) parallel to the regional linear fabric. These structural features are compatible with a horizontal, orogen-parallel, subconstrictional flow, consistent across the entire deeper crustal unit of the Sleafordian, all the way down to the south coast (Fig. 4B). Overall, the remarkable compatibility between the trends of magnetic anomalies and those of the structural fabric over large distances (>40 km) compensates for the lack of exposure and supports the relative homogeneity of the subconstrictional fabric over a large segment of the Gawler craton crust.

Along the coast of the Terre Adélie craton (Fig. 4), L > S fabrics and subconstrictional features are also well developed. N-S–trending horizontal mafic rods are parallel to the mineral and stretching lineation in their surrounding metatexites (Fig. 4D). Ménot et al. (2005) described widespread boudinage and the occurrence of weak conjugate shear zones. We measured monazites with ages of 2450 ± 30 Ma in leucosomes from amphibolite facies migmatites that are lower-grade equivalents to those from the Gawler craton. To explain this structural pattern, we propose a bulk instantaneous constrictional strain regime resulting from the progressive unloading of the tectonic force responsible for the Neoarchean Sleafordian orogeny.

Other Archean cratons record similar bulk strain regimes in the later part of their orogenic histories. The eastern part of the Yilgarn craton of Western Australia displays numerous N-S and NW-SE crustal-scale conjugate strike-slip faults, in between which domains with shallow-dipping shear zones and a subhorizontal stretching lineation are preserved. This regionally developed set of structures results from "complex interplay of both horizontally and vertically directed contractional deformation" and NNW subhorizontal extension (Davis and Maidens, 2003, p. 229). In the eastern Dharwar craton, Chardon et al. (2002) described crustal-scale E-W inhomogeneous shortening accommodated by N-S stretching and spreading of the deep crust during granulite facies metamorphism. In both the Yilgarn and Dharwar cratons, the reported structural features are compatible with bulk subconstrictional flow during the final stages of continental convergence.

CONCLUSIONS

Numerical triaxial experiments show that following a phase of convergence and thickening, soft and buoyant Archean continental lithospheres go through a phase of orogen-parallel instantaneous constriction as the tectonic force progressively vanishes. The evolution of the finite strain shows a progressive strengthening of the linear fabric during the unloading. This constrictional flow relaxes most of the excess in gravitational potential energy. As the bulk strain regime departs from the instantaneous constriction field, strain rates drop to relatively low levels of about a few 10^{-16} s^{-1}. This low strain rate enables the preservation of the L > S fabric. Along with the Yilgarn and the Dharwar cratons, the Terre Adélie and Gawler Neoarchean cratons preserve a crustal-scale late orogenic subconstrictional bulk strain that illustrates the fundamental role of gravity in the structural evolution of Archean continental crust.

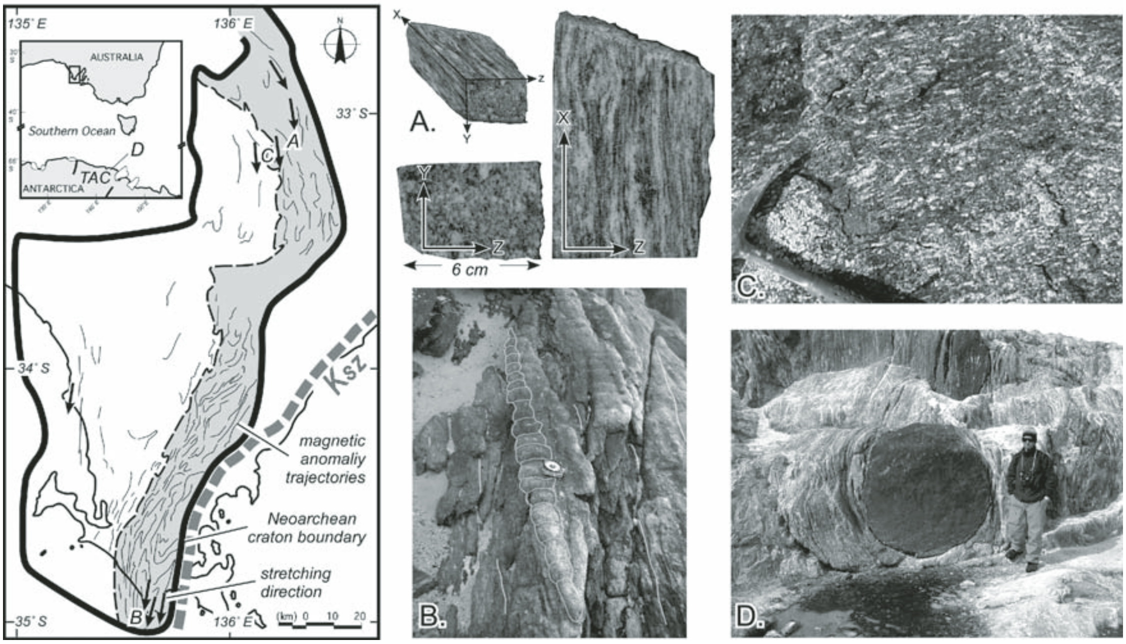

Figure 4. Structural sketch of SE Gawler craton. Magnetic anomalies are parallel to stretching lineation. Ksz corresponds to 1.7 Ga Kalinjala shear zone. Inset shows location of Terre Adélie craton (TAC) in Antarctica. A: three-dimensional view of felsic gneiss illustrating horizontal constriction. B: Horizontal N-S boudinage in gneisses from south coast of Eyre Peninsula. C: Magmatic fabric in a granite. D: Horizontal mafic rod parallel to stretching lineation in surrounding gneisses from TAC.

ACKNOWLEDGMENTS

We thank N. Coltice for comments and discussions. We are grateful for thorough and helpful reviews by A. Cruden, C. Teyssier, and two anonymous referees. This research was in part supported under the Australian Research Council's Discovery funding scheme (ARC DP 0342933) and under the French Polar Institute (IPEV) funding of the GEOLETA program.

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Manuscript received 27 November 2006
Revised manuscript received 1 March 2007
Manuscript accepted 23 March 2007

Printed in USA