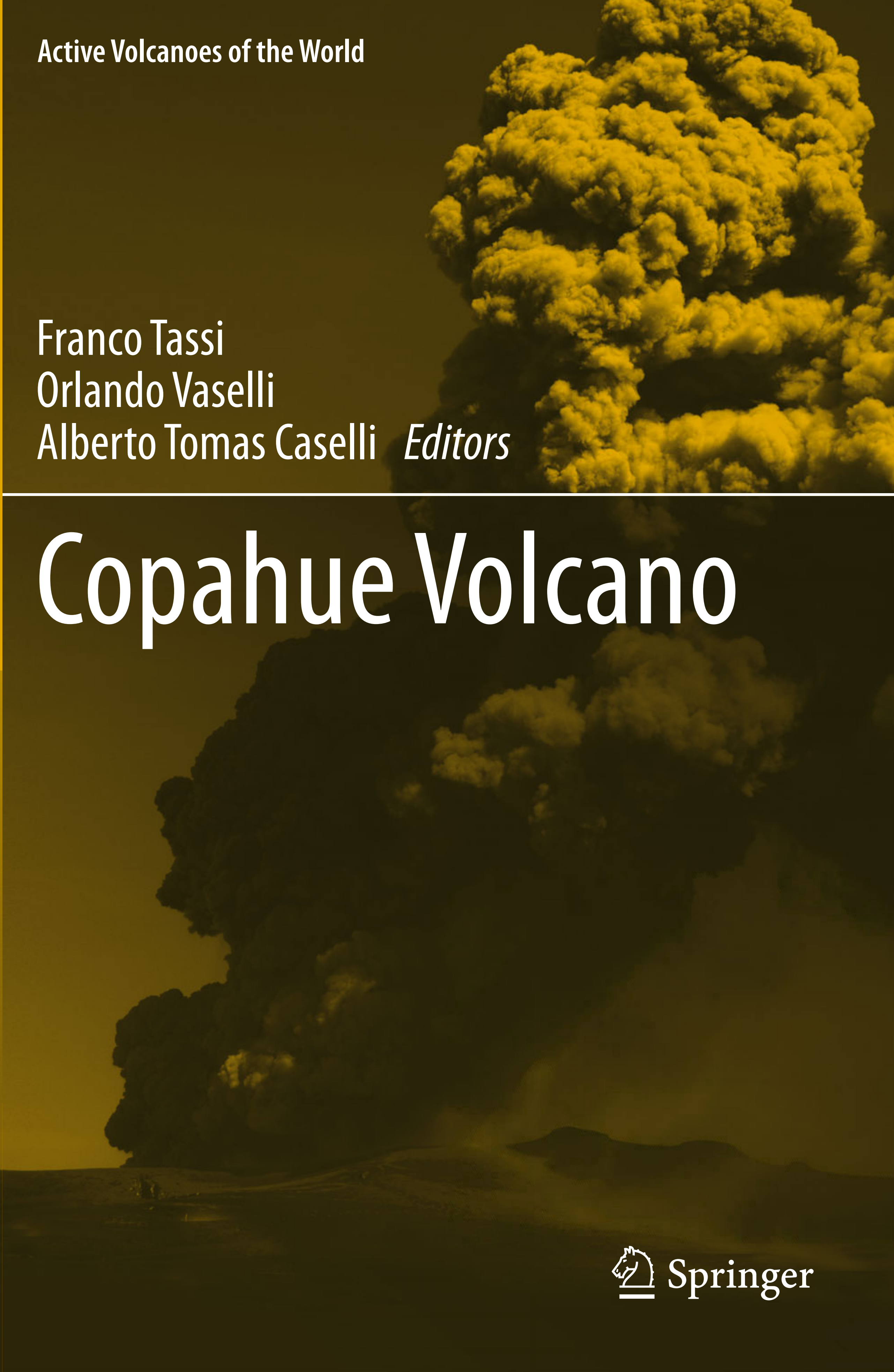
Active Volcanoes of the World

Franco Tassi
Orlando Vaselli
Alberto Tomas Caselli *Editors*

Copahue Volcano



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Foreword

The compilation of chapters in this edited volume covers a wide range of topics on one of the most active volcanoes in Argentina. Copahue is located in the eastern part of the Andean Southern Volcanic Zone at the Argentina–Chile border in a complex tectonic region. The volcanic complex is substantially older than other volcanoes in the area and activity ranges from early Pliocene basaltic–andesitic eruptions to rhyolitic ignimbrites related to early Pleistocene caldera formation. Folguera et al. provide a detailed overview of the evolution of the Copahue volcanic system and how larger-scale tectonic processes such as slab steepening and westward migration of the volcanic arc affected the volcano. The chapter of Varekamp et al. discusses the petrology of Copahue eruptive products and shows that the 2000–2012 rocks were the most mafic of the past 100,000 years. The trace element and radiogenic isotope data imply that Copahue magmas are sourced from a relatively dry mantle with melting of a subduced sediment component. Comparison to back-arc magmatic products allows these authors to draw conclusions with regard to identification of two mantle end-embers. Bonali et al. describe how the regional faults control the magma feeding system and how modeled variations in the stress regime could affect the volcanic activity. This work has implications to forecasting volcanic activity at Copahue, which has had at least 13 eruptions in the past 260 years. Caselli et al. (a) show that, despite scarce historical records, phreatic- and pherato-magmatic eruptions were dominant in the past two centuries but that the most recent activity in 2000 and 2012 were more magmatic and strombolian in character. Further details on the 2012 eruption and the events leading up to it are provided by Caselli et al. (b) Significantly, the Mw 8.8 February 2010 earthquake in Chile seemed to have caused instability in the volcanic system of Copahue, perhaps leading to the phreatic phase in July 2012 that eventually evolved into a magmatic eruption at the end of that year. Copahue hosts an impressive hydrothermal system with gas discharges that have the highest mantle helium component in all of South America. Tassi et al. discuss an extensive gas geochemical data set with samples from 1976 to 2012 and show that the volatiles have chemical signatures related to an extensional regime. These authors also document temporal variations in gas compositions that imply injection of gas-rich magma which may have triggered the 2012 eruption sequence. The volcano also hosts an active acidic crater lake and Agusto and Varekamp show in their contribution how anion concentrations increased in the lake waters, suggesting the ascent of magmatic fluids prior to the 2012 eruptions. The pyroclastic material that was ejected during these eruptions shows clear evidence of hydrothermal mineral precipitation that may have reduced the permeability of the system, leading to some of the phreatic eruptions of 2004. Ground deformation measured by InSAR can provide important information on volcanic activity and at Copahue Velez et al. explore the Small Baseline Subsets technique to compute surface displacements between 2001 and 2013. Their work shows how these analytical techniques can be used to better constrain the sources of ground deformation at Copahue. Such geophysical and geochemical monitoring activities are needed to better understand the ongoing activity of this volcano. Due to the volcano's recent explosive and phreatic activity, hazard assessments, maps, and contingency plans are constantly modified. Caselli et al. (c) discuss in their contribution how critical volcano monitoring is for the evaluation of hazards but also that efficient and clear communication between observatories and the public are important to educate the population and mitigate the volcano's hazards. Copahue, like many active volcanoes provides modern terrestrial analogues for the extreme environments that may have existed on other planets such as Mars. Rodríguez et al. show that some key hydrothermal minerals that have been identified in sedimentary deposits on Mars through remote sensing, are currently forming at Cophaue. In particular, the mineral Schwertmannite may have played an important role in early Mars large lakes and geochemical modeling of the Copahue crater lake waters suggests that this mineral is stable under similar to current conditions. The extensive volcano-hosted Copahue hydrothermal system provided the opportunity for the installation of a small pilot power plant on its southern flanks. Mas and Mas discuss the geothermal potential of the region and how the 1996–1997 eruptions of the volcano led to some interesting changes in the exploitable hydrothermal system, including the appearance of boiling thermal waters near the city of Copahue. Some of these mineral waters and associated muds are significant resources and natural remedies to treat a variety of rheumatic, skin, and respiratory diseases (Monasterio et al.). The book ends with an account on the Mapuche which have been living in the surroundings of Copahue over the past three centuries. Castaño leads the reader through the people's history in the Argentine Andean sector, their deep contact with nature and the narration of the legend that can explain the name Copahue.

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Preface

As Editors and researchers we are flattered to present this monograph dedicated to the Copahue volcano ("The smoking mountain between Argentina and Chile") that is located in a remote site of Patagonia, right at the border between Chile and Argentina. The three recent volcanic eruptions (2000, 2012, and 2013) and the present unrest state have had a global echo. The acidic crater lake on the top of the mountain is suffering strikingly modifications and after the eruptive event of 2012, it completely disappeared and then, after a few months the pre-existing conditions almost recovered, although a balance between the inner (e.g., deep fluids) and outer (e.g., meteoric precipitation and ice melting) forces has not yet been established. These repeatedly changing volcanic situations have seen the involvement of several scientists from different part of the world who have contributed with their efforts to a better understanding of the volcanic plumbing and the hydrothermal/magmatic systems. Attempts to build a seismic monitoring array and periodic geochemical and ground deformation surveys are presently underway. Difficulties in retrieving appropriate financial supports, logistic problems, long distances from the main cities of Argentina, instrumental supplies, and trained personnel are some of the many challenges to be solved. The final target would be that to create a volcanological and seismological observatory in this area of Patagonia, able to monitor Copahue and the other volcanic edifices nearby located, such as Peteroa, Lanin, Tromen, and Domuyo.

This monograph, belonging to the Volcanoes of the World Book Series published by Springer-Verlag, is intended to represent a sort of a benchmark for those researchers who want to know more about Copahue.

The volume is divided into five parts: (1) Geology; (2) Eruptive History; (3) Petrology and Geochemistry; (4) Volcanic Monitoring and (5) Volcano and Society.

The volume opens with two interesting reviews by Folguera et al. and Groppelli et al. on the geological and geodynamical settings of this part of the Andes, whose interpretations indicate the need to acquire more data to achieve a common view on the development of the volcanism affecting the area. These aspects are basic and fundamental tools to explain the volcanic events of Copahue. The two contributions by Caselli et al. on the prehistoric to the recent volcanic activity and the December 2012 event summarize what is known about the eruptive style of this volcano. Varekamp et al. provides a nice review of published and original data of trace and radiogenic elements, highlighting the petrological features of the Copahue volcanic products. This section precedes that of Tassi et al. where a geochemical conceptual model based on chemical and isotope composition of hydrothermal/volcanic gas discharges is presented and gives important hints on a possible gas geochemistry monitoring activity at Copahue. The volcanic monitoring session includes two contributions devoted to ground deformation (Vélez et al.) and water geochemistry (Agusto and Varekamp), where innovative views about the possible volcanic surveillance activities are considered. Caselli et al. provide a comprehensive overview of the risk assessment, focusing on the main hazards related to the activity of this volcano, whereas Rodríguez et al. describe the chemistry of the acid rivers and lakes characterizing this system, interpreted as a good terrestrial analogue for the aqueous paleo-environments on Mars. The fifth part of the volume includes three chapters concerning the geothermal energy and its historical development in the Copahue area by Mas et al., the use of the numerous thermal waters mainly discharging in the village of Caviahue where several spas and resorts are operating (Monasterio et al.), and the religion and popular believes inspired to Mapuche by the presence of the smoking mountain (Castaño et al.).

It is the hope of the Editors that this volume may keep interested the scientific community about the volcanic system of Copahue, which, for different reasons, in the past has somehow not been considered a serious threat for the local population. The recent reactivation of Copahue has unfortunately demonstrated that a lot of work has to be done. To avoid that new and more dangerous eruptions are going to hit unprepared the population, a tighter collaboration between the local and regional authorities and the scientists is a must.

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Contents

Part I

Geology

A Review of the Geology, Structural Controls, and Tectonic Setting of Copahue Volcano, Southern Volcanic Zone, Andes, Argentina

1

A. Folguera, E. Rojas Vera, L. Vélez, J. Tobal, D. Orts, M. Agusto, A. Caselli and V.A. Ramos

Abstract

Copahue Volcano lies in the Southern Volcanic Zone of the Andes Mountains, although its geology and local structural controls differ from nearby active volcanic centers. Most of its geology is substantially older than active volcanoes at these latitudes, as the postglacial component is relatively minor. The basement of Copahue Volcano, represented by the Agrio Caldera products and its basal sections, accumulated in extensional depocenters when the arc narrowed from a broad geometry on both sides of the Andes to its present configuration. Initial stages comprise early Pliocene basaltic-andesitic eruptions associated with extensional (transtensional?) processes that ended with the formation of a series of rhombohedral calderas that emitted important amounts of ignimbrites in latest Pliocene-early Pleistocene time. Copahue Volcano concentrates the Pleistocene activity of one of these calderas, the Agrio Caldera, before the emplacement and development of the Present arc front to the west. Volcano morphology reflects this particular evolution, looking more degraded than Antuco, Callaqui and Lonquimay volcanoes located immediately to the west in the arc front. Most of Copahue's volume is early Pleistocene in age, showing a thin resurfacing cover in synglacial (>27 ka) and postglacial times. A synglacial stage occurred mainly to the east of Copahue Volcano toward the caldera interior in a series of independent, mostly monogenetic centers. Postglacial eruptions occurred

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as both central and fissural emissions reactivating the old Pleistocene conduits. Its particular geological record and eastern longitudinal position indicate that Copahue was probably part of the late Pliocene-Pleistocene arc mostly developed in the axial and eastern Andes. Narrowing and westward retraction of the arc front, proposed in previous works for the last 5 Ma at 38°S, could have been the result of the eastward migration of the asthenospheric wedge during slab steepening. Reasons for this long-lived eruptive history at Copahue volcano could be related to the particular geometry of the active Liquiñe-Ofqui dextral strike-slip fault system that runs through the arc front from south to north when penetrates the retroarc area at the latitude of Copahue volcano. This behavior could be due to the collision of the oceanic Mocha plateau at these latitudes, as recently proposed. This jump and related deflection would have produced local transtensional deformation associated with abundant emissions of syn- and post-glacial products that could have partially resurfaced this long-lived center.

Keywords
Southern volcanic zone · Transtension · Northern Liquiñe-Ofqui fault zone

1.1 Introduction

Copahue volcano has been studied due to its frequent eruptions since the 1990s (see Delpino and Bermúdez 1993, 1995; González Ferrán 1994; Naranjo and Polanco 2004). Structural and tectonic models associated with this center proposed since then are summarized in this review, although it still lacks a robust stratigraphic framework over which these hypotheses are supported. The few available isotopic ages are K-Ar (Linares et al. 1999) and have significant errors (see Melnick et al. 2006a). Available geological maps are based on these ages and proposed lateral correlations that could be inappropriate for volcanic environments. Dellapé and Pando (1975) and Pesce (1989) were the first attempts to represent the different units of the Agrio Caldera, where the Copahue Volcano is hosted. Latter representations were more focused on studying the associated structural controls than the volcanic stratigraphy itself (Folguera and Ramos 2000; Melnick et al. 2006a; Rojas Vera et al. 2009a).

The most outstanding feature associated with Copahue volcano is the Agrio Caldera (Pesce 1989), also denominated in other works as the Caviahue Caldera. This 15 × 20 km depression was initially interpreted as the product of strong glacial erosion (Groeber 1921) based on the finding of presumably related diamictites. However, these were recently reinterpreted as large mass wasting deposits emplaced from the perimeters of the caldera towards its interior (Hermanns et al. 2011). The identification of this depression during the 1920s constituted an important discovery since no remote images existed at that time. Its linkage with volcanic processes waited until the late 1980s when Pesce (1989) identified the perimeter of the caldera and the location of Copahue volcano in one of the main collapse scars. Other resurgent centers, partially coeval to Copahue volcano, have been identified along the caldera perimeters that have been erupted in the last 1 Ma (Linares et al. 1999).

A description of the state of knowledge of the tectonic setting associated with Copahue volcano and the Agrio Caldera is presented, including a discussion about the peculiarities of this center, which is morphologically distinctive and not aligned with the arc front at these latitudes.

1.2 Tectonic Framework at 37–39°S and Sublithospheric Structure

Recently released seismic tomography developed after the Maule earthquake has shed light on the sublithospheric structure of the Southern Volcanic Zone where Copahue volcano is located (Fig. 1.1) (Pesicek et al. 2012). The Nazca plate is illuminated as a zone of fast P-wave velocities, with some complexity previously not noted. Between

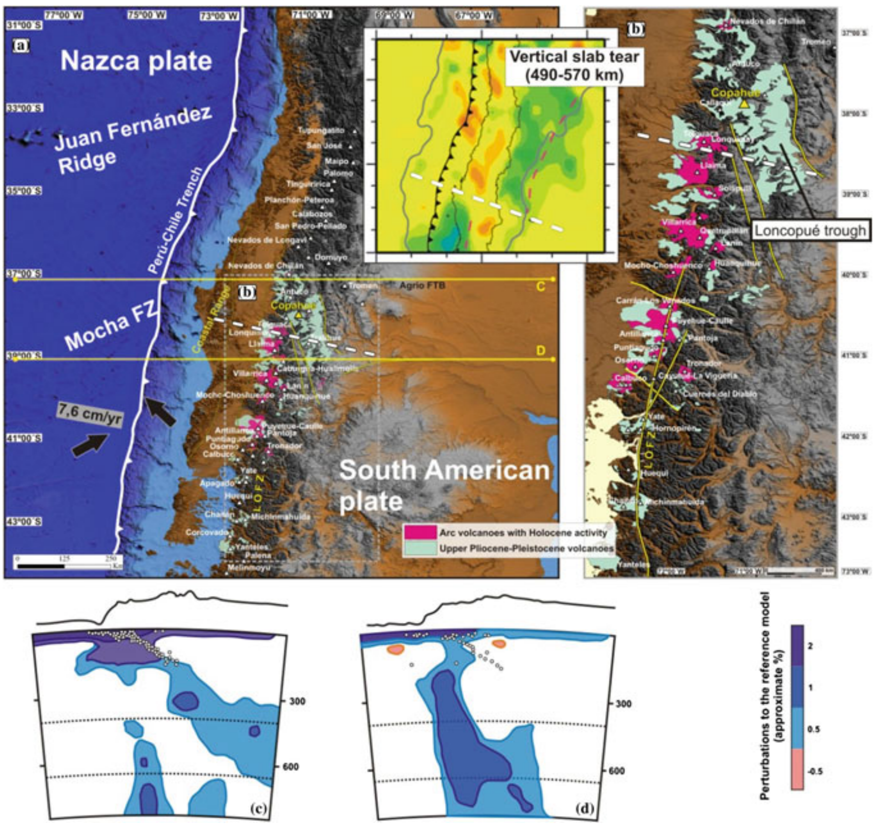

Fig. 1.1 a b Pliocene-Early Pleistocene and Pleistocene-Holocene arc activity in the Main Andes between 37–39°S (Lara et al. 2001; Lara and Folguera 2006), and seismic tomography of the retroarc zone modified from Pesicek et al. (2012). **c d** Pale blue and blue colors indicate P-wave velocity contours that are interpreted as subducted oceanic lithosphere while white dots indicate the Benioff zone (Pesicek et al. 2012). Note that along 39°S a steeper configuration of the subducted Nazca plate is not coincident with the present seismogenic zone. The thick dashed line in **a** and **b** indicates the tearing in the subducted Nazca plate interpreted by Pesicek et al. (2012). The Copahue Volcano is indicated with a triangle in yellow. Note that, as depicted in B, arc volcanoes with Holocene activity between 37° and 41°S are mainly emplaced on the western Andean slope, in comparison with late Pliocene to early Pleistocene centers developed on both sides of the Andes (see text for further details)

37° and 39°S, a tear zone appears to have developed in the subducting Nazca plate, leaving a steeper subduction angle to the south (Fig. 1.1). This tearing likely developed prior to 5–3 Ma, since the interplate seismogenic zone at 39°S, indicating the present fate of the subducted slab, is not coincident with the steeper zone of fast P-wave velocities (Fig. 1.1). Then, the present geometry of the subducting Nazca plate is considerably shallower than that steeper configuration, showing a physical continuation to the north (Pesicek et al. 2012). Thus a change in subduction geometry would have been achieved in the last 5–3 Ma between 37º and 39°S from a steeper configuration to a shallower one.

This important change has a correlation with the pattern of arc activity between 36º and 40ºS. Lara et al. (2001) demonstrated that, over the last 2 Ma the arc passed from a broad and diffuse morphology, covering a wide area from the current active arc to the retroarc zone to the east, to become contracted to a narrow band in the west at the axial Andean zone (Fig. 1.1).

This westward retraction was accompanied by within-plate volcanism in the Loncopué extensional trough in the last 2 Ma (Rojas Vera et al. 2010, 2013). Eruptions at the eastern retroarc zone during Quaternary time cover an area that is coincident at surface with the Nazca slab tearing described by Pesicek et al. (2012).

Shallow structure through this segment is characterized by two distinctive systems: (i) Along the arc front, the Liquiñe-Ofqui fault system accommodates lateral displacements imposed by the oblique convergence between the Nazca and South American plates (Lavenu and Cembrano 1999) from the triple junction among the South American, Nazca and Antarctica plates (~46°S) to the Mandolegüe volcanic lineament (~38°S) (Radic 2010). From this point to the north, strike-slip displacements are absorbed at the western retroarc zone over the Argentinian territory by the Antiñir-Copahue fault system (Fig. 1.2; Folguera et al. 2004). Copahue volcano is located at the transition zone between these two neotectonic systems. (ii) To the east, over the eastern retroarc area, Pliocene to Quaternary within-plate volcanic rocks have been related to extensional deformation (Fig. 1.3) (Kay et al. 2006; Folguera et al. 2006). Normal faults affect postglacial volcanic products, indicating young deformation of the upper crust more than 300 km east of the arc front (Fig. 1.3; Folguera et al. 2006; Rojas Vera et al. 2010). Crustal attenuation is identified beneath the arc and retroarc in coincidence with the area of Pliocene to Quaternary volcanic eruptions at 39°S and extensional deformation using receiver function techniques (Yuan et al. 2006). Density models derived from gravity data predict this area is elongate through the whole retroarc area parallel to the arc (Fig. 1.3; Folguera et al. 2012).

This crustal attenuation and associated retroarc magmatism have been explained by steepening of the Nazca plate during westward arc retraction about 5–2 Ma and consequent injection of hot asthenospheric material, after a period (13–5 Ma) of shallow subduction in the area (Kay et al. 2006; Folguera et al. 2007). This injection of hot asthenosphere material has been recently illuminated through magnetotelluric analysis (Burd et al. 2013).

1.2.1 The Mandolegüe Volcanic Lineament

This 60–70-km-long volcanic lineament is formed by the partial amalgamation of seven main volcanic centers, which from west to east, are the Callaqui Volcano, Copahue Volcano, Las Mellizas volcanic center, Trolón Volcano, Bayo Dome, and Huecú and Mandolegüe monogenetic basaltic fields (Figs. 1.4 and 1.5). This volcanic lineament is interposed between the northern termination of the Liquiñe-Ofqui and the Antiñir-Copahue fault systems along a NE direction (Fig. 1.4).

Mechanisms and ages of the different volcanic vents are highly variable along the strike of the Mandolegüe volcanic lineament (Fig. 1.5). The youngest products are dominant in the eastern sector where the Huecú and Mandolegüe volcanic fields were emplaced. There, monogenetic fields with fissural vents and, more locally,

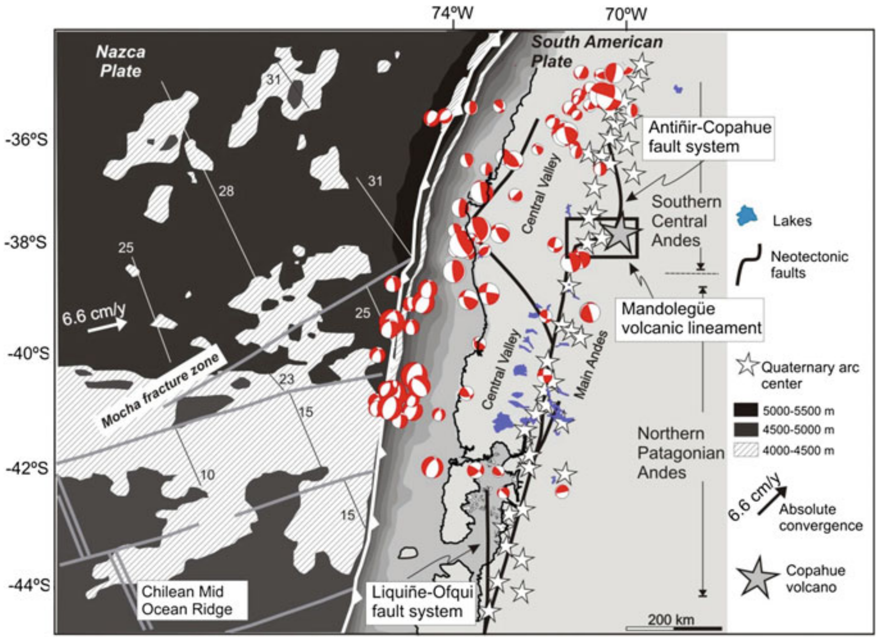

Fig. 1.2 Tectonic framework of the Southern Volcanic Zone (modified from Hervé 1976; Cembrano et al. 1996, 2002; Hervé 1994; López Escobar et al. 1995; Lavenu and Cembrano 1999; Folguera et al. 2004). Note the location of the Mandolegüe volcanic lineament in the site where the Copahue Volcano is hosted at the northern termination of the strike-slip Liquiñe-Ofqui fault zone and the transition to the Antiñir-Copahue fault system. Note also that the Mandolegüe volcanic lineament coincides with the site of inception of the oceanic Mocha transform zone and associated plateau into the Chilean trench

basaltic calderas are associated with broad basaltic fields that are circumscribed by the present drainage network (Fig. 1.5). This fluvial morphology has been flooded in postglacial times and probably also in historical times by reduced lacustrine basins as a response of the youngest eruptions hosted in the southern flank of the Mandolegüe volcanic lineament (Fig. 1.5) (Groeber 1928; Rojas Vera et al. 2009b).

West of the 70º40′W meridian, the average age of the different units becomes older, with pre-glacial volcanic products associated with mostly central polygenetic volcanic vents. Polygenetic stratovolcanoes are represented by the Trolón, Callaqui and Copahue volcanoes. The three centers have postglacial lava flows associated with fissural and central mechanisms, although most of its structure is pre-glacial in age (Pesce 1989; Linares et al. 1999).

In particular, the active Callaqui volcano (Fig. 1.4) is a stratovolcano elongated in a N60°E direction (Moreno and Lahsen 1986). Here, post-glacial eruptions concentrated along a 700-m-long fissure formed by 22 connected individual vents, producing an elliptical 15-km-long and 8 km-wide stratocone, as can be seen in the digital elevation model (Fig. 1.4).

Copahue volcano to the east occupies the southwestern corner of the 15 × 20 km Agrio Caldera (Pesce 1989). This has been formed over a volcanic plateau of 5–4 Ma andesitic flows associated with the Cola de Zorro-Hualcupén Formations that constitute gently sloped to flat sections up to 1,500 m thick (Fig. 1.5) (Vergara and Muñoz 1982; Niemeyer and Muñoz 1982; Muñoz Bravo et al. 1989; Suárez and Emparán 1997). The thickest sections of these packages have been described as controlled by normal

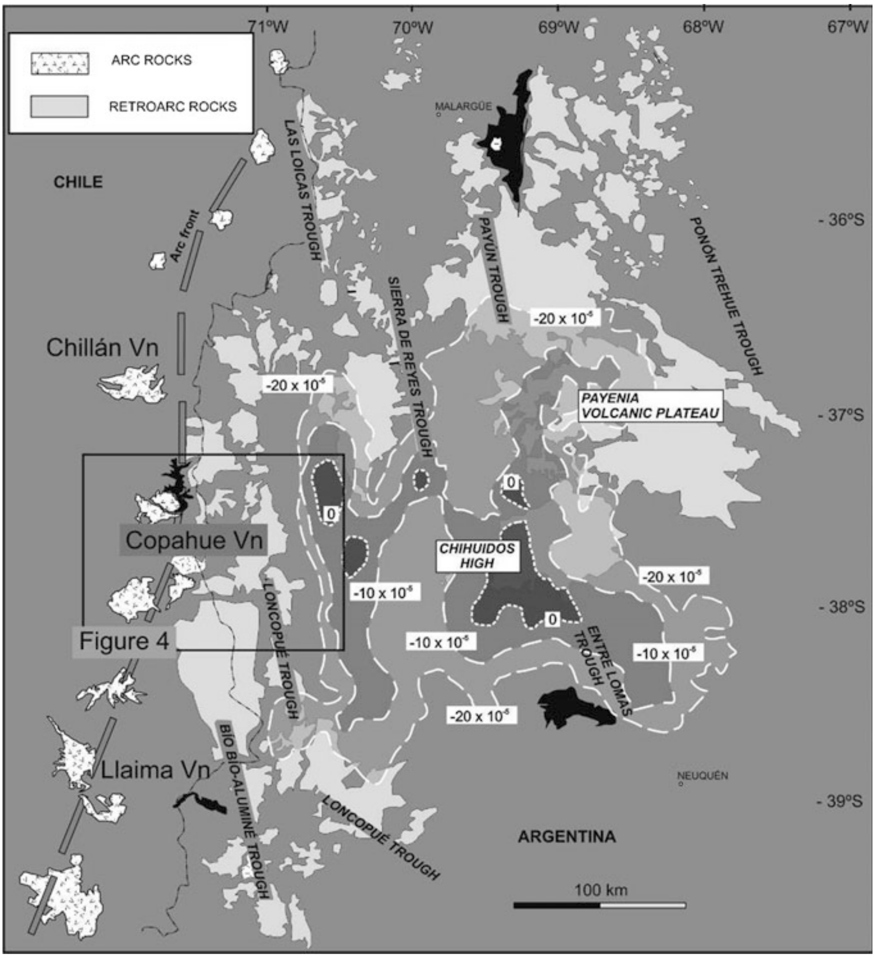

Fig. 1.3 Attenuated crust at the retroarc zone determined from a receiver function profile at 39°S (Yuan et al. 2006) where a plume-like feature is impacting against the base of the lithosphere (Burd et al. 2013) and gravimetric expression. Note that most of the volcanic plateaux at the arc-retroarc zone are coincident with the area of high gravimetric anomalies interpreted from 3D density models as caused by crustal attenuation (Folguera et al. 2012). Gravimetric values are in mGals

faults in a broad region from 36 to 39°S, defining half-graben geometries (Folguera et al. 2006; Melnick et al. 2006b).

Locally, these sections around Copahue volcano determine a broad volcanic morphology that is dipping outward from a central point situated at the 71ºW–37°50′S intersection in the center of the Agrio Caldera (Fig. 1.5). A thin cover of pyroclastic deposits of the Riscos Bayos Formation dated at 1.98 Ma (Pesce 1989; Linares et al. 1999; Mazzoni and Licitra 2000) is irregularly distributed through the external slopes of this feature, being interpreted as the outflow ignimbrites associated with the caldera collapse (Fig. 1.6). Ignimbritic sheets of the Las Mellizas Formation occupy the inner sector of the caldera and were dated at 2.5 Ma (Pesce 1989; Melnick et al. 2006a). The northern rim of the Agrio Caldera is occupied by lava fields associated with monogenetic vents aligned along fissures and have been gathered in an informal category denominated "*Basaltos de Fondo de Valle*" (Pesce 1989) (Fig. 1.6). These lava flows, dated at 1.6–0.8 Ma (Linares et al. 1999), are controlled by the glacial morphology and project through glacial tributaries beyond the rims of the

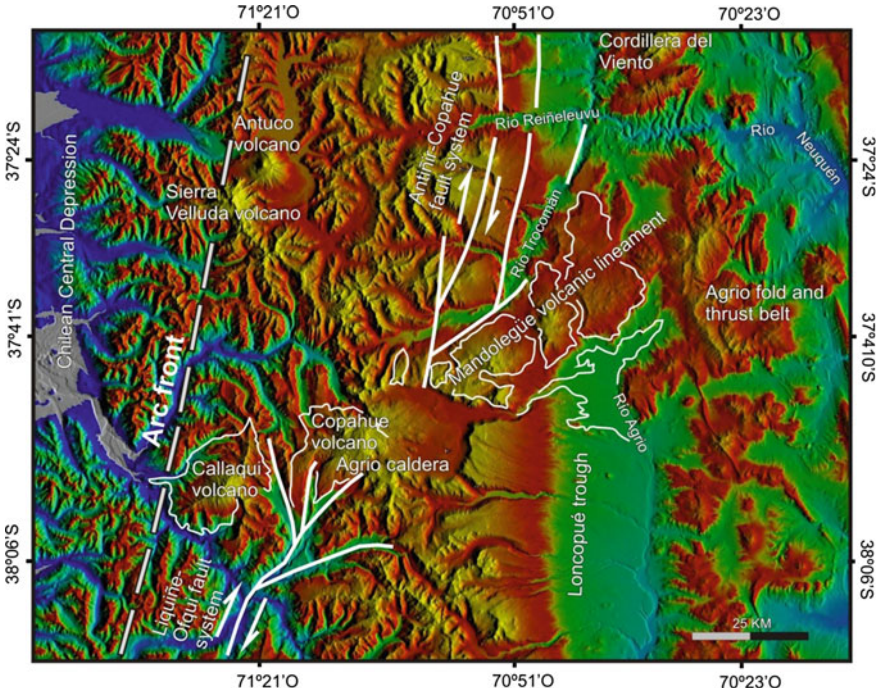

Fig. 1.4 Digital Elevation Model that shows the surficial expression of the Callaqui-Copahue-Mandolegüe volcanic lineament interposed between the Liquiñe-Ofqui and the Callaqui-Mandolegüe fault systems

Agrio Caldera, feeding lava fields corresponding to the El Huecú volcanic field (Fig. 1.5).

Activity less than 1 Ma at Copahue volcano occurred within the Agrio Caldera (Fig. 1.5). The volcano is formed by the amalgamation of several centers along a NE fissure, having 8–9 well preserved craters, similarly the neighboring Callaqui Volcano (Moreno and Lahsen 1986) (Fig. 1.4). The easternmost crater along the Copahue Volcano fissure has concentrated part of the postglacial eruptions as well as the 1990s and the 2000s eruptions. This center has an older section intruded by the 0.9 Ma dacitic Pucón Mahuida dome, which is in turn covered in an erosional unconformity by a younger section that can be divided in two parts, a lower pre-glacial section (Copahue Stage 1; Fig. 1.6) and an upper synglacial and postglacial section (Copahue Stage 2; Fig. 1.6). The upper synglacial section is eastwardly displaced with respect to the central Copahue vents, constituting small centers over the southern flank of the volcano and smaller accumulations of hundred of meters of pillow lavas as independent centers. Even smaller volumes can be tracked up to the eastern rim of the caldera following a W–NW track (Fig. 1.5).

Postglacial vents are related to the volcano edifice itself along fissural systems hosted in its northern slope and central vents associated with the easternmost apical crater of the stratocone (Copahue Stage 3; Melnick et al. 2006a) (Figs. 1.5 and 1.6). Additionally, postglacial explosive products have been identified in the caldera perimeter east of the active crater (Polanco et al. 2000). The age of these products is less than 30–27 ka based on the determination of the final retreat of the ice sheet in the area. The last glacial retreat at these latitudes has been addressed from five different lines of evidence: (i) in 25.6 ± 1.2 and 23.3 ± 0.6 ka by whole-rock $^{40}Ar/^{39}Ar$, dating postglacial lava flows in the

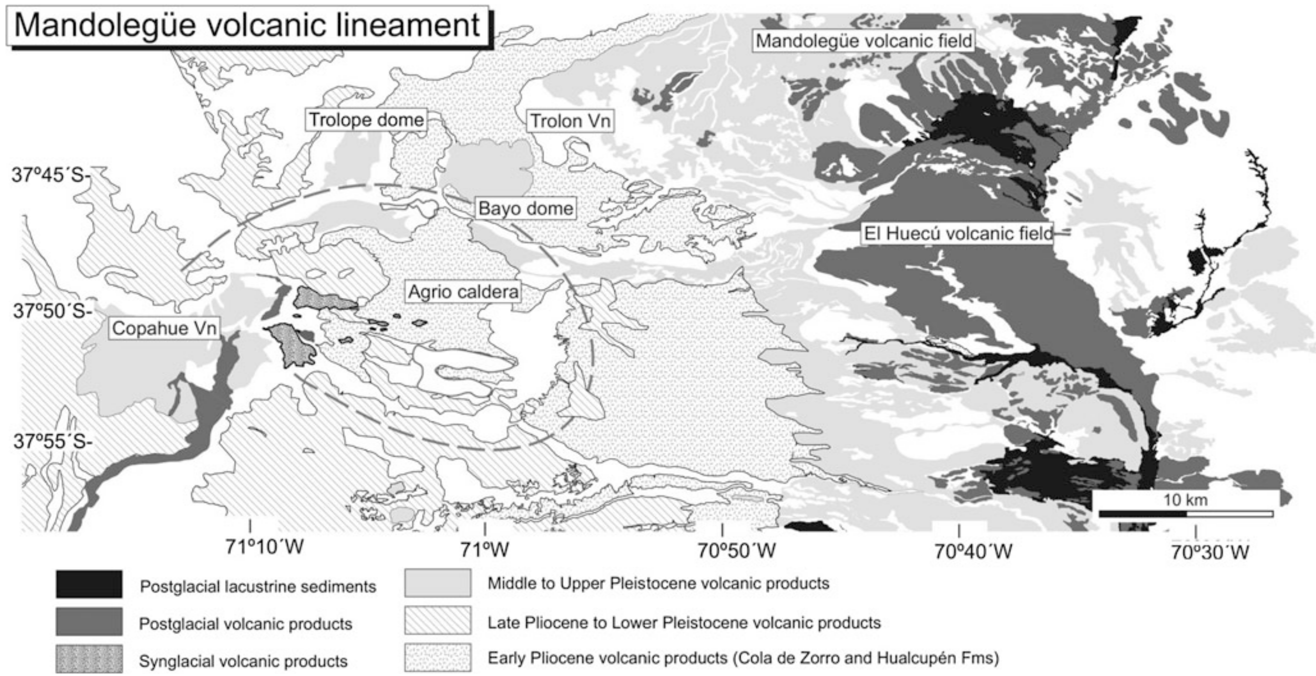

Fig. 1.5 Geology of the Callaqui-Copahue-Mandolegüe volcanic lineament, from the Agrio Caldera to the El Huecú volcanic field. Geology of the Copahue Volcano is based on Pesce (1989), JICA (1992), Folguera and Ramos (2000), Melnick et al. (2006a) and Rojas Vera et al. (2009b). Note that most of the postglacial volcanic eruptions have been emplaced over the retroarc area in the El Huecú volcanic field, while the Copahue Volcano and Agrio Caldera have minimum resurfacing during this stage

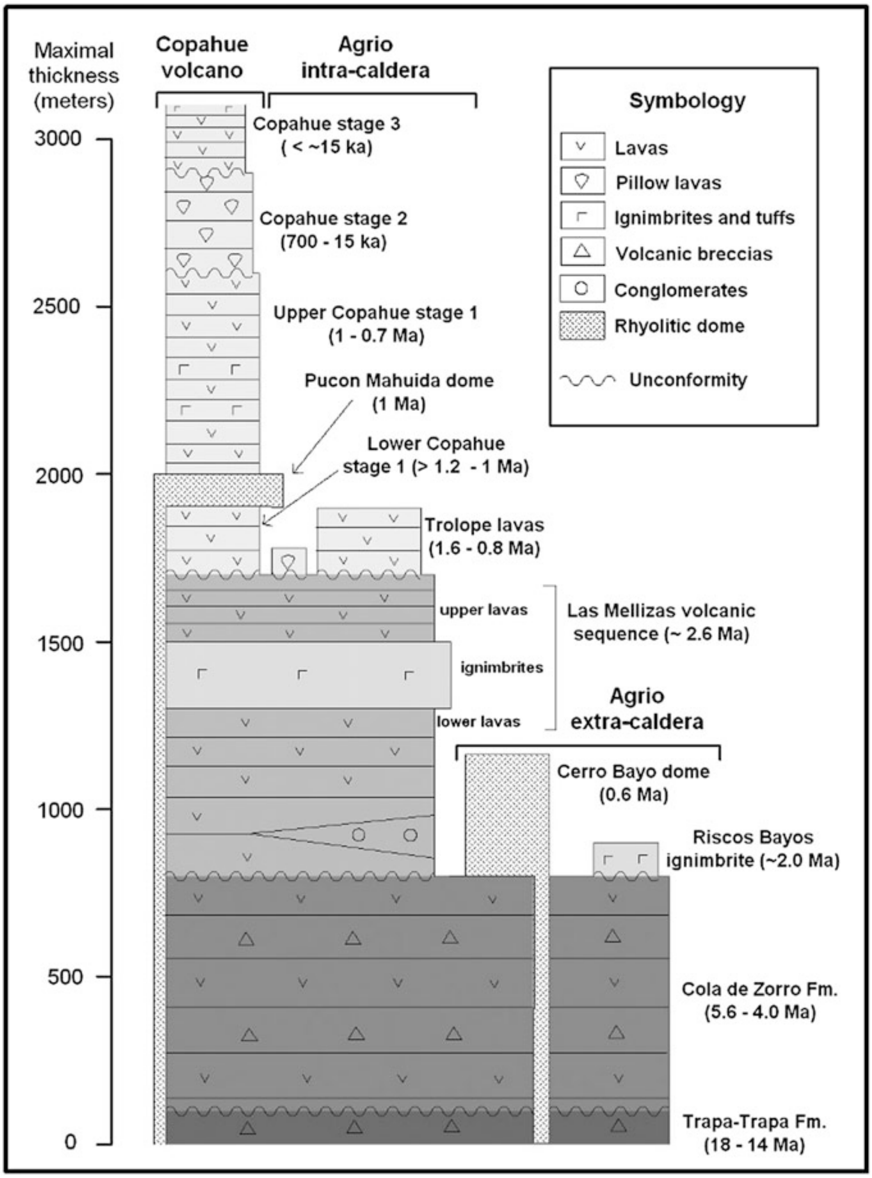

Fig. 1.6 Stratigraphic chart of the Agrio Caldera and Copahue Volcano (after Melnick et al. 2006a; based on Pesce 1989 and Linares et al. 1999)

Laguna del Maule area immediately to the north (36°S, 70°30′W) (Singer et al. 2000); in 30 ka by dating by cosmogenic ^{36}Cl the postglacial Varvarco rock avalanche deposit (36°26′S, 70° 36′W) (Costa and González Díaz 2007); in 25–30 ka by whole-rock ^{40}Ar/^{39}Ar, dating postglacial lava flows from the Chillán Volcano (37°S) (Dixon et al. 1999); in 30–35 ka by ^{10}Be, dating moraine deposits in the Rucachoroi valley (39°S) (Zech et al. 2008); and finally and more locally in 30 ka by ^{14}C, dating glaciofluvial deposits from Copahue volcano circumscribed to a glacial morphology (37°50′S, 71°03′W) (Bermúdez and Delpino 1999).

1.3 Structure of Copahue Volcano and Agrio Caldera

Copahue volcano is situated at the intersection point between two nearly perpendicular structural systems, the two WNW parallel Caviahue grabens and the NE contractional Chancho-Co hill (Fig. 1.7). The Caviahue grabens run through the southern section of the Agrio Caldera from the eastern inner wall to the northern Liquiñe-Ofqui fault system. These constitute symmetrical structures that broaden to the east where they are clearly separated by a small horst, whose deepest part is occupied by the Agrio lake. This extensional depression affects 2.5 Ma ignimbrites and lava flows of the Las Mellizas Formation and controls the emplacement of most of the synglacial volcanic rocks in the region (Fig. 1.7) (Melnick et al. 2006a).

The Caviahue grabens parallel the southern wall of the Agrio Caldera and are formed by a broken structural lineament composed of WNW and NW north-facing scarps affecting early Pliocene sections of the Cola de Zorro-Hualcupén Formations (Fig. 1.7). The northern flank of the caldera is formed by similarly oriented fault systems that, together with a degraded north-facing scarp north of Copahue town, delimits the Trolope graben where 1.6–0.8 Ma lava flows of the "*Basaltos de Fondo de Valle*" were emplaced (Fig. 1.7). North and south inner walls of the Agrio Caldera are tied by NNE and NW normal fault systems constituting the eastern west-facing wall of the Agrio Caldera (Fig. 1.7). The western caldera wall is not well defined south of its intersection with the Caviahue grabens. Pesce (1989) had proposed that this fault section would have been erased by later caldera-forming processes. This caldera perimeter, composed of kilometer-long fault segments, has a rhombhoedral shape with a maximum axis of 20 km in the NW direction and 15 km in the

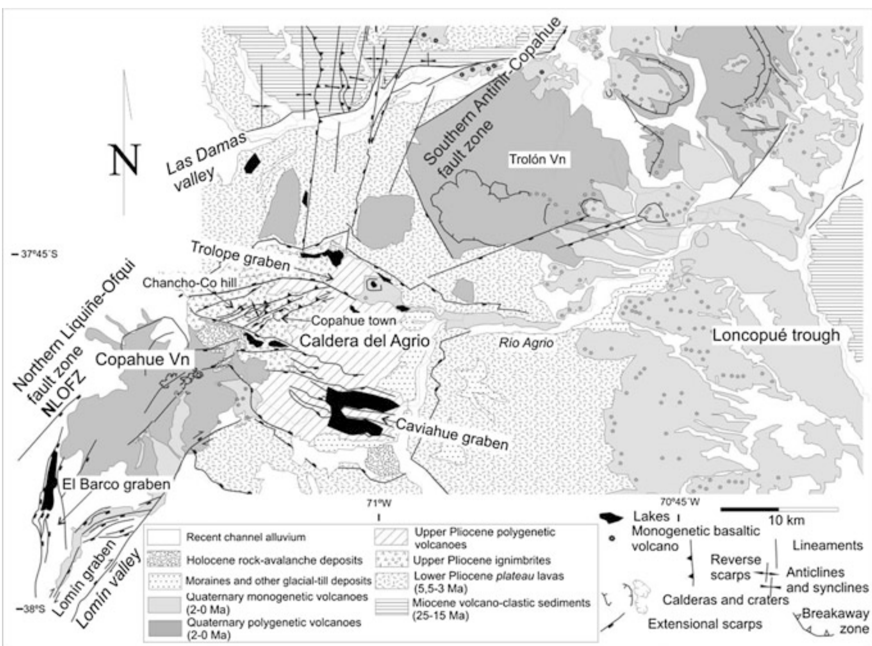

Fig. 1.7 Structural map of the Mandolegüe volcanic lineament between Copahue Volcano and northern Loncopué trough (modified from Folguera et al. 2004). Two main structural trends interact in the Agrio Caldera, a NE trend across the Copahue Volcano composed of reverse and strike slip structures of the Lomín and Chancho-Co structural systems and a WNW pattern of normal faults that define the two western Caviahue grabens

NE direction that suggests a tectonic origin (Folguera and Ramos 2000).

The Chancho-Co hill is north of Copahue Volcano and corresponds to a SW vergent structure that folded and uplifted Las Mellizas Formation in a broad structure in the NW extreme of the Agrio Caldera (Fig. 1.7). This anticline is affected at its southern part by the Caviahue grabens, which displace the Pliocene to Pleistocene sections beneath the basal lavas of Copahue Volcano. This relation suggests a chronology of events that starts with the uplift of the Chancho-Co hill followed by extension that led to the Caviahue grabens formation. However, SW-vergent reverse faults that uplift the Chancho-Co hill affect and displace a Pleistocene glacial pavement defining very fresh scarps, which is indicative of young deformation (Fig. 1.8). Additionally, part of these structures propagates toward Copahue town, where late Pliocene rocks are thrust over Pleistocene till deposits (Rojas Vera et al. 2009a).

Extinct and active hot springs of the Agrio Caldera are associated with the Chancho-Co structural system (see Varekamp et al. 2001, for a recent synthesis). Las Máquinas, Maquinitas, Copahue, Anfiteatro and Chancho-Co hot springs are aligned through the Chancho-Co hill frontal structures. In particular, the last lies in the upper Trapa Trapa river on the Chilean side at the intersection point between the Chancho-Co and the Caviahue structural systems.

South of the Chancho-Co hill, associated reverse faults propagate as southeast-facing scarps into the <1 Ma volcanic rocks and postglacial products of Copahue volcano (Figs. 1.9 and 1.10). These structures act as conducts of fissural postglacial lavas flowing through the northern slope of the volcano towards the Trapa Trapa river in Chile (Figs. 1.7 and 1.10).

These two structural systems are spatially associated with indicators of ongoing deep activity in the caldera interior revealed using geophysical tools. In particular, Ibáñez et al. (2008) have measured shallow seismic activity since 2004 along the broadest and axial section of the Caviahue grabens (Fig. 1.11). This area does not show surficial evidence of young deformation, being fault scarps strongly affected by glacial abrasion, indicating that the structure formed at least in Pleistocene time since it is affecting latest Pliocene products. Additionally, radar interferometry data have shown deflation processes previously to 2011, at the intersection point between the Caviahue grabens and the Chancho-Co hill, where fissural postglacial products are emplaced in the Trapa Trapa upper valley, (Fig. 1.11) (Vélez et al. 2011). This anomaly is shifted with respect to the axial part of Copahue volcano and coincident with an area of normal faults affecting the youngest products at its northern slope. This deflation could indicate that collapse of the Chancho-Co structural system through WNW normal structures remains active. Mass-wasting phenomena associated with the northern slope of the volcano (Figs. 1.7 and 1.10) occurred prior to the postglacial fissural eruptions and coincide with the area of noted deformation, indicating slope instability.

After 2011 a new inflationary process started with an anomaly fairly coincident with the previous slope deflation (Fig. 1.12; Vélez et al., this book). However, in a closer view, it is noted that the area that accumulated nearly 5 cm of vertical displacements in half a year shows an elliptical shape (Fig. 1.12) aligned with the scarp that is affecting and controlling the emission of postglacial lava products (Fig. 1.10). The interferogram also shows displacements through the structures that are associated with the Chancho-Co hill suggesting its reactivation (Fig. 1.12).

1.4 Tectonic Evolution of Copahue Volcano and Agrio Caldera

Copahue volcano, as part of the Southern Volcanic Zone, has evolved through two distinctive southern Andean deformational stages. The description of these processes can explain

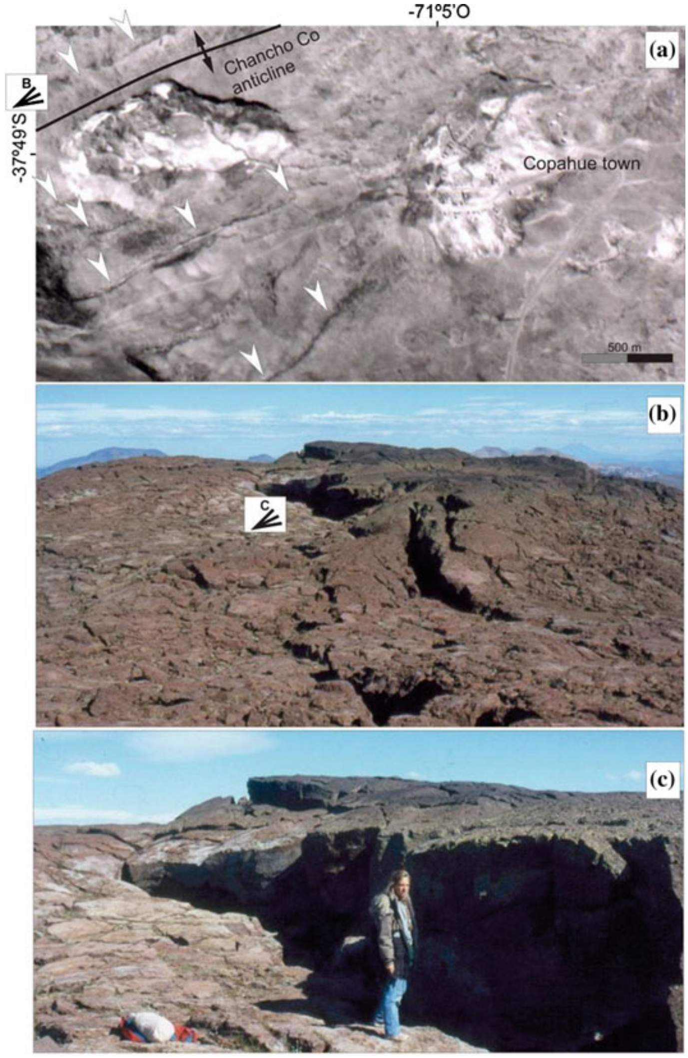

Fig. 1.8 Neotectonics in the basement rocks of the Copahue Volcano flanking the Chancho-Co hill. **a** Aerial picture where spatial relation between fault scarps associated with the Chancho Co hill and Copahue town are displayed (arrows indicate the scarp traces). **b** Axial zone of the Chancho-Co hill where a glacial pavement is folded and broken by a reverse fault. **c** Detail of **b**

variable mechanics through time and distribution of the structures that were developed previously to the emplacement of Copahue volcano, particularly during the Agrio Caldera formation, and synchronously. This center is located in the drainage divide area to the east of the present arc front and its basal section is older than these neighbor active volcanoes. Additionally, the basal section of Copahue volcano, particularly when considering the Agrio Caldera as part of its evolution, is more similar in age to the extinct Pliocene to Pleistocene centers emplaced on both sides of the Andes at these latitudes. Then, Copahue volcano could be considered as part of this old configuration with the exception that it has undergone a thin and restricted resurfacing in

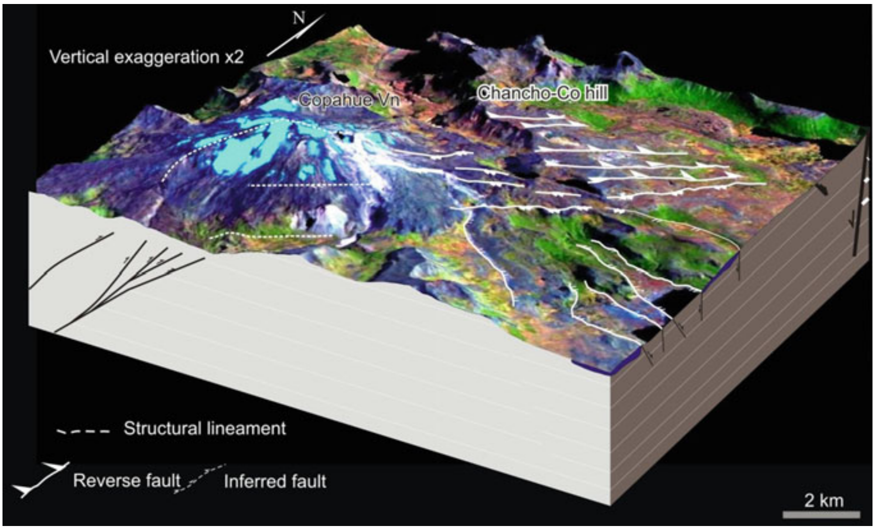

Fig. 1.9 Block diagram constructed with Aster image draped on DEM (modified from Rojas Vera et al. 2009a), where neotectonic contractional structure of the Chancho-Co hill is represented in the basement of Copahue Volcano. Compare these with ground deformation contours determined from InSar studies shown in Vélez et al. (2011)

syn- and post-glacial times. During this stage, early Pleistocene to postglacial sections have been uplifted as a contractional structure in the caldera interior. This uplift constitutes the northern continuation of the Liquiñe-Ofqui fault system, denoting a profound change in deformational mechanisms in the last 1 Ma.

1.4.1 The Pliocene to Pleistocene Evolution

The basement of Copahue Volcano and the Agrio Caldera is formed by the Cola de Zorro and Las Mellizas Formations volcanic sections. These are hosted in quadrangular-rhombhoedral depocenters delimited by normal faults that contain sections up to 1,500 m (Folguera et al. 2006; Melnick et al. 2006b; Rojas Vera et al. 2009c). Younger products in the region are also associated with extensional/transtensional mechanisms in the lasts 2–1 Ma time period, both in the Andean and extra-Andean domains. These processes were contemporaneous to the retraction and narrowing of the volcanic arc in the last 1 Ma from the eastern to the western Andean slope (Fig. 1.1). Even though this process was initially defined as a simple westward migration of the arc front (Stern 1989; Muñoz and Stern 1988, 1989), in the last decade it was redefined on the light of new isotopic ages as an arc narrowing, from a broad geometry through both Andean slopes in Pliocene to Pleistocene times to a narrower configuration in Pleistocene to Holocene times (Fig. 1.1) (Lara et al. 2001).

This arc narrowing coincides with the area of Pliocene to early Quaternary extensional deformation between 36 and 39°S that affected the arc and retroarc areas. In particular, the Loncopué trough, considered the major extensional depocenter in the area with more than 1,500 meters accumulated in the lasts 5 Ma (Rojas Vera et al. 2010), is partially superimposed on the crustal attenuation processes identified in the retroarc zone from receiver function analyses by Yuan

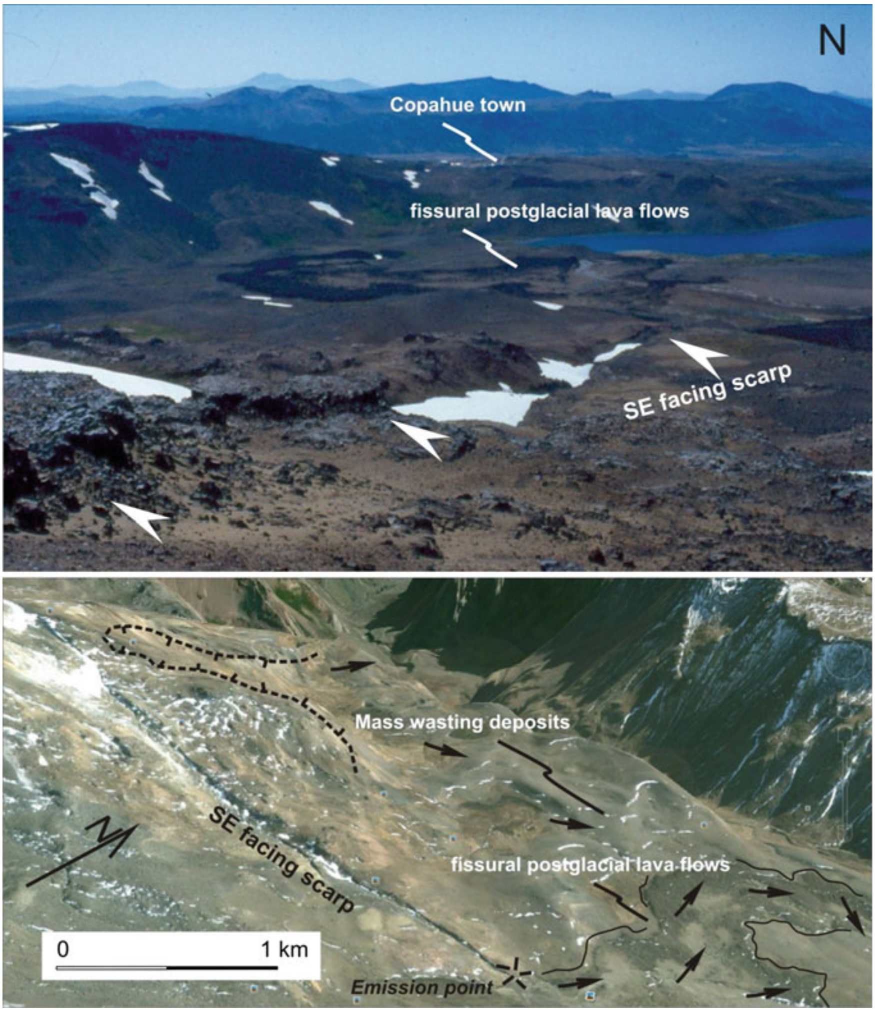

Fig. 1.10 *Above* Picture of the SE facing scarp affecting the northern slope of Copahue Volcano as part of the structures that are flanking the Chancho-Co hill (*below*). *Below* Oblique view (ikonos image taken from Google Earth) and morphological expression of the fault associated with postglacial lava flows and mass wasting deposits

et al. (2006) (Fig. 1.13). This crustal attenuation zone has produced a broad positive gravity anomaly associated with the emplacement of mantle rocks in shallower levels beneath the retroarc zone that has a latitudinal extent similar to the arc narrowing registered in the last 1 Ma and to the extensional deformed zone and related within-plate volcanic series. Asthenospheric upwelling beneath the steepening subduction zone proposed from gravity models coincides with the anomalies in ^{13}C and ^{3}He detected by Agusto et al. (2013) in the hot springs located north of the Copahue Volcano that are indicative of a relatively near mantle source.

The steeper configuration of the subducted Nazca plate at these latitudes (Fig. 1.1) revealed by seismic tomographies (Pesicek et al. 2012) is considered to have developed prior to 2 Ma, and could indicate the broadening of the asthenospheric wedge coeval to crustal attenuation and

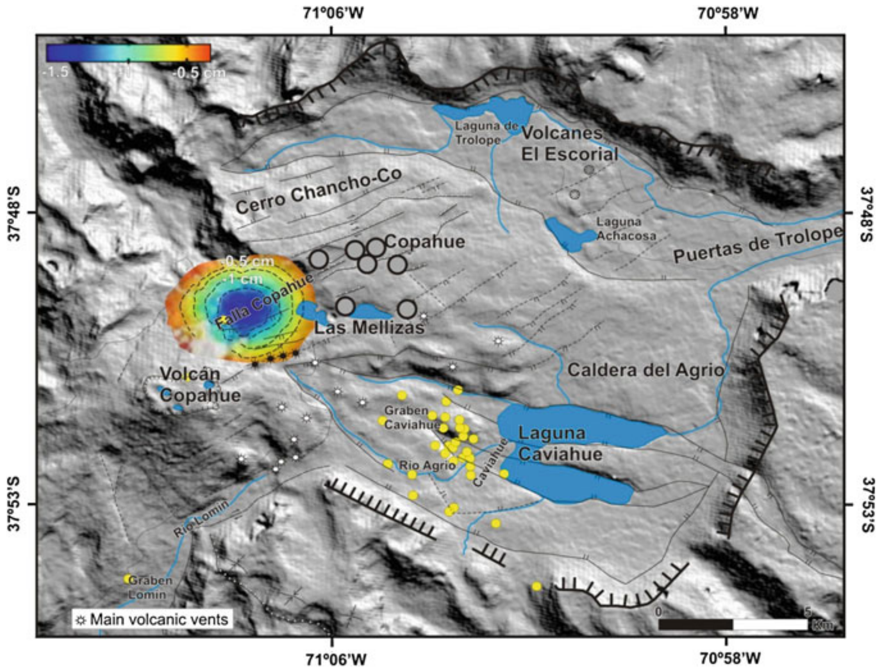

Fig. 1.11 Structural map of the Agrio Caldera and Copahue Volcano (modified from Rojas Vera et al. 2009a), with 2004s superimposed seismic events (small yellow dots; Ibáñez et al. 2008), ground deformation contours determined from satellite interferometry previous to 2011 (2002–2007) when a new inflationary process started (see next figure) (Vélez et al. 2011) and ^{3}He and ^{13}C anomalies determined in hot springs by Agusto et al. (2013). White stars indicate main eruptive synglacial vents. Note that synglacial activity is not coincident with the volcanic axial zone but slightly displaced to the northeast where neotectonic features have been described. Note also that seismic events are aligned with the axial zone of the Caviahue grabens

extensional processes registered in the area (Fig. 1.13). Agrio Caldera and lower sections of Copahue volcano were coeval to these processes and were circumscribed to extensional depocenters.

1.4.2 Processes Younger Than 1 Ma

WNW contractional structures involve glacial deposits and postglacial products of Copahue volcano (Fig. 1.8). Additionally, these control the emplacement of postglacial products. These structures are aligned with the Liquiñe-Ofqui fault system to the south, which abandons the arc front and penetrates at these latitudes to the Argentinian Andean slope (Figs. 1.7 and 1.14).

Reverse structures that affected postglacial products have subordinate right-lateral components displacing Quaternary deposits and landforms and producing small pull-apart depocenters (Folguera et al. 2004; Rojas Vera et al. 2009c). These structures determine the ENE Mandolegüe fault system, where the Chancho-Co hill occupies the western edge. To the north, these structural trends bend to the NW Antiñir-Copahue fault system trending through the eastern Andean front (Fig. 1.14). This system has accommodated maximum shortening in the 1.4–0.8 Ma time period, showing minor reactivations in postglacial times (Folguera et al. 2004). Its development is spatially coincident with the area of the inception of the Mocha transfer zone in the

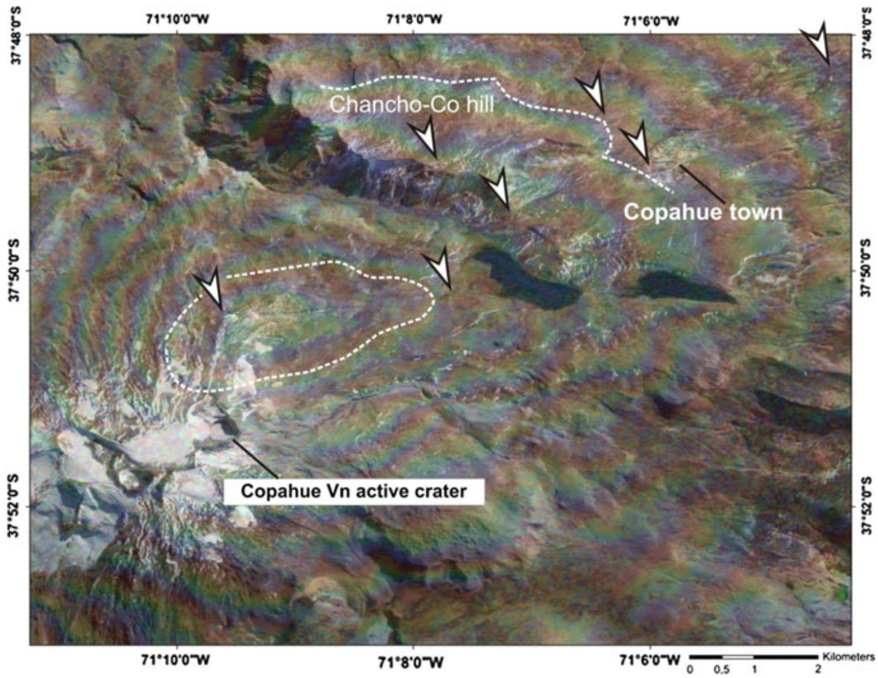

Fig. 1.12 Inflacionary processes detected by Insar over the NE slope of Copahue Volcano since 2011 (Vélez et al. this issue). This inflation accelerated since August-October 2011 and continues after 2012–13 eruptive cycle, accumulating nearly 5 cm in 6 months. Arrows indicate fault traces of the neotectonic structure affecting the northern slope of the volcano (see Fig. 1.10). Note that the area of higher displacements describes an ellipse with a major axis in the W–E direction surrounding the normal fault affecting postglacial products. Note also that curves of iso-displacement seem to be deflected in the north when crossing active faults in the Chancho-Co hill

Chilean trench in the lasts 3 Ma that could have produced an eastward wave of out-of-sequence contractional deformation through the forearc and western retroarc zones. The area of collision of the Mocha transfer zone coincides with a segment where the subducted slab penetrates with an angle 8° shallower in comparison to neighboring areas (Krawczyk et al. 2006; Tašárová 2004). Seismic tomography illuminates this shallow segment that would have been produced in the last 2–3 Ma and replaced a steeper previous configuration (Pesicek et al. 2012), showing a strong change in the subduction regime.

In this context, the Mandolegüe fault system could have officiated as a transfer zone between the Liquiñe-Ofqui and the Antiñir-Copahue fault systems that would have operated accommodating shortening and lateral displacements on opposite sides of the Andean drainage divide (Fig. 1.14) (Folguera and Ramos 2009). This transfer zone forms a 70–80-km-long volcanic lineament that can be explained by the collision of the southern part of an oceanic plateau whose size would be similar to the Mocha plateau presently subducted south of 38°S. Insar data show that this structure near Copahue volcano concentrates present deformation. Seismic tomography may show a steeper subduction configuration concomitant with older products and a shallower one contemporaneous to late contraction and transpressional deformation at the arc and retroarc areas.