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Is the African cratonic lithosphere wet or dry?

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ABSTRACT

Thick continental lithosphere (tectosphere) beneath African cratons has been stable for ~2.5 b.y. despite its mechanical interaction with sublithospheric mantle. Water is known to have significant influence on mechanical stiffness, and the depletion of water is often considered to be a key to preserving the thick lithosphere. Although water-rich environments indicated by the present water content of cratonic xenoliths appear to contradict this hypothesis, these water contents might have been modified at later stages due to the high diffusivity of hydrogen in minerals. Deformation microstructures such as lattice-preferred orientation indicate water-poor conditions (<200 ppm H/Si) during long-term plastic deformation in the continental lithosphere. Analysis of convective instability further constrains the water content to be less than 100 ppm H/Si. We suggest that the continental tectosphere beneath southern Africa must have a low water content, at least one order of magnitude less than oceanic upper mantle, and that the present-day water content of cratonic xenoliths most likely reflects localized metasomatism before eruption.

INTRODUCTION

Water has significant influence on the viscosity of mantle minerals (e.g., Karato et al., 1986; Mei and Kohlstedt, 2000), and consequently mantle dynamics depend strongly on the distribution of water. Continental tectosphere, which is thick mantle lithosphere lying below Archean cratons, has a thermochemical structure that differs from average suboceanic mantle (Jordan, 1975). This special kind of lithosphere is believed to have been stable and not experienced major tectonic disruptions for the last 2 b.y. or so, whereas other regions have undergone intense tectonic episodes (Richardson et al., 1984; Pearson, 1999). Although chemical buoyancy caused by the extraction of basaltic or komatiitic melts may be partly responsible for the stability of continental tectosphere (Jordan, 1975), geodynamic studies indicate that high viscosity is the most essential factor for the preservation of the thick lithosphere (Doin et al., 1997; Shapiro et al., 1999; Lenardic and Moresi, 1999; Sleep, 2003). Water is preferentially partitioned into a melt phase during partial melting (e.g., Koga et al., 2003), and a relatively low water content is expected for the residual mantle. Pollack (1986) proposed that volatile loss due to magmatic events might have increased mechanical stiffness and thus stabilized the continental tectosphere.

Cratonic mantle xenoliths, however, usually point to water-rich environments, as suggested by the common presence of hydrous minerals such as phlogopites (e.g., Pearson et al., 2003). Moreover, direct measurements of water content in cratonic xenoliths from southern Africa show a high amount of water,

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~800 ppm H/Si in olivine (Miller et al., 1987; Bell and Rossman, 1992; Kurosawa et al., 1997). This water content is actually higher than that in olivine from off-craton and from wedge mantle in subduction zones (Peslier and Luhr, 2006). If the mantle beneath cratons has more water than these mobile regions, then it could be very weak and easily disrupted by convection.

The origin of these "wet" signatures is a key question regarding the bulk property of continental tectosphere. Usually, these signatures are interpreted to be of a secondary origin, i.e., associated with metasomatic events prior to the kimberlite magmatism that brought those xenoliths up to the surface. That is, the wet signatures are believed to be highly localized in space and not representative of the lithospheric mantle. On the other hand, because the wet signatures are so commonly observed in cratonic xenoliths, it is also possible to regard them as representative samples and argue for wet and weak continental lithosphere (Maggi et al., 2000; Jackson, 2002). Thus, interpretation of the water contents of cratonic xenoliths has been ambiguous. They are invaluable direct samples, but we also know that they could suffer from severe sampling biases (e.g., Artemieva, 2009). The very fact that they were brought up to the surface could mean that they are fundamentally different from the rest of the continental tectosphere. A frustrating situation is that, whereas dehydrated, stiff mantle appears to be required for the long-term stability, we do not have direct samples to prove this hypothesis.

The purpose of this paper is twofold. First, we would like to point out that the deformation fabric of cratonic olivine can clearly dismiss the wet signatures of mantle xenoliths from the African lithosphere as a secondary origin and provide a direct constraint on the long-term water budget of continental tectosphere. Second, we will show such a constraint can be further tightened by a simple convective instability analysis incorporating xenolith data. We begin with a brief review on the present-day water content of cratonic olivine.

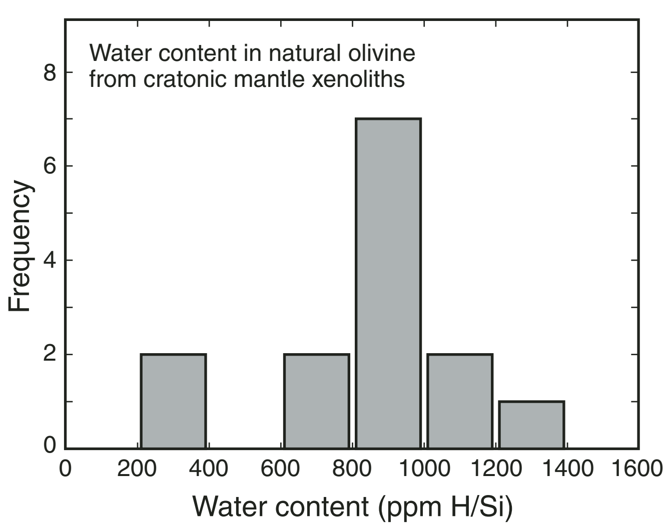

Figure 1. Water content in olivine from African cratonic xenoliths derived from deep continental lithosphere. The data are from Miller et al. (1987), Bell and Rossman (1992), and Kurosawa et al. (1997).

PRESENT WATER CONTENT IN CRATONIC OLIVINE

Trace amounts of water (hydrogen) in nominally anhydrous minerals have been widely detected by infrared spectroscopy and ion mass spectrometry (e.g., Rossman, 2006). Olivines from natural peridotites have been reported to contain ~10–1000 ppm H/Si (note that water content is expressed by atomic ratio of hydrogen and silicon, this corresponds to ~1–100 ppm H_2O by weight); olivines in garnet peridotites usually contain more water than those from spinel-peridotites (Bell and Rossman, 1992). In the cratonic xenoliths that derived from continental lithosphere, olivines show a wide range of water concentration, with an average of ~800 ppm H/Si (Fig. 1). The water contents of olivines from the cratonic lithosphere are higher than those from off-cratons (<600 ppm H/Si) and from mantle wedges (<500 ppm H/Si), both of which are tectonically active (Peslier and Luhr, 2006). Though these direct measurements provide a first clue to the water content of the continental tectosphere, it is not clear whether the present water content reflects the original value in the deep mantle because of the high diffusivity of hydrogen. The diffusion coefficient of hydrogen in olivine is more than ten orders of magnitude faster than oxygen or silicon diffusion (Mackwell and Kohlstedt, 1990), so that the water content of olivine can be easily modified; it takes days or weeks to reequilibrate a millimeter-size olivine (Fig. 2). Cratonic xenoliths are usually trapped by volatile-rich kimberlite diapirs, and this transport mechanism could easily overprint the original water content.

In fact, there are two types of geophysical data suggesting that the observed wet signatures of cratonic xenoliths are unlikely

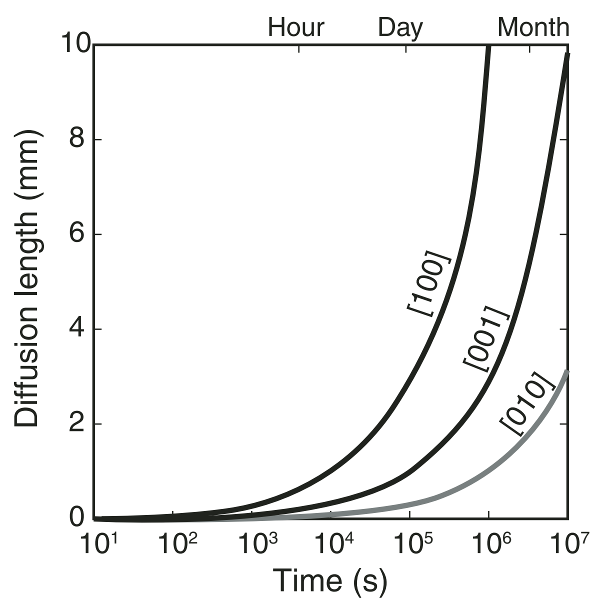

Figure 2. Diffusion length of hydrogen in olivine crystals. The diffusion coefficient is calculated at T = 1000 °C, from Mackwell and Kohlstedt (1990), which depends on crystallographic axis (the [100] axis is the fastest pathway of hydrogen diffusion).

to represent the bulk of tectosphere. First, by noting that mantle metasomatism also increases the content of heat-producing radiogenic elements, Rudnick et al. (1998) argued that low-heat-flow data observed over cratons preclude the possibility of a pervasively metasomatized lithosphere. Second, the lower water content of continental tectosphere is suggested by electrical conductivity (Hirth et al., 2000), though quantitative water contents are debated because electrical conductivity in olivine crystal is strongly anisotropic when hydrogen is the charge-carrying species (Yoshino et al., 2006; Wang et al., 2006).

Note that these geophysical observations are consistent with the notion of dry continental tectosphere but do not prove it, because the heat-flow argument is indirect and the interpretation of electrical conductivity is nonunique. It is not unreasonable, therefore, to hypothesize wet continental lithosphere on the basis of thermochemistry observed in cratonic xenoliths. Maggi et al. (2000), for example, argued for weak lithospheric mantle beneath continents because earthquakes in continental regions are usually confined in the crust, and they attributed the lack of strength in the mantle to its wet nature as suggested by xenoliths. It then becomes difficult to explain the stability of thick continental lithosphere, but the thickness of continental lithosphere itself has been debated for the last few decades (e.g., Anderson, 1979; Gaherty and Jordan, 1995; Gung et al., 2003; Priestley et al., 2006). Weak lithosphere would not pose any dynamic problem if continental lithosphere were not as thick as ~300 km.

How to interpret the water content of cratonic olivine is thus central to the debates surrounding the structure and dynamics of continental tectosphere. The primary water content of tectosphere, if known, could provide an important dynamical context for relevant geophysical data. In the next section, we show that such information can be extracted from the deformation microstructure of cratonic olivine.

WATER CONTENT INFERRED FROM DEFORMATION MICROSTRUCTURES

Recent laboratory experiments have shown that deformation-induced microstructures such as lattice-preferred orientation are sensitive to water content, in addition to stress and temperature (Jung and Karato, 2001; Katayama et al., 2004; Jung et al., 2006). This means that the analysis of deformation microstructures can provide a clue to water content during long-term deformation. Figure 3 shows an experimentally determined olivine fabric diagram as a function of water content and stress; the olivine [100] axis is oriented to the shear direction under water-poor conditions (A, E, and D types), whereas the [001] axis becomes parallel to the shear direction at high water concentrations (C and B types). Naturally deformed mantle peridotites show various types of olivine fabrics that correlate with their tectonic setting, i.e., peridotites from ophiolite sections commonly show A-type olivine fabric (Peselnick and Nicolas, 1978), whereas Alpine-type peridotites from subduction zones often show B- or C-type fabric (Möckel, 1969; Mizukami et al., 2004; Katayama et al., 2005; Skemer et al., 2006). Mantle xenoliths from continental lithosphere beneath southern Africa commonly exhibit an olivine [100] axis subparallel to lineation and a (010) plane subparallel to the foliation plane (Ben Ismail and Mainprice, 1998) (see Fig. 4 for an example), which corresponds to A-type fabric. As shown in Figure 3, this type of olivine lattice-preferred orientation is found under water-poor conditions, less than ~200 ppm H/Si, so that the African cratonic lithosphere should be a dry environment during deformation.

Note that the water content in Figure 3 is based on the Paterson calibration of infrared spectroscopy data (Paterson, 1982), and if we instead apply the new calibration proposed by Bell et al. (2003), the threshold water content for the A-type fabric would be ~600 ppm H/Si. In either case, the deformation fabric indicates that the observed water contents of cratonic olivine as shown in Figure 1 do not represent the bulk water content of tectosphere. If those samples had long been as wet as observed when they were situated deep in the cratonic lithosphere, they would have been deformed more easily and should exhibit the B-, C-, or E-type fabric. Experimentally deformed olivine aggregates show a significant lattice-preferred orientation when the shear strain is larger than ~1 (Zhang et al., 2000). For a typical geological strain rate of 10^{-15} s^{-1}, it takes only ~30 m.y. to develop a significant olivine preferred orientation. Lattice-preferred orientation is difficult to modify by later-stage annealing (Heilbronner and Tullis, 2002). The fact that these samples show only the A-type fabric requires that their present-day water contents (~800–1000 ppm H/Si) must have been acquired relatively recently, and such

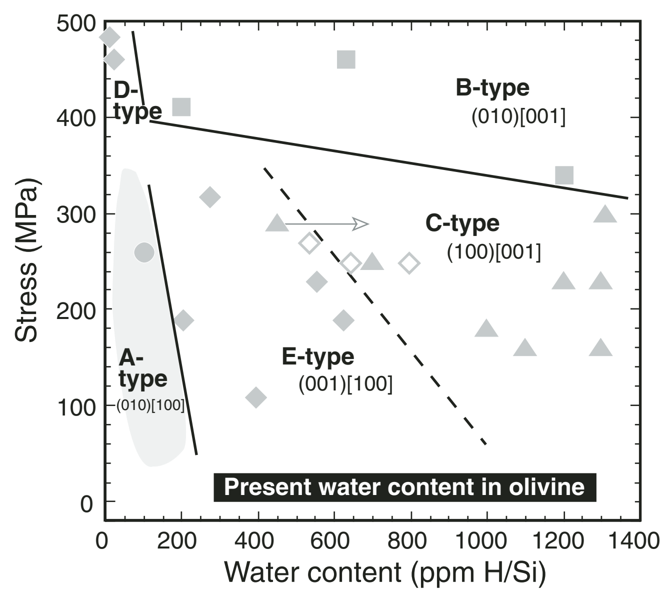

Figure 3. Olivine fabric diagram as a function of stress and water content (after Katayama et al., 2004). The present water contents in cratonic olivine are also shown in this figure, which suggests that E- or C-type olivine fabrics are dominant, whereas cratonic xenoliths commonly have the A-type fabric.

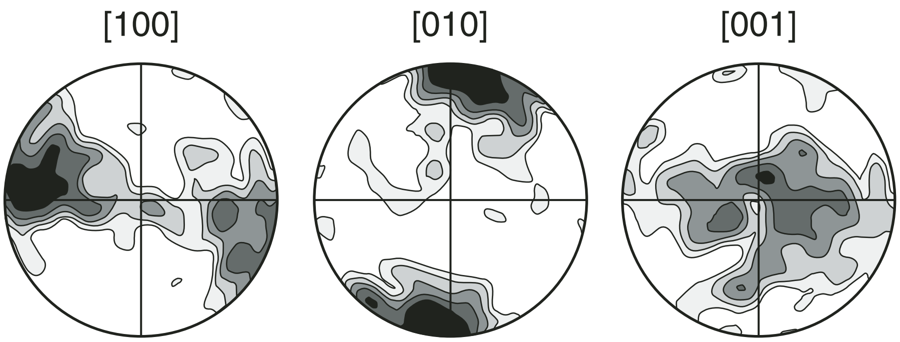

Figure 4. Lattice-preferred orientation of olivines from a kimberlite xenolith in the Kaapvaal craton (modified after Skemer and Karato, 2008). East-west direction corresponds to lineation, and north-south direction corresponds to foliation normal. The sample shows [100] maximum subparallel to lineation and [010] plane subparallel to foliation, suggesting the [100] slip and [010] plane is the dominant slip-system (A-type).

late-stage metasomatism can easily be explained by the associated volatile-rich kimberlite magmatism.

We therefore conclude that the long-term water content of continental tectosphere is lower than indicated by the present-day water content of cratonic xenoliths. The deformation fabric allows us to see through later metasomatic events in those hand samples and constrain their original water contents. As the threshold water content for the A-type fabric is still not very low to be regarded as "dry" (~200 or ~600 ppm H/Si, depending on the calibration adopted), we conducted a convective stability analysis in order to derive a tighter constraint.

CONVECTIVE STABILITY ANALYSIS

Before discussing what the nature of dry continental tectosphere must be in order to be stable over geologic time, we first need to clarify what we mean by "stable." We can think of three different levels of stability. First, tectosphere must be stable on its own. That is, it must have enough strength to support internal density stratification, if any. Second, tectosphere should be stable against horizontal heterogeneities, such as those caused by a continent-ocean transition (Shapiro et al., 1999). Third, it must maintain its integrity over basal drag due to mantle convection (Doin et al., 1997). The last stability criterion is the most restricting and automatically tests the two other stabilities. Testing for this stability, however, involves a number of assumptions because one has to simulate the long-term behavior of mantle convection in a general way. On the other hand, the first stability, which we call the intrinsic stability, is the simplest because we can focus on tectosphere itself, and it may also be regarded as the most fundamental. If tectosphere is intrinsically unstable, it can never satisfy the second and third criteria. The notion of intrinsic stability, therefore, is useful to derive the *upper* bound on the water content of cratonic olivine.

Water-Content–Dependent Rheology

The incorporation of water increases point defects in crystal and hence significantly enhances the rate of deformation (e.g., Griggs and Blacic, 1965). A systematic correlation between water content and creep rate has been well determined for olivine (e.g., Mei and Kohlstedt, 2000; Karato and Jung, 2003). Based on deformation microstructures of xenoliths and seismic anisotropy, the dominant deformation mechanism in continental lithosphere is likely to be dislocation creep, and the effect of water on dislocation creep is expressed as,

$$\dot{\varepsilon} = AC_{OH}^{r} \exp\left(-\frac{E+PV}{RT}\right)\sigma^{n}, \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, A is a scaling constant, C_{OH} is the water content, r is the water-content exponent, E is the activation energy, V is the activation volume, P is the pressure, T is the absolute temperature, R is the gas constant, σ is the differential stress, and n is the stress exponent. The parameters in this constitutive relation are summarized in Table 1. Since the water content exponent is close to 1, the strain rate changes approximately linearly with the water content. The water content in the upper mantle is estimated to be in the range of ~1–1000 ppm H/Si (e.g., Miller et al., 1987), so that the strain rate could differ up to ~3 orders of magnitude, depending on the water distribution

TABLE 1. PARAMETERS USED FOR CALCULATIONS

Crust density	2700 kg/m^3
Lithosphere density	3300 kg/m^3
Crust thickness	40 km
Surface heat flow*	51 mW/m^2
Mantle heat flow*	17 mW/m^2
Thermal diffusivity	1.0×10^{-6} m^2/s
Potential mantle temperature	1350 °C
Lithospheric stress	5 MPa
Flow law of dislocation creep†	
Dry olivine	
Pre-exponential constant	$10^{6.1}$
Stress exponent	3.0
Activation energy	510 kJ/mol
Activation volume	14 cm^3/mol
Wet olivine (closed system)	
Pre-exponential constant	$10^{0.56}$
Stress exponent	3.0
Water content exponent	1.2
Activation energy	410 kJ/mol
Activation volume	11 cm^3/mol

*Data from the Kaapvaal craton (Jones, 1988).
†Karato and Jung (2003).

in the mantle. However, when Equation 1 is extrapolated to significantly lower water content, we must take into account dry olivine rheology because wet creep and dry creep have independent mechanisms (Karato and Jung, 2003). Then, the total strain rate may be expressed (approximately) as the sum of these two creeps, i.e.,

$$\dot{\varepsilon}_{\text{total}} = \dot{\varepsilon}_{\text{wet}} + \dot{\varepsilon}_{\text{dry}}. \quad (2)$$

The total strain rate is mostly controlled by wet rheology under water-rich conditions, and it is sensitive to water concentration, whereas the strain rate becomes less sensitive to the water content under water-poor conditions, where dry rheology controls the rate of deformation. Figure 5 shows the total strain rate of olivine calculated as a function of the water content (with $P = 5$ GPa, $T = 1000$ °C, and $\sigma = 5$ MPa), and the transition between wet and dry creeps occurs at water content of ~10 ppm H/Si. We used Equation 2 to estimate the viscosity of continental lithosphere.

Thermal Structure and Viscosity Profile

The thermal structure of continental lithosphere can be calculated using one-dimensional heat conduction (Turcotte and Schubert, 1982) with the present-day heat flux in the Kaapvaal craton (Jones, 1988). Internal heat generation in the lithospheric mantle was neglected in our calculations (Rudnick et al., 1998). Mantle adiabat was calculated with a potential mantle temperature of 1350 °C and a gradient of 0.5 °C/km, and the geotherm follows the mantle adiabat when they intersect. The parameters used in our calculation are summarized in Table 1. The estimated thermal structure agrees well with the pressure-temperature (*P-T*) conditions of kimberlite xenoliths from southern Africa (Fig. 6). Mantle xenoliths erupted in the middle Proterozoic (ca. 1.1 Ga in the Premier mine) also show similar *P-T* conditions to those of the Mesozoic, whereas the heat-producing elements could have been more abundant in the past. This suggests that the African cratonic lithosphere may have experienced limited changes in the thermal structure (Danchin, 1979). The effective viscosity profile can be calculated from this thermal structure and the olivine flow law (Eq. 2) as

$$\eta = \frac{\sigma}{\dot{\varepsilon}}, \quad (3)$$

in which we assume a lithospheric stress of 5 MPa. This stress is based on the grain-size piezometer of cratonic xenoliths in southern Africa (Mercier, 1980). The lithospheric stress has some uncertainties due to the calibration of piezometers and the variation of grain size in the cratonic xenoliths, but this estimate is in the range of the approximate or maximum values inferred from geophysical constraints including isostatic compensation (e.g., Lambeck, 1980). Cratonic xenoliths must have deformed, probably very slowly, by dislocation creep to develop lattice-preferred orientation with the A-type fabric, and dynamic recrystallization during this dislocation creep dictates the relationship between stress and grain size. Water in the cratonic lithosphere might be heterogeneous as a result of mantle metasomatism; however, such regions could be highly localized (Katayama et al., 2009), having little impact on the bulk properties of lithosphere. In these contexts, we assumed a 300-km-thick chemically distinct lithosphere with a constant water content. The calculated viscosity structure is shown in Figure 6 for different water contents.

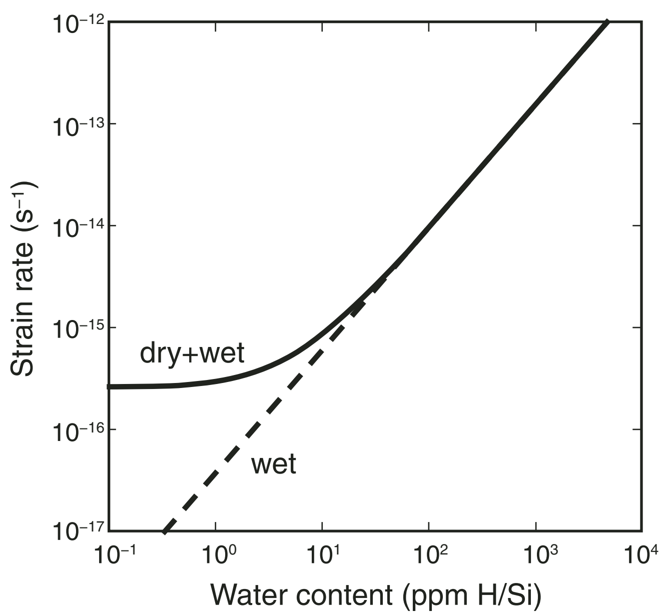

Figure 5. Stain rate of olivine aggregates as a function of water content. The dashed line was calculated using wet olivine rheology, and the solid line was calculated for sum of wet and dry rheology (parameters listed in Table 1). The deformation rate (in terms of viscosity) is sensitive to water content at water-rich conditions, whereas it will be insensitive to water when water content is less than 10 ppm H/Si.

Water Content to Stabilize the African Cratonic Lithosphere

Based on the viscosity profile of the continental lithosphere beneath African cratons, we first calculated the differential Rayleigh number (dRa) as

$$d\text{Ra} = \frac{4\alpha\rho g (z - z_0)^3}{\kappa\eta} \frac{dT}{dz} dz, \quad (4)$$

where α is the coefficient of thermal expansion, g is gravitational acceleration, ρ is the density, κ is the thermal diffusivity, and z_0 is the origin of available buoyancy (for full explanation, see Korenaga and Jordan, 2002). The local Rayleigh number (Ra) is then obtained by integrating the differential Rayleigh number from the top to the bottom of tectosphere as

$$\text{Ra} = \int d\text{Ra}. \quad (5)$$

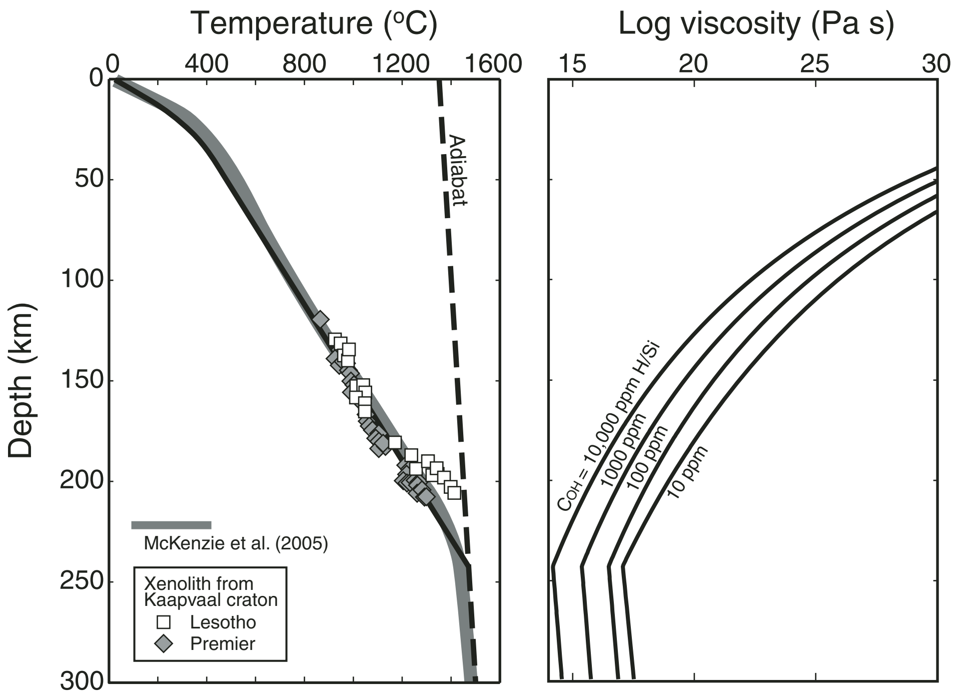

Figure 6. Thermal structure and viscosity profile of the African cratonic lithosphere. The continental geotherm was calculated from surface heat flow (Jones, 1988), and the results agree with pressure-temperature (*P*-*T*) conditions of cratonic xenoliths (Lesotho—Boyd and Nixon, 1975; Premier—Danchin, 1979). The cratonic geotherm calculated by McKenzie et al. (2005) is shown for reference. The viscosity was calculated from Equation 3 with different water contents. The detailed parameters for calculations are shown in Table 1.

We assumed no variation in compositional buoyancy within the lithosphere. The isopycnic hypothesis in the strict sense requires that density variation due to the thermal gradient be compensated by that due to the compositional gradient within the lithosphere (Jordan, 1975), but the inferred depth distribution of cratonic xenoliths does not exhibit such variation (e.g., Pearson and Nowell, 2002). Note that the compositional buoyancy of cratonic lithosphere as a whole with respect to surrounding mantle is probably partially responsible for its longevity (Shapiro et al., 1999) but is irrelevant to the intrinsic stability problem considered here.

The calculated local Ra of the African cratonic lithosphere is shown in Figure 7 as a function of the water content. The local Ra depends strongly on the water content at water-rich conditions, although it becomes less sensitive under water-poor conditions (Fig. 7). More importantly, the local Ra exceeds the critical value (~10^3) when the water content is higher than 100 ppm H/Si. To be stable over billions of years, therefore, the water content must be lower than 100 ppm H/Si. Because we are considering the intrinsic stability only, this is the upper bound on the more likely water content. Also, these calculations are based on the present thermal structure in continental lithosphere, but the temperature of the tectosphere must have been higher in the Archean due to more abundant radiogenic elements in continental crust as well as higher mantle potential temperatures for sublithospheric mantle (e.g., Korenaga, 2006). Thus, more depletion of water would have been necessary in the Archean just to maintain the intrinsic stability. The upper bound of ~100 ppm H/Si is based on the rheological parameters given in Table 1, which are based on the Paterson calibration of infrared spectroscopy. We may thus summarize that, compared to the constraint required

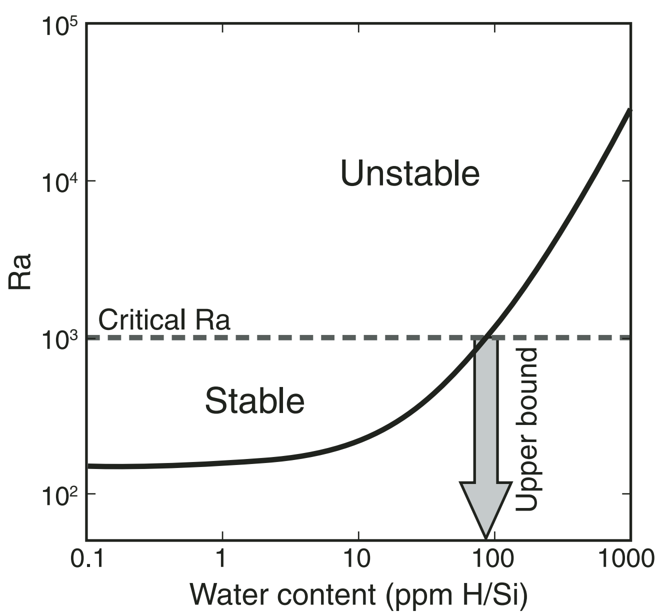

Figure 7. The calculated local Rayleigh number (Ra) is smaller than the critical Ra (~10^3) when water content is less than 100 ppm H/Si, suggesting that continental tectosphere can be stable. However, if water content is higher than 100 ppm, the calculated Ra is higher than the critical value, and continental tectosphere might be entrained by convecting mantle.

by deformation microstructures, the consideration of intrinsic stability tightens the upper bound by a factor of two, regardless of the chosen calibration. If we instead use the calibration by Bell et al. (2003) throughout, the upper bound is ~600 ppm H/Si by the deformation fabric and reduces to ~300 ppm H/Si by requiring intrinsic stability. Given other types of instabilities, a more realistic water content should be lower than these upper bounds, and such depletion of water in the tectosphere can easily be caused by the extraction of large amounts of melts during its formation, because water is preferentially partitioned into a melt phase, as illustrated in Figure 8 ($D_{H_2O}^{olivine/melt}$~0.001; Koga et al., 2003). Our stability analysis (Fig. 7), however, also indicates that values below 10 ppm H/Si would not lead to extra stability. This is because the degree of dehydration stiffening is bounded by dry dislocation creep (Fig. 5). This is also illustrated by recent experimental data, which suggest a relatively large activation volume (>10–15 cm^3/mol; Karato, 2010). This limited effect of dehydration stiffening may be important when considering the higher levels of stability and could provide dynamic constraints on the formation and evolution of continental tectosphere.

CONCLUSIONS

The direct measurement of water in cratonic xenoliths suggests significant amounts of water in the African cratonic lithosphere similar to the oceanic upper mantle, but it has not been clear whether the present water content reflects the original value in the mantle, due to the high diffusivity of hydrogen in minerals. Here, we argue that deformation microstructures such as lattice-preferred orientation from the cratonic xenoliths point to water-poor conditions (C_{OH} <200 ppm H/Si) during the long-term plastic deformation. The convective stability analysis, including water-content–dependent rheology, further tightens the water content constraints by a factor of two (~100 ppm), in order to maintain the intrinsic stability of the continental tectosphere. Given other likely sources of instabilities, this water content must be regarded as the upper bound. At the same time, being very dry (e.g., <1 ppm H/Si) does not necessarily indicate very stiff tectosphere, because the effect of water content on the rheological properties of continental lithosphere is nonlinear. This nonlinear functionality must be appreciated when considering the role of water in the dynamic processes of cratonic lithosphere.

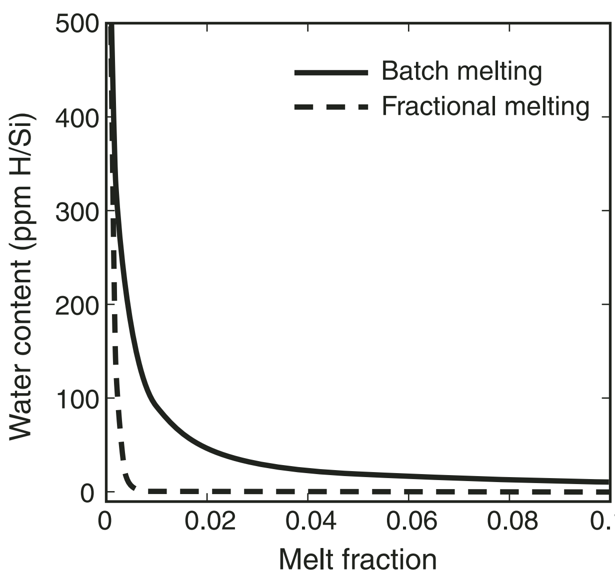

Figure 8. Water content in the residual mantle rock after partial melting calculated from partitioning coefficient of water between olivine and melt (Koga et al., 2003). Water can be removed significantly by melting process, and this results in high depletion of water in the residual lithospheric mantle.

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