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Evolution of the West Andean Escarpment at 18°S (N. Chile) during the last 25 Ma: uplift, erosion and collapse through time

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Abstract

The geological record of the Western Andean Escarpment (WARP) reveals episodes of uplift, erosion, volcanism and sedimentation. The lithological sequence at 18°S comprises a thick pile of Azapa Conglomerates (25–19 Ma), an overlying series of widespread rhyodacitic Oxaya Ignimbrites (up to 900 m thick, ca. 19 Ma), which are in turn covered by a series of mafic andesite shield volcanoes. Between 19 and 12 Ma, the surface of the Oxaya Ignimbrites evolved into a large monocline on the western slope of the Andes. A giant antithetically rotated block (Oxaya Block, 80 km×20 km) formed on this slope at about 10–12 Ma and resulted in an easterly dip and a reversed drainage on the block's surface. Morphology, topography and stratigraphic observations argue for a gravitational cause of this rotation. A "secondary" gravitational collapse (50 km^3), extending 25 km to the west occurred on the steep western front of the Oxaya Block. Alluvial and fluvial sediments (11–2.7 Ma) accumulated in a half graben to the east of the tilted block and were later thrust over by the rocks of the escarpment wall, indicating further shortening between 8 and 6 Ma. Flatlying Upper Miocene sediments (<5.5 Ma) and the 2.7 Ma Lauca–Peréz Ignimbrite have not been significantly shortened since 6 Ma, suggesting that recent uplift is at least partly caused by regional tilting of the Western Andean slope.

Keywords: Central Andes; Western slope; uplift; erosion; sedimentation; volcanism; gravitational collapse

1. Introduction

Understanding the evolution of large mountain chains, their effect on climate and conversely, the role of climate in shaping mountain ranges is of prime interest in understanding the Earth system. The Central Andes is an excellent example to study interplays between tectonic and body forces and effects of climate, erosion and sedimentation. In addition, process, timing and quantification of the Andean uplift have been an issue of considerable debate. Most of the observations and arguments derived from studies on the Altiplano (Lamb et al., 1997), Eastern Cordillera and sub-Andean ranges (Kley, 1996; Kennan et al., 1997; Sheffels, 1990, 1995; Schmitz, 1994) or from transects in the southern Central Andes (Allmendinger et al., 1997). The Western Andean Escarpment at 18°S near the "Arica Bend" has received less attention but provides considerable information on processes, timing and consequences of uplift in a hyperarid region (Salas et al., 1966; Muñoz and Charrier, 1996). This western margin of South America is characterized by

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a difference in elevation from the trench at 7000 m depth to > 5000 m height in the Western Cordillera over 250 km lateral distance. At the same time, the region is characterized by a dry desert with an average present day rainfall at the coast of only 0.5 mm/year. There is paleoclimatic evidence (Gregory-Wodzicki, 2000; Alpers and Brimhall, 1988; Sillitoe and McKee, 1996) that a hyperarid climate was established between 20 and 15 Ma with an intermittent globally controlled less arid period around 7 Ma (Gaupp et al., 1999; Dörr et al., 1994; Jensen et al., 1995; May et al., 1999). In consequence, erosion has been extremely slow over the past 20 Ma even though tectonic movements created a steep morphology.

In this study, we present an account of uplift, erosion, sedimentation, gravitational collapse and volcanism on the West Andean Escarpment (WARP, Fig. 1) since 30 Ma, based on field mapping, aerial photographs, satellite images, sedimentological studies and geochronology. Ar–Ar ages of the stratigraphic units described here are given in Wörner et al. (2000b).

2. Geological background

The active western continental margin of central South America is characterized by subduction of the Farallón–Nazca plate and arc magmatism since Jurassic times. Convergence has been variable with 5 cm/year at 60–30 Ma and increased rapidly to 15 cm/year at around 25–30 Ma (Pardo-Casas and Molnar, 1987; Somoza, 1998). The angle of convergence also changed at that time and is presently trench-orthogonal in the Arica Bend with a convergence rate of 8 cm/year (Somoza, 1998). The dip of the subducting Nazca plate today varies from less than 10° to around 30° underneath the Central Andes (Cahill and Isacks, 1992). Active subduction zone magmatism is only observed in sectors of relatively steep subduction, whereas magmatism is absent in the flat-slab regions (Barazangi and Isacks, 1976; Coira et al., 1982; Jordan et al., 1983; Kay and Abbruzzi, 1996).

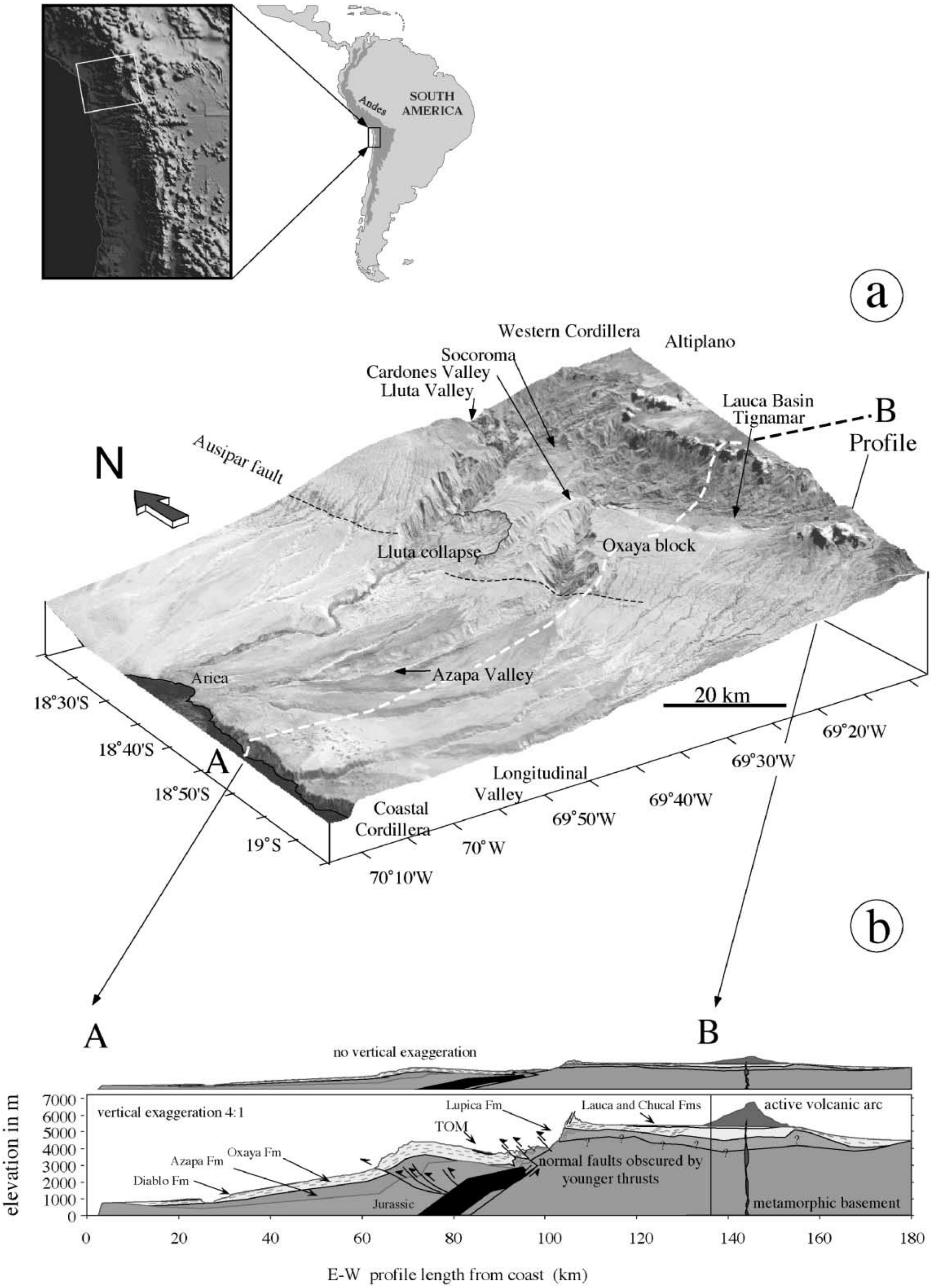
Proterozoic metamorphic basement rocks and overlying Permian (?) to Lower Tertiary rocks are exposed in the steep escarpment towards the Western Cordillera to the east of Arica (Wörner et al., 2000a). Jurassic to Early Cretaceous tholeiitic arc rocks and marine back arc strata constitute the Coastal Cordillera. Magmatism shifted some 100-km from a western position in the Jurassic to the present Western Cordillera in Oligocene times (Coira et al., 1982). This observation was interpreted by Rutland (1971) to reflect tectonic erosion at the leading upper plate edge (see also Scheuber et al., 1994). However, it is likely that changing slab dip also contributes to changing arc location. In fact, the arc widened between 100 and 80 Ma, narrowed around 35 Ma and widened again at around 20 Ma (Coira et al., 1982; Scheuber et al., 1994). Thus, the distribution of magmatism in space and time is consistent with both tectonic erosion and changing dip of the slab.

Prior to Andean uplift that commenced from 30 to 25 Ma ago (Isacks, 1988), northernmost Chile was characterized by continental sedimentation, andesitic volcanism and abundant volcaniclastic sediments. The fluvial and lacustrine facies of these sedimentary rocks and the abundance of andesitc clastic rocks indicate reworking by running water and deposition in shallow lakes. However, since at least 25 Ma, up to 1000 m of coarse-grained sediments (Fig. 2) started to accumulate over some 40 km E–W distance between the Coastal Cordillera and the western slope of the Andes. These molasse-type sediments, assigned to the Azapa Formation in the working area (Salas et al., 1966), are observed all along the Western Andean slope and indicate the initiation of Andean uplift and crustal thickening. The present thickness of the crust is around 70 km (Isacks, 1988; Wigger et al., 1994; Beck et al., 1996; Benjamin et al., 1987; Tosdal et al., 1985; Hartley et al., 2000).

3. Warp evolution between 30 and 19 Ma: uplift, erosion and crustal melting

The evolution of uplift and erosion of the Western Andean Escarpment (WARP) in the working area is best described by using the extensive series of ignimbrites of the Oxaya Formation as a morphological and

Fig. 1. (a) 3-D Landsat image of the West Andean Escarpment between Arica and the Western Cordillera. (b) Topographical cross-section and geological profile along the transect A–B in (a). Note that the normal faults bounding the Oxaya Block on its eastern side have been overthrust during younger tectonic movements and thus can only be inferred.


Andes
SOUTH AMERICA
a
Western Cordillera
Altiplano
Socoroma
Cardones Valley
Lluta Valley
Lauca Basin
Tignamar
B
Profile
N
Ausipar fault
Lluta collapse
Oxaya block
Azapa Valley
Arica
20 km
18°30'S
18°40'S
18°50'S
19°S
A
Longitudinal Valley
Coastal Cordillera
70°10'W
70° W
69°50'W
69°40'W
69°30'W
69°20'W
b
A
B
no vertical exaggeration
vertical exaggeration 4:1
elevation in m
7000
6000
5000
4000
3000
2000
1000
0
Lupica Fm
Lauca and Chucal Fms
active volcanic arc
TOM
Azapa Fm
Oxaya Fm
Diablo Fm
normal faults obscured by younger thrusts
Jurassic
metamorphic basement
0
20
40
60
80
100
120
140
160
180
E-W profile length from coast (km)

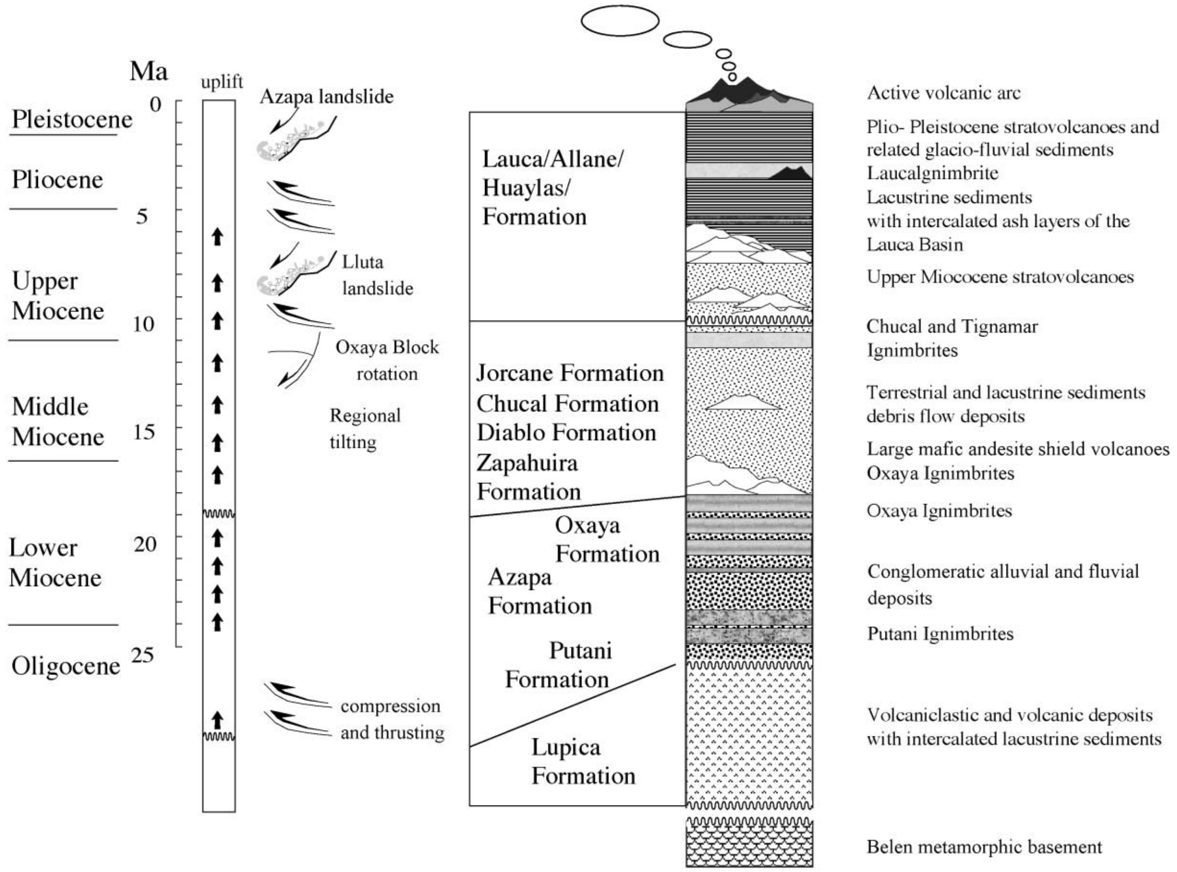


Fig. 2. Summary of stratigraphic units from the Coastal Cordillera to the Chilean Altiplano at 18°S based on field evidence and Ar–Ar dating (modified from Wörner et al., 2000b).

temporal reference. The most precise age available for the Oxaya Formation are those of Wörner et al. (2000b) who reported Ar/Ar sanidine and biotite plateau of ages 22.72±0.15 Ma at the base to 19.38±0.02 Ma at the top. The three thick uppermost ignimbrites representing 90% of the volume, however, erupted very close in time, probably within less than a million years (Wörner et al., 2000b).

3.1. Azapa conglomerates (25–23 Ma)

The ignimbrites are underlain by more than 500 m of sediments of the Azapa Formation (Fig. 2). These are predominantly coarse-grained, river-dominated alluvial fan and ephemeral-braided river deposits. Their direction of transport was from the Andean slope in the east towards the Coastal Cordillera. Distally, they grade into fluvio-lacustrine and salar sediments in the present Longitudinal Valley. Because the sediment source is the N–S-directed western margin of the Proto-Altiplano, the resulting clastic wedge also has a N–S trend. The clastic wedge has a cross-sectional area of ca. 10–12 km^2 and in the N–S extension, this translates into a volume of 10–12 km^3 per km Andean slope. This clastic wedge overlies a prominent unconformity on older Jurassic to early Cretaceous sedimentary, volcanic and plutonic rocks. The paleosurface that was covered by these younger sediments is exposed in all the deep valleys in northernmost Chile (Fig. 1) and can be correlated to southern Peru (Tosdal et al., 1985). It had a steep mountainous topography in the east, whereas in the west, the unconformity is represented by the eastward tilted flat surface of the Coastal Cordillera (see cross-section in Fig. 1b).

Taking the accumulation rate of 0.4 mm/year for the ca. 7-Ma-old Arcas Fan in northern Chile as a reference (Kiefer et al., 1997), we obtain from the observed thickness below the ca. 23 Ma oldest ignimbrite a time span of about 1.25 Ma for deposition. Considering that at 23 Ma, the climate may have been wetter than during the accumulation of the Arcas Fan (Alpers and Brimhall, 1988; Gregory-Wodzicki, 2000); this should be a minimum estimate. As a conservative number, we place the beginning of sediment accumulation of the Azapa Formation at 25 Ma. In other words, a sediment volume of about 10 km^3 was transferred from the Western Andean slope to the Longitudinal Valley per km N–S direction in only 1 million year. Considering its size, extent, homogeneity in facies and stratigraphic position, this clastic event documents a strongly increased topographic gradient and thus, initial uplift of the Andes.

Provenance analysis identifies a source area, with rocks equivalent to those exposed today in the upper WARP region, which includes the Belen metamorphic basement, Jurassic to Lower Cretaceous volcanic, sedimentary and plutonic rocks of the Livilcar Formation (Salas et al., 1966) as well as altered volcanic and sedimentary rocks of the Lupica Formation (Fig. 2).

Thus, initial surface uplift in the Andes commenced around 30–25 Ma (see also Isacks, 1988; Semperé et al., 1990). This uplift coincides with a phase of major plate reorganization in the Pacific region around 28 Ma (Hey, 1977), increased rates of frontal convergence at the South American plate margin (Pardo-Casas and Molnar, 1987; Somoza, 1998) and opening of the Drake Passage at 23 Ma (Staudigel et al., 1985; Beu et al., 1997). Probably, the cold Humboldt Current along the western coast of southern South America was also initiated at that time (Lawver and Gahagan, 1998). Parallel to the tectonic events, the evolving western Andean margin became increasingly arid and may have reached hyperaridity by 15 Ma (Gregory-Wodzicki, 2000; Alpers and Brimhall, 1988). At least two main factors contributed to the prevailing aridity in this area since the Upper Miocene: (1) the Andean mountain range acting as a barrier, even as low as 2000 m (Gregory-Wodzicki, 2000), for moisture from the east and (2) a stable inversion layer over the cold Humboldt Current in the Pacific that inhibits orographic rain fall along the western Andean margin.

3.2. Oxaya Ignimbrites (22.7–19.4 Ma)

Uplift and erosion were interrupted by the deposition of four extensive ignimbrite sheets, up to 1100 m in total thickness. These form most of the present surface on the Western Andean slope (e.g. Pampa Oxaya), except where it is disturbed by tectonism (see below). The Oxaya Ignimbrites (22.7–19.4 Ma) can be traced in an E–W direction over 130 km from the Western Cordillera at ~ 4600 m a.s.l. to the Coastal Cordillera. At the coast, the ignimbrites are less welded but still reach 300-m thickness near Arica. N–S correlation of the Oxaya Ignimbrites is possible for some 300 km from southern Peru (~ 17°S), where they represent the Huaylillas Formation (Tosdal et al., 1981, 1985), to south of the Chilean Camarones Valley (~ 20°S). The areal extent and measured thickness suggest a volume of >3000 km^3.

Thick alluvial fans overlain by extensive ignimbrites are known over all of the Western Andean slope in southern Peru (Moquegua Fm, Tosdal et al., 1981, 1985) and in regions further south (Lahsen, 1982). In the south, however, the overlying ignimbrites are progressively younger (15–17 Ma at 21°S, Francis and Rundle, 1976; 6–12 Ma at 24°S, deSilva, 1989) while towards the north, they appear to be older (>25 Ma; see review by James and Sacks, 1999).

While the onset of surface uplift appears to be reasonably well constrained, it is still uncertain how much of the present uplift was achieved at what time. Paleobotanical evidence summarized by Gregory-Wodzicki (2000) suggests that the Altiplano was no higher than 1300 m at 20 Ma and had not been uplifted to half its modern elevation by 10.7 Ma. However, the errors on these paleoelevation estimates are large (Gregory-Wodzicki, 2000).

4. 19–12 Ma: andesite volcanism, tilting, block rotation and gravitational collapse

4.1. Andesite magmatism

Ignimbrite volcanism (22.7–19.4) was immediately succeeded by large andesitic volcanoes dated at

20.33±0.38, 20.02±0.3, 18.70±0.80, 15.07±0.12 and 9.18±0.33 (Wörner et al., 2000b). These andesite shields occur along a N–S trend from 17°S to 20°S, approximately covering the N–S extent of the Oxaya Ignimbrites (Zapahuira Fm, Fig. 2). These andesite volcanoes provide characteristic detritus to the Upper Miocene conglomeratic Diablo Formation on the lower WARP slope, where they appear as a gray cover on the ignimbrite surface in Fig. 1. Large mafic andesite shield volcanoes of similar age are also known to overly regional ignimbrites further south (see Wörner et al., 2000b) and in southernmost Peru (volcanics of the lower Barroso Fm overlying ignimbrites of the Huaylillas Fm, Tosdal et al., 1981, 1985).

4.2. Regional tilting

Continued uplift resulted in westward tilting and significant steepening of the WARP and the Oxaya surface. This movement formed the giant monocline known over several hundreds of kilometers on the Western Altiplano margin (Isacks, 1988; Lamb and Hoke, 1997; Hartley et al., 2000). The Oxaya Ignimbrites, at the northern and southern margins of the study area, now form a gently sloping surface with a westerly tilt of 3° between the top of the Western Cordillera and the coast at Arica (Figs. 1 and 3). This "Oxaya Surface" is dissected by a parallel (mostly fossil) drainage system and several deep active valleys.

The amount of postdepositional tilt of this surface is difficult to establish, because the depositional angle of the Oxaya Ignimbrites is unknown. The morphological (not present topographical) offset between the base of the Azapa conglomerates in the west and the top of the unconformity on Jurassic and Late Cretaceous rocks further east give a minimum depositional angle prior to deposition (and tilting) of the Oxaya Ignimbrites. This angle is 1° at maximum. Given the present slope of the Oxaya Ignimbrites, an additional tilt of about 1.5–2° must have occurred after their deposition. This estimate is in accordance with a similar westerly tilt proposed by Lamb and Hoke (1997). Over the lateral distance from the coast to the present Western Cordillera, this tilt translates into an uplift of about 1700–2500 m for the eastern margin of the ramp in the Western Cordillera since 19 Ma. This is in accordance with the estimate by Gregory-Wodzicki (2000).

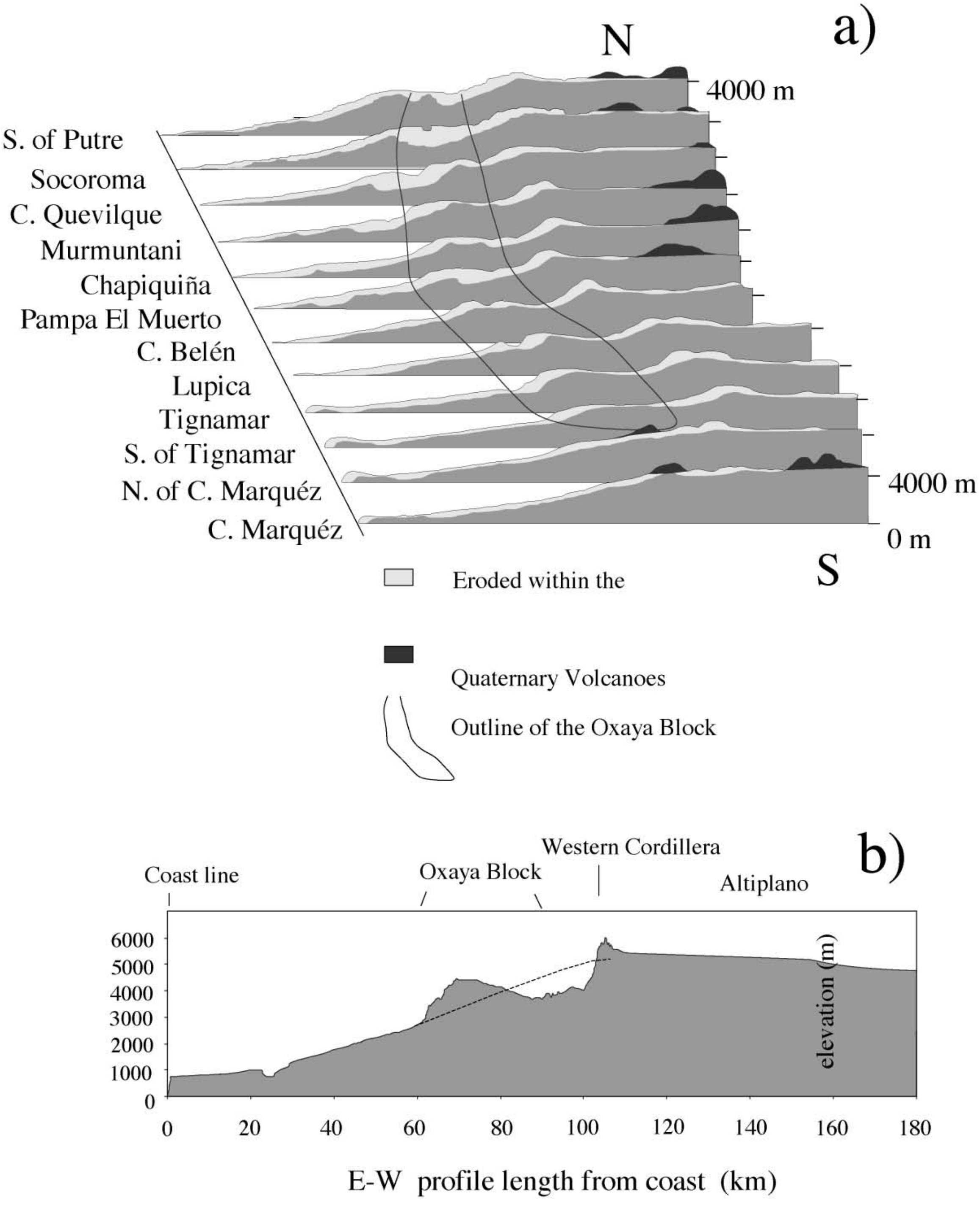
A gently sloping western flank of the Andes is also known from north to south of the Arica Bend area. However, at the Arica Bend, the distance between the coast and Western Altiplano is smaller and thus the slope is steeper than anywhere else on the Western flank of the Andes.

Regional tilt was also postulated by Hartley et al. (2000) for uplift of the western Andean margin further south. However, their model differs from ours in that we do not invoke the tectonically eroded and underplated forearc material as the only cause for tilt and uplift. The volume of eroded and underplated material could explain only the crustal thickening directly in the forearc arc and not the observed increase in crustal thickness below the western Altiplano. We rather concur with Isacks (1988) and Lamb and Hoke (1997) in inferring middle to lower crustal ductile flow from the east. This is more consistent with the timing of uplift, which was accentuated in the Miocene, whereas tectonic erosion at the leading edge of the South American plate is very likely a more continuous process from Jurassic to Present times (Giese et al., 1999).

We therefore conclude that regional tilting rather than movement along discrete fault zones is the dominant process responsible for the uplift and the gentle slope along the western Andean margin.

This conclusion is in conflict with the notion of Muñoz and Charrier (1996) who described a zone of reverse faulting as the "Western Andean Thrust Belt" and attributed the uplift of the Western Cordillera to movements along these faults. They argue that this tectonic activity falls into the age range between 15

Fig. 3. (a) A series of W–E topographic profiles across the Oxaya Block stacked from north to south. Each profile represents a ca. 5 km swath of the digital elevation model, which is based on the 1/250 000 topographic map. Lighter shading depicts the erosion relative to the swath surface. The profiles show that the Oxaya structure is not related to increased uplift of the Altiplano as would be expected if the structure were formed by tectonic stacking. (b) Detailed profile across the center of the Oxaya structure. The dashed line represents the reference line for undisturbed slope of the Oxaya surface to the north of the rotated Oxaya Block. Note the tilted surface and the balance between areas above and below the reference line. Therefore, there is no net uplift related to this structure.


a)
N
4000 m
S. of Putre
Socoroma
C. Quevilque
Murmuntani
Chapiquiña
Pampa El Muerto
C. Belén
Lupica
Tignamar
S. of Tignamar
N. of C. Marquéz
C. Marquéz
4000 m
0 m
S
Eroded within the
Quaternary Volcanoes
Outline of the Oxaya Block
b)
Western Cordillera
Coast line
Oxaya Block
Altiplano
6000
5000
4000
3000
2000
1000
0
elevation (m)
0
20
40
60
80
100
120
140
160
180
E-W profile length from coast (km)

and 5 Ma and that it is related to the uplift of the western Altiplano and the formation of the Oxaya Block (see below).

We agree with the age estimate, which is based on the fact that the age of the thrusting is younger than the Huaylas sediments (10–3 Ma, see below). We disagree that these relatively small thrusts can explain the uplift of the western Altiplano and that this uplift took place only in that time range (for further discussion of this topic, see below). We concur with Lamb et al. (1997) and Isacks (1988) that the major process of crustal thickening below the western Altiplano is regional tilting and lower crustal ductile flow from east to west.

4.3. Block rotation

Between the towns of Socoroma and Tignamar (Fig. 1a), the tilted Oxaya surface is modified by a giant stair case topography (Figs. 1 and 3). The satellite image identifies an area of about 1600 km^2 with a clearly distinct morphological character and drainage pattern (Figs. 1a and 4). The surface on the Oxaya Ignimbrites here dips to the east against the slope of the Andean flank at an angle of 2.3° (Figs. 1b, 3, 4b) and defines the outline of the "Oxaya Block". This block, comprising the Oxaya Formation and its upper surface is thus tilted antithetically against the Western Andean slope. The western limit of the Oxaya Block is close to the Ausipar reverse fault (Figs. 1b and 4), which has a displacement of about 200 m as judged from observed displacement of strata. However, we note that the Oxaya Block and the Ausipar fault may not be directly related. This is because the offset of the reverse Ausipar fault is larger to the north of the Oxaya Block (as exposed in the Lluta Valley, García et al., 1996) compared to further south in the Azapa Valley. To the east, the bounding fault is obscured by sediments and volcanic rocks, erosion and younger reverse faulting (see below). A total throw of the Oxaya Ignimbrites at the eastern border of the block, compared to correlatives in the Western Cordillera, is about 1500 m (Figs. 1b and 3). The morphological offset, however, is enhanced to 2000 m by about 600 m as estimated from displacement along the eastbounding reverse faults (see below).

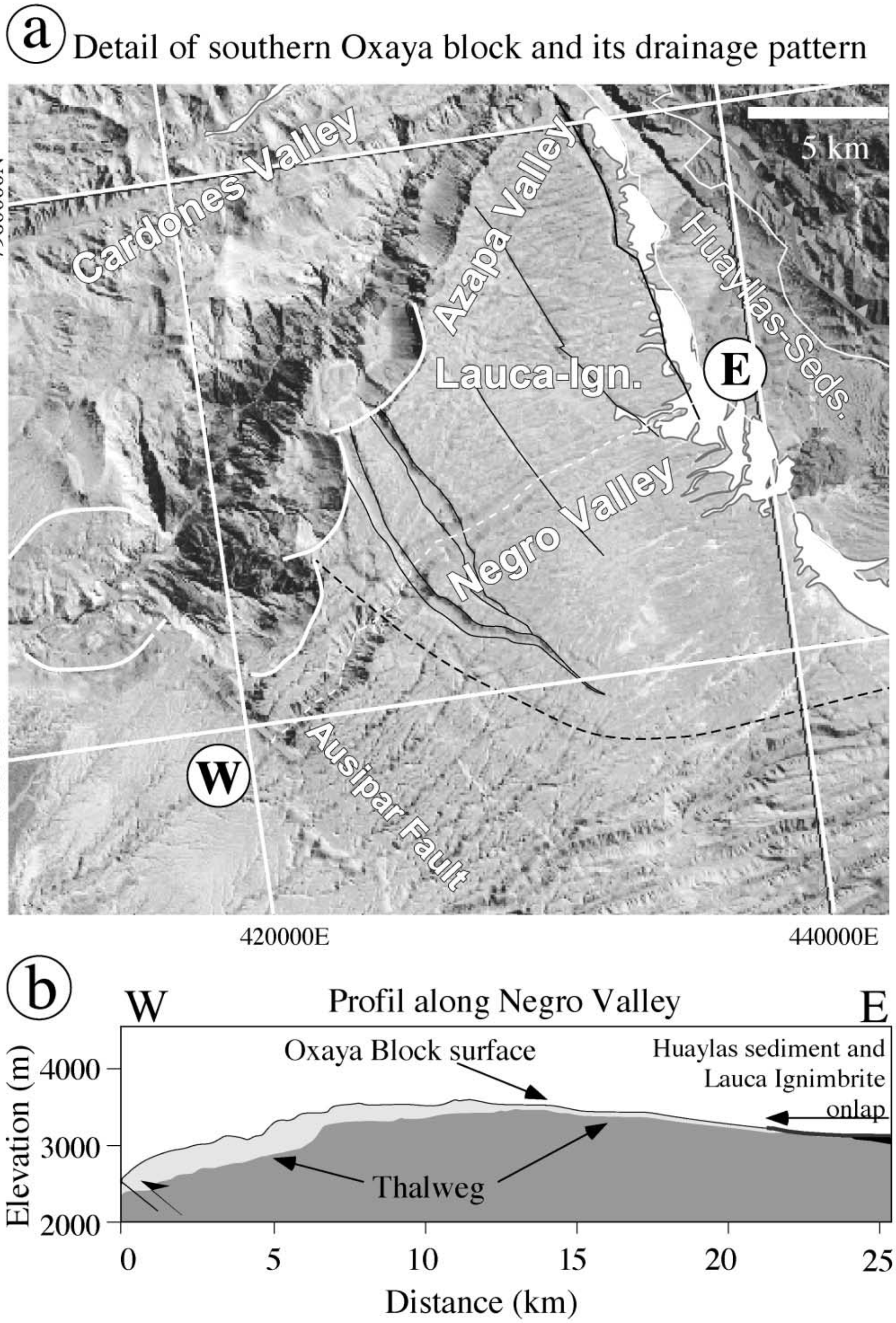
The creation of the eastward dipping surface against the Andean western margin created accommodation space for the Huaylas Fm (Salas et al., 1966), which consists of alluvial and fluvial braided stream sediments >200 m thick (Fig. 4a). The age of this formation is constrained between 10.6 and 2.7 Ma by an intercalated ignimbrite (10.55±0.05, Wörner et al., 2000b), by mammalian fossils (8–9 Ma, Salinas et al., 1991) and by the Lauca–Peréz Ignimbrite (2.71±0.01, Wörner et al., 2000b) overlying the Huaylas sediments. The base of the Huaylas Formation is an erosional surface with both steep morphology and smooth onlap on eroded Oxaya Ignimbrites.

The age of the Oxaya Block rotation is older than, or synchronous with, the oldest overlying sediments (i.e. >10.6 Ma) plus some extra time to allow for erosion. An upper age limit of rotation is given by the age of a rootless lava flow, which is exposed on the Pampa del Torro Muerto (TOM in Fig. 1b) and obviously was tilted together with the Oxaya surface. This lava flow was dated by Muñoz and Charrier (1996) at 11.4±0.3 (K–Ar whole rock age). As a cautious estimate, we conclude that the Oxaya Block began rotating in the short time span between 12 and 10.6 Ma.

The maximum age for the initial drainage system and valley incision on the Oxaya Block is clearly older than its rotation: satellite image and aerial photographs (Figs. 1 and 4) show a network of drainage on the Oxaya Block surface that is morphologically directed towards the west but topographically inclined towards the east. The Cardones (Fig. 1) and Rio Negro valleys are the best examples (Fig. 4). These valleys had their slope reversed and became inactivated by the Oxaya Block rotation and thus are older than at least ca. 10.6–12 Ma.

The Oxaya Block has been recognized as a unique morphotectonic feature on the western slope of the Andes, which is otherwise characterized by a smooth

Fig. 4. (a) Detail of the surface of the southern part of the Oxaya Block showing extensional grabens and the tilted Negro Valley. Note that the drainage pattern changes from parallel and undifferentiated on the westerly-dipping front of the block to subdue on the easterly-dipping surface. The upper course of the Azapa Valley shows a large amphitheatere-shaped collapse scar, suggesting that valley cutting in this arid region is accompanied by catastrophic valley flank failures. (b) Profiles along the thalweg and the surface along the Negro Valley, showing the rotation of the drainage system.


a
Detail of southern Oxaya block and its drainage pattern
5 km
Cardones Valley
Azapa Valley
Huaylas-Seds.
Lauca-Ign.
E
Negro Valley
Ausipar Fault
W
7960000N
7940000N
420000E
440000E
b
Profil along Negro Valley
W
E
Oxaya Block surface
Huaylas sediment and Lauca Ignimbrite onlap
Thalweg
Elevation (m)
4000
3000
2000
0
5
10
15
20
25
Distance (km)

continuous monocline. Its eastward tilted surface has been isolated and protected from erosion and therefore, represents one of the oldest surfaces on Earth. However, the cause for the rotation of the Oxaya Block is unclear. In the next section, we will discuss its possible origin.

4.4. The origin of the Oxaya Block

There are two fundamentally different models to explain the Oxaya Block: the conventional interpretation is that the block represents a tectonic ramp structure and is bound by two west-vergent thrust systems (García et al., 1999). Alternatively the Oxaya Block may result from antithetical rotation of a giant gravitational block due to an oversteepening Western Andean slope in the Arica Bend area (Wörner et al., 1999).

The first interpretation is based on the observation of west-vergent thrusts ("Western Andean Thrust Belt", Muñoz and Charrier, 1996; see also García et al., 1996). A ramp structure would create accommodation space for the Huaylas sediments as a piggyback basin. Such an interpretation has several problems. First, such a ramp structure would produce much steeper limbs as can be modeled by an area-balanced cross-section (R. Allmendinger, personal communication, 2000). Shallower angles are more consistent with regional gravitational sagging. Another problem is the presumed short duration of the rotation (10.6–12 Ma), which is more consistent with a gravitational *event* than continuous tectonic movements. Muñoz and Charrier (1996) also argued that the reverse faults caused a major part of the uplift of the western Altiplano. We see two problems with this interpretation: (i) the amount of uplift (2000 m) is not explained by the observed vertical throw along the faults (see below) and (ii) the morphotectonic structure of the Oxaya Block is restricted to the Arica bend area, whereas uplift and a gently dipping western margin of the Altiplano is observed for many 100 km N–S along the Western Andean slope. While we do not dismiss westward thrusting along the western Andean margin, we observe that regional uplift is not confined to the existence of a ramp-and-thrust structure.

The age of displacement is not consistent with the interpretation that the observed thrusts are related to the major portion of uplift of the western Altiplano: Huaylas sediments are younger than the block rotation, yet they are overthrusted by the reverse faults of the "Western Andean Thrust Belt". What we see, as thrust faults then will be younger than the sediments and the rotation and thus, cannot be responsible for the formation of the basin in which the sediments accumulated. By the same token, the reverse faults can only be related to uplift that occurred after the deposition of the Huaylas sediments, i.e. <2.7 Ma.

The amount of displacement is also limited: while the lateral displacement in ramp and thrust structures is difficult to measure, the vertical displacement is given by the offset of stratigraphically correlated strata. The difference in elevation of the top of the Oxaya Ignimbrites (from 2880 to 3100 m) and the Huaylas sediments (from 3100 to 3250 m), each measured to the west and east of the main thrust fault, on the east of the Oxaya Block, indicate a maximum surface uplift of 200 m along this fault. Two other reverse faults that are, however, rather discontinuous and less extensive regionally, are observed to the east of the main thrust (García et al., 1996). Their additional vertical uplift is difficult to determine precisely, but as a conservative estimate, we assume similar offsets for all three faults. Thus, it is concluded that the maximum vertical offset by the Belen–Tignamar fault system (García et al., 1996) is at 600 m, but likely less.

By contrast, the offset of the Lauca Ignimbrite between the center of the Hualyas basin and its exposures on the andesites of the Zapahuira Fm (from 3080 to 3200 m) is only 120 m. It is most likely due to onlap deposition of the highly mobile pyroclastic flow on higher ground, as is frequently observed for this deposit throughout the area. Therefore, surface uplift along the reverse faults did not affect the Lauca Ignimbrite and is thus older than 2.7 Ma and younger than 10.6 Ma (see above).

In the light of these observations, an alternative explanation for the Oxaya Block, i.e. a large gravitational rotation, is considered. The following points argue for a large gravitational sag-structure:

(1) The Oxaya Block formed in the Arica bend area, where the Western Andean slope from the coast to the Western Cordillera is by far the steepest. The topography in this region produces a strong negative component in Gephart's (1994) antisymmetric residual in the overall Andean topographic symmetry. It is

thus characterized by a topographic anomaly. While the present slope could be steeper than at the time when the Oxaya Block formed, we would argue that the particular location at the Arica Bend would have caused a relatively steep slope also in the geological past.

(2) The short duration of movement (less than 2 Ma) for the Oxaya Block rotation is consistent with a gravitational event rather than long-lasting movements along reverse faults of a ramp and thrust structure.

(3) With reference to the slope of the Oxaya surface to the north and south of the Oxaya Block, the uplifted frontal part of the structure is geometrically balanced by the downward movement of the block (Fig. 3c). Thus, there is no net uplift related to the structure.

(4) The Oxaya Block has its center at the altitude of the Cardones Valley. However, the Ausipar fault has a larger displacement, north of the Lluta Valley, compared to the area south of the Azapa Valley. Thus, the Oxaya Block and the displacement of the Ausipar reverse fault are not directly related.

A problem with our interpretation of the Oxaya Block as a gravitational structure is that the observed frontal thrust plane has a smaller displacement than the offset between the Western Cordillera and the Oxaya Block (1500 m, see above). This difference in movement between the east- and westbounding fault zones would argue for internal deformation of the Oxaya Block as depicted in Fig. 1b. In addition, we do not observe a basal decollement connecting the Ausipar fault with the presumed normal fault on the eastern side of the block. In this respect, the basal fault of the Oxaya Block in Figs. 1b and 5 is speculative. It would be important for our model to document the location and nature of the related normal faults at the eastern margin of the Oxaya Block. However, if the model and the sequence of events is correct, then these faults are necessarily obscured by retreating

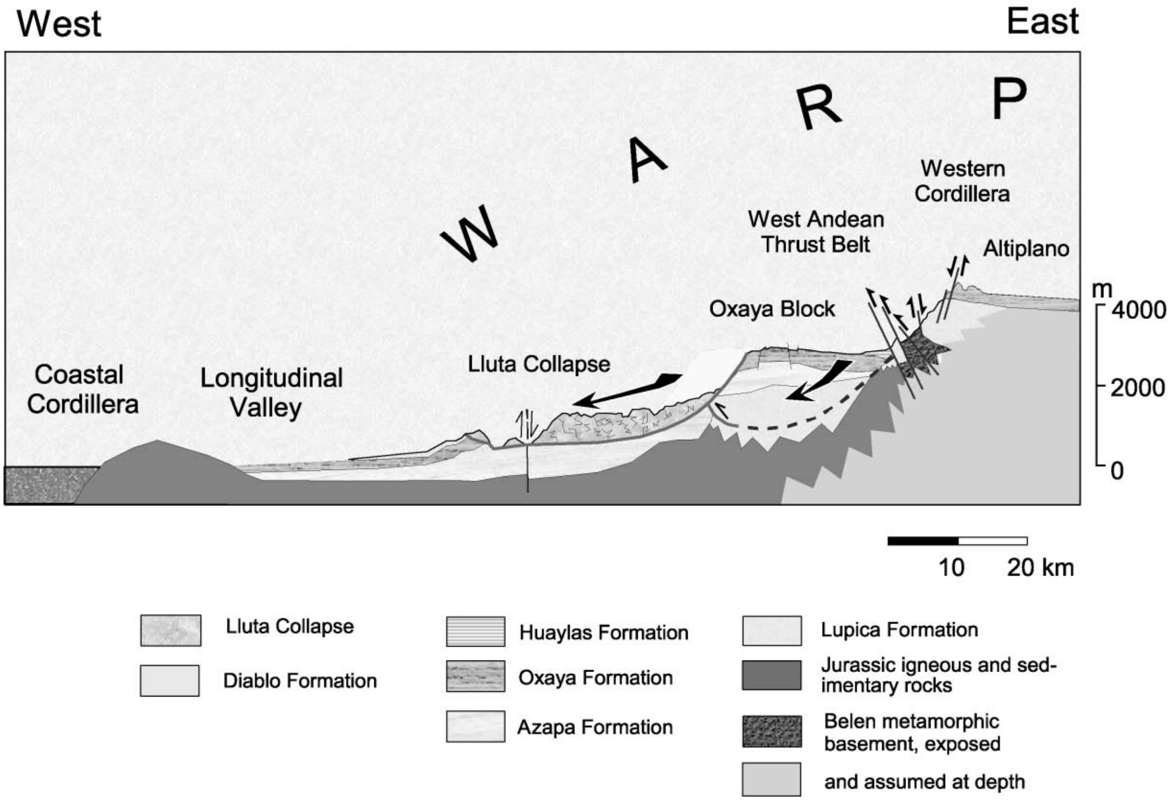


Fig. 5. Schematic cross section summarizing the topography and evolution on the Western Andean Escarpment, for discussion, see text.

erosion of the steep escarpment, sedimentation of the Huaylas sediments and, most importantly, the younger reverse faults.

Our interpretation of a large tilted structure in an overall tectonic regime of convergence and regional tilting is consistent with conclusions derived by Hartley et al. (2000) based on their tectonic and sedimentological analysis of the northern Chilean forearc. Isacks (1988), Lamb et al. (1997) and Lamb and Hoke (1997) also argued for regional westward tilting of the Western Andean slope to explain the uplift of the western Altiplano. These models do not preclude, but rather, imply distributed reverse faulting. The mechanical model of Bailey (1998) also predicts gravitationally induced thrusting on oversteepened orogenic slope and ductile flow within the crust when rheologic properties of the crust are favorable. Rheological weakening due to heating by extensive magmatic activity is certainly attained in the Andean arc region.

One more observation in favor of a gravitational sag structure comes from offshore geophysical investigations: the CINCA (1995) study showed the existence of large N–S oriented sagged blocks in the forearc >30 × 15 km in size (von Huene et al., 1999). These were interpreted to result from frontal (and basal) tectonic erosion of the outer forearc and subsequent antithetical rotation. The Oxaya Block may be an unusual onshore equivalent of these structures.

By weighing the above arguments, we prefer the interpretation of the Oxaya Block as a large gravitational structure.

4.5. Giant landslides

The Oxaya Block rotation had several consequences: (1) the old E–W oriented drainage was reversed, the upper course of the valleys became clogged with sediment and erosion all but ended on the block surface, (2) extensional structures formed on the block, in particular, near its western front (Figs. 1 and 4) and (3) the development of an oversteepened western front of the block. The “Lluta Collapse” (Figs. 1 and 5) formed as a result of these circumstances. It is a giant landslide that covers an area of about 600 km^2, displaced 50 km^3 of rock and its basal decollement is exposed on the sides of the Quebrada Lluta for 20 km. This landslide mass is characterized by large tilted blocks up to 800 m thick and an irregular surface, which in some places rises up to 200 m over the undisturbed surface of the Oxaya Ignimbrite. The collapse left an amphitheatre-shaped scar, east of the Pampa Plazuela (Fig. 1). In size and origin, it is almost identical to the Quaternary landslide described by Philip and Ritz (1999), which formed at a frontal scarp of a thrust fault. The age of the Lluta collapse is younger than the Oxaya Block rotation (from 12 to 10.6 Ma) because it developed at its steep frontal face probably facilitated by the extensional structures in that area. The collapse is also older than the presently deeply incised Lluta Valley that dissects it. A Proto-Lluta Valley, however, already existed at 2.7 Ma when it was entered by the Lauca–Peréz Ignimbrite (see below). Accordingly, we place the Lluta landslide at 5–10 Ma. This brackets the period of increased humidity at 7 Ma identified by Gaupp et al. (1999; and reference therein). The presence of abundant ground water at the time of the Lluta collapse is also indicated by the formation of lacustrine diatomaceous sediments on top of the chaotic mass of the landslide and soft deformation of fine-grained clay material at its base.

This makes the Lluta collapse one of the largest and most probably the oldest paleolandslide recognized in a continental setting (cf. Philip and Ritz, 1999).

5. 12 and 2.7 Ma: continued uplift and increased aridity

Oxaya Ignimbrites (from 23 to 19 Ma) and Miocene andesites of the Zapahuira Formation (19–9 Ma) are thrust onto sediments of the Huaylas Fm (from 2.7 to ≤10.6 Ma) (García et al., 1996). Age equivalents of the Huaylas Formation are found as flatlying lake and salar sediments of the Lauca Formation (Kött et al., 1995) and the Allane basin on the Chilean Altiplano. Kött et al. (1995) have shown that the >6.6–2.7-Ma-old sediments in the Lauca Formation were not significantly affected by tectonism. The sedimentary facies and environment suggest little change in climate, elevation and provenance since 7 Ma (Gaupp et al., 1999). The westernmost Altiplano has therefore remained tectonically relatively inactive and has not recorded major climatic changes since the Upper

Miocene. At the same time, tectonic movements persisted at the WARP and Western Cordillera (García et al., 1999 and reference therein).

At 2.7 Ma, the West Andean Escarpment was characterized by a tectonically and morphologically differentiated staircase topography with small N–S striking basins filled by fluvial and lacustrine sediments. This landscape was sealed by the 2.7 Ma Lauca–Peréz Ignimbrite (Schröder and Wörner, 1996; Wörner et al., 2000b), which originated from an inconspicuous caldera near the active volcanic front. It descended the large valleys (Lluta, Cardones and possibly Azapa) and entered the Pacific Ocean through the Lluta Valley near Arica, where it is found in the valley bottom at sea level.

6. 2.7 Ma to Recent: further incision and collapsing valley flanks

While the Cardones Valley (Fig. 1) has been largely inactive since it was filled by the Lauca–Peréz Ignimbrite, the Azapa and Lluta Valleys grew substantially by headward erosion. These valleys are deeply incised into the Oxaya Block, reaching their maximum relief of 1700-m (Figs. 1 and 4). In the middle course of Quebrada Lluta, the Lauca–Peréz Ignimbrite is found as erosional remnants some 800 m above their present valley bottom, constraining incision since 2.7 Ma to about 0.3 mm/year. Precursors to these large valleys, however, must have existed because the Lauca–Peréz Ignimbrite is found in the valley bottom at the coast and even several tens of kilometers inland. This observation suggests that by 2.7 Ma, the Lluta Valley had already begun to cut into the Oxaya surface and probably had developed to a stage represented by the inactivated Cardones Valley. Increased valley incision since 2.7 Ma was likely associated with increased runoff from the high volcanic peaks and the Western Cordillera due to the onset of glaciation at that time (Clapperton, 1990).

Valley flanks of the lower Lluta and Azapa Valleys are smooth and inclined at angles of 10–20°. These smooth surfaces are left after repeated slope failure. Blocks of up to 400 m in thickness and several kilometers in length are found in many areas. Their morphology suggests sagging to the valley bottom along smoothly inclined surfaces. A major landslide of up to 1 km^3 and unknown age (but 2.7 Ma) dammed the Azapa River, causing accumulation of several tens of meters of lacustrine sediments (Seyfried et al., 2000). In the region near the small village of Socoroma (Fig. 1), the landscape is presently sagging over several km^2. This causes disruption of agriculture and forced repeated correction of long-distance irrigation channels.

7. Summary and plate tectonic interpretation

The Western Escarpment of the Central Andes at 18°S is a good example of an oversteepened mountain range front in a forearc environment of an active continental margin. The overall tectonic regime is convergent and has resulted in tectonic thickening, uplift and erosion. However, the evolution of the mountain front may not only be controlled by plate tectonic forces acting directly onto the crust. Uplift and tectonism may be decoupled from the plate movement reference as suggested by Hartley et al. (2000) and the effects of plate reorganization in the Pacific may also have played a role.

Thus, we may be able to distinguish endogenic, plate-driven effects from more local, exogenic effects.

(1) Subduction of the East Pacific spreading center, below the North American plate in the Upper Oligocene (28 Ma, Hey, 1977), resulted in Farallon plate breakup, formation of the Nazca plate and increased and increasingly frontal subduction rates.

(2) After the opening of the Drake Passage (23 Ma) and a change in ocean circulation, which established the cold S–N Humboldt Current by around 15 Ma, cold water and related cold coastal air masses increasingly inhibited orographic rain and greatly reduced precipitation inland on the Western Andean slope (see discussion in Gregory-Wodzicki, 2000).

The response and geological record on the Western Andean slope to these developments are documented in the following stages of the WARP evolution: (i) a thick conglomeratic wedge evolved between 25 and 23 Ma on the Western Andean slope, (ii) mafic volcanism occurred already at 23 Ma in Bolivia (Tambillo and Chiar Khollu basalts, Lamb et al., 1997) and western Argentina (Kay et al., 1999) at the same time when uplift, erosion and enhanced sedimentation occurred along the West Andean Escarpment, and (iii) from 2 to

3 Ma after the onset of uplift, erosion and clastic sedimentation, large volumes of ignimbrites were erupted between 23 and 19 Ma, which where immediately followed by mafic andesites.

We explain the observed sequence as follows:

(1) Flat slab subduction between 35 and 24 Ma needs to be inferred to explain the absence of magmatism during that time. Evidence for strong erosion and the deposition of a clastic wedge indicates an increased topographic gradient and thus crustal uplift. This may be caused by crustal shortening due to increased tectonic coupling between the upper and lower plate (Allmendinger et al., 1997).

(2) Slab steepening is inferred to explain mafic volcanism in the east at around 23 Ma and crustal melting with large volume ignimbrites in the west. This will have allowed the influx, from east to west, of hot asthenospheric material below the western Andean crust. Heating of the lower crust by hot asthenosphere and advective heating by mantle-derived melts are sufficient to cause a short period of crustal melting (Tanner et al., 1999).

(3) Geochronological data (Coira et al., 1982; Allmendinger et al., 1997; Wörner et al., 2000b, and references therein) suggest that the arc zone widened and the arc front migrated to the west in mid-Miocene times. This resulted in a large volume of mafic andesites from the mantle wedge. By 18–15 Ma, the new arc had established itself once the slab had steepened and the crustal melting zone could be passed by mafic magmas.

(4) Further uplift along the Western Andean slope between 17°S and 20°S since then is related to only minor amounts of forearc shortening while at the same time, deformation and shortening migrated to the east into the sub-Andean belt (Sheffels, 1990, 1995; Allmendinger et al., 1997). Absence of sufficient crustal shortening in the forearc then suggests lower crustal flow from the east to explain further uplift (Isacks, 1988).

(5) Tectonic processes, in combination with the evolution of the ocean currents in the eastern pacific during the Miocene, led to an increased aridification from about 20 Ma onwards (Abele, 1989; Beu et al., 1997; Lawver and Gahagan, 1998), decreasing erosion and morphological oversteepening. As a result, the Western Andean slope thus appears to be in topographical disequilibrium, which results in gravitational movements at several scales, from the giant rotated Oxaya Block, large landslides (Lluta and Azapa collapse), valley flank failure to today's local sagging of irrigated farmlands.

Similar such rock sequences are observed throughout the Western Andean slope at different times. Therefore, if such thick conglomeratic sediments coupled with overlying voluminous ignimbrites are taken as an indicator of crustal thickening, slab steepening and crustal melting, then these processes have clearly been asynchronous along the strike of the Central Andes (Noblet et al., 1996).

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