# THE PATTERN OF DEFORMATION RELATED TO GROWTH OF THE SOUTHERN ALTIPLANO PLATEAU (BOLIVIA)

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**ABSTRACT**:

Structural studies on the Southern Altiplano in Bolivia based on reflection seismic data yield more shortening than previously estimated (56-72 km). Deformation was accumulated during several deformation increments since the Eocene. The spatially and temporally strongly variable fault activation is a characteristic feature during plateau formation. Field data and geophysical observations indicate that the style, timing, and location of deformation in the plateau can be interpreted as a consequence of magmatically controlled thermal weakening of the middle crust.

**INTRODUCTION**

The Altiplano-Puna Plateau is the most prominent feature of the Central Andes. It covers large parts of southern Peru, Bolivia and NW Argentina and has an average elevation of 4000 m. The Bolivian Altiplano is bordered by the bivergent thrust system of the Eastern Cordillera to the east and the active magmatic arc of the Western Cordillera to the west. The latter is also part of the plateau. The high topographic elevation is compensated by an up to 70 km thick crust that reaches its maximum underneath the Eastern Cordillera (Wigger et al., 1994; Yuan et al., 2000).

Crustal thickening and plateau uplift in the arc-backarc domain of the South American convergent margin took place during the Cenozoic (e.g. Allmendinger et al., 1997; Gregory-Wodzicki, 2000; Isacks, 1988; Lamb and Hoke, 1997). Tectonic shortening is believed to be the prime mechanism for crustal thickening and so far many workers directed their interest at the plateau's eastern margin (e.g. Baby et al., 1997; Kley and Monaldi, 1998; Kley et al., 1997; Lamb and Hoke, 1997; Sheffels, 1990). Tectonic shortening in the bivergent thrust system of the Eastern Cordillera and the foreland fold-and-thrust belt of the Interandean and Subandean ranges sums up to ~180-210 km of contraction. This value explains some 60-70% of the required crustal thickness of the Andes (Kley and Monaldi, 1998). Deformation at the western flank of the plateau is characterised by a thick-skinned basement ramp with only very minor horizontal shortening (Victor, 2000).

The structural style associated with plateau formation and uplift is poorly constrained in the central plateau area due, mostly, to widespread coverage with syn- and posttectonic sediments. This study is aimed at constraining style, magnitude and age of tectonic shortening on the southern Altiplano in Bolivia through incrementally balanced cross sections (at ~21°S) based on reflection seismic profiles, 3D-strain analysis, gravity data, age dating, and field observations (see fig. 1 for location).

**CONCLUSIONS**

The southern Altiplano is segmented in two structural domains. The Eastern Altiplano domain (EAP) is interpreted as westernmost part of the N-S-trending west-verging thin-skinned thrust belt of the Eastern Cordillera. The buried deformation front lies ~12 km west of the Vilque well in the EAP (fig. 1). The shallow to medium dipping thrusts merge into a slightly eastward dipping detachment that lies at a depth of ~6-9 km in the Eastern Altiplano within Lower Paleozoic sediments and continues in the Eastern Cordillera.

The Central Altiplano domain (CAP), west of the NNW-SSE trending Khenayani Uyuni fault zone (KUFZ), is characterised by a bivergent thrust system with steep to shallow basement-involving thrusts in the East and fault controlled folds in the west.

The buried thin-skinned deformation front of the Eastern Cordillera has accumulated a minimum shortening of ~6 km (thrusting and folding). Tectonic shortening of the Central Altiplano sums to ~39 km. First results of the 3D-strain analysis show that a significant amount of strain at the grain scale has also been accumulated on the Altiplano (6-15%, i.e. 11-27 km). Including this, total shortening in the plateau increases to 56-72 km (29-35%), about twice the value reported from earlier studies.

Despite the differences in structural style and magnitude of shortening, it is noteworthy that deformation occurred rather synchronous in both, the Eastern and the Central Altiplano domain, but at different relative magnitudes. The oldest structures that recorded contraction are of Lower Oligocene age (>28 Ma). This deformation increment was responsible for ~4,5 km horizontal shortening in the EAP, and for 15-21 km shortening in the CAP, resulting in the uplift of Paleozoic basement ridges that provided a sediment source for the intervening intermontane basins.

Most shortening in the CAP took place during the Middle Miocene (15-8Ma, 18-24 km), resulting in formation of several small thrust top basins filled with equivalent continental sediments. Seismic sequence analysis, map interpretation, and field observations revealed the relative order of fault activation. The absolute ages of the younger deformation increment are based on isotopic ages of angular unconformities and interbedded tuffaceous horizons in the syntectonic thrust-top basins. Horizontal contraction on the Altiplano ended between 11-8 Ma as indicated by the age of overlying undeformed volcanic rocks. Prior to contractional deformation, the CAP experienced a Paleocene/ Eocene extensional increment resulting in significant thickness variations of the Eocene/ Oligocene sediments in a major halfgraben with maximal thickness near the western part of the Khenayani-Uyuni fault zone (>3 km) and reduced thickness (<1 km) on the graben shoulder in the eastern part of the KUFZ. The latter thus is, in part, an inverted normal fault system.

Seismic stratigraphy and interpretation reveals a complex deformation history characterised by spatially and temporally varying fault activity that does not show a systematic pattern. Observing the Eastern Altiplano domain jointly with the adjacent parts of the Eastern Cordillera, tectonic activity is almost continuous from Lower Oligocene to Middle Miocene times. During this period, however, faults were repeatedly reactivated in a complex pattern as evidenced from the infill architecture of thrust top basins. In contrast, deformation in the

CAP is restricted to the main increments given above. Last not least, the Western flank of the plateau developed in two increments, a Late Eocene with high strain rate (“incaic”, 14 km)(Günther, 2001), and a low strain rate stage between 29 and ~10 Ma (~5 km shortening)(Victor, 2000). The younger increment shows continuous deformation in the same time span as the Eastern Cordillera and EAP (see above).

In the CAP, as in the EAP, the activation of faults does not reflect a prograding deformation front in either direction. The spatially and temporally strongly variable fault activation is a characteristic feature during the entire plateau formation and requires a probably self-organized steady state between driving forces, mechanical properties of the faults and underlying basement, and mass redistribution at the surface. Moreover, the syntectonic stratigraphic units of the Central and Eastern Altiplano domain overlie shallow marine Upper Cretaceous sediments that still form a subhorizontal regional near sea level. Surface uplift in this part of the plateau is nearly entirely controlled by sedimentary infilling (3-5 km) of structurally controlled basins with internal drainage.

At the western flank of the plateau, active shortening is coeval with magmatism that resulted from crustal melting (Victor, 2000). In the plateau area we observe a positive correlation between the spatial and temporal distribution of Miocene volcanic centres and the activity of the Altiplano imbricate system. Moreover, the bivergent thrust system of the Central Altiplano is spatially related to a variety of geophysical anomalies. The interpretation of partial melts in the middle crust is based on the presence of a seismic low velocity zone whose upper limit correlates with a bright seismic reflector from the ANCORP’96 section and also with the upper limit of an extremely high conductivity anomaly (Brasse et al., in press; Yuan et al., 2000). Accordingly we favour a model explaining style, timing, and location of deformation in the plateau as a consequence of magmatically controlled thermal weakening of the middle crust.

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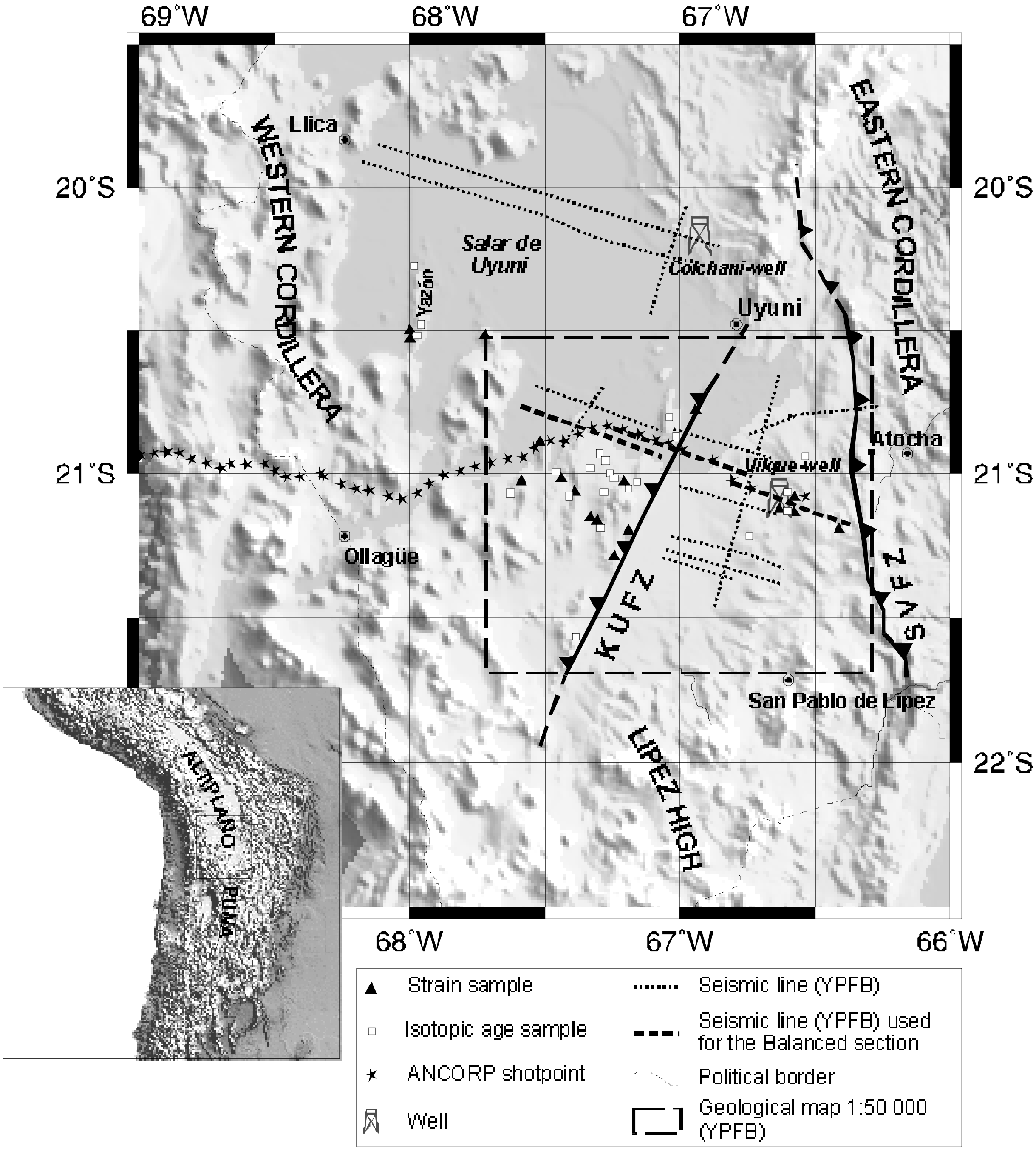


**Fig. 1:** Schematic map of the Southern Altiplano in Bolivia showing the geological and seismic database including sample and well locations and the outline of the geological map from YPFB (Bolivia). The Khenayani-Uyuni fault zone (KUFZ) divides the Southern Altiplano in the Eastern and Central Altiplano structural domain. The San Vicente fault zone (SVFZ) marks the boundary between the Altiplano and the Eastern Cordillera. The Lipez high marks the transition to the Argentine Puna.