Interactions between basement and cover during the evolution of the Salar de Atacama Basin, northern Chile

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ABSTRACT

A reinterpretation of the structural style on the eastern Cordillera Domeyko and the adjacent Salar de Atacama Basin reveals the existence of west-dipping, high-angle, thrust-faults extending below the Cordillera Domeyko and Cordón de Lila, resulting from inversion of Cretaceous extensional faults, that transferred west-ward their displacement into the cover, generating fault-propagation and detachment folds. The most conspicuous of these structures is the Cordillera de la Sal. Contractional structures in the Cordillera Domeyko involved a Paleozoic crystalline, volcanic, and sedimentary, uplifted basement. Seismic reflection sections and available surface geology allows to study the interactions between development of the thick-skinned basement structures, sedimentation within the basin, and the thin-skinned deformation in the sedimentary cover. Geometry of the units in the basin continuously modified. Anticline growth above basement thrust-faults locally controlled syn-thrusting sequences, and generated progressive unconformities. Stratigraphic architecture in the basin seems to have been mainly controlled by tectonic activity. Tectonism generated accommodation space, altered base levels, and controlled source areas. The stratigraphy and geometry of the basin deposits resulted mainly from the succession of the following events: local extensional subsidence during the Early to Late Cretaceous, uplift of the Cordillera Domeyko during the latest Cretaceous to Miocene, uplift of the Puna, and subsidence probably caused by flexural response of the lithosphere during thrust-sheet loading, and sediment accumulation.

Key words: Basin evolution, Thick and thin-skinned tectonics, Cordillera Domeyko, Cordillera de la Sal, Mesozoic-Cenozoic, Chilean Andes.

RESUMEN

Interacciones entre el basamento y la cobertura durante la evolución de la Cuenca del Salar de Atacama, norte de Chile. La reinterpretación del estilo estructural del borde oriental de la Cordillera Domeyko y de la adyacente cuenca del Salar de Atacama, basada en el análisis de la geología de superficie y de perfiles sísmicos de reflección, muestra la interacción entre el desarrollo de estructuras contraccionales de escama gruesa del basamento estructural, la sedimentación en la cuenca, y la deformación de escama delgada en la cobertura sedimentaria. El estilo se caracteriza por la presencia de fallas inversas de alto ángulo con vergencia oriental, buzantes bajo el basamento paleozoico alzado de Cordillera Domeyko y Cordón de Lila, la inversión de fallas extensionales cretácicas, y la transferencia del desplazamiento de la fallas inversas a la cobertura mediante pliegues de despegue y de propagación por falla, que originaron, entre otros, a la Cordillera de la Sal. Las secuencias sedimentarias sufrieron deformación local y su desarrollo estuvo controlado por el crecimiento de anticlinales sobre fallas inversas arraigadas en el basamento y la generación de discordancias progresivas. El tectonismo es el factor principal que controló la arquitectura estratigráfica en la cuenca, generando el espacio de acomodación en su frente, alterando los niveles base, y controlando las áreas de aporte sedimentario. La estratigrafía y geometría de los depósitos dependió principalmente de la siguiente sucesión de eventos: subsidencia por extensión, entre el Cretácico Inferior a Medio y Superior, alzamiento de la Cordillera Domeyko, entre el Cretácico más alto y el Mioceno, y subsidencia por flexión de la litosfera, probablemente como respuesta a la carga producida por las escamas de basamento y la acumulación de sedimentos en la cuenca.

Palabras claves: Evolución de cuencas, Tectónica de escama gruesa y delgada, Cordillera Domeyko, Cordillera de la Sal, Mesozoico-Cenozoico, Andes de Chile.

INTRODUCTION

In the early 1970's, the concept of 'thin-skinned' tectonics, extended mostly from works undertaken in the Rocky Mountains, was widely advertised as a viable mechanism to describe most contractional plate margins (Buchanan and Warburton, 1996). In the late 1980's, basin inversion was recognised as an integral part of the early development of many fold and thrust belts. During the 1990's it was widely agreed that 'thick–skinned' tectonics preferentially occurs where previous extensional structures are subsequently contracted and where basement-penetrating reverse faults develop as irregular chains of uplifts in foreland basins (Copper and Williams, 1989; Coward, 1994; McClay, 1995).

Throughout the Andes it has been recognised that most of the deformation affecting the Sub-Andean basins is controlled by deep-detaching basement-involved faults. As a secondary consequence, the transference of displacement creates thin-skinned thrust detachments in the upper incompetent sedimentary cover (Roeder, 1988; Alvarez-Marrón *et al.*, 1993; Cooper *et al.*, 1995; Cazier *et al.*, 1995; Zapata and Allmendinger, 1996; Ramos *et al.*, 1996; Rojas *et al.*, 1999). However, the structural styles affecting the basement and the cover have been usually presented separately as independent styles of deformation.

PREVIOUS STRUCTURAL MODELS

The Salar de Atacama Basin contains Cretaceous to Recent strata, up to 9,000 m thick, and is today topographically closed. This basin is located in the northern Chilean Forearc of the modern Andes Mountain (Fig. 1), however during the Cretaceous and Paleocene it was in a backarc position. As the primary site of Mesozoic and Cenozoic strata in the Central Andes Forearc of Chile, it provides an unparalleled view of the tectonic history of this part of the Andes.

The origin of the Salar de Atacama Basin has been analysed by several authors. Townsend (1988) interpreted the modern geometry of the basin as a half-graben, whereas Muñoz *et al.* (1989) proposed a model of a retroarc foreland basin during the Late Cretaceous. Wilkes and Görler (1994), based on surface geology studies described the region as an intra-mountain basin in evolution since the Late Oligocene. Flint *et al.* (1993), based on the interpretation of one brute stack seismic line, proposed a single extensional tectonic history for this basin since Late Paleozoic time. Charrier and Reutter (1994) suggested the existence of inverted normal faults in the deformation of the eastern slope of the Cordillera Domeyko. Muñoz *et al.* (1997) communicated the presence of Cretaceous inverted half-grabens within the basin, and Muñoz *et al.* (2000) described the geometry of the deformation along the Cordillera de la Sal. However, none of these works attempted an integrated interpretation of the evolution of the Salar de Atacama Basin and the nearby tectonic units: the Cordillera de la Sal, the Cordillera Domeyko, and the Cordón de Lila (Fig. 2).

In this article, the authors present an integrated seismic-stratigraphic and structural analysis of the Salar de Atacama Basin and its relation with the adjacent major tectonic units, based on (1) previous geologic field studies by several authors along the Cordillera Domeyko, Cordillera de la Sal, and Cordón de Lila, (2) the reinterpretation of exploration seismic profiles across the basin, and (3) the hydrocarbon exploration well drilled in the basin by

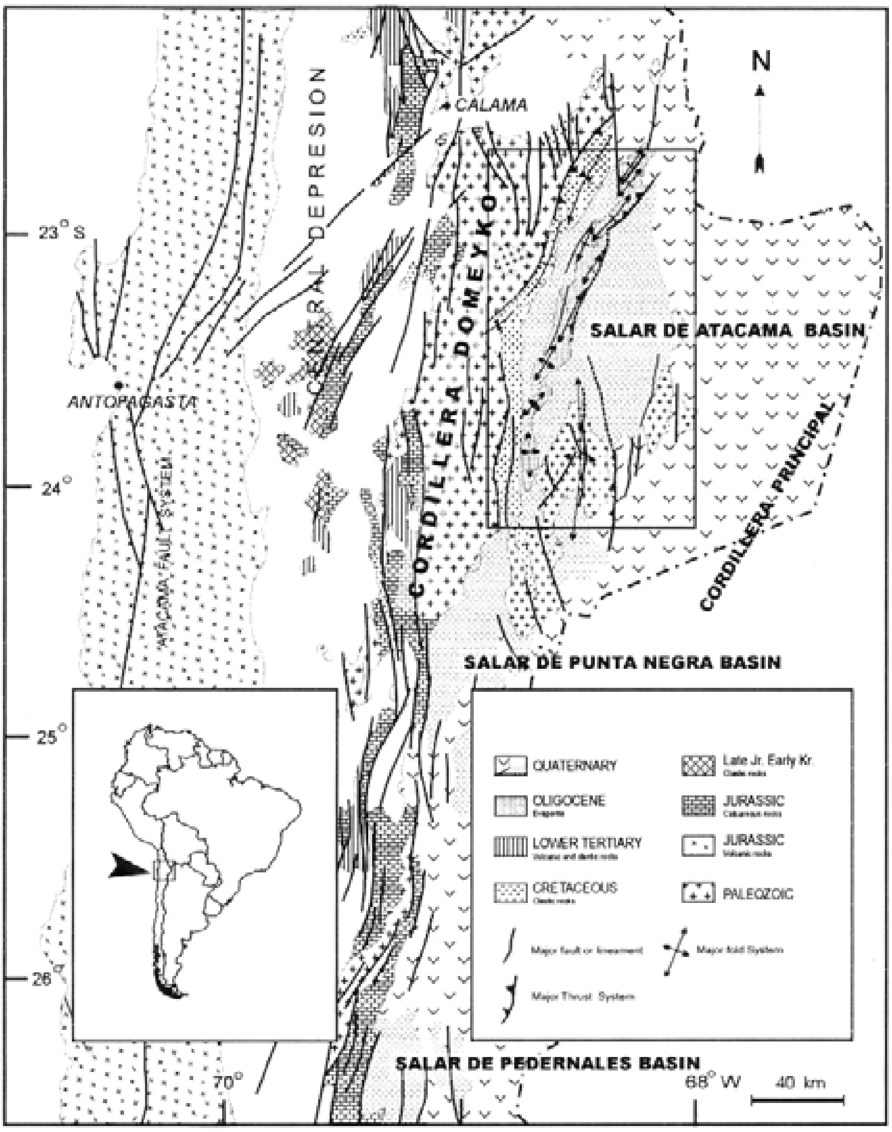


FIG. 1. Simplified geological framework and location of the Salar de Atacama Basin in the eastern side of Cordillera Domeyko, Southern Andes, northern Chile. The figure shows the major geological units and they may not necessarily fit with detailed geological maps.

Chile-Hunt Oil Co. and Empresa Nacional del Petróleo[1]. This integrated approach permitted documentation of the genetic association between deformation affecting both the basement and the cover through inverted faulting, basement involved thrusting, and fault propagation/detachment folding. The information presented supports a regional model in which these deformation mechanisms participated in the development of the Cordillera Domeyko, the Salar de Atacama Basin infill and the generation of the Cordillera de la Sal.

[1] 1990. Final well report for exploration well Toconao -1A (Unpublished), *Chile-Hunt Oil Co. and Empresa Nacional del Petróleo*, 62 p.

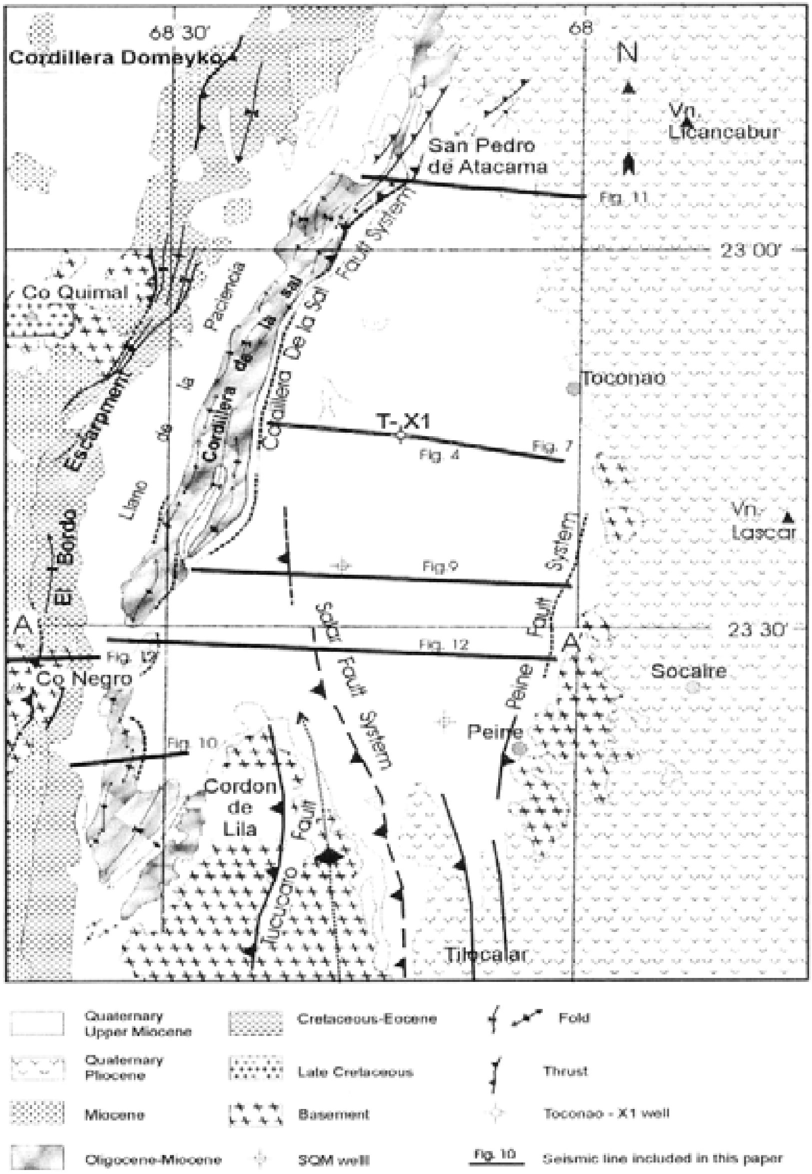


FIG. 2. Simplified geological map of the Salar de Atacama Basin area based on Ramírez and Gardeweg (1982); Charrier and Reutter (1994), and Arriagada (1999). Lines crossing the basin indicate seismic lines included in this paper.

GEOLOGICAL SETTING

The study region is located in northern Chile, at the northern part of an Andean segment that extends from ~22 to 28°S (Fig. 1). This segment is characterised by the existence of the Cordillera Domeyko, a 600 km long ridge that locally reaches altitudes close to 5,000 m, and a major depression located east of the Cordillera Domeyko and west of the Andes mountains, here comprised of Western Cordillera and Puna Plateau (Altiplano). This depression is named the Salars or Preandean Depression and contains, apart from the Salar de Atacama, a series of smaller salars, like the Punta Negra and Pedernales (see Fig. 1). These features (Cordillera Domeyko and Salars Depression) form two first order geological and morphological units, which are not present along the west flank of the Cordillera further north and south in this region of the Andes.

The present study considers units located at the northern portion of this segment (23-24°S); the Salar de Atacama Basin is the main focus (Fig. 1). The Cordillera Domeyko is essentially a Cenozoic, basement-involved thrust belt showing vergence in both east an west directions that resulted, like other Andean features, from the interaction between the Nazca and South American plates (Amilibia *et al.*, 1999; Coira *et al.*, 1982; Jordan *et al.*, 1983). It is characterised by a series of north-south oriented uplifted basement blocks that break through the Andes Cordillera tract. In the Salars Depression, these large-scale features interact towards the East with the sedimentary cover and form thin-skinned detachments.

The Salar de Atacama Basin is a 120 km long and 60-90 km wide north-trending depression, bounded to the east by the Western Cordillera and the Quaternary volcanic chain, which is here deflected to the east around the salar (Fig. 1). At present, the Salar de Atacama at 2,300 m elevation is a desiccated, essentially flat plain in the bottom of a closed drainage basin. In this region, the western slope of the Western Cordillera is draped by Miocene and Pliocene ignimbrites, which in turn, are covered near the basin margin by alluvial fan deposits. Eastwards, on the eastern Puna Plateau, the andesitic volcanic centres that form the present volcanic arc cover mainly the Miocene ignimbrites.

The Cordillera de la Sal is a low ridge, trending NNE, within the Salar de Atacama Basin (Fig. 2), that rises 200 m above the salar along the north and west sides. The Cordillera de la Sal exposes strongly folded and faulted Oligocene to Pliocene strata (Wilkes and Görler, 1988; Naranjo, 1994; Muñoz *et al.*, 2000). The Salar de Atacama extends farther to the west through the Llano de la Paciencia, dying out in the El Bordo Escarpment, in contact with the Cordillera Domeyko. To the south, the Cordón de Lila, formed by Paleozoic basement rocks, protrudes as a peninsula into the salar (Fig. 2).

The basin fill is mainly of Cretaceous to Holocene age and consists of an up to 7,500m thick section of mainly siliciclastic rocks, overlain by 1,000-1,600 m of evaporites (Hartley *et al.*, 1992; Flint *et al.*, 1993). The pre-Cretaceous rocks, referred to here as 'basement', are a heterogeneous group of Paleozoic and Mesozoic granitic rocks, and multiply-deformed and slightly metamorphosed Palaeozoic sedimentary and volcanic rocks.

SESIMIC DATA AND SEISMIC STRATIGRAPHY

METHODOLOGY

A complete set of migrated seismic reflection lines over much of the Salar de Atacama was available to carry out this interpretation (Fig. 2). This is part of a more detailed study conducted by the first author of this paper, as part of a Doctoral thesis at the Universidad de Chile.

A series of regional structural cross-sections were constructed across the basin, supported by available information on the surface geology, seismic reflection and data from the hydrocarbon exploration Toconao -X1 well, located in the centre of the basin.

To constrain the stratigraphic aspects of the basin analysis, seismic stratigraphy as the main technique is used. The authors used seismically defined unconformities across the grid of seismic profiles to delineate discrete sedimentary packages of the basin fill. Nondepositional or erosional truncations of reflectors below the sequence boundary (top lap) and termination of reflectors above the sequence boundary (onlap) seismically define sequence boundaries and unconformities. Additionally, electrical changes in well logs identify stratigraphic breaks. To calibrate seismic boundaries to the well log stratigraphy, a synthetic seismic trace was generated for Toconao -X1 well using a sonic log and rock densities (Fig. 3). The synthetic seismogram is a simulated seismic response computed from the well data that has been used to verify reflection event. The well, located at shot point 425 on the seismic line Z1G-010, allowed to match the different sequences and seismic reflectors. The excellent correlation between the synthetic seismo-

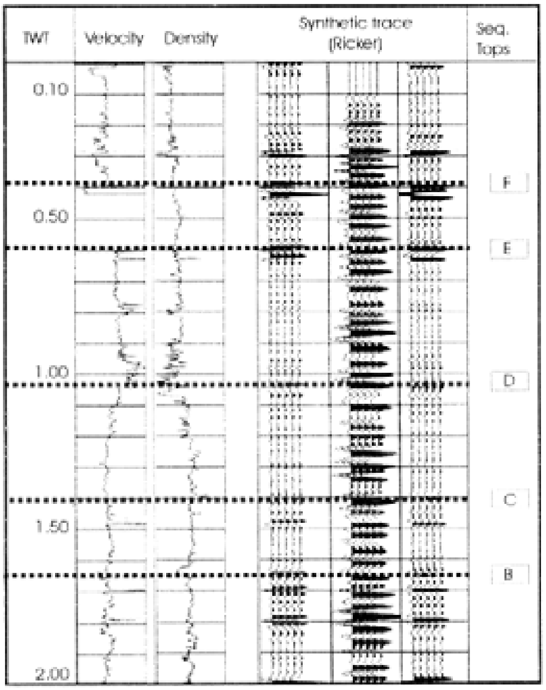


FIG. 3. Synthetic seismic trace generated from velocity and density logs using Richer wavelet of 30 Hz. Projected sequences boundaries used for the seismic interpretation are identified. The tops of sequences B, C, D, E and F are defined based on changes in the physical properties observed in the seismogram and regional geometric relationship between the sequences.

gram and the seismic lines is presented in figure 3. However, the resultant stratigraphic packages for the Salar de Atacama Basin centre may not necessarily fit with the stratigraphy known from outcrops along the western border of the basin.

UNCONFORMITIES

Unconformities are manifested as high-amplitude, low frequency seismic reflections. However, in some cases which there is little or no change in sediment supply to strata above and below the unconformity, there may be little seismic impedance contrast at the unconformity. The seismic character of unconformities in this tectonically active basin appears to be influenced by the superposition of similar lithologies across short-lived (?) unconformities. Deposits above the unconformity correspond in some cases to prograding facies and in other cases to retrograding facies. The most prominent facies migrations and, as a consequence, brightest seismic character of unconformities can be detected in the central part of the basin at the top of the Sequences C and D and to the east at the top of Sequence B (Figs. 4, 5).

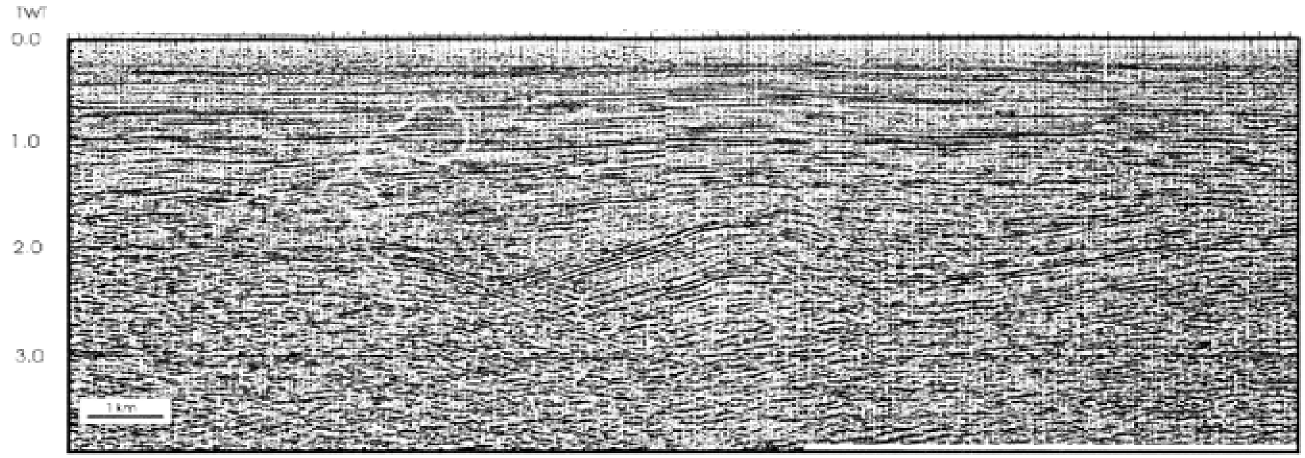
SEISMIC SEQUENCES

Seismic sequences, the strata limited above and below by unconformities resolved on the seismic data and in the well logs, are internally varied. The different internal reflection signatures that include variations in stratal patterns (tilt, continuity, position, and shape of bulk reflectors) and abrupt transitions in acoustic character, thus comprising a diagnostic seismic facies (*e.g.*, base of sequence E). Most of the geometrically defined sequence boundaries coincide with changes in rock properties registered in wireline log data. Each unconformable surface was traced among the set of seismic lines to produce a complete description of the spatial extents of reflection packets bounded by unconformities and their conformable lateral equivalents.

In the Salar de Atacama Basin, seismic sequences defined in this study thicken in lateral and axial directions indicating increasing differential accommodation space. A consistently westwards-increasing thickness of seismic sequences C, D and E towards the Cordillera Domeyko dominantly reflect increased subsidence (?) parallel to the longitudinal basis axis (north-south) during basin evolution (Figs. 7, 5).

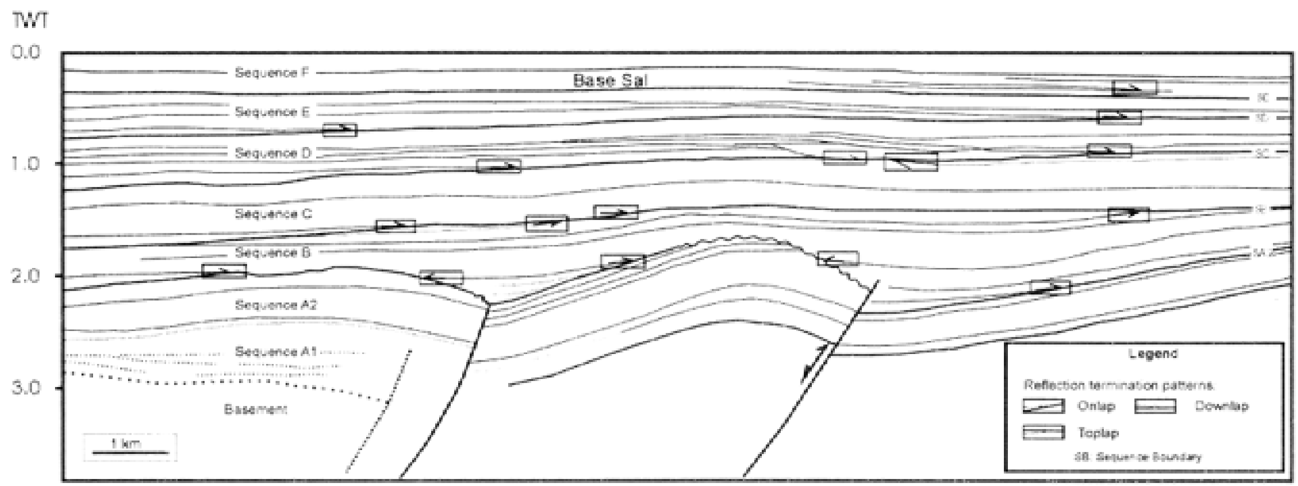
REGIONAL AND BASIN STRATIGRAPHY

The authors present here the stratigraphic succession obtained from the Toconao -X1 well and propose a more refined correlation with the stratigraphy of the western and northern margins of the basin. The correlation with the eastern slope of the Cordillera Domeyko or El Bordo Escarpment is based on the field studies by Hartley *et al.* (1992); Flint *et al.* (1992); Charrier and Reutter (1994); Arriagada (1999) and Mpodozis *et al.* (1999, 2000). Muñoz and Townsend (1997), and Muñoz *et al.*



(a)

FIG. 4. Uninterpreted migrated west-east trending seismic profile representative of the seismic reflectors mapped on the seismic grid available for this paper. Position on figure 2. Vertical scale is two way time travelling (s).



(b)

FIG. 5. Seismic stratigraphic interpretation of seismic reflections showed in figure 4. Seismic stratigraphy fit to Toconao -X1 well and constrained by figure 3. The geometric contacts between the sequences have regional distribution and are interpreted as geological events at basin scale.

(1997) made a first proposition of correlation between surface and subsurface deposits in this region.

THE BASEMENT

Rocks forming the basement of the Cretaceous and Cenozoic deposits in the Salar de Atacama Basin region correspond to a Late Carboniferous to Permian (Lower Triassic?) series composed by acidic and intermediate volcanic rocks with sedimentary intercalations, which has been included in the Peine Group by Breitkreuz (1995).

In the Cordón de Lila (Fig. 2) and in its southern prolongation, the Sierra Almeida, a series of volcanic and sedimentary deposits of possible Ordovician age (Niemeyer, 1989), and marine sedimentary Devonian to Carboniferous deposits are exposed (Davidson *et al.*, 1981; Isaacson *et al.*, 1985; Niemeyer *et al.*, 1997). These rocks are considered to form the basement of the sedimentary sequences in the southern part of the Salar de Atacama Basin. Several plutons of Late Ordovician-Early Silurian age intrude the alleged Ordovician deposits (Mpodozis *et al.*, 1983; Niemeyer, 1989), and plutons of Late Carboniferous to Permian age intrude the Devonian to Carboniferous deposits (Niemeyer *et al.*, 1997).

'THE COVER': SALAR DE ATACAMA BASIN-FILL SEQUENCE

The deposits accumulated in the basin are formed by a <9.000 m thick succession of siliciclastic, evaporites, ignimbrites, tuff and minor carbonatic rocks of Cretaceous to Recent age. These deposits overlie the basement rocks with a low to moderate angle unconformity.

Since the first work by Brüggen (1934) on the El Bordo Escarpment, these deposits have been variably organised in stratigraphic units and assigned to different ages according to different authors. Because of the tectonically active environment developed in this region, described in this article, these deposits form a complex array of sedimentary units with rapid lateral variations.

Figure 6 summarises and correlates the units defined in outcrop with their equivalents in the basin centre, where sampled by the Toconao -X1 well. However, given the tools used in this paper (seismic stratigraphy) other interpretations are possible. Considering the major seismic unconformities within the basin and previous literature, the following six seismic stratigraphic sequences have been differentiated, the lithology and then the paleoenvironment, represent what has been found in the centre of the basin.

SEQUENCE A

The top of this unit was picked at the top of a major unconformity at 2,895 m deep in the Toconao -X1well (Fig. 3). Based on the presence of different facies associations and strata geometry, this sequence has been subdivided into two major sequences (Fig. 6) that form half-grabens fill. The geometric relationships of these sequences with the others (Figs. 5, 7) reveal the variability in space generation during basin evolution at this time.

On the seismic data Sequence A is formed by continuous horizons, which locally show a clear eastwards thickening, towards a west dipping fault and into an asymmetric anticline. This geometry, the facies association obtained from logs and cutting and, the geometry of the unit indicate the existence of a wide space generated by extension and the infill by transitional marine deposits (Figs. 4, 5).

SEQUENCE A1

This sequence is made up of lower amplitude seismic facies exhibiting a predominantly parallel onlap fill configuration thickening to the east toward the Fault 2 in figure 7. From de Toconao -X1 well, it is formed by sandstone and thin limestone beds at the top, and anhydrite interbedded with claystone that overlies a thick, predominantly sandstone interval. The base of this unit is at the top of a thick volcaniclastic and volcanic section grouped into the Permo-Carboniferous/Triassic? basement.

Based on a poor microfaunistic planktonic association including bentic forams, and diatoms found in thin limestone beds, ENAP-Hunt[1] concluded that this part of the sequence corresponds to marine facies of Senonian age. Also few palynomorphs were found in this sequence suggesting an Albian to Cenomanian age.

Marine sequences of Late Cretaceous age have not been described previously in this part of the chilean Andes. Therefore, these new data obtained by ENAP-Hunt[1] are essential for interpreting the geological evolution of this Andean region.

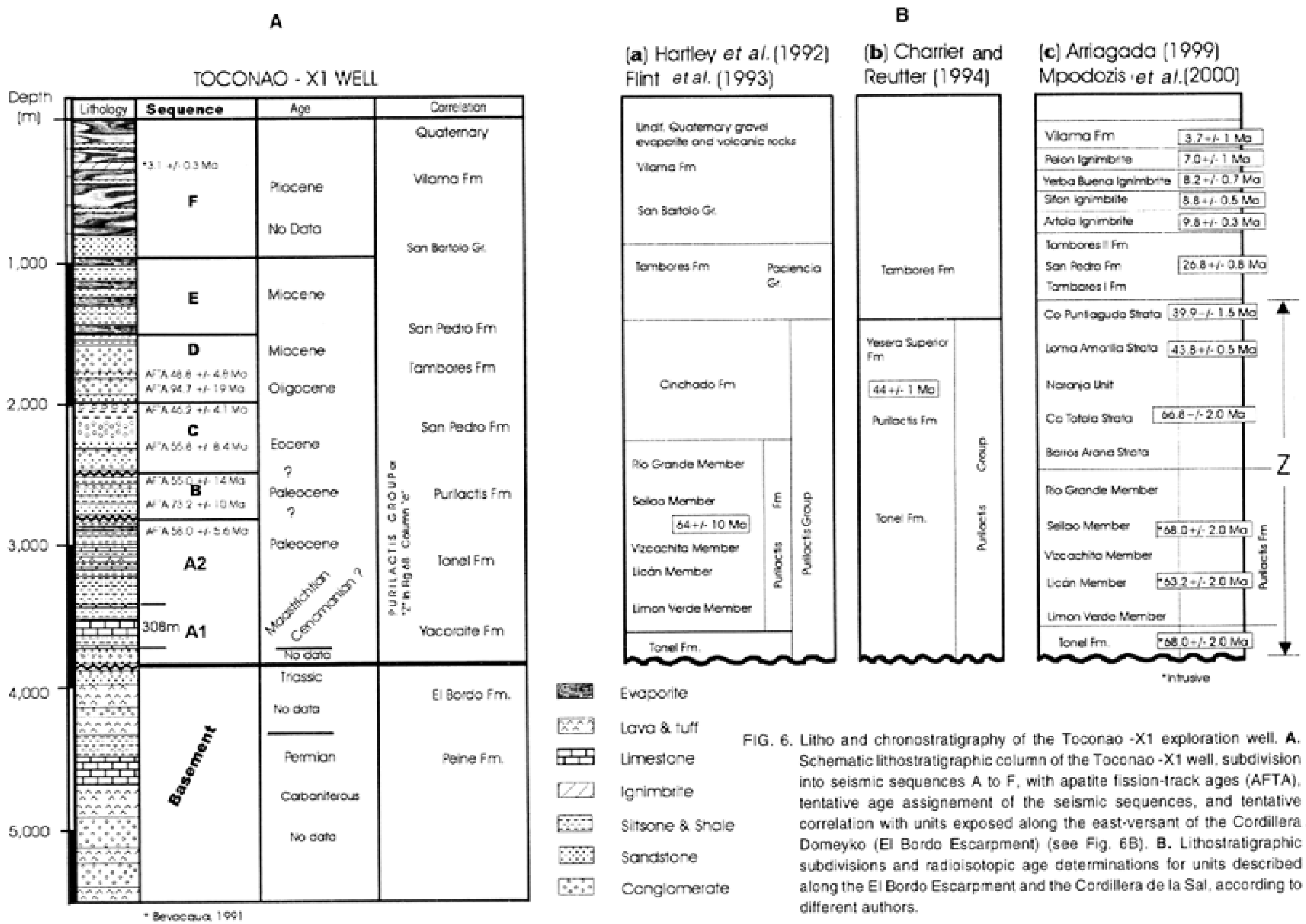


FIG. 6. Litho and chronostratigraphy of the Toconao -X1 exploration well. **A.** Schematic lithostratigraphic column of the Toconao -X1 well, subdivision into seismic sequences A to F, with apatite fission-track ages (AFTA), tentative age assignement of the seismic sequences, and tentative correlation with units exposed along the east-versant of the Cordillera Domeyko (El Bordo Escarpment) (see Fig. 6B). **B.** Lithostratigraphic subdivisions and radioisotopic age determinations for units described along the El Bordo Escarpment and the Cordillera de la Sal, according to different authors.

SEQUENCE A2

Sequence A2 is composed of a parallel fill system, marked by generally horizontal stratification that appears to onlap Sequence A1 (Fig. 7). It is formed of red siliciclastic beds, predominantly claystone to siltstone, with minor sandstone intercalations. The presence of glauconite grains in these deposits and the facies association suggests that this sequence was deposited in an estuarine lagoonal environment.

The top of this sequence is defined by an unconformity where the sequence is partially eroded on the crest of folds (Figs. 4, 5).

Fission-track analysis on apatite has been applied to two representative sandstone borehole samples from the top of this sequence. The fission-track central ages obtained from sandstone clasts range from 48.5±6.5 Ma to 58.0±5.6 Ma.

This sequence has a maximum thickness in the southern part of the basin, to the east of Cordón de Lila. It is likely that in that area it is older than farther north.

SEQUENCE B

Low amplitude discontinuous reflectors form sequence B. It contains predominately red-brown volcaniclastic continental sandstones with scattered volcaniclastic conglomeratic beds. This interval is considerably thinner over the crests of the major anticlines where it may be partly a condensed sequence or partly absent (Figs. 4, 5). Sequence B onlaps from the north, east and west the top surface of Sequence A. The characteristic stratal thinning on both anticline limbs indicates that this sequence was deposited as a syn-tectonic unit within the space generated by the first compressional deformation registered in the basin, which is evidenced by the mentioned anticlines. No diagnostic fauna has been found in this unit.

The apatite fission-track age obtained from sandstone clasts of this sequence is 55.0±14 Ma

To the east, Sequences A and B were truncated by erosion accompanying westward tilting prior to accumulation of Sequence C (Figs. 5, 7).

SEQUENCE C

Sequence C is made up of lower and high amplitude seismic facies exhibiting a predominantly parallel onlap fill configuration. Sequence C shows a westwards thickening and onlapped a west and north facing topographic slope formed by the upper surface of Sequence B. This geometry reveals that the basin space had an asymmetric shape, and that the main source of sediments was located to the west.

This unit gradually coarsens upward from multi-coloured sandstone with frequent interbeds of conglomerate and claystone to a reddish volcanic conglomerate with minor sandstone and claystone. The age of this sequence is very tenuously constrained and may be subject to alternative interpretations. A palynomorph assemblage found in it is identical to the one collected in the overlying section, giving only a broad Cretaceous to Cenozoic undifferentiated age.

The fission-track central ages obtained from sandstone clasts in this sequence range from 46.2±4.1 Ma to 55.8±8.4 Ma.

SEQUENCE D

The top of sequence D is clearly defined by a strong change in the acoustic impedance due to the presence of a horizon described in the logs as 'tuffaceous level', which may be interpreted as an ignimbritic intercalation. In the western side of the basin, Sequence D onlaps a west and northwest facing topographic slope formed by the upper surface of Sequence C. To the east it downlaps above Sequence C (Fig. 5). This unit is formed by at least three coarsening upward sequences, which according to the log description, varies from red-brown sandstone with frequent interbeds of claystone, to volcanic conglomerate with minor sandstone.

No diagnostic fauna has been found in this unit. However, a lithological correlation suggests that it could be equivalent to either the Paciencia Group (San Pedro Formation) or the underlying Tambores Formation (Fig. 6).

SEQUENCE E

On the seismic data Sequence E is formed by high amplitude, continuous horizons, showing eastwards thickening. In the entire set of data Sequence E represents horizontal stratigraphy.

In the centre of the basin Sequence E is formed predominantly by red-brown claystone with minor sandstone and anhydrite beds. Only sparse and non-diverse palynologic assemblages were found in this unit with an age range of Albian-Cenomanian and possibly Oligocene and Miocene, leading to a broad Cenozoic/Cretaceous undifferentiated age. The top of this unit is clearly defined by an unconformity with a strong change in the acoustic impedance due to the change on the depositional system passing to a hypersaline environment (Fig. 3). The general geometry of this unit indicates that accommodation space increased to the west.

SEQUENCE F

This sequence is formed predominantly by evaporitic deposits, mostly halite, with a zone of interbedded shale or claystone and halite between 480 and 624 m. Scarce continental Ostracods were identified as Pleistocene-Pliocene. Near the eastern margin of the salar, ignimbrite interbeds recognised by seismic character and intersected in SQM boreholes, was dated in 3.1±0.3 Ma at 356 m deep (Bevacqua, 1991).

In the Llano de la Paciencia this sequence thins to the South, onlapping the top of Sequence E. The entire sequence is interpreted as deposited in a continental basin space with internal drainage. Depth to the base of the halite sequence serves as a structure contour map for a horizon approximately 5 million years in age (Jordan *et al.*, in press) and the deposition is continuing on the surface today.

From the seismic profiles and synthetic seismogram it is possible to identify eight sequences separated by unconformities, which indicate the activity of the basin at this time. Hidden beneath its uninterrupted flat surface is the 'Salar Fault System' (Fig. 2), known only through reflection seismic studies. This fault system has been active during the Pliocene through Holocene and controlled facies distribution during the Cenozoic and probably during Cretaceous.

CORRELATION BETWEEN THE STRATIGRAPHY DERIVED FROM THE TOCONAO -X1 WELL AND THE OUTCROPS WEST OF THE BASIN

Based on the previous description of sequences and published information from the east versant of the Cordillera Domeyko (El Bordo Escarpment), the authors intent next to correlate the stratigraphy derived from the Toconao -X1 well and the outcrops that surround the basin (see Fig. 6).

Sequence A, which is composed of fine grained and evaporitic sediments, and is developed immediately above the basement units, is correlated with the Tonel Formation. Marine calcareous intercalations may correspond to the Yacoraite Formation facies, known further east in the Puna (Donato and Vergani, 1987) and the Eastern Cordillera (Salfity *et al.*, 1985). Sequence B is probably equivalent to the upper coarser part, with volcanic intercalations, of the Tonel Formation (*sensu* Charrier and Reutter, 1994), or to the Purilactis Formation in the sense of Hartley *et al.* (1992) and Flint *et al.* (1993), or the Purilactis Formation plus the Totola Strata of Arriagada (1999) (see Fig. 6B). The sandstone and conglomeratic Sequence C is tentatively correlated with the coarse sandstone and conglomeratic deposits exposed along the El Bordo Escarpment, that is, Cinchado Formation of Ramírez and Gardeweg (1982), Hartley *et al.* (1992), and Flint *et al.* (1993), or the Purilactis Formation of Charrier and Reutter (1994), or the Naranja Unit, and Loma Amarilla and Cerro Puntiagudo Strata defined by Arriagada (1999) (Fig. 6B). Sequence D, which is unconformably deposited over the underlying sequence (C), could be an equivalent of the Tambores Formation. Sequence E, which is a red-brown, fine grained, detritic unit with evaporitic intercalations, may be related to the finer grained San Pedro Formation. The lower part of Sequence F, which is also evaporitic and contains possible ignimbritic intercalations, is tentatively correlated with the San Bartolo Group, composed by detritic deposits with several ignimbritic intercalations (see Fig. 6B, column c), whereas the upper part is correlated to the Vilama Formation. The uppermost, mainly evaporitic deposits cut by Toconao -X1 well correspond to Quaternary gravels, sandstones and evaporitic deposits.

APATITE FISSION TRACK AGES AND PROVENANCE

Fission-track analysis on apatite is a useful chronological technique to discriminate the sediment provenance and better constrain basin evolution (*e.g.*, Thomson, 1994). Apatite fission track dating has been applied to representative sandstone samples from the top of Sequence D down to the bottom of the well at 5,200 m deep. As indicated above, apatite fission track ages of the different dated sequences range from 38.1±4.7 Ma to 94.7±19.2 Ma, and there is a gradual decrease in apatite fission-track age with increasing depth in the well (D.C. Arne and G. Li)[2].

Fission tracks on apatite crystals from depths > 2.5 km have been partially and strongly annealed, and therefore, do not provide information on the provenance of the sediments. Whereas shallower samples, at present depth of less than 2.5 km, and present-day temperature of less than 80°C still yield apatite fission track ages inherited from their pre-depositional history.

Deposits located between 1.5 and 2.5 km deep, that is, from top to bottom, sequences F, E, D, and C, contain sedimentary components that came from a number of sources, including 70-90 Ma old rocks. It is interpreted that these sediments have been derived from the uplifted flanks proximal to the basin. Therefore, apatite fission-track data provide evidence in support of an early relationship between thrusting and sedimentation in this basin; at least since the Eocene, which is the age assigned to the deposits at 2,500 m deep in the Toconao -X1 well (Fig. 6A).

Andriessen and Reutter (1994) applied fission track analysis to the crystalline rocks located in the Cordillera Domeyko (Pampa Elvira, Cerro Quimal) and in the Cordón de Lila. Interpretation of these data reveal that the crystalline basement rocks of Cordillera Domeyko, on the western side of the basin, were subject to a phase of increased cooling rates related to an accelerated denudation during the earliest Cenozoic, around 60 Ma ago. The Cordón de Lila, in the southern part of the basin, experienced a similar event around 40 Ma ago. These cooling events have been interpreted as the result of uplift related exhumation, and the authors interpret this uplift as an indication of the activity of the here described basement thrust-faults at that time.

BASEMENT-COVER INTERACTIONS

Integration of the different structural styles observed during the analysis of the seismic lines leads to the general conclusion that the mechanisms of deformation that took place in the Salar de Atacama is primarily a west-vergent thrust-system. Shortening in the basement was transmitted to the overlying deposits, or cover, categorised here as basement-cover interactions. In the Salar de Atacama Basin, these basement-cover interactions occur in three tectonic styles: basement-involved inverted faulting, basement-involved thrusting, and propagation/detachment folding.

BASEMENT-INVOLVED INVERTED FAULTING

In collisional mountain belts, where shortening and uplift are most intense, the reactivation of pre-existing fault systems has been recognised as an extremely important control on the structural style of thrust belts (Cooper and Williams, 1989; Buchanan and Buchanan, 1995). Depending on stress orientation a fault plane can be active during extension and during compression.

The term 'inversion' is used to describe regions which have experienced a reversal in uplift or subsidence, this is, areas which have changed from being regions of subsidence to regions of uplift, or viceversa. An area that has changed from subsidence to uplift is considered to have been affected by 'positive inversion', whereas an area which has changed from uplift to subsidence has undergone 'negative inversion' (Harding, 1983; Coward, 1994, 1996).

In many places along the Andes it has been demonstrated that during the Cenozoic this mountain range experienced a positive inversion caused by compression and uplift of the Mesozoic marine back-arc basins developed along the western margin

[2] 1994. Apatite Fission Track Analysis. Samples from the Toconao -X1 well and outcrops. Internal Report (Unpublished),. *Dalhousie University Fission Track Laboratory-Empresa Nacional del Petróleo*, 41 p.

of South America (Mpodozis and Ramos, 1989; Charrier and Muñoz, 1994). Inversion affected also the sub-Andean basins (Uliana *et al.*, 1995; Cristallini *et al.*, 1997; Muñoz *et al.*, 1997).

As will be shown in this article, positive inversion considerably contributed to the deformation and the space generation that the authors observe in the seismic profiles of the Salar de Atacama Basin. During the evolution of this basin two major causes of space generation were recognized: extension, and contraction. Extension occurred first and was followed by several episodes of contraction.

STAGE I: EXTENSION

Figure 7 is a seismic line across the basin that shows two preserved and partially inverted half grabens, which are the remaining evidence of space generated first by extension. F1 and F2 growth-faults characteristically have stratigraphic sequences that are thicker on the hangingwall block than the equivalent sequences on the footwall block. These half grabens can be correlated with a late episode of the major extension event known in southwestern Bolivia and northwestern Argentina, that began in the Early Cretaceous and continued until the Cenomanian (Salfity *et al.*, 1985, 1993). According to the evidence provided by the studied seismic lines, the sedimentation record in the Salar de Atacama begins with marine and continental deposits from a first tectonic phase of extension, Stage I (Sequence A) of basin infill.

STAGE II CONTRACTION (POSITIVE INVERSION)

The central part of the seismic line in figure 7 shows two reverse west dipping faults (*F1* and *F2*). The probably Late Cretaceous sediments of Sequence A clearly thicken eastwards, and form two asymmetric anticlines, one of them drilled by the Toconao -X1 well (Fig. 7b). In *F2* the high-level rocks show net contraction, whereas the deeper-level rocks show net extension. Between the two zones there is a point of zero net displacement (null point) which is not clear in *F1*. From SP 675 to SP 550 Sequence A1 thickens to the east, filling the space generated by the half graben bounded by *F2*. Tectonic inversion leaded to a reversal in stratigraphic separation down the dip of the fault. In the upper levels the net displacement is one of reverse fault geometry or compressive folding.

The inversion ratio (Ri), defined as the ratio of contractional to extentional displacement, can be calculated from:

$$Ri = dc/dh = 1 - de/dh$$

Where: *dh* = thickness of the syn-rift sequence, *dc*= thichness syn-rift sequence in contraction (above null point) and *de* the thickness of the syn-rift sequence below the null point (Williams *et al.*, 1989). In this particular case the half-graben located in the western side of the seismic line has a Ri = 0.13, and the thickness of the syn-rift sequence in contraction is of the order of 330 m.

Accordingly, it is possible to deduce the existence in the Salar de Atacama Basin of an asymmetric rift, contemporaneous with Sequence A, with west dipping extensional faults. The existing faults are, therefore, compound structures that were inverted. Inspection of the limbs of the folds reveals a stratal configuration which is dominated by divergent onlap. This divergent onlap can be seen at (1) and (2) providing evidence that reverse movement began late in Sequence A2 (?) and the main activity took place during Sequence B, in the early stage of basin evolution. Intra-basin thrust systems and basin infill coexisted from the Latest Cretaceous or Early Paleocene, facilitated by the existence of extensional faults. In addition, the hanging wall has been uplifted and eroded at the top producing a relief that controls local sediment supply and deposition of Sequence B.

BASEMENT-INVOLVED THRUSTING

Contractional fault systems where deformation involves the basement are termed 'thick-skinned' thrust systems. In this situation, the thrust faults are commonly steep and do not detach along shallow upper crustal detachments, but penetrate to the middle crust and beyond (McClay and Buchanan, 1992).

It is particularly relevant for this paper to analyse the structural style in those areas of the basin where the basement crops out. It is common in the Chilean literature to find descriptions of structures with the basement involved under an extensional regime (*i.e.*, Flint *et al.*, 1993). However, detailed kinematic field-based analyses or seismic analyses generally

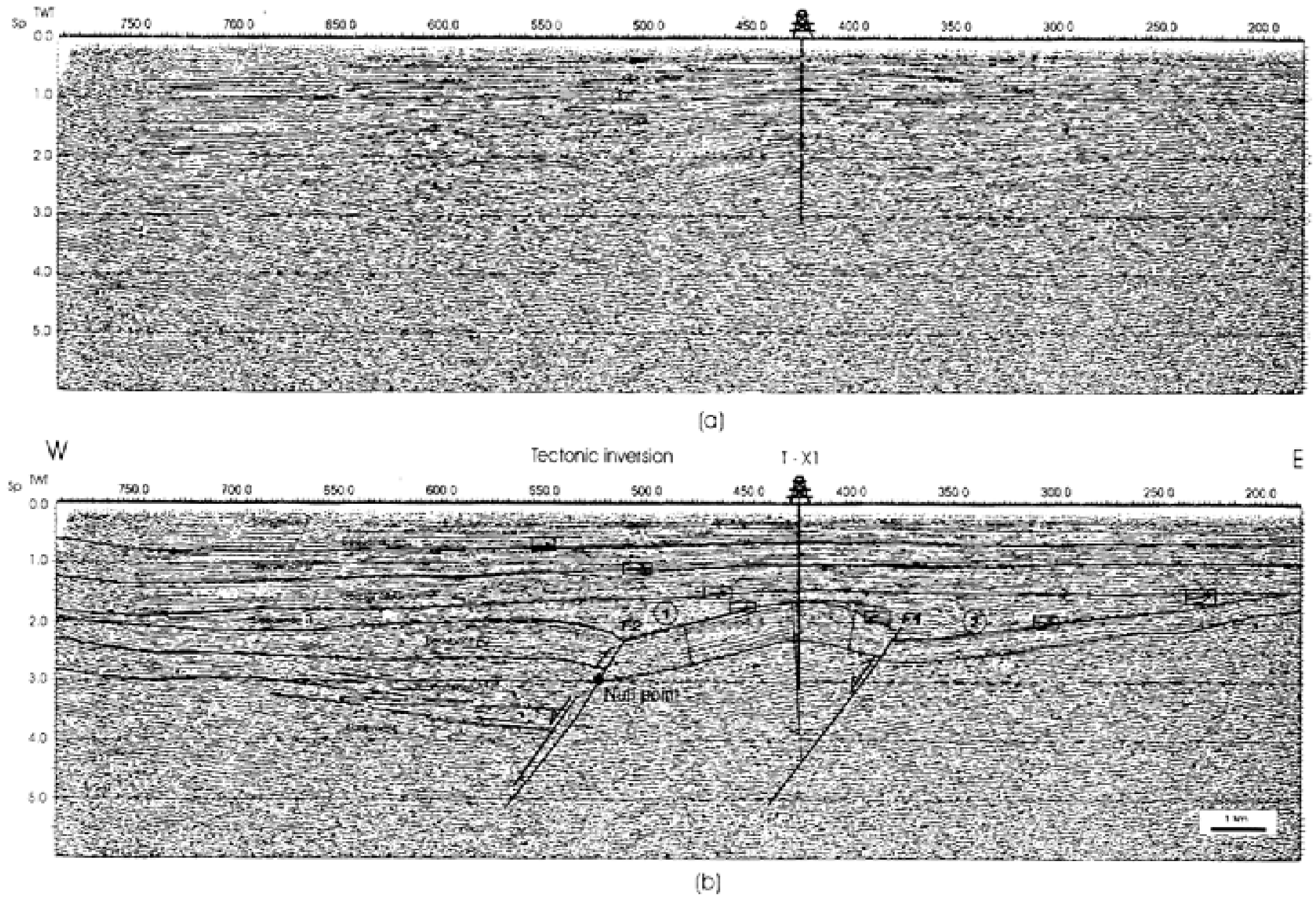


FIG. 7. Seismic time section through the Salar de Atacama Basin. **(a)** Uninterpreted migrated seismic reflection profile; **(b)** Interpreted seismic section showing the variation in stratigraphic separation with depth associated with inversion of normal faults. Note the two degree of inversion and that the inversion is coeval in each half-graben. Note the onlaps and thickening of the sedimentary package of sequences A1 and B. Vertical scale in second (two-way travel time). Horizontal scale approximately equal to vertical scale.

reveal that, what on the surface may look like an extensional fault, at depth appears to be a high angle thrust.

A number of models for the formation of basement structures has been proposed (Fig. 8): the drape or forced-fold model, in which folds are related to vertical uplift along steeply dipping extensional faults (Fig. 8B). This model is the result of rifting, being the Gulf of Suez the best-exposed example in the world. The upthrust model, which invokes uplift on faults that originate as vertical or high-angle faults in the basement, but change to shallower dipping geometries in the cover units (Fig. 8C), and thrust geometries, which interpret the structures as forming primarily by folding and thrusting along single or multiple low angle reverse faults (Fig. 8D) (Mitra and Mount, 1998). Based on the nature of basement involvement, Mitra and Mount (1998) proposed two main end members with the basement faulted along a single plane or internally deformed by multiple branching faults.

In the study region, the basement is well exposed in the Cordón de Lila, at the southern part of the Salar de Atacama (Fig. 2). This ridge is an upthrusted high block of basement that interacted with the sedimentary cover during basin evolution. At a regional scale, the Cordón de Lila high can be interpreted as an asymmetric, north plunging anticline bordered to the East by one of the basement faults of the 'Salar Fault System' (SFS, Jordan *et al.*, in prep.). Its geometry is constrained by seismic line 1g16b (Fig. 9a) and by geologic maps (see Ramírez and Gardeweg, 1982; Niemeyer, 1984; Reutter *et al*, 1994). Seismic sections show that deformation zones within the sedimentary cover correspond to gently dipping frontlimbs and backlimbs, related to synclinal and anticlinal bends in the master fault respectively, that do not dissipate significant fault slip (Fig. 9). The interpretation of the seismic line (Fig. 9b) shows that thrusting within the basement by a high angle west dipping master fault resulted also in thrusting of the sedimentary cover. This upward movement of the basement and its cover caused abundant syn-tectonic deposits (*e.g.*, Sequence C), which cover the tip of the fault (Sequence F). To the north, this fault forms part of the Salar Fault System, which has been active during the last 5 million years. From the seismic section it seems that the fault slip in the basement is accommodated in the cover by a triangular-shaped, gently upwards widening deformation zone in the forelimb. The cover sequence is mechanically homogeneous and welded to the basement and deformation occurs by progressive growth of a triangle deformation zone. The structural relief of the basement along this line, that is up-thrusted blocks west of the fault and down-slipped blocks east of it, and the absence of major faults penetrating the cover up to the surface, indicate that the Cordón de Lila structure is a large basement fault-propagation fold.

The west-dipping fault zone observed in the seismic line affects all units up to the top of Sequence E. The geometry of the contact between sequence B and C (Fig. 9b) indicates that this fault zone was active during the Paleogene. Also displacements of contacts between Sequences B-C, C-D and D-E demonstrate a major episode of contractional tectonics during the Middle Miocene and a small amount of thrusting during Pliocene-Pleistocene. Therefore, it represents a major, long-lived intrabasinal structure, formed by near vertical uplift of the basement.

According to Jordan *et al.* (in press), this segment of the Salar Fault System has been active during the Quaternary and should be considered as a potential earthquake generating zone. Through a restoration of the structure at the Upper Cretaceous level it may be possible to date its activity back to the Middle and Late Cretaceous. Therefore, this basement involved fault has been active, at least, during 80 Ma (?), being probably one of the 'longest active faults' reported for the southern Central Andes in Chile, with an offset in the order of 6,000 m.

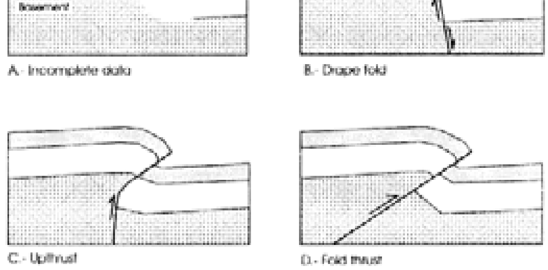
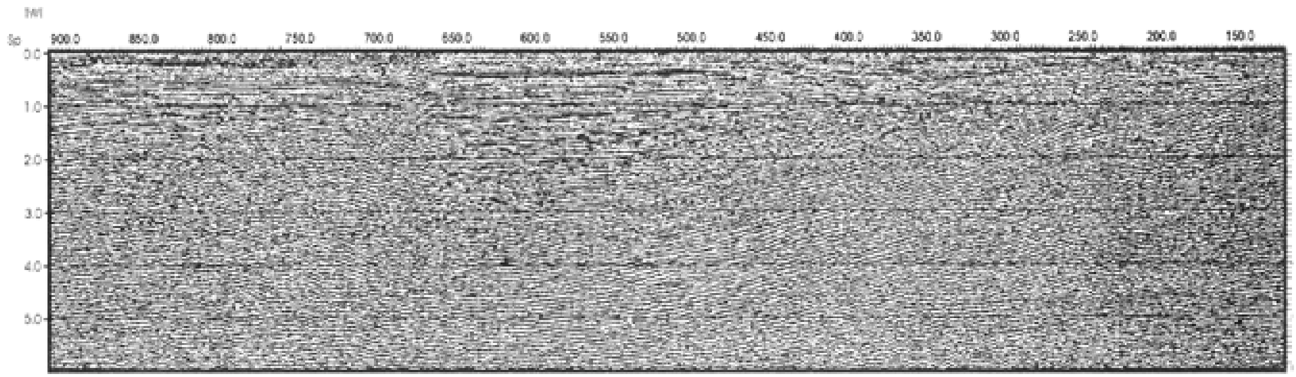
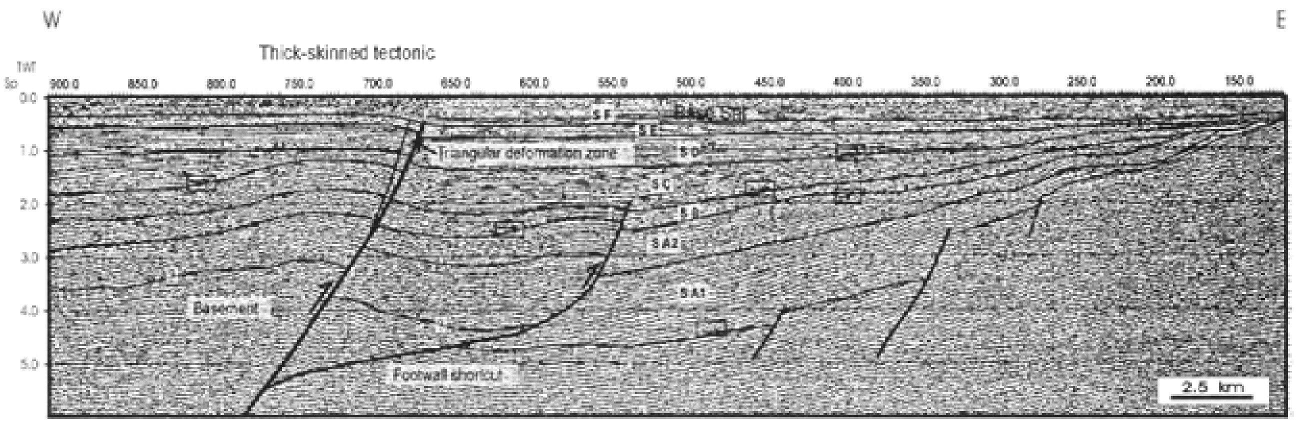


FIG. 8. Main models for the origin of foreland basement-involved structures, showing different alternative to interpret an incomplete set of data (A) on basement structures (Mitra and Mount, 1998).



(a)



(b)

FIG. 9. (a) Uninterpreted migrated seismic reflection profile in the southern half of the basin. Vertical scale in second (two-way travel time). (b) Interpreted seismic line showing in the interaction between a high angle basement fault and the transference of shortening into the sedimentary cover. Note the activity of the shortcut during sequence C. The cover behaves homogeneus and welded to the basement.

Along the El Bordo Escarpment and also along the Cordillera de la Sal Fault System (Fig. 2), characteristic features of the structure developed in the basement include short cuts, a moderately dipping propagating fault and a gently dipping front limb and back limb (Figs. 2, 9).

In these cases a thick basement section is involved in the thrusting, the thrusting faults are steep and may have not detached along shallow upper crustal levels, but might have penetrated to the middle crust and beyond.

FAULT PROPAGATION-DETACHMENT FOLDING

Thrust deformation, involving well-layered, relatively thin stratigraphic sections (less than 10 kilometres) is termed 'thin skinned' thrusting. Traditionally, three types of folds are recognised to be associated with thin-skinned fold and thrust belts: fault-bend folding, fault- propagation folding and detachment folding (Jamison, 1987).

The area where thin-skinned deformation is best represented is in the southern part of the Cordillera de la Sal, in the western side of the basin. In outcrop, the fold geometries structures along the Cordillera de la Sal comprise closed to open, elongate NNE-trending, doubly plunging anticlines that have a southeast sense of overturning. The deformation here is controlled by the mechanical stratigraphy of the basin sequence.

At the western side of the basin, displacement associated with basement thrusts along the El Bordo escarpment was transferred to the sedimentary cover, following three evaporitic horizons. In the southern area, in front of a basement-cored anticline (Cerro Negro area), the displacement associated with thrusting was mainly transferred to the sedimentary cover. The detachment follows a level located within the Cretaceous sequence, perhaps equivalent to the evaporitic layers of the Tonel Formation (Fig. 10; Muñoz *et al.*, 2000) or the same anhydrite layer interbedded with claystone, cut by the well at the top of Sequence A1 (Fig. 6).

To the north, probably due to the pinch-out of the Cretaceous evaporitic layer and the increasing thickness of halite ductile layers in sequences E and F, the displacement of the basement thrust was transferred to detachment levels in the Oligocene-Miocene and Pliocene sequences E and F. Above these detachments the sequences were deformed in systems of detachment folds. In the northern part of Cordillera de la Sal, salt layers have been remobilized forming small diapirs that folded and breached the overlying sequence.

Figure 10 corresponds to an area located in the southern part of the Cordillera de la Sal, in which the transference of displacement to the cover occurred along a deeper incompetent layer, here located at approximately 2,500 m deep.

COEXISTENCE OF THICK AND THIN-SKINNED TECTONIC STYLES

A common observation for the number of basement-involved structures in this area is that they are characterised by significant structural relief associated with movement on a basement master fault(s). The basement thrusts cut into the sedimentary cover directly to the surface (Cordón the Lila) or part of the displacement is transferred into different detachment levels in the cover (South of Cordillera de la Sal, Fig. 10).

In the northern area of the basin, the displacement of the basement thrust, which marks the eastern border of the Cordillera de la Sal, was partially transferred to a detachment level in the Oligocene-Miocene evaporitic sequence E (San Pedro Formation) and a salt layer in Sequence F (Fig. 11). At the western side of figure 11, the movement of the hanging-wall over these beds resulted in the development of a gently-dipping backlimb, and the cover is not deformed independently. It is seems that in this case slip is dissipated on the master fault within a triangular deformation zone in the cover. However, in the same section and in a second basement thrust the shortening is transferred to the cover in a system of propagation and detachment folds and the master fault does not develop a triangular deformation zone. Therefore, the model obtained here implies that the basement is deformed primarily by movement on a major fault and at the same time, the deformation can be dissipated in the cover in a triangular zone, or has been propagated into the cover like a thin-skinned system. This cross-section allows to link the basement thrust to the corresponding frontal thin-skinned structures revealing the coexistence of these two structural styles.

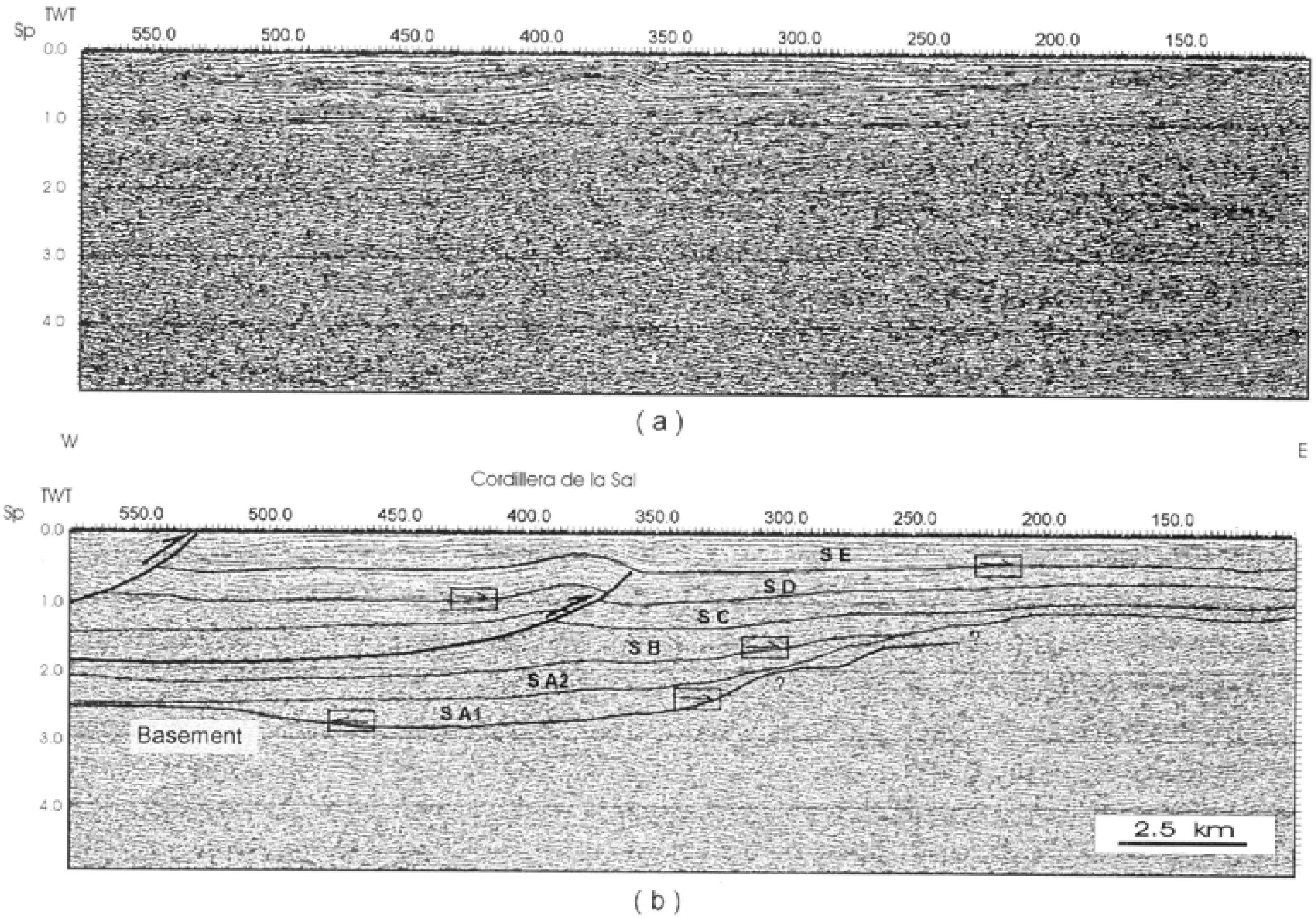


FIG. 10. (a) Uninterpreted migrated seismic reflection profile in the southeastern half of the basin. Vertical scale in second (two-way travel time). Horizontal scale approximately equal to vertical scale. (b) Interpreted seismic line showing the geometry of the deformation in the Cordillera de la Sal. In this area part of the shortening is transferred to the sedimentary cover, which is deformed in a system of propagation-detachment faults. The detachment is located at approximately 2.500 m depth, in the Purilactis Group.

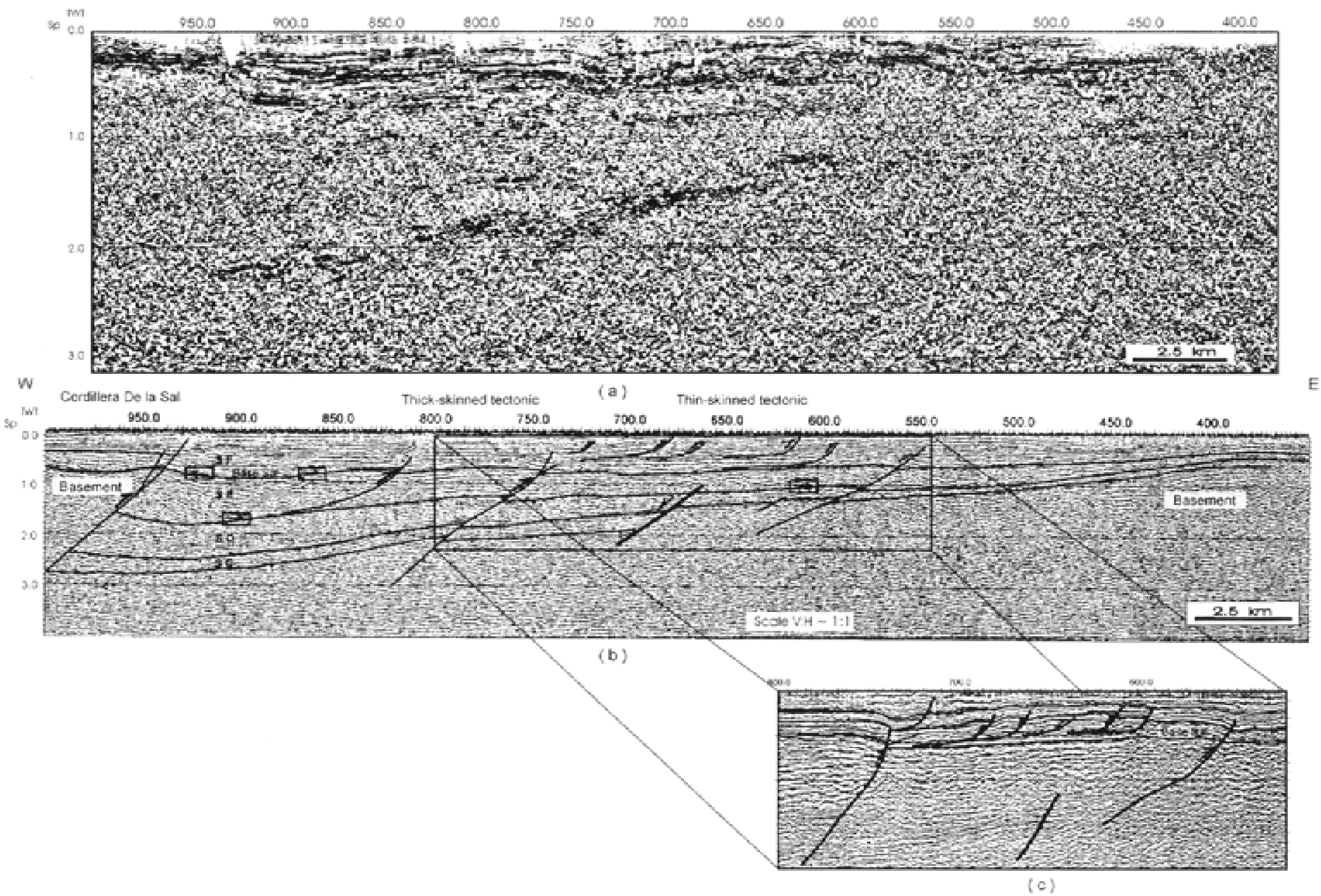


FIG. 11. Cross-section showing the coexistence of two types of structural styles. (a) Uninterpreted migrated seismic reflection profile in the northern half of the basin. Vertical scale in second (two-way travel time). (b) Interpreted seismic line showing in the western side how the basement deforms by a major high angle fault, forming the eastern side of Cordillera de la Sal. In the centre the cover detach by a ductile unit (San Pedro Fm?) that accommodate the basement slip. (c) Detail showing the relationship between a basement fault and detachments in the sedimentary cover.

STRUCTURAL MODEL

Figure 12b is based on the interpretation of seismic line 1g022 and on field data from the southern part of the basin. This section summarises the available information on which the authors base the regional model presented in this paper (Fig. 13). In this model, the authors integrate the development of the geological units present in this region (Cordillera Domeyko, Cordón de Lila, and Cordillera de la Sal) in association with the evolution of the Salar de Atacama Basin and establish a genetic link between structures that affect the basement and those affecting the cover.

This structural model proposes a long lasting interaction between the structures rooted in the basement and those developed in sedimentary cover, as a result of thick-skinned thrusting. In the study region, Late Mesozoic? and Cenozoic deformation was influenced by inversion during Andean contraction of pre-existing crustal heterogeneity associated with the Cretaceous rifting (Fig. 7b).

The Cordón de Lila is primarily controlled by a high angle fault system located at its east-side and developed in the Palaeozoic incompetent units (Fig. 6). The main high-angle fault dies out within a deformation triangle zone in the Upper Cenozoic, Sequence F. The exact nature of the deformation zone in the basement is not clear in the seismic line and could range from a single major fault, to a narrow deformation zone.

The Cordón de Lila high is the result of the activity of the Salar Fault System during a long period of time. This fault system, apart from uplifting the basement block, controlled the facies distribution on both sides of the height and exerted an important influence on the structural style of the cover. In particular, in the southern part of the Cordillera de la Sal fold belt where the thickening of Sequences D and E reduced the amount of folding in the cover. The Cordón de Lila block nucleated the deformation and, consequently, faulting and uplift absorbed most of the deformation. This east-verging basement-cored structure avoided the propagation of the deformation in the shallower horizons to the east of the Salar Fault System and the structural style remained thick skinned (Fig. 13a).

As the Cordón de Lila high decreases on throw to the north and the Oligocene-Miocene-Pliocene evaporite increases its thickness, deformation propagates eastwards by the offsetting of single detach that involved a relatively thin stratigraphic section. Farther north in the basin, the deformation in the basement has been transferred eastwards and in sequence to the cover (Fig. 12).

At the field scale, the transference of shortening produced a fold system with an en-echelon pattern along the Cordillera de la Sal. Clockwise block rotation in conjunction with transpressional deformation, as described by Mpodozis *et al.* (1993), and Arriagada *et al.* (1999), can probably be, at least partially, related to the transference of the contractional deformation here described.

The en-echelon pattern of the folds may be explained because the detached part of the cover underwent differential movement, which may have occurred because the detachment failed to propagate along a transition from evaporitic to an arenaceous facies. At the basin scale, even though the influence of the mechanical stratigraphy seems to have exerted a primary control on the location of the detachments, the influence of basement blocks played a more fundamental role on controlling the precise location of the structures.

In order to test the deformation mechanism of the sedimentary cover, and to validate the structural model presented here, one balanced regional cross section has been constructed (Fig 13). This balanced cross section was constructed using 2D Move software and applying the flexural-slip restoration method, preserving bed thickness and length of strata. In this restoration, beds were placed back into their depositional, pre-deformational position.

Figure 13b is a viable solution that proposed a geometry of the cover during the Early Cenozoic. In figure 13c the regional section has been restored to the Early Cenozoic-Late Cretaceous configuration. This section proposes that folding and thrusting started early during basin evolution and it can be dated back to the later Sequence A, Cretaceous or Early Paleocene.

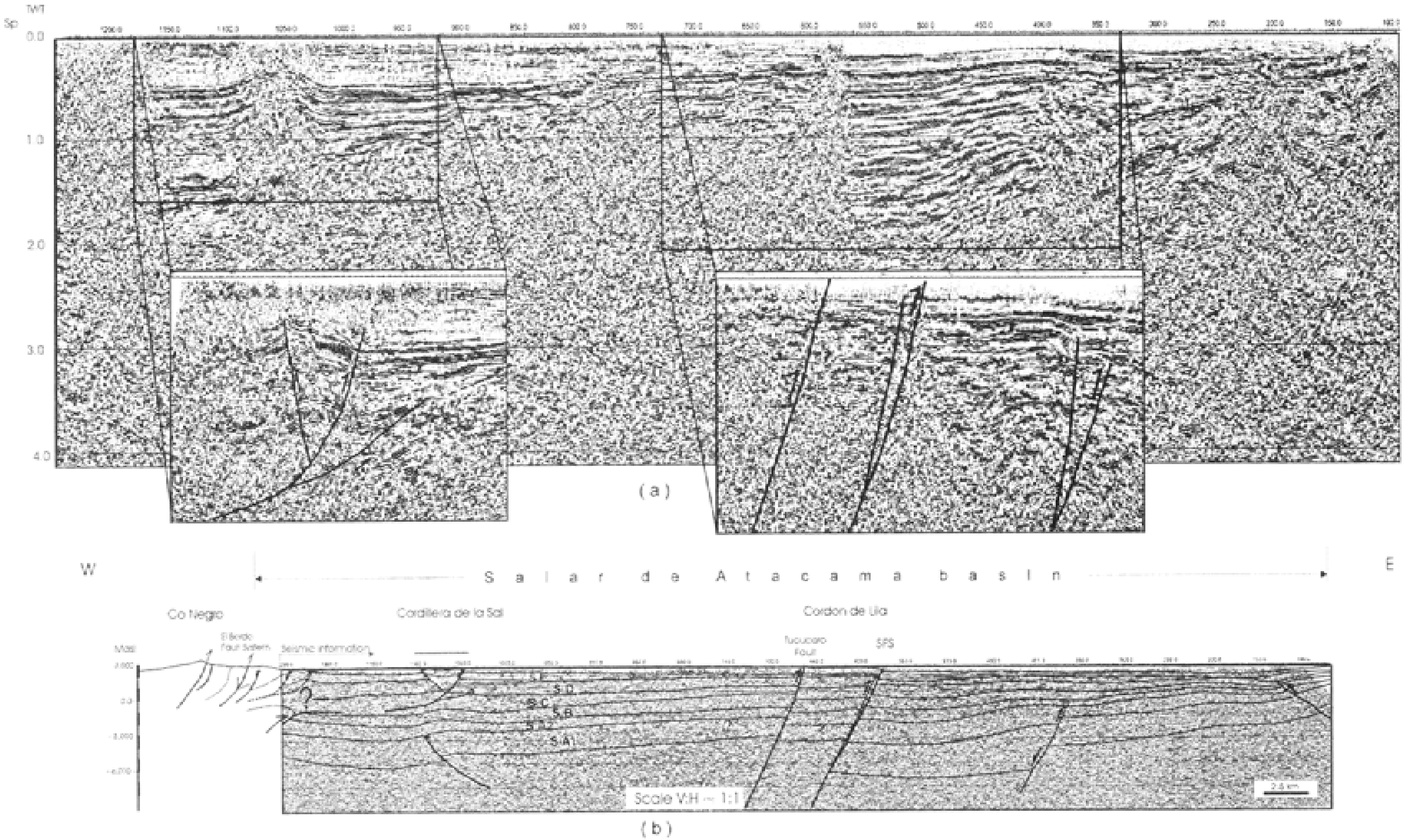


FIG. 12. a) Uninterpreted migrated seismic reflection profile in the southern half of the basin. Vertical scale in seconds (two-way travel time). (b) Interpreted seismic line showing the geometry of the deformation in the El Bordo Escarpment, Cordillera de la Sal and Cordón de Lila. Horizontal scale approximately equal to vertical scale. Note that the basement deforms primarily by movement on major fault and as well as the downward propagation of a triangle deformation zone within the basement.

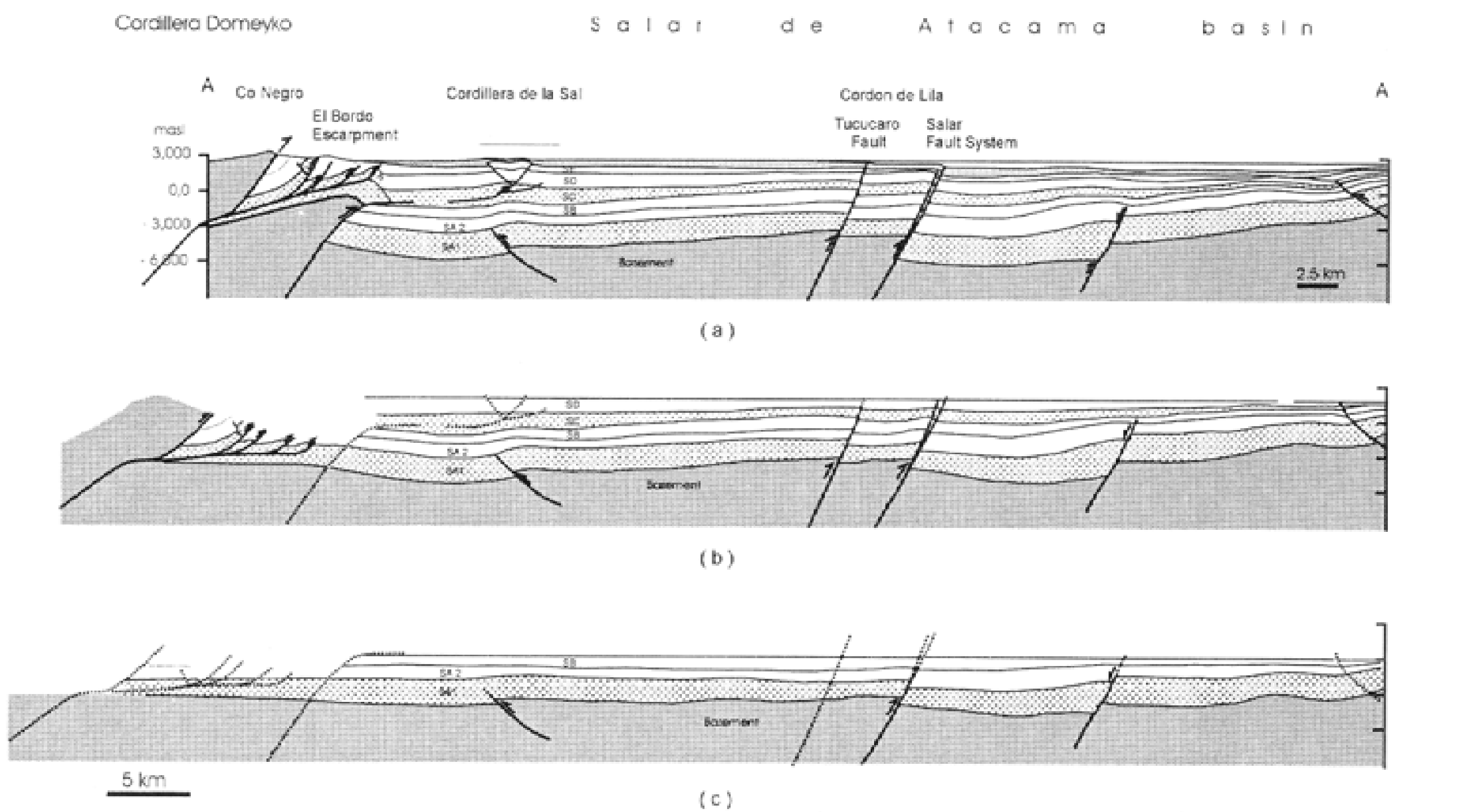


FIG. 13. (a) Cross section integrating interpretation from seismic (Fig 12) and geology of the Cordillera Domeyko in the Cerro Negro area. (b) Viable solution that proposes a geometry of the sedimentary cover during the Early Tertiary. (c) The regional section has been restored back to the Early Tertiary-Late Cretaceous. This section proposes that folding and thrusting started early during basin evolution and that it can be dated back to the Cretaceous.

The vertical displacement calculated at the Cerro Negro area is in the order of 7.5 km, and the calculated shortening of the sedimentary layers in this profile is about 5 km, concentrated mainly in the El Bordo Escarpment.

DISCUSSION AND CONCLUSIONS

As in many contractional provinces, the influence of older extensional fault systems and the mechanical stratigraphy were critical factors in defining the geometric style of deformation in the Salar de Atacama region.

The model presented here invokes both partial and full involvement of the basement through inversion of Cretaceous and possibly older extensional faults, basement involved faults, and accommodation in the cover, which has been taken up by thin-skinned folding and thrusting of a sequence detached above evaporitic levels. Normal faults developed in the extensional stage of the Salar de Atacama Basin were inverted several kilometres of vertical uplift during the Late Cretaceous and subsequent Cenozoic compression. Throughout the Cordillera de la Sal, deformation is controlled by the mechanical stratigraphy of the basin succession. In fact, where a thick sequence of evaporites exists in the northern and western part of the basin, the displacement is transferred directly to the cover.

As a consequence of the uplift of basement blocks forming the Cordillera Domeyko and of the eastward shortening in the thrust-front, sedimentation and space generation in the Salar de Atacama Basin was continuously modified. Continued uplifting of the Domeyko ridge by thrusting ensured a constant supply of sediments from an active source area, especially during Cenozoic. Syn-thrusting sedimentary sequences within the basin are locally controlled by anticline growth above a basement thrust fault. Progressive syn-thrusting unconformities with local erosional truncation are generated by continued anticline growth.

The stratigraphy obtained from Toconao -X1 and the reinterpretation of the seismic information show the record of the basin evolution and it relation with the surrounding geological units. This evolution resulted mainly from the following sequence of events: minor local subsidence during the Cretaceous rift phase, uplift of the Cordillera Domeyko in Cenozoic time, uplift of the Andes and space generation and, consequently, abundant sediment supply.

The increasing thickness of Sequences C, D and E towards the western side of the basin, on the margin next to the Cordillera Domeyko, and the geometric relationship between them reveal the effects of asymmetric space generated in front of the thrust system and the permanent tectonic activity during basin evolution. This feature may be attributed to the generation of accommodation space due to tectonic loading in that direction. This has induced previous authors to classify the Salar de Atacama basin as a foreland basin (see Muñoz *et al.*, 1989). However, retroarc foreland basins are large-scale, long-lived features hundreds of kilometres wide and thousands of kilometres long (Jordan, 1995) and are generally attributed to the enormous load exerted on the asthenosphere by a mountain range located at their rear side. Typically retroarc foreland basins are characterised by the presence of a considerable structural thickening of the upper crust.

Although the Cordillera Domeyko can be considered to represent a thrust belt with upper-crustal shortening, its narrow shape in cross section does not seem to be enough to produce a load capable of causing crustal flexural compensation. Therefore, generation of space by subsidence in this area remains an enigma.

In the restored structural model presented here the basement thrusts in the Cordón de Lila have steep ramp geometry and cut into the sedimentary cover directly to the surface. There are no bedding-parallel detachments present in the sedimentary cover; therefore the thick-skinned tectonism has inhibited the development of a thin-skinned deformation. The westernmost basement-cored anticline (Cerro Negro, Fig. 12) has been resolved by a ramp-flat geometry in which the ramp segment cut stratigraphically upwards and the displacement was transferred to a detachment level located in lower part of the sequence that form the sedimentary sequence of the basin.

In the northern part of the basin the deformation between the Cordillera Domeyko and Cordillera de la Sal is characterised, first, by stacking in the cover and then, by the eastward propagation of thrusting, which is controlled by the facies distribution and basin geometry.

This is a particular area of the Central Andes that can be seen as an example in which a combination of thick-skinned and thin-skinned tectonics is the essential model of thrusting.

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