1 General Chile Overview

Chile is a long (4,300 km) and narrow (180 km wide on average) country in the southwestern extreme of South America that presents varied and pristine landscapes truly unique in the world. Inhabited for around 10,000 year, its territory is bordered by Perú to the north through the Concordia line, Argentina and Bolivia to the east through the huge Andean altitude, the South Pole to the south and the Pacific Ocean along the western side.

Its continental length, between the northern and southern boundaries, is approximately 4,200 km. Including the Chilean Antarctic Territory, its longitude exceeds 8,000 km. A region of the Antarctic continent is also part of Chile, which forms a triangle ending in the South Pole. The continental and insular territory amounts to 756,915 km^2 and the Antarctic territory to 1,250,000 km^2 (Fig. 1.1).

Chilean territory is very asymmetrical in its length and width, 4,300 km and approximately 180 km on average, respectively. The maximum insular width is 468 km and is located at 52°S. The maximum continental width is found in Antofagasta (Region II), between the Mejillones and the Bolivian boundary (at 27°S; 380 km) and the minimum continental width at 31°37'S (90 km). As a nation, Chile became independent in 1818 and today is administratively divided into 15 Regions (Fig. 1.2), 50 Provinces and 341 Municipal Governments.

1.1 Territory Formation: Geology and Geomorphology

Western South America is one of the best known convergent margins on the Earth. The current cycle of ocean-continent convergence began in the Jurassic following the break-up of the Gondwana supercontinent and has been continuing ever since with varying degrees of obliquity. In the evolution of the Andean Orogen in Chile (c. 550 Ma geological history), it is possible to distinguish five separate main periods. The latest of these (Andean), occurring during late Early Jurassic to present, is characterised by continental break-up and represents the archetypal example of a subduction-related mountain belt.

Belts of active volcanoes, the most significant tectonic and geological events in the evolution of the Andes, have occurred since the Late Oligocene, after the break-up of the Farallon plate into the Cocos and Nazca plates at approximately 27 ± 2 Ma. This resulted in a change from oblique to more nearly orthogonal convergence between the Nazca and South American plates, as well as a greater than two-fold increase in convergence rates, which together produced a more than threefold increase in trench–normal convergence. This caused changes in subduction geometry which accelerated crustal shortening, thickening and uplift in the Northern Central Andes, but resulted initially in extension and crustal thinning in the Southern Central and Southern Andes. As a result of the increase in convergence rates, magmatic activity also increased along nearly all the Andean chain.

The Late Cenozoic tectonics of the coast of Northern Chile reflects processes related to the seismic coupling between the subducted Nazca Plate and the overriding South American Plate. Although these processes probably occur in all eroding convergent margins around the globe, only in Northern Chile is the record preserved due to the hyper-arid climate of the region (Allmendinger and González 2010).

The South American central volcanic zone (CVZ; 18–27°S) includes Chile and around 40 active volcanic centres (Fig. 1.3), as well as around 20 active minor centres and/or fields and at least 6 potentially active fields.

A zone where the passive Juan Fernández Ridge is subducting the continental margin is present between approx. 27 and 33°S, corresponding to a flat-slab subduction

M. Casanova et al., *The Soils of Chile*, World Soils Book Series, DOI: 10.1007/978-94-007-5949-7_1,

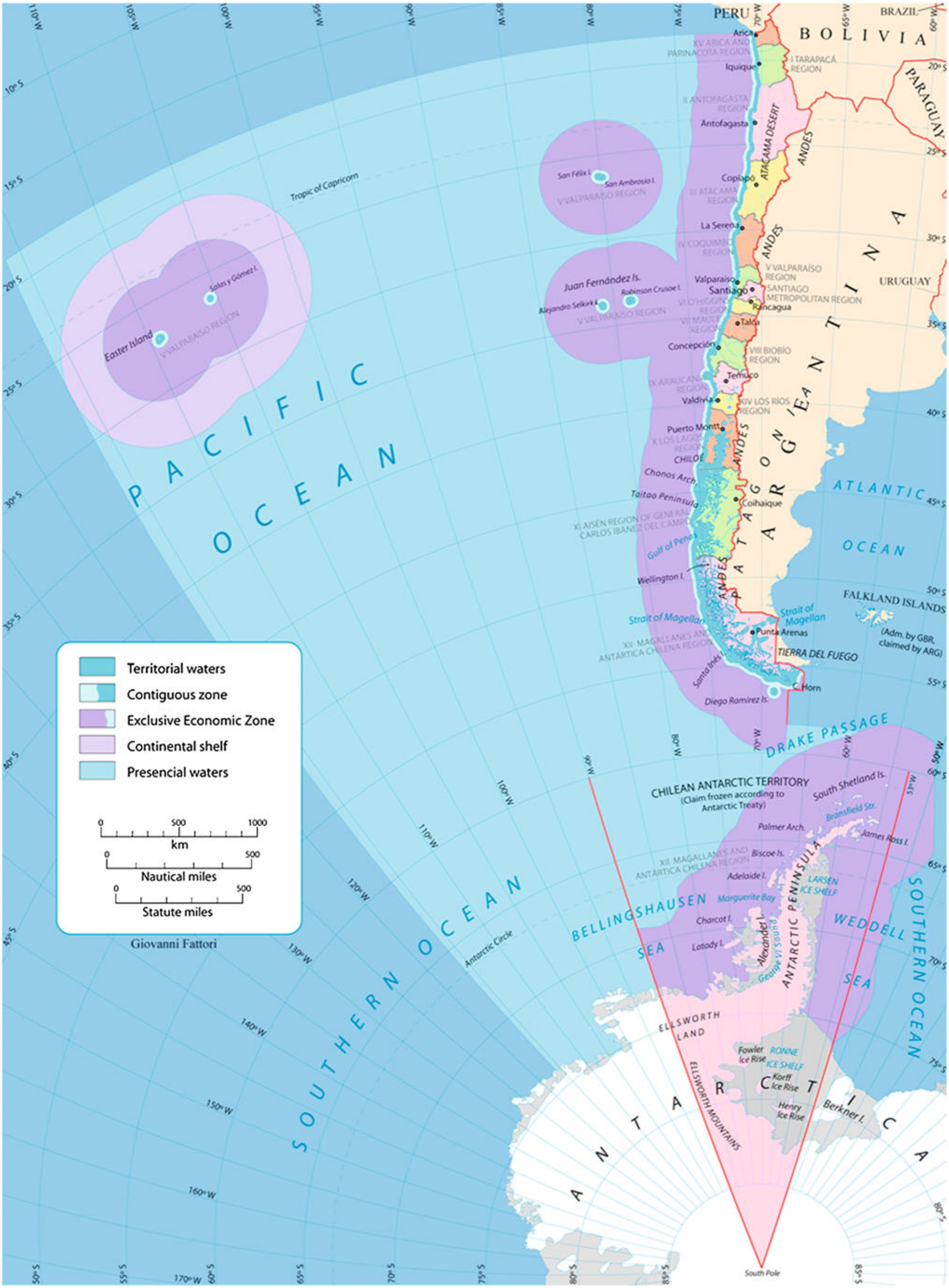


Fig. 1.1 Land and sea space of Chile (http://www.wikipedia.org, Accessed 30 November, 2012)

Key	Region name	Capital
XV	Arica and Parinacota	Arica
I	Tarapacá	Iquique
II	Antofagasta	Antofagasta
III	Atacama	Copiapó
IV	Coquimbo	La Serena
V	Valparaíso	Valparaíso
VI	Libertador Bernardo O'Higgins	Rancagua
VII	Maule	Talca
VIII	Bío Bío	Concepción
IX	La Araucanía	Temuco
XIV	Los Ríos	Valdivia
X	Los Lagos	Puerto Montt
XI	Aysén del Gral. Carlos Ibañez del Campo	Coyhaique
XII	Magallanes and Antártica Chilena	Punta Arenas
MR	**Metropolitan**	**Santiago**

Fig. 1.2 Administrative division of Chile at present

zone, whereas in the zones north and south of this aseismic segment the Wadati–Benioff zone is steeper.

The South American south volcanic zone (SVZ; 33–46°S) includes at least 60 historically and potentially active volcanic edifices in Chile and Argentina, as well as three giant silicic caldera systems and numerous minor eruptive centres. However, the continuity of the strike–parallel morphostructural units is interrupted in the regions where the Juan Fernández and the Chile ridges intersect the continental margin, causing segmentation of the orogen. The Chile Rise is an active spreading centre that marks the boundary between the Nazca Plate and the Antarctic Plate at the so-called Chile Triple Junction.

A gap in active volcanism occurs between 46 and 49°S to the south of the Chile Rise–Trench triple junction, where the south-east extension of the Chile Rise has been subducted during the last ~8 Ma, without a Benioff zone of seismic activity below this volcanic gap.

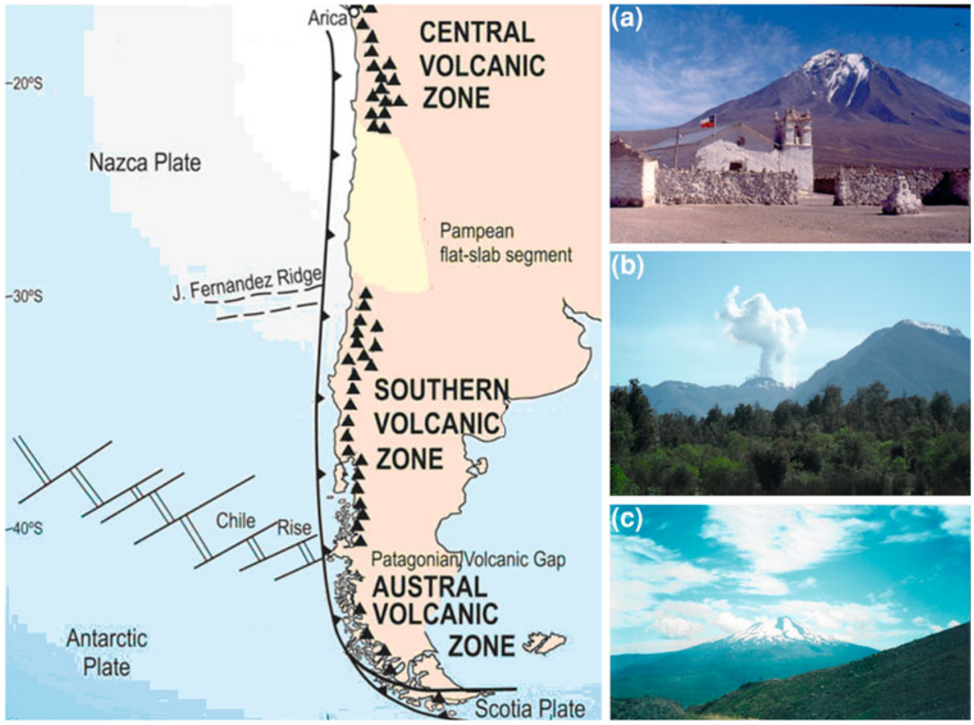


Fig. 1.3 Volcanic zones in Chile. **a** Tacora volcano (Region XV), **b** Llaima volcano (Region IX) and **c** Hudson volcano (Region XI)

The Austral volcanic zone (AVZ; 49–55°S) consists of five stratovolcanoes and a small complex of Holocene domes and flows on Cook Island, the southernmost volcanic centre in the Andes south of the Magallanes Fault zone and therefore on the Scotia plate. Finally, the Antarctic Peninsula in the Chilean Antarctic Territory shares a lot of characteristics with the Andes and is sometimes considered to be an extension of those mountains.

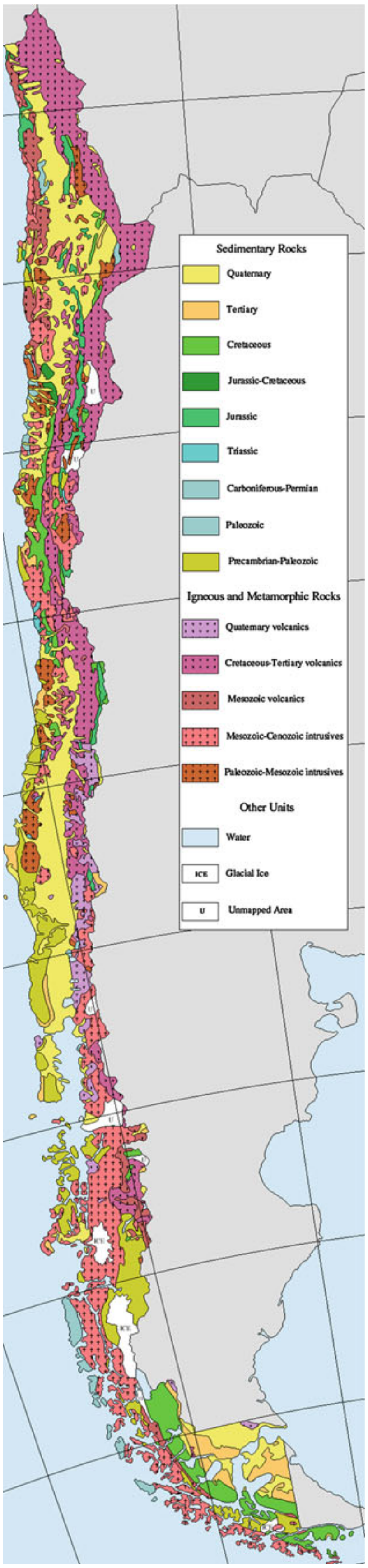
The geological map of Chile shown in Fig. 1.4 (scale 1:2,500,000) gives a general view of the country. A digital geological map of Chile (scale 1:1,000,000) published by SERNAGEOMIN (2003) cannot be presented in this chapter because of the small, detailed units used. Cembrano and Lara (2009) include a map covering SVZ (Fig. 1.5), where regional-scale rock units are organised into several margin–parallel belts, ranging from Paleozoic plutonic and metamorphic rocks in the Coastal Range to Meso-cenozoic plutonic and volcano-sedimentary units in the Main Andes. The Central Valley, located in the middle, is characterised by Oligocene-Recent volcano-sedimentary rocks. Particular portions of Chilean territory have also been mapped on different scales by Muñoz et al. (2002) for the Atacama basin, Gioncada et al. (2010) for Easter Island, Calderón et al. (2007) for the Magallanes Fault zone, etc.

Considering different tectonic and morphostructural features of Chile, at least five macrozones along its territory are defined by Pankhurst and Hervé (2007):

(i) Coastal Range, a western coastal batholith (18 to ~42°S) of predominately Late Palaeozoic and Mesozoic igneous rocks, with paired belts of Palaeozoic metamorphic rocks cropping out south of ~34°S uplifted in an accretionary prism. It is the oldest and most western remnant of a magmatic arc formed at the birth of the modern Andes (195–130 Ma). With a moderate height, 1,000–2,000 m a.s.l., it disappears completely in Northern Chile near Arica.

(ii) Central Depression (125–90 Ma) or Longitudinal Central Valley, a tectonic downwarp with a Mesozoic to Quaternary sedimentary fill of volcanic, glacial, and fluvial origin, is only absent between 27 and 33°S (flat-slab subduction zone). However, according to Farías (2007), this zone is not a subsidence depression *sensu stricto* and valley denomination could be a more appropriate term due to a domain of erosive processes. According to Segerstrom (1964), it corresponds to an erosion surface, of Tertiary age, well denned in Central Chile by concordant summits, some of them are flat and extensive.

(iii) Main Andes, a chain of mountains that dates back to the Miocene, the emergence of which continues today. It is subdivided into three segments: Forearc Precordillera (78–37 Ma) and Western Cordillera (26 Ma to recent) from 18 to 27°S, High Andean Range at flat-slab subduction zone and Principal Cordillera (33°S to



◀**Fig. 1.4** General geologic map of Chile derived by Andrew Alden from US Geological Survey OFR 97-470D (http://geology.about.com/od/othernationgeomaps/ss/South-America-Geologic-Maps_4.htm. Accessed 8 April, 2010)

ca. 42°S). Petrologically distinct to the Coastal Range, the Andes are made up of Cenozoic age basaltic to andesitic volcanic rocks reaching to 1,500–4,000 m a.s.l. in Southern Chile and 4,000 m a.s.l. to nearly 7,000 m a.s.l. in Central and Northern Chile.

(iv) Patagonian Cordillera, the continuation of the Andes right down into *Tierra del Fuego* at the southern tip of Chile, with a continuous reduction in height. The origin of this low portion of the Andes has been related to an allochtonous Palaeozoic terrane. The southwestern margin of the land (42°S to the South) is formed by recent glaciations that carved the coastal areas into fjords and archipelagos comprising thousands of little islands and narrow channels. This estuarine system also resulted from the tectonic sinking of a longitudinal valley south of Puerto Montt (41°31′S) during the Quaternary.

(v) Andean foreland of the southern Patagonian Cordillera or Magallanes basin, consisting of Upper Jurassic to Early Cenozoic sedimentary deposits.

On the other hand, based on shortening rates and tectonic activity, the Central to Southern Andes of Chile is subdivided by Rehak et al. (2010) into only four tectonic provinces:

(1) The central part from 14 to 27°S comprises the Coastal Range, the Central Valley, the Precordillera and the Main Cordillera, with the internally drained intraorogenic plateaus of the Altiplano and Puna displaying mean elevations of 3,700 m. This sector exhibits pronounced crustal shortening in the Main Cordillera and the Subandean Ranges.

(2) A zone between 27 and 33°S with the above-mentioned related absence of late Neogene to Quaternary volcanism and a Central Valley. However, this zone comprises the broken foreland province of the *Sierras Pampeanas* that experiences active deformation and destructive earthquakes.

(3) South of 31°S, total shortening is significantly reduced and south of 37° shortening stopped at the end of the Miocene. South of 33°S the western onshore margin shows a pronounced morphotectonic segmentation integrating the forearc Coastal Cordillera, the Central Valley and the Main Cordillera.

(4) South of ~37°S the Main Cordillera is called Patagonian Cordillera. Here, deformation is partitioned into intra-arc strike-slip tectonics along a fault zone and thrust faulting.

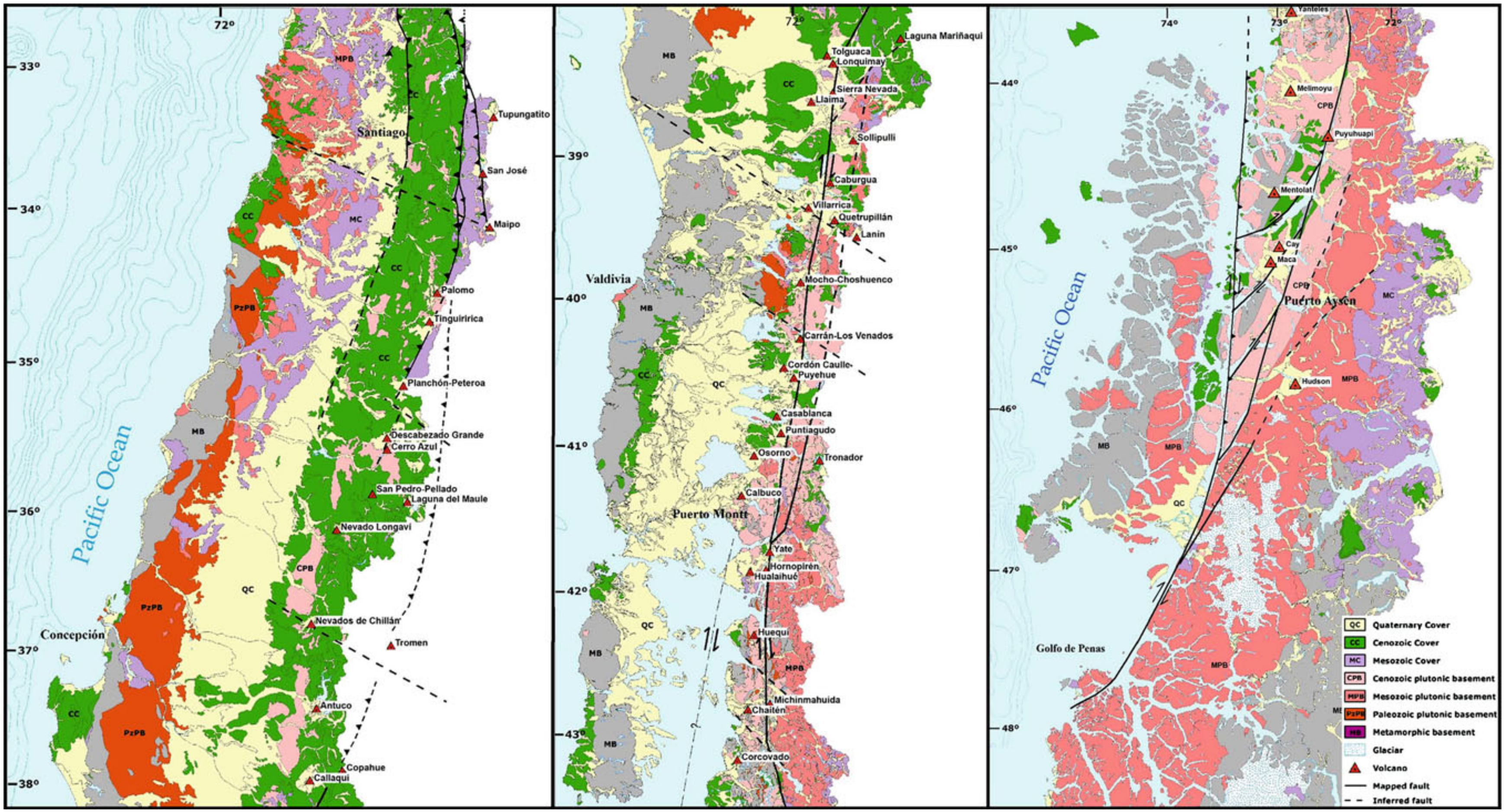


Fig. 1.5 Regional-scale geology of the Chilean Andes between 33 and 47°S (Cembrano and Lara 2009)

Emphasising the general theme of overall plate tectonic control of the geological evolution of the Chilean margin, there also appears to be a close relationship between subduction-related tectonic evolution, magmatic processes and climate along and across the Andean range. In addition, Rehak et al. (2010) suggest that the generation of local relief is a force balance between protracted fluvial erosion and glacial erosion acting as opposite agents; whereas glacial erosion appears to create local relief, persistent moderate rainfall above a critical threshold appears to smooth it. Figure 1.6 gives a general view of current geomorphological features of Chile, including principal transverse profiles east–west along continental territory.

In order to diagnose the imprint of different climate zones on the relief of mountain ranges, Rehak et al. (2010) correlated climate with relief parameters and investigated the impact of different geomorphological regimes on relief evolution. They concluded that the catchment-scale relief of the western flank of the Andean mountain chain distinctly reflects the dominant geomorphological process, which is determined by, and therefore represents, past and present regional climate regimes. However, they do not challenge the claim that the large-scale architecture of the Andes is maintained by tectonic processes and the reactivation of inherited basement structures. The geomorphological signature of the Western Andes between 28 and 35°S, however, expresses significant transient components, which may reflect erosion processes under different climate conditions during the geological past. Figure 1.7 describes basins along most Chilean territory, which according to their location can be grouped into: (a) Forearc, catchments drain only the Coastal Range and have not been affected by Quaternary glaciations; (b) Andean mountain front catchments also including the Central Valley and the Andean foothills (do not extend into the high Andes and have mostly not been glaciated during the Quaternary); (c) arc catchments extending from the Pacific to the principal Andean watershed and d) subcatchments that are parts of the arc catchments and constitute the uppermost headwater basins along the Andean main drainage divide.

Recent works published by Paskoff and Araya-Vergara (2010) and Araya-Vergara (2010) are included here to describe the western margin of Chilean territory (Fig. 1.8).

South of the Peruvian border along to Arica, the coast of the Atacama Desert is mainly cliffed. Lluta and Azapa are two alluvium valleys that are very important for agriculture in Region XV. The Lluta Valley is located only 10 km from the Peruvian border. This valley is formed by the 150 km long Lluta River that extends from the Tacora volcano to the sea. The 4,500 ha Camarones Valley is located 100 km south of Arica city and is crossed by the Camarones River, historically the most important water source in the region.

From Iquique, massive transgressive dunes have been deposited between the present beach and the local megacliff. Due to their position with respect to present sea level and the degree of weathering of their sands, they are thought to have formed during the Pleistocene, when sea level was lower. They are a striking feature, because dunes are scarce on the cliffy coast of the desert. North of Antofagasta (23°S), cliffs are cut into horizontally bedded Tertiary sandstones. In some parts, the coastline has embayments cut in sandstone between protruding headlands where harder rocks outcrop near mean sea level.

At 27°S, the Copiapó River (Region III), the first outlet, appears with permanent stream discharge to the Pacific Ocean, after more than 1,000 km of desert coast. There are Pleistocene marine terraces with deflated beaches on their surfaces, and the ergs of the Atacama Desert. A large part of the sand of the ergs has been supplied directly from the Copiapó River, but dune sands of the ergs located in basins inland have a marine origin. South of the Copiapó River, all the principal rivers (Elqui, Limarí and Choapa, for example, in Region IV) flow permanently to the sea through microtidal estuaries. Over more than 700 km of coastline, increasing supplies of fluvial sediment to the shore form beaches in zeta-form embayments, as at Tongoy (30°S) and Los Vilos (32°S).

Between the estuaries of the Petorca-Ligua and Maipo rivers (33°S), there is a southward transition from rias to estuarine deltas, as in the Aconcagua estuary (Region V). Between the Maipo river outlet and San Antonio harbour, the coastline has been straightened as the result of accretion along a breakwater.

Between Rapel (34°S) and Bío-Bío (37°S), river ebb and flow deltas are typical. The deltaic estuarine banks become more stable south to the Maule estuary (35°S), then decrease and become ephemeral down to the Bío-Bío estuary.

Zeta-form bays are common in this sector, and show increasing volumes of sand downdrift to the north, where there are three generations of dunes: early Holocene, middle Holocene and presently active. The Gulf of Arauco (37°S) is a zeta-form embayment backed by a cliff cut in soft sediment. The width of the beach and surf zones increases down drift (northward), indicating sand drift towards the Bío-Bío estuary. Similar features are seen in the embayment

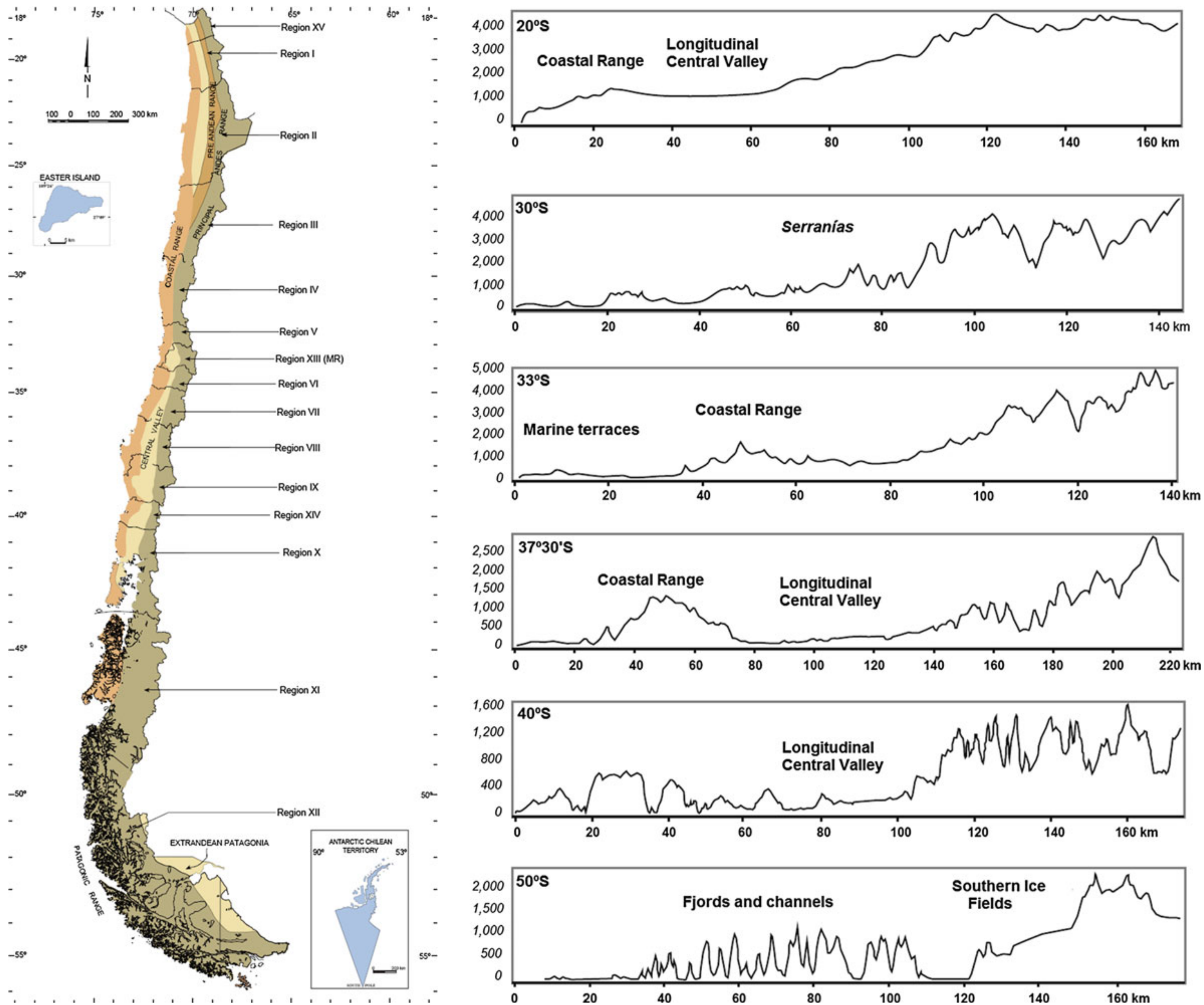


Fig. 1.6 Geomorphology of continental Chile and principal East–West topographical profiles

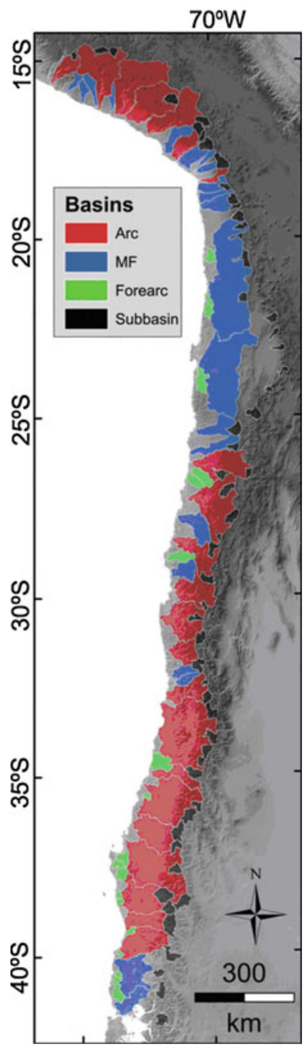


Fig. 1.7 Basins along the western Andean margin (Rehak et al. 2010)

between Lebu and Quidico. Associated with these are the Arauco dunes, the largest coastal erg in Chile, with small impersistent compound barchans because the climate is humid, and there are annual floods. The Imperial River (37°40′ to 38°50′S) meanders across a terrace which is inset in an ancient ria. To the south is a ria coast, formed by partial submergence of river valleys incised into the schistose coast ranges. The intervening sectors are cliffy.

Latitude 40°S is the northern limit of direct influence of the Last Glaciation, giving way south of the present outlet glacier to fjords, marked by a transition from rias to fjords, förde and submarine glacial piedmonts. The floors of the fjords have submerged terraces formed by deposition of fine sediment during Late Glacial and Holocene times, and there are steep bordering glaciated slopes. Deltas at the heads of fjords and mouths of side valleys have streams which discharge clouds of fine sediment that settle on the fjord floor. To the south, periglaciated coastal slopes descend to the sea, undercut by marine cliffs on exposed sectors. Active periglaciation results in the formation of screes on steep slopes. In the inner coastline of Chiloé Island, the key landforms are förde, formed by marine submergence of former subglacial channels. There are many islands of soft glacial drift with coastlines smoothed by erosion, longshore drift and deposition. Tidal currents are strong because of the large tide range.

To the south, the coastline in front of the Patagonian ice fields (~48 to 51°S) is trenched by deep fjords floored by morainic banks, which were formed during the Last Glaciation and Late Pleistocene to Holocene terraces. Above the fjords are the Patagonian ice fields, with calving glaciers at fjord heads. Glacifluvial outwash produces turbidity plumes and deposits fine to coarse sediment in the fjords. The glaciers have been receding.

The Magellan region was shaped during the Last Glaciation, producing fjord and piedmont coastlines. The Strait of Magellan originated as a fjord in the western part, which is similar to the fjords in front to the Patagonian ice field, and a set of piedmont lobes in the eastern part with many cliffs cut in soft glacial, but the fjords are smaller. In the eastern part of the Strait of Magellan the tide range is large and intertidal zones, including well-developed shore platforms, are wide. Tidal currents are very strong in narrow straits, where they contribute to erosion of the coastline. Some valley mouths have small deltas formed in the Holocene.

Finally, Chile's oceanic islands are a group of offshore island territories located west of the Peru–Chile trench and the Nazca plate. All are of volcanic origin and represent the fraction under subaerial volcanic edifices that extend under sea level. Easter Island, Salas y Gómez, San Félix and San Ambrosio along the Juan Fernández archipelago are typical examples of tholeiitic intraplate alkaline volcanism associated with hot spots or hot lines. These islands or groups of islands are part of large chains of seamounts that in any event are independent volcanic complexes, with evolving and compositional differences. Most experts agree on the presence of an initial construction phase with evidence of underwater magma–water interaction and of global variations in sea level (Lara 2010). Figure 1.9 illustrate the simplified geology of this insular Chilean territory.

1.2 Climate: From Desert to Glaciers

In a broad perspective, a pronounced N–S and E–W asymmetry in the distribution of precipitation on both flanks of the Andes was observed by Strecker et al. (2007) as shown in Fig. 1.10.

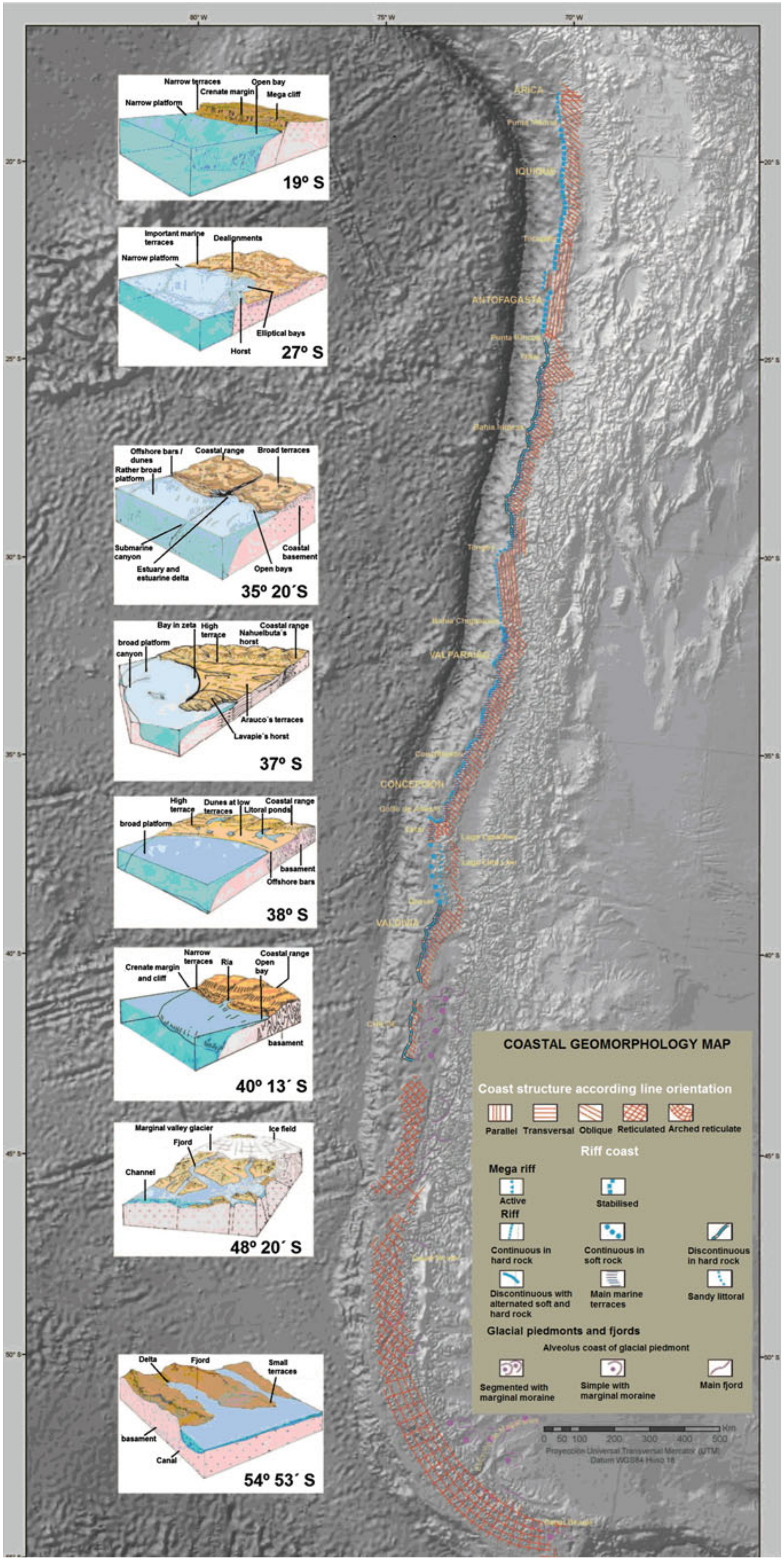


Fig. 1.8 Coastal geomorphology of Chile (Paskoff and Araya-Vergara 2010)

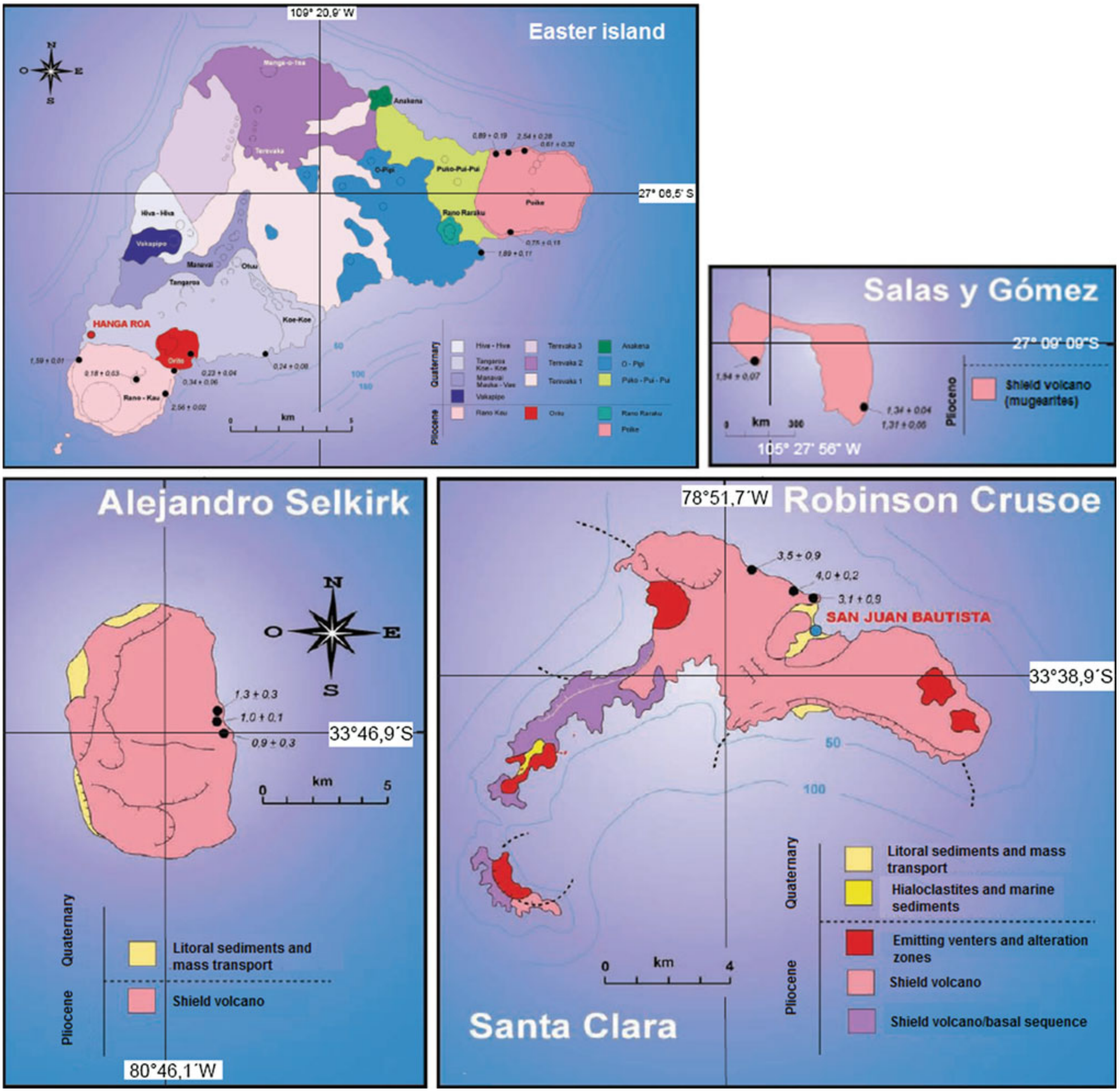


Fig. 1.9 Chilean oceanic islands geology (Lara 2010)

The main features of the weather, climate and climate variability over the Andes Range in South America have been described (Garreaud 2009, Garreaud et al. 2009), providing a basic physical understanding of the mean annual cycle of atmospheric circulation and precipitation over the mountains and adjacent lowlands (Fig. 1.11). In particular, the diversity of precipitation, temperature and wind patterns is interpreted in terms of the long meridianal extent of the Andes and the disruption of the large-scale circulation by this formidable topographical barrier. Among the many factors that determine the interannual climate variability in South America, ENSO (*El Niño* South Oscillation) plays a major role in many regions. ENSO is typically associated with anomalously wet conditions in the southeastern portion of the continent and Central Chile; opposite rainfall anomalies are typically observed during *La Niña* events.

In this context, the Chilean climate in particular is extremely varied due to the abrupt relief, geographical position and elongated shape of the country. The geographical position determines atmospheric circulation,

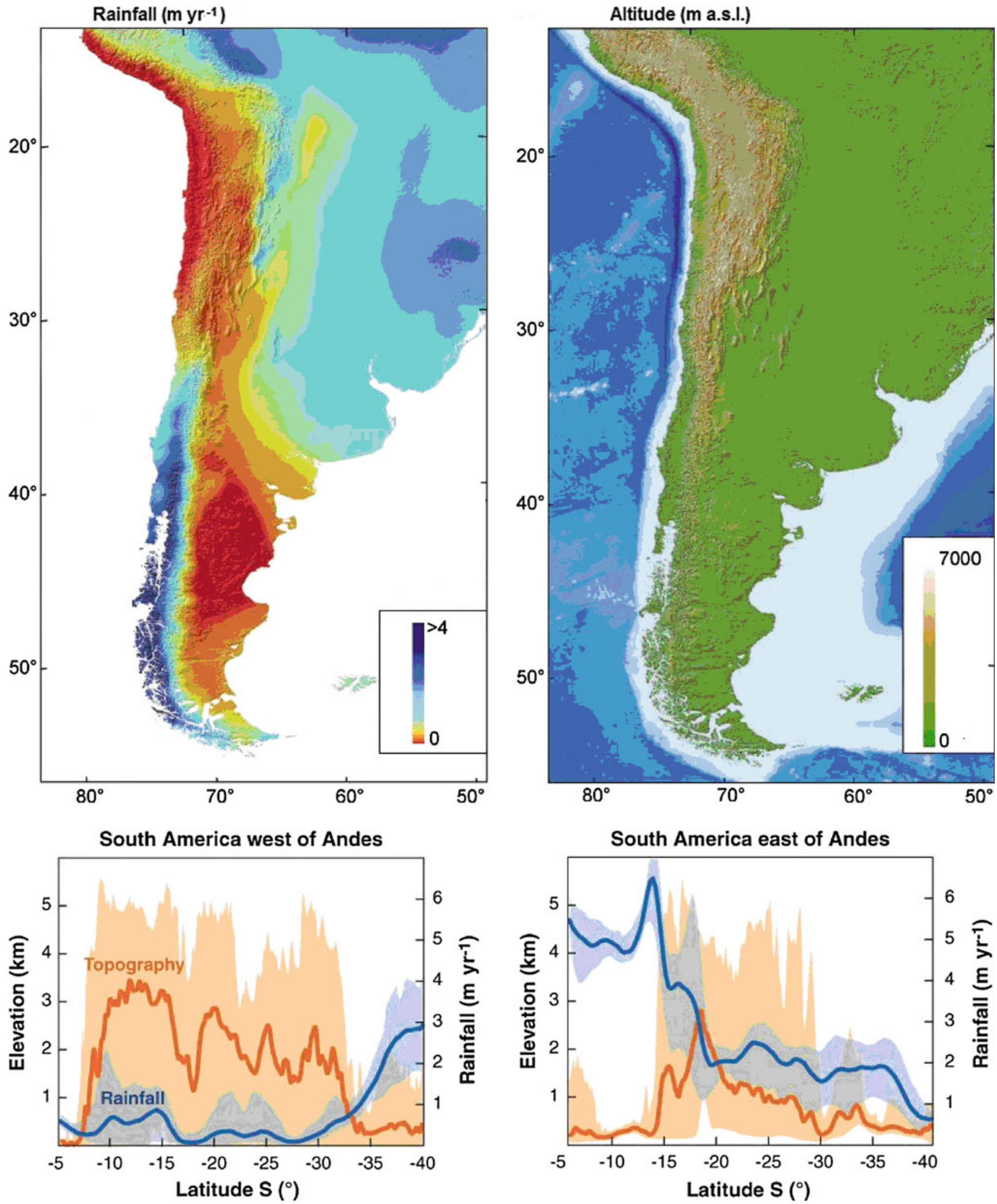


Fig. 1.10 *Above* rainfall and relief at central South America. *Below* rainfall and topographical profiles (250 km wide) on the west and the east side of the Andes (partly from Strecker et al. 2007)

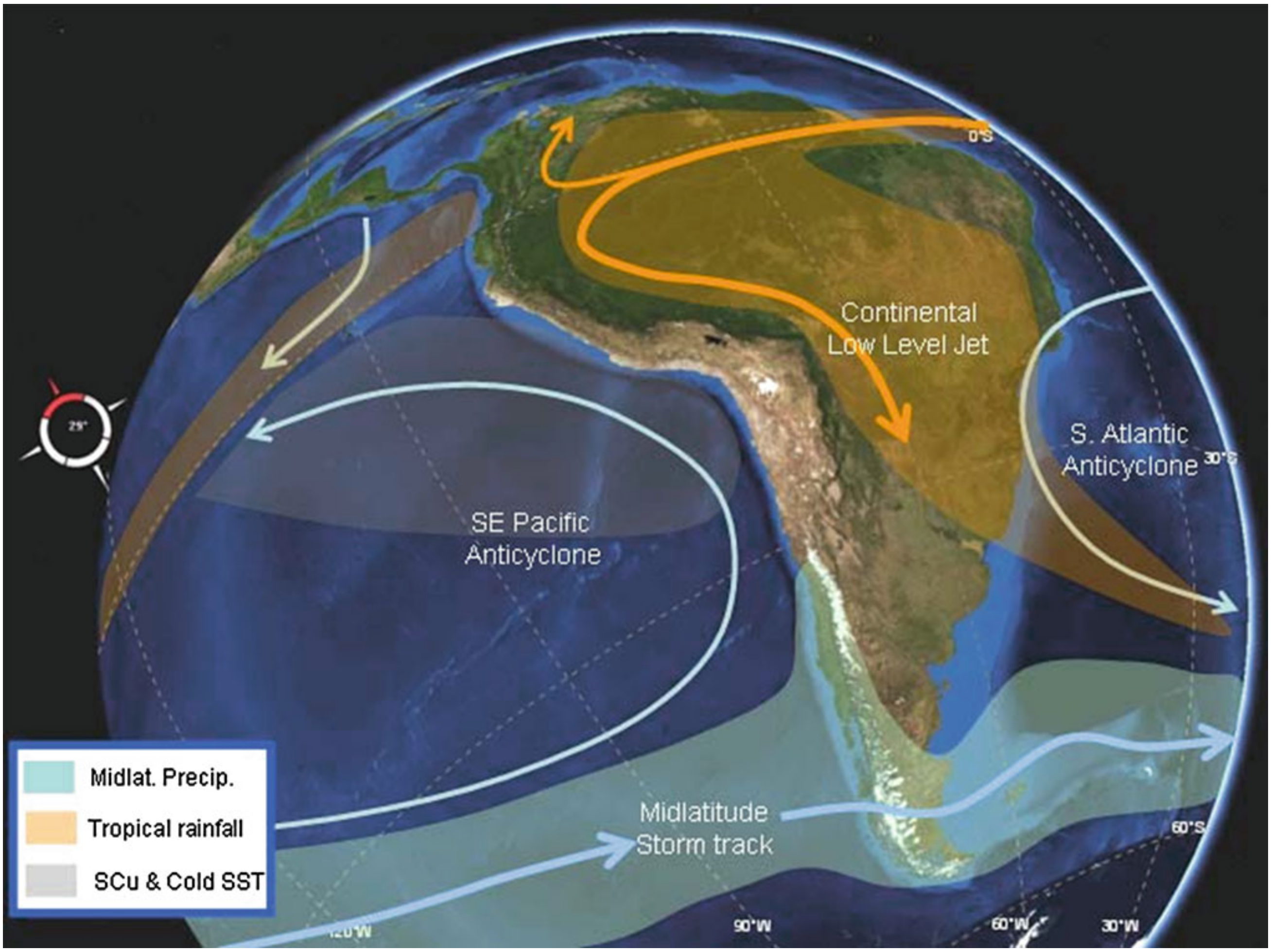


Fig. 1.11 Schematics of the low-level atmospheric flow (roughly from surface to about 1.5 km a.s.l.) around the Andes Range. Major climate features of South America are also depicted (Garreaud 2009)

controlled by the influence of the Pacific Ocean and Antarctic territory. Movement of Antarctic and sub-Antarctic water currents (the Perú–Chile Current) and masses of polar air influence the whole country. The topography of the country strongly controls temperature and rainfall patterns. The Coastal Range and the Andes constitute geographical barriers that block the maritime influence of the Pacific Ocean on their eastern slopes and in the Central Valley. Atmospheric circulation mainly involves the impact of the South Pacific anticyclone, located in front of the Chilean coast, normally between 20 and 40°S. The occurrence of long droughts or large floods is strongly controlled by the location and persistence of that anticyclone and also by *El Niño* currents.

The northern part of Chile (17–27°S), mostly a desert, shows extremely low rainfall (<50 mm yr^{-1}). A recent document (UNESCO, 2010) showing an aridity map for Chile (Fig. 1.12) concluded that 52 % of its territory (northern) is characterised by xeric, hyperarid, arid and semiarid regimes. The Atacama Desert, for instance, has a variation in rainfall from 0 mm yr^{-1} at approx. 2,400 m a.s.l. to 200 mm yr^{-1} at 4,000 m a.s.l. Over the Altiplano Plateau there is some rainfall (200–300 mm yr^{-1}) from December to March, called the *Bolivian Winter*.

According to Houston and Hartley (2003) and Houston (2006), precipitation between 18 and 27°S is dominated by summer convective activity from Amazonia, and data analysis shows that the increase in precipitation with elevation due to the rainshadow effect best fits an exponential correlation. Coupling with limited data from high elevations suggests that the correlation is accurate to 4,500 m a.s.l. and perhaps to 5,500 m a.s.l., suggesting that increased precipitation goes unrecorded over the peaks of the Western Cordillera. Figure 1.13 shows a general climate map with ombrothermic diagrams for different locations in Chile. Insets show mean standardised monthly precipitation for stations dominated by summer and winter rainfall, taken from Houston and Hartley (2003).

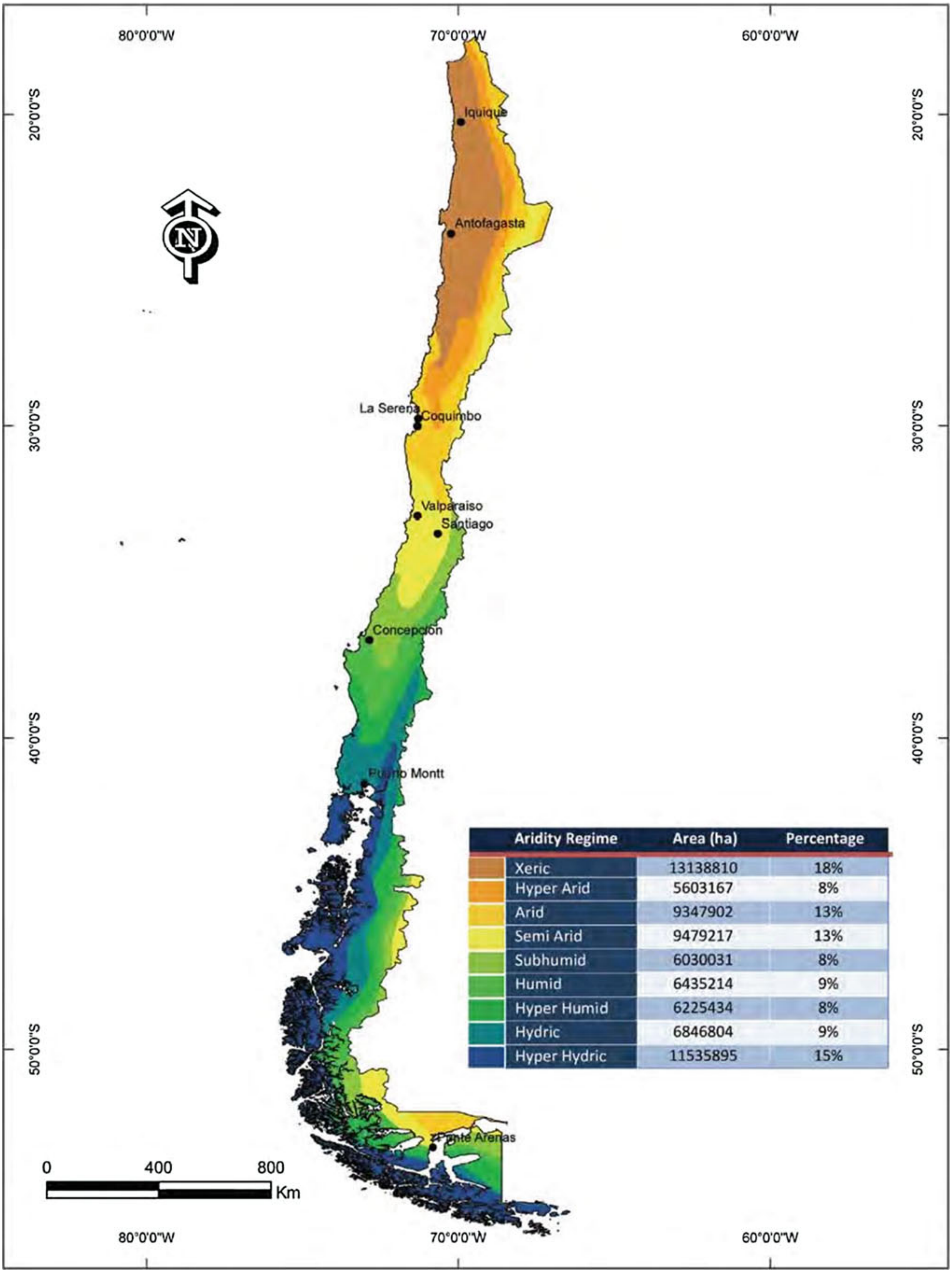


Fig. 1.12 Aridity map of Chile (UNESCO 2010)

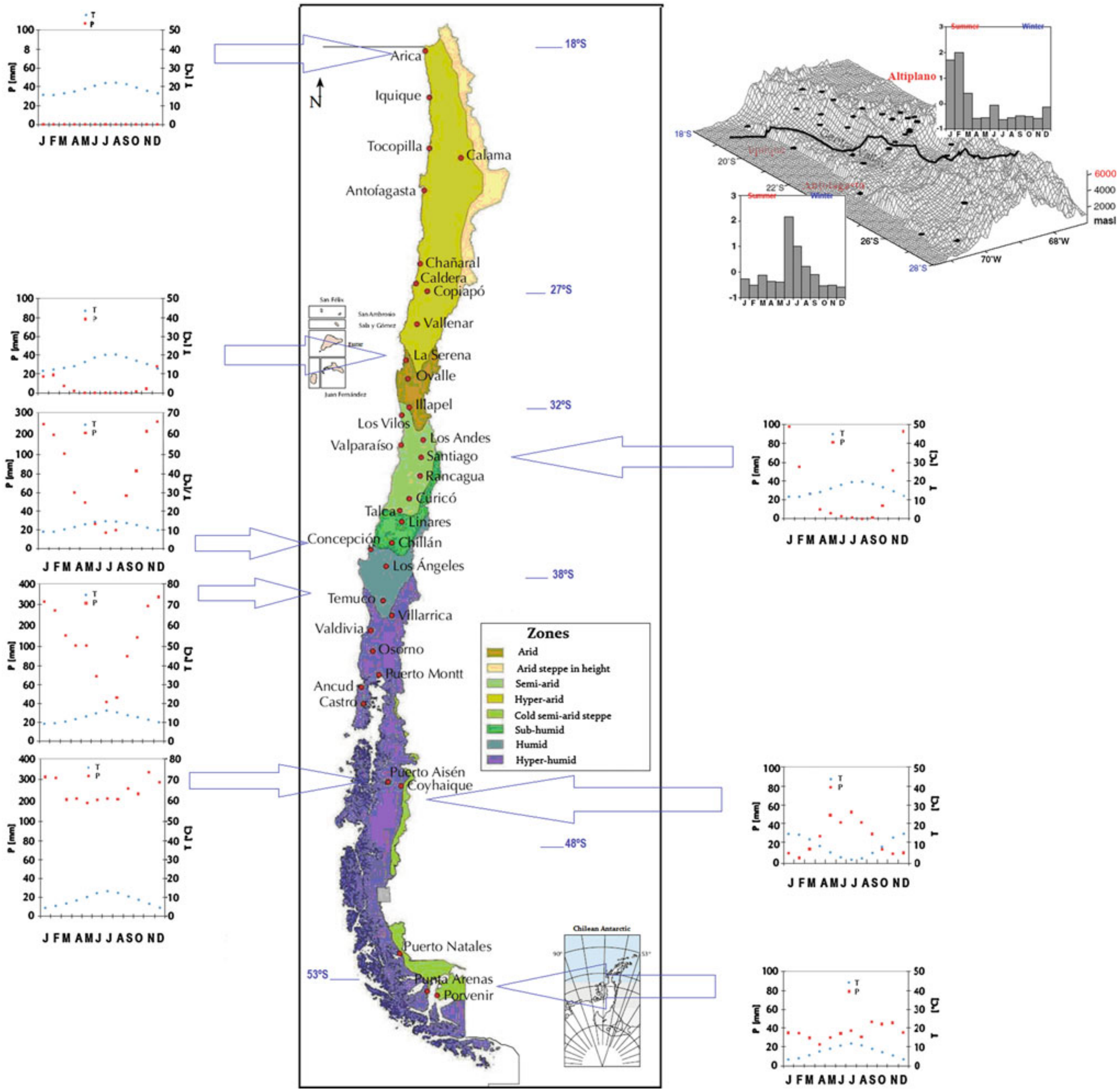


Fig. 1.13 Climate map of Chile (P in *red dots*: rainfall; T in *blue dots*: temperature)

Further south (27–32°S) the climate is semiarid, with scant winter rainfall dominated by winter frontal sources and showing no well-defined relationship with elevation. Between 32 and 38°S, the Mediterranean climate is characterised by rainfall during the winter season (50–1,000 mm yr^{-1}) and a dry summer season.

Even further south (38–42°S) the climate becomes temperate and with increasing rainfall. Between 42 and 46°S, it is very cold and humid, with snow and rainfall of over 3,000 mm yr^{-1}. Due to the predominant humid western winds Western Patagonia as a whole experiences high precipitation. At latitude 40°S, the western slope of the Coastal Range may receive up to 4,000 mm annually. In addition, it is particularly prone to becoming immersed in waves of marine fog. Towards the east, precipitation drops in the Central Valley to 1,000–2,000 mm yr^{-1}, and it increases again on the west-facing slopes of the Andes. There is a narrow zone of transition between 39°S and approximately latitude 47°S, characteristic of most of Eastern Patagonia, that receives about 400 mm yr^{-1} rainfall, beyond which it decreases to 200 mm yr^{-1} or less.

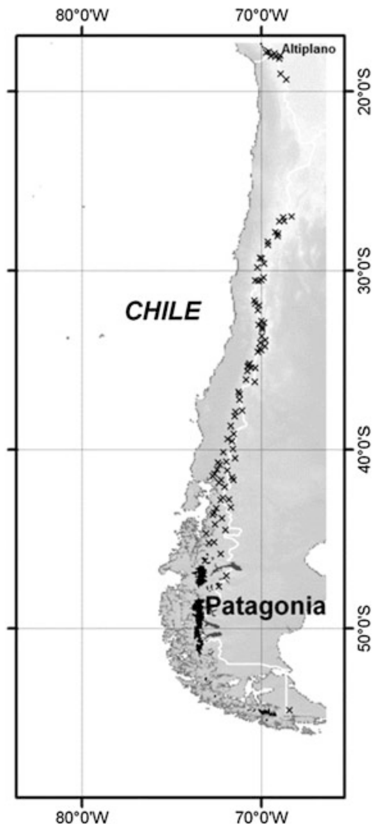


Fig. 1.14 Glaciers along Chile. Single glaciers are shown as crosses, while glacier bodies (ice fields) are shown as black areas (Casassa et al. 2007)

In terms of agrometeorological information, Brunini et al. (2010) report that Chile is known for its use and forecasting of meteorological information for decision support in agriculture, which is either centralised in the Chilean Meteorological Department or in the Regional Centres of Agrometeorological Information (CRIA), where farmers can access operational information, agricultural forecasts and agrometeorological updates in real time. This information ranges from weekly analyses of agrometeorological perspectives to trends and bulletins and effects on different crops and agricultural practices. Issues regarding agrometeorological forecasts for different regions and weekly updates of cold periods are also covered. Agroclimatic risk assessment is made according to the probability of the occurrence of adverse events. Chile is also an active participant in the CYFEN project (Climatic Information Applied to Coping with Agricultural Risk in Andean Countries).

Glaciers in South America have experienced a strong generalised retreat and thinning especially in recent years (Bown et al. 2008) in parallel with the regional and global warming trend. In the Central Chilean Andes, nearly 1,600 glaciers with a total ice area of around 1,300 km^2 have experienced a total volume loss, due to thinning and retreat, of 46 ± 17 km^3 of water equivalent between 1945 and 1996 (Rivera et al. 2002, Casassa et al. 2006). Between 1955 and 2007, a mean frontal rate of -22 m yr^{-1} on the Chilean side of the Andes was estimated by Le Quesne et al. (2009).

Fig. 1.15 Trees of *Prosopis tamarugo* at Zapiga saltlake (Luzio et al. 2010)

Fig. 1.16 Blooming desert (*left*) in Region III and relict southern forest (*right*) in Region IV of Chile

Fig. 1.17 High altitude wetland at Chilean Altiplano (Caquena, Region XV)

Chile has only a few glaciers in its northernmost corner along the border with Bolivia in the Andes that can be considered tropical in the broadest sense, but from 30°S there is an ice-covered area of approximately 27,500 km^{-2}, which contains around 90 % of all glaciers located in the Andes (Fig. 1.14). The Patagonian ice fields are the largest temperate ice masses on the Earth and their outlet glaciers are also some of the most dynamic. Maintained by the southern westerlies, the ice fields have undergone considerable fluctuations throughout the Quaternary and over the past few decades.

1.3 Vegetation

The principal vegetation formations and their main characteristics are briefly described here. This description is based on Moreira-Muñoz (2011), who provided a complete and comprehensive review of Chilean vegetation, including the latitudinal and altitudinal distribution of vegetation formations.

(a) The hyperarid desert formation or desert core, which extends between 18 and 24°S along the coast and interior zones, but vegetation is restricted to the deep agricultural valleys (Lluta, Azapa and Camarones). At the heart of the Atacama desert, vegetation is almost completely lacking, but there are stands of natural and planted forests of *Prosopis tamarugo*, including on five salt lakes (Zapiga, Huara-Pozo Almonte, Pintados, Bellavista and Llamará) with subterranean water dams (Fig. 1.15). Towards the Andes, the vegetation consists mainly of low scrub and in a very thin belt between 2,000 and 2,800 m a.s.l., large cacti of *Browningia candelaris* mark the landscape, responding to constraints described recently by Guerrero et al. (2011).

(b) Sparse coastal shrub vegetation, highly dependent on fog and humidity. The desert coastal scrub extends from 24 to 32°S, generating a transition zone from the desert towards the Mediterranean Central Chile. It encompasses open low scrub that at 30°S gradually changes to xerophytic scrub. This zone harbours two nature phenomena, the blooming desert with only a few mm of rainfall and the isolated forest of Fray Jorge with southern floristic elements on the upper coastal slopes, under the direct influence of maritime fogs (Fig. 1.16).

(c) Andean vegetation, the formation occupying extreme, high environments, ranging from 17°30′S to approx.

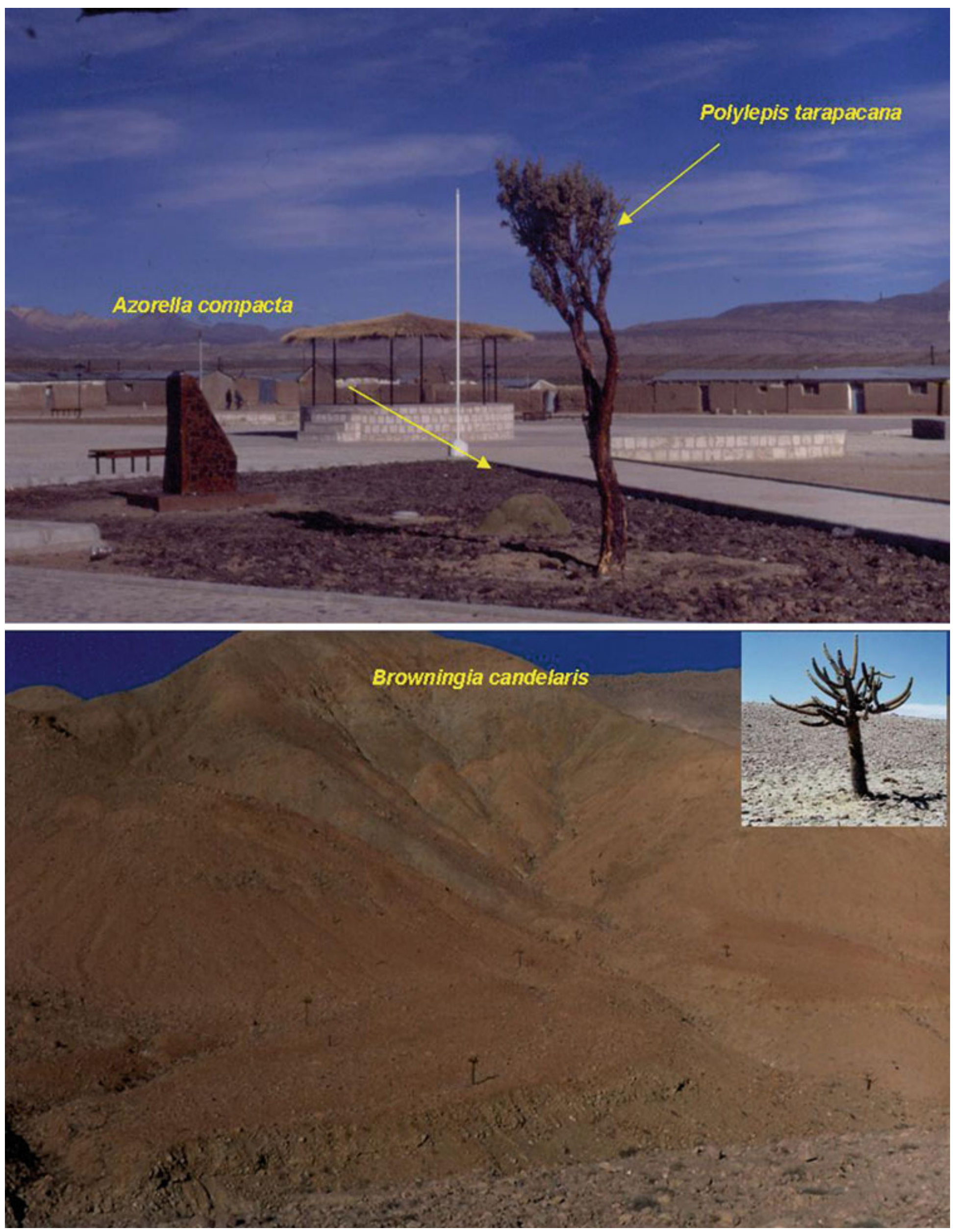


Fig. 1.18 Typical high altitude vegetation at Chilean Altiplano (XV Region)

Fig. 1.19 Typical Mediterranean vegetation (*Acacia caven*) at Santiago in Central Chile

Fig. 1.20 Araucaria trees (*Araucaria araucana*) in the Andes (Conguillío Park, Region IX)

40°S along the western Andean slope. This wide latitudinal extension encompasses a very different composition along the North–South profile and over altitude. The intermediate altitudinal belts show the structurally most developed vegetation, as the lowest belts are affected by aridity and the highest by low temperature. These intermediate belts are composed of cushion grasses. Above 4,700 m a.s.l., diverse high Andean wetlands or peatlands (Fig. 1.17) have been characterised in detail (Squeo et al. 2006; Ahumada and Faúndez 2009). Approaching the most arid part of the Atacama Desert there are shrubs in the lower belts. Towards the south, sparse vegetation is composed of cushion grasses.

The treeline changes constantly along the latitude gradient: in the north it is composed of *Polylepis tarapacana* and *P. rugulosa* (Fig. 1.18), the tree that lives at the highest altitudes in the world, while in the central-north it is replaced by shrubs and between 31 and 34°S the treeline reappears. At this latitudinal range, there are Andean scrub and cushion grass vegetation. From 32°60 ′S to the South, at the lower limit of the Andean formation, conifers appear but disappear at around 37°S, to be replaced by deciduous forests.

(d) Entering into the Mediterranean zone, the vegetation changes to a sclerophyllous high scrub (Fig. 1.19). On favourable south-facing slopes, this scrub shows characteristics of woodland, with trees reaching 20–25 m tall. In the more humid stands, there appears a more hygrophilous forest. In contrast, the most exposed and plain areas contain a woody savannah mainly composed of *Acacia caven* and *Prosopis chilensis*. North-facing slopes show a rich array of annual species and characteristic bromeliads, together with the cactus *Trichocereus chiloensis*.

(e) Around 33°S the Coastal Range reaches far inside the continent, and above 1,200 m a.s.l., the sclerophyllous woodland makes way for a deciduous forest composed

Fig. 1.21 Vegetation changes within Region XI, west Patagonia (Coyhaique city, *above*), low Andes (Cerro Castillo village, *middle*) and eastern Patagonia (road Puerto Ibañez-Chile Chico, *below*)

of deciduous *Nothofagus* species. The northernmost populations at 33°S seem to be remnants of an ancient distribution of the genus.

Deciduous forests dominate along the Andes and the coast towards the south, surrounding the Central Valley. The core of the deciduous forest between 35 and 36°S is a mesic forest type, dominated by the two broadleaved deciduous species *Nothofagus alessandrii* and *N. glauca*. At around 38°S, this forest shows signs of the transition towards a temperate macrobioclimate, with the remarkable presence of the resinous or conifer forests of *Araucaria araucana* at the coast (Nahuelbuta) and in the Andes (Fig. 1.20). Deciduous forests often transition into stands of *Nothofagus antarctica*, while *N. pumilio* composes the treeline along the Andes all the way to Cape Horn.

(f) Located well into the temperate macrobioclimate, and related to high precipitation levels (>2,000 mm yr^{-1}) is the broad-leaved forest (Valdivian forest). It forms a U-shape, with a coastal and an Andean leg between 39 and 42°S.

(g) At around 41°S on the Andes and 41°30′S on the coast, broad-leaved forests are replaced by an evergreen North Patagonian rainforest mainly composed of large trees belonging to the Nothofagaceae. These rainforests are intermingled with the conifer evergreen forests which dominate the coast and interior, being replaced at altitude by deciduous forest.

(h) As the landscape becomes increasingly fragmented into fjords and little islands south of 47°S and the precipitation exceeds 4,000 mm yr^{-1}, the vegetation adopts the low physiognomy of moorlands. Towards the east, the moorlands are less humid and are dominated by the moss *Sphagnum magellanicum* (Arroyo et al. 2005). The wetlands of Torres del Paine National Park in Patagonia have been studied by Clausen et al. (2006), who determined their variety and type. Most of the interior of Patagonia is covered by the two wide ice fields and to the south of these a deciduous forest of *Nothofagus* reappears, together with the sub-Antarctic evergreen rainforest. In association with the marked precipitation gradient ranging from 4,000 mm at the western side to 300 mm at the eastern side of the low Andes in southern Patagonia and *Tierra del Fuego*, a gramineous steppe of *Festuca* spp. dominates the landscape (Fig. 1.21).

1.4 Land Use

Agriculture and forestry patterns of Chile today reflect great differences in the country's natural environments, the influence of international markets, the impacts of national

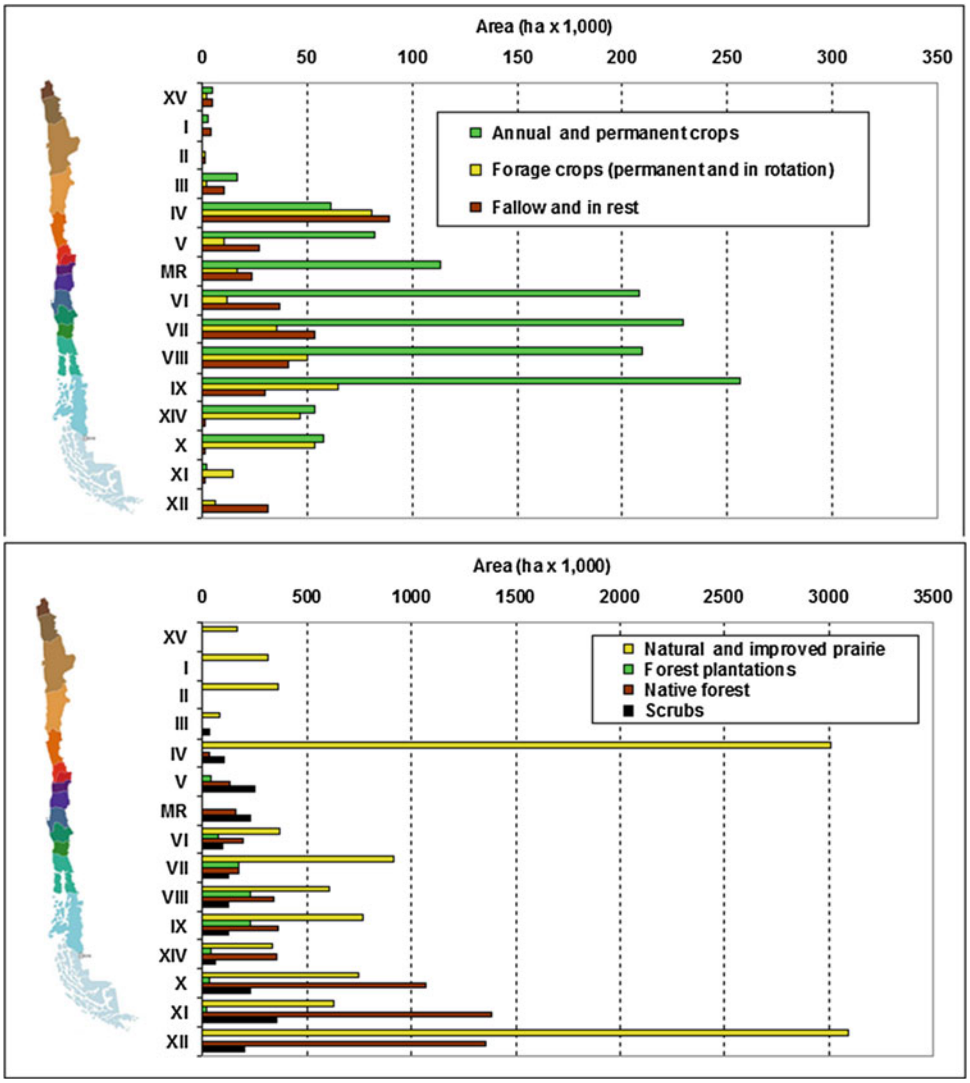


Fig. 1.22 Arable (*above*) and non-arable (*below*) land in the Chilean regions

policies, the imprints of settlement patterns and cultural preferences. The wide range of climates in Chile allows a great variety of crops, vegetables, fruit trees, flowers and grains to be cultivated. Important agriculture is only noticeably absent in rugged portions of the Altiplano and desert landscapes along the Pacific coast of northern Chile. The country invests considerable resources in protecting its privileged phyto- and zoo-sanitary conditions. Agricultural production has adapted well to free markets and the gradual lifting of protectionist barriers and is now modern and efficient.

Land use in Chilean territory according to the last Agriculture and Forestry Census of Chile (INE 2007) is shown in Fig. 1.22 in terms of and non-arable land in each region. The most important annual crops (cereals and potatoes) and perennial species (table grapes and apple) in 2010 occupied almost 600,000 and 88,000 ha of the territory, respectively (Fig. 1.23).

A large number of estates, especially those planted with trees, were auctioned off to large financial groups in the 1970s. By the early 1980s, a few major financial groups controlled 80 % of pine plantations and 100 % of the cellulose and paper-pulp industry. Chilean Forestry Law, Decree 701, provided state subsidies that covered 75 % of the cost of forestation for companies planting pine and eucalyptus in particular (Fig. 1.24). These companies, unlike landowners, encountered few social or political obstacles in their efforts to redraw the ecological landscape of Southern Chile. Throughout the 1970 and 1980s, with subsidies from the state and stimulated by growing markets

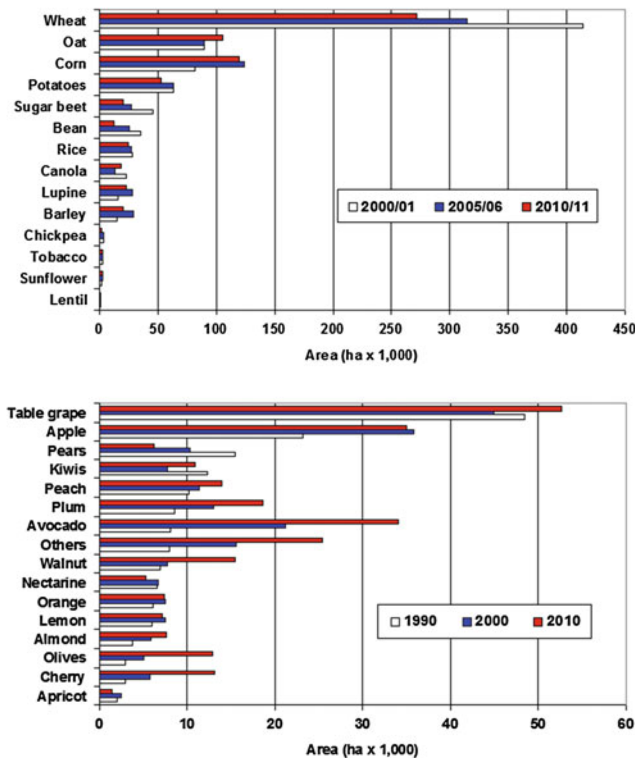


Fig. 1.23 Changes in the area of principal annual crops and fruit trees in Chile over the past decade

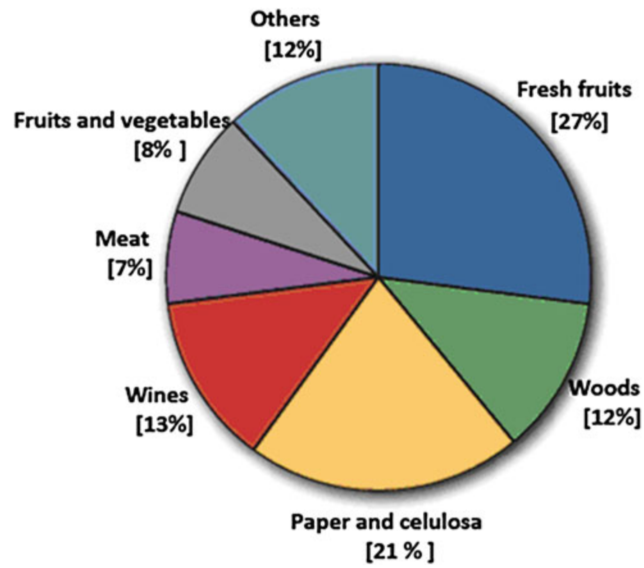


Fig. 1.25 Proportion of exports from different agriculture and forestry sectors in Chile in 2010 (http://www.odepa.cl. Accessed 9 June 2011)

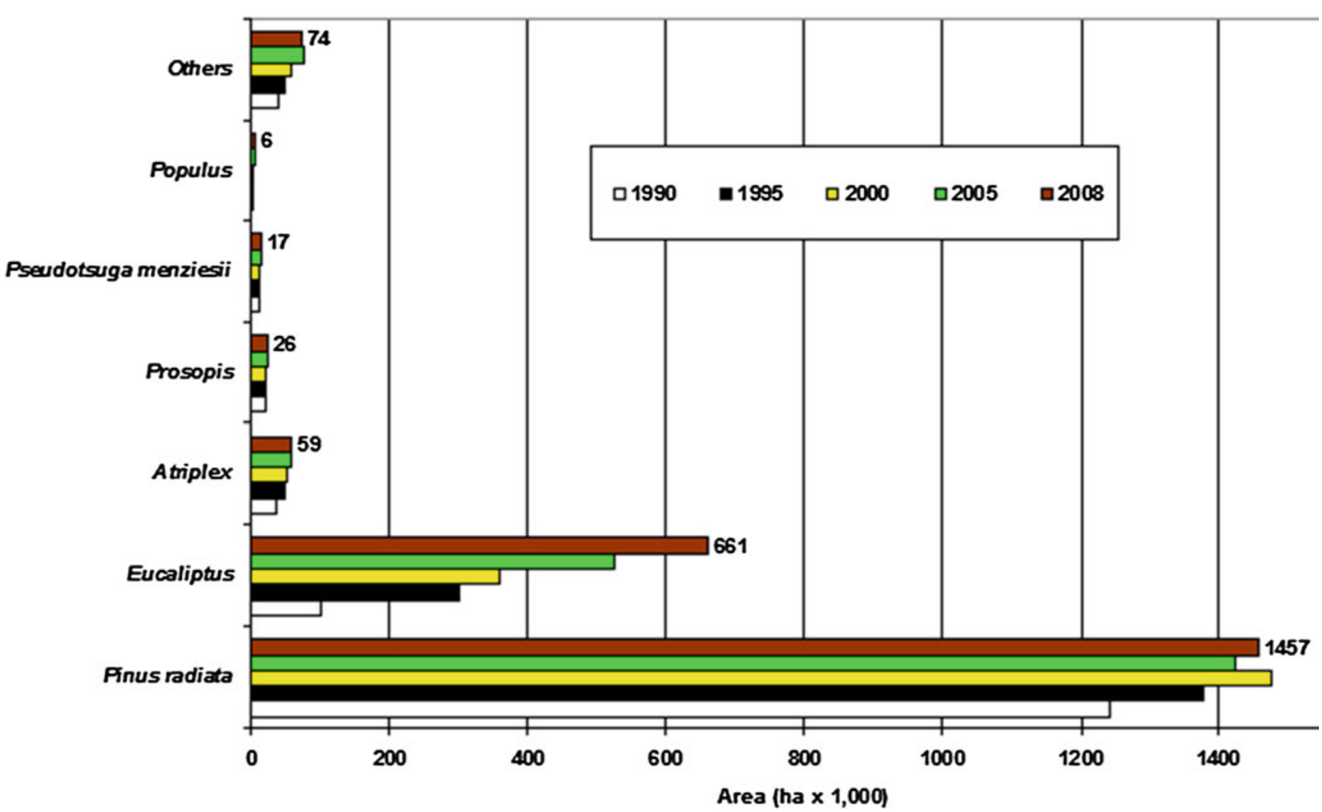


Fig. 1.24 Changes in the area of principal forest trees in Chile in recent decades

Fig. 1.26 Soil (Andic Haploxeroll) with agriculture vocation planted with forest trees in Chile (Region VII)

abroad for cellulose, pulp and wood chips, they proceeded to replace native rainforests with pine plantations.

From an international point of view, fresh fruits, wines, meats and timber were amongst the largest exports (US$ 12.2 billion) from Chile in 2010 (Fig. 1.25).

Chile's economy is one of the most natural resource dependent in the world. According to Altieri and Rojas (1999), over 87 % of Chilean exports are based on only four natural resource sectors, with a quite worrisome ecological footprint of modern agriculture. More recent information (López and Miller 2008) shows that on average, natural resource exports comprised over 40 % of total exports in the period 1990–2004 and that the estimated contribution of natural resource-dependent industries to gross domestic product (GDP) was more than 20 % over the same period.

During recent decades in Chile, the initial agrarian reform was rolled back, restoring some land to the former owners of agrarian estates. Moreover, there is a trend for using soils with agricultural vocation (arable lands) for forestry activities, i.e. soils in Land capability classes (LCC) I to IV are being planted with forest trees (Fig. 1.26).

Therefore, with an economy moving along an eventually non-sustainable path, achieving future food security for all Chilean citizens will depend on conserving soil, water, energy and biological resources. Indeed, knowledge and careful management of all of these vital resources deserves high priority to ensure the effective protection of national agricultural and natural ecosystems.

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