

Lithospheric cooling and thickening as a basin forming mechanism

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ABSTRACT

Widely accepted basin forming mechanisms are limited to flexure of the lithosphere, and lithospheric stretching followed by cooling and thermal subsidence. Neither of these mechanisms works for a group of large basins, sometimes known as “intracontinental sags”. In this paper we investigate cooling and thickening of initially thin lithosphere as a basin forming mechanism, by a combination of forward modelling and a backstripping study of two Palaeozoic North African basins: Ghadames and Al Kufrah. These are two of a family of basins, once unified, which lie over the largely accretionary crust of North Africa and Arabia. Such accretionary crust tends to be juvenile, consisting of amalgamated island arcs, accretionary prisms and melanges, and typically has near-normal crustal thicknesses but initially thin mantle lithosphere. Post-accretion subsidence is modelled using a plate cooling model similar to cooling models for oceanic lithosphere. The crustal composition and thickness used in the models are varied around average values of accretionary crust to represent likely heterogeneity. The model allows the lithosphere to thicken as it cools and calculates the resulting isostatic subsidence. Water-loaded tectonic subsidence curves from these forward models are compared to tectonic subsidence curves produced from backstripped wells from Al Kufrah and Ghadames Basins. A good match between the subsidence curves for the forward model and backstripping is produced when the best estimates for the crustal structure, composition and the present day thickness of the lithosphere for North Africa are used as inputs for the forward model. The model produces sediment loaded basins of 2–7 km thickness for the various crustal assemblies over ~250 Myr. This shows that lithospheric cooling provides a viable method for producing large basins with prolonged subsidence, without the need for initial extension, provided the condition of initially thin mantle lithosphere is met.

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1. Introduction

Conventional basin formation mechanisms can be divided into two categories, lithospheric stretching followed by thermal subsidence proportional to the extension (rift basins) and flexure caused by tectonic loading (foreland basins) (Allen and Allen, 2005). However, there is scant evidence for either of these mechanisms forming a group of basins normally classified as “intracontinental sags”—a term that describes their geometry rather than the process of formation. Examples include the Williston and Michigan basins of North America (Klein, 1995), the Palaeozoic basins of North African and Arabia (Boote et al., 1998; Konert et al., 2001); and the Mesozoic Scythian and Turan platforms (Natal'in and Şengör, 2005). The basins are large features, commonly over 1000 km in length, with remarkably uniform, prolonged, gentle subsidence across them, lasting over 200 Myr. They generally have a polyphase history with a main subsidence phase either preceded or followed by other periods of subsidence and uplift which modify the basin. Armitage and Allen

(2010) recently proposed that these basins are formed by stretching under low strain rates. They argued this based upon the modelling of rifting under low strain rates and the observation that the initiation of subsidence in many intracontinental basins coincides with supercontinent breakup and therefore a broad extensional regime. However, in many basins the evidence for rifting is poor and a number of other mechanisms have been proposed. Subsidence due to cooling of thermal anomalies in the lithosphere has been proposed for the North American intracontinental basins (Kaminski and Jaupart, 2000). The main evidence for this is matching modelling results with the shape and thickness of the present day sedimentary cover. A density change in the crust due to phase changes such as a basalt underplate changing to eclogite has also been suggested based on high velocities in the lower crust interpreted from seismic refraction data (Artyushkov, 2005). However, beneath the Barents/Kara sea region a high density area in the lower crust, suggested by modelling gravity data, has been deemed too local to cause subsidence across the basin. Instead Ritzmann and Faleide (2009) have suggested that a deeper high velocity zone visible in seismic tomography is evidence of a thick cratonic lithosphere, which causes the subsidence. Heine et al. (2008) noted that many intracratonic basins overlie areas of mantle which have been downwelling over the last 100–150 Myr in their coupled

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plate and mantle flow model. They proposed that dynamic topography could form these basins. Other subsidence mechanisms and variations on those above have been suggested and are debated in more detail by Armitage and Allen (2010) and Klein (1995). It is likely that one mechanism does not explain the formation of every intercontinental basin and in some cases the basin may be formed by a combination of mechanisms.

Here we show that cooling and thickening of initially thin mantle lithosphere, beneath a crust of normal thickness (~30 km) is a viable mechanism for producing basin-scale subsidence. Such initial conditions are typical of accretionary crust, a term used to summarise the vast orogenic collages of largely juvenile crust and mantle lithosphere, formed by the collision of non-cratonic terranes: island arcs, accretionary prisms, ophiolites and isolated microcontinents (Murphy and Nance, 1991; Şengör et al., 1993). This would neatly explain the formation of many of the intracratonic basins on juvenile continental crust such as the Pan African mobile belt or the Scythian and Turan platform. However, we show that where the lithosphere is thinned by a thermal anomaly it is also possible to form broad, slowly subsiding basins.

This subsidence mechanism is discussed in greater detail in Section 2, followed by a case study of two of the North African Palaeozoic basins. Thermal subsidence has been suggested as the cause of intracratonic basins before (Kominz, 1995; Kaminski and Jaupart, 2000; Guiraud et al., 2005). Our contribution is to model the subsidence, compare it to subsidence in two case studies and to discuss why the lithosphere is plausibly thin in the first place. The subsidence history of the basins is analysed using backstripping. This analysis is compared to results from a numerical forward model of thermal subsidence acting on accretionary crust, designed to test if it is a mechanism capable of producing the observed subsidence.

2. Geological background and hypothesis

Seismic refraction studies show that present day island arcs can have a crustal thickness of 25–35 km, similar to normal continental crust (Holbrook et al., 1999; Takahashi et al., 2007). However, seismic tomography shows slow velocities in the mantle wedge below island arcs which are interpreted as evidence for the presence of melts and thin (~20 km) mantle lithosphere because it is weakened by the addition of fluids from the subducting slab and then eroded by the corner flow in the mantle wedge (Zhao et al., 1994; Gorbatov et al., 1999). This is supported by numerical models of subduction (Stern, 2002; van Keken, 2003; Arcay et al., 2006), by geochemical evidence from the southward initiation of the Philippine subduction zone (Macpherson, 2008) and from the Cascades (Elkins Tanton et al., 2009). These studies suggest an average overall lithospheric thickness of about 50 km beneath island arcs (Fig. 1a).

Accretionary prisms may be 30 km thick, largely composed of off-scraped and imbricated fragments of oceanic crust and its sedimen-

tary cover. While subduction is active such prisms are underlain by the oceanic plate. When subduction has recycled the oceanic plate in to the mantle, the base of the prism may be in contact with the asthenosphere, particularly if ocean closure resulted in the collision of two such prisms, initially on opposite sides of the ocean, rather than collision of the prism with a continental margin. The Cenozoic East Anatolian Accretionary Complex may be an example of such a lithospheric structure, where tomographic studies suggest a thin or even absent mantle lithosphere (Zor et al., 2003).

A notable feature of accretionary orogenic belts is that they lack evidence for substantial crustal thickening (and presumably lithosphere thickening): there is rarely evidence for pre-collision passive continental margins, Alpine-type nappes, or overfilled foreland basins ("molasse") (Şengör and Okurogullari, 1991). This means that putative lithospheric delamination following an orogeny of this type, hypothesised by Ashwal and Burke (1989), is not our preferred mechanism for thinning the lithosphere. However, it would produce similar starting conditions to those in our model.

As accretionary crust is assembled through subduction and collision, the thin mantle lithosphere of the original terranes is inherited by the final collage (Fig. 1b). We hypothesise that once accretion is completed, and subduction has ceased beneath an area, the underlying asthenosphere will cool, thickening the mantle lithosphere. This cooling will cause prolonged subsidence, forming basins (Fig. 1c).

Our model is similar to the thermal subsidence phase of McKenzie style rifting (McKenzie, 1978) or the subsidence of the ocean floor away from a mid-ocean ridge, except that the crust involved is continental, albeit juvenile, and has not been thinned in any way. In this paper we proceed to show how this mechanism could produce the basins in North Africa. However, there are many other intracratonic basins on accreted crust where this mechanism could apply. Table 1 provides a sample of some of the basins we are aware of, but is by no means an exhaustive list. Allen and Armitage (in press) note a clustering in time of the initiation of intracratonic basins which they link to the breakup of supercontinents. In Table 1 we show that the start of subsidence follows closely the end of accretion and the clustering may be related to the end of periods of accretion of crust. The basins are long lived features and so many have later phases of subsidence which potentially have other causes.

3. Tectonic subsidence history of backstripped North African basins

In order to test whether the proposed mechanism of subsidence provides a good explanation for anomalous basins developed over accretionary crust, subsidence histories for the Ghadames and Al Kufrah Basins were investigated using backstripping. These are Palaeozoic basins situated on the North African crust, which was accreted in the Pan African orogeny during Neoproterozoic times

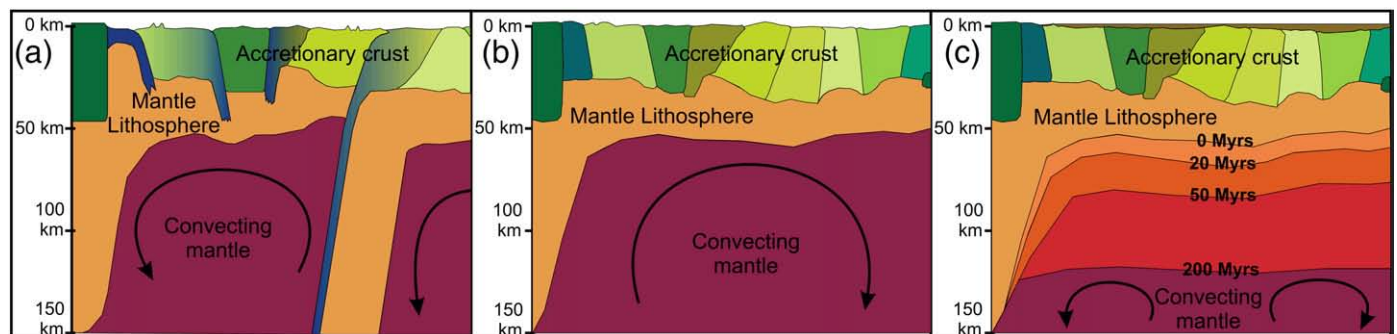


Fig. 1. Formation of accretionary crust and subsequent lithospheric thickening and subsidence. a) Assembly of accretionary crust from island arcs and other crustal fragments through subduction. b) Newly formed accretionary crust with a thinned lithosphere. c) Lithospheric thickening due to cooling causing subsidence.

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