Fault-related folding, drainage network evolution and valley incision during the Neogene in the Andean Precordillera of Northern Chile

Marcelo Garcia[a], Gérard Hérail[b,c,*]

[a]*SERNAGEOMIN. Avenida Santa María 0104, Providencia, Santiago, Chile*
[b]*IRD, LMTG. 14 Avenue Edouard Belin, Toulouse 31400, France*
[c]*Departamento de Geologia, Facultad de Ciencias Fisicas y Matematicas, Universidad de Chile, Santiago, Chile*

Abstract

We describe Neogene drainage network development before, during and after regional folding in the Precordillera of the Andes of Northern Chile (18°–19°S). The drainage network developed on an extensive regular erosional surface formed on Oligocene–Miocene ignimbrites (Oxaya Formation). The folding affecting the rocks of the Precordillera is represented by the Oxaya Anticline (OA) which trends N to NW, is 50-km long and 30-km wide. The fold is gentle, west-vergent and has resulted in an uplift of the hinge zone by up to 850 m. It formed by the propagation, on its western border, of a subvertical east-dipping blind reverse fault (Ausipar Fault [AF]). The folding occurred in the middle–late Miocene, essentially between 11.7±0.7 and 10.7±0.3 Ma; its maximum duration was 2 My. Two phases of drainage development are recognised in the Precordillera. An initial lower–middle Miocene (19–12 Ma) parallel drainage network is well preserved and synchronous with fluvial and lacustrine sedimentation in the Central Depression. The network was poorly structured and attained maximum incision of to 250±50 m. The minimum long-term rate of incision was 36±7 m/My. Folding generated the progressive abandonment and fossilisation of the initial parallel drainage network, which became trellissed and concentrated in a few deeply incised valleys. In the anticline hinge, the Lluta and Azapa main valleys present a total incision of 1650±50 and 1605±50 m, respectively, whereas the Cardones valley presents 595±50 m. During folding, river incision at the fold hinge was equal to or greater than the amplitude of the folding, which is 790±50 m in the Lluta valley and 715±50 m in the Azapa valley. Consequently, the long-term rate of synfolding incision was much greater than 395±25 (Lluta valley) and 358±25 m/My (Azapa valley). The Cardones valley was fossilised approximately in the middle of the folding. After folding (11 to 0 Ma), the incision in the Lluta and Azapa rivers was 610±100 and 640±100 m and with a rate of 56±9 and 58±9 m/My, respectively. The postfolding incision rate is approximately twice than of the prefolding incision rate. This implies an acceleration of valley incision since the late Miocene, which is considered as consequence of regional uplift of the Andean forearc.

Keywords: Tectonics; Fluvial network; Long-term geomorphology; Andes

* Corresponding author.
E-mail addresses: gherail@paris.ird.fr (G. Hérail), mgarcia@sernageomin.cl (M. Garcia).

1. Introduction

In mountain chains, deformation creates relief much more quickly than in other geodynamic environments. The quantification of relief formation by tectonics and its effects on the landscape evolution is a subject of much interest. In particular, the study of geomorphological features, such as river networks and associated interfluve surfaces, can be extremely useful in reconstructing the tectonic evolution and uplift of an area. The deformation/erosion balance in mountain ranges is clearly positive such that geomorphological features of tectonic origin are well preserved. We are able to observe the consequences of this phenomenon by studying the modification of the drainage pattern and hierarchy, the evolution of the thalweg gradient and the river captures (Baulig, 1950; Howard, 1967; Tricart, 1968; Burnett and Schumm, 1983; Molnar et al., 1994; Talling et al., 1997; Jackson et al., 1996; Holbrook and Schumm, 1999; Schumm et al., 2000; Mather, 2000; Replumaz et al., 2001; Stokes and Mather, 2003). These mechanisms have been predominantly described from foreland and fold-and-thrust zones where deformation is recent and rapid

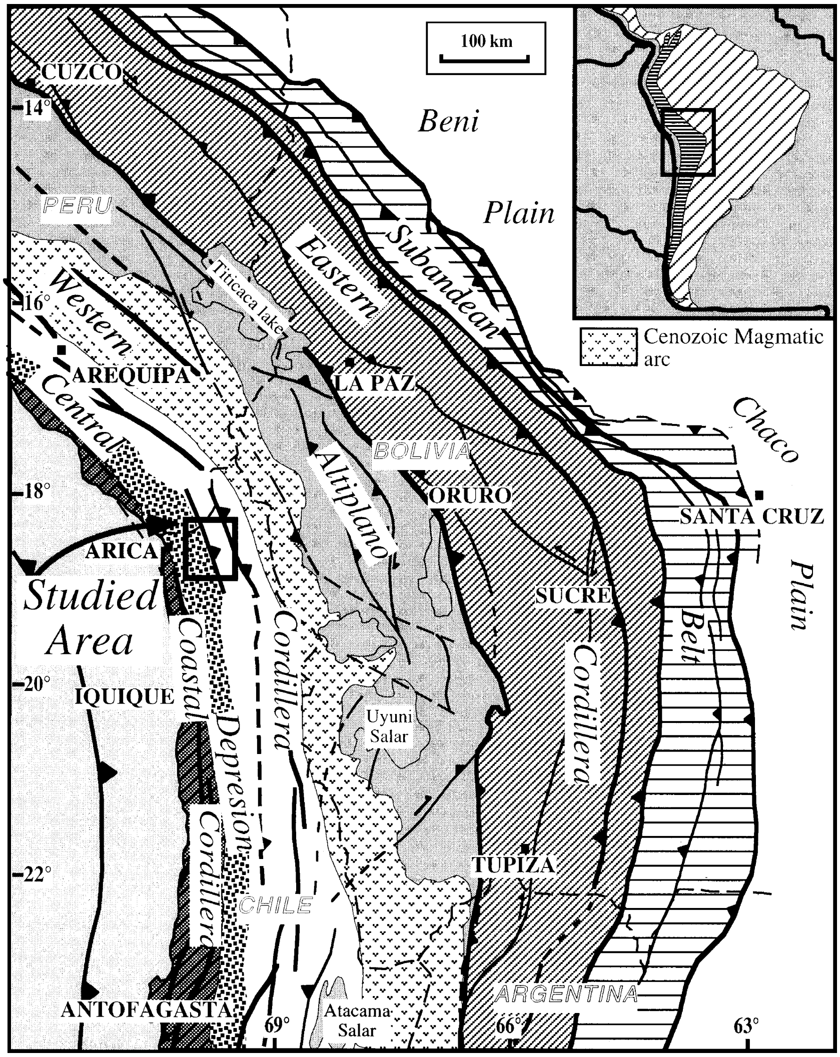

Fig. 1. Location of study area in the Central Andes.

(Delcaillau et al., 1987; 1998; Burbank et al., 1996, 1999; Lavé and Avouac, 2000; Van der Beek et al., 2002; Formento-Triglio et al., 2002) and also in other tectonic settings (Gaudemer et al., 1989; Jackson and Leeder, 1994).

We study these topics in the western margin of the Central Andes (Fig. 1), where ancient geomorphological features are well preserved and observed due to the arid–hyperarid climate and vegetation absence. The study region is located in the northern part of the Atacama Desert, in which the arid climate was established by the middle Miocene (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996) and the hyperarid climate by the late Pliocene (Hartley and Chong, 2002). In such an environment, landform description can be used to analyse tectonic evolution.

The Central Andes forms a wide (up to ~850 km) and high (up to ~6500 m altitude) mountain range. The present relief of the chain is essentially Oligocene–Neogene in age (e.g., Isacks, 1988; Sempéré et al., 1990; Allmendinger et al., 1997; Lamb et al., 1997). Oligocene–Neogene tectonic evolution of the Eastern Cordillera and Subandean Zone in Bolivia (Fig. 1) is mainly controlled by compressive deformation with a large horizontal shortening (190–240 km), which is well constrained by abundant structural and geophysical data (Roeder, 1988; Sheffels, 1995; Schmitz, 1994; Kley et al., 1997; Baby et al., 1997). In contrast, the tectonic evolution of the western part of the Central Andes, in Southern Peru and Northern Chile (Fig. 1), is different and less well known. The Western Cordillera and Precordillera form a moderately deformed domain, which is affected by predominantly Plio-Quaternary subvertical extensional faults (Salas et al., 1966; Lahsen, 1982; Lamb et al., 1997) or by Neogene compressive structures (Muñoz and Charrier, 1996; García et al., 1996, 2002; Victor and Oncken, 1999). The structure and evolution of the Precordillera at the Arica latitude (18–19°S; Figs. 1 and 2) are controversial. This region has been interpreted as a block limited

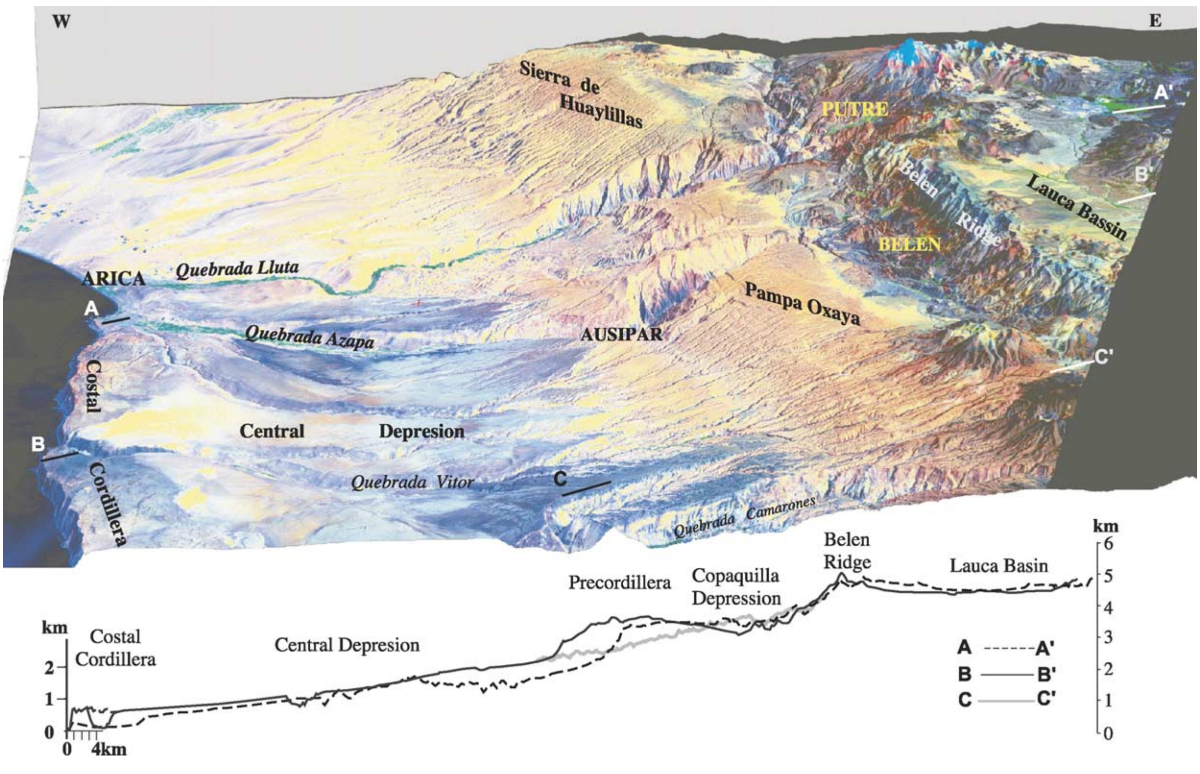

Fig. 2. Block diagram of the forearc of Northern Chile (Arica area), resulting from the superposition of the LANDSAT-TM5 image and the topographic elevation model. Three topographic cross-sections are also shown.

by Late Cenozoic normal faults or as a giant Miocene gravitational rotational collapse (Uhlig et al., 1996; Wörner et al., 2000a; Wörner and Seyfried, 2001). Other studies, however, have considered that the Precordillera of Arica corresponds to a major west-vergent fold (Salas et al., 1966; Muñoz and Charrier, 1996) formed by the late Miocene reactivation of a basement fault (García et al., 1999, 2002; García and Hérail, 2001).

The purpose of this paper is to use geomorphological, structural and geochronological data to:

– describe the morphological evolution of the drainage pattern of the Precordillera (Northern Chile) and to discuss its tectonic meaning,
– quantify the amount and long-term rate of valley incision during the Neogene deformation and
– constrain the geometry, kinematics and timing of deformation and to discuss their local and regional tectonic and geomorphological implications.

2. Geological and geomorphological background

The Andes of Northern Chile and Southern Peru (Fig. 1) represent the arc and forearc of the Cordillera. Around Arica (18–19°S), five physiographic units are present, from west to east: the Coastal Cordillera, the Central Depression, the Precordillera, Copaquilla Depression and the Western Cordillera (Figs. 1 and 2). In this region, extensive Oligocene to Quaternary volcanic rocks and continental sedimentary sequences unconformably overlie PreCambrian to Paleocene rocks (Figs. 2 and 3).

2.1. Coastal Cordillera

It is less than 20-km wide and less than 1200-m altitude (Fig. 2). The relief is essentially formed on Mesozoic rocks and comprises smoothed hills and shallow valleys (Mortimer and Saric, 1972). The altitude of the Coastal Cordillera diminishes progressively to the east where it is overlapped by Tertiary sequences from the Central Depression. To the west, this cordillera is cut by a subvertical escarpment which reach up to 1000-m high (Paskoff, 1979). In the area of the Arica city, the Coastal Cordillera is completely eroded. To the south of Arica, the range is crossed by the gorges of Vitor and Camarones valleys.

2.2. Central depression (or longitudinal valley)

It is 40–55-km wide. The interfluves (“pampas”) correspond to a plateau with an altitude increasing from 500 to 1000 m in the west to 1900 to 2300 m in the east, resulting to a slope of 1.5°–2°W (Fig. 2). The “pampas” are separated by deep gorges (<1000 m) of the Lluta, Azapa, Vitor and Camarones rivers coming from the Western Cordillera. This surface has been associated to late Miocene regional pedimentation and is known as “Atacama Pediplain” in Northern Chile (Mortimer et al., 1974; Naranjo and Paskoff, 1985) and “Multiple Pediment Stage” in Southern Peru (Tosdal et al., 1984). The Central Depression is passive tectonically but locally affected by gentle folds and flexures. This depression is a forearc continental basin (Parraguez, 1998) filled with sub-horizontal Oligo-Miocene sediments and ignimbrites (Azapa, Oxaya and El Diablo Formations). The substratum of the sequence comprises Mesozoic rocks exposed in the west (near of the Coastal Range). The Azapa Formation (Salas et al., 1966; Vogel and Vila, 1980; Parraguez, 1998) consists of up to 500 m of fluvial conglomerates and sandstones. The clasts are well rounded and well imbricated. In the Western Precordillera, at the Lluta valley, the uppermost part of the Azapa Formation onlaps Jurassic–Paleocene rocks (Figs. 3 and 4). The Azapa Formation is conformably overlain by ignimbrites of the Oxaya Formation (25–19 Ma), indicating an Oligocene age for its deposition. The Oxaya Formation, largely exposed in the Precordillera and in the Central Depression, is conformably overlain by the El Diablo Formation (Tobar et al., 1968; Vogel and Vila, 1980). The thickness of the El Diablo Formation is variable but less than 400 m. The lower part of this formation is composed of quartz-rich and volcanic sandstones, silicificated limestones and siltstones with plants remains (Parraguez, 1998). These rocks were deposited in a distal alluvial–fluvial and lacustrine environment. The upper part of the El Diablo Formation is composed of gravels deposited in an alluvial and fluvial fan environment. These gravels were largely derived from the erosion of andesitic lavas of the eastern Precordillera and Western Cordillera. This is

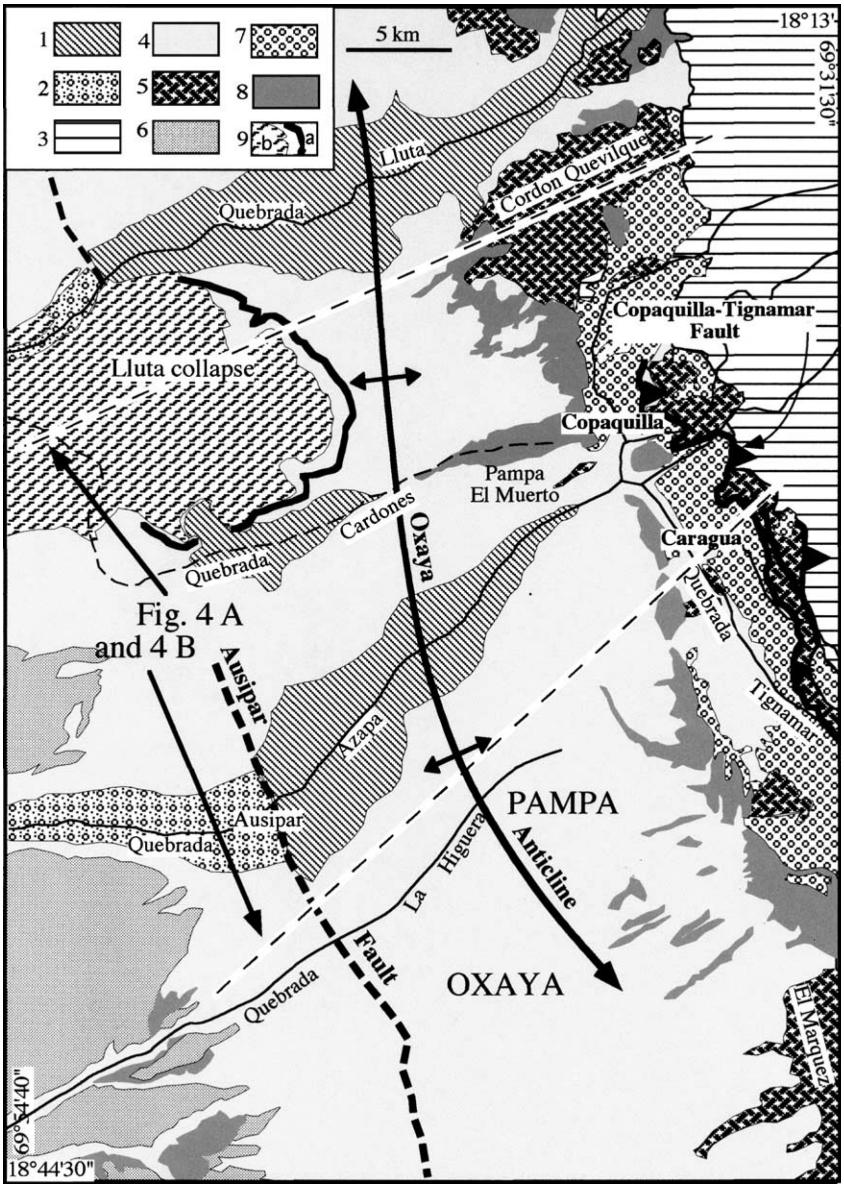

Fig. 3. Simplified geological map of the Precordillera of Arica. 1—Mesozoic to Paleocene rocks (Pre–Oligocene substratum); 2—Azapa Formation (Oligocene sedimentary rocks); 3—Lupica Formation (late Oligocene–middle Miocene volcanic rocks); 4—Oxaya Formation (late Oligocene–early Miocene ignimbrites); 5—Zapahuira Formation and Quevilque Volcano (early–middle Miocene lavas); 6—El Diablo Formation (Miocene sedimentary rocks); 7—Huaylas Formation (middle–late Miocene sedimentary rocks); 8—Lauca Ignimbrite (Pliocene); 9—Lluta collapse (a—break away; b—avalanche deposit). Cross-sections of the Fig. 4 are located.

supported by the petrographic composition of the clasts and the mineralogy of the sandy matrix (Pinto, 2003; Pinto et al., 2004). To the south, near Camiña, the same El Diablo gravels are covered by a lava flow, which has been dated in two sites (Mortimer et al., 1974, recalculated by Naranjo and Paskoff, 1985; Muñoz and Charrier, 1996), yielding concordant ages with an average of 8.4±0.6 Ma. As a result, the deposition of the upper El Diablo Formation is estimated to have ended after 11.9 and before 8.4 Ma.

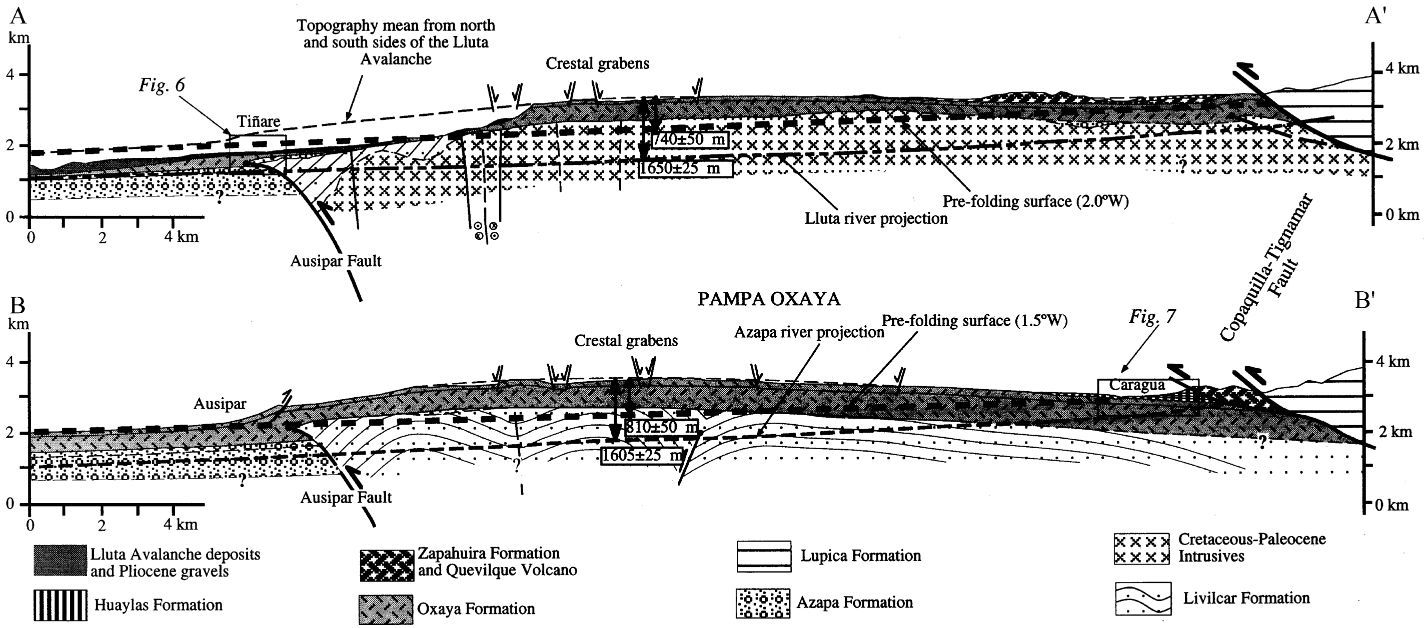

Fig. 4. Cross-sections throughout the Oxaya Anticline, showing the gentle and west-vergent folding and faulting in its western boundary. See Fig. 3 for the location. The inferred prefolding surfaces and the amplitude of the folding are shown. The Lluta and Azapa rivers are projected to indicate the observable geological data. Box shows the location of Figs. 6 and 7.

2.3. Precordillera

It is 20–35-km wide and forms a topographic "step" between 1900–2300 and 3200–3640 m altitude (Fig. 2). It comprise an elongate plateau, which in the north and central parts of the studied area forms a gentle and wide folded zone known as the Huaylillas Flexure and the Oxaya Anticline (OA; Salas et al., 1966; García et al., 1999, 2002). To the south, in Pampa Sucuna (Fig. 2), where the Oxaya Anticline disappears, the surface of the Precordillera is tilted to the west by 3°. The plateau is cut by the gorges of the Lluta, Cardones and Azapa valleys that are up to almost 1700-m deep (Fig. 2). The surface of the Precordillera is broadly formed by the Oxaya Formation (Salas et al., 1966; García et al., 1996). This unit regionally unconformably overlies a folded Lias–Neocomian sedimentary sequence (Muñoz et al., 1988), which is intruded by the Late Cretaceous–Paleocene Lluta granodiorite (Salas et al., 1966; Muñoz and Charrier, 1996). The Oxaya Formation comprises large rhyolitic ignimbrite sheets, interbedded with fluvial and lacustrine sediments. Thickness decreases from 1000 m in the eastern Precordillera to 0–50 m in the western Central Depression. K–Ar and Ar–Ar radioisotopic measurements give a late Oligocene–early Miocene (25–19 Ma) age (Mortimer et al., 1974; Naranjo and Paskoff, 1985; Parraguez, 1998; García et al., 1996, 2002; Wörner et al., 2000a). To the east, the upper part of the Oxaya Formation is interstratified with and covered by andesitic lavas of the Cordón Quevilque (20–18 Ma; Wörner et al., 2000a; Fig. 3). It is conformably overlained by the Sucuna Volcano (15–12 Ma), Marquez Volcano (11–9 Ma) and scattered andesitic rocks of the Zapahuira Formation (García et al., 1996) dated to between 16 and 12 Ma (Table 1). In the western flank of the Precordillera, the giant Lluta Avalanche (Fig. 3) is well exposed (Naranjo, 1993; Wörner et al., 2002). Its volume is estimated at between 50 and 100 km^3. The chaotic deposits of this avalanche are essentially formed by megablocks of the Oxaya Formation and unconformity overlain by Pliocene fluvial sediments.

2.4. Copaquilla depression

It is a very narrow intramontane basin at 3000–3200-m altitude between the Precordillera and the Western Cordillera. The east-dipping Oxaya and Zapahuira formations are unconformably overlain and onlapped by the Huaylas Formation, which comprises fluvial sediments (Salas et al., 1966; García et al., 1996). In Caragua, the lowermost part of the Huaylas Formation consists of sandstones that contain middle–late Miocene mammal remains (Bargo and Reguero, 1989; Salinas et al., 1991, Flynn et al., 2004). The upper part of the Huaylas Formation comprises horizontal polimictic gravels, which overlie the Caragua sandstones with a low angle unconformity. In the upper gravels, a thin interbedded dacitic tuff (Caragua–Tignámar Ignimbrite) has been dated through the K–Ar and Ar–Ar methods (Table 1). The more valuable (smaller error) Ar–Ar biotite mean age is 10.7±0.3 Ma. The Huaylas gravels are derived from the east and are interpreted to represent syntectonic sediments relating to the Miocene uplift of the Western Cordillera (García et al., 1996, 2002).

2.5. Western Cordillera (Belen Ridge)

It has irregular topography with peaks of up to 6350 m and an average altitude of between 3800 and 4500 m. To the west, the most important relief corresponds to the 15–25-km wide Belen Ridge, whereas to the east, the summits are Neogene stratovolcanoes. The Belén Metamorphic Complex of Precambrian to Early Paleozoic age (Salas et al., 1966; Pacci et al., 1980; Basei et al., 1996; Wörner et al., 2000b) is overlain by up 2500 m of andesitic and dacitic lavas, rhyolitic ignimbrites and lacustrine and alluvial sediments of the Lupica Formation (Salas et al., 1966). This formation is late Oligocene–early Miocene in age (García et al., 1996, 2002; Riquelme, 1998) and is highly deformed along the western border of the Western Cordillera where it forms a narrow fold and thrust belt (Muñoz and Charrier, 1996; García et al., 1996, 2002), which accommodates a minimum Neogene shortening of 8 km. The Lupica Formation is unconformably overlain by Neogene volcanic rocks (Wörner et al., 1988; Aguirre, 1990), Miocene sediments (Chucal Formation; Muñoz and Charrier, 1996; Riquelme, 1998) and Plio-Pleistocene sediments (Lauca Formation; Gaupp et al., 1999). The horizontal rhyolitic Lauca Ignimbrite, with a thickness of less than 150 m,

Table 1
K–Ar and Ar–Ar radiometric ages used in this work

N° in Fig. 3	Sample	Approximated location	Coordinate longitude W/UTM km E	Coordinate latitude S/UTM km N	Lithology	Method–material	Age±errors (Ma)	Mean age	Reference	Observations
Lauca Ignimbrite (only new data)										
	MAL-195	N Arica	362.8	7967.35	Ignimbrite	Ar–Ar is biotite	2.6±0.2		This work (1)	
	GAL-115	Copaquilla	432.096	7966.717	Ignimbrite	Ar–Ar is Sanidine	2.76±0.02		This work (1)	
						Ar–Ar p biotite	3.09±0.05			
	GAL-33	W C° Larancagua	465.893	7996.432	Ignimbrite	K–Ar biotite	2.8±0.6		This work (1)	
Huaylas Formation (Caragua–Tignámar ignimbrite)										
1	MAL-138	S Caragua	440.1	7957.25	Ignimbrite	K–Ar biotite	14.8±0.9[a]		This work (1)	*K*=5.5%
						Ar–Ar p biotite	11.4±0.5		This work (3)	
						Ar–Ar p amphibole	10.6±1.1		This work (3)	
2	MAL-142	NW Tignámar	442	7951.85	Ignimbrite	K–Ar biotite	8.7±1.0		This work (1)	
						Ar–Ar p biotite	10.8±0.4		This work (3)	
						Ar–Ar p amphibole	9.9±1.0		This work (3)	
	TIG-94-106	Tignámar	69°28′ 55″	18°35′ 40″	Ignimbrite	Ar–Ar p biotite	10.6±0.2		Wörner et al. (2000a)	
	G-42	Tignámar	448.9	7946	Ignimbrite	K–Ar biotite	16.8±1.5[a]		García et al. (1996)	*K*=5.8%
						Ar–Ar amphibole W.M.A.	10.2±1.1			
						Ar–Ar biotite W.M.A.	10.7±0.3			
Marquez Volcano										
	MAL-63	Vn. Marquez SE	459.8	7928.6	Silicic andesite	K–Ar biotite	9.3±0.4		This work (1)	
	CMA-10	Vn. Marquez E	18°42′ 25″	69°24′ 05″	Andesite	Ar–Ar gt amphibole	9.2±0.3		Wörner et al. (2000a)	
3	MAL-204	Vn. Marquez W (Cobija)	437.988	7928.452	Andesite	K–Ar whole rock	11.2±0.6		This work (1)	
Zapahuira Formation										
4	G-45	Copaquilla (Pampa El Muerto)	432.3	7962.7	Basaltic andesite	K–Ar whole rock	12.0±0.7 11.4±0.6	11.7±0.7	This work (1) García et al. (1996) (2)	Very fresh rock
	MAL-139	W Belén	441.4	7958.7	Andesite	K–Ar whole rock	11.5±0.4 13.6±0.5	12.3±0.4	This work (1)	
	G-44	C° Copaquilla	439.9	7966.9	Basaltic andesite	K–Ar whole rock	12.7±0.2		García et al. (1996) (2)	
	G-43	C° Copaquilla	438.4	7965.4	Basaltic andesite	K–Ar whole rock	12.8±0.4		García et al. (1996) (2)	
	MAL-126	NW Ancache	433.35	7987.6	Basaltic andesite	K–Ar whole rock	12.8±0.4		This work (1)	
	MAL-121	SE Puquios	428.7	7983	Basaltic andesite	K–Ar whole rock	15.0±1.2		This work (1)	

Table 1 (*continued*)

N° in Fig. 3	Sample	Approximated location	Coordinate longitude W/UTM km E	Coordinate latitude S/UTM km N	Lithology	Method–material	Age±errors (Ma)	Mean age	Reference	Observations
Zapahuira Formation										
	COP-94-216	C° Copaquilla	18°23′ 40″	69°35′ 45″	Andesite	Ar–Ar gt whole rock	15.1±0.1		Wörner et al. (2000a)	Slightly disturbed spectrum
	G-25	W Belén	442.9	7957.1	Dacite	K–Ar whole rock	15.7±0.6		This work (1)	
El Diablo Formation										
	MAL-229	Salar Cotots	374.505	7913.29	Andesite (clast)	K–Ar whole rock	11.9±0.6		This work (1)	Maximal age for the formation
5	MAL-129	Ausipar Alto	410.85	7943	Andesite (clast)	K–Ar whole rock	14.7±0.8		This work (1)	Maximal age for the formation
	MAL-44	Conanoxa	396.05	7896.8	Reworked tuff	K–Ar whole rock	15.7±0.7		This work (1)	Maximal age for the formation
	MAL-237	N Qda. El Diablo	398.475	7953.108	Andesite (clast)	K–Ar whole rock	18.8±0.5		This work (1)	Maximal age for the formation

(1)—Laboratorio del Servicio Nacional de Geología Y Minería (Chile).
(2)—Laboratoire du CRPG (France).
(3)—Laboratoire de Géosciences Azur (France).
W.M.A.—Weighted Mean Age.
Ar–Ar p—plateau age.
Ar–Ar gt—total gas age.
Ar–Ar is—isochrone age.
[a] Stratigraphically unconcordant and analytically unreliable age (K in biotite<6% and Ar. Atm>75%). Highly possible contamination by xenocrystals.

extends over most of the region. It has been dated at between 4 and 5 Ma through the K–Ar biotite method (Naranjo and Paskoff, 1985); however, new K–Ar and Ar–Ar determinations on biotite and sanidine (Gaupp et al., 1999; Wörner et al., 2000a; García et al., 2002) yield a more reliable age close to 2.7 Ma (Table 1).

3. Morphology of the drainage network

The arid climate and vegetation absence in the region, in particular in the Precordillera and Copaquilla Depression, allow the observation of two types of superimposed valley networks: a trellis pattern and a parallel pattern. The former corresponds to the active drainage basin of the Lluta and Azapa rivers. The parallel network, composed of mainly dry valleys, is very well preserved in the interfluve zones of the Precordillera (Figs. 2, 3 and 5).

3.1. The trellis network

The main branches of the trellis network are the Lluta and Azapa, rivers that flow from the Western Cordillera to the Pacific Ocean. The present-day annual mean run off of these rivers, in the Central Depression, is 2.3 m^3/s (to 1.4 and 1.3 m^3/s, respectively; M.O.P., 1987). The Lluta and Azapa valleys lie subparallel, E–W- to NE–SW-oriented and separated by 10 to 25 km. In the western slope of the Western Cordillera, the catchment of these valleys forms two dendritic hydrographic networks separated by the Cordón Quevilque (Fig. 3). The surface of the Lluta catchment basin is 2314 km^2 and of the Azapa catchment basin is 911 km^2. The

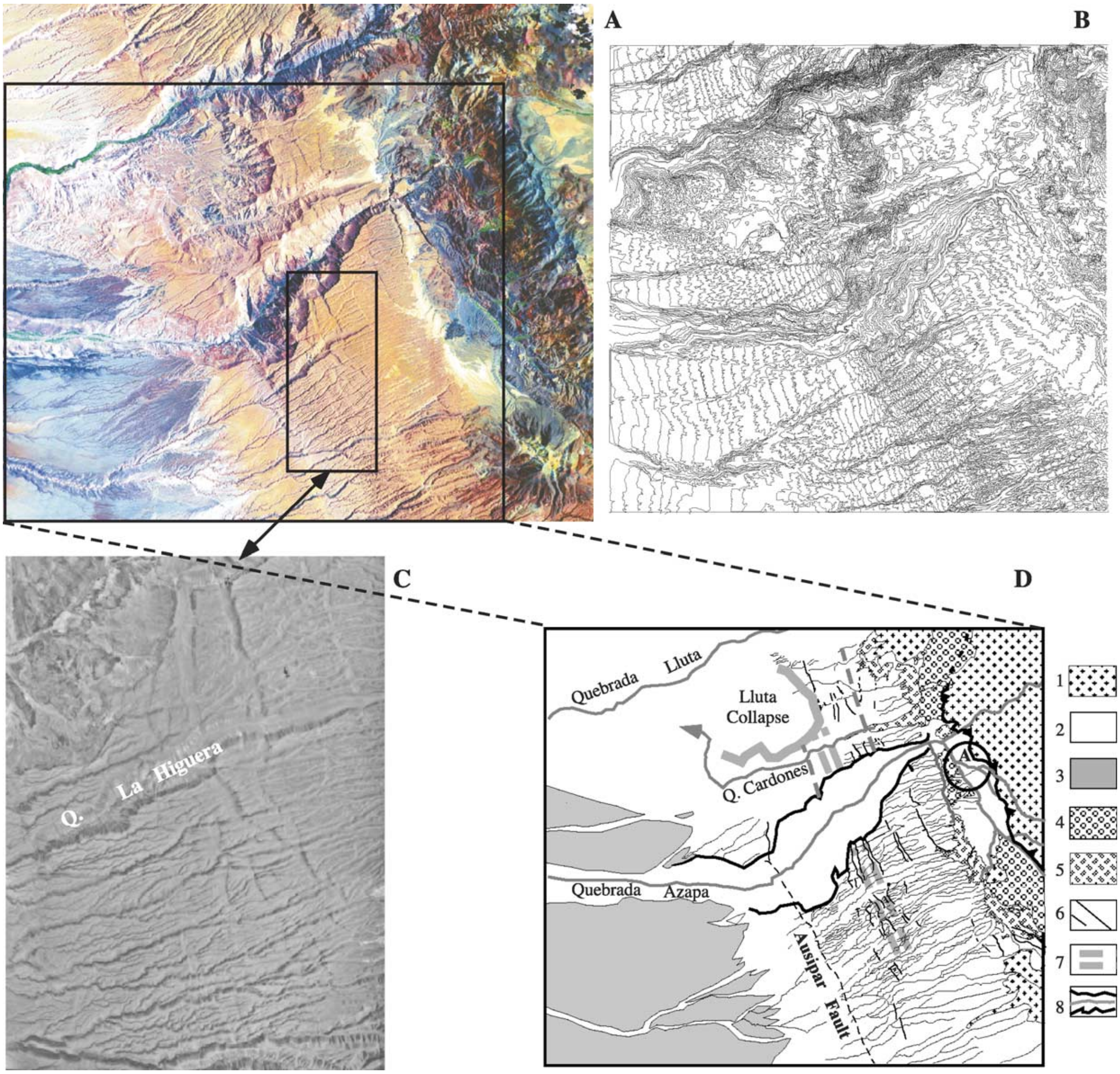

Fig. 5. Geomorphology, tectonics and topography of the Oxaya Anticline. (A) LANDSAT-TM5 image, (B) Topography, (C) detail of normal faults, crestal grabens and valleys network, (D) Geological map, 1—Lupica Formation, Zapahuira Formation and Cordon Quevilque and El Marquez stratovolcanoes; 2—Oxaya Formation; 3—El Diablo Formation; 4—Huaylas Formation; 5—Lauca Ignimbrite; 6—Normal faults; 7—Oxaya Anticlinal axis; 8—Rock-wall of the Azapa gorges.

valleys of the Lluta and Azapa catchments are essentially adjusted to the topography and the tectonic structure (Figs. 3 and 5). Nevertheless, to the west, the Lluta and Azapa valleys cross the Precordillera as watergaps or gorges almost 1700-m deep. In the Central Depression, the incision in these two valleys decreases to a maximum of 1000 m.

The confluence node of the dendritic catchment of the Azapa river is situated in the Copaquilla Depression. In the northern part of the Copaquilla Depression, the main tributary is the Quevilque valley, and in the south, it is the Tignámar river. The major Cardones valley is an intermittent or dry affluent of the Lluta valley (Figs. 3 and 5). In the Precordillera, the upper part of the Cardones valley lies subparallel to the Lluta and Azapa valleys. However, this valley segment is inactive and represents a windgap related to an abandoned parallel drainage network.

3.2. The parallel network

The parallel network is very well developed in the interfluve zones of the Pampa Oxaya between the Lluta and Azapa valleys and to the south of the Azapa valley (Fig. 5). The network is made up of dry or intermittently flowing valleys that are approximately ENE–WSW-oriented with 0.5–1.5-km spacing. The network is very poorly structured; each catchment is composed of a few tributaries of similar dimensions. The confluence angles are acute (less than 30° on average). The dry Cardones valley is the major valley of this parallel pattern, with incision of almost 600 m at the crests of the Pampa Oxaya. The valleys of the Pampa Oxaya are less incised: the largest of them is the head of the La Higuera valley (Fig. 5), which presents an incision of up to 250-m depth at the crests of the Pampa Oxaya. Some parallel valleys are partially filled by middle–late Miocene lavas (Marquez Volcano and Zapahuira Formation), middle–late Miocene fluvial deposits (Huaylas Formation), the Pliocene Lauca Ignimbrite and Plio-Quaternary fluvial sediments (Fig. 3).

The thalwegs of the parallel drainage network head in the Copaquilla Depression at 3000–3200-m altitude (Figs. 2 and 5). These valleys link with the Central Depression at 2000–2100-m altitude and are continued across the crest of the Pampa Oxaya that reaches 3640-m altitude. The most elevated zone of the interfluves has been eroded in such a way that the thalwegs are less well preserved but continuously visible. This implies that the parallel valleys descended to the west, from the Copaquilla Depression to the Central Depression, were developed on a regular surface, gently dipping to the west before the present relief of the Pampa Oxaya existed.

The dry parallel valleys of the Pampa Oxaya are cut by the oblique Azapa valley (trellis network). In the Copaquilla Depression, these dry parallel valleys are cut and captured by the perpendicular N–S-oriented Quevilque and Tignámar valleys, which belong to the catchment of the Azapa river. This is particularly clear in the northern part of the Tignámar river (point A, Fig. 5 D). The bottoms of these parallel valleys hang above the present thalweg of the Tignámar river. The Cardones major valley in its upper course in Copaquilla was captured by the Quevilque valley flowing to the Azapa river (Fig. 3). This capture is an analogue of the capture of the dry valleys by the Tignámar river. The middle course of the Cardones valley (at the contact between Precordillera and Central Depression) can be easily traced downstream (to the West) into the El Diablo valley (Figs. 5 and 8), showing that these two valleys once formed a single stream. This ancient Cardones–El Diablo valley was also captured, but in this case to the north by one affluent of the Lluta valley, which currently forms the lower course of the Cardones. In conclusion, morphological evidence indicates that the parallel network of the Precordillera was established before the trellis network, which captured it and remains active today.

4. Geometry and kinematics of the folding

In the Precordillera of Arica, the top of the uppermost ignimbrite sheet of the Oxaya Formation is coincident with the topography of the interfluve zones and represents a datum on which to describe the deformation. This deformation is represented by the Oxaya Anticline, which is limited to the west by the Ausipar Fault (AF; Salas et al., 1966; Muñoz and Charrier, 1996; García et al., 1999, 2002).

4.1. The Oxaya Anticline

The Oxaya Anticline (OA) is a major gentle fold that can be followed for 50 km along strike with a half-wave length of 25–30 km (Figs. 3 and 4). Its axis shows a smoothly curved trend, varying from N–S to N40W. It plunges to the south, to the Pampa Sucuna, where the Oxaya ignimbrites form an extensive west-dipping (2°–3°) monocline which is locally affected by very gentle minor folds. To the north, in Sierra Huaylillas, the OA transfers into a very gentle anticline, which may be up to 40-km wide. The OA produces a variation in altitude from 1900–2300 to 3500–3640 m. It is a west-vergent asymmetric fold, with a western limb dipping up to 15°W and an eastern limb dipping up to 4°E. The area where the fold is most marked, uplifted and shortened is located between the Cardones and Azapa valleys. Along the fold axis, normal faults and crestal grabens parallel the fold (Fig. 5). The normal faults have a negligible displacement (up to 150 m) compared to their length (1–10 km) and result from crestal collapse due to superficial buckling of the hinge zone.

The prefolding structure and topography are reconstructed. Two representative cross-sections were constructed near the central segment of the fold (Figs. 3 and 4). Immediately to the west of the OA, in the eastern Central Depression, the unfolded Oxaya Formation dips gently to the west at 2° in the north and 1.5° in the south. Consequently, if the dip of the Oxaya Formation is extrapolated eastward, the prefolding dip in the Precordillera can be considered of 1.5° to 2°W (Fig. 4). With this initial dip in the Precordillera, the eastern border of the anticline remains at the same altitude (3000–3500 m) as at the present-day, indicating that the prefolding dip cannot be greater than 2°W. In this model, the western limb and hinge zone of the fold are significantly uplifted (Fig. 4). The horizontal shortening in the two cross-sections varies from 60 to 80 m. We assume a height reading error of 25 m, from available topographic maps (scale 1:50,000 and altitude equidistance of 50 m), therefore, the propagated error measuring the altitude difference is ± 50 m. Thus, the amplitude of the folding or the differential uplift of the hinge surface can be estimated at 740 ± 50 m in cross-section A and at 810 ± 50 m in cross-section B (Fig. 4). This amplitude in the axis of the Lluta and Azapa valleys is thus 790 ± 50 and 715 ± 50 m, respectively.

4.2. The Ausipar fault

The OA is bounded to the west by a very gentle frontal syncline with an axis that strikes N20–30W, parallel to the axis of the anticline. The axial plane of this gentle syncline corresponds to the surface projection of a blind reverse fault, the Ausipar Fault (AF), which is interpreted to be responsible for the development of the OA (Fig. 4). The AF does not cut the upper Oxaya Formation, but its shallower trace is observed in the lower part of the slope of the deeper Lluta and Azapa valleys. Along these slopes, the fault is locally covered by Plio-Quaternary landslide and alluvial deposits, but the juxtaposition of the folded Mesozoic Livilcar Formation to the east, with the subhorizontal Oligocene Azapa Formation to the west, can be observed. In the Lluta valley at Tiñare, the AF is well exposed (Fig. 6). It dips 40°–50°E in the bottom of the valley but shallows upwards to a subhorizontal thrust with decreasing displacement up to a tip line (up ~1500-m altitude). Above the tip line, the upper Oxaya Formation is only folded. Also in the Lluta valley, 6 km to the east of Tiñare, a blind 75°–90° east-dipping fault produces another very small flexure in the upper Oxaya Formation; this fault is considered as a secondary eastern branch of the AF. In the bottom of the Azapa valley, a minimum dip of 60°E is estimated for the AF.

The negligible shortening (<100 m), compared to the important vertical displacement (<850 m) produced by the folding, as shown by the shape and magnitude of the uplifted surface in cross-section, implies a geometrical balance that constrains the AF as an east-dipping high-angle fault at depth. The flattening of this high-angle fault at shallow levels can be considered as local accommodation. In conclusion, the geometry of the OA and AF can be described as a classic basement-involved fault-propagation fold (Narr and Suppe, 1994; Mitra and Mount, 1998).

The age of rocks cut by the AF shows a relatively long-life activity of the fault. The timing of the younger movement of the AF, and by association, of the OA, is discussed in detail in the following section. Below the Oxaya Formation, the AF places an eastern block of Mesozoic basement (covered locally by the upper Azapa Formation) in contact with a western block of predominantly Oligocene Azapa Formation (Figs. 4 and 6). This indicates that early activity on the fault took place prior to the deposition of the middle Oxaya Formation (Muñoz and Charrier, 1996). In the Lluta valley, the early movement affected the lower–middle Azapa Formation and is sealed by the upper Azapa Formation, whereas in the Azapa valley, this movement affected the Azapa and lower Oxaya Formations and is

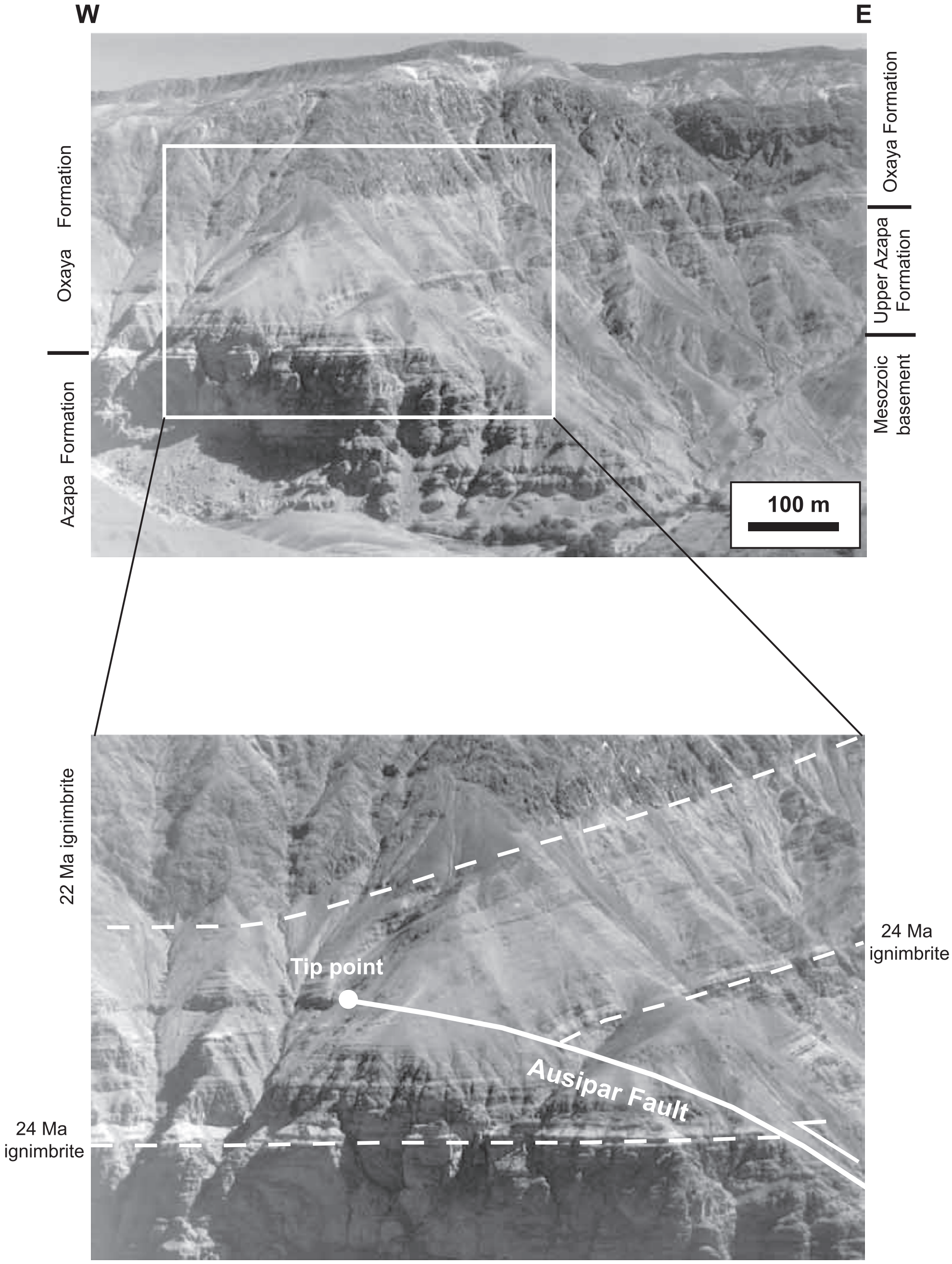

Fig. 6. The Ausipar Fault in the northern side of the Lluta valley (at Tiñare). See Fig. 4 for the location.

sealed by the middle Oxaya Formation (Fig. 4). Therefore, the early activity of the AF is coeval with, or immediately posterior to, the lower–middle Azapa Formation (Oligocene) in the OA northern region, and it is coeval with, or immediately posterior to, the Azapa and lower Oxaya formations (Oligocene–Lower Miocene) in the OA southern region.

5. Interaction between folding and drainage evolution

The landforms related to drainage development in the Andean Precordillera of the Arica area are particularly well preserved. To discuss and quantify the effects of tectonic deformation on the evolution of the drainage networks, we will first describe the age, duration and rate of folding, then the morphological evolution of the drainage patterns. We will finally quantify the amount and long-term rate of incision of the main valleys.

5.1. Timing of the folding

The age and duration of folding of the OA can be well constrained from Ar–Ar to K–Ar determinations of volcanic rock interbeded in the pretectonic or syntectonic strata or preserved on the topographic surface. The OA involves the complete Oxaya Formation (Oligocene–Miocene in age) and is unconformably overlain by the horizontal Pliocene Lauca Ignimbrite. This relationship implies that folding is broadly middle–upper Miocene (19–3 Ma) in age. Early–middle Miocene andesitic clasts present in the upper fluvial gravels of the El Diablo Formation suggest a direct link between the Western Cordillera and Central Depression, implying that folding was post-El Diablo Formation deposition. Immediately to the west of the OA, clasts of the El Diablo gravels are dated at 14.7 and 18.8 Ma (Table 1), and regionally, the same gravels are older than 8.4 Ma. According to these data, the folding is younger than 14.7–8.4 Ma.

On the eastern flank of the OA, the Oxaya ignimbrites dip up to 4° to the east. The Oxaya ignimbrites are overlain by lavas of the Zapahuira Formation; the contact is erosional but structurally concordant. The youngest lava of the Zapahuira Formation, in Copaquilla locality, has yielded a mean age of 11.7±0.7 Ma (Table 1). In Caragua, the tilted Oxaya and Zapahuira formations are truncated by a low angle unconformity and overlain by the Huaylas Formation, which shows an open-to the east onlap fan geometry (Fig. 7). The lower strata comprise up to 20 m of middle–late Miocene sandstones which are tilted and involved in the folding, whereas the up to 250 m of upper gravel become progressively horizontal. The 10.7±0.3 Ma Caragua–Tignámar Ignimbrite is intercalated in the upper part of these gravels (Fig. 7). The major tilting of the eastern limb and by

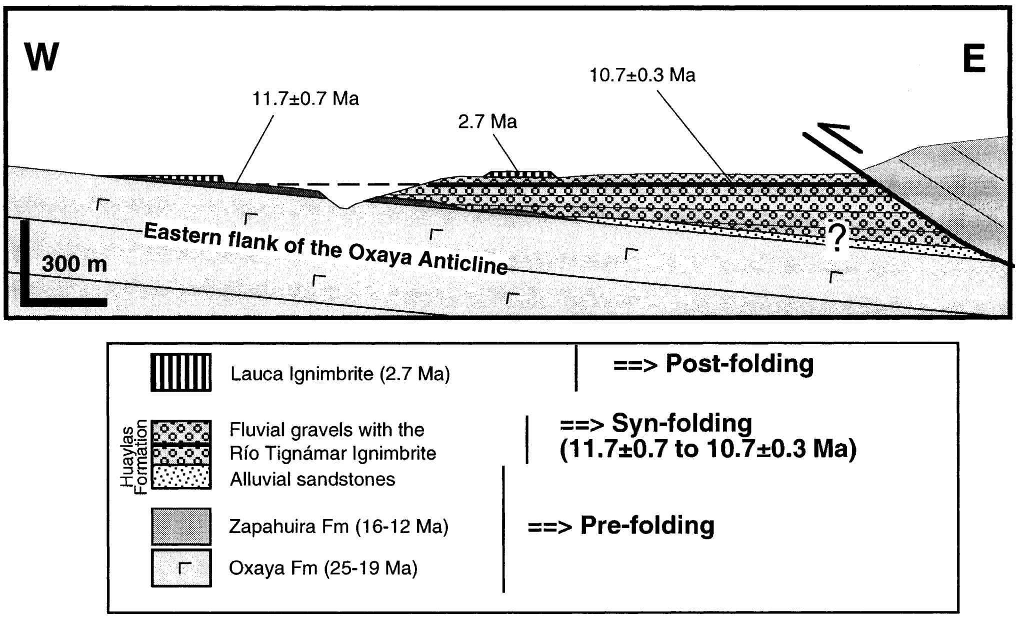

Fig. 7. Cross-section in the eastern limb of the Oxaya Anticline, in Caragua, showing the geometric relation that constrains the age of the folding. See Fig. 4 for the location.

association the folding and the last movement on the Ausipar Fault must have occurred in the middle–late Miocene after the deposition of the youngest folded bed (11.7±0.7 Ma) and before the deposition of the oldest unfolded bed (10.7±0.3 Ma). Maximum and minimum errors of radiometric data show that the absolute age of the folding is constrained to between 12.4 and 10.4 Ma; its maximum possible duration is consequently 2.0 My. The onlap relationship in the eastern limb of the anticline is observed over a relatively confined area (horizontal distance of 3 km) compared with the size of the fold (up to 30 km wide); therefore, a very minor post-10.7-Ma activity cannot be rejected in the western limb of the anticline and thus in the AF. In the axis of the Lluta and Azapa valleys, the amplitude of the folding has been calculated in 790±50 and 715±50 m, respectively. Inasmuch as the maximum duration of folding is 2 My, the minimum rate of hinge uplift is of 395±25 (Lluta valley) and 358±25 m/My (Azapa valley).

5.2. Evolution of the drainage pattern

The initial parallel drainage pattern developed on the upper part of the Oxaya Formation so is more recent than the Lower Miocene (~19 Ma). To the south of the OA, an 11.2±0.6-Ma lava flow (Table 1), from the Marquez Volcano, filled a paleovalley of the parallel network (Fig. 3). This paleovalley was 200-m deep at the time of lava eruption, which means that the first 200 m of incision is older than ~11 Ma. The 11.7±0.7 Ma Copaquilla lava (Table 1) of the Zapahuira Formation, also fills a parallel paleovalley, 50-m deep, indicating that it existed prior to ~12 Ma. Fluvial sediments of the lower part of the Huaylas Formation (middle Miocene in age) were deposited locally in paleoheads of the parallel network. The age and deposition conditions of the El Diablo Formation in the Central Depression are compatible with a fluvial drainage network in the Precordillera during the early–middle Miocene. From these facts, we conclude that the parallel network in the Precordillera is younger than ~19 Ma and that it was still active at ~12 Ma.

The organisation in a poor-organized parallel drainage pattern implies that the valleys were developed on a regular surface and gently westward dipping from the Copaquilla Depression to the Central Depression. On the crests of the Pampa Oxaya, the minor parallel thalwegs are interrupted and fossilised by the OA crestal grabens and normal faults. Fluvial erosion features are not present in the bottom of these grabens. The major thalwegs, as the head of the La Higuera valley, cut and pass the grabens being slightly deflected by them (Fig. 5C). This implies that the parallel drainage network is antecedent to the folding that formed the crestal grabens and normal faults.

Folding created space for deposition of the fluvial Huaylas Formation in the Copaquilla Depression. In this formation, there are no lacustrine facies, implying that, during the folding, the drainage system continued to discharge to the west. The total stream runoff was captured by a few valleys due to topographic uplift by folding, inducing the development of the trellis drainage network (Fig. 8). A negative balance between uplift and incision was established. Therefore, the folding produced modification of the drainage pattern from an early parallel network to a later trellis network which remains active today. Due the chronology determined for the folding, the former network is early–middle Miocene (19–12 Ma) in age and the latter is late Miocene–Quaternary (12–0 Ma) in age.

In the western limb of the OA, the slope increase by folding caused valley incision reactivation and deepening, particularly to the south of the Azapa valley (Figs. 2 and 5). At the break of the slope, one important node of dry parallel valley confluences is identified. The reactived valleys slightly changed orientation from an original ENE–WSW direction to a final NE–SW direction. This is clear for the head of the La Higuera valley, flowing to the SW. This segment of valley captured to the NE, and fossilised, at least two ENE–WSW oriented valleys (north of the La Higuera valley) which are continuous through the limbs of the OA (Fig. 5). The westernmost crestal graben of the OA favoured the capture and connected the final valley. These captures as well as the change of direction of the minor valleys can be explained by growing the topography from the north to the southeast as a product of lateral propagation of the OA. In the northern part of the OA, between Lluta and Cardones valleys, a minor approximately NW–SE-abandoned valley is observed (Fig. 5D). The direction of this valley would result from successive captures to the SE due to the lateral (N–S) fold growth.

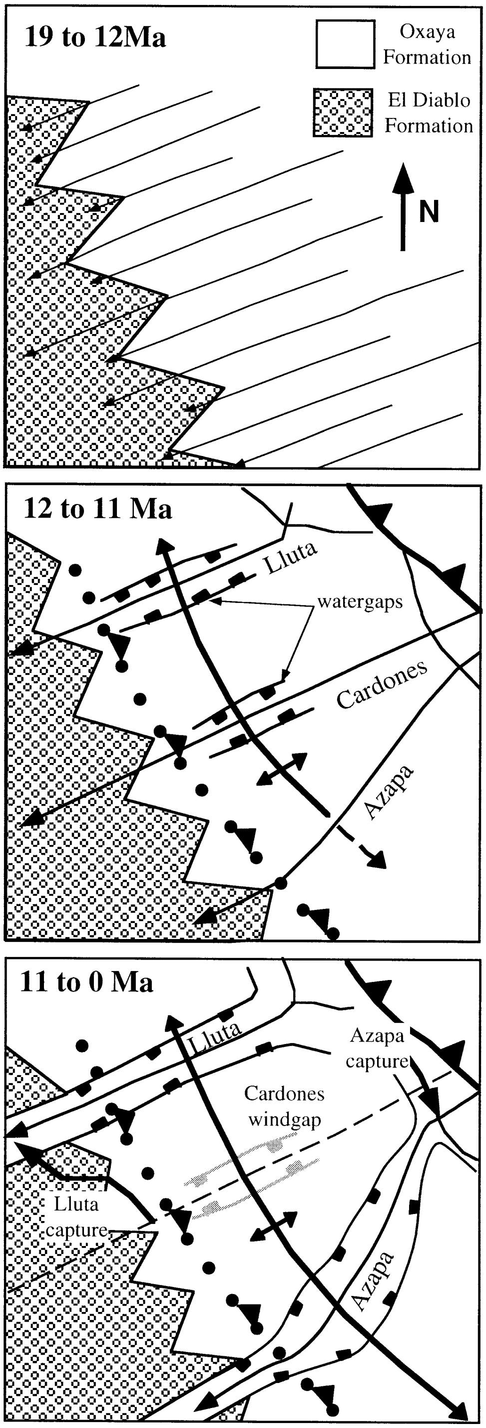

Fig. 8. Schematic diagram showing the long-term drainage evolution of the Lluta, Cardones and Azapa valley and the creation of transverse drainage across the Oxaya Anticlaine.

The evolution of the main three valleys (Lluta, Azapa and Cardones) can be distinguished as following:

(1) The Lluta valley is orthogonal to the fold and parallel to the initial parallel valleys, such that there has been no change to its original direction (Fig. 8).

(2) The Cardones valley is orthogonal to the OA. This valley was captured in two places: upstream by the Azapa river and further downstream by the Lluta river (Fig. 8). The capture by the Azapa river is part of the general capture of the parallel network by the trellis network and thus is directly related to folding. The capture by the Lluta river is most probably due to Lluta Avalanche landsliding (Figs. 3 and 4). If we assume that the avalanche occurred during the final stage of or immediately after the folding, when relief existed in the Precordillera, the capture of the Cardones by the Lluta river could also be directly linked to the folding. The Cardones and Lluta valleys, with an orientation parallel to the initial drainage network, would have been the major streams in the late stage of the parallel drainage and continued as such in the early stage of the trellis drainage. Then, the Cardones valley was captured by the Azapa valley, which later became the second most important valley.

(3) The NE–SW-oriented Azapa valley is oblique to the OA and cuts the parallel drainage system (Fig. 8). Upstream, in Copaquilla, the Azapa valley is fed by tributaries that captured the parallel Cardones and downstream Tignámar paleovalleys. The proto-Azapa valley must have corresponded to a parallel valley. The capture of the downstream Tignámar tributaries (Fig. 5) by the Azapa valley, to the NE, can be explained by an increase in relief from north to southeast as a product of lateral propagation of the folding. The increase in relief induced the development of the Azapa valley at least in the early stage of the folding and in the western part of the OA. Similarly, the head of the La Higuera valley, oriented in the direction of slope maximum, flowed to the SW. Consequently, the present-day direction of the Azapa river results from

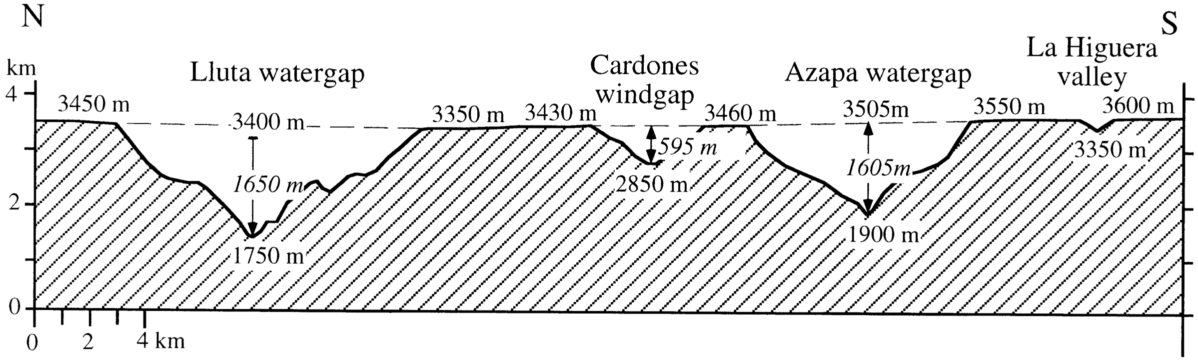

Fig. 9. Cross-section along the axis of the Oxaya Anticline, showing the amount of incision in the main valleys.

successive valley capture by regressive erosion towards the NE.

5.3. *Valleys incision and rates of incision*

Incisional development is analysed in the hinge region of the OA (Figs. 9 and 10). During the lower–middle Miocene, between approximately 19 and 12 Ma, the prefolding incision is well recorded in the fossil parallel network of the Pampa Oxaya. Preserved maximum incision observed in the La Higuera valley ranges between 50±50 m in the Copaquilla Depression, 250±50 m in the OA hinge and 350±50 m in the OA western limb (Fig. 10). The uppermost course of this valley, in the OA eastern limb, is tilted to the east (Fig. 10), indicating that it was fossilised at the beginning of the folding. In the OA western limb, the incision was reactived and continued during and after the folding. The duration of the prefolding incision period, maximum 7 Ma, implies that the minimum rate of long-term incision for the La Higura valley, in the OA hinge, was of 36±7 m/My.

For the Lluta and Azapa valleys, the actual total incision is equal to 1650±50 and 1605±50 m, respectively (Figs. 9–11). During and after the folding, the Lluta and Azapa valleys remained active, thus, their incision rate was greater than or equal to the uplift rate of the interfluve surfaces (or amplitude of the OA). Then, the minimum amount of incision during folding in the anticline hinge is 790±50 m for Lluta and 715±50 m for Azapa. This minimum synfolding incision represents approximately 48% of the total incision in the Lluta valley and 44.5% of this amount in the Azapa valley. As the maximum lifetime of the folding is 2 My, the synfolding incision rate is

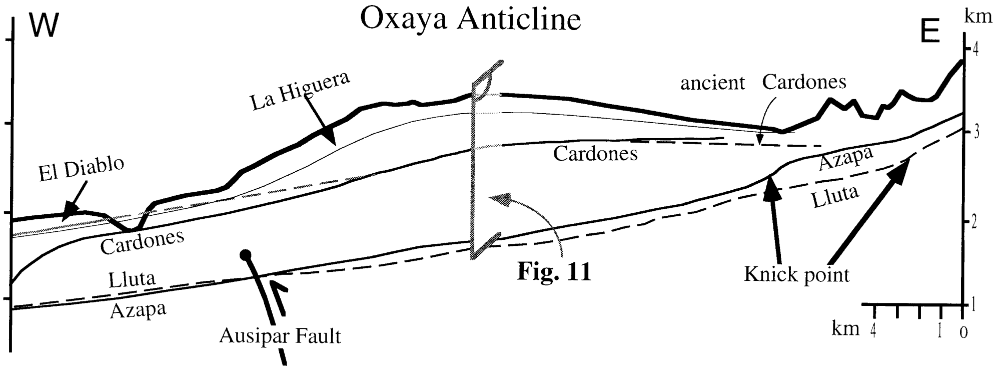

Fig. 10. Longitudinal profiles of the La Higuera, El Diablo, Cardones, Lluta and Azapa valleys projected (in order to allow comparison) along the topographic profile crossing the Oxaya Anticline to the north of the Cardones valley.The western part of the Cardones valley and the eastern part of the Lluta valley are approximately perpendicular to the topographic profile, however, they were projected in the same plane.

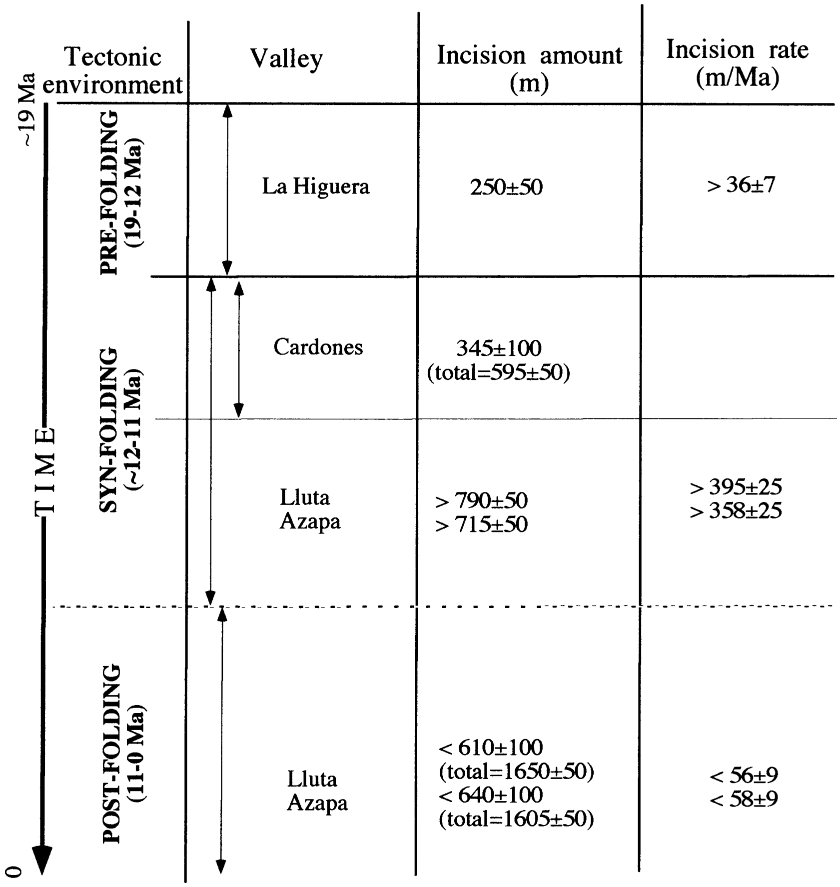

Fig. 11. Compared incision amounts and incision rates of the main rivers in the hinge region of the Oxaya Anticline. Section is located in Fig. 10.

much greater than 358±25 to 395±25 m/My. The poor organisation of the parallel drainage pattern implies that before the folding, the different rivers had similar sizes and incision amounts. Thus, the prefolding incision amount of the Lluta and Azapa valleys, in the anticline hinge, can be inferred similar to one of the La Higuera paleovalleys (250±25 m). Compared to the actual total incision, this prefolding incision value for Lluta and Azapa valleys represents 15% and 15.6%, respectively. After the folding, the amount of incision in the OA hinge corresponds consequently to 610±100 m in the Lluta valley (37% of the total incision) and 640±100 m in the Azapa valley (39.9% of the total incision). The synfolding incision values are a minimum, so the postfolding incision values must be considered as a maximum. The duration of the postfolding incision period is approximately 11 Ma, thus, the maximum postfolding long-term incision rates vary between 56±9 and 58±9 m/My in the anticline hinge. The amount of postfolding incision is significant, and its rate is about twice that of the prefolding incision rate.

In Copaquilla, the Cardones valley is filled by 200 to 300 m of horizontal gravels (Huaylas Formation), which are covered by the Lauca Ignimbrite. This ignimbrite has not been significantly incised subsequent to its deposition, whereas the Huaylas gravels show only 50–70 m of postdeposition incision (ca. 25% with respect to total thickness) near the axis of the paleovalley. This indicates that the main incision of the upper Cardones valley occurred prior to the deposition of the Huaylas gravels and certainly before the Pliocene (~2.7 Ma). In addition, this segment of the valley shows a horizontal paleo-thalweg, which is not tilted to the east, as are the dry valleys of the Pampa Oxaya (Fig. 10). This indicates that the

Cardones valley continued to be active during at least the early stages of folding and then it was fossilised; immediately after the folding, it was filled by the horizontal Huaylas gravels. At the moment of the fossilisation, the incision varied from 250±50 m in Copaquilla to 595±50 m in the anticline hinge (Figs. 9 and 10). In the OA western limb, the incision reactived and continued during and after the folding. If we accept that the prefolding incision in the hinge region was about 250±50 m, similarly to the La Higuera valley (as in Lluta and Azapa valleys), the amount of synfolding incision for the Cardones valley is 345±100 m (Fig. 11). The value of the synfolding incision of the Lluta and Azapa valleys is close to twice that of the Cardones valley. If the incision rate is assumed constant for the three rivers during the folding, then the Cardones valley would have been abandoned approximately at the middle stage of folding.

Knick points are observed in the upper course of the Lluta and Azapa rivers (Fig. 10). They are located approximately 42 and 24 km, respectively, to the east of the Ausipar Fault, which uplifts the eastern block. We interpret these river deflections as formed by the vertical movement of the fault. As the rock substratum is broadly the same for the two rivers, the large difference in the amount of headwards erosion is considered to be due to the runoff of each river and to the area drained by them 2–2.5 times greater in Lluta than in Azapa. The rate of retreat of these knick points, posterior to folding, is thus approximately 3.8 and 2.2 km/My, respectively.

6. Conclusions and implications

The uppermost part of the Precordillera of Arica, in the Andes of the Northern Chile, is broadly constituted by Oligocene–Miocene ignimbrites (Oxaya Formation), which form a major gentle west-vergent fold: the Oxaya Anticline. The fold trends N–NW, is 50-km long and 30-km wide. The horizontal shortening (<100 m) is less than the amplitude of uplift of the hinge surface (~850). Below the Oxaya Formation, the western border of the Precordillera block is bounded by a blind, high-angle, east-dipping reverse fault: the Ausipar Fault. Tectono-stratigraphic relations indicate that this fault had an Oligocene (s.l.) activity, and its last movement in the middle–late Miocene formed the Oxaya Anticline. Radiometric data from volcanic rocks, in the eastern limb of the Oxaya Anticline, show that the folding occurred essentially between 11.7±0.7 and 10.7±0.3 Ma, i.e., between 12.4 and 10.4 Ma; this implies a maximum duration of 2 My. Miocene flexure-folds comparable to the Oxaya Anticline, formed through propagation of subvertical blind faults (involving large uplift and little shortening), have also been described along the Andean Precordillera of Southern Peru (Tosdal et al., 1984) and of Northern Chile to the south of Arica (Galli and Dingman, 1962; Muñoz and Charrier, 1996; Pinto et al., 1999; Victor and Oncken, 1999). At the Arica latitude, the eastern border of the Precordillera is cut by a parallel and west-vergent Neogene thrust–fold system (Muñoz and Charrier, 1996; García et al., 1996, 2002).

The drainage network developed on the Oxaya ignimbrites, and its Neogene evolution is particularly well preserved. The folding of the Oxaya Anticline changed drainage patterns from an early–middle Miocene (19 to 12 Ma) parallel network to a late Miocene–Quaternary (11 to 0 Ma) trellis network. The later trellis pattern corresponds to the active drainage basin of the Lluta and Azapa rivers. The early parallel pattern developed on a gently westward-sloping regular surface and was coeval with the deposition of the fluvial and lacustrine El Diablo Formation (in the Central Depression). The maximum incision amount in the parallel drainage network is registered in the head of the La Higuera paleovalley in the Pampa Oxaya crests and is equal to 250±50 m. Therefore, in this prefolding incision event of 7 My in duration, the minimum long-term incision rate is equal to 36±7 m/Ma.

The folding did not prevent the discharge of water to the west but produced the development of the later trellis drainage pattern with concentration of the drainage into a few valleys. Initially, the Lluta, Cardones and Azapa valleys remained active, and finally, only the strongly incised Lluta and Azapa valleys captured the whole system. In the Oxaya Anticline hinge, the total values of the present incision for the Lluta, Azapa and Cardones valleys are 1650±50, 1605±50 and 595±50 m, respectively. The Lluta and Cardones valleys retained a direction parallel to the early drainage network, whereas the

Azapa valley cut obliquely and captured the parallel valleys of the Pampa Oxaya. The Cardones valley was captured upstream by an Azapa tributary and lower downstream by a Lluta tributary. Stream captures and fossilisation of the parallel paleovalleys resulted from growth of the Oxaya Anticline. The NE–SW direction of the Azapa valley is a consequence of successive valley captures towards the NE by an increase of the relief from north to southeast as a product of lateral propagation of the fold.

The synfolding incision in the anticline hinge is equal to or greater than the fold amplitude, which corresponds to 790±50 and 715±50 m in the Lluta and Azapa valleys, respectively. As maximum duration of the folding is 2 My, the synfolding incision rate is much greater than 395±25 m/My (Lluta valley) and 358±25 m/My (Azapa valley). The prefolding incision for Lluta, Azapa and Cardones valleys in the hinge anticline can be assumed similar to that of La Higuera valley (250±50 m). Thus, for the Cardones valley, the amount of synfolding incision is equal to 345±100 m, indicating that it was abandoned approximately during the middle of folding. For the Lluta and Azapa rivers, the incision amount after folding (during the last 11 Ma) is equal to or less than 610±100 and 640±100 m, respectively, in the anticline hinge. The maximum postfolding long-term incision rate is consequently equal to 56±9 and 58±9 m/My, respectively. The incision during the OA folding (<2 My) was much faster (by about 5 to 10 times) than before and after the folding. The amount of postfolding incision is important (37 to 40% of the total incision), and its rate is about twice that of the prefolding incision rate. This implies an acceleration of the valley incision since the middle–late Miocene. The postfolding incision is not due to the local tectonic deformation but rather as consequence of regional uplift and/or eustatic decent (or river base level decent). In the Andean forearc at the Arica latitude, the valley incision since the late Miocene–Quaternary, from ~1000 (Coastal Cordillera and Central Depression) to ~600 m (Precordillera), cannot be explained by eustatic fall, which has been globally less than 200 m since the middle Miocene (e.g., Hardenbol et al., 1998). Furthermore, an important part of the late Miocene–Quaternary incision cannot be due to the local tectonic deformation but must result from regional uplift of the Andean forearc.

Acknowledgements

This research was initiated and supported by the «Institut de Recherche pour le Developpement» (I.R.D.) and the «Departamento de Geologia de la Universidad de Chile». The study was continued by both Institutions and the Servicio Nacional de Geologia y Mineria (SERNAGEOMIN). We acknowledge particularly G. Parraguez and R. Charrier for discussions in the field and in the laboratory. Radiometric ages were determined by M. Fornari (IRD, GeoscienceAzur) and C. Perez de Arce (SERNAGEOMIN). We thank A. Hartley and an anonymous referee for their useful editorial comments.

References

Aguirre, E., 1990. Geología del Complejo Volcánico Choquelimpie-Ajoya, Altiplano de Arica, I Región. Memoria de Título, U. de Chile. 150 p.

Allmendinger, R., Jordan, T., Kay, S., Isacks, B., 1997. The evolution of the Altiplano–Puna plateau of the Central Andes. Annu. Rev. Earth Planet. Sci. 25, 139–174.

Alpers, C., Brimhall, G., 1988. Middle Miocene climatic change in the Atacama Desert, northern Chile: evidence from supergene mineralization at La Escondida. Geol. Soc. Amer. Bull. 100, 1640–1656.

Baby, P., Rochat, Ph., Mascle, G., Hérail, G., 1997. Neogene shortening contribution to crustal thickening in the back arc of the Central Andes. Geology 25, 883–886.

Bargo, M., Reguero, M., 1989. El primer registro de un mamífero fósil en el extremo septentrional de Chile. Ameghiniana 26, 239.

Basei, M.A., Charrier, R., Hervé, F., 1996. New ages (U–Pb, Rb–Sr, K–Ar) from supposed Pre-Cambrian units in northern Chile: some geotectonic implications. Third Third International Symposium on Andean Geodynamics (ISAG). Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Saint Malo, France, pp. 763–766.

Baulig, H., 1950. Captures fluviales et déversements. Essais de Géomorphologie. Editions Les Belles Lettres, Paris, pp. 114–124.

Burbank, D.W., Meigs, A., Brozovic, N., 1996. Interactions of growing folds and coeval depositional systems. Basin Res. 8, 199–223.

Burbank, D.W., McLean, J.K., Bullen, M., Abdrakhmatov, K.Y., Miller, M.M., 1999. Partitioning of intramontane basins by thrust-related folding, Tien Shan, Kyrgystan. Basin Res. 11, 75–92.

Burnett, A.W., Schumm, S.A., 1983. Alluvial river response to neotectonic deformation in Louisiana and Mississippi. Science 222, 49–50.

Delcaillau, B., Hérail, G., Mascle, G., 1987. Evolution géomorphostructurale de fronts de chevauchements actifs: le cas

des chevauchements intrasiwaliks du Népal central. Z. Geomorphol., B 31 (3), 339–360.
Delcaillau, B., Deffontaines, B., Floissac, L., Angelier, J., Deramond, J., Souquet, P., Chu, H.T., Lee, J.F., 1998. Morphotectonic evidence from lateral propagation of an active frontal fold; Pakuashan anticline, foothills of Taiwan. Geomorphology 24, 263–290.
Flynn, J., Croft, D.D., Charrier, R., Wyss, A.R., Hérail, G., García, M., 2004. A new specimen and taxonomic revision of Mesotheriids (Mammalia, Notoungulata, Typotheria) from the Caragua region, Northern Chile: implications for age of strata on the western flank of the Altiplano. J. South Am. Earth Sci. (in press).
Formento-Triglio, M.L., Burbank, D.W., Nicol, A., Shulmeister, J., Rieser, U., 2002. River response to an active fold-and-thrust belt in a convergent margin setting, North Island, New Zealand. Geomorphology 49, 125–152.
Galli, C., Dingman, R., 1962. Cuadrangulos Pica, Alca, Matilla y Chacarilla, Provincia de Tarapaca. Carta Geologica de Chile. Vol. 3, N. 2, 3, 4, 5. Inst. Investig. Geol., Carta Geol. Chile. 125 p.
García, M., Hérail, G., 2001. Comment on "Geochronology (Ar–Ar, K–Ar and He-exposure ages) of Cenozoic magmatic rocks from northern Chile: implications for magmatism and tectonic evolution of the central Andes". In: Wörner, et al., (Eds.), Revista Geológica de Chile, vol. 28, pp. 127–130.
García, M., Hérail, G., Charrier, R., 1996. The Cenozoic forearc evolution in Northern Chile: the border of the Altiplano of Belén (Chile). Third International Symposium on Andean Geodynamics. Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Saint Malo, France, pp. 359–362.
García, M., Hérail, G., Charrier, R., 1999. Age and structure of the Oxaya Anticline, a major feature of the Miocene compressive structures of northernmost Chile. Fourth International Symposium on Andean Geodynamics (ISAG). Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Göttingen, Germany, pp. 249–252.
García, M., Hérail, G., Charrier, R., Mascle, G., Fornari, M., Perez de Arce, C., 2002. Oligocene–Neogene tectonic evolution of the Altiplano of the Northern Chile (18°–19°S). Five International Symposium on Andean Geodynamics (ISAG). Institut de Recherche pour le Développement (IRD), Toulouse, France, pp. 235–238.
Gaudemer, Y., Tapponnier, P., Turcotte, D.L., 1989. River offsets across strike-slip faults. Ann. Tecton. 3, 55–76.
Gaupp, R., Kött, A., Wörner, G., 1999. Paleoclimatic implications of Mio–Pliocene sedimentation in the high-altitude intra-arc Lauca basin of northern Chile. Palaeogeogr. Palaeoclimatol. Palaeoecol. 151, 79–100.
Hardenbol, J., Thierry, J., Farley, M., Jacquin, T., Graciansky, P., Vial, P., 1998. Mesozoic and Cenozoic sequence chronostratigraphic chart. SEPM Spec. Publ.-Soc. Sediment. Geol. 60, 3–13.
Hartley, A.J., Chong, G., 2002. Late Pliocene age for the Atacama Desert: implications for the desertification of western South America. Geology 30 (1), 43–46.
Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 305, 287–306.
Howard, A.D., 1967. Drainage analysis in geologic interpretation: a summary. Am. Assoc. Pet. Geol. 51, 2246–2259.
Isacks, B., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. J. Geophys. Res. 93 (B4), 3211–3231.
Jackson, J.A., Leeder, M.R., 1994. Drainage systems and the development of normal faults: an example from Pleasant Valley, Nevada. J. Struct. Geol. 16, 1041–1059.
Jackson, J., Norris, R., Youngson, J., 1996. The structural evolution of active fault and fold systems in central Otago, New Zealand: evidence revealed by drainage patterns. J. Struct. Geol. 18, 217–234.
Kley, J., Müller, J., Tawackoli, S., Jacobshagen, V., Manutsoglu, E., 1997. Pre-Andean and Andean-age deformation in the Eastern Cordillera of Southern Bolivia. J. South Am. Earth Sci. 10, 1–19.
Lahsen, A., 1982. Upper Cenozoic volcanism and tectonism in the Andes of northern Chile. Earth Sci. Rev. 18, 285–302.
Lamb, S., Hoke, L., Kennan, L., Dewey, J., 1997. Cenozoic evolution of the Central Andes in Bolivia and northern Chile. In: Burg, J.P., Ford, M. (Eds.), Orogeny Through Time, Geol. Soc. London Spec. Publ., vol. 121, pp. 237–264.
Lavé, J., Avouac, J.P., 2000. Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal. J. Geophys. Res. 105 (B3), 5735–5770.
Mather, A.E., 2000. Adjustment of a drainage network to capture induced base-level change: an example from the Sorbas Basin, SE Spain. Geomorphology 34, 271–289.
Mitra, S., Mount, V., 1998. Foreland basement-involved structures. AAPG Bull. 82, 70–109.
Molnar, P., Brown, E.T., Burchfield, B.C., Qidong, D., Xianyue, F., Jun, L., Raisbeck, G.M., Jianbang, S., Zhangming, D., Yiou, F., Huichuan, Y., 1994. Quaternary climate change and the formation of river terraces across growing anticlines on the North flank of the Tien Shan, China. J. Geol. 102, 583–602.
M.O.P., 1987. Balance Hídrico de Chile. Ministerio de Obras Públicas, Dirección General de Aguas. Santiago, Chile. 58 p.
Mortimer, C., Saric, N., 1972. Landform evolution in the coastal region of Tarapacá Province, Chile. Rev. Géomorphol Dyn. 21, 162–170.
Mortimer, C., Farrar, E., Saric, N., 1974. K–Ar ages from Tertiary lavas of the northernmost Chilean Andes. Geol. Rundsch. 63, 484–489.
Muñoz, N., Charrier, R., 1996. Uplift of the western border of the Altiplano on a west-vergent thrust system, Northern Chile. J. South Am. Earth Sci. 9, 171–181.
Muñoz, N., Elgueta, S., Harambour, S., 1988. El Sistema Jurásico (Formación Livilcar) en el curso superior de la quebrada Azapa, I Región: implicancias paleogeográficas. Actas V Congreso Geológico Chileno, Santiago, vol. 1, pp. A403–A415.
Naranjo, J.A., 1993. Hallazgo de una gigantesca avalancha de detritos del Cenozoico superior en Oxaya, Región de Tarapacá. II Simp. Intern. de Estudios Altiplánicos, Arica, Chile, pp. 47–52.
Naranjo, J.A., Paskoff, R., 1985. Evolución cenozoica del piedemonte andino en la Pampa del Tamarugal, Norte de Chile (18°–21°S). Actas IV Congreso Geológico Chileno, Antofagasta, vol. 5, pp. 149–164.

Narr, W., Suppe, J., 1994. Kinematics of basement-involved compressive structures. Am. J. Sci. 294, 802–860.

Pacci, D., Hervé, F., Munizaga, F., Kawashita, K., Cordani, U., 1980. Acerca de la edad Rb/Sr precámbrica de rocas de la Formación Esquistos de Belén, Departamento de Parinacota, Chile. Rev. Geol. Chile 11, 43–50.

Parraguez, G., 1998. Sedimentología y geomorfología producto de la tectónica cenozoica, en la Depresión Central, Pampa de Chaca, I Región de Tarapacá, Chile. Memoria de Título, U. de Chile. 108 p.

Paskoff, R., 1979. Sobre la evolucion geomorfologica del Gran Acantilado Costero del Norte de chile, Norte grande. Inst. Geogr. Univ. Catol. Chile 6, 7–22.

Pinto, L., 2003. Traçage de l'érosion Cénozoïque des Andes centrles à l'aide de la minéralogie et géochimie des sédiments (Nord du Chili et Nord-Ouest de la Bolivie). Thesis. Univ Paul Sabatier, 107 p. +Annexes.

Pinto, L., Hérail, G., Charrier, R., 1999. Sedimentary register of the cenozoic deformation of the western border of the Altiplano in the Northern Chile (Region of Tarapacá, 19°00′ –19°30′ S). Fourth International Symposium on Andean Geodynamics (ISAG). Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Göttingen, Germany, pp. 593–596.

Pinto, L., Hérail, G., Fontan, F., Moine, B., Charrier, R., Dupré, B., 2004. Using geochemistry to establish the igneous provenances of the Neogene continental sedimentary rocks in the Central Depression and Altiplano, Central Andes. Sediment. Geol. 166, 157–183.

Replumaz, A., Lacassin, R., Tapponnier, P., Leloup, P.H., 2001. Large river offsets and Plio-Quaternary dextral slip rate on the Red River fault (Yunnan, China). J. Geophys. Res. 106 (B1), 819–836.

Riquelme, R., 1998. Evolución tectonosedimentaria post-oligocena del borde occidental del Altiplano, entre Tignámar y el Salar de Surire, I Región, Chile. Tesis de Magister y Memoria de Título, U. de Chile. 123 p.

Roeder, D., 1988. Andean-age structure of Eastern Cordillera (Province de La Paz Bolivia). Tectonics 7 (1), 23–39.

Salas, R., Kast, R., Montecinos, F., Salas, I., 1966. Geología y Recursos Minerales del Departamento de Arica. Provincia de Tarapacá. Inst. Invest. Geol., Boletín 21, 130 pp.

Salinas, P., Villarroel, C., Marshall, L., Sepúlveda, P., Muñoz, N., 1991. Typotheriopsis sp. (Notoungulata, Mesotheridae), Mamífero del Mioceno Superior en las cercanías de Belén, Arica, Norte de Chile. Actas VI Congreso Geológico Chileno,Viña del Mar., pp. 314–317.

Schmitz, M., 1994. A balance model of the southern Central Andes. Tectonics 13 (2), 484–492.

Schumm, S.A., Dumont, J.F., Holbrook, J.M., 2000. Active Tectonics and Alluvial Rivers. Cambridge University Press. 276 p.

Sempéré, T., Hérail, G., Oller, J., Bonhomme, M., 1990. Late Oligocene–early Miocene major crisis and related basins in Bolivia. Geology 18, 946–949.

Sheffels, B., 1995. Mountain building in the Central Andes: an assessment of the contribution of the crustal shortening. Int. Geol. Rev. 37, 128–153.

Sillitoe, R., McKee, E., 1996. Age of supergene oxidation and enrichment in the Chilean Porphyry Copper Province. Econ. Geol. 91, 164–179.

Stokes, M., Mather, A.E., 2003. Tectonic origin and evolution of a transverse drainage: the Rio Almanzora, Betic Cordillera, Southeast Spain. Geomorphology 50, 59–81.

Talling, P.J., Stewart, M.D., Stark, C.P., Gupta, S., Vincent, S.J., 1997. Regular spacing of drainage outlets from linear fault blocks. Basin Res. 9, 275–302.

Tobar, A., Salas, I., Kast, R., 1968. Cuadrángulos Camaraca y Azapa. Provincia de Tarapacá. Inst. Invest. Geol., Carta Geol. Chile 19–20, 13 p.

Tosdal, R., Clark, A., Farrar, E., 1984. Cenozoic polyphase landscape and tectonic evolution of the Cordillera Occidental, southernmost Peru. Geol. Soc. Amer. Bull. 95, 1318–1332.

Tricart, J., 1968. Précis de géomorphologie: T.1. Géomorphologie structurale. SEDES, Paris. 322 pp.

Uhlig, D., Seyfried, H., Wörner, G., Kohler, I., Schröder, W., 1996. Landscape evolution in Northernmost Chile (18.5°–19.5°): its implication in the tectonic, sedimentary and magmatism history of the Central Andes. Third International Symposium on Andean Geodynamics. Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Saint Malo, France, pp. 745–748.

Van der Beek, P., Champel, B., Mugnier, J.L., 2002. Control of detachement dip on drainage development in regions of active fault-propagation folding. Geology 30 (5), 471–474.

Victor, P., Oncken, O., 1999. Uplift and surface morphology of the western Altiplano: an effect of basal accresion and tectonic shortening? Fourth International Symposium on Andean Geodynamics (ISAG). Institut Français de Recherche pour le Développement en Coopération (ORSTOM), Göttingen, Germany, pp. 789–792.

Vogel, S., Vila, T., 1980. Cuadrángulos Arica y Poconchile. Región de Tarapacá. Carta Geol. Chile. Inst. Invest. Geol. 35 (24 pp.).

Wörner, G., Seyfried, H., 2001. Reply to the comment by M. García and G. Hérail on 'Geochronology (Ar–Ar, K–Ar and He-exposure ages) of Cenozoic magmatic rocks from northern Chile (18–22°S): implications for magmatism and tectonic evolution of the central Andes' by Wörner et al. (2000). Rev. Geol. Chile 28, 131–137.

Wörner, G., Harmon, R.S., Davidson, J., Moorbath, S., Turner, D.L., McMillan, N., Nye, C., Lopez-Escobar, L., Moreno, H., 1988. The Nevados de Payachata volcanic region (18°S/69°W, N. Chile): I. Geological, geochemical, and isotopic observations. Bull. Volcanol. 50 (5), 287–303.

Wörner, G., Hammerschmidt, K., Henjes-Kunst, F., Lezaun, J., Wilke, H., 2000a. Geochronology (40 Ar/39AR, K–Ar and He-exposure ages) of Cenozoic magmatic rocks from Northern Chile (18°–22°S): implications for magmatism and tectonic evolution of central Andes. Rev. Geol. Chile 27 (2), 205–240.

Wörner, G., Lezaun, J., Beck, A., Heber, V., Lucassen, F., Zinngrebe, E., Rössling, R., Wilke, H.G., 2000b. Precambrian and Early Paleozoic evolution of the Andean basement at Belen (northern Chile) and Cerro Uyarani (western Bolivia Altiplano). J. South Am. Earth Sci. 13 (8), 717–737.

Wörner, G., Uhlig, D., Kohler, I., Soyfried, H., 2002. Evolution of the West Andean escarpment at 18°S (N. Chile) during the last 25 Ma: uplift, erosion and collapse through time. Tectonophysics 345, 183–198.