CENOZOIC DEFORMATION ACROSS SOUTH AMERICA: CONTINENT-WIDE DATA AND ANALOGUE MODELS

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KEY WORDS: South America, Cenozoic, continent-wide deformation, data, analogue models

INTRODUCTION

According to current seismicity, stresses and plate tectonics, South America is in a state of approximately east-west compression. This is basically attributable to ridge push from the Atlantic and East Pacific rises, modulated by slab pull at the Andean margin. In detail, horizontal compressive stresses vary in trend, especially towards the corners of the continent, where additional forces are associated with strike-slip motions of the Caribbean and Scotia plates, counterclockwise rotation of the Caribbean plate, ongoing collision of Central America with South America and mechanical contrasts between continental and oceanic lithospheres.

The plate tectonic setting of South America has not changed fundamentally since the opening of the Atlantic in the Early Cretaceous. Crustal thickening has accumulated all along the Andes. Thickening appears to have started in the Albian and to have gone through paroxisms in the Early Tertiary and Miocene, all periods of relatively rapid convergence at the Andean margin. Complications can be attributed to collision of Central America in the Miocene, splitting of the Farallon plate into the Nazca and Cocos plates, collision and northwards migration of the East Chile rise, and other events.

Outside the Andes, there is evidence for Cenozoic faulting and deformation at many localities, including the Atlantic margin and central regions of South America. In this paper, we attempt a synthesis of such data at continental scale, paying particulat attention to the reactivation of Mesozoic, Paleozoic and Precambrian faults by Cenozoic stresses. We then compare the data with analogue models of South American plate tectonics.

DATABASE

Current seismicity is concentrated in the subducting oceanic slabs and in the Andes. We also consider intraplate seismicity and stresses deduced from borehole breakouts. Compressive stresses act across the entire continent. Although their average trend is east-west, there are significant deviations. Stresses tend to act parallel or perpendicular to the eastern margins of Brazil.

Digital topographic maps show how (1) large areas of South America have average altitudes of 1000 m or more, whereas other large areas are near sea level; and (2) ridges or scarps with sharp relief cross-cut the continent. To satisfy estimated rates of erosion, such topographic features must have been maintained by ongoing Tertiary vertical motions.

We have also used geological data obtained at outcrop, subsurface data from the petroleum industry, satellite imagery, and paleomagnetic, geochronological and fission-track data.

EVIDENCE FOR CENOZOIC DEFORMATION ACROSS SOUTH AMERICA

1. Serra do Mar

The Serra do Mar forms a prominent escarpment up to 2800 m high on the Atlantic coast of Brazil. Outcropping Precambrian gnesisses and granitoids have been shaped by recent erosion into an inselberg topography. Recent studies of apatite fission tracks show that exhumation has been active during the Tertiary. The eroded material has been deposited offshore in the Campos and Santos basins, where the Tertriary succession is several km thick. Exhumation has been attributed to isostatic rebound of an eroded rift shoulder, formed during the Early Cretaceous. However, this process requires an unusually thick elastic lithosphere and an unusually small initial rift shoulder. We prefer to invoke Tertiary compression. Evidence for this is provided, not only by the current stress state, but also by geological data. A Proterozoic shear zone, running from Sao Paulo to near Rio de Janeiro, has been reactivated during the Tertiary, to form the Taubaté basin. Tertiary sediments are offset by synkinematic and postkinematic faults. Strike-slip motions dominated throughout the Tertiary, becaming transpressive in the Neogene. In the Itaboraí Basin near Rio de Janeiro, strike-slip faults are ubiquitous within Paleogene fresh-water limestones. Topographic bulges mark both the NE and SW ends of the Precambrian shear zone, which was reactivated right-laterally.

2. Central Brazilian Highlands

The Central Brazilian Highlands are mostly over 800 m high and they occupy an area over 1000 km wide. The area is wider than any single rift shoulder associated with Atlantic rifting. Moreover, according to gravity data, topography is compensated at depth over most of the area, probably by a Moho up to 50 km deep. Precambrian crystalline basement crops out over most high parts, whereas valleys and basins contain Tertiary, Mesozoic or Paleozoic sediments. Intraplate seismicity is associated with basement highs. Prominent ridges bound the Tertiary basins. Some of these ridges we identify as active faults, of reverse or strike-slip senses.

3. Northeastern Brazil

The Potiguar Basin, which formed as a rift in the Early Cretaceous, shows positive inversion from the Albian onwards. In the Araripe Basin, marine sediments are currently perched at altitudes over 500 m.

4. Paraná Basin and Pantanal

The Paraná Basin conatins a thick sequence of marine Paleozoic sediments, capped by Early Cretaceous basalts, and a thin sequence of Late Cretaceous to Tertiary continental sediments. The edges of the basin have been uplifted, tilted inwards and bevelled by ersoion. Some of this inversion occurred in the Triassic, after a Variscan phase of folding and thrusting; but most of it post-dates the basalts and is attributable to Andean compression.

The Pantanal Basin contains a sequence of Tertiary sediments, several km thick. At the edges of the basin, the base of the Tertiary is offset across reverse faults. Within the basin, folds and reverse faults are visible at outcrop and on seismic lines. To the west, the Chiquitos hills form a linear scarp up to 1400 m high, where the Precambrian basement has been reactivated as a left-lateral wrench zone and overlying Cretaceous and Tertiary sediments show folds and thrusts.

5. Eastern Patagonia

Eastern Patagonia is a plateau up to 1000 m high. Outcropping Late Cretaceous marine sediments prove Tertiary uplift. Seismic and well data reveal a phase of Early Cretaceous extension, followed by a history of basin inversion, fault reactivation, folding and thrusting, which started in the Albian and has continued until the present day.

6. Central and Northern Argentina

The Sierras Australes of Buenos Aires province form a prominent ridge about 1000 m high, where Paleozoic sediments crop out. Rocks underwent low-grade metamorphism, folding and thrusting during the Cape Orogeny (Permo-Triassic). Mesozoic rifts are visible on seismic lines across adjacent basins. However, the current topography is due to Tertiary reactivation of Paleozoic thrusts.

The Sierras Pampeanas of Northwestern Argentina are ranges up to 5000 m high, separated by basins, some with internal drainage. The ranges consist of Precambrian metamorphic basement with mylonitic thrust zones, attributable to the Ocloyic or Taconic orogeny (Silurian). Later Mesozoic rifts became inverted during the Tertiary. Basement blocks became tilted by reactivation of Precambrian and Paleozoic thrusts. The vergences of Tertiary thrusts are inherited from those of the basement.

7. Southern Andes and Magellan Basin

The Southern Andes form an arc, concave to the NE. Altitudes are mostly below 2000 m. Rifting in the Jurassic and back-arc extension during the Early Cretaceous were followed by Andean compression, from the Albian onwards. During the Tertiary, the regional shortening direction was NE. Transpressional conditions predominated, left-lateral in Tierra del Fuego, right-lateral in the Southern Andes. Slow convergence, thrusting and rapid glacial erosion exposed Late Cretaceous amphibolites in Cordillera Darwin. The foreland Magellan basin filled with up to 7 km of Tertiary sediments. Fold-and-thrust belts developed along the Andean foothills. A system of Tertiary rift valleys, trending along the Straits of Magellan, separated the island of Tierra del Fuego from the mainland.

8. Central Andes

From northwestern Argentina to southern Peru, the Altiplano is a major topographic and structural feature, some 4000 to 5000 m high. In Bolivia, the Altiplano is underlain by 10 km of Tertiary sediments. These were trapped between thrusts of opposite vergences, bounding the Cordillera Real to the west and the Cordillera Oriental to the east. In the Cordillera Oriental, Cretaceous rifts, some with marine sediments, became inverted during the Early Tertiary. However, the main crustal structure is a thin-skinned tectonic prism, formed by reactivation of Paleozoic thrusts and inversion of a deep Paleozoic basin. Beyond the mountains to the east is a Tertiary foreland basin.

In NW Argentina, the Puna plateau is a crustal prism, where Tertiary forethrusts and backthrusts separate ridges of Paleozoic and Precambrian basement from basins with internal drainage, underlain by several km of Tertiary sediments. Almost all thrust vergences were inherited from Paleozoic (Ocloyic) and Precambrian equivalents. Tertiary vulcanism is associated with Andean compression. Some volcanoes are aligned along left-lateral, SE-trending wrench zones, which are the reactivated edges of Paleozoic basins.

Rotations about vertical axes, demonstrated by paleomagnetic studies, are clockwise in the south, counterclockwise in the north. They have played a fundamental role in the building of the Central Andes, allowing the central part to advance eastwards more than its southern or northern margins.

In Peru, the main Tertiary thrusts of the Eastern Cordillera are reactivated Early Paleozoic thrusts. Associated Late Paleozoic and Mesozoic basins became inverted, forming the current Andean foothills. The Brazilian crystalline basement became downwarped under the Ucayali and Marañón foreland basins.

9. Northern Andes

In Ecuador and Colombia, crustal thickening was accompanied by right-lateral wrenching in the Paleogene. The shortening direction veered towards the SE during the Neogene, reflecting collision with Central America. The Western Cordillera of Colombia is an uplifted magmatic and volcanic arc, separated from the Cordillera Oriental by the Magdalena ramp basin with its several km of Tertiary sediments. In the

Cordillera Oriental, an Early Cretaceous rift has been inverted. Marine sediments, exhumed at altitudes of up to 4000 m, show low-grade metamorphism. To the east, the Llanos foreland basin is filled with several km of Tertiary sediments. However, the main Tertiary thrusts of the Cordillera Oriental are reactivated basement structures. Episodes of thrusting and associated metamorphism occurred in the Precambrian, Early Paleozoic and Late Paleozoic. The intense Late Paleozoic episode (due to collision of North and South America) differentiates the Northern Andes from the Central Andes.

Towards the Caribbean plate boundary, the Andes of Northern Colombia and Venezuela show increasing components of right-lateral wrenching parallel to the Caribbean plate boundary. The antithetic left-lateral Bucaramanga Fault is a reactivated basement feature and has helped spread the deformation well into the continent.

ANALOGUE MODELS

We have investigated the plate tectonics of South America and the possibility of continent-wide deformation, using analogue models at fully lithospheric scale. Brittle upper crust was modelled with dry sand; ductile lower continental crust and lithosperic mantle, with silicone putties of appropriate viscosities and densities. For oceanic lithosphere, the ductile lower crust was omitted. Continental South America was given an appropriate triangular shape. The model lithosphere floated on a less viscous asthenosphere. Horizontal forces and velocities were applied at eastern and western boundaries, to simulate spreading at Atlantic and Pacific mid-oceanic ridges. Subduction initiated spontaneously at the Pacific margin of South America. Either crustal thinning or crustal thickening occurred at the Pacific margine, depending on the ratio between the weight of the subducting oceanic slab and the applied rate of convergence. By changing this ratio during the course of an experiment, it was possible to induce tectonic inversions.

For high rates of convergence, deformation tended to occur also at the eastern margin of continental South America, or even in central areas. Because of the triangular shape of the continent, strike-slip motions occurred at boundaries oblique to the convergence direction. At the Pacific margin, partitioning was observed, between dip-slip motions of the subducting slab and strike-slip motions next to it. Strike-slip motions also occurred at the sides of the continent, right-lateral in the north and left-lateral in the south. These motions caused local modifications in the directions of shortening.

In some experiments, we introduced initial weaknesses, by reducing the thickness of the brittle upper crust. In such weak areas, deformation became concentrated, leading to changes in the shape of the continent. A weak area in the central part of the Pacific margin led to indentation of that margin. This may explain the formation of the Arica elbow and the concentration of deformation in the Central Andes.

CONCLUSIONS

Tertiary compression and crustal thickening are widespread across South America. Crustal thickening is concentrated in the Andes, but significant in other areas, including the Atlantic margin of Brazil. Across South America, Tertiary reverse and strike-slip faults are mostly due to reactivation of similar structures formed during Paleozoic or Precambrian orogenies. Andean compression and crustal thickening are widely documented from the Albian onwards, but appear to have increased in intensity in the Neogene. Wrenching is ubiquitous at the ends of South America, right-lateral against the Caribbean plate and left-lateral against the Scotia plate. In analogue models, forces and velocities applied to the oceanic lithosphere resulted in subduction at the Pacific margin. Deformation was either extensional or compressional, depending on the ratio between the weight of the subducting slab and the rate of convergence at the Andean margin.