

## THE ANDEAN STRUCTURE OF THE CORDILLERA ORIENTAL FROM REPROCESSED YPF SEISMIC REFLECTION DATA

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### INTRODUCTION

The processes by which topography is developed and maintained in active mountain belts have captivated geoscientists for the last decade or more. The greatest uplift on Earth, the Tibetan-Himalayan system seems intuitively straight forward in the context of a continent-continent collision, even though the details of the lithospheric architecture and mechanics remain controversial. More enigmatic is the Altiplano-Puna of the central Andes. This second highest continental plateau — more than half a million square kilometers at an average elevation of almost 4 km — has developed in the absence of significant continental collision or terrane accretion. Nearly all workers in the Central Andes agree that crustal thickening by structural shortening is responsible for the topographic uplift, with lesser contributions from magmatic addition and lithospheric thinning (e.g. Isacks 1988). Although shortening is deemed important, virtually nothing is known of the geometry of major faults or the distribution of shortening at depth.

The location and geometry of the Subandean decollement beneath the Cordillera Oriental is a first order problem with substantial importance for estimates of Late Cenozoic shortening and its relation to topographic uplift of the Central Andes. Seismic reflection data have the potential to image that decollement beneath the Cordillera Oriental, but general lack of known economic targets and the rugged terrain have discouraged exploration. The seismic reflection surveys carried out during the mid-1980's by Yacimientos Petrolíferos Fiscales (now, YPF S.A.) just south of the international border in the vicinity La Quiaca, Argentina constitute virtually the only seismic reflection data collected in the entire Cordillera Oriental of the Central Andes. We have reprocessed four crossing lines from that YPF S.A. data set, using the technique of VIBROSEIS extended correlation, to obtain data lengths of 15 s (about 45 km). Our reprocessing shows a remarkable suite of deep reflections which we interpret to be a ramp in the Subandean belt decollement and possible duplexing of the lower crust farther west.

### GEOLOGIC SETTING AND PREVIOUS WORK

The region of study lies within the southern part of the Cordillera Oriental, west of the Subandean fold and thrust belt. These two tectonic provinces are separated from each other by two major fault zones, the Cabalgamiento Frontal Principal (CFP) and the Cabalgamiento Andino Principal (CANP). To the east of the CFP, the decollement of the Subandean fold and thrust belt is within Silurian rocks and, at the surface, isolated ridges of Paleozoic units are surrounded by extensive outcrops of Tertiary

strata (Baby et al. 1992, Dunn et al. 1995, Kley 1993, Mingramm et al. 1979). Although interpretations of internal fold and thrust geometry within the Subandean belt vary widely, the depth to the decollement is similar in most interpretations: it lies between 13 and 15 km below the surface outcrop of the CFP (about 12-14 km below sea level). Shortening within the Subandean belt increases progressively northward from less than 60 km in northern Argentina at 22°30'S latitude (Allmendinger et al. 1983, Mingramm et al. 1979) to 100 or more km in southern Bolivia at 21°S (Baby et al. 1992, Dunn et al. 1995, Kley 1993, Kley & Reinhardt 1994). The Subandean belt dies out between 23° and 24°S, due to southward erosion of the Paleozoic stratigraphic wedge beneath the Upper Cretaceous Salta basin, cutting out the decollement horizon (Allmendinger & Gubbels 1996, Allmendinger et al. 1983, Mingramm et al. 1979). This important lateral change occurs 1-2 degrees of latitude farther south than the seismic lines described here.

West of the CANP, extensive outcrops of Ordovician strata, covered by minor Cretaceous and Tertiary units, characterize the Cordillera Oriental. One of the highest amplitude folds in the Cordillera Oriental is the Camargo syncline, a structure that can be traced for nearly 200 km along strike and is imaged on the seismic lines shown here. The seismic data which we have reprocessed was first interpreted by Bianucci et al. (1987), who described the well-displayed shallow thrust structures, including the Yavi thrust which bounds the west side of the Camargo syncline.

The San Juan de Oro surface truncates virtually all of the major structures in this part of the Cordillera Oriental. Deposits above the surface are flat-lying or gently dipping and have been dated at about 10 to less than 2 Ma (Cladouhos et al. 1994, Gubbels et al. 1993). The youngest deformed rocks, which may be either syn- or pre-deformation in age, are 13 to 18 Ma (Cladouhos et al. 1994, Gubbels et al. 1993). The surface deposits are cut locally by young strike-slip and normal faults which have, in general, displacements of less than 10 m (Cladouhos et al. 1994). The timing of deformation in the Subandean belt is much less certain, owing to the primitive state of knowledge of the upper Cenozoic strata over much of the area. Gubbels et al. (1993) proposed that the deformation was younger than about 10 Ma based on the perceived age of the Yecua Formation. However, Reynolds et al. (1994) have recently shown that the Anta formation of northwest Argentina (25-26°S), which is considered to be the lateral equivalent of the Yecua, is about 14 Ma. They suggest that uplift in the Puna began by 15 Ma and in the Cordillera Oriental by about 13 Ma.

## THE SEISMIC REFLECTION DATA

We have reprocessed four seismic reflection lines located just east and southeast of La Quiaca, Argentina, which were acquired during the middle 1980's by YPF S. A. as a part of the exploratory work carried out in the Puna. We have extended these data to 15 seconds using a "self-truncating" extended correlation (Okaya & Jarchow 1989). The reprocessed lines form an intersecting network, providing excellent 3-D control and confirming that the major features described below are in the plane of section and not side-swipe. Preliminary constant velocity migrations have been carried out to get first order control on the location and dip of the major dipping features on the lines. The datum for the reprocessed lines is 4 km above sea level, all depths are given with respect to sea level, and all times cited below are two-way travel times.

## INTERPRETATION

Because of the east-northeast strike of surface structures, the NW-SE trending Line 4219 provides an approximate true dip section. However, all features described below can be tied with crossing lines.

The main features visible on the original correlated 5 s data and described by Bianucci et al. (1987) can also be seen on our reprocessed lines, although our processing was optimized for deeper parts of the section. The Camargo syncline is clearly visible on all of the lines beneath the Miocene unconformity. The high amplitude reflectors at the base of the syncline were interpreted by Bianucci et al.

(1987) to be from the Cretaceous Salta Group; where they flatten out on the west limb a about 2.5 s, they are about 0 to 2 km below sea level. The syncline is bounded on its western side by the Yavi thrust, which is somewhat listric and dips about 25-30°. Like the syncline, the thrust is exposed in southern Bolivia north of the continuous part of the San Juan de Oro surface. To the east of the Camargo syncline, subtle thrust structures can be discerned on large scale copies of the lines.

One of the most striking features of all the seismic lines is a band of strong mid-crustal reflections which occur between 4.5 and, locally, 6 s (about -9 to -13 km; all depths are given with respect to sea level and the datum of the reprocessed lines is +4 km). The top of this band was imaged on the original fully correlated data but its true extent only became apparent upon extended correlation. The internal structure of the band of events is quite complicated and is distorted by velocity pull-down beneath the Camargo syncline. At least locally, thrust imbrications appear to splay from the band, suggesting that it may be a shallow zone of decollement. However, the band would appear to be 5 to 10 km too shallow for the Subandean belt decollement and does not clearly correlate with any mapped feature farther east; it is, conceivably, related to the down-dip projection of the CANP. Alternatively, it may be related to the shallow zone of high conductivity described by Schwarz (1994), or both.

At about 7-8 s (-16-20 km) on the east end of line 4219, a band of reflections dips steeply west at about 35° (migrated). Cross line control shows that this event dips to the northwest and strikes parallel to Andean folds and faults. Beneath this dipping reflection, scattered horizontal reflections are present to about 12 s (-32 km). Reflections to the west above the dipping event have geometries similar to hanging wall anticlines and appear to be truncated against the event. This dipping event underlies the east limb of the Camargo syncline and correlates closely with the westward projection of the Subandean decollement. In fact, Mingramm's (1979) section showed the beginning of the footwall ramp in the decollement almost exactly where the dipping reflector is located. The crossing lines suggest more complicated structure to the west of the Camargo syncline, with reflections to 15 s (-41 km), displaying a series of truncations and horizontal and dipping segments which we tentatively interpret as ramps and flats and multiple decollement levels. It is unlikely that any of these lines have sufficient penetration to image Moho, which is reported to lie at about 50-55 km on the Berlin refraction data to the north Wigger (1994).

## DISCUSSION

We tentatively propose that the Camargo syncline coincides with the position of the footwall ramp in the Subandean decollement. If correct, this interpretation allows us to determine a minimum displacement of 50-60 km on the Cabalgamiento Andino Principal and the Subandean belt farther east at this latitude; shortening farther west within the Eastern Cordillera has not been determined. The ramp apparently extends to near the base of the crust and, thus, would also mark the western limit of under-thrusting of undeformed craton beneath the orogen. It is possible that the location of the ramp was controlled by Late Precambrian and/or early Paleozoic tectonic features. Shortening should increase farther north as suggested by previous authors and as can be observed by the northward divergence of the Camargo syncline and the major thrusts in southern Bolivia. Indeed, in southern Bolivia at 21°S, Dunn et al. (1995) interpret about 100 km of shortening in the Subandean belt and the distance between the CFP and the Camargo syncline is 105 km.

Although the ramp appears to correlate spatially with the Camargo syncline, the kinematic and temporal relations between the syncline and thrusting on the ramp remain enigmatic. If most of the shortening in the Subandean belt is younger than 10 Ma, then the location of the syncline above the ramp must be totally coincidental because folding of the syncline was completely finished by 9 Ma. Alternatively, if substantial shortening in the Subandean belt is older than suspected (e.g. younger than 14 Ma) then there may be a kinematic relationship between the Camargo "hanging wall" syncline and the footwall ramp of the Subandean belt decollement. Finally, it may be that the CFP, the ramp and the syncline are kinematically and temporally related but that subsequent shortening in the Subandean belt was accommodated along a deeper decollement. However, there is no evidence of such a ramp on the existing seismic.

The steepness of the ramp is striking. This area is located reasonably close to the southern

limit of flexural compensation and it is possible that the steepness is related to that transition. If so, we might expect that the ramp dips at a considerably shallower angle to the north. The northward termination of the Camargo syncline is consistent with this hypothesis. A northward shallowing of the dip of the ramp would be clearly consistent with the observation that deeper structural and stratigraphic levels are exposed in the Argentine Cordillera Oriental than along strike to the north in Bolivia.

We have proposed a regional deep seismic reflection line to test these hypotheses.

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