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Basin formation by thermal subsidence of accretionary orogens

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ABSTRACT

Subsidence patterns of 18 stratigraphic sections from five sedimentary basins around the world are analysed by forward and inverse modelling, in order to explain the mechanisms by which basins form on the juvenile crust generated by accretionary orogens. Study areas are the Paraná Basin (Brazil), Karoo Basin and Cape Fold Belt (South Africa), the Arabian Platform, Scythian and Turan platforms (Central Asia) and eastern Australia. The form of the tectonic subsidence curves derived from backstripping analysis is consistent with results from a forward model, which produces thermal subsidence of crust with normal thickness (~35 km) but low initial mantle lithosphere thickness. This high thickness ratio of crust:mantle lithosphere is the plausible initial configuration of lithosphere produced by accretionary tectonics. Our results do not require late stage orogenic extension or lithosphere delamination as a precursor to the thermal subsidence phase.

1. Introduction

The subsidence mechanism of intercratonic (intracontinental, or simply cratonic) basins has long been debated. These broad, uniform, basins are not easily explained by either rifting or lithospheric flexure (Allen and Allen, 2005). Holt et al. (2010) studied the Ghadames and Kufra basins, North Africa, and suggested that their Palaeozoic subsidence was a consequence of the formational properties of the region's Neoproterozoic accretionary crust (Bumby and Guiraud, 2005; Caby and Monié, 2003; Guiraud and Bosworth, 1999). Such crust inherits the thin mantle lithosphere of many of its constituent building blocks (island arcs, accretionary wedges and young oceanic crust), and as this cools and thickens following tectonic assembly it causes subsidence as an isostatic response. However, it has not yet been proven if the process is an inherent property of juvenile crust generated by accretionary orogeny (Cawood et al., 2009), and therefore generally applicable. This paper aims to test this subsidence mechanism by looking at an overview of the subsidence patterns from a number of regions of accretionary crust.

Accretionary crust is defined as continental crust which forms during an accretionary orogen, which unlike a collisional orogen overlies at least one active oceanic subduction zone throughout its history (e.g. Collins et al., 2011; Kusky et al., 2013; Şengör and Natal'in, 1996; Xiao et al., 2004). It may also be referred to as juvenile crust (in relation to older cratonic crust). Accretionary orogens occur on the margins of pre-existing continental nuclei, and are a focus for crustal growth. For example, the majority of granitoids from the Central Asian Orogenic Belt consist of high proportions (60 to 100%) of mantle-derived material (Jahn et al., 2000). Accretionary crust can vary in thickness from <30 km to >50 km. It is made up of differing terranes including island arcs, slivers of back arc crust, accretionary wedges from the forearc, slices of obducted oceanic crust and older microcontinental blocks embedded in broad collages of more juvenile material.

A key aspect of such crust is that it may be of near normal thickness, but is commonly underlain by thin mantle lithosphere at the time of accretion (e.g. Zhao et al., 1994; Zor et al., 2003). The reason for this is that the tectonic and magmatic processes that produce such crust are not necessarily complemented by equivalent processes to form an underlying mantle lithosphere. For example, slivers of a subducting plate may be scraped-off and accumulate to form an accretionary wedge above the subduction zone, but this is a process that builds crust, not mantle lithosphere. Also, before final accretion and the end of subduction, corner flow of the hydrated, weak mantle wedge may act to limit and reduce mantle lithosphere thickness (e.g. Eberle et al., 2002; Hyndman et al., 2005). Once final subduction has ceased under an accretionary orogeny, any such thin mantle lithosphere will tend to thicken, in the manner of lithosphere thinned after a rifting event (McKenzie, 1978), with the crucial difference that there need not have been any such stretching event to produce the thin mantle lithosphere.

Ultimately, such accretionary orogens may be the principal sites for net crustal growth, and have operated as such back into the Archaean (Cawood et al., 2009). The ages of accretion for the continental crust are shown in Fig. 1. Dimensions may be vast: 1000s × 1000s of km.

Many of these accretionary orogens have large, intact, platformal sedimentary sequences that accumulated upon them. This study examines the Paraná Basin, Cape Fold Belt and Karoo Basin, Arabian Platform, Scythian and Turan platforms and the post-Tasmanide basins of eastern Australia. These areas represent basins established over accretionary crust that formed at various times ranging from the Neoproterozoic to

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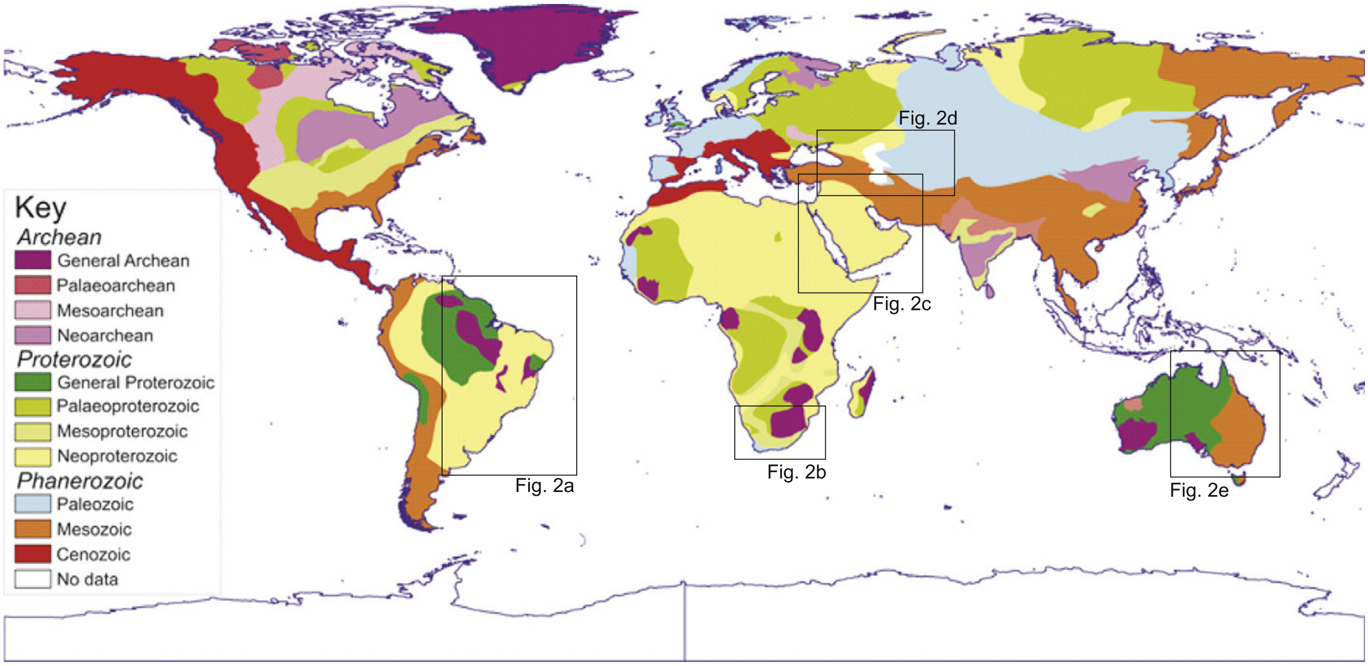

Fig. 1. Age of assembly of continental crust. This is not necessarily the age of the units within each area, but the age at which that region of crust was assembled as a unit. This is a compilation of data from numerous publications covering South America (Almeida et al., 2000; Milani and De Wit, 2008), North America (Canil, 2008; Williams et al., 1991), Europe (Gee and Stephenson, 2006), Africa and Arabia (Begg et al., 2009; Van Hinsbergen et al., 2011), Asia (Şengör and Natal'in, 1996) and Australia (Debayle and Kennett, 2003).

the Mesozoic. The global spread of the study areas gives confidence that we are dealing with a fundamental process, rather than a localised phenomenon. Basins were chosen because they are large, representative features for which data are available; there was no filtering of locations to try and find the best fits to the proposed model.

A number of other subsidence mechanisms have been suggested for these basins. Recently, it was suggested that many such basins form due to stretching of the continental lithosphere at low strain rates for long periods of time (50–100 Myrs) (Armitage and Allen, 2010). This produces a subsidence profile that begins with a straight line during the stretching phase, and then has a slight kink followed by a curved section caused by cooling acting over the stretched area. Dynamic topography has been suggested as an appropriate basin-forming mechanism (e.g. Gurnis, 1992), whereby subsidence is related to large-scale mantle flow patterns. It has also been suggested that regional subsidence is due to orogenic collapse following an accretionary orogeny, because the mantle lithosphere undergoes delamination (Ashwal and Burke, 1989; Burke et al., 2003). This scenario envisions a high density of small rifts, similar to the Basin and Range province, followed by a period of broad scale uniform subsidence with an exponential decay as the delaminated lithosphere is replaced by cooling upper mantle. Avigad and Gvirtzman (2009) suggested that there was a partial mantle lithosphere detachment under the Arabian region in the Late Proterozoic, leading to initial surface uplift, but subsequent cooling and subsidence. There are similarities between this model and our study (in that both models envisage thermal subsidence as thin lithosphere cools and thickens), but we do not require the initial detachment.

There are many other mechanisms which have been suggested for individual basins, such as simple rifting (Oliveira and Mohriak, 2003) or back arc extension (Thomas et al., 1999), and flexure to create a foreland basin (Catuneanu, 2004; Milani and De Wit, 2008). We propose that the large scale and geometry of each of the basins in this study are incompatible with these "conventional" mechanisms. For example, the Palaeozoic basins of North Africa and Arabia represent an original "megabasin" covering ~10,000,000 km^2 from the Atlantic margin to the eastern edge of Arabia. Allowing for continental fragments now dispersed within Iran and adjacent countries, it was probably once even larger (Şengör and Natal'in, 1996).

2. Methodology

The first step in assessing the cause of the subsidence in each region is to backstrip the sedimentary record to get the tectonic subsidence of the region, i.e. inverse modelling. Results can then be compared to subsidence produced by a numerical forward model of thickening and cooling of the mantle lithosphere.

Backstripping is the process of calculating the tectonic subsidence from a sedimentary column. The practice is commonplace and the approach used here follows that of Watts and Ryan (1976), described in detail in Holt et al. (2010). We use standard relationships from published work (Sclater and Christie, 1980) for the porosity-depth relationships. A global eustatic sea-level curve (Haq and Schutter, 2008) is used to remove the effects of sea-level changes. Some of the study areas already have backstripped subsidence curves available in the literature. In other areas backstripping was carried out using available published records of the stratigraphy, either from well data, regional cross-sections constructed using seismic data, or regional stratigraphic columns based on thicknesses from fieldwork studies. In each region different data sources are used if available, to allow comparison between subsidence curves calculated from different data sets. Where there is disagreement in the literature as to the ages of the sediments, a subsidence curve is calculated for each conflicting interpretation.

The subsidence produced by thickening and cooling of the lithosphere beneath accretionary crust is calculated using a numerical forward model described in Holt et al. (2010), and explained below. This model calculates the conductive heat flow through a column of crust and upper mantle material and then the resultant subsidence of the column. The subsidence calculated is water loaded tectonic subsidence and therefore is directly comparable to that calculated from the backstripping.

The numerical subsidence model is based on and tested against the plate models for sea floor spreading (Parsons and Sclater, 1977). It is