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## Crustal seismicity and the earthquake catalog maximum moment magnitude ( $M_{cmax}$ ) in stable continental regions (SCRs): Correlation with the seismic velocity of the lithosphere

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### ABSTRACT

A joint analysis of global seismicity and seismic tomography indicates that the seismic potential of continental intraplate regions is correlated with the seismic properties of the lithosphere. Archean and Early Proterozoic cratons with cold, stable continental lithospheric roots have fewer crustal earthquakes and a lower maximum earthquake catalog moment magnitude ( $M_{cmax}$ ). The geographic distribution of thick lithospheric roots is inferred from the global seismic model S40RTS that displays shear-velocity perturbations ( $\delta V_S$ ) relative to the Preliminary Reference Earth Model (PREM). We compare  $\delta V_S$  at a depth of 175 km with the locations and moment magnitudes ( $M_w$ ) of intraplate earthquakes in the crust (Schulte and Mooney, 2005). Many intraplate earthquakes concentrate around the pronounced lateral gradients in lithospheric thickness that surround the cratons and few earthquakes occur within cratonic interiors. Globally, 27% of stable continental lithosphere is underlain by  $\delta V_S \geq 3.0\%$ , yet only 6.5% of crustal earthquakes with  $M_w > 4.5$  occur above these regions with thick lithosphere. No earthquakes in our catalog with  $M_w > 6$  have occurred above mantle lithosphere with  $\delta V_S > 3.5\%$ , although such lithosphere comprises 19% of stable continental regions. Thus, for cratonic interiors with seismically determined thick lithosphere (1) there is a significant decrease in the number of crustal earthquakes, and (2) the maximum moment magnitude found in the earthquake catalog is  $M_{cmax} = 6.0$ . We attribute these observations to higher lithospheric strength beneath cratonic interiors due to lower temperatures and dehydration in both the lower crust and the highly depleted lithospheric root.

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### 1. Introduction

Although moderate to large earthquakes are rare in stable continental regions, they can cause significant loss of life and property. Therefore there is great interest in estimating the earthquake potential of continental intraplate regions. Most approaches rely on instrumental and historical catalogs of earthquakes (e.g., Triep and Sykes, 1996; Engdahl and Villaseñor, 2002) and paleoseismic investigations of suspected active fault zones (e.g., Crone et al., 1997, 2003). However, these approaches are not entirely satisfactory. For example, it is well known that instrumental earthquake locations present an inadequate view of the seismic potential of intraplate regions where earthquake recurrence intervals commonly exceed 500 years. Likewise, historic records of seismicity inevitably contain gaps. Paleoseismology has made great

strides in recent years, but ongoing investigations will require decades of additional fieldwork before the earthquake faulting history on the majority of active faults can be determined.

Given these limitations, complementary approaches have been developed for estimating the seismic potential of continental intraplate regions. For example, it has been suggested that regions with higher seismic potential have pre-existing zone of weakness (Sykes, 1978), intersecting faults (Talwani, 1988, 1999), elevated heat flow (Liu and Zoback, 1997), crustal anomalies (Campbell, 1978; Kenner and Segall, 2000) or can be identified by crustal boundaries inferred from aeromagnetic and gravity maps (Langenheim and Hildenbrand, 1997; Lamontagne et al., 2003; van Lanen and Mooney, 2007).

Here we demonstrate that Archean and Early Proterozoic cratonic lithosphere with higher than average shear-wave velocity ( $V_S$ ) at a depth of 175 km have fewer crustal earthquakes and a lower value of the maximum moment magnitude found in the SCR earthquake catalog, also known as  $M_{cmax}$ . We associate higher  $V_S$  at this depth with a lower lithospheric geotherm and chemical

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depletion (Jordan, 1988). In turn, lithospheric strength is controlled by both the lithospheric geotherm and composition (particularly dehydration) through the solid-state creep law:

$$\frac{d\varepsilon}{dt} = \frac{C\sigma^m}{d^b} e^{(-Q/kT)}$$

where  $\varepsilon$  is the strain;  $t$  is time;  $C$  is a constant that depends on the material and creep mechanism;  $\sigma$  is the shear stress,  $d$  depends on the grain size, exponents  $m$  and  $b$  are constants that depend on the creep mechanism;  $Q$  is the activation energy;  $k$  is the Boltzmann constant and  $T$  is temperature.

According to this equation, creep will decrease for lower temperatures within the lower crust and sub-crustal lithosphere and for specific material properties, particularly water content and grain size (Kohlstedt et al., 1995; Hirth, 2002). Lateral variations in lithospheric strength are commonly estimated from measurements of flexure, effective elastic thickness, heat flow, or seismic shear-wave velocities (Burov and Diament, 1995; McKenzie and Fairhead, 1997; Cloetingh et al., 2005; Karato, 2008; Jordan, 1988). However, heat flow measurements are lacking in many continental intraplate regions (Artemieva and Mooney, 2001; McKenzie et al., 2005), and we therefore use the shear-wave velocity perturbation,  $\delta V_S$ , at a depth of 175 km as a proxy for lithospheric temperature and composition. Positive values of  $\delta V_S$  are indicative of relatively low lithospheric temperatures and/or melt depletion and dehydration due to high temperature melting. Lithospheric dehydration in particular will result in higher strength (Mai and Kohlstedt, 2000a, b).

This study complements previous work that has primarily focused on correlations between seismicity in non-cratonic regions and the strength of the upper lithosphere, i.e., the crust and lithosphere to a depth of ca. 80 km (Maggi et al., 2000; Jackson, 2002a, b). More recent studies have examined the relationship between crustal seismicity and lithospheric rheology, especially the role played by a low lithospheric geotherm and metamorphic dehydration of the lower crust beneath cratons (Jackson et al., 2008; Craig et al., 2011; Sloan et al., 2011).

## 2. Seismic catalog for stable continental regions (SCRs)

Stable continental regions (SCRs) were defined by Johnston et al. (1994) as regions of continental crust that have experienced no major deformation, magmatism, basement metamorphism or anorogenic intrusions since the early Cretaceous and no rifting, major extension or trans-tension since the Paleogene. This definition is purely geologic and does not refer to seismic activity. For this study, we use the SCR earthquake catalog of Schulte and Mooney (2005) which contains 50% more earthquakes than the catalog presented by Johnston et al. (1994). The catalog includes 1371 crustal earthquakes with moment magnitudes ( $M_w$ )  $\geq 4.5$  through November 2003. Instrumental (Engdahl and Villaseñor, 2002) and historical earthquakes (Triep and Sykes, 1996; Johnston et al., 1994) have been assigned a moment magnitude based on the methodology described by Johnston (1989). Our catalog includes 203 earthquakes that pre-date 1900, of which 182 span the time period 1500–1899. Only 21 historical events span the time period 494–1499.

We estimate this catalog to be globally complete for  $M_w \geq 5.0$  from 1964 onwards, with the exception of South America, which is complete from 1968 onwards, and Indochina, which is complete only since 1970. The catalog is complete for  $M_w \geq 7.0$  from 1900 onwards (Triep and Sykes, 1996; Engdahl and Villaseñor, 2002).

We refer to the largest earthquake in our catalog within a given SCR region as the earthquake catalog maximum moment

magnitude, abbreviated  $M_{cmax}$ . This parameter is distinct from  $M_{max}$  which is the maximum credible magnitude for a particular region or fault assuming a catalog of infinite length (Smith, 1976; Yeats et al., 1997; Kijko, 2004). We consider our earthquake catalog to be “short” and hence incomplete with respect to the long (500 years or more) recurrence time for earthquakes with  $M_w \geq 7.0$  in stable continental interiors (Yeats et al., 1997; Bird and Kagan, 2004). An additional limitation in our earthquake catalog is that we have not reassessed the geographical distribution of SCR regions defined by Johnston et al. (1994). Nearly two decades of geologic, geochemical, geochronologic and geophysical measurements, particularly GPS observations since 1994, have provided an opportunity to reassess the global distribution of SCRs, which we have not undertaken in this study.

## 3. Lithospheric shear-wave seismic velocity model

The map of  $\delta V_S$  at 175 km is from the global shear wave model S40RTS (Ritsema et al., 2011). Since more than 20 million fundamental-mode and overtone Rayleigh wave dispersion measurements are used in developing S40RTS, shear-wave velocity variations are well resolved in the upper 300 km of the mantle. Given the model parameterization, the smallest resolvable shear wave anomalies are at least 500 km wide and vertical resolution is roughly 30–50 km.

The S-wave velocity anomaly,  $\delta V_S$ , is defined as the perturbation of the measured seismic velocity  $V_S$  with respect to the reference seismic velocity,  $V_0$ , in the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981):

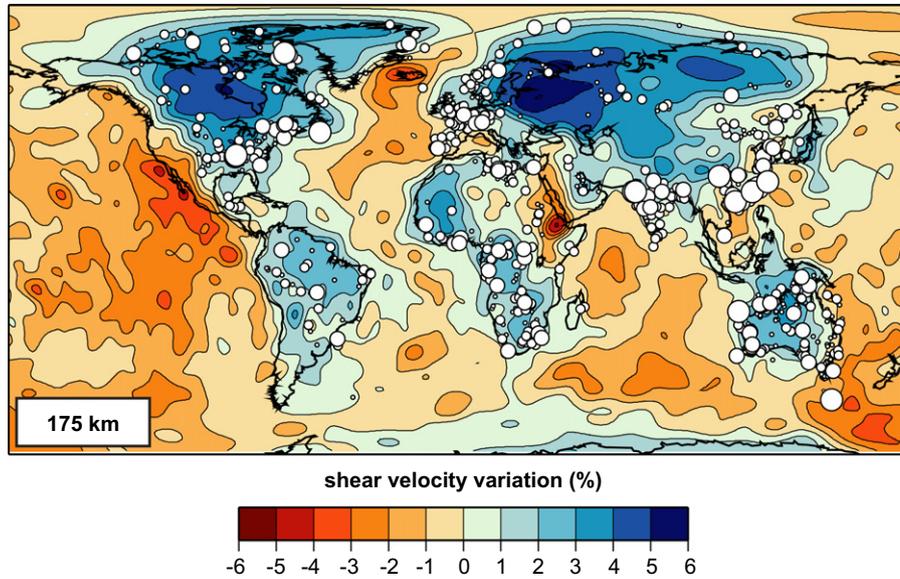
$$\delta V_S = (V_S - V_0) / V_0.$$

Values of  $\delta V_S$  at a depth of 175 km range from  $-4\%$  to  $+6\%$  and are clearly associated with plate tectonic processes and the age of the overlying crustal provinces (Fig. 1). Low-velocity anomalies at a depth of 175 km below the ocean basins correspond to the asthenosphere, consistent with the observation that the oceanic lithosphere is everywhere less than 175 km thick (Stein and Stein, 1992). Continental margins generally show near-zero  $\delta V_S$ , whereas  $\delta V_S$  is positive beneath Precambrian continental interiors such as central North America. Some continental collision zones show positive  $\delta V_S$  due to subduction of relatively cold lithosphere into the mantle (e.g., the South American Andes, Tibet, Japan, and the northern continental margin of Australia). Archean cratons commonly have lithospheric roots that are 200–240 km thick while Phanerozoic crust has a lithospheric thickness of ca. 100–150 km. Hence, a depth of 175 km correlates with the edge of thick cratonic lithosphere (e.g., Grand et al., 1997; Prestley and McKenzie, 2006; Yuan and Romanowicz, 2010; Ritsema et al., 2011). Our results are not strongly dependent on the selected depth of 175 km; we obtain similar correlations between lithospheric properties and crustal seismicity for  $\delta V_S$  in a depth range of 150–200 km. The depth of 175 km was selected because our goal is to investigate the correlation of crustal seismicity with the pronounced lateral gradient in lithospheric thickness that surrounds cratonic lithosphere.

## 4. Crustal seismicity versus lower lithospheric shear-wave seismic velocity

### 4.1. Global continental seismicity

We first compare lithospheric  $\delta V_S$  anomalies and crustal seismicity on a global scale. Fig. 1 shows a map of  $\delta V_S$  at a depth of 175 km. Superposed are the locations of earthquakes in the



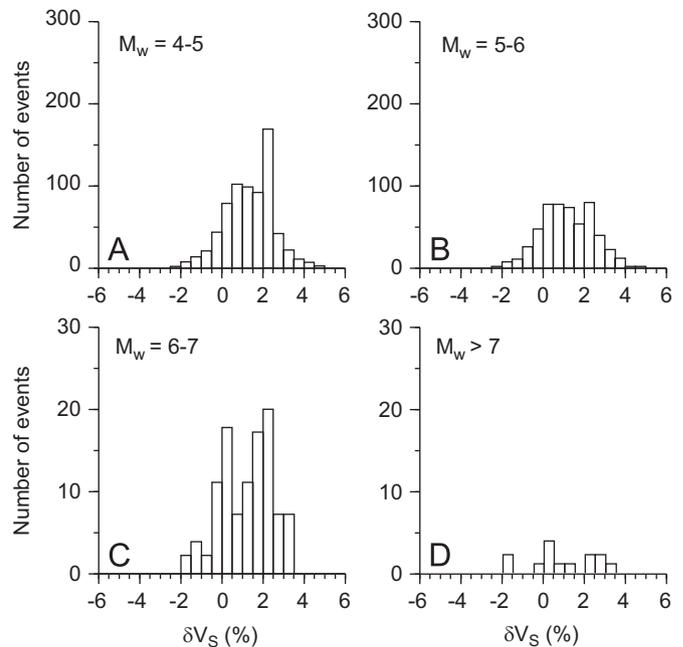
**Fig. 1.** Crustal intraplate seismicity (solid circles) plotted on a global map of mantle S-wave velocity variations,  $\delta V_S$ , at a depth of 175 km. Earthquakes outside stable continental regions (SCRs) have been excluded. Orange and red regions show negative  $\delta V_S$  anomalies and correspond to regions with lithospheric thickness less than 175 km. Blue regions show positive  $\delta V_S$  anomalies and correspond to regions with lithosphere thicker than 175 km. Blue regions, corresponding to  $\delta V_S$  anomalies greater than 2%, are restricted to the continents, and dark blue regions with  $\delta V_S$  anomalies  $> 3\%$  correspond to stable Precambrian cratons underlain by thick lithospheric roots. Few crustal earthquakes occur within the seismically-defined cratons, however many earthquakes are located in the region surrounding these cratons.

overlying crust scaled by moment magnitude. Only SCR earthquakes are plotted. The majority of Eurasian SCR earthquakes occur in regions with  $\delta V_S$  anomalies in the range of 0–2%. Many events in Africa and North America are concentrated at the edges of positive  $\delta V_S$  anomalies that correspond to thick lithospheric roots beneath cratons. In South America, SCR earthquakes commonly fall within the 0–2%  $\delta V_S$  contours. Australian seismicity shows a somewhat weaker correlation with  $\delta V_S$  contours, although numerous earthquakes are at the edge of the main positive  $\delta V_S$  anomaly. Globally, very few SCR earthquakes occur in regions with strongly positive (4–6%)  $\delta V_S$  anomalies, and all of these earthquakes have relatively low magnitudes.

The correlation between SCR crustal seismicity and lithospheric  $\delta V_S$  anomalies can be further quantified using histograms for specific ranges of  $M_w$ . Our earthquake catalog contains more than 700 continental intraplate earthquakes with  $M_w$  in the range of 4.5–4.99. Only 7% (50) of these crustal earthquakes occur above mantle lithosphere with  $\delta V_S \geq 3.5$  (Fig. 2A). There is a pronounced peak in the number of events at the edges of the continental cratons where  $\delta V_S$  ranges between 2.0% and 2.5%. Significantly more earthquakes occur in regions where  $\delta V_S < 2.5\%$  than in regions where  $\delta V_S > 2.5\%$ . Thus, crustal seismicity with  $M_w$  4.5–4.9 decreases significantly within cratonic interiors compared to seismicity within non-cratonic crust.

Of the 538 SCR events with a  $M_w$  of 5.0–5.99, only 7% occur above mantle lithosphere with  $\delta V_S > 3.0\%$ . Ninety percent of the events occur above mantle lithosphere with  $\delta V_S$  values between  $-0.5\%$  and  $2.5\%$ . All 108 events with a  $M_w$  of 6.0–6.99 occur above mantle lithosphere with values of  $\delta V_S \leq 3.5\%$ . Eighty-seven percent of the events occur above mantle lithosphere with  $\delta V_S < 2.5\%$ , corresponding to the edges of cratons. There are pronounced peaks in the number of events above  $\delta V_S$  of 0–0.5% (continental margins) and  $\delta V_S = 2.0$ –2.5% (edges of cratons).

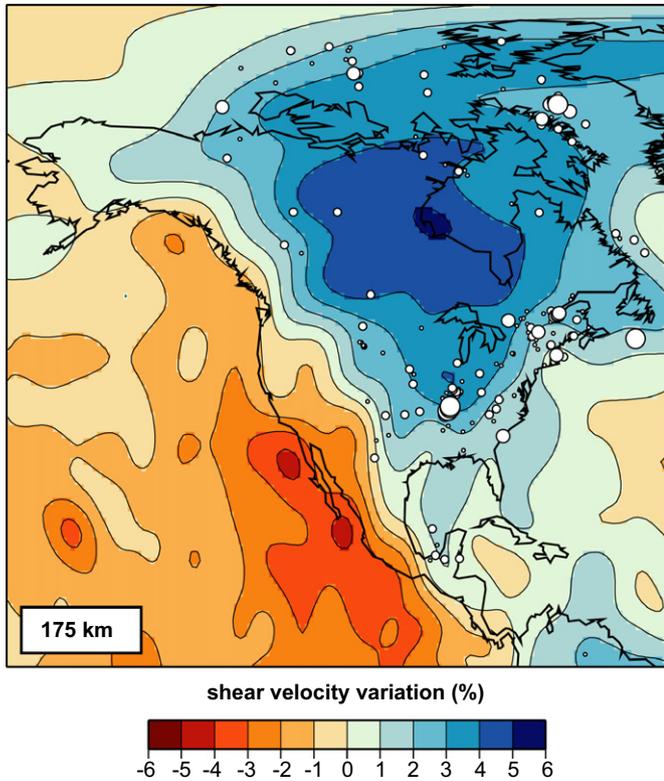
None of the 14 SCR events with  $M_w \geq 7$  occur above mantle lithosphere with values of  $\delta V_S > 3.5\%$ . These 14 events are evenly distributed above mantle lithosphere with  $\delta V_S$  values between  $-2\%$  and  $3.5\%$ . There are weak correlations with  $\delta V_S = 0\%$  (continental margins) and  $\delta V_S = 2.5\%$  (edges of cratons).



**Fig. 2.** Histograms of the number of global crustal intraplate earthquakes versus four ranges of seismic moment magnitude and the S-wave seismic velocity anomaly ( $\delta V_S$ ) at a depth of 175 km. (A) Earthquakes with  $M_w = 4.5$ –4.9 occur above mantle  $\delta V_S$  ranging from  $-2\%$  to  $5\%$  and have a maximum for  $\delta V_S$  at  $2\%$ ; (B) earthquakes with  $M_w = 5.0$ –5.9 occur above mantle with  $\delta V_S$  ranging from  $-2\%$  to  $5\%$ ; (C) earthquakes with  $M_w = 6.0$ –6.9 are limited to  $\delta V_S \leq 3.5\%$  and show two peaks,  $\delta V_S = 0\%$  (continental margins) and  $\delta V_S \sim 2\%$  (edge of cratons); (D) earthquakes with  $M_w \geq 7$  are limited to  $\delta V_S \leq 3.5\%$ .

#### 4.2. North American earthquakes

The lithospheric root beneath the North American craton is well defined by  $\delta V_S = 3\%$  contour on the seismic anomaly map (Fig. 3). Crustal seismicity is clearly concentrated near the seismically defined



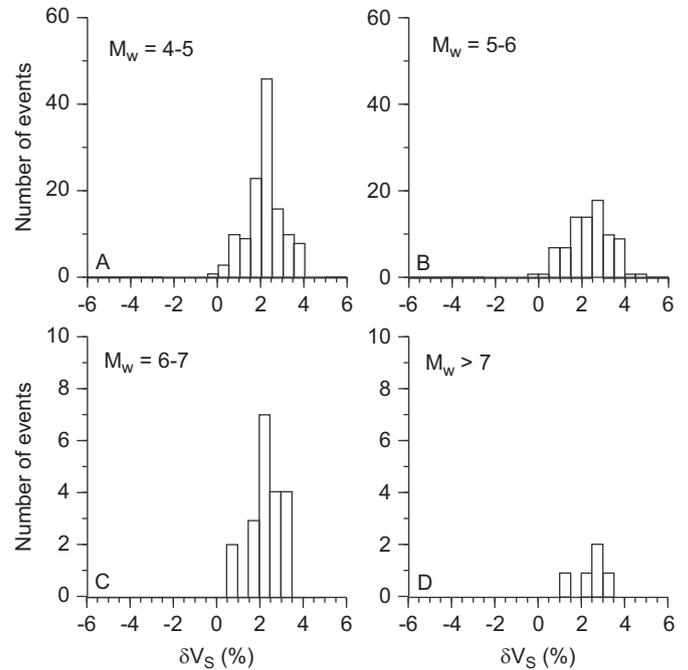
**Fig. 3.** Crustal intraplate seismicity (solid circles) of North America plotted on a map of mantle S-wave anomalies,  $\delta V_S$ , at a depth of 175 km. Earthquakes outside the North American Stable Continental Region (SCR) have been excluded. Yellow and red regions show negative  $\delta V_S$  anomalies and correspond to regions with lithospheric thickness less than 175 km in the western US and oceanic regions. These regions are not intraplate regions, and we therefore do not consider here the earthquakes that occur in these regions in this study. Green and blue regions show positive  $\delta V_S$  anomalies and correspond to regions with lithosphere thicker than average oceanic lithosphere. Blue regions, corresponding to  $\delta V_S$  anomalies greater than 2%, are generally restricted to the continents, while dark blue regions with  $\delta V_S$  anomalies greater than 3.5% correspond to thick ( $\sim 220$  km) lithospheric roots found beneath Precambrian cratons. Crustal intraplate seismicity is concentrated in those portions of North America that are underlain by lithospheric  $\delta V_S$  anomalies between 1% and 4% (green and light-to-medium dark blue colors). Few intraplate earthquakes occur in crust that is underlain by cratonic lithosphere with  $\delta V_S$  anomalies of 4% or greater.

craton boundary. In addition, events within the interior of the craton ( $\delta V_S > 3\%$ ) have relatively low  $M_w$  values.

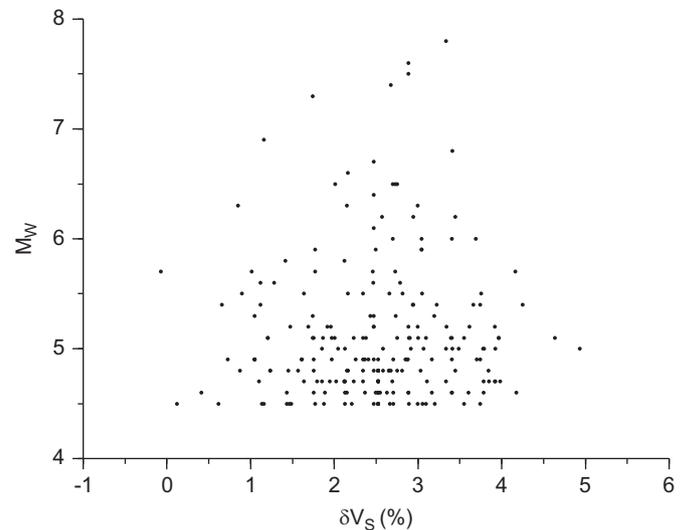
Histograms of the number of North American earthquakes versus lithospheric  $\delta V_S$  anomalies (Fig. 4) further illustrate these observations. There are 126 North American events in our catalog for  $M_w$  of 4.5–4.99. Ninety-two percent of these events occur above mantle lithosphere with  $\delta V_S \leq 3.5\%$ , while 73% of these events occur above mantle with  $\delta V_S \leq 2.5\%$  (Fig. 4). There is a peak in events (69 out of 126 events) for a value of  $\delta V_S = 1.5$ –2.5% corresponding to the region surrounding the craton.

There are 103 events with  $M_w$  5.0–5.99, and 85% of these occur above lithosphere with a  $\delta V_S \leq 3.5\%$ . The correlation with the edge of the craton is less clear for this magnitude range. Our catalog contains 20 events with  $M_w = 6.0$ –6.99. None of these events are located for  $\delta V_S \geq 3.5\%$  and there is a clear peak corresponding to  $\delta V_S = 2.0$ –2.5%, at the edge of the craton. Our catalog contains just five North American events with  $M_w \geq 7.0$ . No events occur above mantle lithosphere with  $\delta V_S \geq 3.5\%$ . Four out of the five events, including the 1811/1812 New Madrid sequence, occur for  $\delta V_S$  values of 2.0–3.5% (Fig. 4)

A scatter plot of the number of North American earthquakes versus  $\delta V_S$  (Fig. 5) illustrates three key points: (1) very few

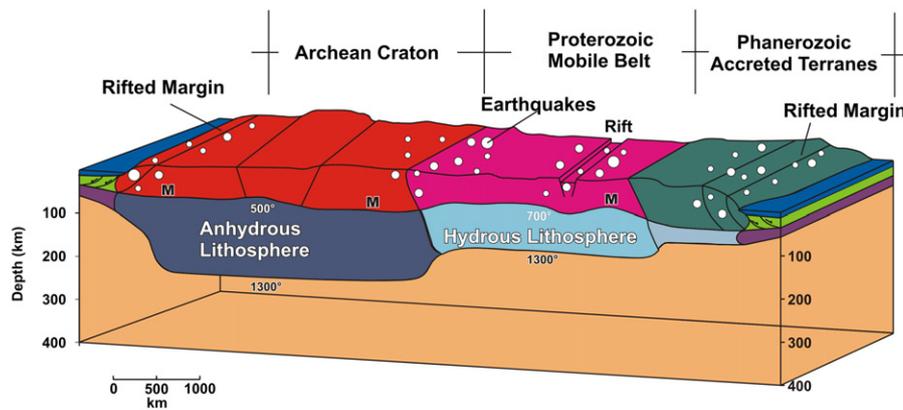


**Fig. 4.** Histogram of the number of North American intraplate earthquakes with moment magnitude versus the S-wave seismic velocity anomaly ( $\delta V_S$ ) at a depth of 175 km. (A) earthquakes with  $M_w = 4.5$ –4.9 occur above mantle  $\delta V_S$  ranging from 0% to 4% and have a maximum for  $\delta V_S$  at  $\sim 2\%$  corresponding to the edge of the craton; (B) earthquakes with  $M_w = 5.0$ –5.9 occur above  $\delta V_S$  of  $\sim 0$ –4%; (C) earthquakes with  $M_w = 6.0$ –6.9 are limited to  $\delta V_S \leq 3.5\%$  and show peaks for  $\delta V_S = \sim 2\%$  corresponding to the edge of the craton; (D) earthquakes in our catalog with  $M_w \geq 7$  are limited to  $\delta V_S \leq 3.5\%$ .



**Fig. 5.** Scatter plot of earthquake moment magnitude ( $M_w$ ) vs.  $\delta V_S$  at a depth of 175 km for North American continental earthquakes. The maximum  $M_w$  in our catalog is 7.8, and the catalog contains 5 events with  $M_w$  greater than 6.9. Values of  $\delta V_S$  range from 0% to 6%. There is a noticeable decrease in the number of events for  $\delta V_S > 4\%$ .  $M_{cmax}$  (the earthquake catalog maximum moment magnitude) for North American lithosphere with  $\delta V_S > 3.5\%$  is  $M_{cmax} = 6.0$ .

earthquake occur above mantle lithosphere with  $\delta V_S$  anomalies  $> 3.5\%$ ; (2) all earthquakes with  $M_w \geq 6$  occur above mantle lithosphere with  $\delta V_S \leq 3.5\%$ ; (3) four out of five earthquakes with  $M_w$  7.0–7.7 occur above mantle lithosphere with  $\delta V_S = 3\% \pm 0.5\%$ , corresponding to the edge of the craton Fig. 6.



**Fig. 6.** Conceptual model for intraplate seismicity and its correlation with properties of the lower crust and sub-crustal lithosphere. Bold M refers to Moho boundary. Intraplate crustal seismicity is concentrated at rifted margins, interior rifts and the edges of cratons as defined by seismic tomography (e.g., Ritsema et al., 2011). The latter correlation is newly established in this study. The lower crust and sub-crustal mantle lithosphere beneath Archean cratons is cold and anhydrous, which increases its viscosity in comparison with the warmer, hydrous lithosphere beneath Proterozoic and younger crust. Seismicity rates are low within cratonic interiors (as defined by  $\delta V_s > 3.5\%$ ) and the earthquake catalog maximum moment magnitude,  $M_{\text{cmax}}=6.0$ .

## 5. Discussion and conclusions

Continental crust can be divided into cratonic and non-cratonic crust. A distinguishing feature of cratons is a ca. 200–240 km lithospheric root that provides mechanical stability (Pollack, 1986; Jordan, 1988). Age data from lithospheric xenoliths show that the cratonic root is generally of the same age as the overlying Archean/Early Proterozoic crust (Pearson, 1999). This age agreement indicates that the cratonic root has sufficient strength to survive  $> 2$  Ga of basal shear associated with plate motion. The high viscosity of cratonic lithosphere can be attributed to a combination of relatively low temperatures and dehydration associated with high-degree partial melting during the formation of the lithosphere (Pollack, 1986; Jordan, 1978, 1988; Carlson et al., 2005). The relatively high strength of a dry, olivine-rich mantle lithosphere has been documented in the laboratory by Kohlstedt et al. (1995), Mai and Kohlstedt (2000a, b), and Hirth (2002). Evidence for dry conditions within cratonic lithosphere is provided by rock samples brought to the surface in kimberlites (Boyd, 1989; Poudjom Djomani et al., 2001; Carlson et al., 2005; Peslier et al., 2010). In addition, cratonic lower crust appears to be composed of anhydrous mafic granulite facies rocks on the basis of seismic velocity measurements (Christensen and Mooney, 1995; Prodehl and Mooney, 2012), lower crustal xenoliths (Rudnick and Fountain, 1995), and thermal considerations (Artemieva and Mooney, 2001; McKenzie et al., 2005; Jackson et al., 2008). Dry, granulitic cratonic lower crust has significantly higher strength than the more felsic composition lower crust that is common to Phanerozoic terrains (Kohlstedt et al., 1995; Mai and Kohlstedt, 2000a, b; Karato, 2008). Recent experimental data demonstrate pronounced weakening of lower crustal rocks with increased plagioclase content, as would be the case for felsic non-cratonic lower crust (Homburg et al., 2010).

Global seismic tomographic models clearly identify lithospheric roots beneath cratonic crust on the basis of their relatively high seismic velocities (Woodhouse and Dziewonski, 1984; Grand et al., 1997; McKenzie and Priestley, 2008; Romanowicz, 2009; Yuan and Romanowicz, 2010; Ritsema et al., 2011). Here we use positive shear-wave velocity perturbations,  $\delta V_s$ , at a depth of 175 km to identify thick lithospheric roots. We investigate the correlation between these thick lithospheric roots and the locations and magnitudes of continental intraplate earthquakes.

Our analysis of global SCR earthquakes indicates that a high proportion of these intraplate events are concentrated around the pronounced lateral gradient in lithospheric thickness that

surrounds the cratons. In terms of shear-wave velocity perturbations, no events in the earthquake catalog with  $M_w \geq 6.0$  occur above cratonic lithosphere with  $\delta V_s > 3.5\%$ . For moderate sized events,  $5 \leq M_w \leq 7$ , there are pronounced peaks in the number of events above  $\delta V_s = 0-0.5\%$  (rifted continental margins) and  $\delta V_s = 2.0-2.5\%$  (the younger crust surrounding the ancient cratons). The correlation with rifted continental margins has been discussed by several authors, including Stein et al. (1989), Johnston et al. (1994) and Schulte and Mooney (2005). The association of seismicity with the crust surrounding the craton is reported by Sloan et al. (2011) for the Siberian shield and Craig et al. (2011) for the Congo craton. Mazzotti (2007) also postulates a correlation of the seismicity of eastern North America with the edge of the North American craton. He associates the low rate of seismicity within the cratonic interior to a low geotherm and a high level of integrative lithospheric strength. These correlations are consistent with the numerical modeling of Lenardic et al. (2000) that showed the younger lithosphere surrounding Archean/Early Proterozoic cratons acting as a “crumple zone” adjacent to the stronger cratons.

Our analysis of North American SCR earthquakes is consistent with our global analysis but the North American data have the advantage of more accurate epicentral locations and  $\delta V_s$  anomalies. The North American data clearly confirm the correlation of crustal seismicity with the younger lithosphere ( $\delta V_s = 2.0-3.0\%$ ) surrounding the ancient cratons. Furthermore, no earthquakes are found in the catalog with  $M_w > 6.0$  for  $\delta V_s > 3.5\%$ .

These observations demonstrate a clear correlation between deep (175 km) lithospheric properties and seismic activity in the overlying crust. We find that cold, stable cratonic interiors ( $\delta V_s > 3.5\%$ ) have significantly fewer crustal earthquakes and a maximum earthquake catalog moment magnitude,  $M_{\text{cmax}}=6.0$ . We attribute these correlations to dry, cold conditions within cratonic lower crust and mantle lithosphere that provide significantly higher lithospheric strength, and a corresponding lower strain rate within the seismogenic upper crust, in accord with the studies by Jackson et al. (2008), Sloan et al. (2011) and Craig et al. (2011).

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