SEQUENCE OF LATE OLIGOCENE-MIOCENE FOLD-THRUST DEFORMATION AND DEVELOPMENT OF PIGGYBACK BASINS IN THE EASTERN CORDILLERA, SOUTHERN BOLIVIA

Brian HORTON

Department of Geosciences, University of Arizona, Tucson, Arizona 85721 USA

KEY WORDS: Bolivia, thrust-belt kinematics, piggyback basins

INTRODUCTION

Late Oligocene-Miocene piggyback basins in the Eastern Cordillera of southern Bolivia developed on top of the evolving Andean thrust belt. These orogenic wedge-top basins contain progressive unconformities and have been folded and cut by thrust faults. Field mapping, measured stratigraphic sections, and $^{40}Ar/^{39}Ar$ isotopic dates reveal the sequence of fold-thrust deformation in the region. In general, out-of-sequence thrusting within an east-directed thrust system led to the development of fault-propagation and fault-bend folds that flank individual piggyback basins.

GEOLOGIC SETTING

Three north-trending basins, referred to as the Estarca, Tupiza, and Nazarano basins (from west to east), are separated by mountain ranges that average ~4 km elevation. The basins themselves are ~10 km wide by ~80 km long and situated at elevations of ~3 km. In southern Bolivia, the Eastern Cordillera is part of the thrust-belt hinterland consisting of a thick section of penetratively deformed, low-grade metamorphosed Ordovician rocks with subvertical slaty cleavage and narrow north-trending synclinal belts of modestly deformed, unmetamorphosed Cretaceous rocks. Cenozoic fold-thrust deformation in the hinterland thus affected a geologic column consisting of a pre-existing "slate belt" of Ordovician rocks and a few isolated occurrences of Cretaceous rocks. This complex pre-thrusting geometry may have inhibited development of continuous regional decollements in specific stratigraphic horizons and favored development of both east- and west-vergent structures.

BASIN STRATIGRAPHY

The piggyback basins contain nonmarine clastic deposits of late Oligocene-Miocene age. Rapid lateral facies changes and stratigraphic pinch-outs within and among the basins have led to differing stratigraphic interpretations (Montano, 1966; Herail et al., 1996). The Tupiza basin consists of three north-trending outcrop belts representing three distinct piggyback basins. The oldest deposits, herein named the Bella Vista unit, are exposed in a syncline in the eastern outcrop belt. This unit consists of a 400-600 m thick alluvial-fan conglomerate dominated by clasts of Ordovician shale on the east limb of the syncline and clasts of Cretaceous sandstone on the west limb. The eastern section and underlying Ordovician rocks were folded prior to deposition of the overlying Tupiza Formation volcanic rocks. The 300 m thick Tupiza Formation volcanic rocks overlie the eastern Bella Vista section with a highly angular unconformity and conformably overlie the western Bella Vista section. The Tupiza volcanic rocks and probable equivalents to the north have been dated at 22.7 +/- 0.6 Ma and 29.9 +/- 0.9 Ma (K/Ar ages; Herail et al., 1996).

The oldest deposits of the central outcrop belt of the Tupiza basin are the Catati Formation, a 400 m thick section of floodplain/lacustrine shale with thin gypsum layers deposited with slight angular unconformity on Ordovician strata. Paleocurrent indicators show that a basal conglomerate/sandstone with predominantly Cretaceous sandstone clasts was derived from the west and ripple-cross-stratified sandstones from the uppermost Catati were derived from the southeast. The Catati Formation is correlated with similar lithologies at the top of the Tupiza volcanic rocks of the eastern outcrop belt and is thus early Miocene in age. The Tupiza Formation conglomerate is a red alluvial-fan deposit conformably overlying the Catati Formation in the central outcrop belt and the Tupiza volcanic rocks in the eastern outcrop belt. The Tupiza conglomerate, about 500 m thick in the eastern belt and 1000 m thick in the central belt, exhibits an unroofing sequence in which basal strata are dominated by Cretaceous sandstone clasts and upper strata contain mainly clasts of Ordovician shale. Large clasts of Tupiza volcanic rocks are present only in the eastern belt. A tuff near the base of the eastern belt of the Tupiza conglomerate yielded an $^{40}Ar/^{39}Ar$ age of 16.14 +/- 0.06 Ma. Clast-size variations and cross-stratified conglomerate/sandstone in both outcrop belts reveal paleoflow toward the east.

The Nazareno Formation, the oldest deposit in the western outcrop belt of the Tupiza basin, is up to 1000 m thick and is typically in unconformable contact or fault contact with Ordovician rocks. A basal, 200 m thick red conglomerate dominated by clasts of Ordovician shale pinches out eastward, suggesting that it could not have been continuous with the Tupiza conglomerate. The rest of the Nazareno Formation is composed of shale and fine-grained sandstone. A tuff within the Nazareno Formation has been dated at 18.0 +/- 0.5 Ma (K/Ar; Herail et al., 1996). The Oploca Formation is a 600 m thick section of braided-fluvial conglomerate/sandstone that unconformably overlies Nazareno and Ordovician strata. Conglomerate clast compositions include Ordovician shale and Tertiary volcanic rocks. Sediment transport was dominantly along the basins's north-trending axis, with a probable Ordovician source terrane to the west and volcanic sources to the north. A tuff near the base of the Oploca Formation yielded an $^{40}Ar/^{39}Ar$ age of 13.33 +/- 0.15 Ma. A tuff near the top is 8.28 +/- 0.74 Ma (K/Ar age; Herail et al., 1996).

The Estarca basin is composed of an eastward-coarsening and thickening section of conglomerate, sandstone, and shale. The basin deposits overlie Ordovician strata with a highly angular unconformity and are up to 800 m thick. The section is dominated by Ordovician detritus and is presumably the temporal equivalent to the Nazareno and Oploca Formations of the Tupiza basin.

The Nazareno basin contains a fining-upward, shale-dominated section up to 800 m thick. Conglomerate horizons contain clasts of Ordovician shale and Tertiary volcanic rocks. A 20.9 +/- 0.6 Ma tuff near the base (K/Ar age; Herail et al., 1996) and a 12.79 +/- 0.12 Ma tuff near the top ($^{40}Ar/^{39}Ar$ age; Gubbels et al., 1993) reveal a Miocene age for the basin.

SEQUENCE OF DEFORMATION

Progressive unconformities, provenance characteristics, and cross-cutting thrust relationships involving Tertiary deposits define a pattern of out-of-sequence thrusting within an overall east-vergent thrust belt.

(1) A late Oligocene west-directed thrust on the eastern margin of the Tupiza basin provided an eastern source of Ordovician detritus for the Bella Vista unit. This thrust folded the conglomeratic unit in a footwall syncline prior to unconformable overlap by the late Oligocene-early Miocene Tupiza volcanic rocks. Syndepositional deformation west of the Bella Vista unit is suggested by interbedded Cretaceous-clast conglomerates derived from the west.

(2) Early middle Miocene east-directed thrusting and associated growth of a fault-propagation fold and fault-bend fold is linked to deposition of the lower-middle Tupiza conglomerate (16.14 +/- 0.06 Ma;

$^{40}Ar/^{39}Ar$ age). A progressive unconformity in the eastern strata suggests syndepositional growth of a structure on the western margin of the eastern outcrop belt. The central outcrop belt lacks progressive unconformities, suggesting no nearby structures with actively rotating limbs. However, both the central and eastern belts of Tupiza conglomerate record unroofing of a major sediment source to the west. The eastern belt also contains clasts of Tupiza volcanic rocks reworked from the area between the central and eastern belts. These provenance indicators and growth strata suggest growth of a fault-propagation fold with active limb rotation within the Tupiza conglomerate depositional area. This feature provided minor amounts of Tupiza volcanic rocks to the east. A fault-bend fold that lacks evidence for rotating limbs is present on the west flank of the Tupiza conglomerate depositional area; this structure was the primary source of sediment. Both folds are consistent with an east-directed thrust system with a ramp-flat geometry.

(3) Late middle Miocene-late Miocene east-directed, out-of-sequence thrusting and fold growth is associated with deposition of the upper Tupiza conglomerate and lower Oploca Formation (13.33 +/- 0.15 Ma; $^{40}Ar/^{39}Ar$ age). In the central outcrop belt, a progressive unconformity in upper strata of the Tupiza conglomerate suggests a growing structure to the west. In the western outcrop belt, a progressive unconformity in the lower Oploca Formation suggests a growing structure to the east. A fault-propagation fold at the tip of an east-directed out-of-sequence thrust accounts for both progressive unconformitites and a mapped thrust on the west margin of the central outcrop belt which places Ordovician rocks on the upper Tupiza conglomerate. This break-back thrust may have cut up from the footwall ramp of the pre-existing fault-bend fold on the west margin of the Tupiza conglomerate depositional area.

(4) Post-middle Miocene (post Tupiza conglomerate) folding and thrusting characterized the eastern outcrop belt of the Tupiza basin. Tight folding of the Tupiza conglomerate may be related to reactivation of the west-directed thrust on the eastern basin margin, which cuts the upper Tupiza conglomerate, and potential reactivation of a thrust between the central and eastern outcrop belts.

(5) Late Miocene fault-bend fold growth post-dates the Oploca Formation and deposits of the Estarca and Nazareno basins. The eastern Estarca deposits, western Oploca deposits, and western Nazareno deposits lack significant progressive unconformities and have been tilted approximately parallel to the slopes of their adjacent range fronts. These features are consistent with growth of two fault-bend folds separating the Estarca, Tupiza, and Nazareno basins during translation along a deeper decollement.

CONCLUSIONS

Late Oligocene-Miocene deformation within the predominantly east-vergent hinterland portion of the Andean thrust belt led to isolation of individual piggyback basins. Shortening within this ramp-flat thrust system produced fault-bend folds that served as major sediment source areas and fault-propagation folds with actively rotating limbs which led to growth of progressive unconformities in adjacent deposits. Out-of-sequence thrusting within the Eastern Cordillera of southern Bolivia from late Oligocene to late Miocene time may represent a prolonged phase of subcritical thrust-wedge conditions such that the thrust front could not migrate eastward. By late Miocene time (~10 Ma) thrust-wedge taper had apparently increased enough to initiate thrusting farther east in the Subandean Zone.

ACKNOWLEDGMENTS

Supported by an NSF Graduate Fellowship and grants from GSA, AAPG, Sigma Xi, and the University of Arizona. I am grateful to P. Copeland for the $^{40}Ar/^{39}Ar$ dates, and C. Gorman and Ugo Palmito for field assistance.

REFERENCES:

Gubbels, T., Isacks, B., and Farrar, E., 1993, High-level surfaces, plateau uplift and foreland development, Bolivian Central Andes: *Geology*, 21, 695-698.

Herail, G., Oller, J., Baby, P., Bonhomme, M., and Soler, P., 1996, Strike-slip faulting, thrusting and related basins in the Cenozoic evolution of the southern branch of the Bolivian Orocline: *Tectonophysics*, in press.

Montano., D., 1966, Estudio geologico de la region de Tupiza-Estarca-Suipacha (Ph.D., thesis): Universidad Mayor de San Andres, La Paz, 76 p.