Journal of South American Earth Sciences 53 (2014) 1–19

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Tectonic repetitions of the Early Cretaceous Agrio Formation in the Chos Malal fold-and-thrust belt, Neuquén Basin, Argentina: Geometry, kinematics and structural implications for Andean building

M. Turienzo*, N. Sánchez, L. Dimieri, F. Lebinson, V. Araujo

Instituto Geológico del Sur (INGEOSUR), CONICET, Departamento de Geología, Universidad Nacional del Sur, San Juan 670, 8000 Bahía Blanca, Argentina

ARTICLE INFO

Article history:
Received 20 December 2013
Accepted 12 April 2014

Keywords:
Andean tectonics
Neuquén Basin
Thin-skinned structures
Kinematics
Forward modeling

ABSTRACT

The Neuquén Basin, developed in a retroarc setting in the central-west of Argentina, contains more than 6000 m of Mesozoic marine and continental sedimentary rocks. These rocks were deformed during the Andean orogeny leading to several thick and thin-skinned fold-and-thrust belts. The Early Cretaceous Agrio Formation is composed by a thick marine succession predominantly of black shales in which highlights a thin fluvial-aeolian sandy interval named Avilé Member. The Avilé Member, one of the most important hydrocarbon reservoirs of the Neuquén Basin, constitutes an excellent structural marker. At the Chos Malal fold-and-thrust belt, the strong mechanical anisotropy given by the contrasting lithology of the Avilé Member within the Agrio Formation favored the location of detachments along the shales and ramps affecting the sandstones during the Andean compression. Detailed field mapping at the Chacay Melehue area allowed us to recognize tectonic repetitions of the Avilé Member, which form imbrications in the simplest case whereas in other places constitute a more complex combination of imbrications, including fault-bend folding that duplicates stratigraphic sequences and fault-propagation folding that deforms more intensely the duplicated units. Along three structural cross-sections we illustrate the geometry of these tectonic repetitions of the Agrio Formation, which in the northern area have an eastward-vergence and in the central and southern regions show a clear westward-vergence. A tear fault along the arroyo Chacay Melehue could explain this vergence change. Forward modeling of the structures at the central cross-section, where a backthrust system produced imbrication, duplication and folding of the Agrio Formation, allows us to propose a balanced kinematic reconstruction of this complex structure and to compare the features produced at different stages of the deformation sequence with field observations. Our kinematic interpretation shows that the tectonic repetitions of the Agrio Formation involve 3 km of shortening above a basal detachment within the lowermost black shales. Based on a regional balanced cross-section constructed from the basement-cored Cordillera del Viento anticlinorium toward the east, across the thin-skinned sector of the Chos Malal FTB, it is possible to connect the backthrust system with east-vergent fault-bend folds that involve the stratigraphic units below the Agrio Formation. Finally, we propose a regional structural model considering the Cordillera del Viento as a basement wedge related to a low angle Andean thrust that is inserted into the sedimentary cover producing structures of different order, which evidence a strong relationship between thick and thin-skinned structures during the Andean orogeny.

1. Introduction

The Neuquén Basin, one of the most important and well-studied petroliferous basins of Argentina, was developed in a retroarc setting due to the convergence of the Nazca and South American plates (Fig. 1a). In the last three decades profuse research and seismic exploration increased substantially the knowledge about the regional configuration, sequential stratigraphy and oil potential of this basin (Legarreta and Gulisano, 1989; Uliana et al., 1989;

* Corresponding author. Tel.: +54 (0)291 4595101x3061.
E-mail addresses: turienzo@uns.edu.ar, mmturienzo@hotmail.com (M. Turienzo), natalia.sanchez@uns.edu.ar (N. Sánchez), ldimieri@uns.edu.ar (L. Dimieri), fernando.lebinson@uns.edu.ar (F. Lebinson), vanesa.araujo@uns.edu.ar (V. Araujo).

http://dx.doi.org/10.1016/j.jsames.2014.04.004
0895-9811/

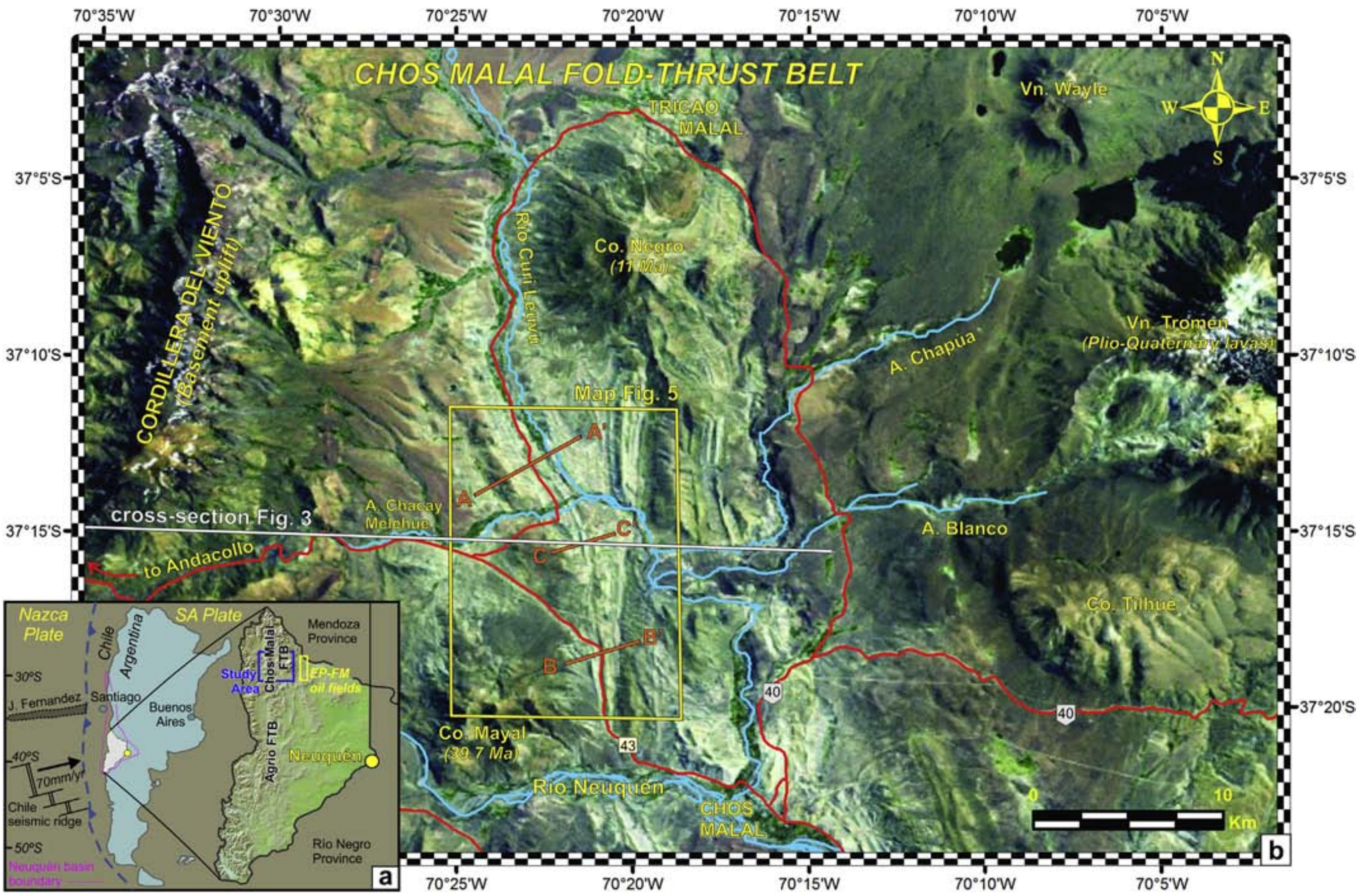


Fig. 1. a) Present tectonic setting of the Neuquén Basin at the central-west of Argentina. The Chos Malal fold-and-thrust belt develops in the north of the Neuquén Province. Important oil fields as El Portón and Filo Morado (EP-FM) are situated in the mountain front. b) Location of the study area in the Chos Malal fold-and-thrust belt, between the Cordillera del Viento and the Tromen volcano. The squared sector surrounding the confluence of the Río Curí Leuvú and the arroyo Cahacay Melehue correspond to the mapped area containing tectonic repetitions of the Early Cretaceous Agrio Formation. Ages of subvolcanic rocks are from Cobbold and Rossello (2003) at Cerro Mayal and from Gürer et al. (2012) at Cerro Negro.

Vergani et al., 1995; Franzese et al., 2003; Howell et al., 2005). Modern studies based on thermochronological, geophysical and field data propose changes in the angle of the subducted slab as a first order control in the tectonic evolution of the Neuquén Andes (Ramos and Folguera, 2005; Kay et al., 2006; Folguera and Ramos, 2011). From Late Cretaceous to recent times, the Andean orogeny deformed intensely the Mesozoic infill of the Neuquén Basin and its underlying basement. This deformation have generated the Agrio and Chos Malal fold-and-thrust belts (FTB) in the Neuquén Province (Fig. 1a) and the Malargüe and Aconcagua FTB in Mendoza Province, to the north of the study area. Specific works about the structural style and evolution of these Andean belts are abundant in the Agrio FTB (Zapata and Folguera, 2005; Zamora Valcarce et al., 2006a, 2007, 2009) and in the northernmost Malargüe FTB (Manceda and Figueroa, 1995; Dimieri, 1997; Giambiagi et al., 2008, 2009; Turienzo, 2010; Turienzo et al., 2012). On the contrary, most of the structural studies in the Chos Malal FTB consist of very regional cross-sections (Ramos and Barbieri, 1988; Both and Coward, 1996; Chaveau et al., 1996; Kozlowski et al., 1996, 1998; Cobbold et al., 1999; Cobbold and Rossello, 2003; Zapata et al., 1999; Folguera et al., 2007; Rojas Vera et al., 2014). In the last years, we started to map in detail the region of the Chos Malal FTB located between the Cordillera del Viento and the Tromen volcano (Fig. 1b). The purpose of this field work was to characterize geometrically the thin-skinned structures of the FTB and to evaluate its relationship with the basement uplift that forms the Cordillera del Viento (e.g. Sánchez et al., 2014). One of the best exposed Mesozoic units in this area is the Early Cretaceous Agrio Formation (Weaver, 1931), subdivided in three members: Pilmathué, Avilé and Agua de la Mula (Leanza et al., 2005). The Pilmathué and Agua de la Mula Members, mainly integrated by marine black shales, reach several hundred meters of thickness. The Avilé Member, represented by aeolian-fluvial sandstones with only a total thickness of approximately 50 m, lies between them. During our field work, in the region near the confluence of the Arroyo Chacay Melehue and the Río Curí Leuvú (Fig. 1b), we have recognized and measured several tectonics repetitions of the Agrio Formation, particularly observed as imbrications and duplicated beds of the Avilé Member. The first aim of this work is to examine the particular geometrical features of these structures and to consider their variations in the study area based on a detailed map and three structural cross-sections. The more complex structure was observed in the central cross-section, where a hinterland-vergent thrust system formed by three backthrusts produced a noticeable anticlinorium that we have denominated Chacay Melehue anticline. This structure involves imbrication and fault-related folding of the Agrio Formation. The second purpose of our study is to analyze the kinematic of this complex backthrust system using the non-commercial Fault-Fold-Forward software (Allmendinger, 2012) to generate a balanced sequential reconstruction of the

Chacay Melehue structures. Restoration of this complex structure allows us to estimate the shortening affecting the rocks overlying the black shales of the Pilmathué Member. Consequently, we can also interpret the existence of larger-scale structures transferring tectonic displacement above the basal detachment of the back-thrusts system. Moreover we elaborate a regional balanced structural cross-section and propose a structural model connecting thick and thin-skinned structures of the Chos Malal FTB along several flat-ramp-flat thrust trajectories in order to comprehend the temporal and spatial link between the repetitions of the Agrio Formation and the major structures affecting the lowermost sedimentary units and even the basement rocks.

2. Geological framework

2.1. Tectonic setting

The geological and structural configuration of the central-west side of Argentina, as in most of the Andean Cordillera, was produced by a complex evolution related to several tectonic, magmatic and accretionary processes occurred from Early Paleozoic to recent times (Ramos, 1999, 2010). The development of an active margin at the western border of Gondwana during Permian-Early Triassic produced noticeable mesosilicic and silicic volcano–plutonic complexes included within the Choiyoi Group (Llambías et al., 2003). This widespread magmatism took place after the Early Permian compressive San Rafael orogenic phase (Caminos and Azcuy, 1991). Then, these rocks were subjected to strong erosion during the Early to Middle Triassic, creating an undulated erosion surface known as Huarpican unconformity (Fig. 2) that resulted in the exposure of the plutons (Llambías et al., 2003, 2007; Leanza, 2009). From the Middle Triassic to the Early Jurassic, diverse volcanic and sedimentary sequences were accumulated in a series of subparallel half-grabens with alternating polarity recognized on seismic sections and well log (Legarreta and Gulisano, 1989; Manceda and Figueroa, 1995; Vergani et al., 1995). This sedimentation took place in a tectonic scenario dominated by continental extension and strike-slip movements (Franzese and Spalletti, 2001; Franzese et al., 2003). From Early Jurassic to Early Cretaceous, the development of a steeply dipping, active subduction zone and the associated magmatic arc along the western margin of Gondwana led to back-arc subsidence within the Neuquén Basin (Howell et al., 2005). This period of thermal subsidence locally accounts for more than 4000 m of the basin fill (Vergani et al., 1995), including most of the rocks that constitutes the petrolifeorus system of the Neuquén Basin (Fig. 2). Numerous structural, magmatic and stratigraphic data support a Late Cretaceous age for the beginning of Andean compression (Cobbold and Rossello, 2003; Ramos and Kay, 2006; Zamora Valcarce et al., 2006a, 2007; Tunik et al., 2010; Di Giulio et al., 2012; Mescua et al., 2013). This was probably related to the increasing of the convergence rate and the shallowing of the Benioff zone (Ramos, 1998; Ramos and Folguera, 2005), initiating a stage of foreland basin with a predominance of continental deposits (Fig. 2). Continued subduction during the Cenozoic was closely related to emplacement of arc magmatism, development of fold-thrust belts and molasic sedimentation in foreland basins ahead of the thrust front. These combined processes undoubtedly moulded the actual configuration of the Neuquén Andes, but a controversy exists about the prevailing tectonic regime during the Andean orogeny. Some authors argue that alternating periods of compression and extension were related to changes in the angle of the subducting slab, where shallowing stages of the Benioff zone produced foreland shifting of the arc magmatism and concomitant thrust-belt development, while stages of slab steepening generated retreats of the magmatic arc and Cenozoic extensional basins (Ramos and Folguera, 2005; Kay et al., 2006; Folguera et al., 2007; Folguera and Ramos, 2011; Folguera et al., 2012; Rojas Vera et al., 2014). On the other hand, a continued Aptian to recent compressional deformation is proposed (Cobbold and Rossello, 2003), with Cenozoic sediments accumulated in a compressional or transpressional foreland basin (Cobbold et al., 1999, 2008) and magmatism emplaced in a compressive tectonic setting (Galland et al., 2007; Gürer et al., 2012). Regardless of this debate, a broad consensus exists about the existence of a significant Miocene compressive episode, which created some of the structures that form the fold-thrust belts in the northwest of Neuquén province (Ramos and Barbieri, 1988; Kozlowski et al., 1996, 1998; Zapata et al., 1999; Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Folguera et al., 2007; Zamora Valcarce et al., 2006a, 2007; Rojas Vera et al., 2014). Subduction continues currently active, with a relative convergence rate between the Nazca and South American plates in the order of 70 mm/yr at this latitude (Fig. 1a), but the deformation conditions prevailing at the easternmost region of the Andean thrust belt is a matter of discussion. Some geological and geophysical data support Plio-Quaternary

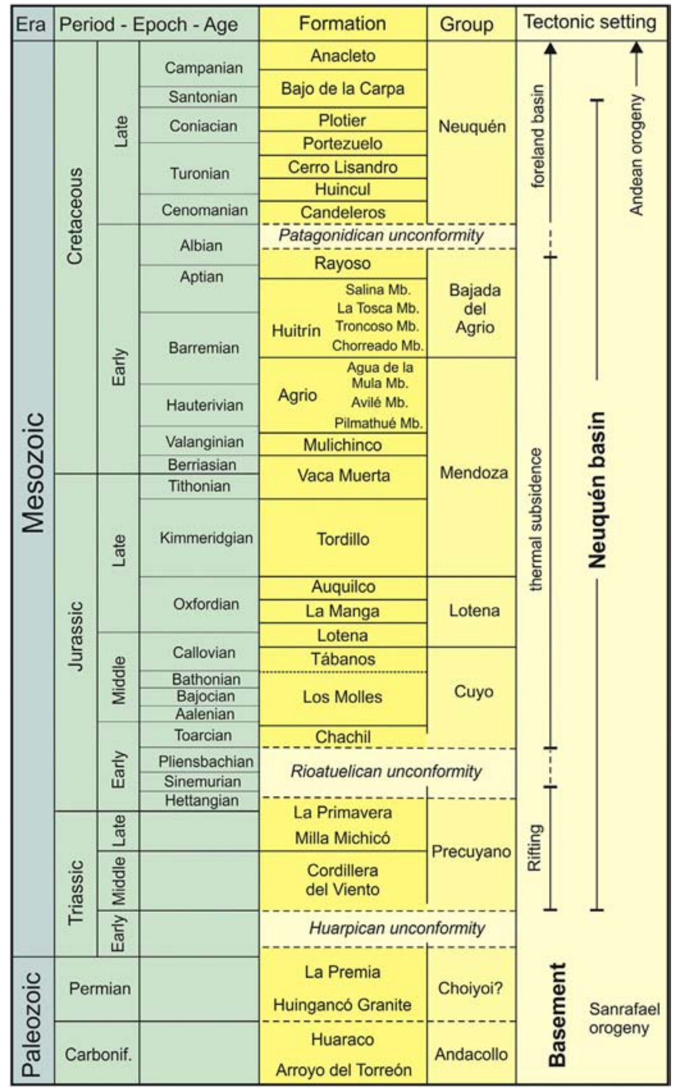


Fig. 2. Generalized stratigraphic column of the Neuquén Basin at the Chos Malal region, showing the nomenclature, age and tectonic setting of the units exposed in the studied area (based on Gulisano and Gutiérrez Pleimling, 1995; Leanza, 2003, 2009; Leanza et al., 2005, 2013; Llambías et al., 2007; Tunik et al., 2010).

extensional tectonics and normal faulting associated with the steepening of the subduction zone (Ramos and Folguera, 2005; Folguera et al., 2008, 2012), where the active thrust front has migrated to the west leaving inactive or fossil the easternmost Chos Malal and Agrio FTB (Ramos and Folguera, 2005; Zapata et al., 2005; Folguera et al., 2007). Other structural and geomorphological evidences have demonstrated the existence of Pliocene to recent compression and shortening in the Chos Malal FTB and toward the foreland (Cobbold and Rossello, 2003; Galland et al., 2007; Guzman et al., 2007; Messager et al., 2010).

2.2. Stratigraphy of the Neuquén Basin

The Neuquén Basin was developed above a heterogeneous Paleozoic to Early Triassic basement, with a diversity of lithologies that are exposed in the Cordillera del Viento at the northwest Neuquén province (Fig. 1b). This basement includes a variety of plutonic and volcanic rocks of diverse age and nomenclature (Fig. 2) that represent important magmatic and tectonic events at this portion of the Andes (Llambías et al., 2007). Middle to Late Triassic andesitic to rhyolitic volcanic rocks were accumulated in half-grabens during a rifting stage. These synrift deposits cover unconformably the Paleozoic units and they are commonly referred as Pre Cuyo Group or Precuyano cycle (Legarreta and Gulisano, 1989; Gulisano and Gutiérrez Pleimling, 1995; Vergani et al., 1995; Franzese and Spalletti, 2001; Llambías et al., 2007). The Early Jurassic La Primavera Formation (Fig. 2) contains marine sediments with fossil invertebrates and fossil wood, interbedded with basaltic flows and rhyolitic ignimbrites, deposited in marine waters with a strong influence of extensional tectonics (Leanza et al., 2013). The Chachil Limestone unconformably overlies the synrift deposits and new radiometric U–Pb ages obtained by Leanza et al. (2013) on zircon crystals from ash layers interbedded between the limestones confirm their Pliensbachian to earliest Toarcian ages (185.7 $\pm$ 0.4 Ma to 182.3 $\pm$ 0.4 Ma). Leanza et al. (2013) consider the Chachil Limestone as an important Early Jurassic stratigraphic marker representing an almost instantaneous widespread flooding episode in western Gondwana that marks the beginning in the Neuquén Basin of the Cuyo Group (Fig. 2). This initial sedimentation in shallow water marine environments was followed by off-shore black shales and turbidites of Los Molles Formation, with a subsidence regime that began to be dominated by thermal downwarping, while evaporites of the Tábanos Formation at the top of the Cuyo Group reveal an important shallowing of the marine conditions (Legarreta and Uliana, 1996). Accumulation of the Lotena Group from the Middle Callovian to the Oxfordian took place in sub-aerial and shallow water environments as a result of the complete desiccation of the basin (Gulisano and Gutiérrez Pleimling, 1995). Late Jurassic red beds of the Tordillo Formation were accumulated, with highly varying thicknesses, on diverse continental sedimentary environments (Spalletti and Veiga, 2007). These continental deposits were covered by dark bituminous marine shales and marls that constitute the Vaca Muerta Formation, which is the most important oil source rock of the Neuquén Basin. A tectonically driven relative sea-level fall that occurred during the Early Cretaceous has led to the deposition of a predominantly clastic, continental to shallow marine wedge corresponding to the Valanginian Mulichinco Formation (Fig. 2). A widespread transgressive phase started in the late Early Valanginian with the deposition of the Agrio Formation (Weaver, 1931), the upper unit of the Mendoza Group (Fig. 2), whose heterogeneous lithological content including shales, sandstones and limestones exert a primary control on the subsequent development of the tectonic repetitions analyzed in this paper. The Early Cretaceous Agrio Formation has an ample distribution both in outcrops and subsurface of the Neuquén Basin. It has been divided in three members: Pilmathué, Avilé and Agua de la Mula (Leanza et al., 2005). The Pilmathué Member is mainly composed of thin-bedded dark-gray shales and subordinated limestones, with a very rich fossil content (Aguirre-Urreta et al., 2005; Lazo et al., 2009). The thickness of this unit is commonly around 570–680 m (Leanza et al., 2005; Lazo et al., 2005) but exceptionally, in the area of San Eduardo mine to the southeast of Chos Malal, it reaches approximately 1000 m and contains a thick package of fine-grained massive sandstones (Zavala et al., 2011a,b). The Avilé Member is mostly formed of sandstones, whose accumulation was characterized by a close interaction between fluvial and aeolian processes developed after a major relative sea-level drop that almost completely desiccated the entire basin (Veiga et al., 2002). This member has a very variable thickness, usually oscillating between 30 and 50 m, with a maximum of 180 m near to Tricao Malal (Veiga et al., 2011). The Agua de la Mula Member is a marine succession composed of shales, mudstones, sandstones and bioclastic carbonates, with a thickness of 400–500 m (Spalletti et al., 2001a,b; Lazo et al., 2005). The abundance of marine fauna and microfossils led to elaborate an accurate biostratigraphy that gave an Early Hauterivian – Early Barremian age for this member (Aguirre-Urreta et al., 2005; Leanza et al., 2005; Lazo et al., 2009), while an U–Pb zircon age of 132.5 $\pm$ 1.3 Ma from a tuff layer intercalated in the ammonoid bearing shales provides a robust geochronologic date to improve the relative chronology of the Agrio Formation (Aguirre-Urreta et al., 2008). The Agrio Formation is the last unit of the Mendoza Group (Fig. 2) and it was deposited in an open-marine, mixed siliciclastic and carbonate ramp depositional system under storm influence (Spalletti et al., 2001a,b; Lazo et al., 2005, 2009). It represents the last marine inundation of the Neuquén Basin from the Pacific Ocean. The Huitrín Formation is a clastic-carbonatic-evaporitic complex that together with a series of fine-grained red beds and evaporites of the Rayoso Formation constitute the Bajada del Agrio Group (Leanza, 2003; Leanza et al., 2005), accumulated in continental environments. Within the Huitrín Formation, the Troncoso Member has a lower section of mostly fluvial-aeolian sandstones that constitutes, together with the Avilé Member sandstones, one of the most important hydrocarbon reservoirs in northern Neuquén province. An apparent discordant relationship between flat-lying Rayoso Formation and gently dipping Huitrín Formation has led to Cobbold and Rossello (2003) to propose an Aptian age for the beginning of the Andean compression. An angular unconformity separating inclined beds of the Rayoso Formation from overlying subhorizontal beds of Candeleros Formation, which forms the base of the Neuquén Group (Fig. 2), verifies a Late Cretaceous compressive pulse (Ramos and Folguera, 2005). Recent detrital zircon provenance studies indicate a Cenomanian age for the synorogenic deposits of the Candeleros Formation (Tunik et al., 2010; Di Giulio et al., 2012), supporting that the Neuquen Group was accumulated in a foreland stage of the Neuquén Basin related to the onset of the Andean orogeny (Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Tunik et al., 2010).

3. Regional structure of the Chos Malal fold-and-thrust belt

The Chos Malal FTB is located in the north of the Neuquén Province (Fig. 1) and it shows a huge basement-involved structure that originated the Cordillera del Viento and many folds and thrusts affecting the Mesozoic infill of the Neuquén Basin. Detailed structural works at this region are scarce and they are restricted to specific sites associated with important oil fields near the Andean thrust front (e.g. Ploszkiewicz and Viñes, 1987; Zapata et al., 2001; Allmendinger et al., 2004; Zamora Valcarce et al., 2006b). Despite of the petroliferous interest of the whole area, the published

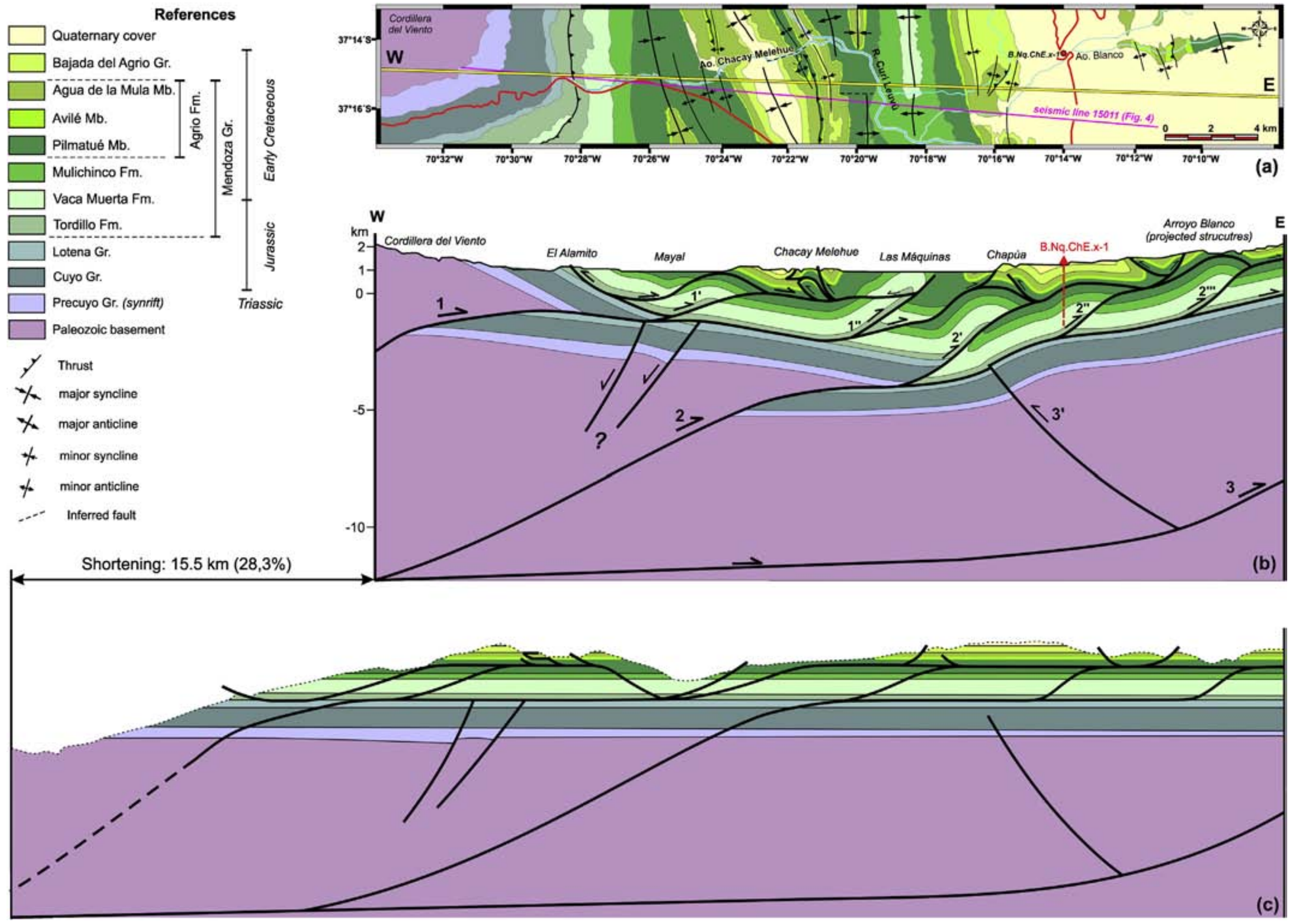


Fig. 3. Structures across the Chos Malal fold-and-thrust belt. a) Regional geological map based on own field data. b) Interpreted structural cross-section supported by structural data measured on the field, well data at the eastern end and a poor quality seismic line (Fig. 4). The structural style is characterized by thick-skinned structures at the Cordillera del Viento, combining differentially inverted Mesozoic normal faults (e.g. Zapata et al., 1999; Cobbold and Rossello, 2003; Folguera et al., 2007, 2011) and new formed Andean thrusts that originated wedge-shaped basement structures (e.g. Kozlowski et al., 1996, 1998). The interpretation of a seismic line lead us to recognize a second basement slice further extended to the east below the thin-skinned structures. The deformation in the cover rocks is characterized by structures of different scales, most of them connected along flat-ramp-flat thrust geometries that link the thick and thin-skinned structures. The westward-dipping basement-cover contact at the right side of the section is related to the development of the easternmost basement-cored Las Yeseras and Pampa Tril structures (e.g. Kozlowski et al., 1996, 1998). c) Restored section that allows us to estimate a minimum regional tectonic shortening of 15.5 km (28.3%).

structural cross-sections of the Chos Malal FTB are very regional (Ramos and Barbieri, 1988; Both and Coward, 1996; Chaveau et al., 1996; Kozlowski et al., 1996; Cobbold et al., 1999; Zapata et al., 1999; Folguera et al., 2007, 2011; Rojas Vera et al., 2014), focused on the major thrusts affecting basement blocks. Consequently, the general lack of accurate geometric reconstructions of the thin-skinned structures makes it difficult to precise the tectonic shortenings and to analyze the temporal and spatial relationships among different structures of the thrust belt. Although a variety of structural models have been proposed to explain the basement uplifts along the Chos Malal FTB, including inversion of Mesozoic normal faults (Both and Coward, 1996; Chaveau et al., 1996; Cobbold et al., 1999; Zapata et al., 1999; Zamora Valcarce et al., 2006b), new formed Andean thrusts (Ploszkiewicz and Viñes, 1987; Kozlowski et al., 1996; Allmendinger et al., 2004) or combination of both styles of faults (Folguera et al., 2007, 2011; Rojas Vera et al., 2014), most of these authors agree that the thick-skinned structures were partial or totally inserted in the sedimentary cover producing the adjacent thin-skinned structures. Thus it is evident the importance of the recognition and accurate reconstruction of the structures affecting the Mesozoic units in the thrust belt, estimating the thin-skinned shortening in the cover in order to establish the associated displacement of the thick-skinned structures. To address this issue we have carried on an exhaustive field mapping along the Chos Malal FTB to the north of the Río Neuquén (Fig. 1b), which allowed us to construct balanced structural cross-sections. A southern cross-section at approximately 37°18′S was made to illustrate in detail the structures and to analyze their relative kinematics (Sánchez et al., 2014). In the present paper, based mainly on field structural data, but also considering a poor quality 2D seismic line (15011) and information from the B.Nq.ChE.x-1 well, we have elaborated a structural cross-section at 37°15′S (Fig. 3). This section is approximately 40 km long and it extends in a W–E direction, from the Cordillera del Viento to the western side of the Tromen-Tilhue volcanic suite (Fig. 1b). Eastward of the Cordillera del Viento we have mapped numerous folds and thrust, of different scale, affecting the Mesozoic sedimentary cover (Fig. 3a). Although it is still matter of discussion, the basement uplift at the Cordillera del Viento could have arisen during at least two compressive deformational events and along several faults with opposite dip

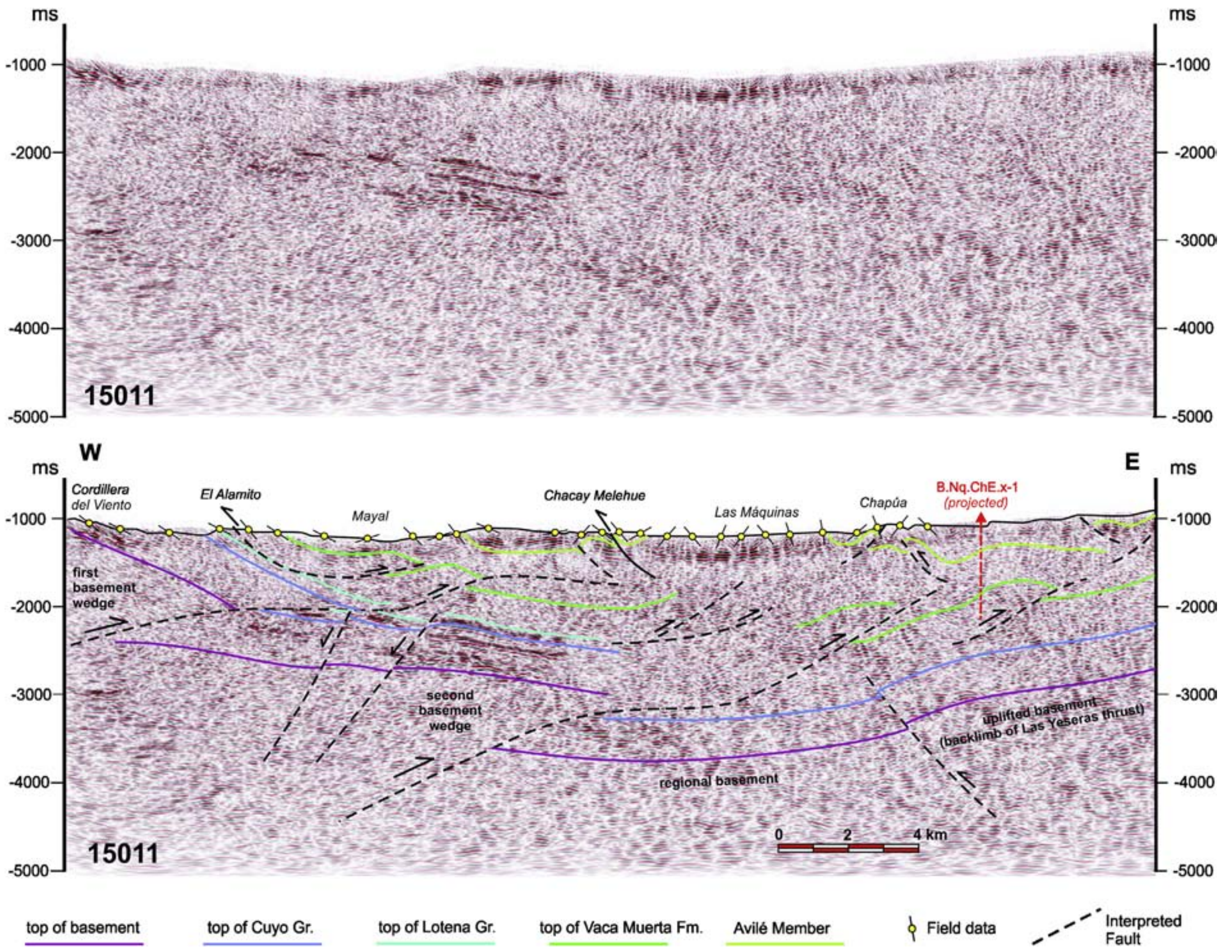


Fig. 4. Uninterpreted and partially interpreted two-way traveltime seismic line 15011 across the Chos Malal FTB (location in Fig. 3a).

senses. In the western slope of this range, out of the study area, there are evidences of backthrusts that could be related to Mesozoic normal faults inverted due to Late Cretaceous-Paleogene compression-transpression (Cobbold et al., 1999; Zapata et al., 1999; Cobbold and Rossello, 2003; Folguera et al., 2007). In the eastern side of the Cordillera del Viento the existence of a west-dipping blind fault was interpreted either as an inverted normal fault (Both and Coward, 1996; Zapata et al., 1999) or as a low angle Andean thrust ramping up into the Jurassic shales of Vaca Muerta Formation where it becomes the main detachment of the thin-skinned structures (Kozlowski et al., 1996; Cobbold et al., 1999). This foreland directed deformation took place in a first pre-Miocene stage, because folded Mesozoic strata are unconformably covered by Miocene volcanic rocks, while a second Late Miocene compressive pulse produced the Curileuvú fault, exposed to the north of the study area, which puts the entire Mesozoic sequence over the middle to Late Miocene volcanic rocks (Folguera et al., 2007). At the latitude of our cross-section there are not field evidences of faults affecting the Mesozoic layers that form the eastern slope of the Cordillera del Viento. Thus, we interpret this gently-dipping flank as the frontal part of a large basement wedge (Fig. 3b). Few kilometers to the south along this flank, we mapped the El Alamito backthrust placing the Tordillo Formation over the younger Vaca Muerta Formation (Fig. 3a). This fault was interpreted with a flat-ramp-flat geometry detached below the Tordillo Formation, probably along the evaporites of the Auquilco Formation (Sánchez et al., 2014), which suggest the existence of a detachment level within the cover deeper than that previously considered along the Vaca Muerta shales (Kozlowski et al., 1996; Cobbold et al., 1999). Toward the east of the Cordillera del Viento, the shales of Pilmathué Member are widely exposed affected by several structures that form the Mayal synclinorium (Fig. 3b). Field data and seismic interpretation allow us to recognize at least two anticlines, with relatively low structural reliefs, which are interpreted as fault-bend folds (Suppe, 1983) involving the whole Mendoza Group. Measured dips on the fold limbs demonstrate an eastward vergence. We interpret that these fault-bend folds have advanced toward the foreland along an upper detachment located into the Pilmathué Member shales, forming duplex structures. The displacement along this shallow level in the cover gave birth to the backthrust system that duplicated the Agrio Formation creating the Chacay Melehue anticline (Fig. 3b), which be further explained in detail in the next section. Despite of the poor resolution of the seismic line 15011, it is possible to identify the geometry of major thick-skinned structures (Fig. 4). One of the more relevant aspects in our interpretation is the differentiation of two large thrust slices involving the basement rocks. The Cordillera del Viento has been uplifted through the westernmost major thrust (1 in Fig. 3b), which was inserted in the cover along the Auquilco Formation and so it produced several thin-skinned folds involving the Mendoza Group. The easternmost fold associated with the first basement wedge is the Las Máquinas anticline, a noticeable N–S trending fold cored by shales of the Vaca Muerta Formation (Fig. 3a). We have interpreted the very high structural relief of the Las Máquinas anticline as attained by the superposition of two faults in depth (Fig. 3b). The lower thrust created initially an incipient fault-bend fold. Then, a new thrust branching off from the fault ramp produced a fault-propagation fold and the anticline acquired its final configuration. Below these thin-skinned structures, we interpret a set of eastward gently-dipping reflectors on the seismic line (Fig. 4) as the top of a second basement-involved thrust slice (2 in Fig. 3b. Two west-dipping normal faults displaced slightly these reflectors below the Mayal structures (Fig. 4). Kozlowski et al. (1996) interpreted one of these normal faults as a post-orogenic structure cropping out at the surface. However, we have not found field evidences of such faulting and the seismic line shows that the misfit of some reflectors cannot be extended up section through the overlying reflectors. Two new alternative interpretations arise from these evidences. i) The normal faults could be previous structures formed during the Late Triassic-Early Jurassic rifting stage, non-inverted during the Andean compression. In this case the normal faults should have been reactivated extensionally, since they are affecting upper reflectors that we interpreted as the Lotena Group (Fig .3b), probably as the result of the tension related to the differential subsidence of the grabens (e.g. Cristallini et al., 2009). The renewed extensional movement along these faults could also explain the variable thicknesses of the Late Jurassic Tordillo Formation in this region. If the normal faults displaced the Auquilco Formation, the underlying extensional geometry can control the location of the younger thrusts that form the Mayal duplex structures during the subsequent Andean compression, as has been shown in other places of the Andes (e.g. Torres Carbonell et al., 2013). ii) Wedge-shaped synrift geometries are not imaged on the seismic line. The normal faults affect layers assigned to the Lotena Group but they did not disturb the overlying duplex structures, thus they cannot be post-Andean faults. Based on such features, these structures can be interpreted as younger normal faults formed contemporaneously with the development of the uppermost Andean structures, as accommodation faults in response to the tectonic load exerted by the stacked thrust slices.

Like the Cordillera del Viento structure, the second basement-involved thrust slice (2 in Fig. 3b) was inserted in the Auquilco Formation transferring displacement to the cover rocks and thus producing several thin-skinned fault-related folds (2′, 2″ and 2‴ in Fig. 3b). This deeper low angle thrust involving basement rocks was recently interpreted as a shortcut fault ahead of inverted Mesozoic normal faults that border the Cordillera del Viento (Rojas Vera et al., 2014). In the cover rocks, we interpreted three kilometer-scale anticlines as fault-bend folds, drilled by the B.Nq.ChE.x-1 well to the north of the cross-section, which are connected to an upper detachment located on the shales of the Pilmathué Member forming duplex structures. Deformation transferred to this shallow decollement creates minor-scale structures involving the Agrio and Huitrín Formations, as those exposed in the arroyo Chapúa area (Fig. 3b). These hectometer-scale folds, which Kozlowski et al. (1996, 1998) described as *"Codo del Chapúa"* type, are related to opposite-vergent thrusts creating small triangle zones and pop-up structures as in the arroyo Blanco valley (Fig. 3a). These easternmost thin-skinned structures overlie a west-dipping basement-cover interface recognized on the seismic line (Fig. 4), which is related to a third major thrust within basement rocks (3 in Fig. 3b). This basement-involved structure is part of an east-vergent fault system that forms the basement-cored Las Yeseras and Pampa Tril anticlines, eastward of the Tromen Volcano (Kozlowski et al., 1996, 1998). We interpreted a backthrust affecting the backlimb of the Las Yeseras anticline, as it was described in the Tromen western slope (Galland et al., 2007), although normal faults were also documented in adjacent areas (Folguera et al., 2008). A detachment depth of about 9.4 km below sea level was calculated based on trishear modeling of the Pampa Tril anticline (Allmendinger et al., 2004). Taking into account this value and a mild regional inclination to the west of this decollement we have considered that the thick-skinned structures at the Chos Malal FTB are nucleated at a deep of about 11–12 km in the study area (Fig. 3b). In our interpreted cross-section, the geometry of the basement-involved thrust sheets and the concomitant slip on the fault planes were adjusted in order to match the measured displacements along the thin-skinned faults. Line-length restoration of the cross-section allows us to calculate a tectonic shortening of 15.5 km (28.3%) for the studied structures (Fig. 3c). This value is a minimum estimation because we have not included the easternmost basement-involved structures in our reconstruction.

4. Structures of the study area

The study area is situated surrounding the confluence zone between the Río Curí Leuvú and the Arroyo Chacay Melehue, few kilometres to the northwest of Chos Malal city (Fig. 1b). In this region we have mapped a series of NNW trending folds, of different scales, involving Early Cretaceous rocks (Fig. 5). The oldest unit exposed in the area corresponds to the Pilmathué Member of the Agrio Formation, while the younger Huitrín and Rayoso Formations are located in the core of the large Mayal and Cañada Seca synclines. Following the NNW major fold structural trends there are a number of minor folds, thrusts and backthrusts involving the strata of the Agrio Formation, which are recognized due to the repetitions of the Avilé Member (Fig. 5). This remarkable and notably well exposed structures, detached above the Pilmathúe Member shales, were originally mentioned and briefly described by Kozlowski et al. (1996). During several field trips to the region we have collected structural data with the purpose of fully characterize the geometry of these repetitions, which show a varied order of complexity throughout the study area. Based on these field data we made a detailed map and constructed three short cross-sections, A–A′, B–B′ and C–C′, approximately normal to the strike of most of the structures in the zone, in order to illustrate and entirely describe the thrust systems on the Agrio Formation (Fig. 5). Because the best exposures of the structures are observed in the south side of the valleys and creeks, and consequently most of the field data were acquired there, the three cross-sections are presented in a south view to allow a direct comparison with the field photographs.

4.1. Cross-section A–A′

This is the longest cross-section, located at the northern area (Fig. 5), and it shows two different sectors, to the west and to the east of the Cañada Seca syncline, where the Agrio Formation is tectonically repeated (Fig. 6a). At the west end of the cross-section it can be observed the Cañada Seca anticline, a tight east-vergent anticline, with sandstones of the Avilé Member in the core forming a rounded hinge and a low topographic relief (Fig. 6b and c). This fold has a gently-dipping backlimb (15°–30° W) and a steeper forelimb (30°–50° E) that exceptionally reaches near 80° E in the north area (Fig. 5). According to its small fold wavelength, the Cañada Seca anticline could be interpreted as a fault-propagation fold detached along shales in the upper part of the Pilmathué Member. Covering the sandstones of the Avilé Member in the backlimb of the anticline there is a sequence of shales and then a set of west-dipping sandy layers, forming the crest of a small hill (Fig. 6b and c). It could be misinterpreted as the normal succession of the Avilé Member–Agua de la Mula Member–Huitrín Formation such as in the frontal limb of the anticline (Fig. 6a). However, several stratigraphic and structural evidences support the existence

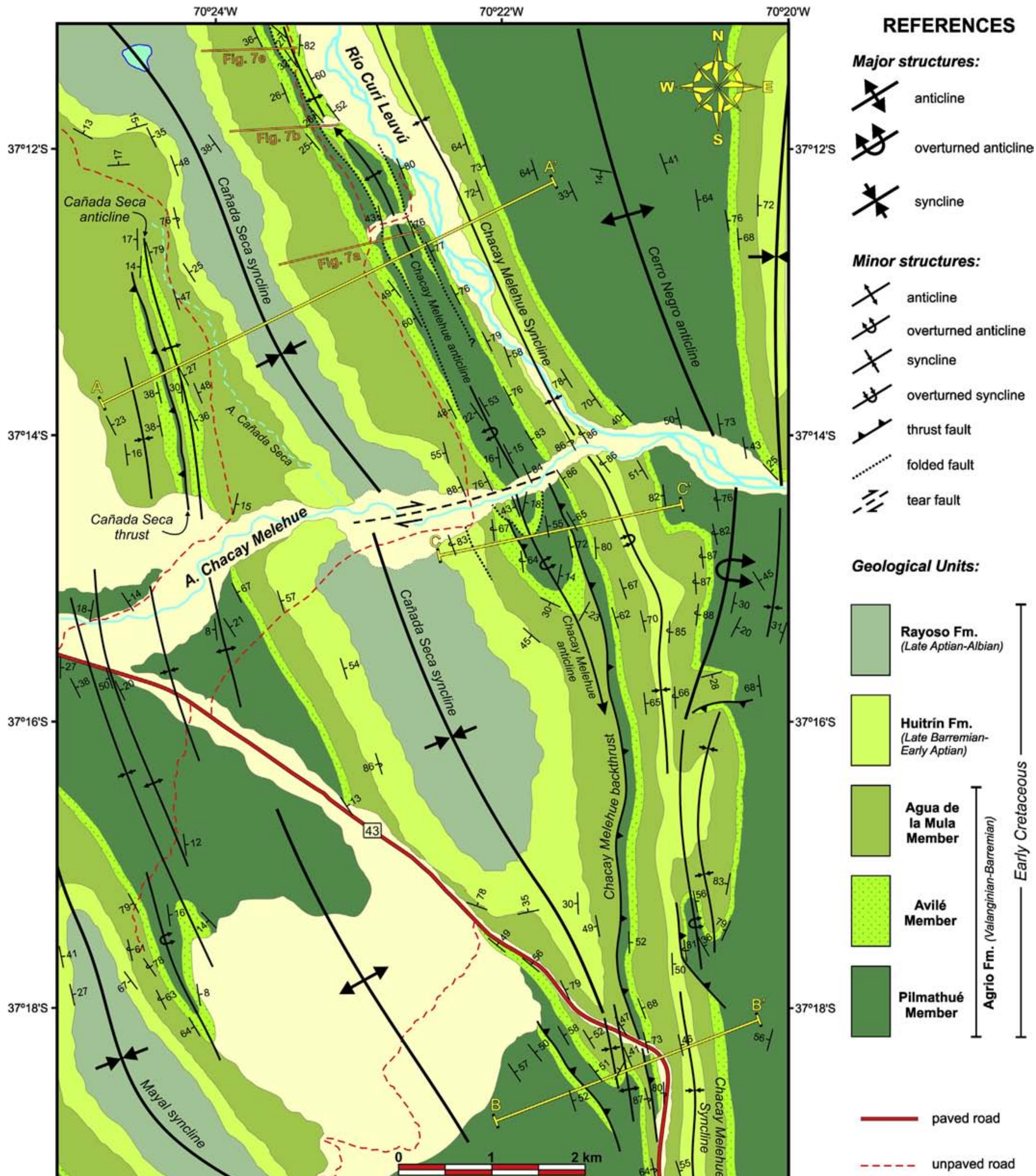


Fig. 5. Detailed geological map of the sector where the Early Cretaceous Agrio Formation is tectonically repeated (see location in Fig. 1b). East-vergent thrusts, duplications and fault-propagation folds were recognized at the northern area, along the A–A′ cross-section. Similar structures but with a clear vergence to the west were developed at the southern and central areas, along the B–B′ and C–C′ cross-sections respectively. We have inferred that this change of the tectonic vergence on these thin-skinned structures took place by means of a WSW-trending tear fault located along the arroyo Chacay Melehue.

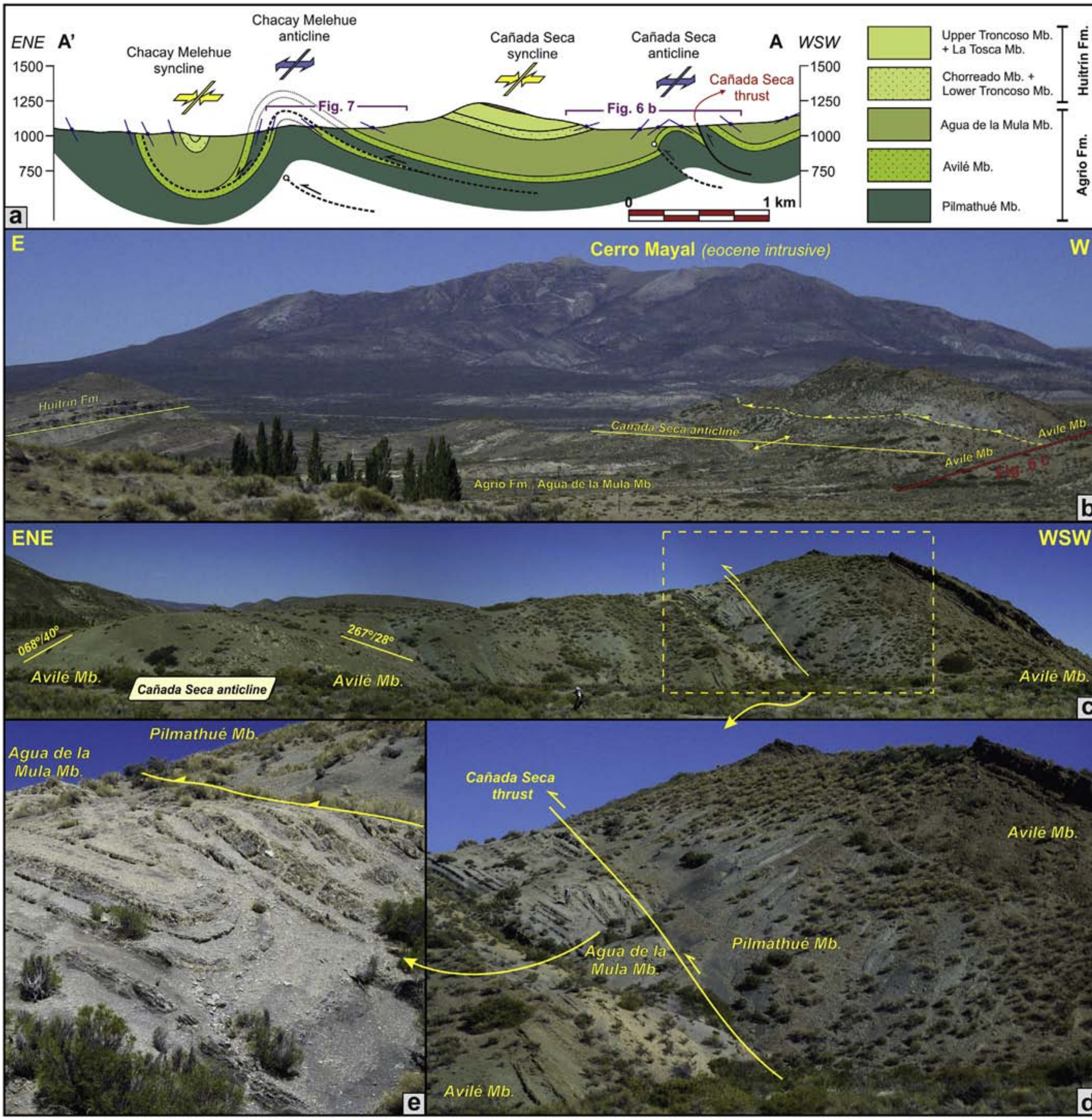


Fig. 6. a) Southward view of the structures in the A–A′ cross-section, showing the east-vergent thrusts and anticlines involving the Agrio Formation (see location in Fig. 5). b,c) Panoramic photograph toward the south of the Cañada Seca anticline exposing sandstones of the Avilé Member in the core, which are repeated in the fold backlimb. d) Detailed view of the Cañada Seca thrust placed in the anticline backlimb, which put the shales of the Pilmathué Member over the younger shales of the Agua de la Mula Member. e) Shales in the footwall are intensely folded corroborating the east-vergence of the Cañada Seca thrust.

of an east-vergent thrust, named Cañada Seca thrust, which repeats part of the Agrio Formation (Fig. 5). These evidences include the following assertions: i) the thickness of shales between the two levels of sandstones is considerably smaller than the stratigraphic thickness of the Agua de la Mula Member; ii) the calcareous beds of Chorreado Member, which we commonly observed in other places of the study area laying between the Agua de la Mula shales and the sandstones at the base of Huitrín Formation, are absent in this place; iii) to the west of the hill, above the sandy layers, there are again shales of Agrio Formation indicating that the sandstones correspond in fact to the Avilé Member; iv) at the backlimb there is a clear discontinuity that separates intensely folded light-gray shales from unfolded dark-gray shales (Fig. 6d and e). Thus we have recognized and interpreted the Cañada Seca thrust that repeated the Avilé Member, which locally places in contact the undeformed shales of Pilmathué Member in the hangingwall with the folded shales of the younger Agua de la Mula Member in the footwall (Fig. 6a and d).

To the east of the Cañada Seca syncline it can be observed the Chacay Melehue anticline, another NNW trending, east-vergent fold, cropping out parallel to the valley of the Río Curí Leuvú (Fig. 5). This anticline has dips in the order of 30°–50°W in the backlimb and 50°–80°E in the forelimb, and it extends more than 7 km along strike. The Chacay Melehue anticline has a great breadth along the cross-section A–A′ (Fig. 6a), with a good exposure of shales of the Pilmathué Member in the core (Fig. 7a), and its amplitude diminishes to the north where only is exposed the Avilé Member (Fig. 7b and e). In the backlimb of the fold there are two well exposed suites of sandstones of the Avilé Member, with similar low angle dips to the west (Fig. 7), separated by a section of black shales (Fig. 7c). The same happens in the forelimb where the Avilé Member was found twice and with equals dips of 76°E (Fig. 5). We interpret these duplication and parallelism of the Avilé Member beds in the flanks of the Chacay Melehue anticline (Fig. 6a) as the hinge zone of a wide fault-bend fold, with a lower detachment along the upper part of the Pilmathué Member and an upper detachment at the base of the Agua de la Mula Member. Later, these duplicated beds were equally folded by means of an east-vergent blind thrust in depth. The evolution of this complex structure implies more displacement on the fault system than in the westernmost Cañada Seca anticline, where duplication of the Avilé Member took place as an imbrication exclusively at the fold backlimb. We have considered these two sandstone intervals as a tectonic repetition based on stratigraphic and structural

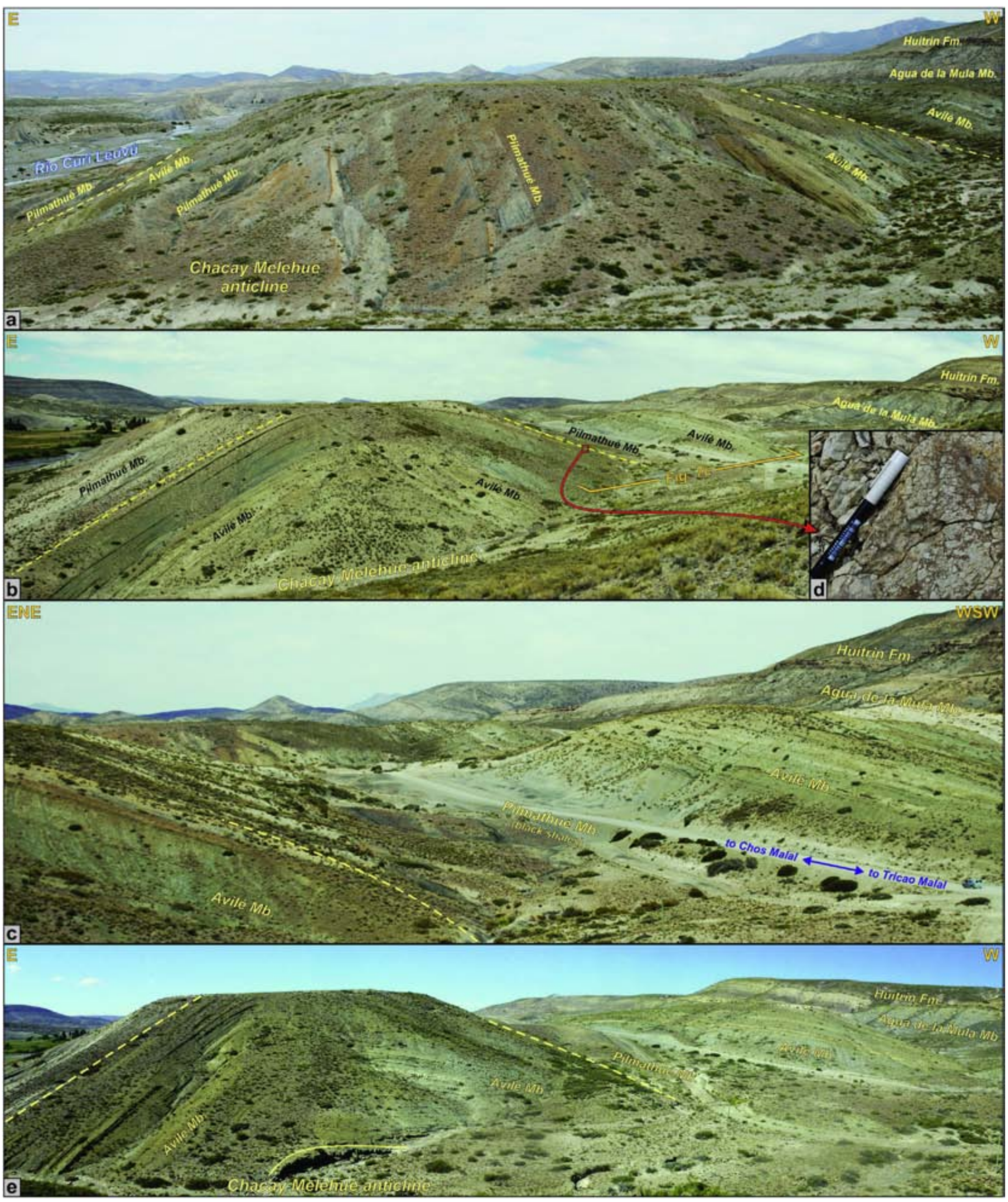


Fig. 7. Panoramic photographs toward the south of the Chacay Melehue anticline, where a duplicated sequence of the Pilmathué and Avilé Members are lately deformed as an east-vergent fault-propagation fold (see Fig. 6a). Shales of Agua de la Mula Member are cropping out in the core of the anticline (Fig. 7a), while the Avilé Member is exposed to the north (Figs. 7b and e), suggesting a northward plunge of the fold axis (see the location of successive photographs in Fig. 5). c) Detailed view of the sequence Pilmathué-Avilé Members duplicated on top of the Avilé Member in the backlimb of the Chacay Melehue anticline. d) Tectonic breccias found at the fault zone where we also measured slickensides with striations and steps indicating an eastward movement of the hangingwall.

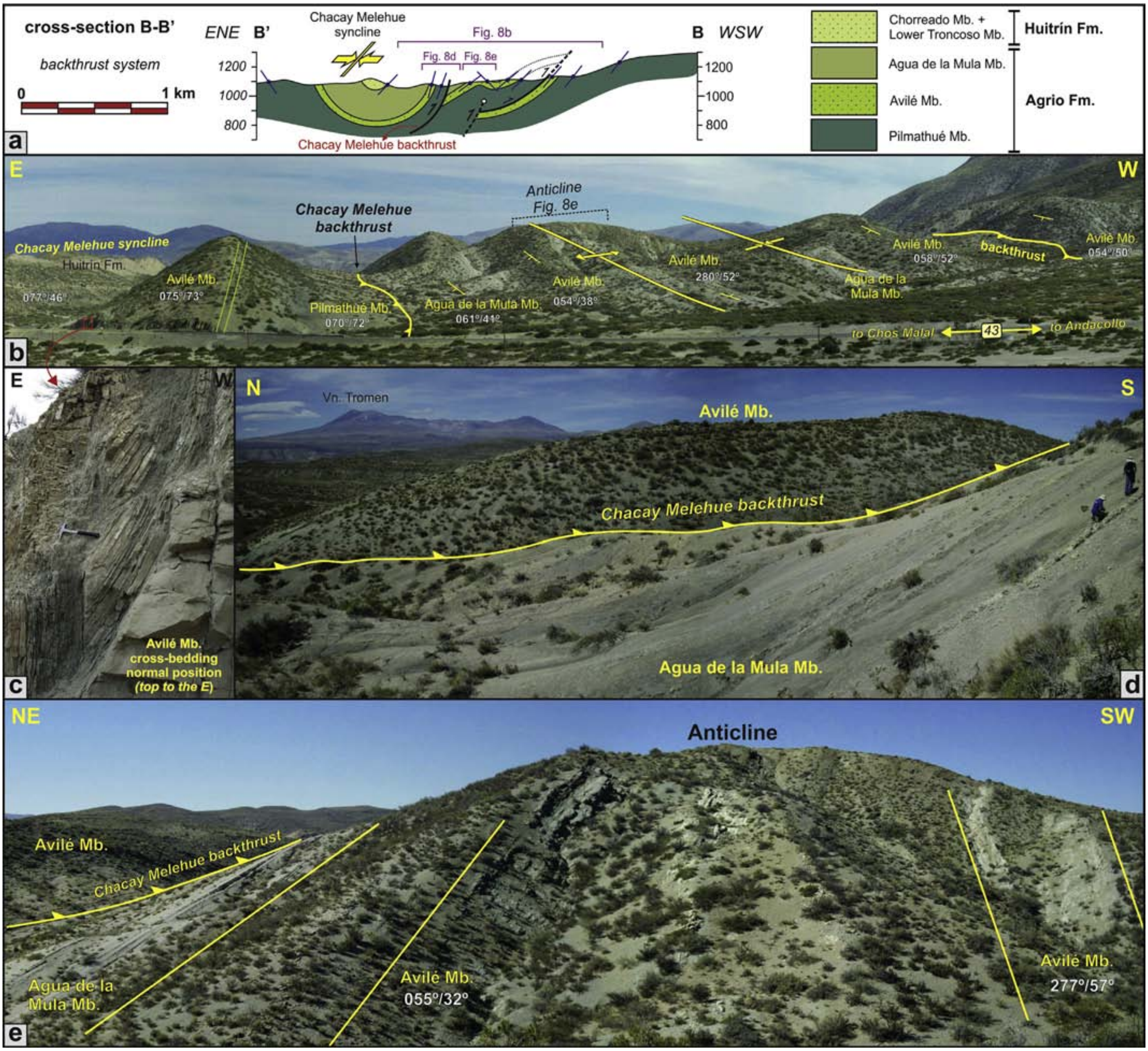


Fig. 8. a) Southward view of the B–B′ cross-section, showing west-vergent structures involving the Agrio Formation related to a backthrusts system (see location in Fig. 5). b) Panoramic photograph from the north of the measured structures, where small topographic highs correspond to outcrops of the Avilé Member. c) Cross-bedding and other primary sedimentary structures on sandstones of the Avilé Member indicate the polarity of the layers, which in most of this area is in normal position. d) Frontal view of the Chacay Melehue backthrust that put the Pilmathué and Avilé Members over the younger Agua de la Mula Member. e) West-vergent anticline located at the west of the Chacay Melehue backthrust, which is considered a fault-propagation fold that evidences a second backthrust in depth.

arguments. First, if these sandstones separated by shales were related to fluctuations in the depositional environments, we would expect that they show a more widespread geographic distribution. In fact, this kind of stratigraphic repetitions of sandy layers within the Pilmathué Member of the Agrio Formation occurs in other regions of the Neuquén Basin, as in the San Eduardo mine located ~30 km to the southeast of Chos Malal (Zavala et al., 2011a, b). In that area above a 130 m thick basal sequence of massive sandstones, there are two additional sandy intervals, considerably thinner (~20 m). These layers include calcareous sandstones with marine fossils, coquinas, and they have sedimentary structures that are very different from those of the overlying Avilé Member. Mapping and measurement of all the sandstones of the Pilmathué Member demonstrated that they have a very regional extension toward the south but disappear relatively fast toward the north (Zavala et al., 2011a,b). In the flanks of major folds that we mapped to the north of Chos Malal where the Agrio Formation is completely observed, in agreement with the northward onlap of San Eduardo beds, the only noticeable marker is a succession of sandstones corresponding to the Avilé Member. In the whole area between the Cordillera del Viento and the Tromen volcano (Fig. 1b), we found the repeated sequence of sandstones exclusively in the region of confluence of the Río Curí Leuvú and the Arroyo Chacay Melehue (Fig. 5). This suggests that it is a local structural phenomenon. Structural data, although poorly preserved due to the low competence of the shales, support the tectonic origin of these repetitions. A fault breccia affecting interbedded mars and shales, possibly assignable to the base of the

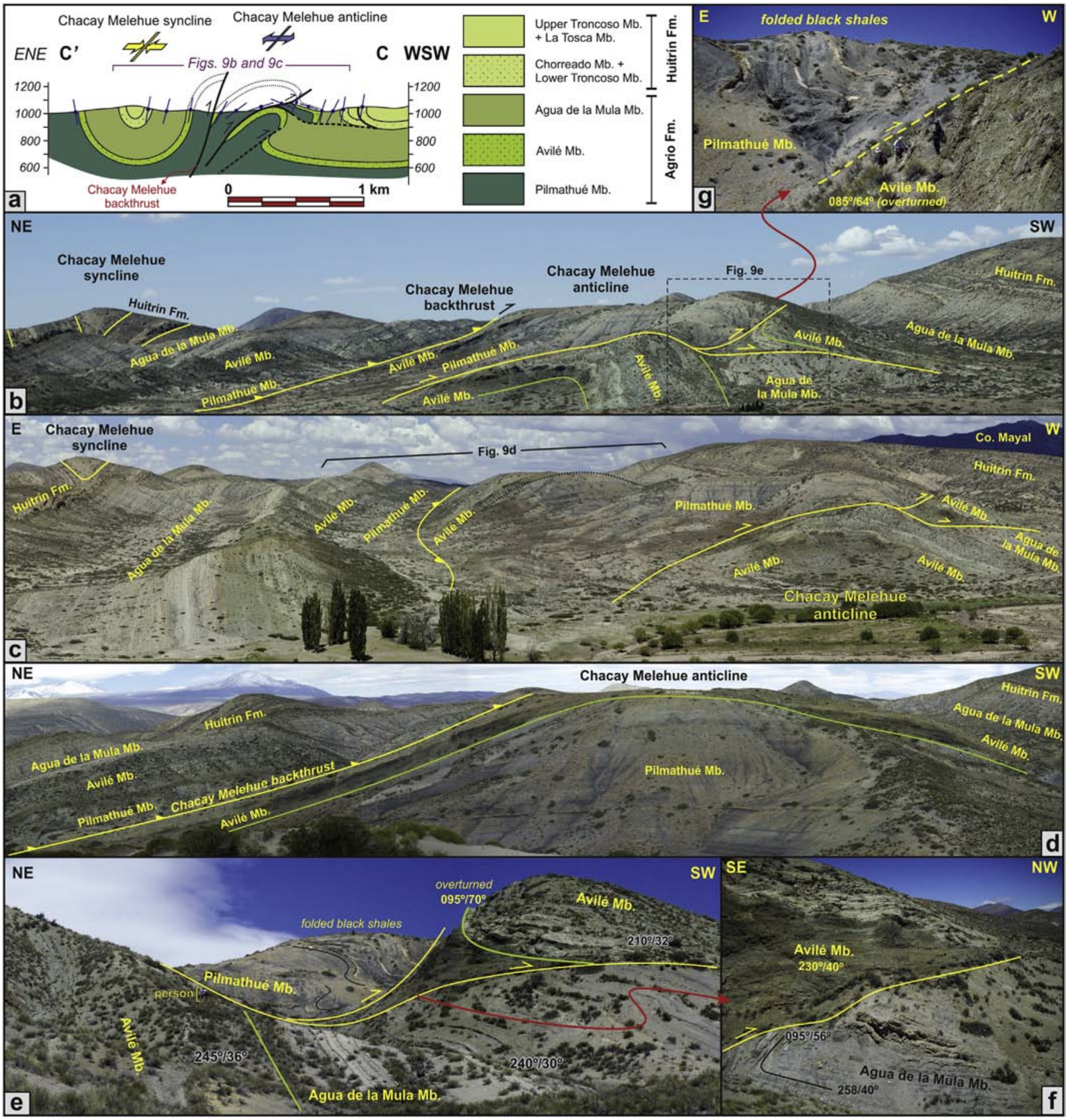


Fig. 9. a) Southward view of the C–C′ cross-section, evidencing a complex deformation of the Agrio Formation related to a backthrusts system (see location in Fig. 5). b) Panoramic photograph of the Chacay Melehue anticline, with a vergence to the west, where the Pilmathué-Avilé Members were completely duplicated on top of the Avilé Member and subsequently folded by means of a backthrust at depth. c-d) The Pilmathué and Avilé Members are imbricated at the backlimb of the anticline due to the Chacay Melehue backthrust. e-f) Detailed view of the forelimb of the Chacay Melehue anticline where the duplicated Avilé sandstones are displaced on top of the Agua de la Mula shales along a thrust ramp. g). In the anticline forelimb, the duplicated shales of the Pilmathue Member are intensely folded and were thrust toward the west over the Avilé Member beds that locally are overturned near the fault plane.

Agua de la Mula Member, was found over the Avilé Member in the backlimb of the Chacay Melehue anticline (Fig. 7d). At the same place we measured a diffuse fault plane (254°/42°) with down-dip slickenside lineations and shear-sense indicators that point to an eastward directed movement over the fault plane. Unfortunately, no kinematics indicators of faulting were found in the forelimb.

4.2. Cross-section B–B′

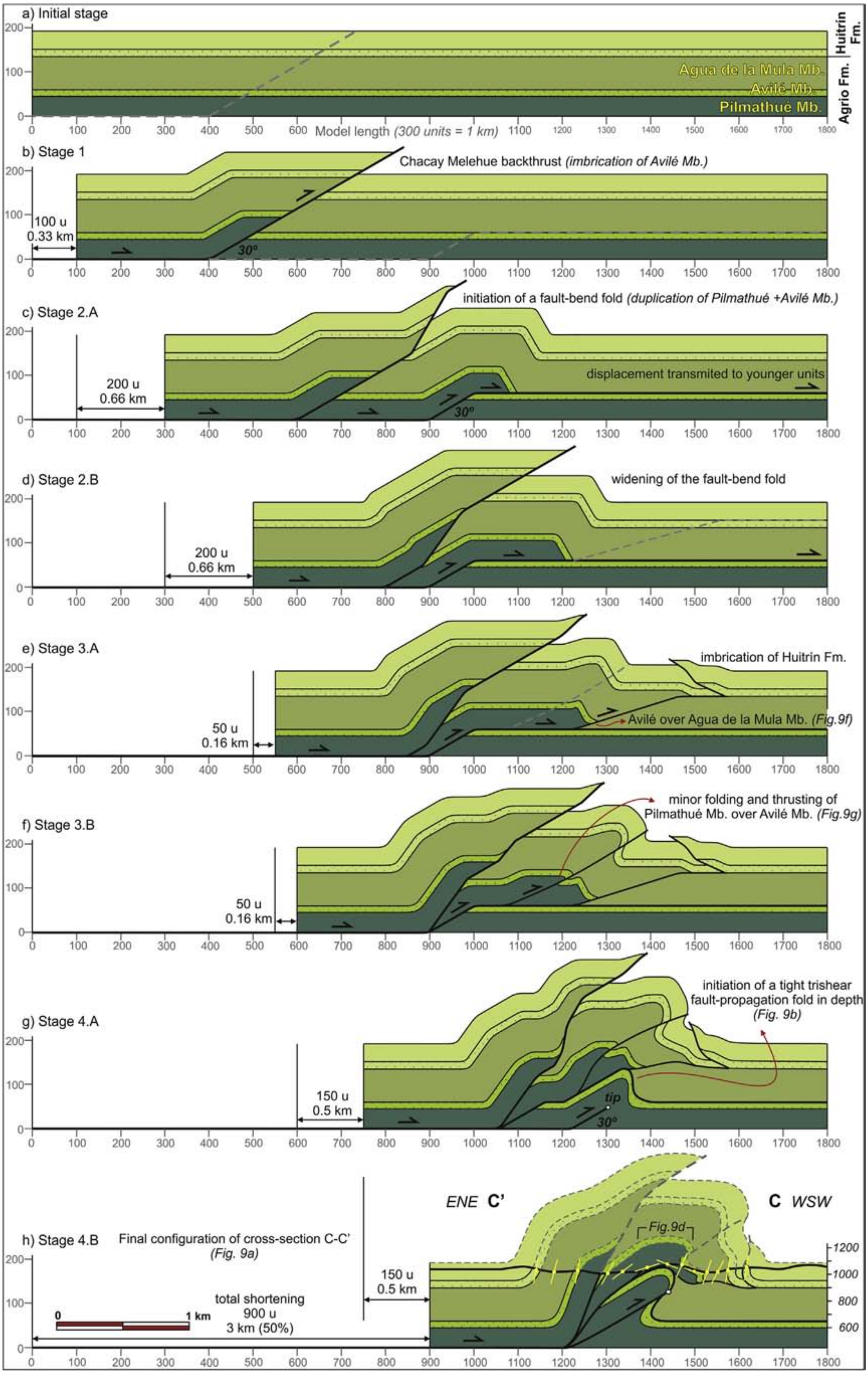
This cross-section is located in the southern portion of the study area (Fig. 5), to the northeast of the Eocene subvolcanic rocks that form the Sierra del Mayal (Fig. 1b). Along this section there is a well-developed backthrust system composed of three west-vergent thrusts affecting the Agrio Formation (Fig. 8a). Between the Chacay Melehue syncline and the eastern slope of the Sierra del Mayal we found repeated outcrops of east-dipping sandstones of the Avilé Member separated by shales (Fig. 8b). In the core of the Chacay Melehue syncline there are evaporites of the Huitrín Formation and the Agrio Formation is completely exposed in the flanks. Beds of the Avilé Member in the western limb of the syncline have steep dips (68°–73°E) and they contain sedimentary structures evidencing a normal polarity (Fig. 8c). Below the sandstones, few meters of dark-gray shales of the Pilmathué Member are exposed with similar dips (72°E). These rocks, which form an elongated crest, were thrust on top of the younger light-gray shales of the Agua de la Mula Member, which are dipping 41°E, by means of the NNW trending Chacay Melehue backthrust (Fig. 8d). These different dips on both sides of the fault allow us to interpret this part of the backthrust as a footwall-ramp with a reasonable cut-off angle of approximately 30° (Fig. 8a). Shales of the Agua de la Mula Member are covering sandy layers of the Avilé Member, forming a west-vergent anticline with a 32°E dipping backlimb and a 57°W dipping forelimb (Fig. 8e). The sandstones of the Avilé Member in both limbs of the fold, as in all the others outcrops of this sector, have excellent primary sedimentary structures corroborating a normal position of the beds. This anticline could be interpreted as a fault-propagation fold associated with a blind backthrust (Fig. 8a). Toward the west, the Agua de la Mula shales are located in the core of a minor syncline that could be the southern end of the greater Cañada Seca syncline (Fig. 5). The Avilé and Pilmathué Members are exposed in the western flank of the syncline with dips of 50°–60°E. A third backthrust is recognized between these rocks and the westernmost exposures of the Avilé Member with dips of about 50°E at the eastern slope of the Sierra del Mayal (Fig. 8b). Parallelism showed by both packages of Avilé sandstones suggests a large displacement along this backthrust indicating a hangingwall flat configuration (Fig. 8a).

4.3. Cross-section C–C′

The third cross-section is the shortest but structurally the most complex section of the study area and it is situated at the south side of the arroyo Chacay Melehue (Fig. 5). As in the other two cross-sections, at the eastern end, the Chacay Melehue syncline shows the Huitrín Formation in the core and the Agrio Formation in the limbs (Fig. 9a). Steeply-dipping beds of the latter unit in the western flank form a notorious topographic ridge that extends more than 6 km to the south and at least 3 km to the north of the arroyo Chacay Melehue and consequently it is observed in all three cross-sections (Fig. 5). The Pilmathué Member at the base of this ridge was thrust over east-dipping sandstones of the Avilé Member through the Chacay Melehue backthrust (Fig. 9b and c). On the fault plane of this backthrust we measured slickensides orientated 074°/82° and 075°/81° (dip direction/dip), containing striations with a pitch of 72°N and 76°N respectively and steps that indicate a westward movement of the hangingwall. To the west of the backthrust the Avilé and Pilmathué Members form the Chacay Melehue anticline, a broad fold with horizontal layers in the hinge zone (Fig. 9d). A lowermost package of the Avilé Member sandstones are exposed in the core of the Chacay Melehue anticline, beneath the shales of the Pilmathué Member, forming a tight west-vergent anticline (Fig. 9b) that we interpret as a fold-propagation fold related to a blind backthrust. In the frontal limb of this anticline the Agua de la Mula Member overlays the Avilé Member showing comparable dips of 30°–36°SW (Fig. 9e). These younger shales of the Agrio Formation are absent in the fold backlimb, where we can recognize the Pilmathué shales and Avilé sandstones repeated over the Avilé Member (Fig. 9b and c). The described features allow us to interpret these repeated Members of the Agrio Formation as a fault-bend-fold with the lower detachment within the Pilmathué Member shales and the upper detachment at the base of the Agua de la Mula Member. Thus this repeated package, that includes a portion of the Pilmathué Member and the Avilé Member, is a thrust sheet that has advanced a considerable distance toward the west and subsequently a new ramp in front of the structure placed the duplicated Avilé Member over the shales of the Agua de la Mula Member (Fig. 9e). Shales of this younger member of the Agrio Formation form a drag syncline in the footwall of the ramp corroborating the westward movement of the structure (Fig. 9f). A minor backthrust affects the duplicated units in the frontal limb of the anticline, placing intensely folded black shales of the Pilmathué Member over sandstones of the Avilé Member that are locally overturned near the fault plane and form a drag syncline in the footwall (Fig. 9g). The Chacay Melehue anticline, formed by a duplication of the Pilmathué and Avilé Members of the Agrio Formation that afterward were folded above a blind thrust, is very similar in the cross-sections A–A′ and C–C′. However, the repetition and the fault-propagation fold described for the north area show an east vergence, while the same structures in the C–C′ section evidence a clear vergence to the west. We interpret that this change in the direction of movement of the Chacay Melehue structures should be associated with the existence of a tear fault. In the study area this change seems to occur along the valley of the arroyo Chacay Melehue, which constitutes a marked WSW trending structural lineament (Fig. 1b). We have called such lineament as the Chacay Melhue tear fault, which represents a right-lateral strike-slip fault that separates an east-vergent north domain from a west-vergent south domain involving the Chacay Melehue structures (Fig. 5). To the north of this WSW tear fault the axis of the Chacay Melehue anticline plunges in a NNW direction, as evidenced by different units exposed in the core of the fold along strike (Fig. 7). On the other hand, to the south of the Chacay Melehue tear fault the fold axis plunges to the SSE and consequently the Avilé Member disappears in the same direction (Fig. 5). The interpreted tear fault has acted as a structural discontinuity transverse to the fold axis that originated the change in vergence of the structures although it shows a minimum right-lateral offset, which decreases to zero eastward where stratigraphic contacts and the axis of the Chacay Melehue syncline are not displaced (Fig. 5).

5. Kinematic evolution of the Chacay Melehue backthrusts system

In the previous section we have described the characteristics of thrust systems and related folds found in the Agrio Formation. Undoubtedly, the most complex of these structures is the well exposed backthrust system developed to the south of the arroyo Chacay Melehue as shown in the C–C′ cross-section (Fig. 9a). The west-vergent thrusts belonging to this system have a common basal detachment along shales of the Pilmathué Member, as was early recognized by Kozlowski et al. (1996), repeating and folding the upper part of this member together with the sandstones of the Avilé Member. We think that the structures of the C–C′ cross-section are appropriated to analyze the kinematic evolution of the tectonic repetitions that affect the Agrio Formation associated with the Chacay Melehue backthrusts system. Our structural evolution considers only the relative sequence of deformation because geochronologic data exist at adjacent regions whereas they are lacking in the area of the cross-section. Nevertheless, there is a general consensus about the occurrence of at least two periods of compression, during Late Cretaceous-Paleocene and Late Miocene (Zapata et al., 1999; Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Folguera et al., 2007; Rojas Vera et al., 2014),


a) Initial stage
Huitrín Fm.
Agua de la Mula Mb.
Avilé Mb.
Pilmathué Mb.
Agrio Fm.
Model length (300 units = 1 km)
b) Stage 1
Chacay Melehue backthrust (imbrication of Avilé Mb.)
100 u
0.33 km
30°
c) Stage 2.A
initiation of a fault-bend fold (duplication of Pilmathué +Avilé Mb.)
200 u
0.66 km
displacement transmited to younger units
30°
d) Stage 2.B
widening of the fault-bend fold
200 u
0.66 km
e) Stage 3.A
imbrication of Huitrín Fm.
50 u
0.16 km
Avilé over Agua de la Mula Mb. (Fig.9f)
f) Stage 3.B
minor folding and thrusting of
Pilmathué Mb. over Avilé Mb. (Fig.9g)
50 u
0.16 km
g) Stage 4.A
initiation of a tight trishear
fault-propagation fold in depth
(Fig. 9b)
150 u
0.5 km
tip
30°
h) Stage 4.B
Final configuration of cross-section C-C'
(Fig. 9a)
ENE C'
C WSW
Fig.9d
150 u
0.5 km
total shortening
900 u
3 km (50%)
0
1 km

although the relative magnitude of each event is an open issue. Andesitic subvolcanic rocks exposed at the Cerro Mayal (Fig. 1b) have a Late Eocene age (39.7 ± 0.2 Ma) by Ar–Ar on whole rock (Cobbold and Rossello, 2003). Field mapping at this southern region evidence that these intrusions affected the axis of the Mayal syncline (Sánchez et al., 2014), which suggests a pre-Eocene contraction. Early to Middle Miocene volcanic rocks cropping out near Tricao Malal (Fig. 1b), are folded and faulted and unconformably cover folded Mesozoic strata, suggesting pre-Miocene and Late Miocene compressive pulses (Folguera et al., 2007). Recent structural studies and U–Pb data on zircons of andesitic dykes and sills at the Cerro Negro (Fig. 1b) indicate that the magmatic system was coeval with substantial regional shortening active at least until 11 Ma (Gürer et al., 2012).

In order to understand the sequential development of the structures we construct a forward model using the Fault-Fold-Forward software (Allmendinger, 2012). This software allowed us to create a balanced reconstruction of the Chacay Melehue structures, combining fault-bend folds over flat-ramp-flat thrust geometries and trishear fault-propagaion folds, and to estimate the tectonic shortenings in each deformational stage (Fig. 10). The Fault-Fold-Forward software has some limitations and cannot reproduce multi-bend kink fault-bend folds because kink axes due to the active ramp do not refract across higher level inactive ramps and thus bed thickness is not preserved across higher ramps (Allmendinger, 2012). In our initial forward model this problem caused a marked thinning of the Agrio Formation when several slices were imbricated in the backlimb of the Chacay Melehue anticline. In consequence, we have adjusted manually the geometry of the imbrications in the model calculating the appropriated angles for each thrust sheet based on the equations of the fault-bend fold model (Suppe, 1983).

Before running the model, we inserted in the program a template of the C–C′ cross-section in order to adjust the scale between the model and field structures and to draw the pre-deformed beds with their respective stratigraphic thicknesses (Fig. 10a). Again, the model shows a southward view of the structures to easily compare data on the cross-section with field examples. In the interpreted sequence of deformation the first structure is the Chacay Melehue backthrust, which only requires a small shortening of 0.33 km to originate the imbrication of the Avilé Member (Fig. 10b). The Chacay Melehue backthrust, as well as all the faults of the backthrust system, branch off from a basal decollement located within the shales of the Pilmathué Member approximately 150 m below the base of Avilé Member. This depth to detachment was established based on the thickness of Pilmathué Member shales involved in the repetitions that is very similar throughout the study area. We interpret the Chacay Melehue backthrust with a flat-ramp geometry cutting up section, and not propagated along an upper flat on top of the Avilé Member, because southward the Pilmathué Member was thrust over the Agua de la Mula Member (Fig. 5). This backthrust and the next ones were reconstructed with a cutoff angle of 30°, which is in agreement with the Mohr-Coulomb failure criterion, letting us to reproduce the dips measured on the field for the successive imbrications.

In the second stage of deformation, a new backthrust is generated toward the hinterland, but in a normal sequence of deformation because it is in the footwall of the previous Chacay Melehue backthrust (Fig. 10c). In this case the fault-ramp is connected with an upper flat located at the base of Agua de la Mula Member, forming a fault-bend fold that duplicate the Pilmathué and Avilé Members. The hinge of the anticline widens with continued slip and part of this displacement is transferred forward along the upper detachment (Fig. 10d). Shortening at this stage after the complete duplication is 1.32 km. Once the hangingwall has advanced a considerable distance above the upper flat, a new minor backthrust ahead of the forelimb of the fault-bend fold puts the Avilé Member over the Agua de la Mula Member (Fig. 10e). This structure was attained with very low displacement, which is enough to produce the configuration observed on the field (Fig. 9e and f). The same fault slip could explain a minor repetition of the Huitrín Formation observed at the western end of the cross-section (Fig. 9a). As the deformation proceeds another minor backthrust, but relatively out-of-sequence, cut the hinge of the anticline (Fig. 10f). We have interpreted this small structure as a fault-propagation fold that has uplifted and folded the shales of the Pilmathué Member in the hangingwall over the sandstones of the Avilé Member, which are locally overturned near the fault plane (Fig. 9c and e).

After these minor structures, deformation continues with a new backthrust formed toward the west in a piggy-back sequence of faulting (Fig. 10g). This backthrust propagates to the surface from the lower detachment and produces a trishear fault-propagation fold. The Fault-Fold-Forward program lets to change diverse parameters in order to reproduce the more appropriate fold geometry. We tried with many different combinations until we obtained a configuration of the structure comparable with field observations. Among the main parameters considered we used a low propagation to slip relationship ($p/s = 0.6$) and an open trishear angle of 90°, associated with a 30° east dipping fault. The modeled fault-propagation fold has initially a tight and rounded hinge, with higher dips in the frontal limb (Fig. 10g). With continued slip the backthrust breaks through the forelimb and beds in front of the tip line become overturned (Fig. 10h). At the same time, the inclination of the previously imbricated thrust slices in the backlimb increases when they move over the lowermost flat-ramp bend. The hinge of the fault-propagation fold is completely uplifted up to its final position, showing the Avilé Member at the present day erosion profile, after 1 km of shortening. With the last episode of deformation the whole structure in our kinematic model acquires the final configuration (Fig. 10h), which fits very well with the structural data along the C–C′ cross-section (Fig. 9a). At the end of the sequential reconstruction, the cumulative total shortening is of 3 km that represents a 50% of the initial length of the model.

6. Discussion

6.1. Relationship between the tectonic repetitions of the Agrio Formation and the structural development of the Chos Malal FTB

All the structures described in Section 4 evidence notorious tectonic repetitions of the Agrio Formation and imply an important

Fig. 10. Kinematic evolution of the backthrusts system along the C–C′ cross-section (Fig. 8a). Forward modeling was made with the Fault Fold Forward program (Allmendinger, 2012). a) Stage previous to the beginning of the deformation. Bed thicknesses and length of the model were scaled with the data cross-section (300 model units = 1 km). b) Imbrication of the Pilmathué and Avilé Members through the Chacay Melehue backthrust. c-d) Development of a new backthrust producing a fault-bend fold that duplicates the Pilmathué and Avilé Members along an upper decollement at the base of Agua de la Mula Member. e) A new ramp forms above the upper decollement thrusting the Avilé over the Agua de la Mula Member (Fig. 9f). f) A minor out-of-sequence thrust place folded shales of Pilmathué Member over overturned sandstones of Avilé Member (Fig. 9g). g–h) A third backthrust form in depth generating a west-vergent, trishear fault-propagation fold. It produces the final uplift of the anticline hinge exposing the lower slice of the Avilé Member, showing overturned dips in the forelimb and increased dips at the backlimb due to the stacking of successive imbrications. The final shortening due to these structures is 3 km (50%).

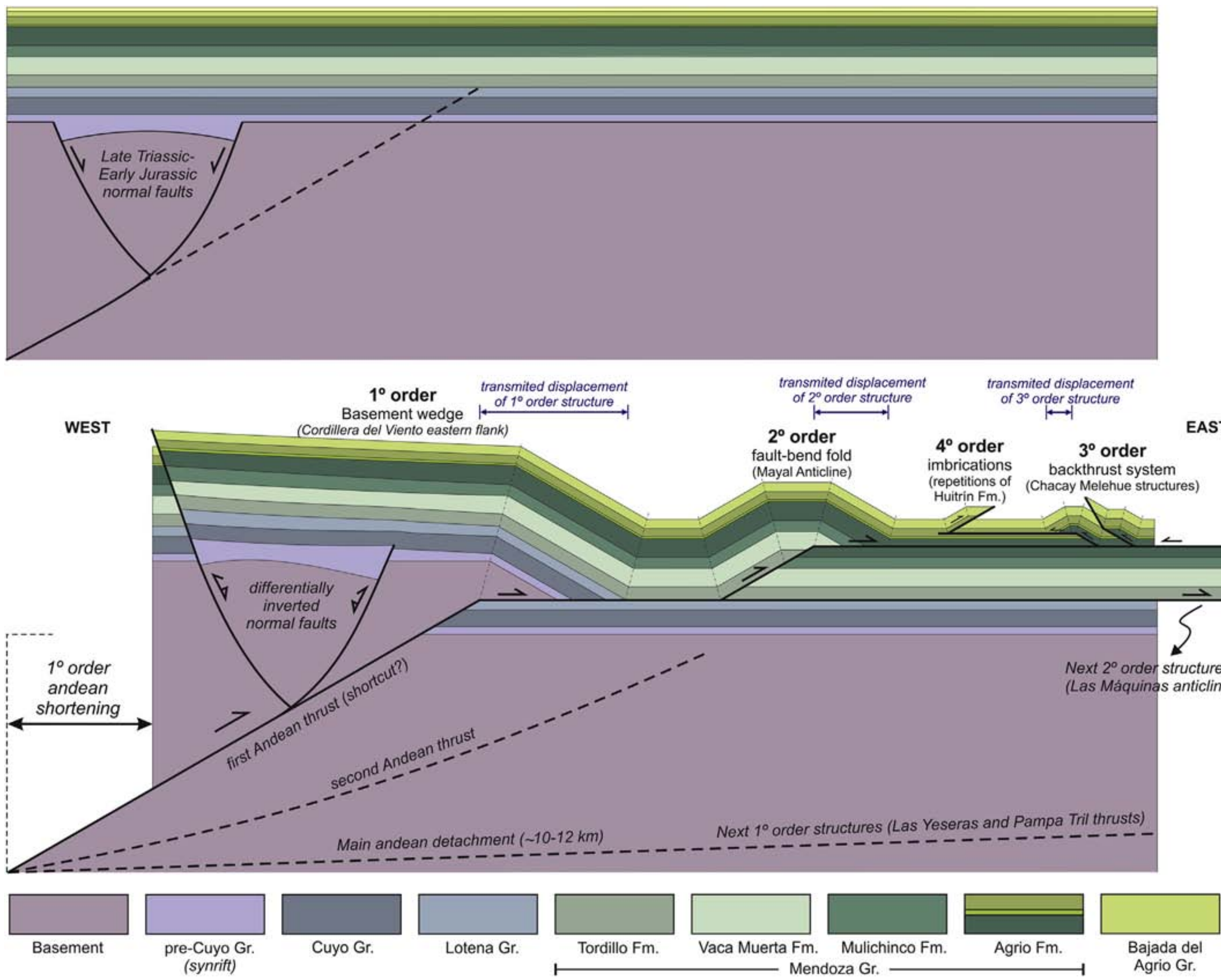


Fig. 11. Regional structural model of the Chos Malal fold-and-thrust belt combining previous interpretations and the new kinematic analysis and reconstruction of the thin-skinned structures in the study area. East and west-dipping Mesozoic normal faults, with different degree of inversion were proposed at the Cordillera del Viento (Both and Coward, 1996; Chaveau et al., 1996; Zapata et al., 1999; Cobbold and Rossello, 2003; Folguera et al., 2007, 2011; Rojas Vera et al., 2014). A new formed Andean thrusts cut and transport these older faults and is inserted in the cover along the evaporites of the Auquilco Formation creating a basement wedge. This thick-skinned or first order structure transfer displacement to the cover forming second order thin-skinned folds (Kozlowski et al., 1996, 1998). We interpret that the second order anticlines are originated as fault-bend folds that transmit deformation to an upper decollement along the Pilmathué Member of the Agrio Formation. As a consequence, third order structures form over this detachment generating in this case the backthrust system studied in this paper (Fig. 10). Finally, when some of the backthrusts propagate to a flat detachment at the base of Agua de la Mula Member, a fault-bend fold is created, which transfer part of the displacement to shallower units giving birth to fourth order structures such as minor thrusts and folds involving the Huitrín and Rayoso Formations.

horizontal shortening that took place along a local detachment within the shales of the Pilmathué Member. A kinematic reconstruction of the backthrust system at the Chacay Melehue area, cross-section C–C′, demonstrates that these complex structures were formed due to approximately 3 km of westward-directed slip above the basal decollement (Fig. 10). Such deformation affecting the Early Cretaceous Agrio Formation requires the existence of structures involving older units of the sedimentary sequence of the Neuquén Basin that were able to transfer tectonic displacement from deeper to shallow levels of the cover. Most of the regional structural cross-sections along the Chos Malal FTB highlight the major basement uplifts overshadowing and simplifying the thin-skinned structures (Both and Coward, 1996; Chaveau et al., 1996; Kozlowski et al., 1996; Cobbold et al., 1999; Zapata et al., 1999; Folguera et al., 2007, 2011; Rojas Vera et al., 2014). A structural model connecting thick and thin-skinned structures of the Chos Malal FTB was presented by Kozlowski et al. (1996, 1998). This model considers that the Cordillera del Viento is a first order structure formed as a large basement-involved fault-bend fold that inserts in the cover along the shales of Vaca Muerta Formation creating thin-skinned or second order structures. These second order folds in front of the Cordillera del Viento (e.g. Las Máquinas anticline) were reconstructed as detachment folds (Kozlowski et al., 1996, 1998) or fault-propagation folds (Cobbold et al., 1999), even as basement-involved fault-propagation folds (Zapata et al., 1999), all mechanisms that consume the fault slip to produce folding. Chaveau et al. (1996) have interpreted the Las Máquinas structure as a fault system associated with the inversion of an east-dipping normal fault and ahead of these structures they depicted a west-vergent fault-bend fold.

In order to link the recognized tectonics repetitions of the Agrio Formation with the major thick and thin-skinned structures of the

Chos Malal FTB we elaborate a regional structural model emphasizing the importance of the fault-bend folding mechanism to transfer tectonic displacements at different structural levels (Fig. 11). As we have mentioned previously several authors have proposed east and west dipping Mesozoic normal faults beneath the Cordillera del Viento that suffered different magnitude of inversion during the Late Cretaceous compression (Both and Coward, 1996; Chaveau et al., 1996; Zapata et al., 1999; Cobbold and Rossello, 2003; Folguera et al., 2007, 2011; Rojas Vera et al., 2014). In our schematic interpretation we considered that after the inversion, these normal faults were passively transported above new-formed low-angle faults or shortcuts (Fig. 11), which is in agreement with recent regional reconstructions in the area (Rojas Vera et al., 2014). These Andean thrusts inserted on the cover within the evaporites of the Auquilco Formation form basement wedges that are equivalent to the first order structures proposed by Kozlowski et al. (1996, 1998). The amount of displacement transferred by this thick-skinned structure depends on the frontal dip of the wedge and it will be maximum when this frontal dip is equal to the fault angle (Fig. 11). In this context, the Curileuvú fault, which puts Mesozoic sedimentary rocks over Miocene volcanic rocks to the north of the study area (Folguera et al., 2007), could be interpreted as a Late Miocene out-of-sequence thrust that breaks through the front of the wedge. The displacement transferred by the first order structure produces several second order thin-skinned structures detached above the Auquilco evaporites, some of which necessarily should be reconstructed as fault-bend folds permitting the translation of part of the fault slip to shallow units (Fig. 11). A second order anticline involving the whole Mendoza Group moves over a flat-ramp-flat thrust geometry and transmits part of its displacement from the Auquilco Formation to an upper detachment within the Pilmathué Member. Contraction above this upper decollement generates the east-vergent thrusts or alternatively the backthrusts that repeat the Agrio Formation, which are considered third order structures (Fig. 11). These structures include imbrications and/or duplications involving the upper part of the Pilmathué Member and the Avilé Member. When these layers are moved over an upper flat, for instance at the base of Agua de la Mula Member (Fig. 10c and d), the transferred displacement generates structures that involve the younger units of the sedimentary sequence. These shallower or fourth order structures can include small repetitions of the basal members of the Huitrín Formation (Fig. 11) or as we have observed in other places of the Chos Malal FTB, minor folding and faulting involving the Huitrín and Rayoso Formations commonly preserved in the core of synclines.

6.2. Implications for oil exploration

Our model of a backthrust system that stacks several slices of the Avilé Member (Fig. 10), well exposed at the Chacay Melehue area (Fig. 9), and its temporal and spatial relationship with major thin and thick-skinned structures (Fig. 11), could be suitable to explain the development of structural traps in neighbor areas of economic relevance such as the El Portón and Filo Morado oil fields. These oil fields are some of the most important oil accumulations at the north of Neuquén Province, which are situated along the Andean mountain front approximately 35 km to the east of the Tromen volcano (Fig. 1). These hydrocarbon deposits occur in complex structural traps associated with thin-skinned structures that were developed in front of the major east-vergent basement-cored Pampa Tril anticline (Ploszkiewicz and Viñes, 1987; Zapata et al., 2001; Allmendinger et al., 2004; Zamora Valcarce et al., 2006b). The most important reservoir units on these oil fields are the sandstones with high primary porosity of the Lower Troncoso Member of the Huitrín Formation and the Avilé Member of the Agrio Formation, and the naturally fractured rocks of the Mulichinco Formation (Zapata et al., 2001). Early workers have emphasized the roll of thrusting and fault-bend folding mechanisms to transmit deformation from the basement to the cover rocks attempting to explain the basement-involved Pampa Tril structure and the easternmost thin-skinned structures that form the Filo Morado oil field, interpreted as a classic triangle zone (Ploszkiewicz and Viñes, 1987; Ramos and Barbieri, 1988; Kozlowski et al., 1998). Later acquisition of 3D seismic and numerous drilled oil wells enabled to reinterpret the El Portón – Filo Morado structural trend as a combination of initial detachment folding above the Auquilco–Vaca Muerta Formations and subsequent fault-propagation folding in front of an inverted basement-involved normal fault (Zapata et al., 2001; Zamora Valcarce et al., 2006b). Backthrusts repeating the Lower Troncoso and the Avilé Members at the fold crest were interpreted from well data (Zamora Valcarce et al., 2006b). An alternative interpretation of the basement-cored Pampa Tril anticline as a trishear fault-propagation fold predicts that the basement fault responsible for the structure nucleated at about 9.4 km below sea level and strongly indicates that this is a newly formed fault and not a reactivated Mesozoic rift structure (Allmendinger et al., 2004). Beyond the increased knowledge about geometry of the Pampa Tril and Filo Morado structures, we believe that the persistent uncertainties at depth make possible to consider alternative interpretations. We think that our model relating thick and thin-skinned structures (Fig. 11) could explain in a different way the structural configuration of the El Portón and Filo Morado oil fields. In particular, some specific points to be considered include: i) The Pampa Tril structure can be interpreted as a ramp-anticline forming a basement wedge in depth similar to the Cordillera del Viento structure, with differentially inverted normal faults being passively transported in the hangingwall. This model could explain the basement uplift together with an important horizontal shortening that can be consumed in the generation of the El Portón – Filo Morado structures; ii) The thin-skinned structure could also be interpreted as a combination of fault-bend folding, permitting the duplication of some units as the Mulichinco Formation, and fault-propagation folding that increase the fold dips; iii) Displacement associated with the development in depth of a fault-bend anticline can be transferred to a shallower decollement within the Pilmathué Member creating a third order backthrust that causes the repetition of the Avilé and Lower Troncoso Members detected by oil wells. Summarizing, field surveys and the understanding of the kinematics of complex thrusting structures as the exposed in the studied area, which have produced duplication and folding of important reservoir sandstones as the Avilé Member, can help to improve the interpretations in oil fields poorly imaged by seismic data and additionally can provide a robust structural model to look for new complex structural traps in unexplored areas.

7. Conclusions

Based on a detailed field work we have recognized, mapped and interpreted a suite of tectonics repetitions involving the Early Cretaceous Agrio Formation. Faults producing such duplications are detached along the marine dark-gray shales that form the Pilmathué Member and consequently involve the upper part of this member and the sandstones of the overlying Avilé Member. These hectometer to kilometer-scale structures include: simple imbrications, complete duplications above an upper flat along shales of the younger Agua de la Mula Member, and fault-propagation folding at depth. In the northern sector of the study area these structures have a clear east-vergence while in the central and southern regions they show a defined west-vergence. This change in the vergence apparently takes place through the WSW trending Chacay Melhue tear fault, a marked structural lineament that represents a strike-slip fault with a minimum right-lateral offset. The more complex of such structures, observed in the central region of the study area, combines imbrication, duplication and folding of the Agrio Formation related to a backthrust system. By means of the Fault-Fold-Forward software we made a forward model of these structures in order to interpret the relative sequence of deformation. A total shortening of 3 km (50%) was necessary to obtain the structural configuration associated with the backthrust system. This shortening calculated for the structures that deformed the Pilmathué Member and younger units implies the existence of other structures capable of transferring displacement from deeper to shallower stratigraphic levels. We constructed a regional cross-section of the Chos Malal FTB interpreting kilometer-scale fault-bend and fault-propagation folds, detached above the evaporites of the Auquilco Formation. Restoration of this cross-section results in a minimum tectonic shortening of 15.5 km (28.3%). We propose a regional structural model in which the basement-involved or first order structures transfer displacement to the cover producing second order fault-bend folds that involve the whole Mendoza Group and connect to an upper flat along the Pilmathué Member of the Agrio Formation. Thus, the transmitted displacements of these fault-bend folds generate the third order thrusts, backthrusts and folds, affecting the Agrio Formation. When some of the structures duplicate the units as a fault-bend fold, part of the deformation is transferred to overlying rocks along the shales of the Agua de la Mula Member and it creates minor or fourth order structures commonly affecting the younger Huitrín and Rayoso Formations. The proposed structural model suggests a strong connection between the thick and thin-skinned structures of the Chos Malal FTB during the Andean orogeny by means of associated flat-ramp-flat thrust trajectories placed at different structural levels. Our regional structural model together with the detailed kinematic analysis of complex thrusting structures repeating reservoir sandstones as the Avilé Member, offer an alternative way to interpret prospective structures for oil exploration in fold-and-thrust belts.

Acknowledgments

The present studies were supported by several grants from CeCyT-UNS (24/H091), ANPCyT (Pict 0166) and CONICET (PIP 0390). We kindly acknowledge Mauricio Espié, Joaquín Lavios and Candela Gorza for their valuable help during field works. Seismic and well data were provided by the Subsecretaría de Minería e Hidrocarburos de la Provincia de Neuquén. We are very grateful to Veronica Guler (Universidad Nacional del Sur) for her collaboration in the search and study of micro fossils in samples of the Agrio Formation. The comments and suggestions by Beatriz Aguirre-Urreta and an anonymous reviewer improved considerably this paper.

References

Aguirre-Urreta, B., Rawson, P., Concheyro, A., Bown, P., Ottone, E., 2005. Lower Cretaceous (Berriasian-Aptian) Biostratigraphy of the Neuquén Basin. In: Veiga, G.D., Spalletti, L.A., Howell, J.A., Schwarz, E. (Eds.), The Neuquén Basin: A Case Study in Sequence Stratigraphy and Basin Dynamics, Geological Society of London, Special Publication, vol. 252, pp. 57–81.

Aguirre-Urreta, B., Pazos, P., Lazo, D., Fanning, M., Litvak, V., 2008. First U–Pb SHRIMP age of the Hauterivian stage, Neuquén Basin, Argentina. J. South Am. Earth Sci. 26, 91–99.

Allmendinger, R., Zapata, T., Manceda, R., Dzelalija, F., 2004. Trishear kinematic modeling of structures, with examples from the Neuquén Basin, Argentina. In: McClay, K. (Ed.), Thrust Tectonics and Hydrocarbon Systems, AAPG memoir, vol. 82, pp. 356–371.

Allmendinger, R.W., 2012. Fault Fold Forward.v.6. http://www.geo.cornell.edu/geology/faculty/RWA/programs/faultfoldforward-v-6.html.

Both, J., Coward, M., 1996. Basement faulting and inversión of the NW Neuquén Basin, Argentina. In: 3° International Symposium on Andean Geodynamics, St. Malo (France), pp. 295–298. Extended Abstracts.

Caminos, R., Azcuy, C., 1991. Fases diastróficas neopaleozoicas. In: Archangelsky, S. (Ed.), El Sistema Pérmico en la República Argentina y en la República Oriental del Uruguay, 12° Congreso Internacional de la Estratigrafía y Geología del Carbonífero y del Pérmico, Academia Nacional de Ciencias, Córdoba, pp. 255–265.

Chaveau, V., Niviere, B., Cobbold, P., Rossello, E., Ballard, J., Eichenseer, H., 1996. Structure of the Andean foothills, Chos Malal Region, Neuquén Basin, Argentina. In: 3° International Symposium on Andean Geodynamics, St. Malo, pp. 315–318. Extended Abstracts.

Cobbold, P., Rossello, E., 2003. Aptian to recent compressional deformation, foothills of the Neuquén Basin Argentina. Mar. Pet. Geol. 20, 429–443.

Cobbold, P., Diraison, M., Rossello, E., 1999. Bitumen veins and Eocene transpression, Neuquén Basin, Argentina. Tectonophysics 314, 423–442.

Cobbold, P., Rossello, E., Marques, F., 2008. Where is the evidence for Oligocene rifting in the Andes? Is it in the Loncopué Basin of Argentina?. In: 7° International Symposium on Andean Geodynamics, Niza, pp. 148–151. Extended Abstracts.

Cristallini, E., Tomezzoli, R., Pando, G., Gazzera, C., Martínez, J., Quiroga, J., Buhler, M., Bechis, F., Barredo, S., Zambrano, O., 2009. Controles precuyanos en la estructura de la Cuenca Neuquina. Rev. la Asoc. Geol. Argent. 65 (2), 248–264.

Di Giulio, A., Ronchi, A., Sanfilippo, A., Tiepolo, M., Pimentel, M., Ramos, V., 2012. Detrital zircon provenance from the Neuquén Basin (south-central Andes): Cretaceous geodynamic evolution and sedimentary response in a retroarc-foreland basin. Geology 40, 559–562.

Dimieri, L., 1997. Tectonic wedge geometry at Bardas Blancas, southern Andes (36° S), Argentina. J. Struct. Geol. 19 (11), 1419–1422.

Folguera, A., Ramos, V., Zapata, T., Spagnuolo, M., 2007. Andean evolution at the Guañacos and Chos Malal fold and thrust belts (36°30'-37°S). J. Geodyn. 44, 129–148.

Folguera, A., Bottesi, G., Zapata, T., Ramos, V., 2008. Crustal collapse in the Andean back-arc since 2 Ma: Tromen volcanic plateau, Southern Central Andes (36°40'-37°30'S). Tectonophys. Special Issue Andean Geodyn. 459, 140–160.

Folguera, A., Rojas Vera, E., Spagnuolo, M., Orts, D., Sagripanti, L., Mariot, M., Ramos, M., Bottesi, G., Ramos, V., 2011. Los Andes Neuquinos. In: Leanza, H., Arregui, C., Carbone, O., Danieli, J., Vallés, J. (Eds.), Geología y Recursos Naturales de la Provincia del Neuquén, Relatorio, pp. 349–365.

Folguera, A., Alasonati Tasárová, Z., Götze, H., Rojas Vera, E., Giménez, M., Ramos, V., 2012. Retroarc extension in the last 6 Ma in the South-Central Andes (36°S-40°S) evaluated through a 3-D gravity modeling. J. South Am. Earth Sci. 40, 23–37.

Folguera, A., Ramos, V., 2011. Repeated eastward shifts of arc magmatism in the Southern Andes: a revision to the long-term pattern of Andean uplift and magmatism. J. South Am. Earth Sci. 32 (4), 530–545.

Franzese, J., Spalletti, L., 2001. Late Triassic–Early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. J. South Am. Earth Sci. 14, 257–270.

Franzese, J., Spalletti, L., Gómez Pérez, I., Macdonald, D., 2003. Tectonic and paleoenvironmental evolution of Mesozoic sedimentary basins along the Andes foothills of Argentina (32°–54°S). J. South Am. Earth Sci. 16, 81–90.

Galland, O., Hallot, E., Cobbold, P., Ruffet, G., de Bremond d'Ars, J., 2007. Volcanism in a compressional Andean setting: a structural and geochronological study of Tromen volcano (Neuquén province, Argentina). Tectonics 26, TC4010. http://dx.doi.org/10.1029/2006TC002011.

Giambiagi, L., Bechis, F., García, V., Clark, A., 2008. Temporal and spatial relationships of thick- and thin-skinned deformation: a case study from the Malargüe fold-and-thrust belt, southern Central Andes. Tectonophysics 459 (1–4), 123–139.

Giambiagi, L., Ghiglione, M., Cristallini, E., Bottesi, G., 2009. Kinematic models of basement/cover interaction: insights from the Malargüe fold and thrust belt, Mendoza, Argentina. J. Struct. Geol. 31, 1443–1457.

Gulisano, C., Gutiérrez Pleimling, A., 1995. The Jurassic of the Neuquén Basin, a) Neuquén Province. Asociación Geológica Argentina, Buenos Aires, pp. 1–111.

Gürer, D., Galland, O., Leanza, H., Sassier, C., Cobbold, P., Rossello, E., 2012. The structure and evolution of magmatic complexes in fold-and-thrust belts: a case study of Cerro Negro, Neuquén Province, Argentina. Geophys. Res. Abstr. 14, EGU2012–13410.

Guzmán, C., Cristallini, E., Bottesi, G., 2007. Contemporary stress orientations in the Andean retroarc between 34°S and 39°S from borehole breakout analysis. Tectonics 26, TC3016. http://dx.doi.org/10.1029/2006TC001958.

Howell, J., Schwarz, E., Spalletti, L., Veiga, G., 2005. The neuquén Basin: an overview. In: Veiga, G., Spalletti, L., Howell, J., Schwarz, E. (Eds.), The Neuquén Basin: a Case Study in Sequence Stratigraphy and Basin Dynamics, Geological Society of London, Special Publications, vol. 252, pp. 1–14.

Kay, S., Burns, W., Copeland, P., Mancilla, O., 2006. Late Cretaceous to Recent magmatism over the Neuquén Basin: evidence for transient shallowing of the subduction zone under the Neuquén Andes (36°S to 38°S latitude). In: Kay, S., Ramos, V. (Eds.), Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén Basin (35°-39°S lat), Geological Society of America, Special Paper, vol. 407, pp. 19–60.

Kozlowski, E., Cruz, C., Sylwan, C., 1996. Geología estructural de la zona de Chos Malal, Cuenca Neuquina, Argentina. In: 13° Congreso Geológico Argentino y 3° Congreso Argentino de Exploración de Hidrocarburos (Buenos Aires). Actas, vol. 1, pp. 15–26.

Kozlowski, E., Cruz, C., Sylwan, C., 1998. Modelo exploratorio en la faja corrida de la Cuenca Neuquina, Argentina. Boletín Inf. Pet. 55, 4–23.

Lazo, D., Cichowolski, M., Rodríguez, D., Aguirre-Urreta, B., 2005. Lithofacies, palaeoecology and palaeoenvironments of the Agrio Formation, Lower Cretaceous of the Neuquén Basin, Argentina. In: Veiga, G., Spalletti, L.A., Howell, J., Schwarz, E. (Eds.), The Neuquén Basin: A Case Study in Sequence Stratigraphy and Basin Dynamics, Geological Society of London, Special Publication, vol. 252, pp. 295–315.

Lazo, D., Concheyro, A., Ottone, G., Guler, V., Aguirre-Urreta, B., 2009. Bioestratigrafía integrada de la Formación Agrio en su localidad tipo, Cretácico temprano de Cuenca Neuquina. Rev. la Asoc. Geológica Argent. 65 (2), 322–341.

Leanza, H., 2003. Las sedimentitas huitrinianas y rayosianas (Cretácico inferior) en el ámbito central y meridional de la cuenca Neuquina, Argentina. In: Servicio Geológico Minero Argentino, Serie Contribuciones Técnicas-Geología, vol. 2, pp. 1–31. Buenos Aires.

Leanza, H., 2009. Las principales discordancias del Mesozoico de la Cuenca Neuquina según observaciones de superficie. Rev. del Mus. Argent. Ciencias Nat. 11 (2), 145–184.

Leanza, H., Hugo, C., Repol, D., Gonzalez, R., Danieli, J., 2005. Hoja Geológica 3969-I Zapala, Provincia del Neuquén, vol. 275. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Boletín, Buenos Aires, pp. 1–128.

Leanza, H., Mazzini, A., Corfu, F., Llambías, E., Svensen, H., Planke, S., Galland, O., 2013. The Chachil Limestone (Pliensbachian-earliest Toarcian) Neuquén Basin, Argentina: U-Pb age calibration and its significance on the Early Jurassic evolution of southwestern Gondwana. J. South Am. Earth Sci. 42, 171–185.

Legarreta, L., Gulisano, C., 1989. Análisis estratigráfico secuencial de la Cuenca Neuquina (Triásico superior-Terciario inferior). In: Chebli, G., Spalletti, L. (Eds.), Cuencas Sedimentarias Argentinas, Serie Correlación Geológica, vol. 6. Universidad Nacional de Tucumán, pp. 221–243.

Legarreta, L., Uliana, M., 1996. The Jurassic succession in west-central Argentina: stratal patterns, sequences and paleogeographic evolution. Palaeogeogr. Palaeoclimatol. Palaeoecol. 120, 303–330.

Llambías, E., Quenardelle, S., Montenegro, T., 2003. The Choiyoi Group from central Argentina: a subalkaline transitional to alkaline association in the craton adjacent to the active margin of the Gondwana continent. J. South Am. Earth Sci. 16, 243–257.

Llambías, E., Leanza, H., Carbone, O., 2007. Evolución tectono-magmática durante el Pérmico al Jurásico Temprano en Cordillera del Viento (37°5'S–37°15'S): Nuevas Evidencias geológicas y geoquímicas del inicio de la Cuenca Neuquina. Rev. la Asoc. Geol. Argent. 62 (2), 217–235.

Manceda, R., Figueroa, D., 1995. Inversion of the Mesozoic Neuquén Rift in the Malargüe Fold and Thrust Belt, Mendoza, Argentina. In: Tankard, A.J., Suárez, S., Welsink, H.J. (Eds.), Petroleum Basins of South America, American Association of Petroleum Geologists Memoir 62, pp. 369–382.

Mescua, J., Giambiagi, L., Ramos, V., 2013. Late Cretaceous Uplift in the Malargüe fold-and-thrust belt (35°S), southern Central Andes of Argentina and Chile. Andean Geol. 40 (1), 102–116.

Messager, G., Niviére, B., Martinod, J., Lacan, P., Xavier, J., 2010. Geomorphic evidence for Plio-Quaternary compression in the Andean foothills of the southern Neuquén Basin, Argentina. Tectonics 29, TC4003,. http://dx.doi.org/10.1029/2009TC002609.

Ploszkiewicz, V., Viñes, R., 1987. Filo Morado: Un descubrimiento exploratorio en cinturón plegado. Boletín Inf. Pet. 4 (10), 97–102 (Buenos Aires).

Ramos, V., 1998. Estructura del sector occidental de la faja plegada y corrida del Agrio, Cuenca Neuquina, Argentina. In: 10° Congreso Latinoamericano de Geología. Actas, vol. 2, pp. 105–110. Buenos Aires.

Ramos, V., 1999. Plate tectonic setting of the Andean Cordillera. Episodes 22 (3), 183–190.

Ramos, V., 2010. The tectonic regime along the Andes: present-day and Mesozoic regimes. Geol. J. 45, 2–25.

Ramos, V., Barbieri, M., 1988. El volcanismo cenozoico de Huantraico: edad y relaciones isotópicas iniciales, provincia de Neuquén. Rev. la Asoc. Geol. Argent. 18, 210–223.

Ramos, V., Folguera, A., 2005. Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic arc and foreland deformation. In: Veiga, G., Spalletti, L., Howell, J., Schwarz, E. (Eds.), The Neuquén Basin: A Case Study in Sequence Stratigraphy and Basin Dynamics, Geological Society of London, Special Publications, vol. 252, pp. 15–35.

Ramos, V., Kay, S., 2006. Overview of the tectonic evolution of the southern Central Andes of Mendoza and Neuquén (35°–39°S latitude). In: Kay, S., Ramos, V. (Eds.), Evolution of an Andean margin: A Tectonic and Magmatic view from the Andes to the Neuquén Basin (35°-39°S lat), Geological Society of America, Special Paper, vol. 407, pp. 1–18.

Rojas Vera, E., Folguera, A., Zamora Valcarce, G., Bottesi, G., Ramos, V., 2014. Structure and development of the Andean system between 36° and 39°S. J. Geodyn. 73, 34–52.

Sánchez, N., Turienzo, M., Dimieri, L., Araujo, V., 2014. Evolución de las estructuras andinas en la faja corrida y plegada de Chos Malal: interacción entre el basamento y la cubierta sedimentaria de la Cuenca Neuquina. Rev. la Asoc. Geológica Argent. 71 (2) (in press).

Spalletti, L., Poiré, D., Schwarz, E., Veiga, G., 2001a. Sedimentologic and sequence stratigraphic model of a Neocomian marine carbonate-siliciclastic ramp: Neuquén Basin, Argentina. J. South Am. Earth Sci. 14, 609–624.

Spalletti, L., Poiré, D., Pirrie, D., Matheos, S., Doyle, P., 2001b. Respuesta sedimentológica a cambios en el nivel de base en una secuencia mixta clástica-carbonática del Cretácico de la Cuenca Neuquina, Argentina. Rev. la Soc. Geol. España 14, 57–74.

Spalletti, E., Veiga, G., 2007. Variability of continental depositional systems during lowstand sedimentation: an example from the Kimmeridgian of the Neuquén Basin, Argentina. Lat. Am. J. Sedimentol. Basin Anal. 14 (2), 85–104.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. Am. J. Sci. 283, 684–721.

Torres Carbonell, P., Dimieri, L., Olivero, E., 2013. Evaluation of strain and structural style variations along the strike of the Fuegian thrust-fold belt front, Argentina. Andean Geol. 40 (3), 438–457.

Tunik, M., Folguera, A., Naipauer, M., Pimentel, M., Ramos, V., 2010. Early uplift and orogenic deformation in the Neuquen Basin: constraints on the Andean uplift from U-Pb and Hf isotopic data of detrital zircons. Tectonophysics 489, 258–273.

Turienzo, M., 2010. Structural style of the Malargüe fold-and-thrust belt at the Diamante River area (34°30'–34°50' S) and its linkage with the Cordillera Frontal, Andes of central Argentina. J. South Am. Earth Sci. 29, 537–556.

Turienzo, M., Dimieri, L., Frisicale, C., Araujo, V., Sánchez, N., 2012. Cenozoic structural evolution of the Argentinean Andes at 34°40' S: a close relationship between basement and cover deformation. Andean Geol. 39 (2), 317–357.

Uliana, M., Biddle, K., Cerdán, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins. In: Tankard, A., Balkwill, H. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins, American Association of Petroleum Geologists Memoir, vol. 46, pp. 599–614.

Veiga, G., Spalletti, L., Flint, S., 2002. Aeolian/fluvial interactions and high resolution sequence stratigraphy of a non-marine lowstand wedge: the Avilé Member of the Agrio Formation (Lower Cretaceous) in central Neuquén Basin, Argentina. Sedimentology 49, 1001–1019.

Veiga, G., Spalletti, L., Schwarz, E., 2011. El Miembro Avilé de la Formación Agrio (Cretácico Temprano). In: Leanza, H., Arregui, C., Carbone, O., Danieli, J., Vallés, J. (Eds.), Geología y Recursos Naturales de la Provincia del Neuquén, Relatorio, pp. 161–173.

Vergani, G., Tankard, A., Belotti, H., Welsink, H., 1995. Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. In: Tankard, A., Suárez, R., Welsink, H. (Eds.), Petroleum Basins of South America, American Association of Petroleum Geologists Memoir, vol. 62, pp. 383–402.

Weaver, C., 1931. Paleontology of the jurassic and cretaceous of west Central Argentina. Memoirs Univ. Wash. 1, 1–595.

Zamora Valcarce, G., Zapata, T., del Pino, D., Ansa, A., 2006a. Structural evolution and magmatic characteristics of the Agrio fold-and-thrust belt. In: Kay, S., Ramos, V. (Eds.), Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén Basin (35°-39°S lat), Geological Society of America, Special Paper, vol. 407, pp. 125–145.

Zamora Valcarce, G., Zapata, T., Ansa, A., Selva, G., 2006b. Three-dimensional structural modeling and its application for development of the El Portón field, Argentina. Am. Assoc. Petrol. Geol. Bull. 90 (3), 307–319.

Zamora Valcarce, G., Rapalini, A., Spagnuolo, C., 2007. Reactivación de estructuras cretácicas durante la deformación miocena, Faja plegada del Agrio, Neuquén. Rev. la Asoc. Geol. Argent. 62 (2), 299–307.

Zamora Valcarce, G., Zapata, T., Ramos, V., Rodríguez, F., Bernardo, L., 2009. Evolución tectónica del Frente Andino en Neuquén. Rev. la Asoc. Geol. Argent. 65 (1), 192–203.

Zapata, T., Folguera, A., 2005. Tectonic evolution of the Andean Fold and Thrust Belt of the Southern Neuquén Basin, Argentina. In: Spalletti, L., Veiga, G., Schwarz, E., Howell, J. (Eds.), The Neuquén Basin: A case study in sequence stratigraphy and basin dynamics, Geological Society of London, Special Publication, vol. 252, pp. 37–56.

Zapata, T., Brissón, I., Dzelalija, F., 1999. La estructura de la faja plegada y corrida andina en relación con el control del basamento de la Cuenca Neuquina. Boletín Inf. Pet. 60, 113–121 (Buenos Aires).

Zapata, T., Dzelalija, F., Olivieri, G., 2001. Desarrollo de reservorios fracturados de la formación Mulichinco usando modelado structural 3D: yacimiento Filo Morado, Cuenca Neuquina, Argentina. Boletín Inf. Pet. 66, 38–47.

Zavala, C., Arcuri, M., Di Meglio, M., Zorzano, A., 2011a. Las Capas de San Eduardo: 130 metros de arenas en el Miembro Inferior de la Fm. Agrio. Cretacico Inferior, Cuenca Neuquina. In: 8° Congreso de Exploración y Desarrollo de Hidrocarburos, Mar del Plata, Actas CD, pp. 215–224.

Zavala, C., Arcuri, M., Di Meglio, M., Zorzano, A., Turienzo, M., 2011b. Estudio de las arenas del Miembro Inferior de la Formación Agrio. YPF (unpublished report), pp. 1–74.