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The Evolution of the Chilean-Argentinean Andes

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For our partners of marvelous voyages through the Andes

Preface

This book analyzes the tectonic evolution of the Argentinean and Chilean Andes through four parts: the first dealing with the structure of the fore-arc from bathymetric, gravimetric, and seismic data; the second part that discusses the Paleozoic evolution of this sector, first showing the paleomagnetic behavior of the continent during this period and then discussing the different hypothesis associated with the accretion of continental slivers and consequent closure of ocean basins, producing deformation and metamorphism, reconstructing the geometry of the Early Paleozoic orogens and arcs across South American western sector; the third part that analyzes the proto-Andean arc evolution, showing the paleomagnetic path of the margin, clues about its early arc activity, its relation to LIP activity associated with Pangea supercontinent desintegration and subduction zone; the fourth part that discusses early development of the Andes that started as a non-organized collage of within-plate deformation sectors that lately established next to the subduction zone when the south Atlantic Ocean started to expand; and finally, the fifth part that discusses different aspects of the Cenozoic evolution of the Andes and its contemporaneous volcanic arc, such as development of shallow subduction settings through time, the role of dynamic subsidence, opening and closure of intra- and back-arc basins.

In detail, the first part is composed of three chapters. The first chapter by Contreras Reyes et al. analyzes from wide-angle seismic data the structure of the submerged fore-arc as a result of the balance between sediment accretion and sediment subduction and crustal erosion. Then, different segments are subdivided that are characterized by dominant frontal erosion or accretion and are defined by climate conditions, sediment dispersal pattern along the trench, and subduction of bathymetric highs. The second chapter by Maksymowicz and Tassara analyzes the geometry of the submerged frontal prism as a function of basal and poral pressure conditions. Those systems that are subjected to frontal crustal erosion become oversteepened since these are affected by normal faulting that triggers internal saturation with seawater. Additionally, this chapter highlights the role of these morphological variations on seismic segmentation along the subduction zone. The third chapter in this first part belongs to Álvarez et al. and analyzes vertical gradients in gravity anomalies and their relation to co- and post-seismic rupture zones of giant earthquakes along the subduction zone and their complex internal structure. Additionally, satellite measurements can show changes in the gravity field that could be used to predict rupture propagation along the subduction zone. Then, variable fore-arc structure revealed by gravity data shows to have an important influence in the way that ruptures propagate and therefore in seismic segmentation and their potential.

The second part starts with Rapalini et al. chapter that deals with paleomagnetic reconstructions that describe South American path as part of Gondwana during the Paleozoic. The second chapter by Heredia et al. discusses the complex collage of continental slivers that have formed the western Gondwana border that is being reconstructed on the basis of the recognition of different deformational vergences, superimposed metamorphic and deformational events, and recognition of internal and external parts of collisional orogens. The third chapter by Ramos is a reconstruction of the Early Paleozoic arc and consequently the western border of Gondwana, allowing identifying subsequent crustal accretions though differential exhumation levels preserved along the margin.

The third part starts with Oliveros et al. chapter that analyzes magmatism in northern Chile showing that arc activity had already established since the Triassic, a period that had been considered devoid of subduction processes in western Gondwana. A short lapse characterized by a decrease in magmatic activity appeared at the time when the arc established nearer the subduction zone, at the time when the crust became less assimilated by mantle derived products. Naipauer et al. discuss this same magmatic stage in Northern Patagonia discussing its relation to the proto-Pacific border and LIP activity in the Karoo-Ferrar anomaly, concluding that at these latitudes plume activity influenced considerably composition of near-trench magmatism.

The fourth part starts with Iglesia Llanos chapter that analyzes using paleo-magnetic data the path of southern Gondwana in Jurassic times. During this time the supercontinent experiments important latitudinal variations, first displacing to the north, and then returning to southern latitudes. Continental absolute displacements together with the opening of the Weddell Sea at southern Gondwana are the clue to explain within-plate deformations in Patagonia, analyzed in the second chapter by Navarrete et al. This chapter also describes early deformations through the western border of Patagonia at the time of South Atlantic opening. These proto-Andean deformations are also recorded in northern Chile, lately reactivated during the development of the Neogene Chilean-Pampean flat subduction zone, as it is described in the third chapter made by Martínez et al., Gianni et al. in the fourth chapter study synorogenic sedimentation in Northern Patagonia and southern Central Andes showing a diachronism in the uplift of the Cretaceous proto-Andes. This is interpreted as due to the subduction of active ocean ridges that are depicted in recent plate models. The next chapter by Arriagada analyzes first-order inflections of the South American subduction border using paleomagnetic data, determining their origin as oroclines formed diachronously and linked to basement heterogeneities associated with crustal amalgamation in Proterozoic to Paleozoic times. Finally in this part, the chapter of Iannelli et al. calculates ancient crustal thicknesses and degree of influence of the subduction slab on arc-related rocks of Paleogene age, determining that the Andean roots produced during the proto-Andean evolution times were practically lost during Eocene to Oligocene extensional stages along the Southern Andes. This crustal stretching could have developed in relation to the combination of an opening of a slab window during mid-ocean ridge subduction and trench rollback.

The fifth part starts with Dávila et al. chapter that quantifies subsidence and uplift influenced by the mantle dynamics, superimposed to tectonic topography. This chapter predicts within-plate subsidence next to flat subduction settings and discusses subsidence components in ancient rift systems that cannot be fully explained by thermal decay, such as the Triassic rift systems in central Argentina. Additionally, this chapter analyzes mantle upwelling component associated with Neopaleozoic regional uplift and glacial activity in southern Gondwana. The second chapter by Lossada et al. is a review centered on the Frontal Cordillera uplift constituting the major mountain system developed in central Argentina whose origin was thought to be associated with the development of Chilean-Pampean flat subduction zone. Thermochronological data show that exhumation of this system is previous to the development of the flat subduction and is most likely influenced by preexisting heterogeneities linked to the Gondwana breakup. The third chapter by Turienzo et al. analyzes mechanics of deformation of fold and thrust belt at the Southern Central Andes suggesting that shortenings have been somehow underestimated and that the structure could be considerably more complex than previously assumed. The fourth chapter by Encinas et al. discusses subsidence mechanisms associated with the Late Oligocene to Early Miocene transgressions in Patagonia as part of the rifting activity that started in Eocene times and continued in the Early Neogene, as broad sag basins that flooded most of the ancient collapsed Andes. The fifth chapter by Folguera et al. analyzes Cenozoic deformations of the North Patagonian Andes from the study of synorogenic sedimentation. This concludes that an intra-arc basin closure and a shallowing of the subducted slab could have contributed together to the Neogene uplift of western Patagonia. In the sixth chapter, Litvak et al. study arc-related composition of magmatism associated with the development of the Chilean-Pampean flat subduction zone and Payenia shallow subduction setting to the south, concluding that most likely these behaved as one single system in the 15–4 Ma period. Finally, the seventh chapter by Collo et al. constitutes a compilation of heat flow from wells that illustrate how the Chilean-Pampean flat subduction zone has refrigerated the lithosphere, expelling the mantle asthenosphere off the shallow configuration as shown in Fig. 1.

Buenos Aires, Argentina Andrés Folguera et al.

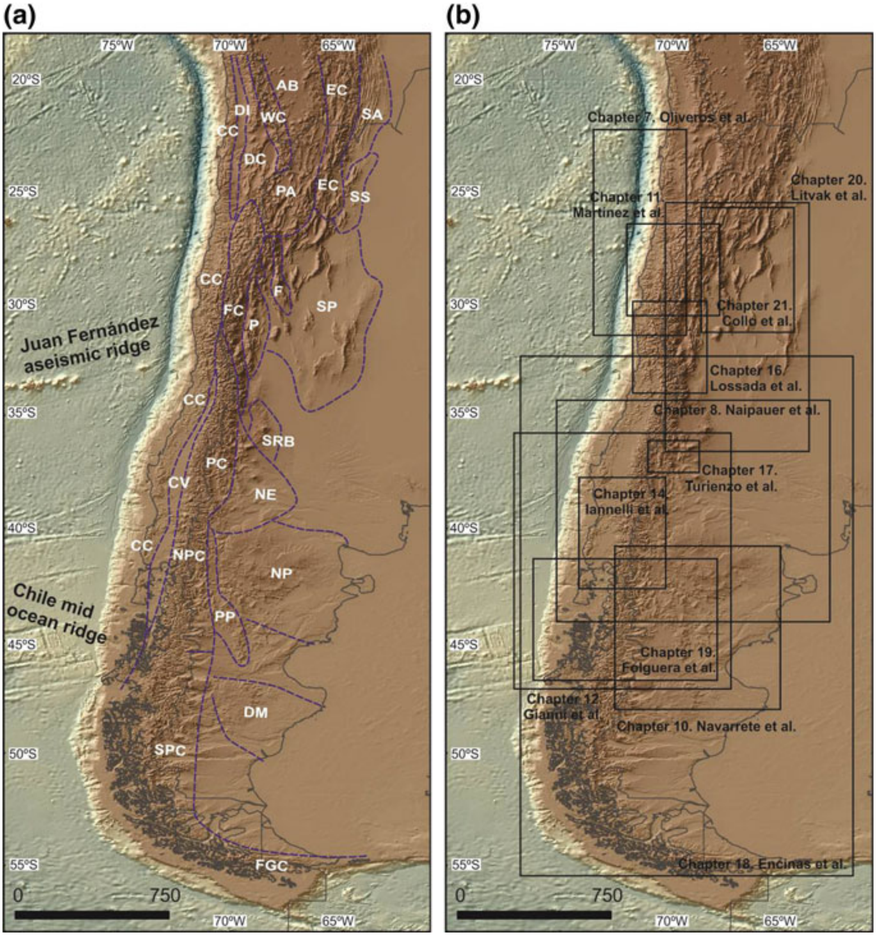

Fig. 1 To the left: Main morphostructural provinces in which the Southern Andes are divided. CC: Cordillera de la Costa, DI: Depresión Intermedia, DC: Cordillera de Domeyko, WC: Cordillera Occidental; PA: Puna; AB: Altiplano Boliviano; EC: Cordillera Oriental; SA: Sierras Subandinas; SS: Sistema de Santa Bárbara; FC: Cordillera Frontal; P: Precordillera; F: Sistema de Famatina; SP: Sierras Pampeanas; CV: Valle Central; PC: Cordillera Principal; NE: Engolfamiento Neuquino; SRB: Bloque de San Rafael; NPC: Cordillera Norpatagónica; PP: Precordillera Patagónica; NP: Macizo Norpatagónico; SPC: Cordillera Surpatagónica; DM: Macizo del Deseado; FGC: Cordillera Fueguina. To the right: book structure (empty rectangles indicate areas analyzed in each chapter)

Acknowledgements

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Part I
Crustal and Seismic Structure of the Chilean Fore-Arc

Structure and Tectonics of the Chilean Convergent Margin from Wide-Angle Seismic Studies: A Review

Eduardo Contreras-Reyes

Abstract Based on a compilation of published 2-D velocity-depth models along the Chilean margin (22°–48° S), I review the structure and tectonic processes that govern this convergent margin in terms of subduction erosion and sediment accretion/subduction. North of the collision point between the Juan Fernández Ridge with the overriding continental South American plate (Chile at ~32.5° S), subduction erosion has been active since Jurassic resulting in large-scale crustal thinning and long-term subsidence of the outermost forearc. Published 2-D velocity–depth models show a prominent lateral velocity contrast that propagates deep into the continental crust defining a major lateral seismic discontinuity (interpreted as the volcanic-continental basement contact of the submerged Coastal Cordillera characterized by a gravitational collapse of the outermost fore arc). Between the Juan Fernández Ridge and the Chile Triple Junction (CTJ) of the Nazca-Antarctic-South American plates (Chile at ~46.5° S), an accretionary prism 5–50 km wide has been formed due to an increase of trench sedimentation triggered by denudation processes of the Andes after the last Pleistocene Glaciation. However, the relatively small size of the accretionary prism is not compatible with an efficient history of sediment accretion since the Pleistocene, and sediment subduction is a dominant process especially south of the oceanic Mocha Fracture Zone (Chile at ~38° S) and north of the CTJ. In the overriding plate, seismic studies reveal two prominent velocity transition zones characterized by steep lateral velocity gradients, resulting in a seismic segmentation of the marine fore arc. The southern central Chilean margin is composed of three main domains: (1) a frontal prism at the toe of the continental slope, (2) a paleoaccretionary complex, and (3) the seaward edge of the Paleozoic continental framework that forms part of the Coastal Cordillera. Near the CTJ, where the Nazca-Antarctic spreading center (Chile Rise) collides with the margin, subduction erosion is active, and rapid uplift followed by subsidence of the forearc area, normal faulting and intensive sedimentary mass wasting are documented. South of the CTJ, the convergence between the oceanic Antarctic and continental South American plate is slow allowing more

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time sediment accumulation at the trench enhancing the formation of relatively large accretionary prisms (width of 70–90 km).

Keywords Wide-angle seismic studies · Fore-arc · Crustal erosion Accretion · Subsidence · Uplift

1 Introduction

The tectonics and structure of the Chilean convergent margin varies significantly from the arid Atacama Desert in the north to the glacial climate of Patagonia in the south. Among the main factors controlling the tectonic segmentation of the outer fore-arc are the morphology of the subducting oceanic Nazca and Antarctic plates, the variability in sediment supply to the trench, and the sediment transport within the trench. The most prominent feature of the oceanic lithosphere is the Nazca-Antarctic spreading center known as the Chile Rise or Chile Ridge, which is currently colliding with the margin off Península de Taitao at ~46.5° S (Fig. 1). North of ~34° S, the oceanic Nazca plate was formed at the East Pacific Rise (Nazca-Pacific spreading center) more than 38 Myr ago, whereas between 34° and 46° S it was formed at the Chile Rise within the past 35 Ma (Herron et al. 1981; Cande et al. 1987) (Fig. 1). The relative convergence rate between the oceanic Nazca and South American plate is currently ~67 km/Myr (Angermann et al. 1999; Khazaradze and Klotz 2003), although the average convergence rate during the last 20 Myr is about 85 km/Mr (DeMets et al. 2010). The relative convergence rate between the oceanic Antarctic and continental South American plate is ~20 km/Myr in a direction perpendicular to the trench between ~46° S and 53° S, but southwards, the direction becomes quite oblique to the margin (DeMets et al. 2010).

The collision of the Chile Rise with the Chilean margin configures the Chile Triple Junction (CTJ) where the Nazca, Antarctic, and South American plates join at the trench. Fracture zones (FZs) cut the Chile Rise into several segments, resulting in abrupt plate age and morphological changes along the plate boundary (Fig. 1). One of the most striking features is the Valdivia FZ-system composed of ten individual fracture zones (Tebbens et al. 1997) with a total offset of about 600 km which orientate roughly perpendicular to the trench axis (Fig. 1). The seafloor from the CTJ up to the Valdivia FZ system is characterized by an uplifted topography associated to the young, hot and buoyant oceanic Nazca lithosphere formed during the last 20 Ma (Tebbens et al. 1997). Another striking oceanic feature is the NE (55°) trending Mocha FZ which intersects the trench at ~38° S (Fig. 1). Due to its obliqueness related to the trench axis, the Mocha FZ intersection with the trench migrated southward at about 3.1 cm/a over the past millions years relative to South America (Contreras-Reyes et al. 2008). The Mocha Block is known as the triangulation of the Chile Trench, Valdivia FZ system, and the Mocha FZ. North of the Mocha Block, the oceanic lithosphere approaching the trench is significantly older and the seafloor becomes deeper (Tebbens et al. 1997).

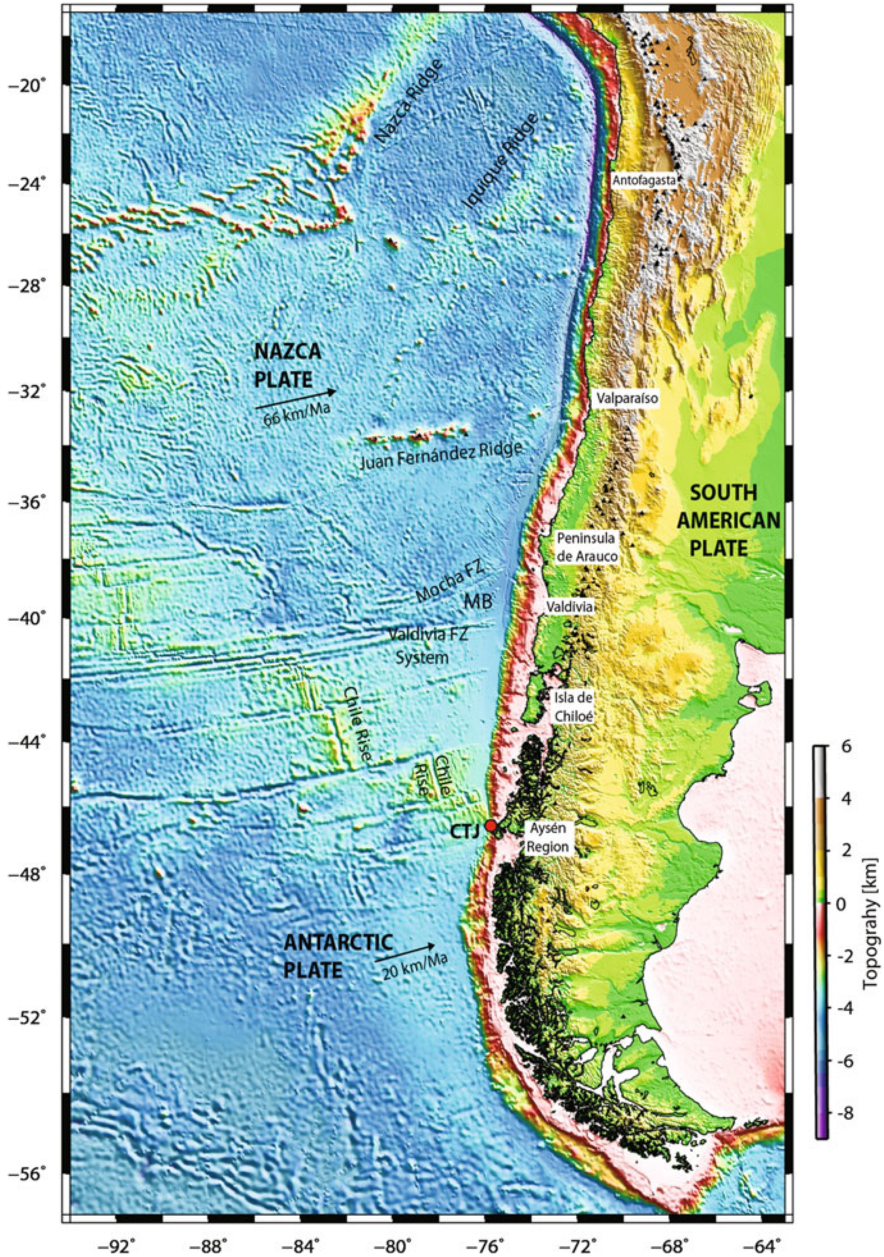

Fig. 1 Geodynamic setting of the Nazca, Antarctic and South American plates. These plates meet at the Chile Triple Junction, where the Chile Rise is currently colliding with the Chilean margin at $\sim$46.5° S. The oceanic Nazca and Antarctic plates are segmented by several fracture zones, resulting in a strong variability in the age of the incoming oceanic plate. MB: Mocha Block

Because of the buoyancy of the hot and young oceanic Nazca lithosphere formed south of the Mocha Block, the seafloor is approximately 500–1000 m shallower than north of the Mocha Block.

The first collision of the Chile Rise with the continental South American plate occurred south of 48° S at ~14 Ma, and since then, the CTJ has been migrating northwards (Cande and Leslie 1986; Maksymowicz et al. 2012). The high relief topography in the area of the CTJ has caused trench sedimentation to be preferentially transported towards deeper topography of the trench (northward and southward of the CTJ as the oceanic Nazca and Antarctic plates become older, respectively). At the CTJ, the trench is almost devoid of sediments (Fig. 2), in contrast to the north (35°–44° S) where the trench is heavily sedimented in response to the sediment supplied by the rivers and rapid glaciation denudation of the Andes (Thornburg et al. 1990; Blumberg et al. 2008). The trenchward transport of sediment that is sourced by the denudation of the Andes is controlled by submarine landslides, submarine canyons, and turbidity currents (Thornburg et al. 1990; Blumberg et al. 2008; Voelker et al. 2013).

Another prominent feature on the oceanic Nazca lithosphere is the Juan Fernández Ridge (JFR), a hot spot track formed at the Juan Fernández Hotspot located some 900 km west of the Chile Trench (Fig. 1). The easternmost, yet unsubducted portion of the JFR is composed by two prominent seamounts: the O'Higgins Guyot (~4,000 m above the surrounding seafloor) and the O'Higgins seamount (~3,500 m above the surrounding seafloor) (Fig. 2). The O'Higgins seamount group is surrounded by a topographic swell obscured by the bending of the oceanic plate (Kopp et al. 2004). The first collision of the JFR with the Chile margin occurred approximately 22 Myr ago in north Chile at ~22° S. Then the ridge has migrated southwards to the current collision zone located off Valparaíso at 32°–33° S (Yáñez et al. 2001). The O'Higgins seamount group behaves as a barrier to the northward transport of turbidites within the trench, separating a sediment-starved trench to the north from a sediment flooded trench to the south (Fig. 2).

Thus, the southern-central Chilean margin is characterized by a filled trench confined between the JFR and the Chile Rise. Figure 2 shows the sediment thickness at the Chile trench. Sediment within the trench are redistributed from south to the north of the CTJ (Thornburg et al. 1990), which is explained by the deepening of the trench floor (e.g., Voelker et al. 2013).

North of the JFR (18°–33° S), the incoming oceanic crust carries only a thin sediment drape (<500 m), and the trench axis is poorly sedimented (Fig. 2). In contrast, south of the CTJ, the trench is filled by an up to 3 km thick thick sequence of turbidites (Fig. 2). Thus, a heavily sedimented trench is confined between the collision zones of the JFR and Chile Rise with the margin, respectively. The subduction of these two large topographic features on the oceanic plate defines the most important borders of tectonic segments along the Chilean margin in terms of the structure of the margin, continental slope morphology, trench fill thickness, and size of the accretionary prism.

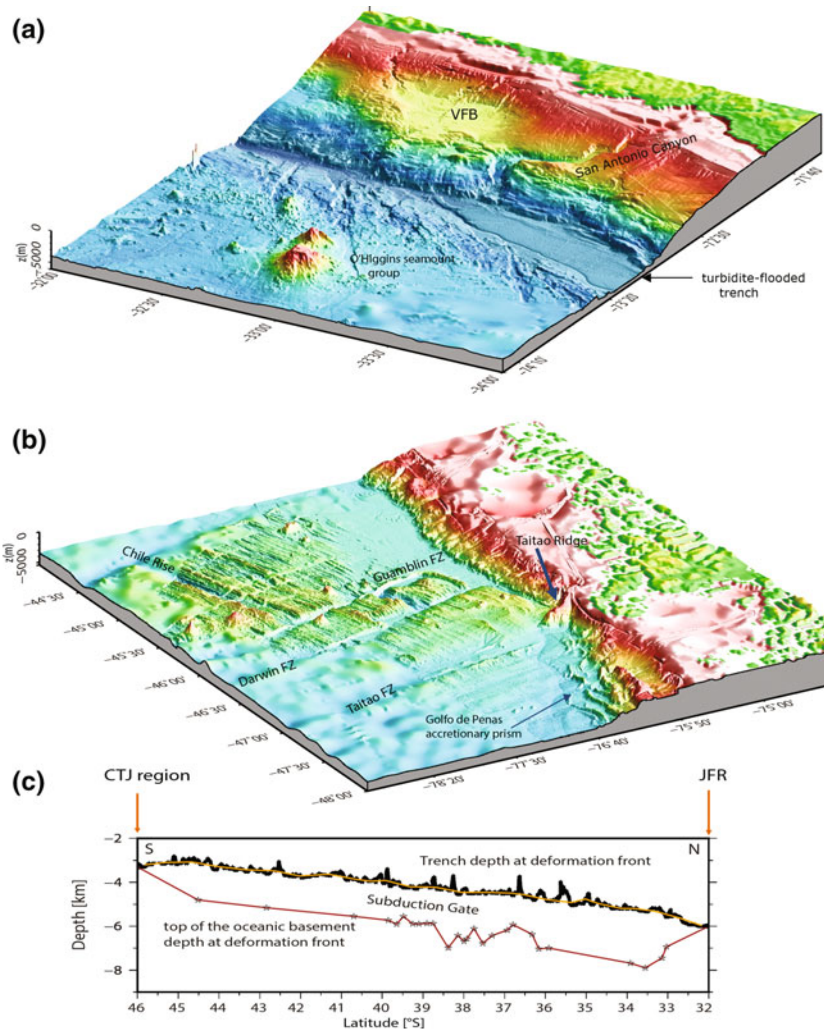

Fig. 2 Swath bathymetric image of the seafloor. **a** Collision zone between the Juan Fernández Ridge and the Chilean margin. VFB: Valparaíso Fore-arc Basin. **b** Collision zone between the Chile Rise and the Chilean margin. The Chile Triple Junction is coincident with the subduction of the Taitao Ridge. **c** Depth of the trench axis off Chile. Trench fill thickness values were computed by a compilation of published seismic reflection lines imaging the southern-central Chilean trench basin (Voelker et al. 2013)

In this chapter, I review the structure of the Chilean margin from Tocopilla (northern Chile at ~22° S) to Golfo de Penas (Chilean Patagonia at ~48° S) using a compilation of nine 2-D wide angle seismic velocity-depth models published during the last 12 years (see Fig. 3 for map location). The presented results

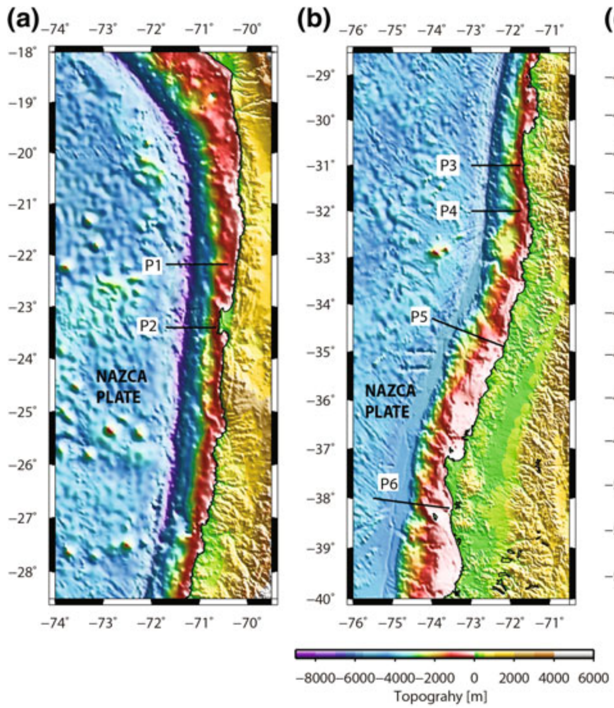

Fig 3 Black lines denote the wide-angle seismic profiles studied by Contreras-Reyes et al. (2012), **P1**; Sallares and Ranero (2005), **P2**; Contreras-Reyes et al. (2015), **P3** and **P4**; Moscoso et al. (2011), **P5**; Contreras-Reyes et al. (2008), **P6**; Scherwath et al. (2009), **P7** and **P8** and Maksymowicz et al. (2012), **P9**. CTJ: Chile Triple Junction

should be considered as the short-term structure of the margin that is the current outcome of long term geological processes.

Likewise, the tectonics segments defined in this chapter corresponds to large-scale regions of the Chilean margin (several hundred kilometers). It is worth-mentioning that at small scale (10 km-scale), subduction erosion can be coeval within segments of tectonic accretion where sediment layer are not thick enough to smooth the oceanic high features that collide with the margin (Clift and Vannucchi 2004; Stern 2011). Similarly, small frontal prisms made of debris material can be coeval in segments where subduction erosion dominates (i.e., von Huene et al. 1999; Laursen et al. 2002; Ranero et al. 2006). In this chapter, the distinction between subduction erosion, sediment accretion and subduction refers to the most dominant feature of the margin at large scale. For the next sections, I will refer to the following regions of the Chilean margin as the first-order tectonic segments: (i) the northern Chilean margin (22°–32° S) that is bounded at the south by the collision of the JFR with the Chilean trench, (ii) the south-central Chilean margin (33°–46.5° S) bounded in the north by the JFR and in the south by the CTJ, and (iii) the austral Chilean margin (south of the CTJ).