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Localization of intraplate deformation through fluid-assisted faulting in the lower-crust: The Flinders Ranges, South Australia

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ABSTRACT

In this paper we present a hypothesis for localized, intraplate deformation in the continental crust of south-central Australia that involves fluid-assisted reactivation of faults in the mid- to lower crust. Using data from a temporary seismometer deployment in the Flinders Ranges, we show that earthquakes, relocated in a 3D velocity model, cluster in elongated low v_p/v_s anomalies that extend to depths exceeding 20 km, and are aligned with the axis of the Flinders Ranges. In the northern Flinders Ranges these low v_p/v_s anomalies can be interpreted as fractured Neoproterozoic to Cambrian sediments that separate two cratonic blocks, the Gawler Craton to the west and the Curnamona Province in the east. Previous studies of Helium isotopes in springs to the north of the area provide evidence of mantle-derived fluids that may influence faulting at depth. Our focal mechanism and stress inversion results show a regionally compressive stress field that provides no evidence for stress concentration. We also argue that mechanisms for localized faulting such as thermal weakening and isostatic rebound also fail to account for the occurrence of earthquakes at mid- to lower crustal depth in this area of high heat flow and that the focused seismicity can only be explained by high pore fluid pressure in the lower crust.

1. Introduction

Understanding the interplay between continental intraplate seismicity, stress and deformation is important for elucidating the forces driving plate tectonics and the tectonic processes that shape the continents, as well as for reliably assessing earthquake hazard. But this interplay is still poorly understood. Australia is an important end-member for studying this topic, since it has one of the highest rates of seismicity of Stable Continental Regions (SCRs) worldwide (Johnston, 1994), and a complex stress field that is not aligned with the direction of plate motion (Coblentz et al., 1995).

Within Australia, the Flinders Ranges region stands out as experiencing concentrated and sustained seismic activity (Leonard, 2008), with a strain rate inferred from this seismicity of 10^{-16}–10^{-15} s^{-1} that is roughly commensurate with neotectonic slip rates inferred for range-bounding faults (Quigley et al., 2006; Sandiford, 2003). It is also an area of relatively pronounced topography and high heat flow (averaging 90 mW/m^2 with a high of 125 mW/m^2 in the north, see Neumann et al., 2000).

For these reasons the Flinders Ranges have been the subject of many studies trying to understand why deformation of the Australian continent appears to be localized there, with explanations ranging from erosion-driven isostatic rebound (Lambeck et al., 1984), lithospheric flexure (Célérier et al., 2005), stress concentration due to change in lithospheric strength (Dyksterhuis and Müller, 2008), and thermal weakening (Holford et al., 2011). While all of these studies have remarked on the high seismicity, none of them have considered the information provided by earthquake data – spatial and depth distribution of hypocenters, arrival time anomalies, and focal mechanisms – in any detail.

In this paper we present results from a temporary network of seismometers deployed during 2003–2005 in the Flinders/Mt. Lofty Ranges area (Cummins et al., 2004). Due to the high rate of seismicity in what we will henceforth refer to as the Flinders Ranges Seismic Zone (FRSZ), this network managed to record a large number (over 500) of small earthquakes that provided a unique opportunity to study FRSZ seismicity. We show that these data reveal important constraints on structure, rheology, and stress that are crucial for understanding intraplate deformation in the FRSZ, with possible implications for high-seismicity zones in SCRs elsewhere.

2. Background

2.1. Tectonic setting

The FRSZ comprises a Paleoproterozoic to Mesoproterozoic cratonic basement overlain by Neoproterozoic to Cambrian rift sediments (Preiss, 2000). Rifting and subsidence occurred in several phases during

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827–700 Ma, when the region formed part of a Rodinian passive margin, and this was accompanied by the formation of a basin complex. Normal faults formed during extension of this basin complex were reactivated as thrust faults in the Delamerian orogeny (~500 Ma), resulting in as much as 15% shortening (Paul et al., 1999). Deep seismic profiling has established that, at mid- to lower crustal depths, the Archean–Mesoproterozoic Gawler Craton to the west is juxtaposed against the Palaeo-Mesoproterozoic Curnamona Province to the east, along the east-dipping Aliena Fault (Preiss, 2010). This tectonic history is reflected in the surface geology of South Australia, where Gawler Craton and the Curnamona Province are separated by the Neoproterozoic–Cambrian sedimentary basin infill associated with the Adelaide Rift Complex (Fig. 1).

Recent studies of neotectonic activity in the FRSZ area have established that the region is actively uplifting, with range-bounding faults showing clear evidence of significant Quaternary displacements (Célérier et al., 2005; Quigley et al., 2006; Sandiford, 2003). This activity is thought to be associated with the onset at 5–10 Ma of the present-day stress field, with roughly E–SE oriented direction of maximum horizontal compressive stress (S_{Hmax}) attributed to compressional tectonics along the Pacific–Australian plate boundary associated with the generation of the Southern Alps of New Zealand (Coblentz et al., 1995; Quigley et al., 2006; Sandiford et al., 2004).

2.2. SCR paleorifts elsewhere

As in Australia, paleorifts in other stable continental regions (SCRs) account for a disproportionately large fraction of seismic moment release (see e.g. Johnston and Kanter, 1990; Schulte and Mooney, 2005). The most spectacular examples are the Reelfoot Rift in the U.S. (associated with the M_w 7.2–8.1 1811–1812 New Madrid earthquakes, see e.g. Braile et al., 1982), and the Kutch Rift in India (associated with the M_w 7.7 1819 Rann of Kutch and M_w 7.6 2001 Buhj earthquakes — see Bilham, 1999 and Rastogi et al., 2001, resp.).

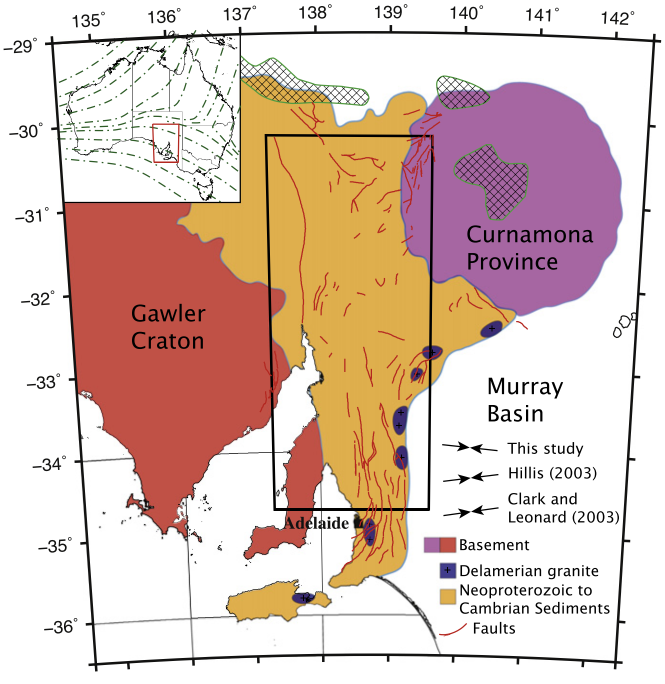

Fig. 1. Simplified geology of the Flinders Ranges adapted from Pilia et al. (2013). Previous estimates of stress from Clark and Leonard (2003) and Hillis and Reynolds (2003) are shown. Green hatched areas are the approximate locations of springs with elevated He^3/He^4 ratios (Commission, 2013). The black box in the main figure represents the region of study. The inset of Australia shows S_{Hmax} trajectories also from Hillis and Reynolds (2003), and the red box represents the region of geology shown in this figure. The area of Neoproterozoic/Cambrian sediments includes the Adelaide Rift Complex.

However, other less well-known paleorifts offer closer comparisons to the FRSZ. These include the Charlevoix Seismic Zone in Canada (Lamontagne and Ranalli, 1996), the Narmada–Son Rift in India (Rajendran and Rajendran, 1999), and the Amazonas Rift in Brazil (Zoback and Richardson, 1996). These paleorifts are similar to the FRSZ in that they have significant earthquake activity in the lower crust.

Previous studies have offered at least four mechanisms explaining the seismic activity and apparent localization of deformation in SCR paleorifts:

2.2.1. Thermal weakening

High surface heat flow can be inferred to result from raised geotherms at depth, resulting in a ductile lower crust, a reduced effective elastic thickness of the lithosphere, and a concentration of stress in the upper crust. This mechanism has been proposed for the Flinders/Mt. Lofty Ranges region itself (Holford et al., 2011), and for the Reelfoot Rift (Liu and Zoback, 1997) (see, however McKenna et al., 2007), and implies a shallow seismogenic zone and ductile lower crust.

2.2.2. Stress concentration

Rifting of continental crust can result in emplacement of a dense material ("rift pillow") in the lower crust, and the bending and isostatic buoyancy forces associate with this density anomaly could concentrate stress in its vicinity. Zoback and Richardson (1996) argue that this is consistent with a change in direction of maximum horizontal stress near the Amazonas Rift. Stuart et al. (1997) also suggest it may be important for the Reelfoot Rift. This mechanism should result in substantial changes in stress, both in the horizontal plane as well as in vertical cross section, which can result in changes to the direction of S_{Hmax}, and possibly the faulting regime as a function of depth.

2.2.3. Isostatic rebound

Post-tectonic, erosion-driven isostatic rebound of these high-elevation regions like the FRSZ may give rise to enhanced seismicity (Lambeck et al., 1984). However, most of the earthquakes in the FRSZ are compressional, which does not support the deformation pattern that one would expect from an isostatically rebounding region.

2.2.4. Fluid-assisted faulting

Several studies have invoked high pore pressure to explain earthquakes in SCR paleorifts. High pore fluid pressure has been suggested as a mechanism for earthquake occurrence in the Cherlovoix (Lamontagne and Ranalli, 1996), and the Narmada–Son paleorift (Rao and Rao, 2006). Also, Mishra and Zhao (2003) claimed to detect the presence of fluids near the hypocenter of the 2001 Buhj earthquake in the Kutch rift. High pore fluid pressure may enable failure on high-angle reverse faults, but the maintenance of high pore fluid pressure in the absence of tectonic or magmatic activity is difficult to explain (Frost and Bucher, 1994).

3. Data and analysis

3.1. Seismograph deployment

A temporary network of broadband seismometers was deployed by Geoscience Australia (GA) and the Geological Survey of South Australia (GSSA) in the Flinders Ranges from 2003 to 2005 (Cummins et al., 2004, see Fig. 2). Although this is a relatively short period of time to record intraplate seismicity, the resultant dataset included over 500 local earthquakes. This study utilizes recordings of these earthquakes by a total of 27 stations, including both those of the temporary deployment and stations of the permanent networks in the region operated by GSSA and GA. All earthquakes in this dataset are quite small, with the largest earthquake having $M_L = 4.05$. As discussed below, 65 focal mechanisms were determined from the dataset — a dramatic increase over the six