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The intraplate character of supercontinent tectonics

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ABSTRACT

For several decades geoscientists have recognised intraplate tectonic activity far from plate margins, both from modern and ancient examples. This apparent disconnect with the drivers of plate tectonics does not necessarily imply unconnected processes, but rather an uncertainty in understanding exactly how these systems operate. Are the driving forces derived locally or do they propagate from plate-margins? How do these forces interact with a complex tectonic inheritance to generate the observed tectonism? Furthermore, what novel approaches have been applied to understand these processes? Here we review the general literature and the contents of this special issue to develop some partial answers to these questions. Key observations include the critical importance of local lithospheric heterogeneities as a control on the mode of orogenesis, and also the role of locally derived forces from mantle upwelling or from depositing thick piles of magmatic or sedimentary rocks. These processes happen within the overarching tectonic setting provided by far-field plate margins, which show intimate links in both time and observed processes with many intraplate regions. These insights would not be possible without a growing arsenal of geological, geophysical and numerical methods that can be applied to intraplate regions, and this is reflected in the varied approaches within the issue. We envisage that this special issue will provide a stimulus for further progress in understanding intraplate tectonics.

1. Introduction

It is well established that under the influence of plate tectonics, the Earth's continents do not behave as rigid and inert entities, but rather respond dynamically through deformation, magmatism and metamorphism. These processes can occur far from plate boundaries in continental interiors. Several regions of the modern Earth contain spectacular examples of intraplate tectonism, including Tibet (England, 1983; Harrison et al., 1992; England and Molnar, 1997; Dayem et al., 2009), the Tien Shan and Altai in central Asia (Tapponnier and Molnar, 1976, 1979; Avouac and Tapponnier, 1993; Avouac et al., 1993; Cunningham, 2007), the Baikal Rift (Petit et al., 1996, 1997; Thybo and Nielsen, 2009), the Altiplano-Puna (Allmendinger et al., 1997; Capitanio et al., 2011) and the Basin and Range (Wernicke, 1981; Zandt et al., 1995) (Fig. 1). Added to these there are numerous regions of more subtle intraplate tectonics, that may not be imaged on global-scale maps, but are nevertheless significant tectonic episodes, examples include those found in Europe (Ziegler et al., 1995; Dèzes et al., 2004), Australia (Dyksterhuis and Muller, 2008; Sandiford and Quigley, 2009) and North America (Liu and Zoback, 1997; Calais et al., 2006) (Fig. 1.) The abundance of these examples indicate that, rather than being anomalous, significant intraplate tectonic activity is a normal part of the overall plate tectonic system. To date, however, it remains unclear how intraplate tectonics relates exactly to the better understood tectonic processes at plate margins. For example, how do plate tectonic forces propagate to continent interiors from the margins where they are sourced? and how these forces balance with the continents' internal deformations? In particular, better understanding is required of fundamental issues such as:

1– What are the driving forces of intraplate tectonics, and how do they relate to plate-margin processes?
2– How do intraplate regions respond to these driving forces? What role does complex tectonic inheritance play, and what is the nature of the lithospheric processes induced?
3– What are the best techniques to gather regional evidence for intraplate tectonics, and how can we use geodynamic models to maximise our understanding?

A salient observation is that supercontinental events such as the assembly and growth of Gondwana and the Alpine–Himalayan Orogeny have a significant capacity to generate deformation far removed from evolving plate boundaries (e.g. Rogers and Santosh, 2003; Rino et al., 2008; Santosh et al., 2009). In this special issue, we focus on these

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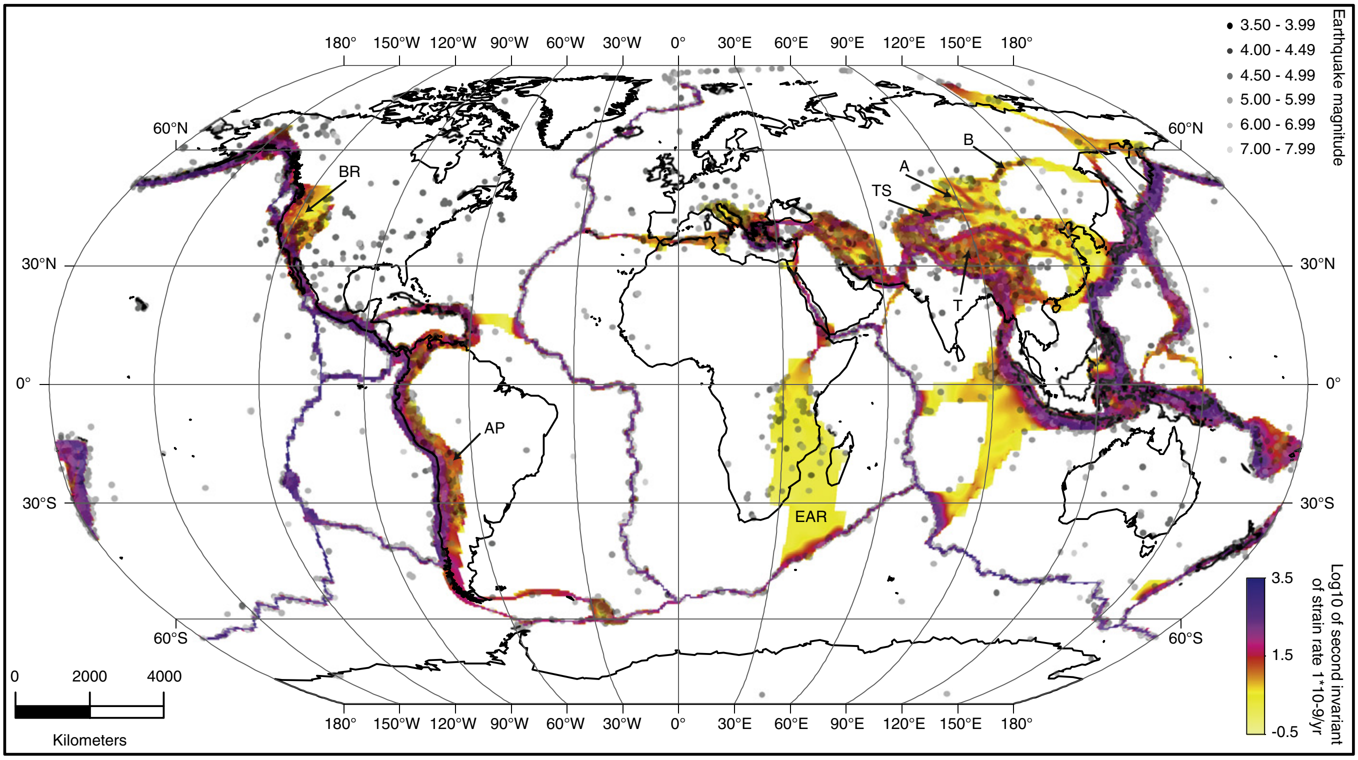

Fig. 1. Global image of strain-rate and recent seismicity. Strain rate is derived from the model of Kreemer et al. (2003), plotted with a log-scale. Seismicity data are an extract of events in the year 2012 from the IRIS database, limited to magnitudes 3.5 and above and depths of less than 150 km. Strain rate is several orders of magnitude greater at plate margins than even the fastest deforming continental interior regions, e.g. Tibet (T), Tien Shan (TS), Altai (A), Baikal rift (B) Basin and Range (BR), Altiplano-Puna (AP) and East African Rift (EAR). Seismicity is also overwhelmingly focused at the plate margins, but with significant populations in the aforementioned high-strain-rate areas. Sparse earthquake activity throughout several continents (e.g. North America, Europe, Australia) indicates that intraplate tectonism is active, as recognised in several studies (Ziegler et al., 1995; Liu and Zoback, 1997; Sandiford and Quigley, 2009). For small magnitude earthquakes, there is some bias in the seismicity data towards better sampled regions, in particular the USA.

major events as natural laboratories through which to better characterise and explain the nature of intraplate tectonics.

2. Supercontinental tectonics and intraplate lithospheric responses

Intraplate tectonic activity is not equally distributed in either space or time, and establishing what processes have dominated its locus and evolution is a complicated issue. Nevertheless, several examples show a clear association between supercontinent assembly or dispersal and the occurrence of intraplate tectonism. This relationship is most evident in the modern Earth (Fig. 1), where intraplate provinces such as the Tien Shan (Tapponier and Molnar, 1979; Avouac and Tapponnier, 1993; Abdrakhmatov et al., 1996; Yin et al., 1998; Zhao et al., 2003; De Grave et al., 2007; Aitken, 2011), Altai (Cunningham et al., 2003; Cunningham, 2005, 2007) and Baikal Rift (Petit et al., 1996; Polyansky, 2002; Thybo and Nielsen, 2009; Jolivet et al., 2013, this issue) are dynamically responding to remote large-scale events such as the India–Eurasia collision and Pacific subduction (Fig. 2). In more ancient cases, uncertainty regarding the location and nature of plate-margins can make such direct correlations difficult, but temporal associations remain significant. For example, Neoproterozoic tectonic activity in the Petermann Orogen of central Australia (Aitken et al., 2009a,b; Raimondo et al., 2010; Walsh et al., 2013, this issue) and the Borborema Province of northeastern Brazil (Tommasi et al., 1995; Vauchez et al., 1995; Tommasi and Vauchez, 1997; Neves, 2003) are both intimately tied to Gondwana assembly. In the central Australian case (Fig. 2), subsequent intraplate basin formation and shortening events during the Palaeozoic are linked with the early stages of western Pacific subduction (Goleby et al., 1989; Sandiford and Hand, 1998; Raimondo et al., 2011; Maidment et al., 2013, this issue). Earlier supercontinents such as Rodinia and Columbia are also temporally associated with intraplate activity (e.g. Percival and West, 1994; Sheppard et al., 2005; Smithies et al., 2011; Aitken et al., 2013, this issue), although palaeogeographical uncertainties are much higher for those periods. Furthermore, pre-Gondwana lithospheric conditions were significantly warmer (Brown, 2007), leading to different coupling mechanisms between plate margins and continental interiors.

The above examples demonstrate that both convergent and divergent plate-margin processes can affect the geological evolution of continental interiors, and for supercontinent-scale interactions, their impact is often dramatically expressed. In the following paragraphs, we introduce some of the basic processes and concepts surrounding their association with intraplate tectonics.

2.1. Convergent plate-margin influences

Convergent plate-margin processes impart significant forces on the edges of continental plates, often producing an associated intraplate stress field. Large stresses propagate into continental interiors during both continent–continent collision (Tapponnier and Molnar, 1976; Zoback, 1992; Petit et al., 1996; Flesch et al., 2001) and at Andean-type margins (Allmendinger et al., 1997; Capitanio et al., 2011). For Asia, the nature of this convergence-induced stress field has been explained by the indentation of a rigid body into a deformable medium (Tapponnier and Molnar, 1976; Avouac and Tapponnier, 1993), although how this results from the interactions between subducting and overriding lithospheres at convergent margins is not well understood. In addition, processes internal to the continent can further complicate the lithospheric response to this stress field. These include mechanical and thermal differences in the strength of the lithosphere (Ziegler et al., 1995; Cloetingh and Burov, 1996; Ranalli, 1997; Tommasi and Vauchez, 1997; Sandiford and Hand, 1998; Ziegler et al., 1998; Ranalli, 2000; Sandiford and McLaren, 2002; Cloetingh et al., 2006; Neves et al., 2008), and additional stress fields induced by, for