The longevity and stability of cratonic lithosphere: Insights from numerical simulations of coupled mantle convection and continental tectonics

A. Lenardic

Department of Earth Science, Rice University, Houston, Texas

L.-N. Moresi

Australian Geodynamics Cooperative Research Centre, CSIRO Exploration and Mining

H. Mühlhaus

Australian Geodynamics Cooperative Research Centre, CSIRO Exploration and Mining

Short title: LONGEVITY OF CRATONIC LITHOSPHERE

Abstract. The physical conditions required to provide for the tectonic stability of cratonic crust and for the relative longevity of deep cratonic lithosphere within a dynamic, convecting mantle are explored through a suite of numerical simulations. The simulations allow chemically distinct continents to reside within the upper thermal boundary layer of a thermally convecting mantle layer. A rheologic formulation, that models both brittle and ductile behavior, is incorporated to allow for plate-like behavior and the associated subduction of oceanic lithosphere. Several mechanisms that may stabilize cratons are considered. The two most often invoked mechanism, chemical buoyancy and/or high viscosity of cratonic root material, are found to be relatively ineffective if cratons come into contact with subduction zones. A high brittle yield stress for cratonic lithosphere as a whole, relative to oceanic lithosphere, is found to be most effective. A high yield stress for only the crustal or mantle component of the cratonic lithosphere is found to be less effective as detachment zones can then form at the crust-mantle interface which decreases the longevity potential of cratonic roots. The degree of yield stress variations between cratonic and oceanic lithosphere required for stability and longevity can be decreased if cratons are bordered by continental lithosphere that has a relatively low yield stress, i.e., mobile belts. Simulations that combine all the mechanisms can lead to crustal stability and deep root longevity for model cratons over several mantle overturn times but the dominant stabilizing factor remains a relatively high brittle yield stress for cratonic lithosphere.

Introduction

Oceanic lithosphere is relatively short lived. The operation of plate tectonics efficiently recycles the entire oceanic lithosphere back into the Earth's mantle on a time scale of 10^8 years, much shorter than the geologic age of the Earth. The age of the continental crust makes it clear that continental lithosphere, unlike oceanic lithosphere, is not efficiently recycled as a whole. However, the preservation of continental crust at the Earth's surface says nothing about the longevity of the deeper lithosphere. Evidence for the longevity of deep continental lithosphere comes instead from kimberlite pipes that have been erupted within continental cratons.

The depth of origin for kimberlites, combined with their rapid eruption rates, has allowed them to remove bits of the mantle lithosphere on their ascent to the Earth's surface. This, in turn, has provided us with direct samples of deep cratonic lithosphere. Geothermobarometry, combined with dating of garnet inclusions from diamond xenocrysts within kimberlites, provided the first evidence that the lithosphere below the Kaapvaal craton of Africa was 200 km thick over 3 Gyr ago [*Richardson et al., 1984*; *Boyd et al.*, 1985]. The ancient crystallization age of diamonds, combined with the fact that they were not erupted to the surface until some 100 Myr ago, further suggested that deep cratonic lithosphere served as a long-term storage reservoir that was isolated from recycling into the convecting mantle for billions of years [*Boyd et al.*, 1985]. Since these first Kaapvaal studies, similar studies have supported the view that ancient cratonic lithosphere has remained thick and isolated from mantle recycling below several other cratons including the Superior craton of North America [*Bell and Blenkinshop*, 1987] and the Siberian craton of Asia [*Pearson et al.*, 1995; *Richardson and Harris*, 1997].

The inferred longevity of cratonic lithosphere is only interesting in context. If we lived on a single plate planet, such as present day Mars or Venus, the longevity of any portion of the lithosphere would hardly be a surprise as the bulk of the lithosphere is permanent on a single plate planet for so long as a single plate state prevails [*Solomatov and Moresi*, 1995]. The longevity of cratonic lithosphere becomes intriguing when viewed relative to the more fundamental observation noted in the first paragraph: The fact that the entire oceanic lithosphere is relatively short lived. The evidence that large portions of non-cratonic, continental mantle lithosphere avoid recycling is sparse relative to the evidence from cratons and several studies suggest that the mantle lithosphere below non-cratonic continental regions can be recycled on a relatively rapid time scale [e.g., *Bird*, 1979; *Tao and O'Connell*, 1992; *Willet et al.*, 1993; *Houseman and Molnar*, 1997; *Rowland and Davies*, 1999]. Thus, the question is not why is deep cratonic lithosphere long-lived but how can it remain long-lived when the majority of the Earths lithosphere is efficiently recycled.

Most studies that have addressed the question above owe a debt to *Jordon* [1975; 1978] who reasoned, based on a variety of observations, that the subcrustal lithosphere below cratons must be chemically distinct from the convecting mantle. This chemically distinct, deep cratonic lithosphere has come to be termed a "cratonic root" and the majority of ideas related to the longevity of cratonic lithosphere attribute it to the chemical buoyancy and/or the high viscosity of root material [e.g., *Jordon*, 1975; 1978; *Pollack*, 1986; *Shapiro*, 1995; et al., 1997; *Shapiro et al.*, 1999; *Sengor*, 1999].

There is evidence that root material is chemically lighter than reference mantle [e.g., *Boyd*, 1989]. It is also likely that root material has a high viscosity due to cool conditions and a dehydrated nature [*Pollack*, 1986]. However, it is incorrect logic to conclude, for example, that the chemical buoyancy of roots is indeed what provides for their longevity simply because we have evidence that roots are long-lived and are chemically light relative to reference mantle; oceanic crust is chemically buoyant relative to reference mantle but it is recycled because its positive chemical buoyancy is overcome by the negative thermal buoyancy of subducting slabs. Similarly, young oceanic lithosphere as a whole is buoyant relative to reference asthenosphere yet it can be recycled if attached to an older section of subducting lithosphere. The same caution holds for too quickly attributing root longevity to high root viscosity; oceanic lithosphere has a very high viscosity relative to the bulk mantle but this does not stop it from being recycled at subduction zones. Thus, to fully explore the idea that the buoyancy and/or viscosity of cratonic roots is indeed what gives them longevity, one must consider the question of how buoyant and/or how viscous roots must be in order to resist being pulled into the mantle at a subduction zone. It is of course possible that cratons simply avoid regions of mantle downflow but if this is the case then the longevity of cratonic lithosphere is not principally tied to its material properties. While we acknowledge this possibility, and indeed explore it later in this paper, we begin by exploring the more prevalent idea that the material properties of cratonic lithosphere are somehow the fundamental keys to root longevity.

To explore the specific material properties that can allow for cratonic root longevity we have undertaken a suite of numerical simulations that send a model continent, with a cratonic root, into a subduction zone environment. As well as deep lithospheric longevity, the models are also used to address the related question of what provides for the tectonic stability of cratonic crust. The modeling approach and numerical solution techniques are first described. Simulation results that vary key parameters such as root buoyancy and viscosity and then discussed.

Modeling Approach and Numerical Methods

Our modeling approach is best introduced by considering a prototype simulation near its initial start time. The top frame of Figure 1 serves this purpose. A chemically distinct continent resides within the upper thermal boundary layer of a convecting mantle layer. Three chemically unique materials are present: Continental crust, subcrustal continental mantle lithosphere, and bulk mantle. All materials have unique reference densities with different values implying different degrees of chemical buoyancy. The vigor of thermal convection depends on a bottom heating Rayleigh number, Ra, and a heat ratio, H, which parameterizes the ratio of internal to bottom heating. Boundary conditions are free-slip and isothermal for upper and lower surfaces. A wraparound boundary condition is used for vertical side walls to remove artificial edge boundary effects. The initial thermal field is obtained by running a simulation with a non-deformable continent for several convective overturn times. This leads to a thicker thermal boundary layer in continental versus oceanic regions and a continental thermal boundary layer that is locally thicker than the continental chemical boundary layer across a continents extent, as must be the case if the system is at or near thermal equilibrium. Running a simulation with a non-deformable continent, in order to obtain an initial thermal field, is required in order to minimize transient start up effects that can result if simulations with deformable continents were to be started with far from thermal equilibrium conditions.

The presence of a chemically distinct continent in Figure 1 is only one of the minimum model requirements for the problem we wish to address. Another is that we must allow oceanic lithosphere to participate in convective overturn despite having, an on average, high viscosity due to cool temperature. This requirement comes from the fact that we would like to explore the potential that high root viscosity may lead to its longevity but we must also self-consistently account for the efficient subduction of high viscosity, oceanic lithosphere. If we do not do this we run the risk of having models "achieve" cratonic root longevity at the implicit expense of sacrificing plate tectonics.

The self-consistent incorporation of lithospheric subduction and plate-like behavior into mantle convection models has experienced a recent surge [e.g., *Moresi and Solomatov*, 1998; *Tackley*, 1998; *Trompert and Hansen*, 1998]. These recent modeling studies are all based on a simple idea: Localized lithospheric failure beyond a critical stress level leads to the formation of weak faults or shear zones that allow otherwise cold and strong lithosphere to participate in convective mantle overturn. Our modeling approach follows this trend by incorporating a rheologic formulation akin to that used by *Moresi and Solomatov* [1998]. The rheology law remains on a temperature-dependent viscous branch for stresses below a specified yield stress. For stresses above the yield stress, the flow law switches to a depth-dependent plastic branch. The yield criteria and the form of the plastic flow law is based on a continuum representation of Byerlee's frictional law [*Byerlee*, 1968] and, in this sense, the plastic branch parameterizes brittle behavior within the lithosphere. The approach of *Moresi and Solomatov* [1998] has been extended to allow for a variable component of added weakening along the plastic branch, a factor that has been found to be important for generating plate-like behavior in mantle convection models [*Bercovici*, 1996; *Tackley*, 1998]. After a material fails, its yield stress decreases as a linear function of accumulated strain. The degree of added weakening is a variable that is expressed as a percentage (e.g., a value of 0.5 indicates that post-yield weakening can lower a materials initial strength by, at most, fifty percent).

The general rheologic formulation above is applied to each chemical component but specific rheologic parameters can vary between components. These parameters are: 1) The cohesion term which sets the surface value of the material yield curve, 2) The effective friction coefficient which sets the depth-dependent slope of the yield curve, 3) The maximum amount of post yield weakening, 4) The pre-exponential term in the temperature-depenendent viscosity law, and 5) The activation term of the temperature-depenendent viscosity law.

Material yielding in Figure 1 is indicated by bright white zones that are marked as "failed" just above above the top frame. The location of yielding in the top frame of Figure 1 reflects a key aspect of our modeling approach. After the non-deformable continent simulation had reached a statistically steady state, we monitored the simulation and stopped it at a point when the continent was just moving into an incipient subduction zone. At this point the assumption of a rigid continent was relaxed, a model continent was given varied material parameters, and the simulation was allowed to continue. The philosophy is to determine the physical conditions that can make cratonic lithosphere unsubductable. As noted in the introduction, if it is truly the material properties of cratonic lithosphere that provide it with stability and longevity then, unlike oceanic lithosphere and non cratonic continental lithosphere, it must be able to resist subduction induced deformation and recycling. We do also acknowledge the potential that cratons may be shielded from subduction stresses and we will explore this. The approach is to first consider the more commonly held idea that the properties of cratonic lithosphere make it unsubductable and provide for its stability. From there we will move to more complex models that explore how cratons may be removed from subduction induced stresses. The reason such models become more complex is that they inherently assume that the material properties of cratonic lithosphere are not the sole physical factors leading to stability. From a modeling standpoint, added physical factors mean added parameter effects working together which makes for a more complex model.

One other point is worth noting in regard to the implications of our approach. In considering root stability in relation to subduction forces to be the key issue we are, in effect, a priori granting that a cratonic lithospheric column can be, and likely is, neutrally buoyant relative to a reference asthenospheric column [*Jordon*, 1975; 1978]. That is, we do not explore the idea that the density structure of cratonic lithosphere, relative to the asthenosphere, can cause it to sink into the mantle under its own weight (i.e., a Rayliegh-Taylor type instability). There is much petrologic evidence suggesting that the buoyancy of cratonic lithosphere makes it stable against spontaneous gravitational sinking into a static mantle [e.g., *Poudjom Djomani et al.*, 2001]. We take this evidence as valid and move directly to the issue of craton stability in a dynamic mantle.

The numerical solution strategy is based on a particle-in-cell finite element methodology that allows for the tracking of an arbitrary number of materials with unique physical properties [*Sulsky et. al.*, 1995; *Sulsky and Schreyer*, 1996]. The approach has been extended to model localized shear band formation and to be able to deal with the large strains associated with mantle convection [*Moresi et al.*, 2000]. A large number of material points are embedded in the standard finite element mesh of the CITCOM finite element code [*Moresi and Solomatov*, 1995]. The material points form a Lagrangian reference frame which remains attached to the fluid as it moves. The finite element mesh remains undeformed. The link between the Eulerian reference frame of the mesh and that of the particles is through the finite element integration scheme: The particles in a given element serve as the integration points of the element integration scheme. That is, they replace the standard fixed Gauss points generally used in finite element formulations. ***
**LOUIS - ADD MORE AS YOU SEE FIT OR ADD AN APPENDIX IF YOU LIKE **
****

We have tested the finite element code against standard thermal mantle convection benchmark problems [*Blankenbach et al.*, 1989] and against thermal-chemical benchmark problems [*van Keken et al.*, 1997] with good results. We also performed convergence tests for our specific cratonic stability problem. Three different mesh densities where used for convergence testing: a 32x160 element mesh, a 48x240 mesh, and a 64x320 mesh (the domain aspect ratio being fixed at five). Based on tracking the Nusselt number, the rms velocity, and the extent of a cratonic root (see below), we could determine that mesh errors on the intermediate mesh are not in excess of 5-7 % for a particle density of at least 9 material points per element.

Numerical Simulations

The large parameter space available to our model system has lead us to focus on the effects of continental buoyancy parameters and on the effects of rheologic parameters. We have fixed the parameters that define the vigor of thermal convection in the mantle to constant values. For all simulations, $H = 1$ and $Ra = 2 \times 10^7$, based on the viscosity at the system base. For a convecting layer depth of 670 km, a driving temperature drop of 2000 K, and standard mantle thermal properties [*Turcotte and Schubert*, 1982], this implies an average viscosity of $\approx 10^{20}$ Pa s within the bulk interior of the mantle. The choice of upper mantle convection and a relatively low internal mantle viscosity is justified for the problem at hand as the longevity of cratonic roots means we must consider not only present day conditions but also past conditions when convection was more vigorous. Under such conditions the potential of mantle layering increases [*Christensen and Yuen*, 1985] and the interior viscosity of the mantle decreases [*Tozer*, 1972].

The modeling domain size (dimensional values: 670 Km depth by 3350 Km width), the reference density of mantle material (3300 kg/m^3), the initial extent of a continent (1340 km), boundary conditions, and initial conditions also remain constant for all simulations discussed. Finally, the temperature-dependent viscosity law used for all components allows for a factor of 10^5 viscosity variation from the maximum to the minimum system temperature. As the thermal Rayleigh number of the mantle is fixed, this implies that the pre-exponential term in the mantle's temperature-dependent viscosity law is also fixed (the dimensional mantle viscosity at the surface is $\approx 10^{24}$ Pa s). The effects of intrinsic viscosity variations between chemical components are explored by varying the pre-exponential term in the temperature-dependent viscosity laws. This allows us to set the viscosity of root material, for example, to be higher than mantle material at equivalent temperatures.

We performed over 100 numerical simulations to map a significant region of parameter space. Results are discussed in subsections. The first three focus on the effects of buoyancy, viscosity, and yield-stress parameters. Buoyancy parameters are the reference densities of crust and root material and their relative initial depths. Viscosity parameters are the pre-exponential constants in the temperature-dependent viscosity laws associated with each chemical component. Yield-stress parameters are the cohesion, effective friction coefficient, and post yield weakening factor associated with the plastic deformation branch of each chemical component. The forth subsection discusses the effects of allowing for lateral strength variations within a model continent. This introduces added chemical components that represent non-cratonic crust and non-cratonic subcrustal lithosphere. Varying the rheologic parameters of these added components relative to cratonic components leads to strength variations across a model continent. The final subsection discusses how the stability and longevity of cratonic lithosphere may depend on combinations of mutually active parameter effects.

The launching point for all the parameter variation subsets is a prototype simulation with nominal parameter values (Figure 1). For this prototype simulation, the reference densities of the crust and subcrustal cratonic lithosphere are set to 2800 and 3200 kg/m^3, respectively. The initial thicknesses of the chemically distinct cratonic lithosphere and of the cratonic crust are 180 and 40 km, respectively. The viscous behavior of the mantle is determined by an exponential temperature-dependent flow law [*Solomatov and Moresi*, 1995] that allows for a factor of 10^5 viscosity variation. The mantle viscosity at the system base is $10^1$9 Pas. The yielding behavior of the mantle is determined by setting the cohesion term in the plastic flow law to 10 MPa, the effective friction coefficient to 0.1, and the post yield weakening factor to 0.5. The rheology of cratonic root material is considered equivalent to that of the mantle. The same is true for cratonic crust except that its viscosity is an order of magnitude lower than mantle at equivalent temperature. The yield properties of the crust remain the same as those of the mantle. The choice of these values is simply to provide for a reasonable reference case. The effects of varying each parameter values will be explored in turn as will the effects of varying several parameters in unison.

Although, as noted, all parameters will be varied, a word or two should be said about our choice for the nominal friction coefficient value. The choice is driven by the fact that the simulations must allow for plate-like behavior and subduction of oceanic lithosphere if they are to fully address the problem at hand. In their study of plate generation in a convecting mantle layer, *Moresi and Solomatov* [1998] found that an effective friction coefficient between 0.03-0.13 allowed for plate-like behavior and associated lithospheric subduction. As discussed in *Moresi and Solomatov* [1998] this value, although low relative to laboratory values, is consistent with seismic field studies, with the lack of heat flow anomalies associated with major faults, and with effective fault friction values deduced from studies of trench topography. The value is also not unphysical as it can result from the development of a fault gouge layer or through pore fluid pressure effects. This issue will be taken up again in the sub-section that explores the effects of yield parameters.

To present parameter sweep results in a condensed and easily understandable form we must define a measure of cratonic longevity and stability. The normalized lateral extent of a cratonic root serves as an effective measure. In all simulations the lateral extent of a cratonic root is tracked. The extent is defined by considering a point within the center of the craton at a depth just below the cratonic crust. From this point, the horizontal distance to the left and the right over which cratonic root material extends coherently is used to define root extent. If root material is recycled into the mantle this extent decreases. If a root is deformed to the point that it splits in two the extent also decreases. Plotting this measure versus various model parameters is one methods we use to present our results. Image plots, showing the evolution of representative simulations from the various parameter sets explored, are also used.

Buoyancy Parameters

Figure 1 shows a prototype simulation. The buoyancy structure of cratonic lithosphere can be varied by varying the crustal density, the subcrustal cratonic lithosphere density, the crustal thickness, and/or the thickness of the chemically distinct lithosphere. We first discuss the dynamic behavior of the prototype simulation and then discuss how variations in the four buoyancy parameters effect the system dynamics. It should be noted that in the protoype simulation the integrated buoyancy of a column of cratonic lithosphere is already greater than the integrated buoyancy of an equivalent thickness column of mantle at an average interior system temperature. That is, a cratonic lithosphere as a whole is buoyant relative to asthenosphere.

As the model craton moves toward the subduction zone, slab induced stresses are sufficient to cause failure zones to form within the cratonic lithosphere. The second evolution frame shows that this failure generates detachment surfaces near the base of the crust which allow the sub-crustal cratonic lithosphere to become decoupled from the crust above. A key effect is that the high chemical buoyancy of the crust can not contribute to the preservation of subcrustal lithosphere. Instead the subcrustal cratonic lithosphere is subducted in manner reminiscent of the A-type subduction discussed by *Bally* [19xx] and subsequently taken up in models of doubly-vergent orogen formation [e.g., *Willet et al.*, 1993].

Figure 2 shows the effects of increasing the chemical buoyancy of cratonic root material. The reference density of root material in the simulation of Figure 2 is 3100 kg/m^3. Raising the root buoyancy does lead to significant changes in the exact manner by which root material is recycled into the convecting mantle but it does not change the fact that it is recycled. Root recycling is no longer as coherent as it was in the simulation of Figure 1. It now involves the root being stretched and split into smaller bits that are then pulled into the mantle by cold subducting slabs. The simulation shows that the integrated buoyancy of a blob of root material, relative to the integrated buoyancy of cold subducting mantle, is key to determining if a blob will be recycled which is in accord with theoretical considerations of root recycling in zones of dynamic mantle downflow [*Lenardic and Moresi*, 1999].

Figure 3a plots the normalized root extent at different times from several simulations with variable reference densities of root material and variable root depths. Results are plotted in terms of a buoyancy ratio. The ratio provides a measure of chemical relative to thermal buoyancy forces. It is defined as the chemical density difference between a reference element of root material and mantle material divided by the thermal density difference between a reference element of mantle material at the coldest and hottest system temperature. As it contains no length scale, it does not adequately characterize the integrated relative buoyancy of a root. The amount of root material is also required. As the initial crustal depth is 40 Km for all the simulations in Figure 3a, the initial root depth provides this information. The advantage of using a buoyancy ratio versus a reference chemical root density for plotting purposes is that it contains information about thermal and chemical buoyancy. For those who find no advantage to this, we note that in Figure 3 a buoyancy ratio of 0.5 corresponds to a reference density of 3200 kg/m^3 for root material while a ratio of 1.0 corresponds to a root density of 3100 kg/m^3. This last value is greater than upper bound, geochemically based, estimates of root density [e.g., *Poudjom Djomani et al.*, 2001]. In short, Figure 3a suggests that the chemical buoyancy of root material is insufficient to provide for the stability of cratonic crust and/or the longevity of cratonic roots. This is not to say that root material is not chemically buoyant relative to reference mantle or that it can not partially contribute to stability and longevity. The simulations simply suggest that it is likely not the principal physical factor at work.

Viscosity Parameters

Figure 3b shows the effects of varying intrinsic crustal and root viscosity parameters from the nominal simulation values. The most obvious viscosity parameter that could provide for root longevity is the intrinsic viscosity of root material relative to the convecting mantle. Figure 4 shows the evolution of a simulation that sets the viscosity of root material to be 1000 times that of the mantle at equivalent temperature. This is at the upper-end of rheologically based estimates of how much more viscous a cratonic root could be relative to the mantle due to dehydrated conditions [*Hirth and Kohlstedt*, 1996]. It should be noted that the initial conditions of the simulations lead to a lower geothermal gradient in the cratonic, relative to the oceanic, lithosphere. The temperature-dependence of material viscosity means that this has the effect of providing a higher viscosity for cratonic lithosphere relative to bulk mantle. The simulations of the previous section showed that this temperature-dependent effect was not sufficient to provide for root longevity. This is why we now explore the effects of also introducing chemically driven viscosity variations.

Increasing the intrinsic viscosity of root material means that the brittle behavior can occur at greater depths within the root. This is because the rheologic behavior, brittle versus ductile, of a material at any depth is determined by the condition that stress be minimized. At the start of the simulation of Figure 4, large stresses near the left continent margin cause failure within the oceanic lithosphere and within the upper portion of the cratonic lithosphere. As the simulation evolves, a failure zone propagates through the entire cratonic lithosphere near its left most margin. This failure zone "slices off" a portion of the sub-crustal lithosphere. The sliced off block of cratonic lithosphere is relatively thin in lateral extent and is entrained into the deeper mantle by the subducting slab of cold bulk mantle. As the model continent moves leftward toward the subduction zone, large stresses continue to be generated near the craton margin due to the subducting slab centered below it. This causes further failure of the craton lithosphere and allows added portions of it to be recycled into the deeper mantle. Over time subsection ceases at the left continental margin and initiates to the right of the continent in the model oceanic region. The mantle flow that results eventually pulls the continent toward the subduction zone and cratonic recycling commences at the right continental margin as it enters into the region of subduction.

The simulation of Figure 4 points out that if the chemical components that make up the lithosphere can fail in a brittle mode then the viscosity of deep root material alone is not what determines its strength. Increasing root viscosity can amplify stress levels within the lithosphere and if the lithosphere can only maintain a fixed stress level before it fails than recycling can still occur. Figure 3b further quantifies this. It also shows that the viscosity of the lower crust can effect root longevity. A low viscosity lower crust promotes detachment at the crust-mantle interface which removes the potential effects of crustal buoyancy on lithospheric preservation. The main message of these simulations however is the one previously noted, for the rheologic formulation employed, lithospheric strength does not equate solely to the ductile properties of the deep lithosphere. That is, the brittle yielding properties of the crust and mantle lithosphere must also be considered. The simulations of the next subsection explore this avenue.

Yield Parameters

Figure 5a shows the effects of varying the effective friction coefficient for all chemical components in unison. Once the value exceeds 0.15 a cratonic root can become long-lived. However, this is deceptive as what is happening is that the entire system has moved to a stagnant-lid mode of convection [*Moresi and Solomatov*, 1998]. This can be seen in Figure 5b which shows that once the effective friction coefficient globally exceeds 0.15 the surface velocity of the entire system effectively goes to zero. That is, the simulations no longer allow for subduction of oceanic lithosphere but rather come to mimic a single plate planet. This is clearly not a satisfying way to account for cratonic stability.

A more satisfying avenue involves varying the effective friction coefficient of cratonic components while leaving the mantle value at a level that allows for subduction of oceanic lithosphere. Figure 6 and 7a show the results from several simulations that do just that. The ratio of the effective friction coefficient of cratonic relative to mantle components is termed a yield ratio. The friction coefficient determines the slope of the brittle yield curve and thus the maximum stress level the lithosphere can withstand. Thus as the yield ratio increases, cratonic components can withstand higher and higher levels of stress.

The image plots of Figure 6 show the importance of having a high effective friction coefficient value for both the crustal and mantle component of cratonic lithosphere. Cases in which only the mantle component is assigned a higher friction coefficient still allow for the formation of detachment surfaces within the lower crust. This promotes recycling of cratonic root material as it decouples the crust, and its high degree of buoyancy, from subcrustal lithosphere. Such cases also allow continental rifting to occur. If only the mantle component has a higher friction coefficient than the thickness of the high strength layer in the lithosphere will be lower than if both crust and mantle components can withstand higher degrees of stress. A thinner high strength layer tends to promote stress focusing which in turn favors rifting [e.g., *Kusznir and Bott*, 1977]. The considerations above also hold true if only the crustal component of a craton is assigned a higher friction coefficient (this was confirmed by running added simulations). An enhanced rifting potential does not favor tectonic stability and it also mean that cratonic roots can be broken into smaller bits and, as noted in the buoyancy parameter section, this allows for enhanced recycling of root material. Thus, a relatively high friction coefficient for both the mantle and crustal component of cratonic lithosphere does appear to be required for tectonic stability and root longevity (Figure 7a).

Increasing the cohesion term of the brittle yield curve had a qualitatively similar effect to increasing the friction coefficient in that it also increased the maximum stress level a chemical component could withstand. Quantitatively, the effect was not as great. That is, whereas increasing the friction coefficient of cratonic components by only a factor of two lead to pronounced changes for craton stability (Figure 7a), a greater increase in the cohesion term was required. This is not surprising as increasing the cohesion term by some increment increases the maximum yield stress by the same increment but the same is not true for increases in the friction coefficient. As the friction coefficient sets the slope of the yield curve increasing it by some increment has a greater effect on the maximum yield stress.

The effects of varying the post yield weakening factor are shown in Figure 7b. For the simulations represented the weakening factor was adjusted for all chemical components in unison. An enhanced post yield weakening factor tended to cause a spatial focusing of yielding zones and it also tended to cause a temporal stabilization of the yielded zones. That is, any given failure zone that formed in some region of the domain became longer lived within that region. More specifically, once failed regions formed at the edge of a craton they tended to be longer lived at the edge as opposed to migrating deeper into the craton. The stabilization effect was not large and we are limited as to how much post yield weakening we can allow for as values beyond those used would focus failure zones to the point that we could not resolve them numerically. Figure 7b does, however, suggest an intriguing possibility in that a more pronounced history-dependent effect, which would tend to keep once failed regions weak for a longer stretch of time, might act to enhance craton stability. We have not explored this specifically as our formulation at present does not allow for true history-dependent effects. The next subsection does, however, explore an indirect history effect by considering the potential role of preexisting weakness within continents.

Mobile Belt Parameters

Geologists have long known that long-lived lateral strength heterogeneities within continents can have a profound influence on patterns of tectonic deformation [e.g., *Smith and Mosley*, 1993]. Cratonic lithosphere is seen by most workers as anomolously strong relative to reference mantle which is why most proposed mechanism for craton stability have focused on the properties of cratonic lithosphere itself. What has gone less appreciated, in discussions of craton stability and root longevity, is the fact that the pervasively deformed continental regions that border many cratons may well be anomolously weak [e.g., *Ring*, 1994]. These mobile belt regions have experienced episodes of tectonic activation and re-activation over their lifetimes suggesting that their inherited weakness may also be relatively long-lived. The influence of long-lived continental weak zones on rifting has been addressed [*Vink et al.*, 1984; *Dunbar and Sawer*, 1989; *Vauchez et al.*, 1997] and the role of long-lived weak zones for issues of global mantle convection is coming to be appreciated [e.g., *Gurnis et al.*, 1999]. The role of long-lived weak zones for issues of craton stabilization and root longevity has, however, received little if any attention. This motivates the simulations of this subsection.

To model the effects of peripheral weak zones on craton stability we must introduce added chemical components to our simulations. These new components will represent mobile belt crust and subcrustal mantle lithosphere. To limit parameter space we will consider these components to be equivalent to their cratonic counterparts in terms of density and initial thickness but to differ in terms of rheologic parameters. The previous subsections showed that, of the available rheologic parameters, variations of the effective friction coefficient had the greatest relative effect on craton stability and root longevity. Given this, we will focus on the effects of varying the effective friction coefficient for mobile belt, relative to cratonic and reference mantle, components.

Figure 8 shows the evolution of a mobile belt simulation. The friction coefficient of bulk mantle and cratonic components is set to the nominal value of 0.1. The effective friction coefficient of mobile belt components is varied between simulations. This allows the effects of weak mobile belts to be isolated. Once this has been done we can move on to mixed effect simulations in which cratonic components have a high friction coefficient relative to bulk mantle while mobile belt components have a relatively low value. An analogy exists between the weak mobile belts of our simulations and the crumple zones of an automobile which buffer its cab and passengers from collisional forces. Thus, for brevity, we will refer to the ratio of the friction coefficients between mobile belt and cratonic components as a crumple/craton yield ratio. A value of less than one will, in effect, provides cratons with peripheral crumple zones that can fail at relatively low stress.

In the simulation of Figure 8, lithospheric failure again allows subduction to initiates at the left continental margin. The positive chemical buoyancy of mobile belt lithosphere can not overcome the negative thermal buoyancy of the subducting slab and portions of the continental lithosphere are recycled at the subduction site just as they were for the nominal parameter case simulation (Figure 1). The mobile belt simulation differs from the nominal case in that continental recycling, driven by subduction, does not proceed as deeply into the continent. Rather, recycling proceeds only until the locus of subduction comes into contact with the mobile belt/craton boundary (Figure 8). Stresses then concentrated at the right continental margin and, as the simulation was allowed to proceed, the right margin became the site of a new subduction zone.

The driving force in the simulations of Figures 1 and 8 is the negative thermal buoyancy of cold, convectively unstable mantle, i.e., slabs. The simulations are also similar in that the maximum stress levels the lithosphere can withstand are limited by the yield stress of any lithospheric section. The key difference is that preexisting, lateral yield stress variations exist within the simulation of Figure 8. In the simulation of Figure 8 the same buoyancy force drives the initial recycling of oceanic and continental lithosphere but the stress level in the oceanic lithosphere is higher than that in mobile belt continental lithosphere due to differences in the effective friction coefficients between chemical components. In the simulation of Figure 1, oceanic and continental lithosphere experienced the same stress levels as they came into contact with a subducting slab. The relatively low friction coefficient of mobile belt components in the simulation of Figure 8 means that the maximum stress that the mobile belt lithosphere can maintain is lower than the stress required to cause failure in the cratonic lithosphere. Although cratonic lithosphere does feel the force of the sinking slab once it comes near a subduction zone, the fact that slab induced stresses are transmitted to it by the weak mobile belt lithosphere means that it does not experience stress levels in excess of its yield stress. Thus, the failure surfaces associated with lithospheric recycling do not form within the cratonic lithosphere over the evolution time shown in Figure 8.

The effects of mobile belts are further quantified in Figure 9. Figure 9a shows that root longevity increases dramatically once a critical mobile belt to craton yield ratio is exceeded, with the critical value itself depending on mobile belt extent. Figure 9b further shows the strong effect mobile belt extent can have on root longevity. Over longer time scales than those shown, cratons did rift which caused portions to be exposed to oceanic mantle. Once subduction initiated at these newly formed continental margins cratonic lithosphere was relatively easily recycled as it now had no peripheral crumple zone to buffer it. This suggests that either a mechanism for buffer zone regeneration needs to be included into the simulations if they are to preserve cratonic lithosphere over a time scale of 10^9 years or other craton stabilizing effects must operate mutually with the crumple zone effect. The next subsection explores the mutual operation of several craton stabilization mechanisms.

Mixed Parameter Effects

A number of simulations have been performed that combine several or all of the parameter effects discussed above. Figure 10 shows the evolution of a mixed parameter effect model that does a particularly good job in preserving deep cratonic lithosphere and maintaining tectonic stability of the crust above. The simulation is among our preferred ones in that it also does not involve extreme values of any one parameter. The reference density of root material is within the range of geochemical estimates [*Poudjom Djomani et al.*, 2001]. The intrinsic viscosity of root material is only a factor of 10 greater than reference mantle which is within the range of rheologic estimates [*Hirth and Kohlstedt*, 1996]. The effective friction coefficient of cratonic and mobile belt components is, respectively, a factor of two greater and a factor of two less than reference mantle. These variations can be accounted for by reasonable variations in pore fluid pressures [].

The simulation of Figure 10 spans several mantle overturn times. Mobile belt mantle lithosphere is almost completely recycled into the deeper mantle save for small portions that remain attached to the craton peripheries. Sections of the mobile belt crust are also rifted from the craton but significant portions do also remain attached to the craton peripheries as well. Thus, at the final evolution time shown the craton does maintain peripheral weak zones. To explore whether the weak zones, for this mixed effect simulation, did have a nontrivial role we explored a similar simulation that starts with a craton exposed to a subduction zone (Figure 11). In this case, the cratonic crust is deformed and portions of the deeper cratonic lithosphere are recycled.

We also ran additional variations for the mixed effect case of Figure 10 to further gauge the relative roles of specific parameter effects. The dominant effect was the relatively high effective friction coefficient of cratonic crust and mantle lithosphere. Embedding the craton deeper into a continent could add to cratonic stability and longevity, as shown in Figure 11, as could providing cratonic roots with a higher viscosity and/or buoyancy but these effects alone or in tandem could not fully provide for stability and longevity within the parameter ranges explored within the previous subsections for any effect of its own. Allowing the effective friction coefficient of both cratonic crust and mantle lithosphere to be a factor of 4-5 greater than reference mantle could, on the other hand, provide for craton stability and longevity independent of the other parameter effects. The other parameter effects could lower the relative effective friction coefficient increase required for cratonic components but, as already noted, they could not remove the need for the increase itself within the simulation set explored.

Discussion

Any theory related to cratonic lithosphere must account for: 1) Geologic evidence that cratonic crust can remain tectonically stable for on the order of a billion years []; 2) Seismic evidence that cratonic lithosphere is relatively thick at present []; and 3) Geochemical evidence that the lithosphere below several cratons has remained thick for on the order of a billion years []. Evidence that the mantle component of cratonic lithosphere is chemically buoyant compared to asthenospheric mantle [] has driven the most popular theory in regard to just what it is that makes a craton a craton. The theory holds that the deep lithosphere below a craton, i.e., a cratonic root, is chemically buoyant which allows it to resist being recycled into the mantle and that this sub-crustal, lithospheric preservation has a stabilizing effect on the cratonic crust above [e.g., Sengor, 1999]. Although attractive, the logical progression leading to this theory should be kept in mind. It is based on the following chain of reasoning: a) There is evidence that cratonic crust is stable and that cratonic roots are long lived, and (b) There is evidence that root material is chemically buoyant relative to reference mantle, therefor (c) It is the chemical buoyancy of a root that is providing for its longevity and this, in turn, provides for crustal stability. It is not a logical necessity that the physical factor identified in (b) is what leads to the observations contained in (a). However, this is arguably the simplest possibility and, as such, the one to quantitatively explore first.

Such explorations began almost as early as the first suggestions that deep cratonic lithosphere is petrologically unique [*Jordon*, 1975; 1978]. Early arguments where of a one-dimensional nature. The integrated density of a cratonic lithospheric column was compared to that of a column of reference asthenosphere, using the available petrologic evidence of the day to constrain lithospheric composition and surface heat flow to constrain thermal profiles. In effect, the arguments where of isostatic type. Although petrologic evidence has increased, these types of arguments have remained the prevalent ones to this day for quantifying whether the chemical makeup of deep cratonic lithosphere can protect it against mantle recycling [e.g., *Poudjom Djomani et al.*, 2001; *Lee et al.*, 2001]. The general result, from the earliest to the most recent, of such density calculations has been that the chemical makeup of a cratonic lithospheric column does make it buoyant relative to the asthenosphere. From this, it is often concluded that it is the chemical buoyancy of cratonic lithosphere that makes a craton a craton. This is not as straightforward as it may seem.

Efforts of the type above begin with a major premise: A lithospheric column that is buoyant relative to a reference asthenospheric column will be long-lived and stable as a whole. From there, 1-D buoyancy arguments are used to show that, based on petrological estimates as to composition, cratonic lithospheric columns are buoyant relative to a reference asthenospheric column. This, together with the fact that added petrological evidence shows that the lithosphere below many cratons is long-lived, forms the minor premise. The conclusion that follows is that lithospheric buoyancy is what provides for the longevity and stability of cratonic lithosphere. This deductive reasoning simply brings out something already present in the major premise. This does not weaken the argument unless the premise is just as questionable as the conclusion. In that case, one is just "begging the question".

The major premise above does beg several questions. It assumes a priori that a cratonic column remains coherent, it does not account for lateral dimensions at all, and it only considers recycling due to the sinking of a cratonic column into the mantle under its own weight. The numerical simulations of this paper contain their own assumptions, but, within the confines of these assumptions, they suggest this major premise noted above is not valid. Even if a cratonic root is composed of material that is chemically buoyant relative to reference mantle this can not preserve large portions of it from being recycled in subduction zone settings. Chemical buoyancy can not prevent a root from being rifted into smaller and smaller pieces nor can it prevent root material from detaching from the crust above. The simulations of this paper show that accounting for the potential of lithospheric detachment and the effects of lateral root extent significantly decreases the survival potential of cratonic roots relative to what would be inferred from isostatic buoyancy arguments. In short, the simulations suggest that the chemical buoyancy of deep cratonic lithosphere is not the key factor that makes a craton a craton.

This conclusion is not entirely new. There have been previous numerical simulation studies that have explored cratonic root longevity in a dynamic context [*Shapiro*, 1995; et al., 1997]. These studies differ from our own in the specific manner by which they model the dynamics of mantle convection. None the less, pointing out the problems associated with explaining cratonic stability and root longevity solely through the buoyancy of cratonic roots is a common conclusion [*Shapiro*, 1995; et al., 1997]. Indeed, it was anticipated some time ago that root buoyancy was likely not the key factor to stability and longevity but that a high root viscosity was [*Pollack*, 1986]. More specifically, that an intrinsically high viscosity, due to dehydrated conditions, was key to stabilizing cratonic lithosphere as opposed to simply a high viscosity driven by cool conditions within cratons.

Dry conditions within deep cratonic lithosphere, relative to reference mantle, can ideed increase the viscosity of cratonic roots [*Hirth and Kohlstedt*, 1996]. However, this does not guarantee root stability and longevity. Even if we assume that the purely viscous behavior of root material is the only rheologic response that need be considered, there is the issue of just how great a viscosity increase is required [*Manga and O'Connell*, 1995; *Lenardic and Moresi*, 1999]. More problematic and more in line with our modeling philosophy, the rheologic response of the lithosphere also depends on its brittle properties. Just as a high ductile viscosity for oceanic lithosphere can not prevent it from being recycled within a convecting mantle if brittle behavior is considered [*Moresi and Solomatov*, 1998] so to the brittle properties of cratonic lithosphere could well offset the effects of any intrinsic increase of deep root viscosity.

BlahBlahBlah

Whats our preferred story based on simulation results How can we test it using observations What does all this mean for the big picture Whats the next step

Conclusions

What have we learned

Acknowledgments. Supported by NSF Grant EAR-0001029.

References

Bickle, M.J., Implications of melting for stabilization of the lithosphere and heat loss in the Archean, *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., Compositional distinction between oceanic and cratonic lithosphere, *Earth Planet. Sci. Lett., , 96,* 15-26, 1989.

Boyd, F.R., J.J. Gurney, and S.H. Richardson, Evidence for a 150-200 km thick Archean lithosphere from diamond inclusion thermobarometry, *Nature, 315,* 387-389, 1985.

de Smet, J.H., A.P. van den Berg, and N.J. Vlaar, Stability and growth of continental shields in mantle convection models including recurrent melt production, *Tectonophysics, 296,* 15-29, 1998.

Doin, M.-P., L. Fleitout, and U. Christensen, Mantle convection and the stability of depleted and undepleted continental lithosphere, *J. Geophys. Res., , 102,* 2771-2787, 1997.

Dunbar, J.A., and D.S. Sawyer, How preexisting weaknesses control the style of continental breakup, *J. Geophys. Res., 94,* 7278-7292, 1989.

Gurnis, M., S. Zhong, and J. Toth, On the competing roles of fault reactivation and brittle failure in generating plate tectonics from mantle convection, in *The History and Dynamics of Global Plate Motions,* M.A. Richards, R. Gordon, and R. van der Hilst (editors), American Geophysical Union, Washington D.C., in press, 1999.

Hirth, G., and D.L. Kohlstedt, Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere, *Earth Planet. Sci. Lett., , 144,* 93-108, 1996.

Houseman G.A., and P. Molnar, Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere, *Geophys. J. Int., 128,* 125-150, 199

Jordan, T.H., Composition and development of the continental tectosphere, *Nature, 274,* 544-548, 1978.

Kusznir, N.J., and M.H.P. Bott, Stress concentration in the upper lithosphere caused by underlying visco-elastic creep, T̂ectonophysics, 43, 247-256, 1977.

Lee, C.-T., Q. Yin, R.L. Rubnick, and S.B. Jacobsen, Preservation of ancient and fertile lithospheric mantle beneath the soutwestern United States, *Nature,* in press, 2001.

Lenardic, A., and L.-N. Moresi, Some thoughts on the stability of cratonic lithosphere: Effects of buoyancy and viscosity, *J. Geophys. Res., , 104,* 12,747-12,758, 1999.

Manga, M., and R.J. O'Connell, The tectosphere and postglacial rebound, *Geophys. Res. Lett., , 22,* 1949-1952, 1995.

Moresi, L.-N., and V.S. Solomatov, Mantle convection with a brittle lithosphere: Thoughts on the global styles of the Earth and Venus, *Geophys. J. Int., 133,* 669-682, 1998.

Pollack, H.N., Cratonization and thermal evolution of the mantle, *Earth Planet. Sci. Lett., , 80,* 175-182, 1986.

Ring, U., The influence of preexisting structure on the evolution of the Cenozoic Malawi rift (East African rift system), *Tectonics, 13*, 313-326, 1994.

Sengor, A.M.C., Continental interiors and cratons: any relation ?, *Tectonophysics, 305,* 1-42, 1999.

Shapiro, T.H., Structure and dynamics of the continental tectosphere, Ph.D. thesis, Mass. Inst. of Technol., Cambridge, 1995.

Smith, M., and P. Mosley, Crustal heterogeneity and basement influence on the development of the Kenya rift, East Africa, *Tectonics, 12*, 591-606, 1993.

Tao, W.C., and R.J. O'Connell, Ablative subduction: A two-sided alternative to the conventional subduction model, *J. Geophys. Res., , 97,* 8877-8904, 1992.

Vauchez, A., G. Barruol, and A. Tommasi, Why do continents break-up parallel to ancient orogenic belts ?, *Terra Nova, 9,* 62-66, 1997.

Vink, G.E., W. J. Morgan, and W.-L. Zhao, Preferential rifting of continents: a source of displaced terranes, *J. Geophys. Res., 89,* 10,072-10,076, 1984.

Willet, S., C. Beaumont, and P. Fullsack, Mechanical model for the tectonics of doubly vergent compressional orogens, *Geology, 21,* 371-374, 1993.

A. Lenardic, Department of Earth Science - MS 126, P.O. Box 1892, Rice University, Houston, TX 77251-1892. (adrian@geophysics.rice.edu)

L.-N. Moresi, CSIRO Exploration and Mining, PO Box 437, 39 Fairway, Nedlands, 6009 Western Australia, Australia. (louis@ned.dem.csiro.au)

H. Mühlhaus, CSIRO Exploration and Mining, PO Box 437, Nedlands, 6009 Western Australia, Australia. (hans@ned.dem.csiro.au)

Received
, 2001; accepted
, 2001.

Figure 1. High root buoyancy model evolution.

Figure 2. Higher root buoyancy model evolution.

Figure 3. (a) Normalized root extent versus root buoyancy ratio. The effects of variable initial root depth are also shown. (b) Normalized root extent versus root to mantle viscosity ratio. The effects of variable crustal viscosity are also shown.

Figure 4. High root viscosity model evolution.

Figure 5. (a) Normalized root extent versus global friction coefficient value. (b) Root mean square velocity versus global friction coefficient value.

Figure 6. High continent yield models after 50 Myr evolution. Two situations are explored. For the first, an enhanced continental yield stress applies for the cratonic root and the continental crust while for the second, an enhanced yield stress applies only for the root material.

Figure 7. (a) Normalized root extent versus continent to mantle yield ratio. Two simulation sets are considered. For one set both crust and root material have enhanced yield while for the other only the root has an enhanced yield stress. (b) Normalized root extent versus post yield weakening factor.

Figure 8. Crumple zone model evolution.

Figure 9. (a) Normalized root extent versus crumple zone to mantle and craton yield stress ratio. (b) Normalized root extent versus crumple zone width.

Figure 10. Mixed model evolution.

Figure 11. Mixed exposed model evolution.