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Deformation driven by deep and distant structures: Influence of a mantle lithosphere suture in the Ouachita orogeny, southeastern United States

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ABSTRACT

Mantle lithosphere heterogeneities are well documented, are ubiquitous, and have often been thought to control lithosphere-scale deformation. Here, we explore the influence of deep scarring in crustal deformation in three dimensions by considering the Ouachita orogeny in the southeastern United States, an example of a continental collision where mantle structure is present but not previously linked to the regional crustal tectonics. We present state-of-the-art continental compressional models in the presence of inherited three-dimensional lithospheric structure. Our models find that the surface expression of the Ouachita orogeny is localized by, and projected from, the controlling mantle scarring, in keeping with geological and geophysical observations. We are able to produce a large-scale arcuate orogeny with associated basin development appropriate to the Ouachita orogeny, alongside smaller-scale crustal faulting related to the region. This study offers a new and alternative hypothesis to the tectonic history of the Ouachita orogeny, with previous research having focused exclusively on crustal structures. The findings have broad implications, demonstrating the important potential role of the mantle lithosphere in controlling crustal dynamics and highlighting the requirement to consider deeper structure and processes when interpreting tectonic evolution of lithospheric-scale deformation.

INTRODUCTION

For decades, a catalogue of structures within the mantle lithosphere has been available and the structures' genesis widely interpreted (e.g., Vauchez et al., 1997; Holdsworth et al., 2001). However, the fundamental role of the mantle lithosphere, and structures within it, as a guide for crustal tectonics is still commonly overlooked in geological interpretation. In the example of the Ouachita orogeny in the southeastern United States, a lithospheric seismic and gravity profile images an inferred mantle lithosphere suture (Mickus and Keller, 1992) that we propose has played an important role in the tectonic evolution of the region. Previous studies have considered crustal heterogeneities only (e.g., Calignano et al., 2017), but here we apply observationally constrained numerical geodynamic models to test whether a mantle lithosphere scar (inherited from an earlier suturing event) generates deformation similar to that displayed by the regional tectonics—in this case, an arcuate orogeny with associated basin development. We present a suite of forward models showing the influence of a mantle lithosphere scar in the presence of other forms of lithospheric inheritance.

OUACHITA OROGENY

The crustal tectonics of a north-south section of the Ouachita orogeny within the Ouachita embayment (Fig. 1A) is given in Figure 1B (Mickus and Keller, 1992), where thrusting and folding of Cambrian–Mississippian sediments and the development of the Arkoma Basin are believed to have occurred during late Paleozoic convergence (Thomas, 1991). Data from wide-angle seismic reflection-refraction surveys of the orogeny indicate that zones of crustal tectonics connect to mantle suture zones (Keller and Hatcher, 1999), with an offset of ~100–200 km, linking surface to Moho deformation across the Ouachita orogen.

There are a number of tectonic mechanisms proposed for the Ouachita orogeny. The closure of an interior ocean to the south of the Ouachita Mountains has previously been proposed, with a southward-dipping subduction zone thought to have played a role in accreting the Sabine block to Laurentia during the Ouachita orogeny (e.g., Lillie, 1985; Houseknecht, 1986). Another model requires early Paleozoic thinning (Lowe, 1985), with subsequent north-south shortening across the Ouachita orogeny (Craddock et al., 1993) reactivating oblique preexisting crustal rift structures (e.g., Thomas, 2010). It has also been suggested that the Sabine block accreted to North America in the Proterozoic and that the Ouachita orogeny represents a reactivation of an older suture (Dunn, 2009; Griffin et al., 2011). If the Ouachita orogeny is a reactivation of inherited structures, it can be thought of as an intracontinental orogeny (Fig. 1C), where no interior ocean was closed in the convergence (Keller and Cebull, 1973; Clift et al., 2018).

In this study, we outline a two-phase tectonic history where a mantle suture is generated and then contributes to crustal deformation. We consider that the mantle lithosphere heterogeneity inferred from existing geophysical profiles (Fig. 1B) is inherited from a Proterozoic collision of North America and the Sabine block (Figs. 1Ci–1Cii; Dunn, 2009). However, the timing of the suture could have been at any point before the Ouachita crustal deformation commenced for our models to be valid—the two-phase tectonic process is key. This deep seismic-velocity heterogeneity and density contrast between mantle blocks (Mickus and Keller, 1992) is interpreted to be a lithosphere shear zone that we propose has facilitated the intracontinental collisional tectonics of the Ouachita orogeny (Fig. 1C). Our study represents the first to demonstrate quantitatively the possible role of the mantle lithosphere in controlling the tectonic style expressed in the near-surface geology.

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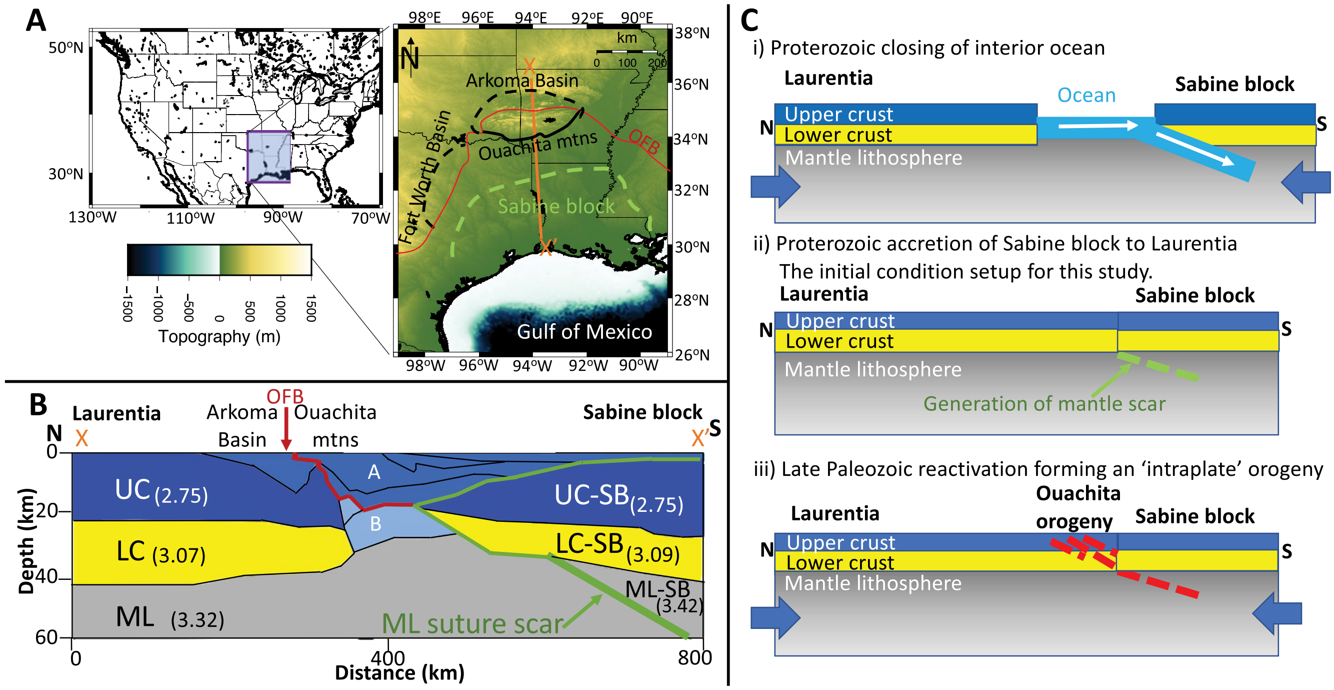

Figure 1. A: Present-day map of Ouachita orogeny in southeastern United States and Gulf of Mexico. Ouachita fold belt (OFB, red), Ouachita Mountains (solid black), Arkoma and Fort Worth Basins (dashed black), and Sabine block outline (dashed green) are shown (Mueller et al., 2014). B: Crustal-scale section of X-X′ from A. Modified from Mickus and Keller (1992) and Calignano et al. (2017). Stratigraphic interpretation (UC—upper crust; LC—lower crust; ML—mantle lithosphere; SB—Sabine block; A—crustal deformation; B—transitional crust) from Jusczuk (2002). Model density values from Mickus and Keller (1992) in parentheses (g/cm³). C: Proposed tectonic history of region following Dunn (2009) and Keller and Cebull (1973).

MODEL

The role of three-dimensional (3-D) mantle lithosphere structure in a continental collisional tectonic setting similar to that of the Ouachita orogeny is investigated. The models are implemented in a high-resolution 3-D Cartesian box (Fig. 2A), using the numerical code ASPECT (Heister et al., 2017). We use a nonlinear viscous flow (dislocation creep) and Drucker-Prager plasticity for the model rheology (e.g., Naliboff and Buiter, 2015). The rheological profile is defined by "normal" lithosphere (e.g., Ranalli and Murphy, 1987) as shown in Table DR1 and Figure DR1 in the GSA Data Repository[1].

The model setup is described in Figure 2A, where the 3-D box undergoes north-south compression at 1 cm/yr on both sides of the lithosphere (with prescribed return flow below to ensure mass balance). All models have ~1 km of resolution in the crust and upper mantle lithosphere (Fig. DR2). In the reference case, model ML, we implement a mantle lithosphere (ML) scar (green outline in Figs. 2A and 2B) that approximates the shape and extent of the suture surrounding the Sabine block (Fig. 1A). There are a number of mechanisms for which a mantle lithosphere suture could remain weak over time (Heron et al., 2016b), one of which is through grain-size reduction of peridotite mylonites at ancient plate boundaries (Bercovici and Ricard, 2014). Here, the ML scar for the reference model ML is 10 km thick, dipping at an angle of 15° from the horizontal (Fig. 2A), and rheologically weak by having a reduced angle of internal friction compared to the surrounding material. The influence of changing shape and dip angle of generic styles of such weak scars is explored in detail in Heron et al. (2016b), Jourdon et al. (2017), and the Data Repository.

ROLE OF MANTLE LITHOSPHERE SCARRING

Plate convergence is applied to continental lithosphere in the presence of a mantle suture in model ML (e.g., Fig. 1Cii). Figure 2C shows the surface strain rate and tectonic deformation after 4 m.y. (80 km) of convergence. The high surface strain rate represents the main deformation front, with orogen and basin development outlined in solid and dashed lines, respectively (Fig. 2C). The mantle lithosphere heterogeneity, modeling the suture of the Sabine block (original position given by green lines), produces basin deformation and an arcuate orogeny with a main front generated at an offset of ~100 km from the edge of the mantle lithosphere (Fig. 2C).

Lithosphere-scale cross sections of the model show crust and lithosphere deformation alongside areas of high strain rate (Figs. 2D–2F). In Figures 2D and 2E, the main thrust fault (denoted by the high strain rate) of the orogeny is generated back from the original mantle lithosphere scarring. There is also strong crustal deformation above the mantle scar just to the south of the center of cross section E-E′. The most eastern cross section (Fig. 2F) displays mantle lithosphere and more subdued crustal deformation despite not sampling the original mantle "suture" (F-F′, Fig. 2C). Notably in this case, the deep heterogeneity is controlling tectonics at some lateral distance from its location.

The regional tectonic shape of model ML (Fig. 2C) matches that of the Ouachita orogeny (Fig. 1A)—an arcuate thrust front is clear in both, following the outline of the Sabine block at an offset (a formal comparison is given in Fig. DR6). This front and the model orogen and basin position are similar to the Ouachita fold belt, the Ouachita Mountains and complex Fort Worth–Arkoma Basins, respectively (Fig. 1A). This comparison continues when analyzing the cross sections across the orogeny (Figs. 1B and 2E), with the main thrust cutting the crust and mantle lithosphere in both the seismic and model images, with additional zones of deformation to the south of the orogeny above the mantle lithosphere scar and bounding the basin that develops in the north.

In Figure 3, we present the impact of a mantle lithosphere scar in the presence of an inherited crustal structure, simulating deformation remaining from the accretion of the Sabine block to Laurentia (Fig. 1C). Like the ML scar in model ML, the crustal scars have a reduced angle of internal friction to simulate an inherited

[1]GSA Data Repository item 2019056, methods in this work, as well as supplementary figures, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

weakness, and have the same dip as the ML scar. In model UC (Fig. 3A), strain rate patterns due to the crustal scarring only (with no mantle lithosphere heterogeneity in place) are presented. After extensive shortening, the crust fault does not generate localized lithosphere-scale deformation and only produces shallow tectonics (Fig. 3C). Furthermore, such crustal inherited structures become secondary zones of deformation in the presence of a mantle lithosphere suture (model UC-ML; Figs. 3D–3F). In model UC-ML, the deep scar controls tectonics over the shallow crustal inheritance as shown in the early development of strain rate patterns (Fig. 3E) and in the lithosphere cross section (Fig. 3F), producing similar deformation to that in model ML.

WE SHOULD BE LOOKING DEEPER

Our mechanism for Ouachita deformation has broad implications for lithosphere geodynamics and supplements recent studies on the role of mantle heterogeneities. In keeping with an extensive suite of simulations analyzing the importance of lithosphere rheology in the role of mantle lithosphere scars (Heron et al., 2016b), Jourdon et al. (2017) also found that the reactivation of a mantle suture strongly influences the localization and deformation of tectonics. Hansen and Nielsen (2003) presented numerical models of shortening in the presence of a preexisting crustal rift basin, which developed "marginal troughs" in a flexure response to crustal thickening (e.g., Sydorenko et al., 2017). The work presented here may offer an alternate, deeper source mechanism for the evolution of marginal sedimentary depocenters and the geometry of shortening throughout the lithosphere generally (Fig. 2C).

A number of recent seismic imaging studies have presented a possible deeper cause of

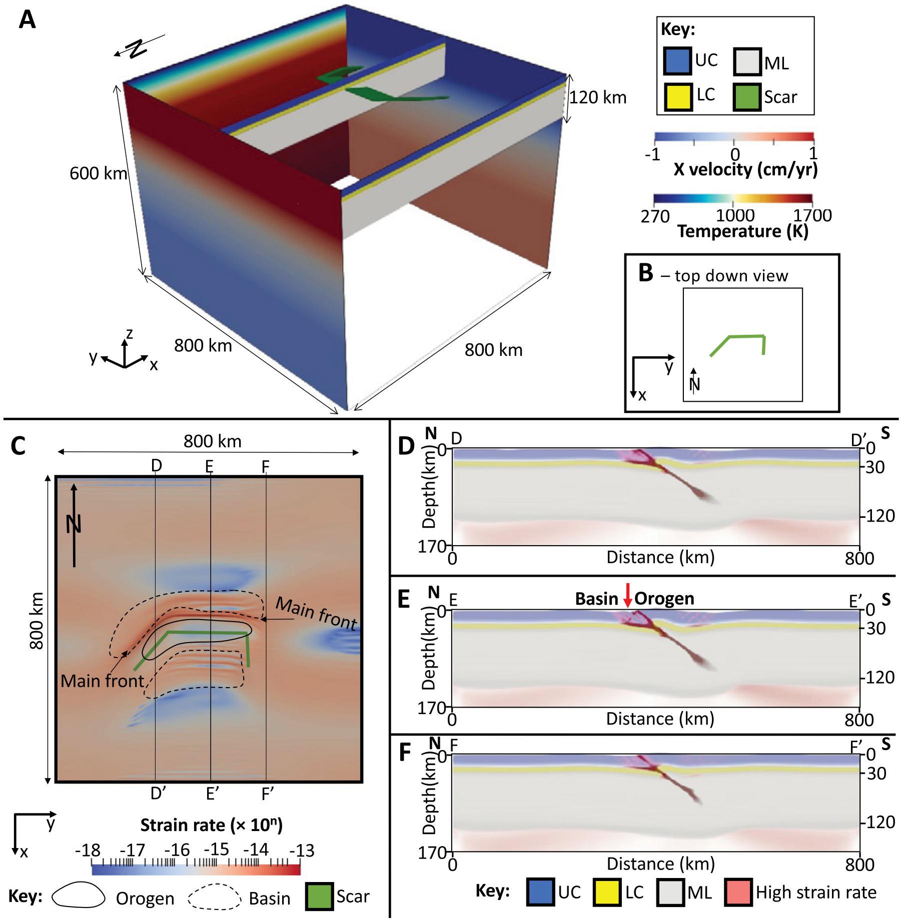

Figure 2. A: Initial setup of numerical models presented here: three-dimensional box featuring crust, mantle lithosphere, and mantle scar with compression applied to top 120 km (lithosphere) in north-south direction, with outflow applied in mantle below. East panel shows initial temperature profile across whole box. UC—upper crustal; LC—lower crustal; ML—mantle lithosphere. B: Top-down view of outline of mantle scar taken at 32 km depth. C: Modeling results for model ML after 4 m.y. of compression: top-down view of surface strain rate with main thrust front, showing orogenic (>1 km topography) and basin (>0.5 km) region highlighted and original position of mantle lithosphere scar at depth. D–F: Lithosphere cross sections as shown in C with upper and lower crust and mantle lithosphere shown. High strain rate is applied on top of material fields. Deformed mantle lithosphere scars are coincident to high strain rate.

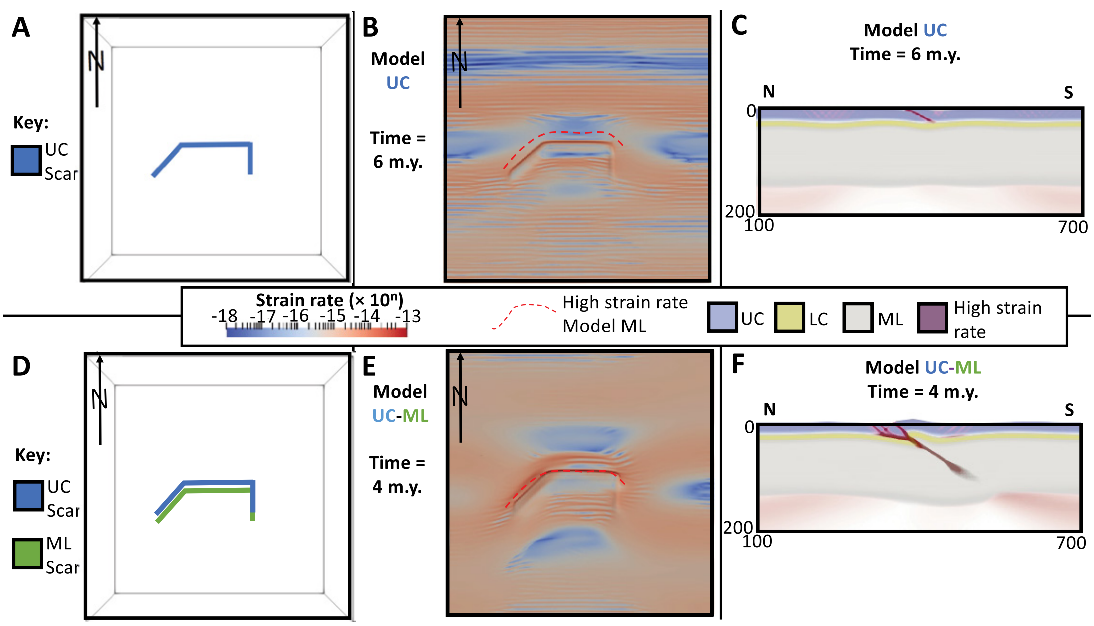

Figure 3. Deformation patterns in presence of crustal heterogeneities. A–C: Outline of upper crustal (UC) scar for model UC (featuring just UC scars) (A), with corresponding surface strain rate plot (B) and cross section of lithosphere deformation for line E-E′ (C) (Fig. 2B) at 6 m.y. Crustal scarring does not localize deformation on lithosphere scale. D–F: Outline of upper crustal scar for model UC-ML (featuring UC and ML [mantle lithosphere] scars) (D), with corresponding surface strain rate plot (E) and cross section of lithosphere deformation for line E-E′ (F) (Fig. 2B) at 4 m.y. Reactivation of mantle scarring dominates tectonic evolution of region. LC—lower crustal.

crustal tectonics. In discussing the Sorgenfrei-Tornquist Zone (southern Scandinavia), Phillips et al. (2018) highlighted that structures within the sub-crustal lithosphere are commonly associated with complex upper-crustal rift systems and may exert a strong influence over their geometry and development. Mid-lithosphere discontinuities beneath the northern United States craton (Hopper and Fischer, 2015), interpreted from converted wave imaging, have also added to a growing body of work that is enhancing our understanding of plate-tectonic inheritance. Such deep structures may be potential tectonic triggers that indicate that ancient plate boundaries may be geologically very long-lived, remaining "perennially" active (Heron et al., 2016a).

CONCLUSIONS

For the first time, 3-D numerical models for the Ouachita orogeny are presented that include mantle heterogeneity previously identified by geophysical data (e.g., Mickus and Keller, 1992). The complex arcuate orogeny and basin formation of the Ouachita regional tectonics (Fig. 1) can be simulated through taking into consideration ancient mantle sutures (Fig. 2). Our models indicate that the presence of a mantle lithosphere structure in lithosphere-scale tectonics can override inherited crustal-level structural controls and dominate the geological expression of regional tectonics. The results are an important contribution to a growing body of work that is posing questions on the fundamentals of tectonic activity and shows that we should be looking deeper than the Moho for controls on the tectonic style of lithosphere-scale deformation.

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