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ABSTRACT

The Llano uplift of central Texas, United States, exposes the core of a Mesoproterozoic orogenic belt that formed along the southern margin of Laurentia during Grenville time. A new collisional model is proposed that reconciles differences in structural stacking, apparent tectonic transport, and deformation conditions between the eastern and western portions of the uplift and explains uplift and exhumation of high-pressure eclogitic rocks, emplacement of ophiolitic rocks, and subsequent late-stage to postcollisional plutonism. Our model proposes that subduction with southward polarity resulted in collision of an exotic arc with Laurentia, emplacement of ophiolitic rocks, and telescoping of the intervening basinal sediments, followed by overriding of the arc and margin of Laurentia by a southern continent with transport toward Laurentia. The model further proposes that convergence led to subduction of the Laurentian margin, resulting in high-pressure metamorphism, but buoyancy forces due to subduction of continental crust under the southern continent resulted in uplift and retrotransport away from Laurentia, in a manner similar to that proposed for the Alpine orogeny. Slab breakoff resulted in upwelling of the asthenosphere, leading to intrusion of juvenile granitic plutons. Subduction along strike caused continued contraction that waned with time. The eastern uplift records continent-arc-continent collision, whereas the western uplift records continent-continent collision; the two regions also expose different crustal levels in the orogen. The striking similarity with Phanerozoic orogens, including emplacement of ophiolites and formation of high-pressure rocks, implies that plate tectonic processes including subduction were active prior to the Neoproterozoic.

Keywords: Grenville, Llano uplift, plate tectonics, Mesoproterozoic, subduction.

INTRODUCTION

Evolution of Proterozoic orogens is commonly explained in terms of modern-day plate tectonic processes (e.g., Hoffman, 1980; Tyson et al., 2002). However, others cite an apparent lack of ophiolites and high- to ultrahigh-pressure rocks to suggest that modern subduction processes did not begin until the Neoproterozoic (e.g., Maruyama and Liou, 1998; Stern, 2005). In this paper we provide an example of a Mesoproterozoic orogen along the southern margin of Laurentia that has a tectonic history—including continental subduction, continent-arc-continent collision, emplacement of ophiolitic rocks, and exhumation of high-pressure rocks—that is very similar to Phanerozoic orogens, suggesting that tectonic processes were not appreciably different during the Mesoproterozoic.

GEOLOGIC SETTING

The Llano uplift of central Texas, United States, consists of multiply deformed, Mesoproterozoic metasedimentary, metavolcanic, and metaplutonic rocks intruded by late syntectonic to post-tectonic granites (Fig. 1) (Mosher, 1998). An early high-pressure eclogite facies metamorphism is overprinted by dynamothermal, medium-pressure metamorphism at upper amphibolite facies conditions and a subsequent low-pressure, middle amphibolite facies metamorphism associated with widespread intrusion of late granites (Carlson et al., 2007).

Previous work has subdivided the metamorphic rocks into three lithotectonic domains on the basis of lithology, field relations, geochemistry, and metaplutonic and metavolcanic U/Pb zircon ages: (1) the Valley Spring domain (VSD) consists of 1288–1232 Ma plutonic and supracrustal rocks, with one older gneiss dated at 1366 ± 3 Ma, interpreted as a continental margin arc and terrigenous clastics formed on Laurentia (Mosher, 1998; Reese et al., 2000); (2) the Packsaddle domain (PSD) consists of 1274–1238 Ma supracrustal and intrusive rocks interpreted as an adjacent forearc basin (Mosher, 1998; Reese et al., 2000); and (3) the Coal Creek domain (CCD) constitutes a 1326–1275 Ma tonalitic to dioritic plutonic complex and ophiolitic rocks interpreted as an exotic arc terrane and obducted oceanic crust (Garrison, 1985; Roback, 1996). Ophiolitic material includes serpentinized harzburgite, Fe-rich low to medium K_2O metabasalts, and cumulate metagabbros with chemistry similar to island arc and abyssal tholeiites, hornblendites, and mafic schists (Garrison, 1982). The CCD has Pb and Nd isotopic and geochemical signatures distinct from PSD and VSD (Roback, 1996). All domains are intruded by granites, confirming accretion by ca. 1119 Ma (Mosher, 1998). Granites have a juvenile Nd signature and geochemistry compatible with combined crustal and depleted mantle sources (Smith et al., 1997).

The ~9000 km^2 uplift has been divided into the eastern, central, and western uplift (Fig. 1); major sets of Paleozoic normal faults delineate the boundaries. We contrast the eastern and western uplift in the following.

Eastern Uplift

Most evidence for the orogenic history comes from the well-studied eastern uplift (Fig. 1); results from previously published work (Mosher, 1998; Reese and Mosher, 2004; Mosher et al., 2004; Carlson et al., 2007) are summarized here.

Synmetamorphic deformation resulted in a regional composite S_1-S_2 fabric and associated isoclinal folds and discrete domain-bounding and intradomainal shear zones (Mosher, 1998; Reese and Mosher, 2004; Mosher et al., 2004). Structural stacking from highest (and southernmost) to lowest (and northernmost) is CCD thrust over PSD thrust over VSD. Continued

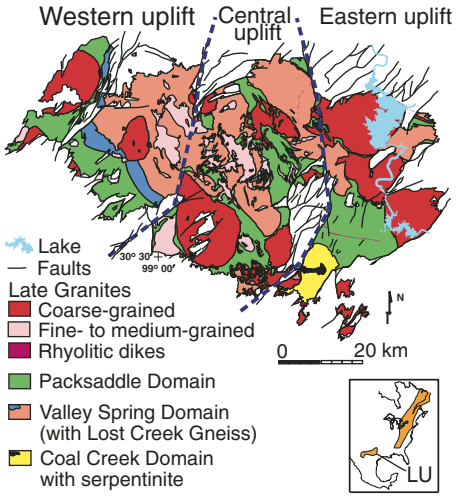

Figure 1. Geologic map of Llano uplift (LU) of central Texas. Boundaries between western, central, and eastern portions of uplift are shown (dashed dark blue lines). Inset shows surface and subsurface location of Grenville orogenic belt in North America.

deformation folded early fabrics and shear zones in three later phases of folding. Tectonic transport throughout was northeastward (F_1-S_1 through F_3-S_3 and F_5-S_5) to northward (F_4-S_4), and the dominant fabrics and domain boundaries dip southwest. The CCD was regionally metamorphosed and deformed along with the PSD and VSD. A large (6 by 2.3 km) tabular body of serpentinized harzburgite, interpreted as CCD arc basement or backarc-spreading–related oceanic crust, was tectonically emplaced within the CCD early in the deformational history (Roback, 1996).

The earliest metamorphism is recorded by eclogitic mafic layers in the VSD that yield minimum pressures of ~1.4 GPa at temperatures near 650 °C (Carlson et al., 2007); garnet cores formed at amphibolite facies conditions, whereas rims grew at eclogite facies conditions, indicating that pressure increased during metamorphism. These mafic layers parallel compositional layering in the surrounding gneisses and most likely represent sills. Nearly identical petrologic characteristics are exhibited by a large (~0.5 km diameter) eclogitic metaplutonic body that is in the central uplift, just across its boundary with the eastern uplift.

Subsequently, a medium-pressure dynamothermal metamorphism affected the eastern uplift, producing fairly uniform temperatures near ~700 °C (Carlson et al., 2007). In the VSD at deepest structural levels, deformation associated with partial melting occurred during F_1-S_1 through F_3-S_3, at reduced pressures with sillimanite (not kyanite) as the stable aluminosilicate. In the PSD, end-member Fe staurolite that grew between S_2 and S_3 records temperatures of ~700 °C at ~0.7 GPa. In the CCD, relict metamorphic enstatite and forsterite in a later reserpentinized harzburgite record temperatures ≥700 °C. Temperature conditions decreased somewhat after F_3-S_3; F_5 folds are temporally related to the late granite plutonism, which was accompanied by low-pressure metamorphism (525–625 °C at ~0.3 GPa).

Extension occurred several times during the deformational history (Mosher et al., 2004). Boudinage in orthogonal directions of the eclogitic mafic layers began while the eclogites were significantly more competent than the surrounding gneisses (forming spheres), but extension continued during retrogression to upper amphibolite facies, as shown by the pinch-and-swell structures and formation of an amphibole foliation parallel to the boudin margins and in boudin necks. These mafic layers form a series of nested boudins with surrounding gneisses and adjacent pegmatites; within these gneisses and pegmatites, S_1 and S_2 (axial planar to F_2) wrap the mafic boudins, indicating that much if not all of the extension is post-S_2. The timing relative to S_3 is unknown. Gneisses farther from the mafic layers show boudinage post-S_2 with extension in several directions. A later period of extension under somewhat lower temperature conditions is recorded in the VSD and PSD and within the shear zone bounding the PSD and CCD.

Western Uplift

The western third of the uplift (Fig. 1), which contains the highest pressure rocks, differs from the eastern uplift in many respects; we summarize new unpublished structural work (Hunt, 2000; Levine, 2005) and recently published pressure-temperature data (Carlson et al., 2007).

The deformational history is similar to the eastern uplift, though locally more complex, but deformation is widely distributed and intimately associated with partial melting and intrusions (Hunt, 2000; Levine, 2005). No shear zones have been identified, other than minor late-stage local zones. The CCD is not present, and much of the PSD-VSD domain boundary has been intruded by a predeformational plutonic body (Lost Creek Gneiss, LCG; Fig. 1). Dominant fabrics and contacts between the PSD-LCG-VSD dip northeast, thus showing structural stacking opposite to that in the eastern uplift.

In the far western uplift, eclogitic mafic bodies yield temperatures of ~775 °C and pressures that decrease from ~2.4 GPa to ~1.6 GPa prior to dynamothermal metamorphism associated with the dominant early fabrics (Carlson et al., 2007). Contacts with the adjacent rocks are not exposed, but outcrop patterns suggest that the mafic bodies also represent boudins of mafic layers. Metamorphic conditions for the adjacent rocks support in situ metamorphism of these eclogites similar to that documented in the eastern uplift. In adjacent areas ~15 km eastward along strike (Hunt, 2000; Levine, 2005), early fabrics formed under conditions at which sillimanite (not kyanite) was stable during F_1-S_1 through F_3-S_3, marking medium-pressure metamorphic conditions, similar to the deepest structural levels of the VSD in the eastern uplift. This deformation was intimately associated with extensive partial melting and abundant intrusions of pegmatites and aplites. These early fabrics must have formed after substantial exhumation. As in the eastern uplift, temperature conditions decreased after F_3-S_3. F_5 folds, late-stage boudins, and local shear zones are temporally related to the late granite plutonism, which was accompanied by the low-pressure metamorphism.

Timing of Tectonism

Early high-pressure metamorphism is dated as 1147–1128 Ma in the western uplift and 1133–1134 Ma in the central and eastern uplift (one Lu-Hf garnet-rutile age; three U/Pb zircon ages, all following ages are U/Pb zircon ages; Carlson et al., 2007). The regional medium-pressure dynamothermal metamorphism apparently occurred soon afterward (1129 ± 3 Ma, mafic rocks, eastern uplift VSD; Mosher et al., 2004), although this date could possibly record the earlier high-pressure metamorphism. Temporal constraints on low-pressure metamorphism are provided by the associated granite plutons. The oldest 1119–1118 Ma plutons are folded by F_5 in the central uplift and cut by shear zones in the eastern uplift (Reed, 1999). In the western uplift, a 1126 +5/–4 Ma granitic dike is folded by F_5 (Hunt, 2000), though pressures during dike intrusion are unknown. Plutons younger than 1093 Ma are undeformed internally, although country rock around plutons as young as 1080 Ma was deformed during intrusion (Reed, 1999).

Tectonic Model

Rocks exposed in the Llano uplift record the deepest levels of the collisional orogen; all evidence of upper crustal deformation has been eroded. Earlier subduction with a northward polarity producing the continental margin arc (Mosher, 1998) ceased sometime after ca. 1232 Ma, as evidenced by the lack of subsequent plutonism or volcanism in the uplift. No record exists of the ~80 m.y. prior to subduction of the continental margin producing the high-pressure metamorphism. Presumably a passive margin sequence formed along the Laurentian margin and was involved in the initial stages of collision. Subduction leading to collision most likely had a southward polarity (Fig. 2A), because no evidence exists for subduction-related magmatism in the uplift. In the following we present a new tectonic model for the collision (Fig. 2) and then discuss how the various parts of the uplift record these events and support this model.

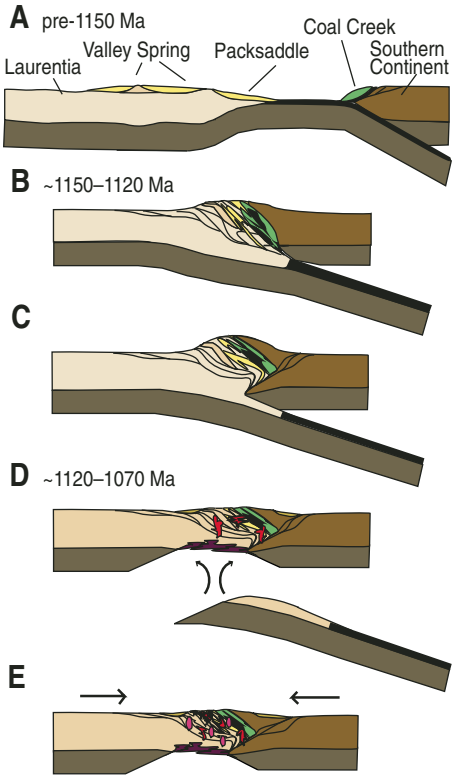

Figure 2. Tectonic model for Grenville orogeny along southern margin of Laurentia, showing evolution of Llano uplift. A: Subduction with southward polarity was active before 1150 Ma. Locations of future lithotectonic domains are shown. B: Collision resulting in juxtaposition of lithotectonic domains including exotic arc and overriding of arc by southern continent, plus internal imbrication and interleaving of ophiolitic rocks. Subduction of Laurentian margin, resulting in high-pressure metamorphism of continental crust at depth, buoyant rise of coherent fragments of subducted continental crust, and jamming of subduction zone. C: Overall orogenic thickening and increase in temperatures at depth as perturbed thermal structure reequilibrates. At middle to upper orogenic levels, tectonic transport continues toward Laurentia; deformation partitioned between major shear zones and distributed deformation (eastern uplift F1-S1 through F3-S3). Buoyancy of overthickened continental crust leads to uplift of high-pressure rocks and retrodeformation (backfolding on nappe scale; western uplift F1-S1 through F3-S3). D: Exhumation accomplished by erosion and extension. Slab breakoff results in further uplift, upwelling of asthenosphere, and underplating of basaltic magmas leading to intrusion of late syntectonic juvenile granites. E: Continued subduction along strike in west Texas causes further shortening, deforming oldest late granites (F5). Younger granites intrude in contractional stress field.

Subduction of the Laurentian continental margin led to high-pressure metamorphism of continental crust at depth, buoyant rise of coherent fragments of subducted continental crust within the subduction zone, and eventual jamming of the subduction zone (Figs. 2A, 2B). Orogenic thickening from the overriding of Laurentia by the CCD and of both by the southern continent led to structural imbrication of Laurentian basement, VSD, PSD, and CCD, including tectonic interleaving of ophiolitic rocks with other components of the CCD (Fig. 2B). This overall thickening resulted in increasing temperatures at depth with time as the perturbed thermal structure reequilibrated. At some point the positive buoyancy of the continental crust led to uplift and retrodeformation (southwestward tectonic transport, shearing, and backfolding) at deeper crustal levels, while simultaneous northeastward transport continued at higher crustal levels (Fig. 2C). Some combination of extension and erosion accompanied the uplift, rapidly exhuming high-pressure rocks to medium pressures. Slab breakoff enhanced uplift and retrodeformation, resulting in exhumation to lower pressure conditions (Fig. 2D). Upwelling of the asthenosphere and underplating of basaltic magmas resulted in melting of lower continental crust and intrusion of juvenile granitic bodies. The orogenic welt continued overall thinning and erosion. Continued subduction along strike in west Texas caused further shortening that dissipated with time, deforming early plutons and providing a contractional stress field during the later intrusions (Fig. 2E). This model is similar to that proposed for the Alpine orogeny on the basis of geodynamic models combined with field, petrologic, and geochronologic data (Beaumont et al., 1996; Escher and Beaumont, 1997; Pfiffner et al., 2000).

Subduction of the Continental Margin

Eclogitic rocks in the far western uplift represent continental crust in the deepest portion of the orogen, recording high-pressure metamorphism at ~70 km depth continuing during exhumation to ~50 km depth. This high-pressure metamorphism followed by rapid exhumation requires subduction of the continental margin and partial exhumation while still under high-pressure conditions. The latter may indicate buoyant rise of a deeply subducted continental sliver prior to jamming of the subduction zone (e.g., Ernst, 2001). No evidence of associated deformation has been documented in surrounding gneisses, suggesting that this subducted crust acted as a rigid block, although later intense overprinting could obscure early deformation.

Rocks in the eastern uplift record shallower depths (~42–46 km) during the earliest high-pressure metamorphism, with evidence of increasing depth with time. Thus the eastern uplift represents structurally higher levels of subducted crust that underwent continued subduction and/or was overridden by colliding crust. Although early deformation could have begun during high-pressure metamorphism, the exposed sillimanite-bearing S1–S3 fabrics must have occurred after exhumation to depths of ~23–26 km (7–8 kbar).

Collision and Retrodeformation

In the eastern uplift, the tectonic emplacement of ophiolitic rocks and regional deformation and metamorphism of the CCD together with the PSD and VSD are consistent with collision of the exotic arc with Laurentia and overriding of both by a southern continent. Transport toward Laurentia is compatible with a southward subduction polarity. Partitioning of deformation between movement along major shear zones and distributed progressive deformation between zones supports a mid-orogenic crustal depth for the eastern uplift rocks. Temperatures increased with time, and synkinematic partial melting and the proportion of flattening relative to shear strain within shear zones increased with depth (Mosher et al., 2004). All are consistent with overall thickening of the crust and progressive reequilibration of the perturbed thermal structure during collision (e.g., Coward, 1994).

In the western uplift, deformation under medium-pressure conditions, resulting in structural stacking and dip of lithotectonic domain boundaries and structural fabrics opposite to that of the eastern uplift, supports retrodeformation to the southwest. Melts and associated fluids apparently were channelized along the zone of retroshear (as is observed in other similar zones; e.g., Pfiffner et al., 2000). Partial melting and small igneous intrusions occurred throughout most of the deformation. F_1-S_1 through F_3-S_3 occurred at temperatures near the second sillimanite isograd. The presence of melt, coupled with very high temperatures, led to widely distributed deformation with no apparent vergence and a lack of discrete shear zones.

Exhumation and Plutonism

Exhumation apparently resulted from both erosion and extension. Mesoproterozoic sedimentary basin deposits represented by the Grand Canyon Unkar Group are thought to be sourced by this Grenville-aged orogenic belt (Timmons et al., 2001). In the Llano region, extension apparently accompanied the transitions from high to moderate to low pressures. Eclogitic layers and surrounding gneisses show evidence of extension in multiple directions prior to and during retrogression to moderate pressures, dominantly after the formation of S_2. This extension records early exhumation to mid-orogenic levels; the best evidence is observed in the eastern uplift. The later post-S_3 extension at somewhat lower temperatures, recorded across the eastern uplift, most likely reflects exhumation to low-pressure conditions. In the western uplift, late extension is associated with the late-stage plutons that intruded at low pressures.

The onset of plutonism immediately following uplift and abundant juvenile granite intrusions (Smith et al., 1997) are compatible with slab breakoff. The different (northward) kinematics during F_4-S_4 may mark a change in motion at the time of slab breakoff. Certainly, F_5-S_5 and subsequent minor shearing and extension occurred at low pressures. The syntectonic (F_5-S_5) nature of the oldest granites and the intrusion of later post-tectonic granites in a contractional environment are consistent with slab breakoff (e.g., Davies and von Blanckenburg, 1995). Much younger (ca. 1.05–1.0 Ga) contractional deformation in west Texas along this Grenville orogenic belt (Grimes and Copeland, 2004) implies that subduction continued along strike of the Llano area after collision, resulting in continued convergence in the Llano region.

DISCUSSION

The Mesoproterozoic tectonic history recorded by the Llano uplift is very similar to that of Phanerozoic orogens (e.g., Coward, 1994; Pfiffner et al., 2000). The tectonic juxtaposition of the exotic arc (CCD) with basinal deposits tied to the Laurentian margin, the tectonic emplacement of ophiolitic rocks, and the high-pressure metamorphism of continental crustal materials along a geothermal gradient of ~10 °C/km are best explained by plate tectonic processes of convergence, subduction, and collision. All other orogenic processes recorded within the uplift are likewise consistent with Phanerozoic plate tectonic processes and geodynamic plate tectonic models (e.g., Davies and von Blanckenburg, 1995; Beaumont et al., 1996). This consistency supports the contention that modern tectonic processes were globally active prior to the Neoproterozoic (cf. Brown, 2006, 2007; Cawood et al., 2006).

CONCLUSION

The tectonic evolution of the Llano uplift during the Mesoproterozoic supports continent-arc-continent collision, emplacement of ophiolitic rocks, subduction of continental crust, and high-pressure metamorphism, followed by buoyant uplift of deeply subducted continental crust and slab breakoff during erosional and extensional exhumation. The eastern and western portions of the Llano uplift expose different segments of the orogenic belt at different crustal levels and thus record different parts of the overall Grenville orogenic history along the southern margin of Laurentia. We conclude that subduction and collisional processes along the southern margin of Laurentia in the Mesoproterozoic were similar to modern-day processes.

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