Crustal shortening in the backarc of the Central Andes, Eastern Cordillera (S Bolivia)

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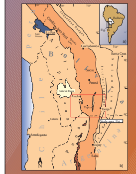


Fig. 1: Position of the study area.

Introduction

Along a geotraverse Tarija - Tupiza - San Vicente/Atocha balanced cross-sections have been developed on the base of structural and geophysical data, aiming to derive the amount of crustal shortening during the Andean orogenesis.

Principal **preconditions** for this investigation were:

- definition and geochronological dating of Palaeozoic deformations within the Cambro-Ordovician basement,
- investigation of Late Mesozoic rifting processes,
- definition of Andean deformation by analysing the tectono-sedimentary development of Neogene basins and geochronological dating of volcanics intercalated in the basin deposits.

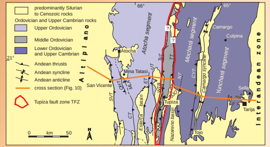


Fig. 2a: Tectonic sketch-map of the Eastern Cordillera, distribution of the rocks and location of the cross-section (Fig. 10). More details in the Landsat image below (Fig. 2b): CT Chilcobija thrust, CYT Camargo-Yavi thrust, ET Estarca thrust, MLA Mojon Loma anticline, NT Nazareno thrust, QHT Quebrada Honda thrust, SJO San Juan del Oro peneplain, SVT San Vicente thrust, TT Tocloca thrust, TuT Tupiza thrust, UT Urulica thrust, WTB Western Tupiza basin.

Geologic framework

The Eastern Cordillera is part of the Central Andean back arc between the Altiplano and the Interandean zone (Fig.1). In southern Bolivia it consists of at least 8-9 km thick Cambro-Ordovician siliciclastics unconformably covered in places by some hundred meters thick, lagoonal to continental Cretaceous-Palaeogene and/or Neogene sediments and volcanics (Figs. 2a, b; 3a).

Tectonically, the Eastern Cordillera of southern Bolivia forms a bi-vergent thin- to thick-skinned fold-and-thrust belt; W-vergent to the west and E-vergent in the east (Fig. 10). Due to different structural styles and degrees of metamorphism the Eastern Cordillera of southern Bolivia can be subdivided into three segments (Figs. 2, 6, 10).

- The **Atocha segment** in the west is characterised by W-vergent major thrusts like the San Vicente thrust (SVT), the Chilcobija thrust (CT), the Estarca thrust (ET, Fig. 3b) and E-vergent back thrusts like the Quebrada Honda thrust (QHT) and the Urulica thrust (UT).
- The **Mochará segment** comprises W-vergent thrusts and associated E-vergent back thrusts to the west as well as E-vergent thrusts and associated W-vergent back thrusts to the east.
- In the **Yuncharà segment** E-vergent thrusts and folds predominate (Kley 1993).
- Concerning the basement, the ages of the Palaeozoic rocks at the surface become younger from E to W (Fig. 2a, 6a, 10):
- **Cambrian to Lower Ordovician** rocks form the Yuncharà segment in the east and the eastern part of the Mochará segment,
- **Middle Ordovician** rocks outcrop in the westernmost part of the Mochará segment,
- the Atocha segment comprises **Upper Ordovician** rocks, only, in the western part of the Eastern Cordillera.

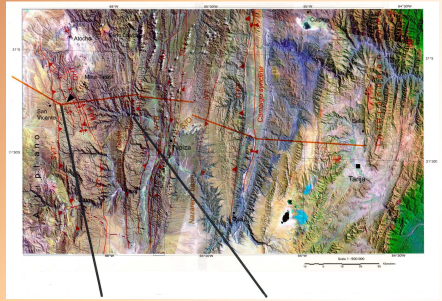


Fig. 2b: Landsat image with major structures and intramontane basins of the Eastern Cordillera (correlate with Fig. 2a). In the center the Camargo syncline with Upper Cretaceous and Tertiary rocks is a very conspicuous structure. In the NW white colors mark the volcanic center near Atocha. The red spot is the Cerro Chorolque (Fig. 3b). Abbreviations see figure 2a.

Fig. 3a: View from the area of San Vicente to the Cerro Chorolque, what is the highest mountain in this area, in the NNE. Ordovician marinoclastics (in front) are overlain by Cretaceous to Paleogene (white) and Tertiary (red) sediments.

Fig. 3b: Along the W-vergent Estarca thrust (ET) the Ordovician siliciclastics (grey) are thrust upon the Tertiary Estarca formation (red).

THE UPPER CARBONIFEROUS TOCO EVENT

In the Cambro-Ordovician basement folds below less deformed Cretaceous and Tertiary strata as well as rotated penetrative cleavage give evidence of at least one pre-Andean event between Ordovician and Cretaceous times. But age and type of the pre-Andean event in southern Bolivia are still under discussion. In NW Argentina a late Ordovician (Oclóyic) age of deformation has been assumed and in northern Bolivia as well as southern Peru a Devonian/Carboniferous (Eohercynian/Chanic) age has been proposed. KLEY & REINHARDT (1994) assumed a Hercynian tectonic event for southern Bolivia.

Age of metamorphism (Fig. 4)

The clay fractions of < 2µm and < 0.2 µm are used by our collegues K. Wemmerand H. Ahrendt (IGDL, University of Göttingen) to determine the ages of the smectites and illites, which were synchronically formed during cleavage. Since the K-Ar ages of the fraction of < 2 µm are affected by detrital illites up to the middle anchizone, the K-Ar ages of the fraction of < 0.2 µm gave the best values resulting in an Upper Carboniferous (Hercynian) event at **310 - 290 Ma**. This age of metamorphism correlates with the Toco event in N Chile and corresponds to ages that have recently been reported from the metamorphic basement of NW Argentina (Becchio and Viramonte, pers. comm.), and from granites and metamorphism in the Chilean Precordillera (G. Franz & F. Lucassen, pers. com.). Furthermore, our data let us assume an Upper Triassic (220-208 Ma) and a Lower Cretaceous event (137-133 Ma) in the area of the Tupiza fault zone (TFZ).

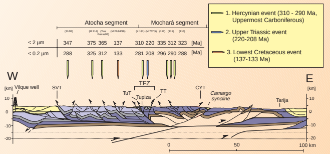


Fig. 4: Metamorphic events as indicated by K-Ar ages of clay-mineral assemblages in Ordovician slate of the Eastern Cordillera (IGDL, Göttingen). TFZ Tupiza fault zone, other abbreviations see figure 2.

Range of metamorphism (Fig. 5)

Since significant mineral assemblages are absent in the low grade metamorphic rocks of the Eastern Cordillera, the illite crystallinity is measured systematically in fine-grained terrigenous Ordovician slate of all the three segments to evaluate the range of metamorphism of the Eastern Cordillera.

- The **Atocha segment** shows an irregular distribution of the illite-crystallinity values ranging between anchi- and epizone. The samples were derived from stratigraphic levels of the Lower to the Middle Caradocian.
- The **Mochará segment** shows a regular epizonal distribution of the illite-crystallinity values within the stratigraphic level of the Upper Tremadocian to the Middle Arenigian. The Llanvirnian deposits reveal an anchimetamorphic overprint.
- The **Yuncharà segment** is characterised by a significant increase of the illite crystallinity from diagenesis to epizone in a W to E cross section which is correlated to the stratigraphic position of the samples from the Middle Arenigian to the Cambrian.

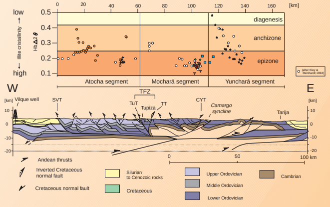
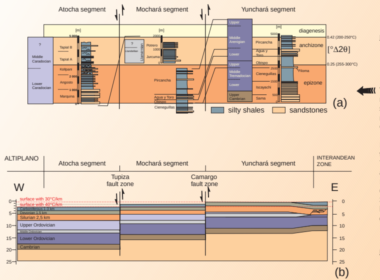


Fig. 5: Illite-crystallinity values of the Ordovician slate in a cross section through the different segments. The illite-crystallinity values are plotted in relation to their locality. High Hb $\Delta 2\theta$ values refer to a low illite cristallinity. The distribution of the values reveals the differences in the degree of metamorphism in the different segments. This becomes even more clear in plots of illite-crystallinity values versus stratigraphic position (Figs. 6 a, b). TFZ Tupiza fault zone, other abbreviations see figure 2.



The age of the Ordovician strata decreases from the west to the east. Therefore, the metamorphism according to the stratigraphy is characterised by shifts between the three segments (Figs. 6 a, b). These shifts can be explained by pre-Upper Carboniferous W-dipping normal faults. Another explanation would be to assume W-vergent thrust faults of Upper Carboniferous age, what is proposed herein (Fig. 8).

Based on the value trend of the illite crystallinity in combination with the known thicknesses of the Cambro-Ordovician strata a geothermal gradient of about 30°/km is deduced for the Yuncharà segment. The diagenetic and anchi- to epizonal values of the segments lead to the assumption of a thick pile of overlying younger rocks. For example, the exposed Pircancha Formation in the Yuncharà segment in the east is assumed to have been buried below at least 6 km of Silurian and Devonian sediments. Assuming a geothermal gradient of 30°/km, the overlying rock pile should increase in its thickness towards the west due to the higher illite-crystallinity values in younger stratigraphic levels. Even if we assume a geothermal gradient of 40°/km a covering pile of 5 km would result for the Atocha segment to the west.

Fig. 6: (a) Metamorphic range in relation to the Cambro-Ordovician units of the three segments. (b) Simplified model of the position and overlying rock pile of the three segments in relation to the expected geothermal gradients of 30°C/km and 40°C/km during the Carboniferous metamorphic event.

GEOLOGICAL EVOLUTION OF THE EASTERN CORDILLERA OF SOUTHERN BOLIVIA

Late Ordovician (Oclóyic): The middle Ordovician convergent **Gandacol event**, culminating in the late Ordovician **Oclóyic orogeny** is documented by slumps and turbiditic deposits in the Upper Ordovician rocks, only (MÜLLER et al. 1996, Fig.7).

Upper Carboniferous (Hercynian, 310-290 Ma): The penetrative cleavage of the Cambro-Ordovician basement was originated during the compressive **Toco event**. Illite-crystallinity values indicate a diagenesis up to a epimetamorphic overprint. W-vergent thrusts developed most probably at the Tupiza and the Camargo fault zone (Fig.8).

Upper Triassic (220-208 Ma): First indicators of extensional movements.

Cretaceous-Palaeocene: (150-58 Ma) Rifting has developed correspondingly in southern Bolivia and NW Argentina during the early Cretaceous (150-90 Ma). In the Tupiza region the small San Lorenzo-Tupiza rift was formed (Fig. 9). The rifting caused a diastathermal metamorphism as indicated by K-Ar dating of the clay fraction < 2 µm and < 0,2 µm (Fig. 4). Post-rift sedimentation took place in Upper Cretaceous to Palaeocene times (90-58 Ma).

Tertiary: In Eo-Oligocene times parts of the Eastern Cordillera belonged to a large foreland basin.About 26-22 Ma (late Oligocene to early Miocene) large overthrusts verging predominantly to the W were active. They induced the development of basins, which have been filled by alluvial fans and playa deposits (Estarca and Tupiza basins, Fig. 2). During this timespan Andean compression and volcanism reached their climax and in some cases, Cretaceous normal faults have been inverted. Subsequently, tectonic shortening decreased during the Miocene. The Nazareno basin was installed. The shift of compression towards the eastern Interandean zone is marked by the Rio San Juan del Oro peneplain (SJO, Fig. 4), which has originated about 12 Ma ago.

Present

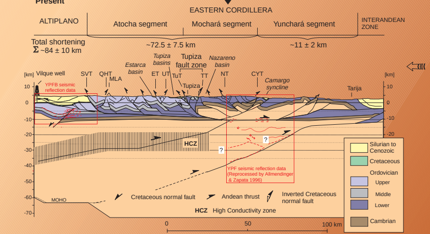


Fig. 10. Cross section of the Eastern Cordillera of southern Bolivia, showing the main Andean thrusts combined with seismic data from YPFB (pers. com.), and ALLMENDINGER & ZAPATA (1996). For localization see Figs. 2, 3.

Guandacol event Oclóyic orogeny

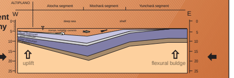


Fig. 7: The foreland basin with the associated flexural buldge in the east during late Ordovician times.

Toco event

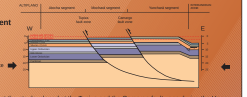


Fig 8: W-vergent thrusts developed at the Tupiza and the Camargo fault zone during the Upper Carboniferous (Toco event, 310 -290 Ma).

Cretaceous rifting

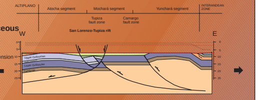


Fig. 9: A small rift developed and rift deposits accumulated in the area of the Tupiza fault zone in early Cretaceous times. Thermal subsidence took place during the late Cretaceous and post-rift sediments (light green) covered the rift sediments (dark green).

Crustal shortening of the Eastern Cordillera

The crustal shortening of the Eastern Cordillera was defined to about 84 km along our geotraverse (see Figs. 2, 3). We believe, that no more than 20 km of that amount due to Palaeozoic deformations. Thus, Andean shortening reaches 60-70 km. The shortening rate of the Interandean and the Subandean zones east of our section is about 140 km (KLEY et al. 1997). For the southern Altiplano, on the other side, 40 km may be a cautious estimation. Thus, Andean crustal shortening reached altogether 240-250 km in the backarc of the Andes at 21°-22° S. This amount is, however, not sufficient to explain thickening of the crust to 60-70 km beneath the Altiplano and the Eastern Cordillera. For that about 320 km would be necessary. As it is highly questionable that magmatic underplating might have contributed about 25% to the thickening of the backarc crust, we have to look for additional mechanisms of crustal accretion such as the addition of serpentinized mantle material to account for the crustal thickness of the south Bolivian Andes. Furthermore, poorly constrained pre-Neogene crustal thickening should be taken into account.

Fig. X: Hard working geologist in the field (That`s why trees are so scarcy in the Eastern Cordillera of S Bolivia).

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