Earth and Planetary Science Letters 282 (2009) 294–298

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Evidence and implications for a widespread magmatic shutdown for 250 My on Earth

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ARTICLE INFO

Article history:
Received 9 January 2009
Received in revised form 17 March 2009
Accepted 18 March 2009
Available online 21 April 2009

Editor: T.M. Harrison

Keywords:
zircon ages
plate tectonics
crustal growth
episodicity
mantle evolution
magmatic age gap

ABSTRACT

Analysis of the global distribution of U/Pb ages of both subduction-related granitoids and of detrital zircons suggests that a widespread reduction in magmatic activity on Earth beginning about 2.45 Ga and lasting for 200–250 My. There are no arc-type greenstones or tonalite–trondhjemite–granodiorite (TTG) suites and only one large igneous province (LIP) reported in this time window. There is little Nd or Hf isotopic evidence to support significant additions to the continental crust at convergent plate margins between 2.45 and 2.2 Ga. Also during this time, there are major unconformities on most cratons and a gap in deposition of banded iron formation (BIF), both consistent with a major drop in sea level. Oxygenation of the atmosphere at 2.4 Ga followed by widespread glaciation at 2.4–2.3 Ga also may be related to the initiation of the global magmatic lull. We suggest that an episodic mantle thermal regime, during which a large part of the plate circuit effectively stagnates, may explain the 250-My magmatic age gap on Earth and a remarkable feature of the Paleoproterozoic record.

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1. Introduction

The question of when plate tectonics began on Earth and what alternative processes may have operated in its absence is largely speculative and unresolved (Davies, 1992; Stern, 2008; Condie and Pease, 2008). Clearly some recycling mechanism was at work given the current extent of early Archean crust (Armstrong, 1981; Taylor and McLennan, 1985; Condie et al., 2009), but a key obstacle to interpreting the Precambrian geological record of crustal growth is the representativeness of the preserved record.

Many investigations have considered various causes of episodicity, with suggestions ranging from catastrophic slab avalanches in the mantle and resulting mantle plume generation to supercontinent cycles (Stein and Hofmann, 1994; Tackley et al., 1994; Condie, 1998, 2004). More recently, studies by O'Neill et al. (2007) and Silver and Behn (2008) have presented mechanisms by which the global subduction system can entirely shutdown. They suggest that a shutdown of subduction can explain many observations in the Precambrian geological record, from periods of scant volcanism and crustal growth, to orogenic quiet zones and stationary apparent polar wander paths.

Since most volcanism on Earth is related to plate tectonics, a subduction shutdown should precipitate a significant lull in volcanism and crustal production. The rapidly expanding global zircon age database provides a means to identify such periods, if they exist. The distribution of U/Pb zircon ages from both granitoids and detrital sediments shows an exceptionally strong minimum between about 2450 and 2200 Ma (Condie et al., 2005; Rino et al., 2008; Condie et al., 2009). The fact that the minimum is well defined in both granitoid and in detrital zircon populations is remarkable, since the sampling control and bias are probably very different in the two populations. While the granitoid zircon ages largely reflect areas where geologists have worked (driven for instance by mineral exploration or easy accessibility), the detrital zircon ages sample parts of the continental crust where river systems have propagated and sediments have been preserved. In this respect, detrital ages probably approach a more uniform and complete sampling of the continents than ages from granitoids. In fact, many detrital zircons end up in basins several thousand kilometers from their sources (Dickinson and Gehrels, 2009). Because many detrital zircons (both modern and ancient) come from recycled sediments, sources that are no longer preserved or exposed also may be represented in these populations. As the database of zircon ages has grown in the last 30 years, the 2450–2200 Ma minimum has persisted, suggesting that it is robust and not due to inadequate sampling of rocks of these ages.

In this study, we review the evidence from both zircon ages and from the geologic record for an age minimum of about 250 My in the early Paleoproterozoic in the context of a hypothesized global magmatic slowdown or shutdown. We also suggest a geodynamic model to explain the age minimum that invokes episodic subduction. It is characterized by a partial shutdown or widespread slowdown of plate tectonics activity prior to the long-term establishment of the present mode of planetary cooling and plate tectonics.

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doi:10.1016/j.epsl.2009.03.033

2. Evidence for an early Paleoproterozoic age gap

U/Pb zircon ages from granitoids on all continents show highly episodic distributions (Kemp et al., 2006; Campbell and Allen, 2008; Condie et al., 2009) (Fig. 1; App. A). Granitoids related to subduction and collision show similar episodic age patterns and provide a record of ancient convergent plate margins, which allows us to track plate tectonics into the past. Australia, Laurentia, Europe and Africa all show major periods of granitoid production around 2.7 Ga, whereas in China, India, and Antarctica most granitoid activity is centered near 2.5 Ga. Detrital zircon age distributions (Fig. 1) show similar features, except that the 2.5 Ga peak is poorly represented outside of Antarctica. The next large period of granitoid activity at 2.2–2.1 Ga is best represented in West Africa and South America, and South America and Antarctica show detrital age peaks at this time. Numerous periods of granitoid activity occurred between 2.0 and 1.5 Ga in South America, Laurentia, Europe and Australia, and these also are found in the detrital ages from Laurentia, Europe, Africa and East Asia. Although granitoid and detrital zircon ages between 2.45 and 2.2 Ga are widely distributed geographically (Brazil, Canada, South Africa, East Asia, Scandinavia), they are few in number (Condie et al., 2005, 2009; Wang et al., 2009) (Figs. 1 and 2). The only possible age peak in this time window (at about 2.35 Ga) is recorded in detrital zircon ages from Africa and Europe (Mapeo et al., 2006), and possibly as a small granitoid age peak in South America and Laurentia (Bowring and Podosek, 1989). Detrital zircons from sediments of the world's largest rivers also show relatively few ages in the 2.45–2.2 Ga time frame (Rino et al., 2008; Campbell and Allen, 2008; Wang et al., 2009). Thus, if the distribution of global zircon ages is representative of the continental crust, there was a 200–300 My period (hereafter 250 My) in the early Proterozoic during which the rate of granitoid magma production was notably reduced.

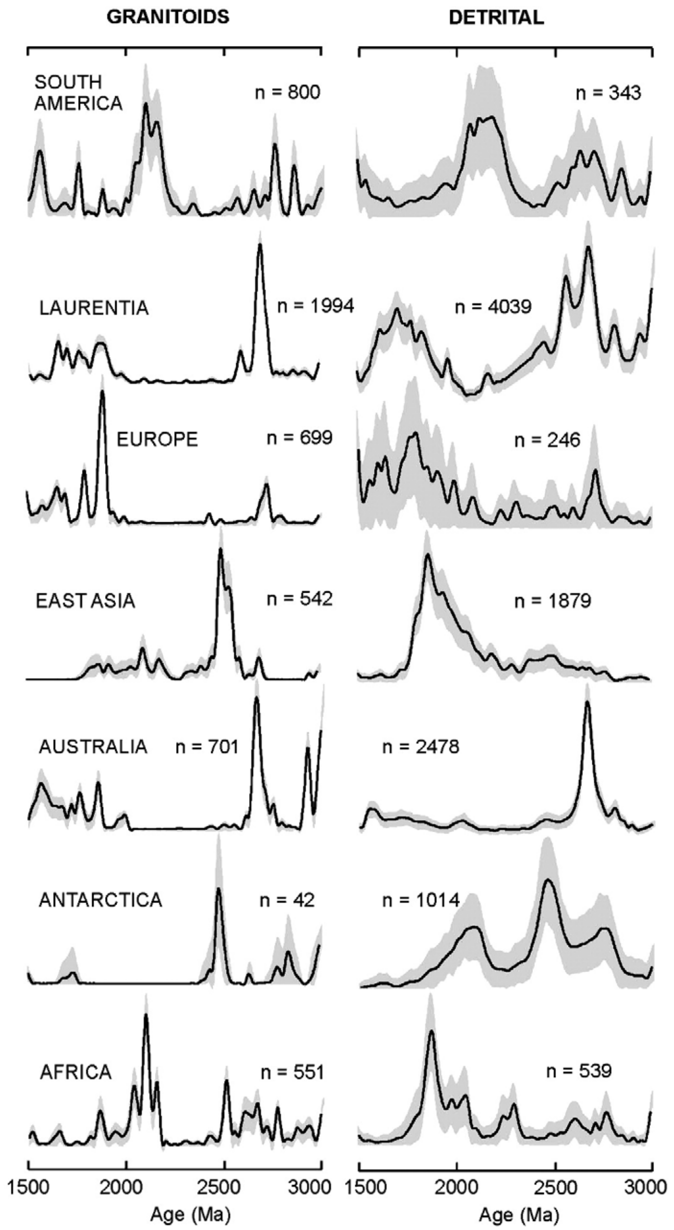

Fig. 1. Distribution of U/Pb zircon ages in subduction-related granitoids (left) and detrital zircons (right) expressed as probabilistic histograms with bin widths of 20 My. A discussion of the types of ages, uncertainties and plotting techniques is given in Condie et al. (2009). These histograms are constructed by re-sampling age data sets utilizing reported U/Pb age standard deviations and normal statistics. Gray envelopes indicate 3σ standard deviation values on sample counts within the 20 My-wide bins. We note that at the approximately 99.5% confidence level, many key peaks and troughs are readily apparent. In the left column, ages come only from granitoids that appear to be subduction-related (i.e., TTG and calc-alkaline suites). Detrital zircons sample granitoids of many different tectonic settings including those that have been largely removed by erosion. See Supplementary data and References (Apps. A and C).

An important question for continental growth in the context of plate tectonics is how much of the granitoid activity during the 250 My age gap reflects juvenile additions to the continental crust attributable to subduction-related processes. Ages of juvenile crust additions, as monitored by samples with positive whole-rock $\varepsilon_{\mathrm{Nd}}(T)$ values (Fig. 2; App. B), are very similar to those of global granitoids. This suggests that major episodes of convergent-margin granitoid production are coincident with crustal growth, with notable peaks near 2700 and 1890 Ma. Combined Hf and oxygen isotope studies of precisely dated zircons confirm that 2700 and 1890 Ma were times of widespread juvenile continental crust production (Kemp et al., 2006; Pietranik et al., 2008; Wang et al., 2009). As with global granitoid ages, juvenile granitoids exhibit an age gap between about 2.45 and 2.2 Ga. Although the Arrowsmith orogen in western Canada (2.4–2.3 Ga) may be an ancient convergent margin, largely negative $\varepsilon_{\mathrm{Nd}}(T)$ values from granitoids in this orogen provide little evidence for juvenile crustal additions between 2.45 and 2.2 Ga (Hartlaub et al., 2007), and are thus suggestive of older crustal magmatic sources (Andean-type convergent margins often involve older crust and thus negative $\varepsilon_{\mathrm{Nd}}[T]$). Another convergent orogen with Nd isotopic evidence for minor juvenile continental crust production at 2.35 Ga is the Borborema orogen in eastern Brazil (Fetter and Van Schmus, 1997). Juvenile sources of detrital zircons can also be identified with positive $\varepsilon_{\mathrm{Hf}}$ values. Although 2.45–2.2 Ga detrital zircons with positive $\varepsilon_{\mathrm{Hf}}(T)$ values are widely distributed (India, Australia, Brazil, Ukraine, East Asia, western Canada), again they are relatively few in number (Bodet and Scharer, 2000; Condie et al., 2005; Campbell and Allen, 2008). Thus, there is little Nd or Hf isotopic evidence to support significant additions to the continental crust at convergent plate margins between 2.45 and 2.2 Ga.

During a shutdown in magmatic activity over much of the planet, greenstones and associated granitoids should dramatically decrease in abundance. Fig. 2 shows occurrences between 3.0 and 1.5 Ga of greenstones and granitoids (TTG [tonalite–trondhjemite–granodiorite] and calc-alkaline plutons) that probably formed at convergent margins, referred to below as arc-types. Based on lithologic association and geochemistry, there are no arc-type greenstones identified between about 2.45 and 2.2 Ga (Condie, 1994; App. B). In addition, the TTG suite, which is widespread in Archean continental crust, has not been reported between 2.4 and 2.2 Ga (Condie, 2008) (Fig. 2). Beginning with the Transamazonian–Birimian orogeny at 2.2–2.1 Ga, arc-type greenstones and TTG and calc-alkaline plutonic suites again become common in the geologic record. Granitoids produced during the 2.45–2.2 Ga crustal age gap are chiefly granites with continental-rift or continental back-arc affinities (Fetter and Van Schmus, 1997;

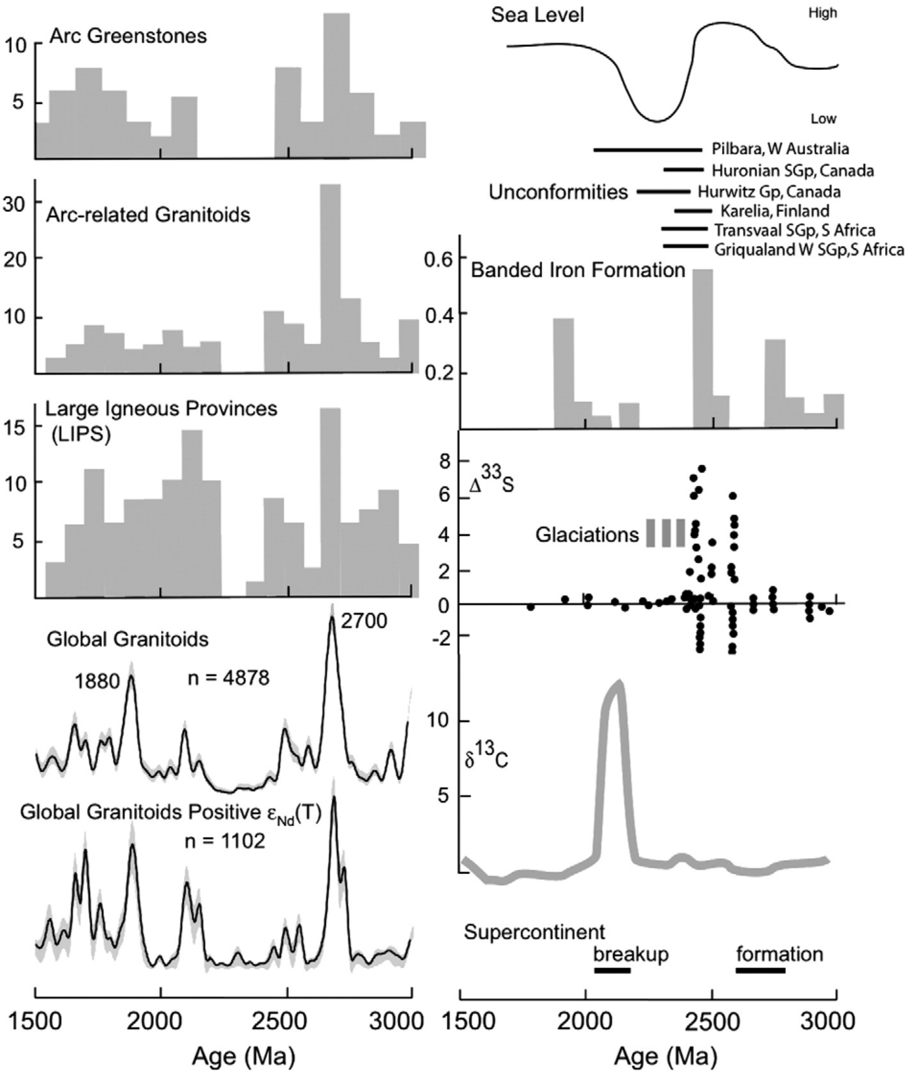

Fig. 2. Secular distribution of U/Pb zircon ages, rock types, and other features between 3000 and 1500 Ma. An explanation of using ε_{Nd} and ε_{Hf} for monitoring juvenile continental crust are given in DePaolo and Wasserburg (1976) and Condie et al. (2005). Vertical axis for greenstones, granitoids and LIPS is number of occurrences, and vertical axis for banded iron formation is fraction of known iron ore reserves. Unconformity locations, from top to bottom: Hurwitz Group, Canada; Huronian Supergroup, Canada; Transvaal Supergroup, South Africa; Karelia craton, Finland; Pilbara craton, Western Australia; Griqualand West, South Africa. See Supplementary data and References (Apps. B and C).

Hartlaub et al., 2007) derived from older crustal sources. Remnants of large igneous provinces (LIPS; giant dyke swarms, oceanic plateaus, and flood basalts), which probably formed from mantle plume sources, show a similar age distribution to arc-type greenstones (Ernst and Buchan, 2001) (Fig. 2). Although LIPS are quite widespread at 2.45 Ga, a notable gap occurs between 2.4 and 2.2 Ga, with only one example at 2365 Ma from southern India (Pradhan et al., 2008).

3. Constraints from the geologic record

O'Neill et al. (2007) suggested that a global reduction in magmatic activity and crust production could be caused by a period of extended tectonic quiescence due to widespread lithospheric stagnation characteristic of an episodic mantle overturn regime. Such an event at 2.45 and 2.2 Ga should manifest itself in the geologic record. For instance, ocean ridge volume should drop as oceanic lithosphere cooled, leading to deeper ocean basins and lower sea level (Moucha et al., 2008). A drop in sea level should lead to extensive erosion on the continents and therefore, to widespread unconformities in the stratigraphic record. As shown in Fig. 2, major unconformities representing 100 to over 300 My that occur on most cratons between 2.45 and 2.2 Ga are consistent with this inference (Aldermann and Nelson, 1998; Eriksson et al., 1999; Barley et al., 2005). In typical cases where mid-crustal metamorphic rocks are exposed beneath such unconformities, it is evident that 10–15 km of crust was removed by erosion before deposition of the overlying sediments. A possible reason we do not see extensive remnants of these sediments today is that they were largely subducted after plate tectonics became re-established around 2.2 Ga. If a sufficient volume of sediment was subducted, an increased level of large ion lithophile elements would have been transferred into mantle wedges, and ultimately, these elements may have been partially recycled into arc magmas. The long established increase in large ion lithophile element content of post-Archean juvenile continental crust (Taylor and McLennan, 1985; Condie, 1993, 2008) is consistent with this scenario. A further result of increased deposition of continent-derived sediments into deep ocean basins during a period of weak magmatic activity is that $^{87}Sr/^{86}Sr$ in seawater should increase. Although there is a suggestion of a peak in the seawater Sr isotope ratio between 2.4 and 2.2 Ga (Shields and Veizer, 2002), data are presently too few to be confident of this.

The largest volume of banded iron formation (BIF) was deposited at about 2.45 Ga (Hamersley basin, W Australia) followed by a BIF depositional gap until about 1.9 Ga (Isley and Abbott, 1999; Barley et al., 2005) (Fig. 2). This is consistent with a widespread shutdown of submarine magmatism (including LIP volcanism), which would decrease Fe^{+2} input into the oceans, and thus the rate of BIF deposition. Also, the large drop in sea level discussed previously would greatly reduce (or eliminate) marginal basins necessary for BIF deposition. The resumption of igneous activity and re-establishment of plate tectonics and LIP activity at 2.2 Ga may have led to renewed deep sea hydrothermal activity with Fe^{+2} input, as well as re-development of marginal basins, and thus contribute to renewed deposition of banded iron formation at 1.9 Ga. The fact that the BIF age gap (550 My) is much longer than the crustal age gap, however, clearly shows that other factors also must have contributed to the deposition of BIF.

What changes in the carbon cycle might result from a lull in global magmatism? The end of mass-independent sulfur isotope fractionation (S-MIF) and associated oxygenation of the atmosphere at about 2.4 Ga approximately coincides with the onset of the hypothesized magmatic shutdown (Zahnle et al., 2006; Kasting and Ono, 2006) (Fig. 2). A widespread shutdown of global volcanism would decrease the rate of CO_2 input into the atmosphere–ocean system. This, in turn, could lead to global cooling and hence to the global glaciation at 2.4–2.3 Ga (Aldermann and Nelson, 1998; Eriksson et al., 1999; Barley et al., 2005; Melezhik, 2006). The increased area of the continents exposed to weathering due to a sea level drop could also lead to increased removal of atmospheric CO_2 and further global cooling by weathering (Melezhik, 2006). This scenario is complicated, however, by the decrease in ocean ridge volcanism, which would reduce the rate at which inorganic carbon is removed by hydrothermal alteration at ridges (Bjerrum and Canfield, 2004), which may partially offset any cooling effect.

A drop in the rate of CO_2 venting from the mantle also could decrease the rate of biomass production and lead to a reduction in the rate of O_2 and CH_4 production (Catling and Claire, 2005). However, the decrease in banded iron formation deposition (discussed above) would free up O_2. Also, a global drop in submarine volcanism would decrease the input of such gases as H_2 and H_2S into the oceans, which normally act as reductants for oxygen. In addition, an increase in phosphorus delivered to the oceans from extensive erosion of the continents could enhance biomass production, leading to more O_2 production (Aharon, 2005). All three of these effects may have provided positive feedback for oxygen entering the atmosphere at 2.4 Ga. Most investigators agree that the atmosphere became oxidizing and cooled enough to support global glaciation by about 2.4–2.3 Ga. The positive α^{13}C excursion in inorganic carbon at about 2.15 Ga (Fig. 2) reflects large-scale burial of organic carbon at this time (Bjerrum and Canfield, 2004), which coincides with the proposed resumption of widespread magmatism. At about 2.2–2.1 Ga, late Archean supercratons may have begun to fragment and disperse (Bleeker, 2003). One possibility is that the fragmenting supercratons created basins where organic carbon was buried, leading to the carbon isotope excursion in marine carbonates.

4. Discussion

The question of when and how plate tectonics began is fundamental to understanding Earth history. Most investigators interpret the geologic database to reflect an onset of modern plate tectonics by 3 Ga (Condie and Pease, 2008). However, the near-absence of ophiolites, blueschists and ultra-high pressure metamorphic rocks before about 1 Ga has been interpreted by Stern (2008) to indicate that modern plate tectonics did not begin until late in Earth history. Others have argued that steeper geotherms, lack of preservation, or weaker Archean lithosphere can account for the pre-1 Ga sparsity of these features (Cawood et al., 2006; Condie and Kroner, 2008; van Hunen and van den Berg, 2008). Geodynamic modeling for high mantle temperatures in the early Precambrian and consideration of supercontinent dynamics suggests that plate tectonics had several false starts, each followed by a return to stagnant lid tectonics. This style of convection is known as episodic overturn, and has been previously postulated as a candidate for Archean and Venusian tectonics (Moresi and Solomatov, 1998; O'Neill et al., 2007). Episodic mantle overturn makes a number of predictions that are of interest for the 2.45–2.2 Ga magmatic gap. First, plate velocities should reflect rapid subduction (O'Neill et al., 2007). These velocities (up to 40–80 cm/yr) far exceed the fastest current plate velocities (e.g., 24 cm/yr for the North Tonga Trench [Bevis et al., 1995]), or velocities predicted by a model under steady-state plate tectonics (<10 cm/yr). They are, however, consistent with velocities inferred for the Pilbara at ~2.7 Ga from paleomagnetic observations (~100 cm/yr [Blake et al., 2003]). Between these peaks, during periods of plate tectonic shutdown, plate velocities are negligible (Moresi and Solomatov, 1998; O'Neill et al., 2007). Unfortunately, existing paleomagnetic data cannot presently confirm (nor deny) this for the 2.45–2.2 Ga interval (Evans and Pisarevsky, 2008). Subducting slabs also efficiently cool the upper mantle during times of subduction (when cold slabs dominate the average temperature). However, between subduction pulses when cooling is inefficient, upper mantle temperature rises. If this model correctly explains the early Proterozoic magmatic age gap, the increased upper mantle temperatures may have partially melted and rifted thickened continental crust in orogens giving rise to non-juvenile granites, such as those in the Arrowsmith and Borborema orogens (Fetter and Van Schmus, 1997; Hartlaub et al., 2007). With the re-establishment of plate tectonics, the mantle should be cooled and average upper mantle temperatures should drop by several hundred degrees.

The sparsity of LIPS during the 2.4–2.2 Ga crustal age gap suggests that plate tectonics and mantle plume generation may be related, although at present the nature of this relationship is not clear. Although slabs sinking into the "D" layer may affect the rate of mantle plume formation, the timescales for this process are not well constrained (Jellinek and Manga, 2004).

Ocean-floor topography is dominated by the thermal structure and expansion of the lithosphere, and thus for young hot lithosphere during times of active spreading, the average ocean basin depth can be shallow (~4 km, compared to 5 km at present). Global sea-level variations are a direct function of average ocean basin depth, although the exact relationship depends on near-shore bathymetry (Eriksson, 1999). When the lithosphere thickens and cools during periods of reduced seafloor spreading, the average ocean basin depth can increase significantly, leading to a major drop in sea level relative to cratons. This would result in widespread unconformities on most exposed landmasses, and the transport of significant quantities of sediment into the ocean basins as noted above (Fig. 2).

A major question is how geographically widespread a global tectonic stagnation event could be in a complex 3-dimensional system. Both numerical modeling (O'Neill et al., 2007) and conceptual models (Silver and Behn, 2008) suggest that a complete shutdown of the plate circuit is plausible, but is not essential to explain the observations in the 2.45–2.2 Ga interval. A crucial point made by Silver and Behn (2008) is that subduction zone shutdown is not necessarily related to subduction onset somewhere else on the Earth's surface. Instead subduction zone shutdown need only impact the global plate circuit and plate velocities. At a large enough scale, a subduction zone shutdown without new subduction initiation will have a profound effect on the thermal state of the mantle, particularly over a 250 My time period. For instance, if circum-Pacific subduction ceased at present, the bulk mantle would lose its primary cooling mechanism. This would terminate or slow seafloor spreading in the Pacific resulting in large-scale cooling of the oceanic lithosphere and a drastic global sea level drop over a 100 My period, while deeper mantle temperatures would simultaneously rise. Though local subduction might still occur in non-Pacific subduction zones (e.g., the Caribbean, Scotia Sea, or Mediterranean) none of these convective systems is of a sufficient scale to power the global plate circuit.

5. Conclusions

The distribution of U/Pb zircon ages from both subduction-related granitoids and detrital sediments shows a pronounced and robust minimum between 2.45 and 2.2 Ga. Furthermore, there is a sparsity of greenstones and subduction-related granitoids, as well as evidence for juvenile continental crust in this 250-My time window. We hypothesize that this reflects a globally significant period of cessation or slowdown global magmatism and perhaps in plate tectonics.

Acknowledgments

We acknowledge reviews of an earlier version of this paper by Peter Cawood, Bob Stern, Ian Dalziel and Wouter Bleeker that resulted in substantial improvement and clarification of the paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.03.033.

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