Main Features of Chilean Soils

2

Chilean soil scientists have combined their efforts for a long time to produce a soil map of the country and special mention should be made of the work of Robert and Díaz who compiled a first map of the main Chilean soil groups (Fig. 2.1) following similar criteria used by the Dokuchaev classification system. Three decades later, Luzio and Alcayaga (1992) published a complete map showing soil associations, classified at Great Group level of USDA Soil Taxonomy (Fig. 2.2). Both works give a clear notion of the soil spatial variability along Chilean territory, which reflects its geology, geomorphology and climate diversity. Luzio and Alcayaga (1992) report in the hyper-arid zone only Orthids and Orthents without argillic horizons (due to extreme aridity), Argids which are more frequent in the arid zone, Ochrepts, Xerolls and Xeralfs in the central zone, besides some weakly developed volcanic soils (Xerands), while more developed volcanic ash soils (Udands and Aquands) together with organic soils (Hemists and Saprists) could be the most important soils in extreme southern zones. It is important to note that information on soils in extreme zones was scarce and the Andisol concept was still in the definition process (Beinroth et al. 1985), so most volcanic soils were classified as Inceptisols at the time of the Luzio and Alcayaga (1992) report.

Soil Taxonomy (USDA) is the classification system used in all soil surveys of Chile, while for World Reference Base (WRB) only some correlations have been developed. Salazar et al. (2005) observed a 100 % correlation between Andosols and Andisols in Region X, with Vitric Andosol associated to the Andean Mountains, Silandic Andosol to the Central Valley and the Aluandic Andosol to Chiloé Island. The Umbrisols associated to the Andean Mountains and also to the Coastal Range are correlated to Inceptisols. Cambisols, Acrisols and Luvisols are acceptably correlated to Inceptisols, Ultisols and Alfisols, respectively. Casanova et al. (2007) identified 11 reference soil groups from WRB in VII Region, located mainly in the Central Valley of Chile. They described Andosols towards the Andean Mountains and Lixisols mainly towards the Coastal Cordillera. Lixisols and Alfisols, Umbrisols, Cambisols and Inceptisols, Phaeozems and Mollisols and finally Andosols and Andisols were described as the best soil-correlated reference soil groups and soil orders.

For readers looking for more detailed information on the soils of Patagonia and who are familiar with the WRB classification, Fig. 2.3 includes a partial old map of Chile reported by Gut (2008).

Chilean Natural Resources Information Centre (CIREN) is the official repository institution of soil surveys in Chile, which offers products as paper orthophotos or a digital file containing the image raster georeferenced area of the orthophoto for any site and a vector digital file with the boundaries of the property. Delivered on CD-ROM as a georeferenced TIF file and a vector file, it includes separate layers of farm boundaries, soil cartography and Land capability classes (LCC).

Around 65 % of Chilean territory has been covered by detailed and semi-detailed soil cartography (Fig. 2.4), with soil cartographic units (phases of soil series and soil associations in remote areas) traced over the above-mentioned orthophotos (Fig. 2.5) and at agrological scale, normally 1:20,000 and in more remote areas 1:500,000 (Table 2.1).

The standard notation used for map units includes three letters corresponding to soil series name (examples in Fig. 2.5, RLV: Rinconada Lo Vial soil series; PUD: Pudahuel soil series; MPC: Mapocho soil series), followed by an Arabic numeral denoting different soil phases, which are described in references to Table 2.1. The Roman numeral and minor case letter represent LCC and sub-class, respectively.

2.1 Soil Formation in Chile

As regards geological and geomorphologic patterns in Chile (see Sect. 1.1), the soil parent material is varied, including old rocks, volcanic ash, fluvial and/or glacial deposits and colluvial and/or alluvial deposits. Residual and colluvial

M. Casanova et al., *The Soils of Chile*, World Soils Book Series, DOI: 10.1007/978-94-007-5949-7_2,
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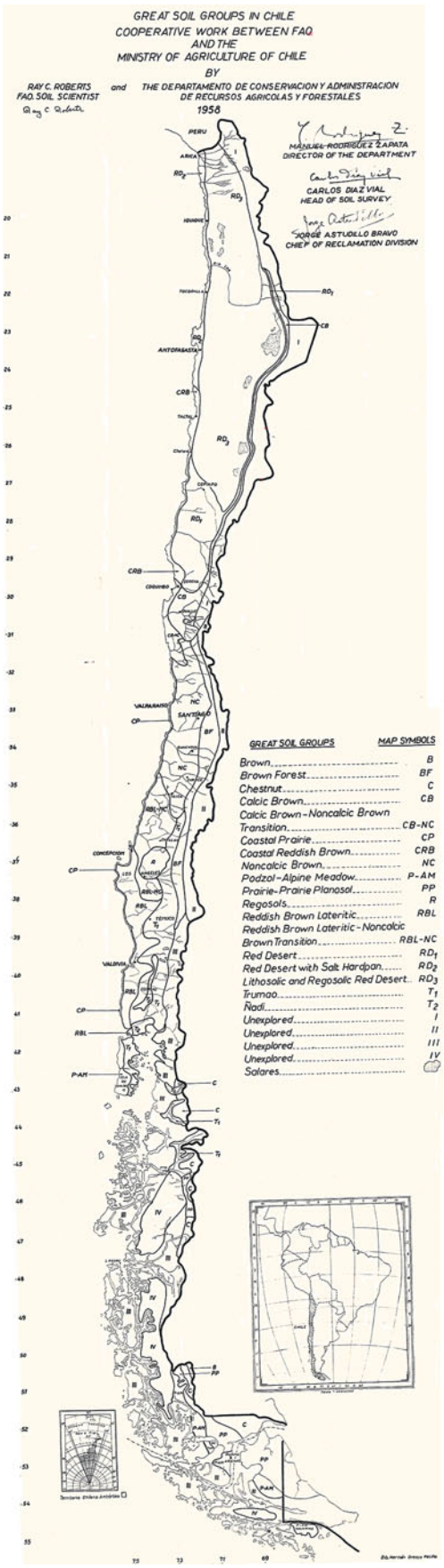

◀ **Fig. 2.1** Soil map of Chilean soils (http://eusoils.jrc.ec.europa.eu/esdb_archive/eudasm/latinamerica/lists/ccl.htm). Accessed 31 March 2012

cessation of leaching losses, silicate transformation and biological activity and key processes in pedogenesis almost everywhere on Earth. When long-term hyperaridity minimises these processes, the result is soils composed primarily of atmospheric salts and dust, which physically expand the landscape as they form (Ewing et al. 2006).

On the other hand, topographical position results in younger soils deposition in the Central Valley of Chile being in an active process of construction, while some old alluvial soils often show the development of a cambic horizon. Watersheds with opposing slope aspect in the central Coastal Range show diverse soil development, as noted by Casanova et al. (2000) when soil hydraulic conductivity was measured and morphological features described (Fig. 2.10). In fact, Badano et al. (2005) in the Mediterranean zone of central Chile observed that slope aspect strongly influences mesoclimate conditions. In an altitudinal sense, soil diversity observed by Cavieres et al. (2000) in central Chile and Squeo et al. (1993) in the Andes of the Hyper-arid zone of Chile determines a certain vegetation zonation in response not only to temperature and radiation gradients, but also changes in soil chemical properties. Physical soil properties such as soil water content must also be included as a variable with altitude.

Douglass and Bockheim (2006) used 34 pedons on 4 moraine groups to investigate mechanisms and rates of soil development in Argentinian Patagonia with coarse-loamy, mesic, Typic Haplocalcids or Calcic Haploxerolls occurring under short grass-shrub steppe in a semi-arid climate. For similar soils observed in Chilean Patagonia, dominant soil-forming processes reported in this environment are melanisation, calcification and the accumulation of clay-sized particles. Organic carbon (OC) accumulates rapidly in these soils, but significantly higher amounts in the oldest two moraine groups are most likely the result of slight differences in soil-forming environment or grazing practices. Accumulation rates of carbonate and clay decrease with age, suggesting either decreased influx in the earliest part of the record or attainment of equilibrium between influx and loss. There are no changes in soil redness, and preservation of weatherable minerals in the oldest soils indicates there is little chemical weathering in this environment. Measured dust input explains the accumulation of both clay and carbonate. The authors present a carbonate cycling model that describes potential sources and Ca mobility in this environment. Calibration of rates of soil formation creates a powerful correlation tool for comparing other glacial deposits in Argentina to the well-dated moraines (Fig. 2.11) at Lake Buenos Aires (Lake General Carrera, in Chilean territory).

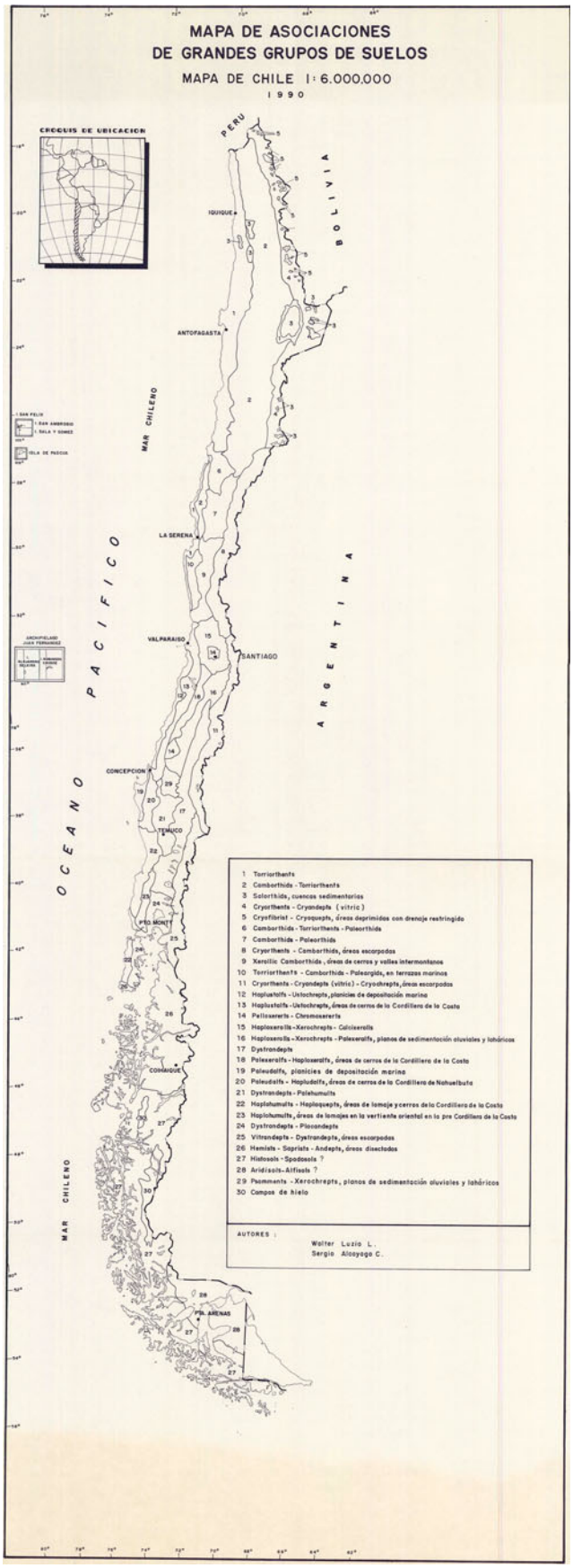

Fig. 2.2 Soil map of Chilean soils, after Luzio and Alcayaga (1992)

2.2 Major Soil Zones

Using soil surveys along Chile, the various soil formation factors and diverse soil formation processes, Luzio et al. (2010) defined in detail eight so-called edaphic zones of Chile (Table 2.2). However, these are characterised and synthesised here as four major soil zones (Table 2.3 and Fig. 2.12).

2.2.1 Soils of the Hyper-Arid to Semi-Arid Zone

Soils of this zone are associated with diverse geomorphic features along nearly 1,600 km of Chilean territory, where it is possible to differentiate soils of the Altiplano, soils of the Longitudinal Central Valley, soils of the Coastal Range, soils of marine terraces, soils of valleys and soils of *serranías* (Fig. 2.13).

According to the age of geological materials in the Hyper-arid sector, advanced pedogenic evolution should not be expected and even less translocation of components within the profile, because of the climate characteristics, a factor that creates a weak organic regime, at least in the northern sector of this zone. Many workers (Risacher et al. 2003; Berger and Cooke 1997) report that crusts and salars are characteristic features not linked to any particular geomorphic position within this zone.

Duricrusts are a common feature of the Central Valley and on the inland slopes of the Coastal Range. Salts occur either as fabric-preserving cement, consisting of original depositional textures of alluvium or colluvium or as fabric destructive nodules and masses. Where extensive precipitation of salts has destroyed the original fabric, the coarse fraction appears to have been expelled to the surface. Because dissection is so limited, duricrusts are best exposed in workings for nitrates and other salts or on dissected slopes where erosion has exposed slope duricrusts. Sulphate duricrusts are found on the inland slopes of the Coastal Range and in the Central Valley. In the latter, they may be impregnated by exotic salts such as nitrates, perchlorates and iodates. The presence of calcium and sulphate in the soils is due to rock weathering and groundwater remobilisation weathering, rather than accession as cyclic salts, followed by aeolian redistribution in the landscape. Sulphate duricrusts are absent from the comparatively higher rainfall areas of the pre-Andean sector. Further south, towards Copiapó city, sulphate duricrusts are replaced by calcretes. The origin of the nitrate salts has been the subject of much debate, but the most recent geochemical studies appear to confirm deposition of atmospheric nitrate as the source (Prellwitz 2007; Mishalski et al. 2004).

Northern Chile is also characterised by a succession of north–south trending ranges and basins occupied by

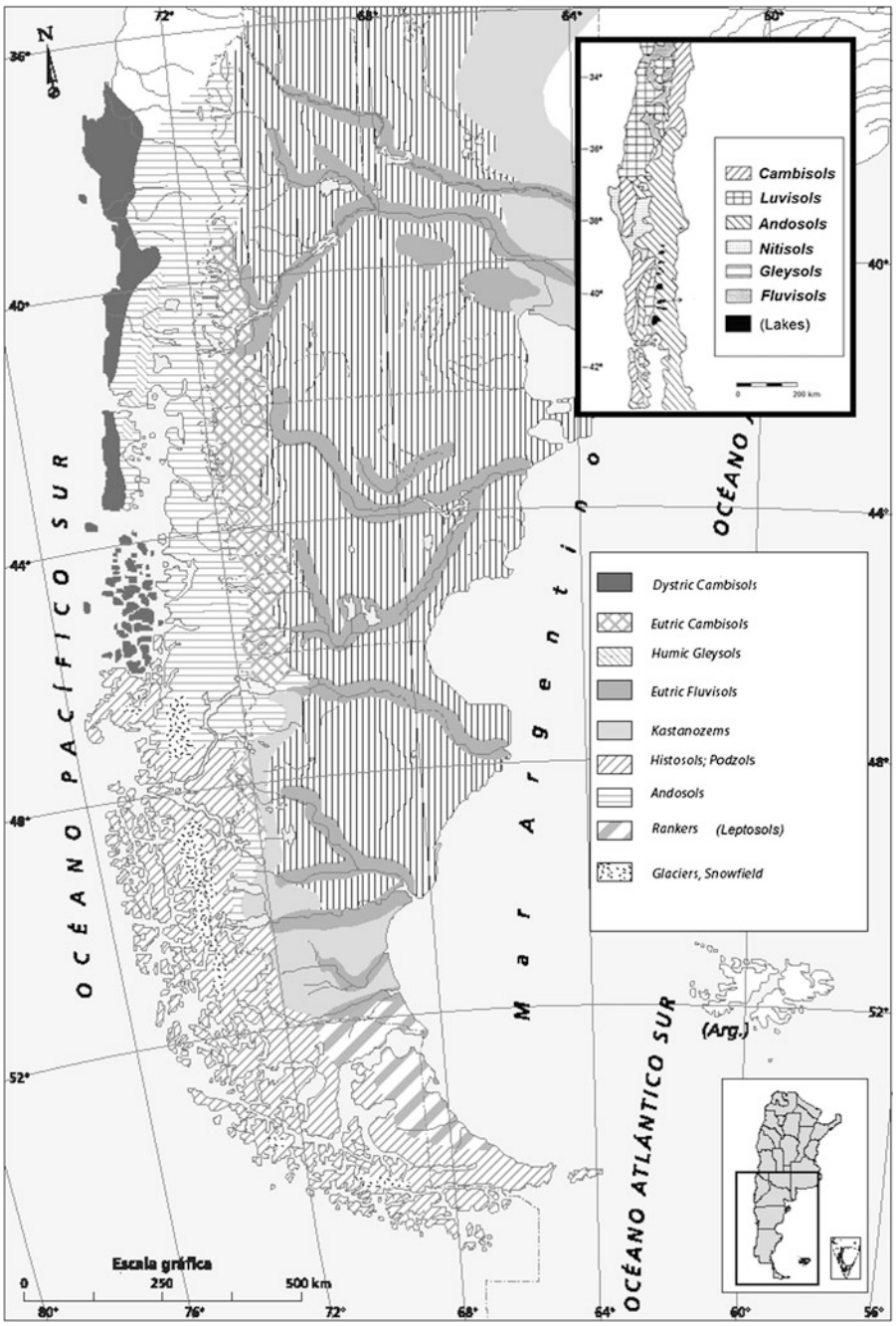

Fig. 2.3 Generalised WRB system map of southern South America and Chile. Adapted from Gut (2008) and Aravena et al. (1993)

numerous saline lakes and salt crusts, collectively called *salares* (salars). Fossil salt crusts are found to the west in the extremely arid Central Valley, while active salars receiving permanent inflows fill many intravolcanic basins to the east in the semi-arid Coastal Range. Sea salts and desert dust are blown eastward over this range, where they constitute an appreciable fraction of the solute load of very dilute waters (salt content <0.1 g L^{-1}).

2.2.1.1 Soils of the Altiplano

This group of soils starts at an altitude around 1,500 m a.s.l., i.e. including the pre-Andean, Andean and Altiplano area. In general, Casanova et al. (2008) in a contribution to the knowledge on extreme altitude soils make a distinction between net organic soils (NOS) and net mineral soils (NMS) within altiplanic areas (Fig. 2.14). They report that according to Soil Taxonomy, only one NMS meets the

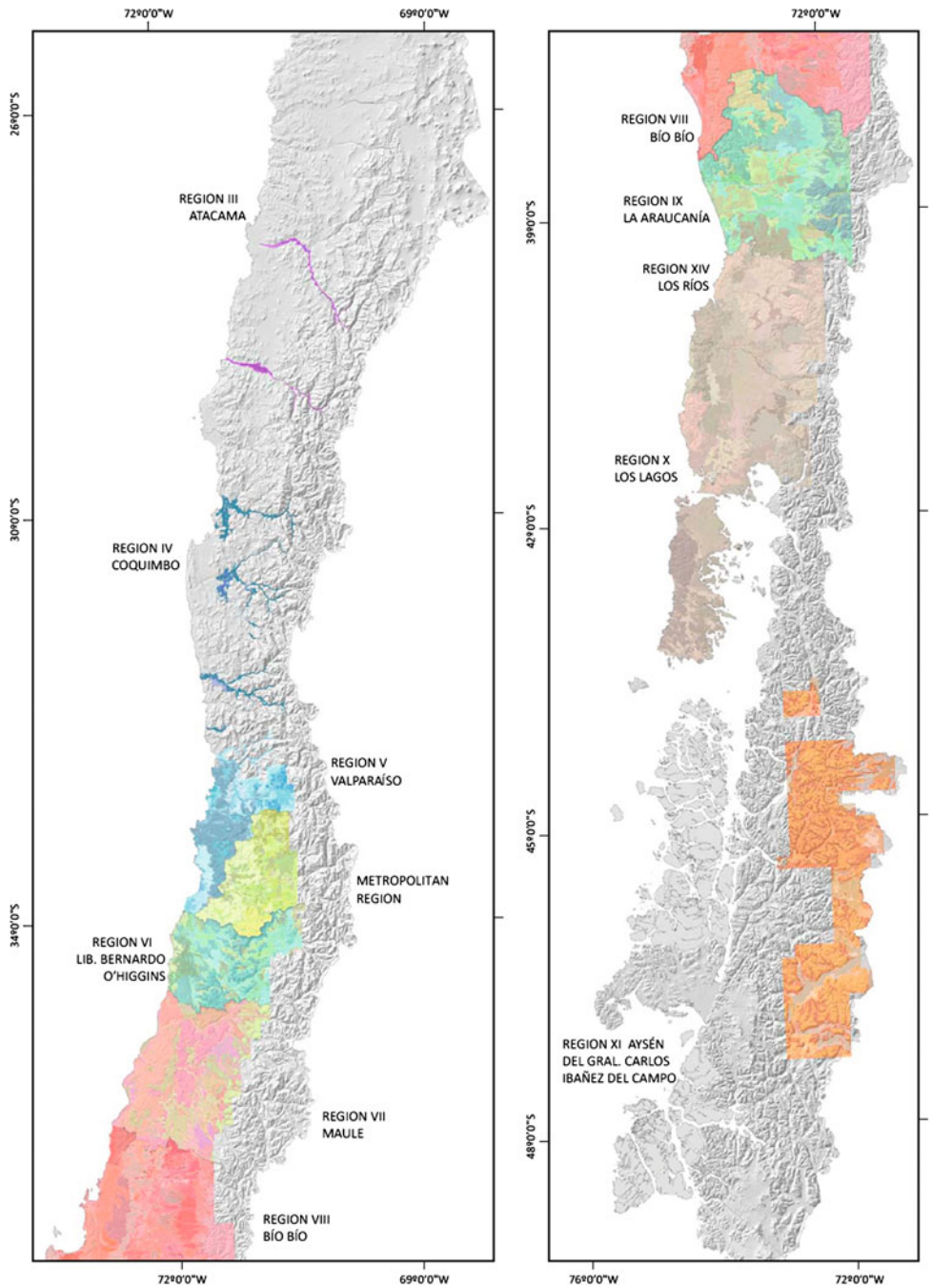

Fig. 2.4 Map showing soil survey cover in Chile, Region III–XI (see Table 2.1)

requirements for Andisols, while six of eight pedons meet the requirements for Andosols according to WRB, the others corresponding to Leptosols and Regosols. With regard to NOS, one profile is classified as a Histosol (Soil Taxonomy), while both profiles analysed meet the requirements to be considered as Histosols (WRB).

Later, Luzio et al. (2010) distinguished soils with skeletal morphology, soils with incipient pedogenesis and soils on depressive basins.

Skeletal Soils

These incipient soils are developed only with primary pedogenesis and from diverse parent materials, and it is possible to identify a common undeveloped coarse-textured and eventually medium-textured A horizon (ocric epipedon). Weak subangular block structures are sometimes observed, but massive or single-grain conditions are more frequent. With a typical A–R profile (A-Cr, when some weathering is possible), these soils normally reach

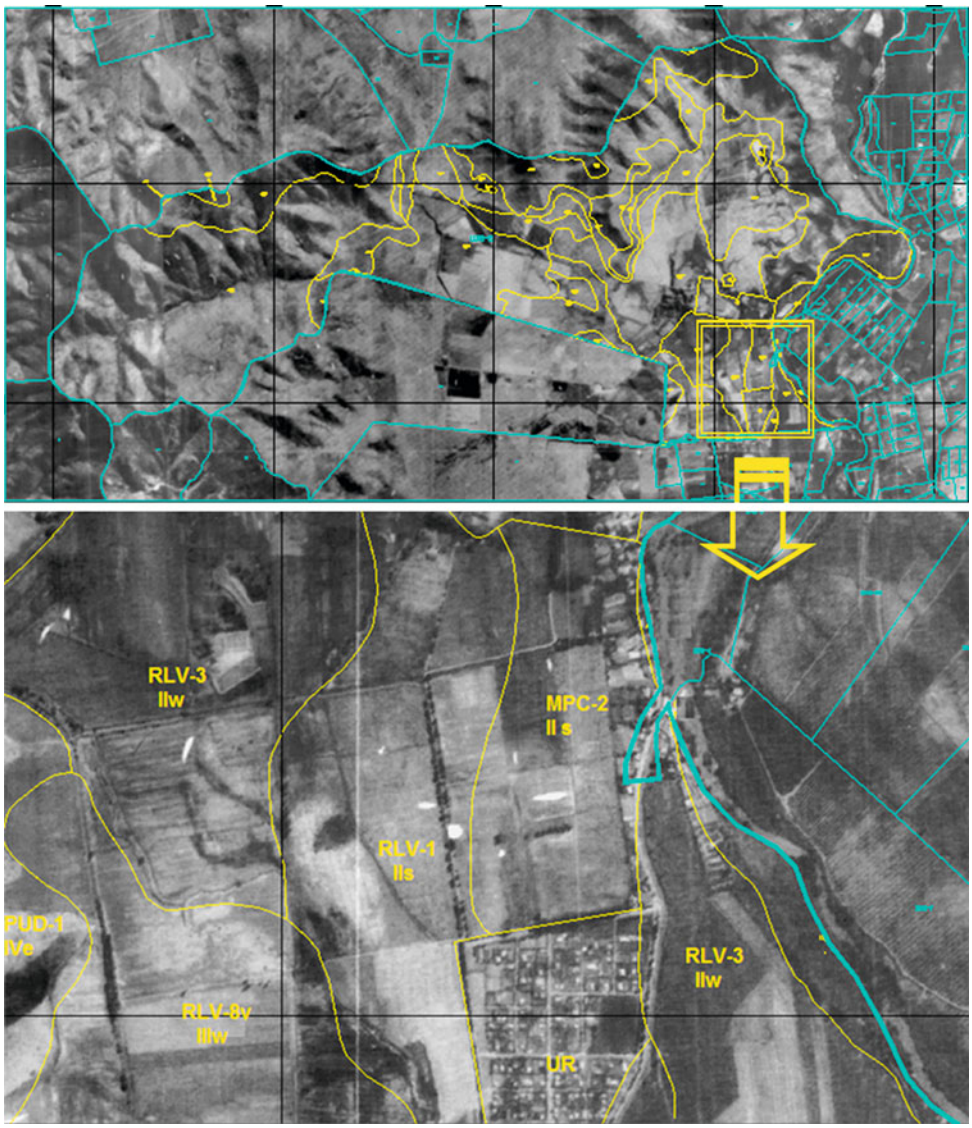

Fig. 2.5 Example of predial window with digital soil cartography information. *Above* cartographic units (phase of soil series) in *yellow* within Experimental Agronomic Station (Germán Greve Silva) belonging to Faculty of Agronomic Sciences, University of Chile. *Below* zoom to *upper yellow inset* (elaborated from www.ciren.cl)

Table 2.1 Soil survey scale and cover in Chile

Region	Cartographic scale	References
III	1:20,000 (valley)	CIREN (2007)
IV	1:20,000 (valleys)	CIREN (2005a)
V	1:20,000 and 1:50,000 (valleys); 1: 100,000 (hills)	CIREN (1997a)
Metropolitan	1:50,000 (valleys); 1: 100,000 (hills)	CIREN (1996a)
VI	1:20,000 and 1:50,000 (valleys); 1: 100,000 (hills)	CIREN (1996b)
VII	1:20,000 and 1:50,000 (valleys); 1: 100,000 (hills)	CIREN (1997b)
VIII	1:20,000 and 1:50,000 (valleys); 1: 100,000 (hills)	CIREN (1999)
IX	1:100,000	CIREN (2002)
X and XIV	1:50,000 (valleys); 1: 100,000 (hills)	CIREN (2003)
XI	1:20,000 and 1:60,000 (valleys); 1:250,000 and 1:500,000 (hills)	CIREN (2005b)

Fig. 2.6 Coastal Range residual igneous soil (Ultic Palexeralf) observed in Regions VII and VIII of Chile

Fig. 2.7 Coastal Range residual metamorphic soil (Typic Rhodoxeralf) observed in Region VIII of Chile

Fig. 2.8 Soil (Vitrandic Durixerept) derived from acid volcanic sands and pumice. Metropolitan Region of Chile

40–60 cm depth. Volcanic coarse fragments are normally present at the soil surface in 5–50 % abundance, with sizes from coarse angular gravel to pebbles. In addition, a thin (1–10 cm) sandy surface coating is observed, with its origins in aeolian transport processes. In IREN (1976), andesitic, rhyolitic and basaltic gravels are characterised, while sands correspond to pumice. The very low organic matter content (OC $<$ 1 %) decreases with depth in most soils, except in those with more stratified profiles. These soils have largely been classified as Lithic Usthorthents.

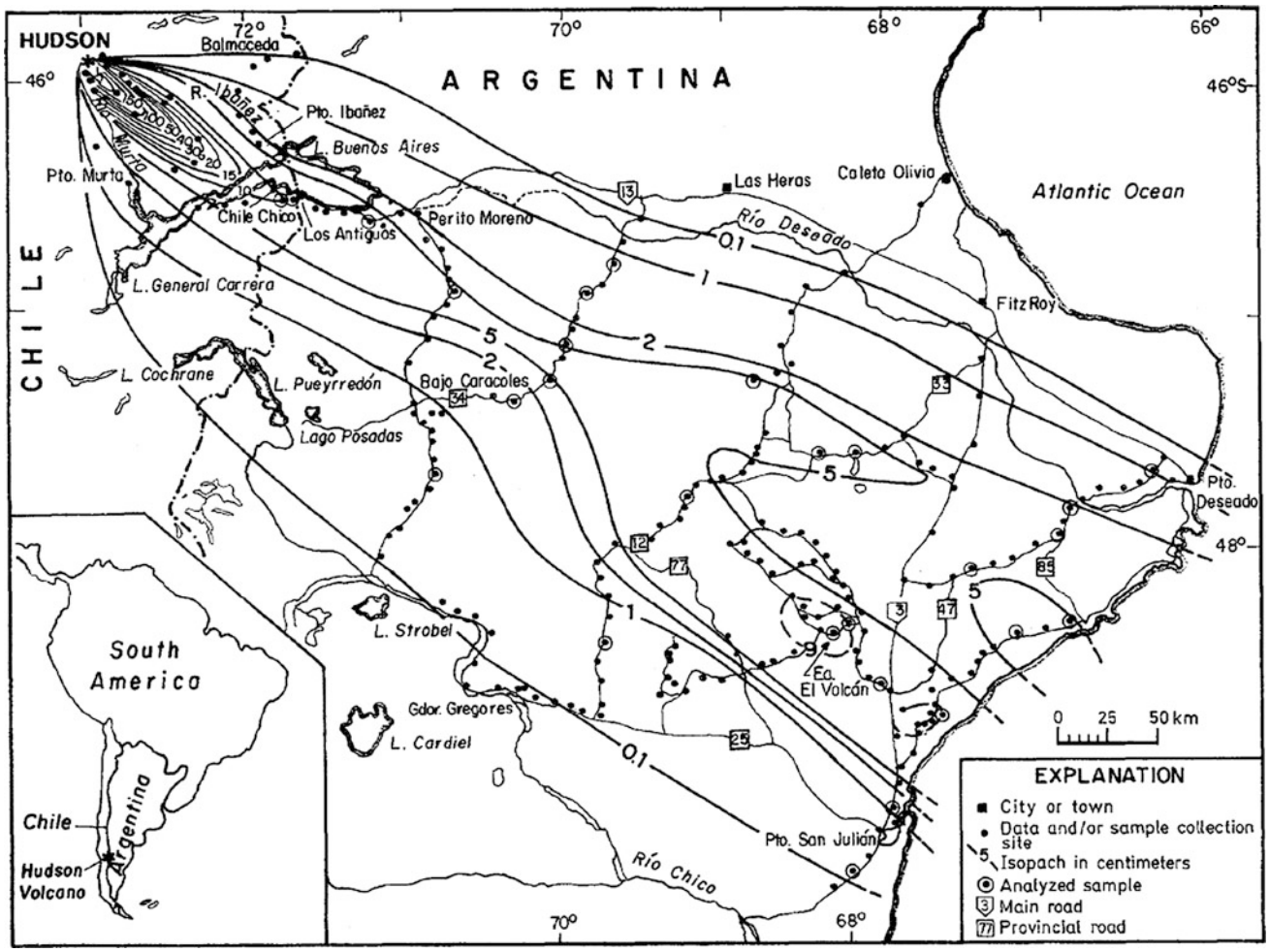

Fig. 2.9 Location and isopach map of primary eruptive deposits (cm) in Region XI of Chile (Scasso et al. 1994)

Fig. 2.10 Slope aspect differences within a Coastal Range small watershed (Metropolitan region)

Fig. 2.11 Glacial features around Lake General Carrera (Chile, Region XI) or Lake Buenos Aires (Argentina)

Table 2.2 Edaphic zones of Chile (Luzio et al. 2010)

Edaphic zone	N limit	S limit
Desert zone	18°00′S	29°00′S
Arid and Semi-arid zone	29°00′S	32°00′S
Arid Mediterranean zone	32°00′S	37°45′S
Wet Mediterranean zone	37°45′S	43°00′S
Rainy zone	43°00′S	50°00′S
Magellan zone	50°00′S	55°00′S
Antarctic zone	62°00′S	63°00′S
Easter and Juan Fernández Islands	–	–

Table 2.3 Major soil zones of Chile

Soil zone	Subdivisions	Soils
Hyper-arid to Semi-arid zone	Altiplano	Skeletal soils
(18–32°S)		Soils with incipient pedogenesis
		Soils in depressive basins.
	Longitudinal Central Valley	Soils of depositional plains and Andean piedmonts
		Salty soils
	Valleys	Soils of intermittent rivers
		Soils of permanent watercourses
	Coastal range	
	Coastal plains	Undeveloped soils
		Indurate soils
		Soils with natric horizons
		Sedimentary soils
	Serranías	
Mediterranean zone	Andean mountains	Non volcanic soils
(32–43°S)		Volcanic soils
	Pre-Andean mountain	Non volcanic soils
		Volcanic soils
	Longitudinal Central Valley	Soils with high base saturation
		Soils with argillic horizons
		Soils with cambic horizons
		Typical Andisols (trumaos)
		Aquic Andisols (ñadis)
		Holocene sandy soils (arenales)
	Coastal range	Igneous parent materials
		Metamorphic parent materials
	Coastal plains	
Rainy and Patagonian zone	West side of North Patagonia	Andisols
(43–56°S)		Other soil orders
	East side of North Patagonia	Soils with high base saturation
		Soils with low base saturation
	South Patagonia (Magallanes)	Organic soils
		Mineral soils
Insular and Antarctic zone	Easter Island and Juan Fernández Archipelago	
	Antarctic	Mineral soils
		Ornithogenic soils

Figures 2.15 and 2.16 illustrate a typical profile and landscape, respectively.

Soils with Incipient Pedogenesis

Figure 2.17 shows an example of soils developed from stratified tephras between Calama and Ollagüe, with an A–C profile. Other shallow soils from volcanic materials (pumice fragments throughout profile) can also be observed between Putre and Parinacota (Fig. 2.18). Textural classes are medium to moderately fine at the surface and coarse sandy with pumiceous gravel (almost 70 % with diameter <4 cm) to 120 cm depth. Although blocky structure is well-developed near the surface, below 20 cm depth massive conditions are generally seen.

Exceptionally, more intense pedogenetic processes are observed in some highland soils which are not occupying a

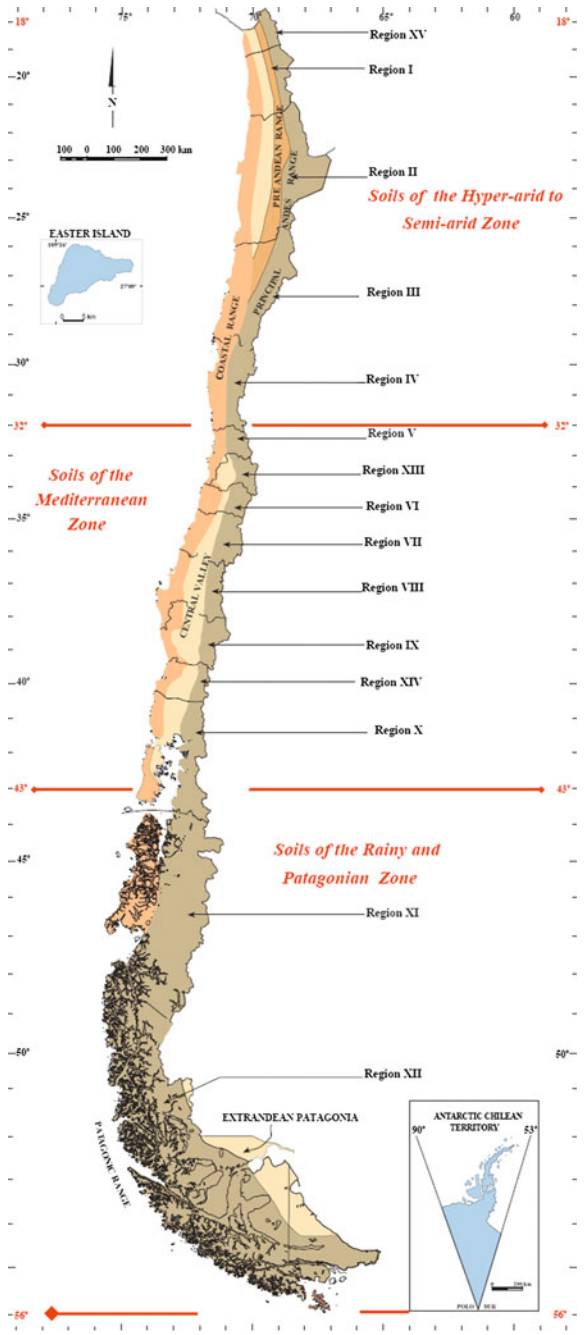

Fig. 2.12 Major soil zones of Chile

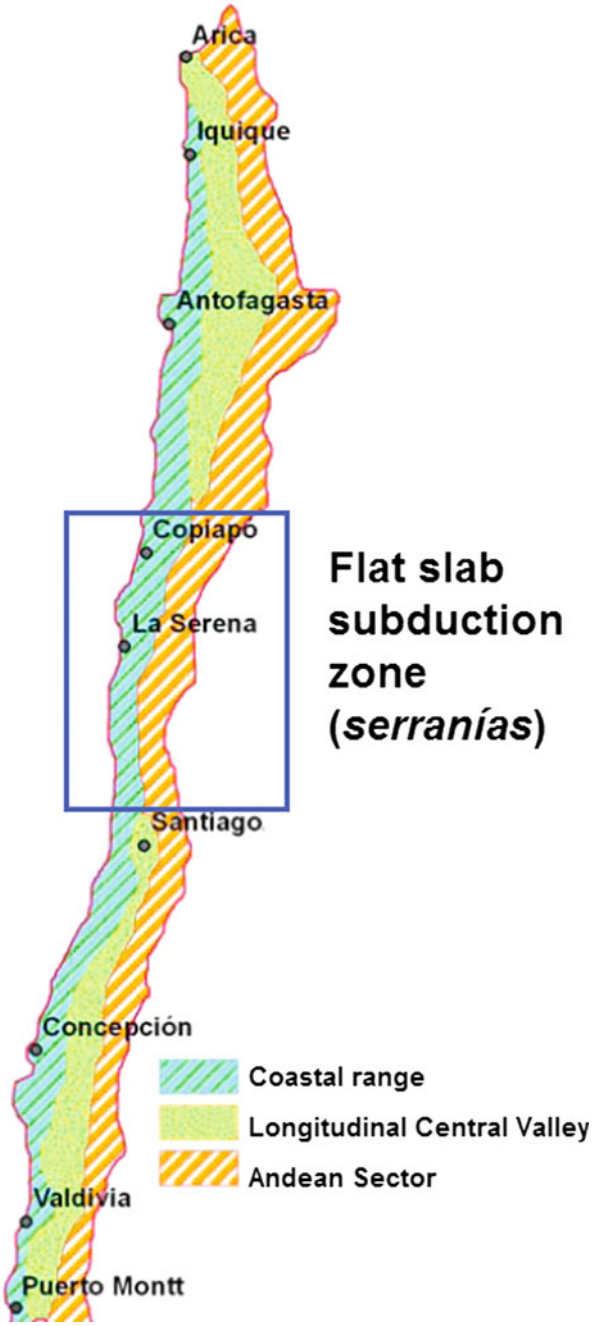

Fig. 2.13 Main physiographical changes along the Hyper-arid to Mediterranean zone of Chile

defined geomorphic position and show evidence of cambic horizon formation (B_w). Fine and moderately fine-textured B horizons with angular or subangular blocks are frequently observed but, occasionally, a strong coarse prismatic structure has been reported. Some C horizons are strongly compacted and present abundant pumice gravel or tuff, with different degrees of weathering. Significant lithologic discontinuities have been formed by frequent and successive petrographically diverse alluvial, aeolian or volcanic materials, transported/deposited by flooding. The clay fraction in their profiles must be responsible for the higher soil water retention capacity and cation exchange capacity (CEC), because as in skeletal soils, the organic matter (OM) content is low.

Considering previous antecedents, normally some of these incipient soils are very close to meeting the minimum requirements to be classified as Andisols. Therefore,

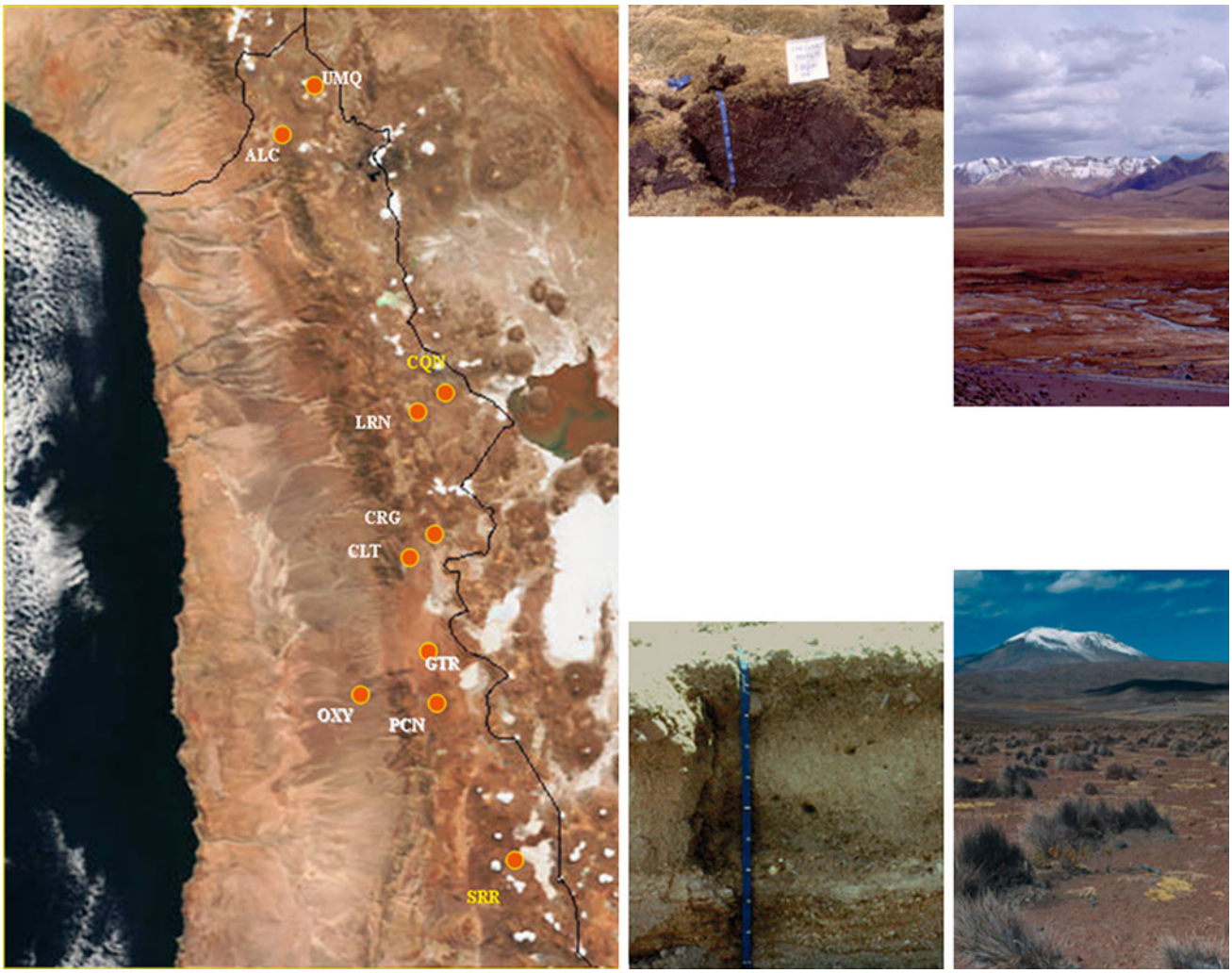

Fig. 2.14 Sites where 10 Altiplanic net organic (NOS) and net mineral (NMS) soils occur. *Inset*, *above* an example of NOS (CQN, Caquena soil) and *below* a NMS (GTR, Guallatire soil)

Usthorthent denomination is appropriate in some cases, but when a cambic B horizon is developed the soil is classified as a Haplocambid (Soil Survey Staff 2006).

Soils on Depressed Basins

Common features of these soils or wetlands are constrained drainage, high organic matter content and accumulation of salts (Table 2.4). In a depressed landscape associated with inundation sectors of streams, poor drainage sites rich in plants are formed which are locally named as *vegas*, are mostly characterised as mineral soils rich in organic matter. However, other organic soils are formed in closed basins with very poor drainage, which are known as *bofedales*.

Ahumada and Faúndez (2009) classified these soils according to their salinity levels, vegetation characteristics and drainage conditions, including an additional soil organic type named *pajonal* (Fig. 2.19). The same authors reported that all these soils occupy a total area of 43,234 ha (48 % in Region XV, 21 % in Region I, 22 % in Region II and 9 % in Region III). Cepeda and Novoa (2006) studied soils in the highlands of Region IV and reported that where water accumulates or the watertable is at the soil surface, sites with characteristics of wetlands/wet pastures are found, locally named *vegas* or *veranadas*. In ecological terms, these are the richest most diverse and productive sites in the highlands, making possible seasonal livestock (normally goats) transhumance (Fig. 2.20).

Luzio et al. (2002a) reported some soil characteristics in two *bofedales*, classified as Haplofibrist and Haplohemist, normally with fibric surface horizons and sapric at depth (Fig. 2.21). Other highly saline pedons have been classified as Endoaquents and Halaquepts/Endoaquepts.

2.2.1.2 Soils of the Longitudinal Central Valley

The Longitudinal Central Valley with 40–55 km wide interfluves (pampas) that correspond to a plateau with altitude

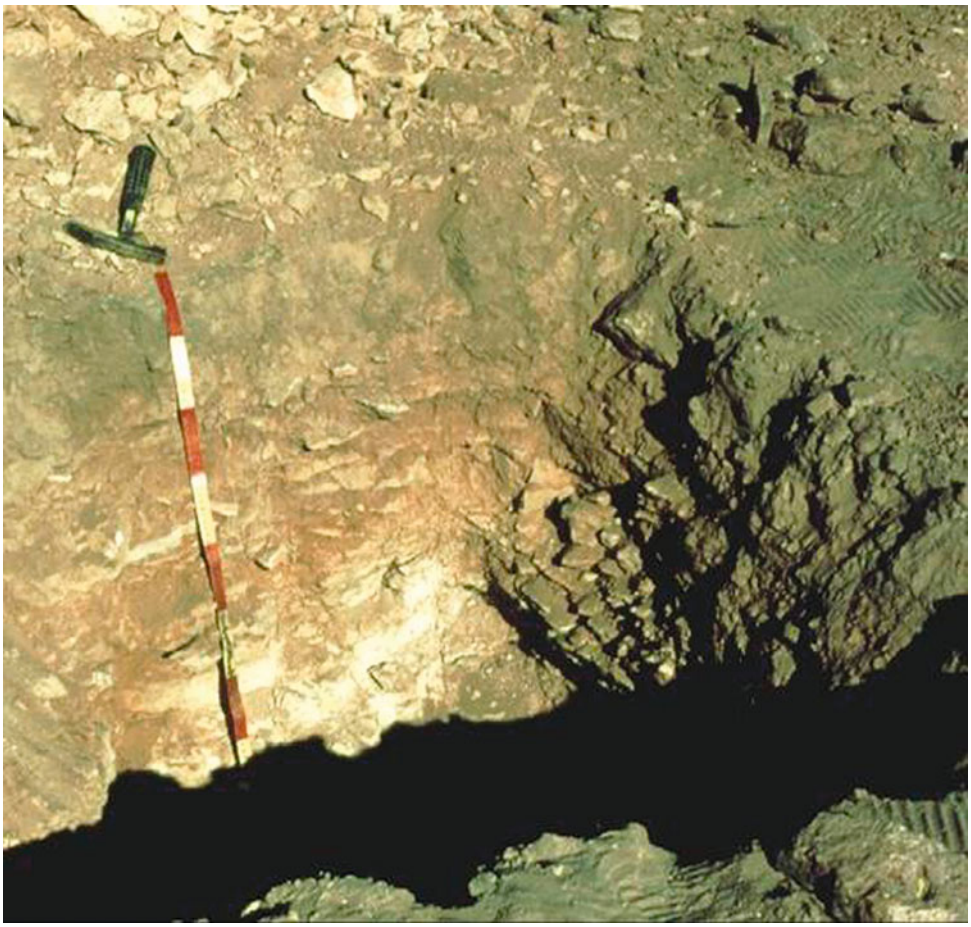

Fig. 2.15 Skeletal soil (Lithic Ustorthent) of 20 cm depth over liparite stone, Region I (Luzio et al. 2010)

increasing from 500 to 1,000 m a.s.l. in the west to 1,900–2,300 m a.s.l. in the east, resulting in a slope of 1.5–2.0°W. The pampas are separated by the deep gorges (1,000 m) of a few rivers coming from the Andes. In physiographic terms this area is gently undulating and deflated, apart from hard crust sectors with salts or silica. The Central Valley is a thick fill of detrital and lacustrine sediments (gravel, sand, silt and clay) of the middle Tertiary to Holocene age, often covered with salt crust remnants of ancient salars. Roughly between 22 and 25°S lies what is known as the Atacama Desert, the oldest continuously arid region in the world. Within this desert, Quillagua (21°39′S–69°32′W, mean rainfall 0.05 mm) can lay claim to being the driest place on Earth.

The Longitudinal Central Valley becomes increasingly discontinuous south of about 26°S (see Fig. 2.13), although the general features of the Coastal Range and pre-Andean ranges remain in place, and disappear entirely near 27°S. The topography to the south of 27°S is continuously hilly to mountainous from the ocean to the Andes (*serranías*).

As shown in Sect. 1.1, the Central Valley is bordered by a steep, <2,000 m high escarpment that rises from the Pacific Ocean to the west, and by the high Andes (>5,000 m) to the east, but its southern boundary is subject to debate. Rundell et al. (1991) suggest that the present-day desert border lies at Elqui Valley (~30°S) based on a shift in vegetation pattern, but the nearly lifeless zone for which the Atacama is renowned ends north of the first transverse Copiapó Valley (Chañaral, ~26°S).

Large, low-angle alluvial fans fill the Central Valley and converge onto the broad pediment and pediplain surfaces. Extensive ephemeral, dendritic drains join axial channels at valley centres, particularly to the north and east. Ewing et al. (2006) and Amundson (2003) reported some developed soils in the zone and described three profiles corresponding to Aridisols (Fig. 2.22), either on alluvial fan (Yungay and Copiapó pedons) or stream terrace (Altamira pedon) positions.

Soils in Depositional Plains and Andean Piedmonts

These soils cover an area between 18 and 29°S, with altitude from 1,000 to 2,800 m a.s.l., i.e. an area laid out by the Andes (and pre-Andes) and the Coastal Range. Clarke (2006) in a detailed description reports that the extensively deflated surface consists of fragments of gypsum duricrust, andesitic pebbles and a lag of lithic sand. Stone circles and polygons form a network of stones enclosing areas of bare ground, being locally common in a number of areas. The soils are characterised by very weak profile development and a

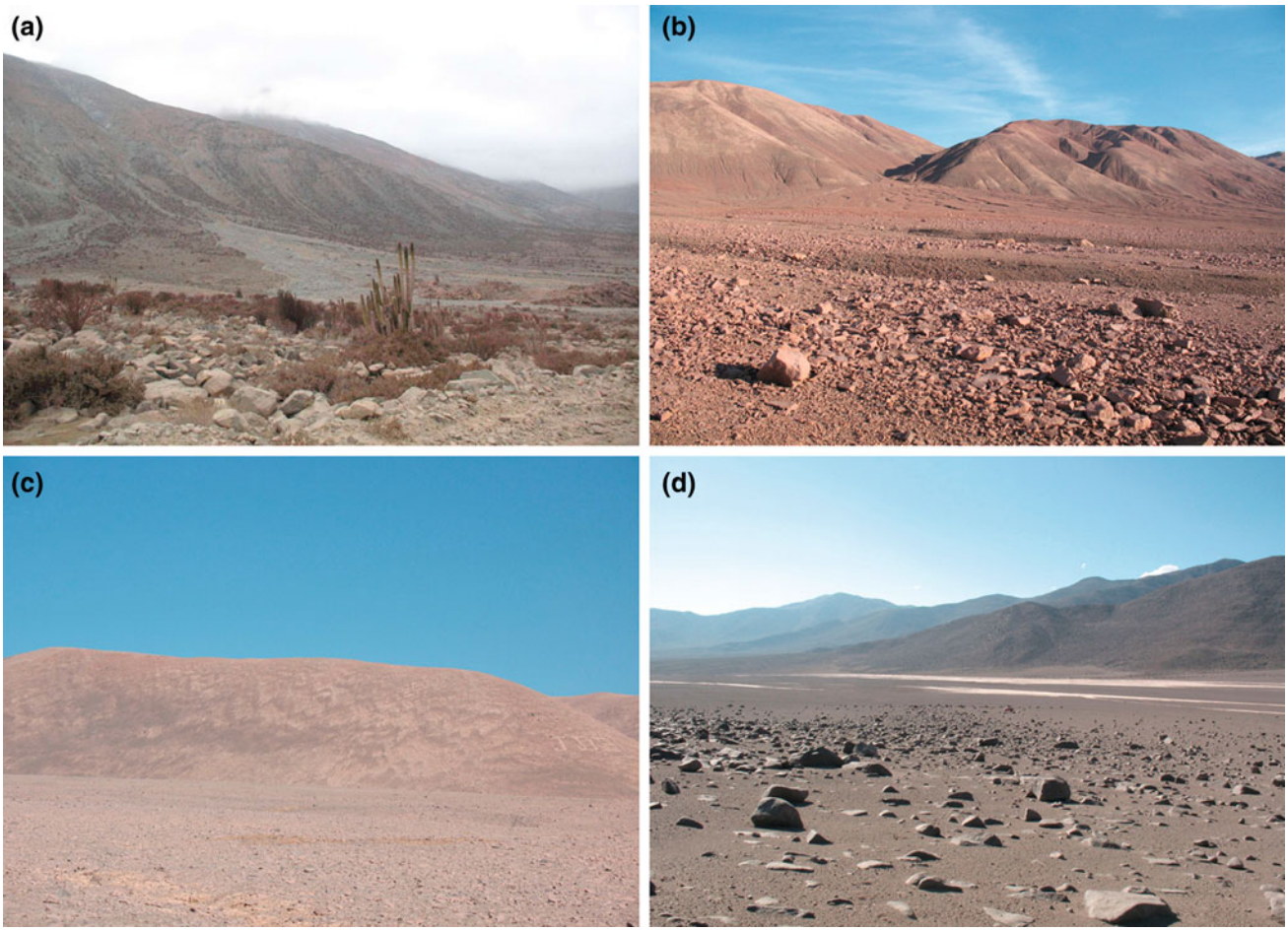

Fig. 2.16 The Atacama Desert. **a** The western Coastal Range. **b** The eastern Coastal Range. **c** Hillslope in the longitudinal Central Valley. **d** Boulder field in the absolute desert, where skeletal soils are present (partially from Placzek et al. 2010)

mixture of alluvial and colluvial sediments, which may be saline, also including soils occurring in the Andean piedmont.

These regular plains, including soils with different salinity levels, were dissected mainly by alluvial processes, probably more intensely at the beginning of the Quaternary. As a consequence, some hilly (slope gradient <10 %) landscape can be observed, with remnant plains (called *pampas*) separated by valleys and streams of different sizes. Soils from main valleys (Lluta, Azapa, Camarones, etc.) are described later.

According to Luzio et al. (2010), these extensive plain sectors contain what could be considered true desert soils, as described by Díaz and Wright (1965) and the most representative Atacama Desert soils, Aridisols. Abundant (>40 %) surface angular coarse fragments are observed, with a mixed acid and basic composition. Like an extensive pavement, similar to a stone desert, armoured surfaces comprise intricate mosaics of coarse particles, where deflation may be a relatively unimportant process of pavement formation.

Shallow soils developed on rhyolitic tephras, coarse-textured at the surface and with a single-grain structure, are common, but in some cases it is possible to find somewhat evolved soils in terms of a weakly expressed B horizon and moderately coarse-textured and subangular blocks structure. Calcareous coatings occur at a cracked R layer, expressing some translocation through the soil profile.

In some planar depositional basins, stratified soils (sandy and sandy loam) are observed (Fig. 2.23) in sectors with accentuated microrelief, but some fine-textured layers (silty and silty loam) can be included in some cases. Although excluded from a salar concept, irregular EC values at depths (2–30 dS m^{-1}) have been measured. The $CaCO_3$ content is also variable (1–6 %).

Salty Soils

The pre-Andean Depression, also called the salar de Atacama Depression, is a large intramontane basin at 2,500 m elevation, filled with Tertiary to Holocene clastic and evaporitic sediments of continental origin. According to

Fig. 2.17 Stratified volcanic soil with abrupt tephras (ashes and lapillis) layers, located between Calama and Ollagüe, Region II (Luzio et al. 2010)

Hardie and Eugster (1970), in most saline lakes worldwide, three main groups of brines may be generated by evaporation and chemical division: alkaline brines (Na/HCO_3–CO_3–Cl, $pH > 9$, traces of Ca and Mg), sulphate-rich brines (Na/SO_4–Cl, low Ca, $pH < 9$) and Ca-rich brines (Na–Ca/Cl, low SO_4, $pH < 9$). In northern Chile, most belong to the SO_4-rich and Ca-rich groups, and alkaline salars are almost completely lacking, due to the abundance of native sulphur in the Andes and atmospheric deposition of gypsum-rich desert dust from the Central Valley (Bao et al. 2004; Risacher et al. 2003).

Fig. 2.18 Volcanic origin soil profile (*above*) in sedimentation plain (*below*), located between Putre and Parinacota. Acid pumice ash is apparent in the subsoil, Region XV (Luzio et al. 2010)

Soils developed in these evaporite deposits represent an extreme in terms of characteristics and properties. Although these soils have a surface extremely hard crust (which in some cases can be up to 1 m thick), they consist of salts where vegetation can eventually thrive in good conditions (see Fig. 2.24).

Fig. 2.19 Characteristic vegetation on altiplanic soil types in depressed geomorphic positions, after Ahumada and Faúndez (2009). *Bofedal* (*above*), *pajonal* (*middle*) and *vega* (*below*). Saline (*left*) and no saline (*right*) types

2.2.1.3 Soils of the Valleys

A number of valleys and streams cut across northern Chile from the Andes Mountains to the Pacific Ocean where alluvial soils have developed on fluvial deposits, while between the rivers (interfluves) the soils are dry and some are infertile.

Responding to intense mining activity and an exponential increase in tourism during recent decades, high capacity infrastructure (roads, gas and water pipes and power lines) have been built in the northern Hyper-arid to Semi-arid zone to facilitate the exchange of goods and energy, and to supply urban and industrial centres located in the absolute desert with food and water. Therefore, a high demand for water for industrial and urban purposes is creating severe conflicts with natural ecosystems, farmers and indigenous cultures. In this regard, Lagos and Blanco (2010) recently claimed that the coexistence of high income levels and inequalities in the zone is not the result of insufficient resources, but of a lack of commitment to development by the main regional stakeholders.

Soils of Intermittent Rivers on Desert Valleys

In the northern Hyper-arid to Semi-arid zone only intermittent rivers or dry valleys are present in a superimposed network. The former corresponds to the active drainage basin of the Lluta River, San José River (Azapa Valley) and Camarones Valley (Fig. 2.25). Parallel valleys are very well-preserved in the interfluve zones of the pre-Andean sector.

The rivers differ greatly from one another in amount of water, seasonality of flow, fluctuation from year to year and character of accessible irrigable lands. Maximum flow

Fig. 2.20 Surire *bofedal* at Surire salt lake, Region XV

Fig. 2.21 Caquena *bofedal*, Region XV. Landscape (*left*) and soil profile (*right*)

Table 2.4 Altiplanic soil types in depressed geomorphic positions. Adapted from Ahumada and Faúndez (2009)

Type		Water supply	Vegetation architecture	SOM contents	Salts outcrop cover (%)
Bofedal	Saline	Permanent from lagoons, surface runoff and high water table, with permanent soil wet	A cushion, low grass with a growth very compact	High	>5
	Non saline	Permanent from lagoons, surface runoff and high water table			<5
Pajonal	Saline	Lagoons and surface runoff. More restricted summer soil saturation	Caespitose plants, >40 cm tall	Moderate	>30
	Non saline	Lagoons and surface runoff. Summer soil saturation			<30
Vega	Saline	High plasticity, with soil low saturated to completely saturated	Non caespitose and rhizomatic plants, <40 cm tall	Very variable	>20
	Non saline	Lagoons and surface runoff. Soils at least in field capacity during summer			<20

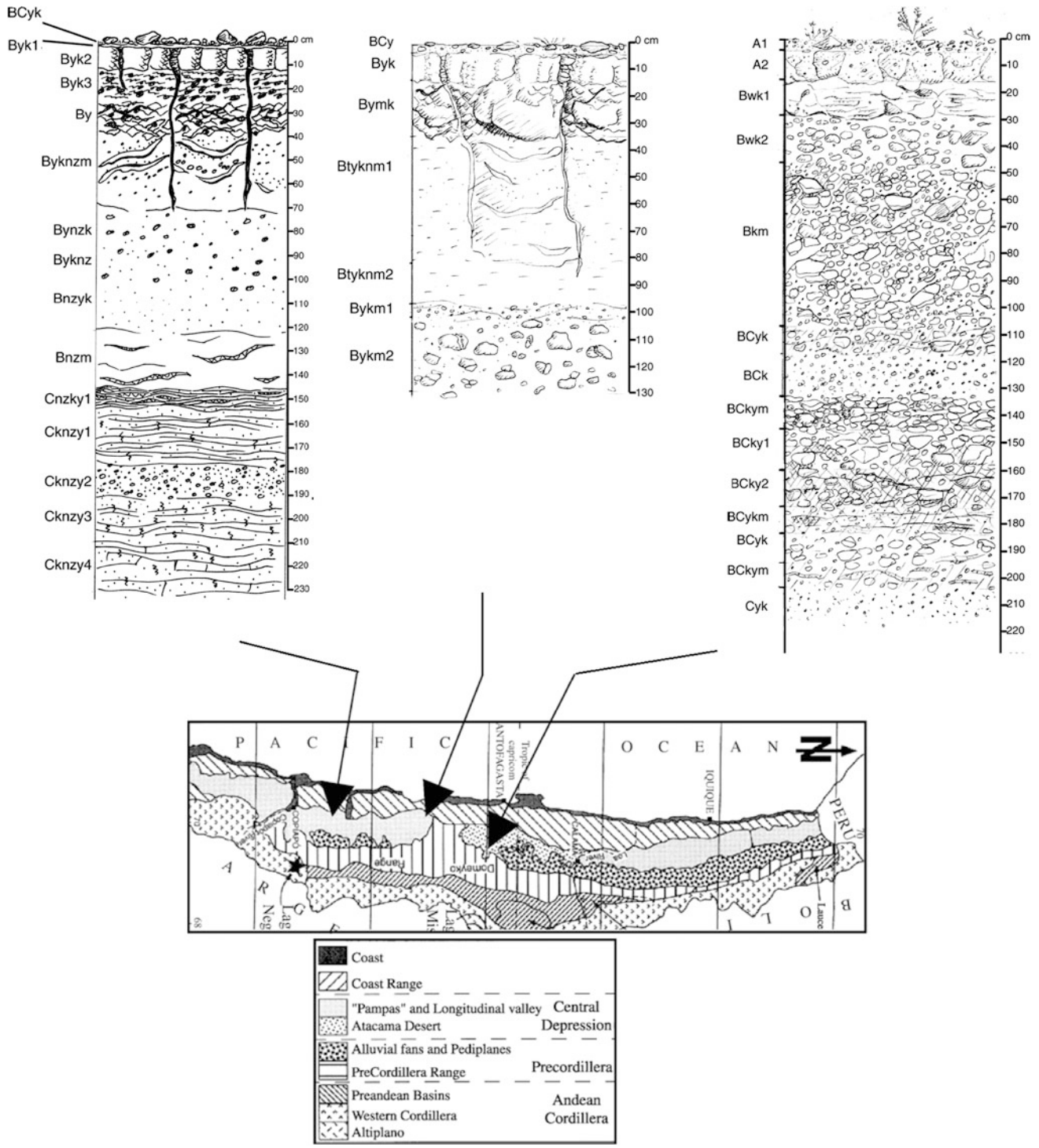

Fig. 2.22 Aridisol profiles from the Atacama Desert (see characteristics in Appendix, page 160), after Ewing et al. (2006) and Amundson (2003). Above, from left to right: Yungay, Copiapó and Altamira pedons

occurs during the southern summer (October–April), and many of the streams dry up completely during the winter. The water provided by these rivers, directly or through the intermediary of groundwater, supports irrigation agriculture along the valley floors, the deltas by the coast or the alluvial fans where the streams emerge from the mountains (Meigs 1966).

Although most soils in these valleys are alluvial, a few colluvial soils or soils with colluvial influence pedons are present. Apart from the Chacalluta Valley near Arica city

Fig. 2.23 Characteristic soil of depositional plains very stratified and with an A–C profile (Luzio et al. 2010)

(SAG 2002), there are only some old soil surveys such as for the Lluta River (Díaz 1958), Camarones Valley (Díaz and Meléndez 1958) and Azapa Valley (Wright and Meléndez 1961). From very general soil descriptions of these surveys, it is possible to conclude that stratified, poorly developed but deep soils occupy several alluvial terraces, with variable salinity and diverse drainage classes, where agriculture is practised.

After *Pampa del Tamarugal*, a continuous desert plateau (crossed only by the Tarapacá basin) in the longitudinal valley (19–22°S), 30–60 km wide and with elevations of 900–1,200 m, and the Loa River emerge in the desert. Occupying 2,430 km^2 in a conspicuous embayment along the Andean front, the Salado River basin is an important source of surface water and groundwater and is the main perennial tributary of the Loa River, the only river in northern Chile to start in the Andes and actually reach the coast.

In general, at the Andes mountain level, narrow valleys with slopes of up to 100 % are found (Fig. 2.26). Most valley bottoms are composed of coarse sediments such as rounded and/or faceted gravel. There are sectors where there has been possible alluvial terrace formation, constituted by sands in a clear graded stratification. In those cases, where slight pedogenesis exists, an A horizon is formed by organic matter accumulation. Indeed, these soils reach the minimum to be classified as Entisols (Ustorthent Great Group). However, at the margin of water streams, common paludisation processes determine the existence of organic or mineral soils (rich in organic matter), despite the thin and poorly developed soil profiles.

Muñoz et al. (2007) found Histosols, Mollisols and Entisols in the Tarapacá basin, the Entisols being derived from coarse sediments with high salt content and elevated pH. Peaty soils and the presence of salts in soil at depth have been reported north of the Loa basin, but to the west sandy

Fig. 2.24 Soil profile at the Pintados salar. Under a 30 cm thick crust, plant roots can be observed (Luzio et al. 2010)

loams to sandy-textured soils with a silty loam layer at depth can be found.

Soils of Valleys with Permanent Watercourses

The exorheic basins begin near 27°S (Region III) in Chile, where rivers of pluvial and snowy regimes run with a general East–West orientation (Fig. 2.27). At this southern portion of the Hyper-arid to Semi-arid zone, more detailed soil surveys have been carried out for main valleys corresponding to Region III (Copiapó and Huasco rivers; CIREN 2007) and Region IV (Elqui, Limarí and Choapa rivers; CIREN 2005a).

The Quaternary continental and coastal deposits along the Copiapó River, the first river of this group, are associated with morphostratigraphic units such as alluvial fans, dunes, fluvial and marine terraces (Fig. 2.28). According to CIREN (2007), along the Copiapó Valley, the main soil series are classified principally as Typic Haplocambids, Typic Haplocalcids, Typic Haplosalids and Sodic Haplocambids.

An incipient geomorphic development can be observed at the upper and medium portions of this valley with abrupt hillsides and without meanders and dominated by coarse materials (fine sands to medium gravel), although locally fine sediments have been deposited. Apacheta (piedmonts) and Amolana (terraces) soil series (Typic Haplocambids) characterise these sectors (Fig. 2.29). Other less developed colluvium soils coexist in this sector, with those used for table grape production showing weak soil structure, abundant coarse fragments and some profile HCl reaction.

The landscape in the lower section of this valley, i.e. from Copiapó city to the coast, is open, with fine-textured soils in remnant terrace positions, which are rich in soluble salts (EC can reach 85 dS m^{-1}) and carbonates (pH 8.0–8.8) throughout their deep and stratified profiles. Most soils present a darker Ap horizon, where the highest values of chemical properties are expressed, and then decrease below ~20 cm depth. As in the upper part of the valley, less developed colluvial soils are found and are considered skeletal. A representative soil in this sector is Ramadilla soil series (Sodic Haplocambid).

Therefore, considering the presence of coarse sediments in the upper part of the valley and fine materials in the lower part, the principal constraints of these Aridisols are stoniness, drainage in some cases, salinity, alkalinity and sodicity. However, most soils are included in I–IV LCC, where table grape production is an important activity.

The Huasco River runs through the second most important permanent valley of the Hyper-arid to Semi-arid zone, where the main soil series are classified as Typic Torriorthents, Aquic Torriorthents, Xerollic Haplargids, Xerollic Camborthids, Xerollic Torriorthents, Typic Natrargids and Xerollic Calciorthids (CIREN 2007). Like the Copiapó Valley, the Huasco Valley opens (~1.5 km) near Vallenar city (~28°S), showing at both river margins alluvial terraces, differentiated in at least three levels (higher, intermediate and lower recent terraces). In addition, some soils in the piedmont position are present at intermediate and high levels of this valley with stony soil profiles, coarse-textured and resting over an alluvio-colluvial substratum. Variable but not excessive slope gradients are observed.

Very stratified and poorly developed soils occupy the lower plain alluvial terraces of this valley. These coarse to medium-textured stony soils have drainage and salinity constraints and are classified as Aquic Torriorthents (soil series Paona and Bellavista).

Medium or intermediate terraces include more productive soils of this valley, with good drainage, and also stratified and medium to fine-texture classes. According to

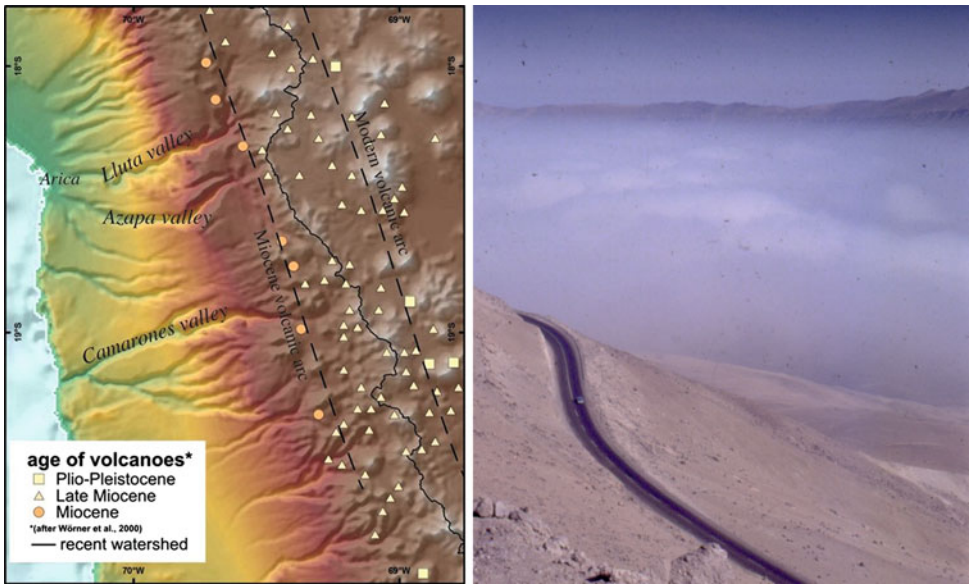

Fig. 2.25 *Left* valleys with intermittent rivers in the extreme north of Chile. *Triangles and circles* represent volcanoes of different ages (partially from Schlunegger et al. 2010). *Right* fog or *camanchaca* in Lluta Valley

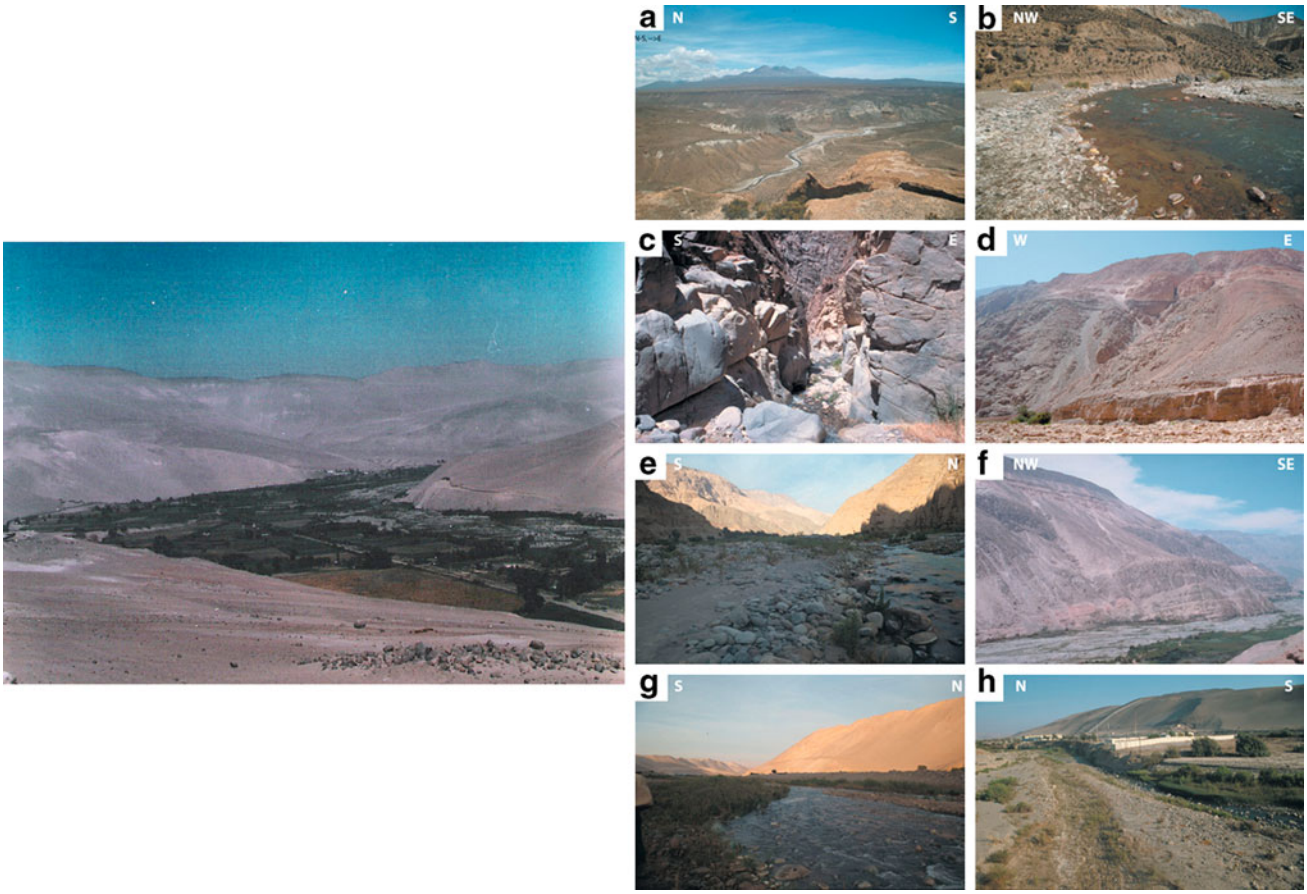

Fig. 2.26 Lluta River and eight sections (*left*) along the watercourse, described by Kober et al. (2009)

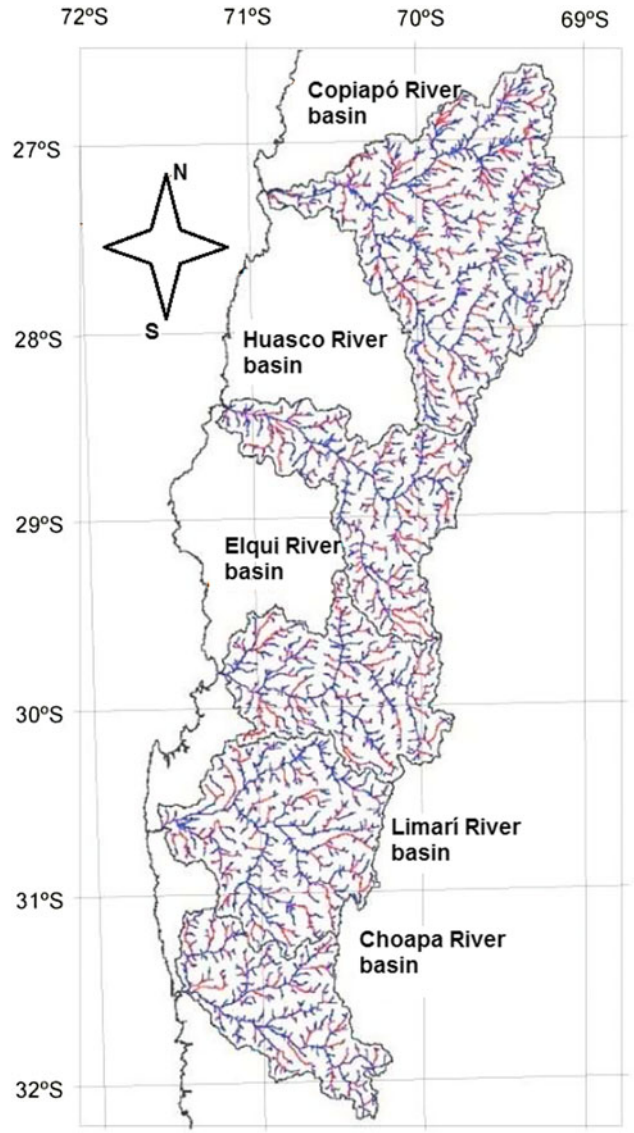

Fig. 2.27 Principal valleys with permanent watercourses. Regions III and IV of Chile

CNR (1993), the Chanchoquín soil series (Xerollic Camborthids) is very representative of these soils.

The highest level of these alluvial terraces shows at least three different types of soil profile. Those with exiguous development, well-drained plains and coarse-textured over a coarse alluvial substrate are represented mainly by the soil series Tatara (Typic Torriorthents). Some soil profiles include a shallow calcareous hardpan (locally named tertel) or only $CaCO_3$ in the case of Xerollic Calciorthids (soil series Ventana). Other calcareous soil profiles, but without tertel, coexist in these high level terraces, e.g. the Cavancha soil series.

Figure 2.30 displays characteristic soil profiles of the three pedons selected as examples here.

The Elqui River represents the next important permanent watercourse in this zone. A nival regime drives this basin and it is expected to be among the ecosystems most affected by climate change. Glacial or fluvio-glacial processes determine, in the highest portion, deep and narrow valley formation, which added to strong winds and reduced vegetal soil cover commonly, triggers landslides, debris flows and avalanches. However, organic wetlands (*vegas*) are frequent in less inclined sites. Alluvial soils on recent and remnant terrace positions (3–6 km wide) are the most representative soil in the lower and medium portions of this valley, respectively (Fig. 2.31).

More developed soils on older terraces have been also described, which are associated with slopes of the valley and can be confused with piedmonts and colluviums, despite the alluvial characteristics present in their profiles. The common A–C horizon sequence can reach a certain development expressed by a cambic horizon within the soil profile (A–B–C).

At the lower terraces, the soils are thin (<40 cm depth), loamy to loamy sand at the surface (A horizons) and abruptly changing to a C horizon constituted by rounded gravel and stones (~80 %), interstitial sands and fine gravels. In general, soils with a well drained and plain topography are included in II and III LCC, although some soil phases can be slightly undulating and others stony and thin and classified as VI LCC. These poorly developed soils are taxonomically classified as Typic Torriorthents (Chapilca soil series) and Typic Torrifluvents according to CIREN (2005a).

However, more developed Typic Haplocambids can be found in similar geomorphic positions with an A–B–C profile and 60–90 cm depth over a sandy and very gravelly alluvial substrate. These are mostly classified as II and III and some cases as IV when imperfect drainage is verified.

In the coastal sector, alluvial soils on marine terraces and in the valley bases have evolved from both continental and marine sediments with both terrace types and a long beach framing the bay of Coquimbo.

The Limarí River drains into a basin along a stretch between 30°S and 31°30′S where, apart from the A–C and A–B–C soil horizon sequences observed in other valleys, A–B_t–C and vertic B_{ss} horizons have been described (Aburto et al. 2008a, b).

Soils with A–C profiles are present in alluvial terraces or occupying colluvial positions with variable slope gradient (1–3 % to 15–20 %). Slightly deep (<60 cm) and well drained, these soils rest over a substrate of angular and subangular gravel and stones (~40 % in volume) with a fine-textured matrix. Surface horizons range between sandy clay loam and clay loam, with a subangular blocky structure in contact with the substratum (massive). Organic carbon content is <2 % at surface and ~0.2 % at depth. The topographical variability determines that these soils be

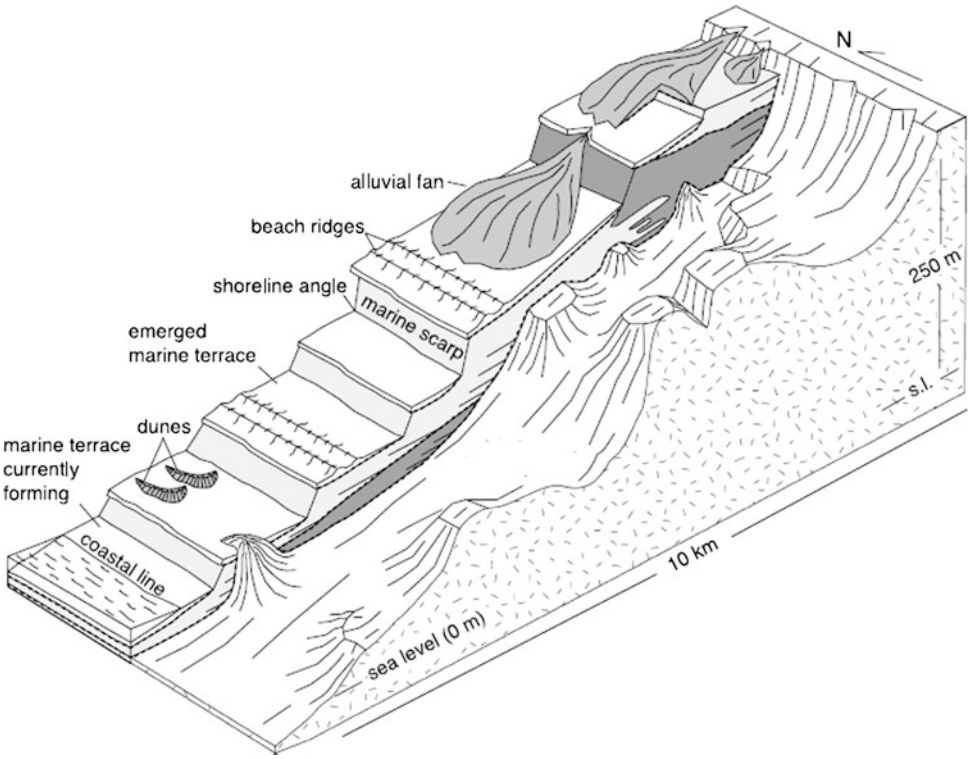

Fig. 2.28 Schematic sedimentary units along the Copiapó Valley (Marquardt et al. 2004)

Fig. 2.29 Characteristic pedon (Typic Haplocambids) in the upper part of the Copiapó Valley. Apacheta soil series (Luzio et al. 2010)

included in III–VII LCC. The pedons classified (see Appendix, Huatulame soil series) clearly represent the characteristics of this soil group.

Soils with B horizons (generally Haplocambids) are found on slightly sloping alluvial terraces (2–5 %). Also slightly deep, these soils rest over a gravelly substratum with sandy to sandy loam matrix. A strong blocky structure dominates, OC content is <2 % at the surface, decreasing regularly with depth. Some profiles (Huamalata soil series) have EC < 5 dS m^{-1} at the surface. LCC varies between II and IV, mainly with drainage conditions (imperfect to poor).

Other soils with a depth of around 90 cm are present in well-drained colluvial and piedmont positions, with slope gradients from 5–8 % up to 20–40 %. Below the strongly structured clay loam-textured A horizons, the clay content increases significantly, showing advanced pedogenetic evolution, as evidenced by development of an argillic B_t horizon. Due to topography, these are classified in III–VII LCC. Taxonomically, the Typic Haplargid (Serón soil series) represent good example of this group of soils.

Coexisting with the soils described above, it is possible to find deep Vertisols in high alluvial terraces of the Limarí Valley, differentiated as Petrocalcic Calcitorrerts (Tuquí soil series, CIREN 2005a) with a subsoil rich in $CaCO_3$, and Sodic Haplotorrerts (San Julian soil series, Aburto et al. 2008a) with elevated exchangeable Na and EC values and gypsum

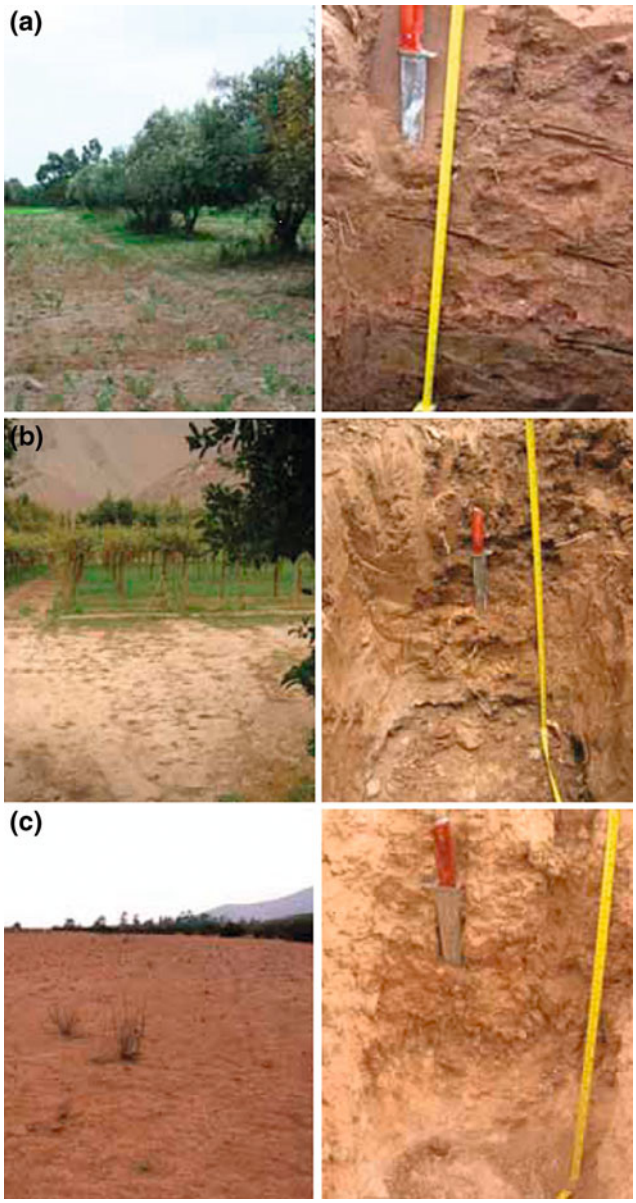

Fig. 2.30 Characteristic pedons on alluvial terraces of the Huasco Valley (CIREN 2007). **a** Paona soil series (Aquic Torriorthent), **b** Chanchoquín soil series (Xerollic Camborthid) and **c** Cavancha soil series (Xerollic Haplargid)

content. Cutans and slickensides are common in both soils, which are well drained and have been included in III–VI LCC, depending on soil profile depth and/or slope (Fig. 2.32).

The Choapa basin (including the Choapa and Illapel rivers), like the above valleys, also includes alluvial soils in terrace positions and colluvial pedons in piedmont positions (Fig. 2.33). The age of terraces varies and colluvial material derives from granitic rocks of different degrees of weathering. Compared with the other valleys analysed, all pedons observed here present an A–B–C horizon sequence with cambic horizons, denoting greater pedogenic maturity.

Alluvial soils can exceptionally reach slope gradients of 5–8 % and commonly <3 %. A gravelly substratum with coarse interstitial material is frequent and, although surface horizons are fine-textured (silty clay loam and sandy clay loam), subsoil can be finer (clay loam, silty clay or clayey). The well-structured subsoil can reach depths between 55 and 110 cm. Organic carbon content is <2 % in A horizons, decreasing regularly with depth (~0.3 %). Only the Tunga soil series contains free $CaCO_3$ (2.9 % at the surface and 9.3 % at depth). Drainage classes and surface coarse fragments represent criteria to classify soil phases into I–IV LCC. However, all this group of soils (Choapa, Huintil, Illapel, Quelén, Tranquilla and Tunga soil series) correspond to Haplocambids (Fig. 2.34).

On the other hand, colluvial soils coexist in the valley with slope gradients between 1–3 % and 2–5 % in plains situations or 15–20 % and 20–30 % in scarped positions. Granite mainly comprises the substrate in different weathering states or granitic sands (maicillo). Clay at depth follows a similar trend to that in alluvial soils and the structured solum varies between 50 and 80 cm. The OC content is higher than in those soils (2 and 4 % in surface), but also undergoes a regular decrease to 0.3 % at depth. Although carbonates are absent, EC varies between 0.4 and 4.9 dS m^{-1}. Due to their topographical position in the valley, all these soils present good drainage and depending on stoniness, rock outcrops and inclination, are classified from III to VII LCC. Taxonomically, they also belong to the Haplocambids except the Tahuinco soil series, which is classified as a Typic Paleargid that includes a B_t horizon. Other soil series of these colluvial soils are Camisas, Cuncumén, Chillepín and El Tambo.

After less prominent rivers (La Ligua, Petorca and Putaendo) at the extreme south of the Hyper-arid to Semi-arid zone, the Aconcagua River is the largest mid-latitude river of Chile, and its characteristics are typical of the temperate latitudes of western South America. Located at the boundary with the Mediterranean zone of Chile, it drains the ice- and snow-fields of the Andes and Coastal Plain. The river basin is located about 50 km north of Santiago and the upper watershed has several peaks above 5,000 m a.s.l. and vegetation is sparse. In the lower watershed, intensive agricultural production depending almost entirely on irrigation takes place. The Aconcagua River crosses important cities at Region V of Chile (Los Andes, San Felipe and Quillota), ending in the Pacific Ocean near Valparaíso.

Soils in recent and remnant alluvial terrace, colluvium (piedmont) and sedimentation basin positions have been described. The former are less developed than other soils in the valley; coarse to medium-textured, stony along soil profiles and resting over a substratum with rounded coarse fragments. However, according to CNR (1993), the soil series most representative are Chagres and Hualcapo, both

Fig. 2.31 Highest sectors of the Elqui Valley, with intense agriculture use (Luzio et al. 2010)

Fig. 2.32 Vertisols in alluvial terraces of the Limarí Valley, San Julián soil series (Sodic Haplotorrert) and Tuquí soil series (Petrocalcic Calcitorrert)

classified by CIREN (1997a) as Mollisols. Most of these soils are included in III and IV LCC due to coarse fragment amounts, depth and drainage.

On the other hand, remnant terraces host the best and more productive soils in the valleys formed on alluvial plains or mudflows reshaped by watercourses. Deep, well-structured and drained fine-textured profiles are characteristic. The Pocuro soil series (Fig. 2.35) is a clear example of these soils, also classified as Fluventic Haploxerolls but included in I and II LCC, although it is frequently possible to observe a plough pan.

Colluvial soils in piedmont positions present a variable slope, stoniness and depth, but are well drained (LCC: III and IV). Mainly classified as Inceptisols, some pedons are included in order Mollisol (CIREN 1997a). As an example, only the Ocoa soil series is included here (see Appendix).

Some soils in the valley are derived from fine sediments evolving under excessive soil water contents (lacustrine

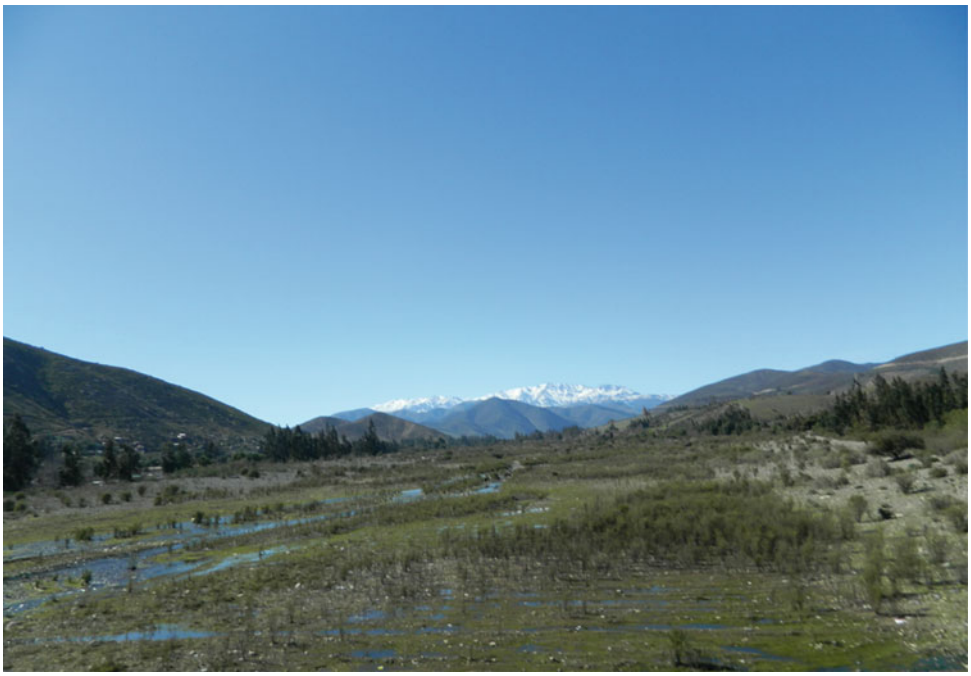

Fig. 2.33 Illapel River descending from the Andes Mountains, Region IV of Chile. Alluvial terraces and piedmonts are apparent

Fig. 2.34 A Typic Haplocambid (Quelén soil series) in the Choapa Valley, Region IV of Chile (Luzio et al. 2010)

conditions). Situated in low and depressed landscape positions, they are fine-textured and show imperfect to very poor drainage and elevated $CaCO_3$ contents. In general, taxonomically, these soils have been classified as Inceptisols, Mollisols or Histosols (Typic Xerumbrepts, Petrocalcic Palexerolls, Typic Calcixerolls, Entic Haploxerolls, Typic Medihemists or Fluvaquentic Endoaquolls) and the Palomar soil series is included here as an example (see Appendix).

2.2.1.4 Soils of the Coastal Range

The Coastal Range or Coastal Cordillera in northern Chile, which is 10–50 km wide, is a prominent forearc, a morphological feature in northern Chile that runs parallel to the coast. The most remarkable feature is a very steep, nearly 1,000–2,000 m, coastal cliff that plunges 45° into the sea in the extreme north. Cut by a series of faults, it is characterised by high relief that contrasts with the smooth, duricrusted surfaces further inland, which is probably due to strong salt weathering under the influence of periodic coastal fogs (*camanchaca*). According to Juez-Larré et al. (2010), uplift and delineation of the range as a separate morphotectonic unit (i.e. distinct from the adjacent Central Valley) is considered to have taken place in the Oligocene and continues to the present day.

The western margin of the range comprises the coastal scarp—a prominent break in slope—that extends for 900 km along the coastline. Although the origin of the scarp has been the subject of some debate, the absence of active fault scarps and the irregular morphology of the scarp

Fig. 2.35 Pocuro soil series, a Fluventic Haploxeroll (CIREN 1997a), near Los Andes city, Region V of Chile

suggest that it represents a weathered paleo-cliff line. This plunging paleo-cliff most likely developed through marine erosion during post-mid-Miocene uplift. Onlap of Middle to Upper Miocene marine sediments onto the scarp can be observed in a number of places between 21 and 27°S in northern Chile.

The top of the Coastal Range is an ancient, well-preserved erosive surface and testifies to the extremely arid conditions that prevailed in the Atacama Desert since the Early Pliocene. Such a surface is believed to result from intense erosion of the northern Chilean margin during past time periods. The eastern side of the Coastal Range is a transitional zone where a smooth topography marks the gradual boundary of the Coastal Range with the Central Valley.

Along the Coastal Range of the Hyper-arid to Semi-arid zone, soils can be separated into two broad types according to development of soil profiles: A–C–R and A–B–C. The former are skeletal sandy or sandy loam soils, in hillside positions, stony at the surface and with frequent rock outcrops, over fresh or weathered rock at least 50 cm deep. Soil organic matter content in the A horizon is <1 %, base saturation (BS) is low (<8 %) and pH varies between 6.2 and 7.0. Soil salinity is also low (EC < 1 dS m^{-1}). These Torriorthents (Luzio et al. 2010) are frequently included within LCC IV and VI.

Luzio et al. (2010) describe a Coastal Range soil at 25°S (Taltal, Region II) in a scarped landscape without terrace transition, where the slope gradient is over 20 % with abundant coarse angular fragments (~80 %) at the surface and at depth, and common rock outcrops (Fig. 2.36). The thin superficial A horizon shows a slight accumulation of carbonates and an abrupt boundary with underlying B or C horizons. A coarse-textured pedon is reported by these authors with high amounts of organic matter and soluble salts in surface layers.

In contrast, in Region IV of Chile, some soils of the Coastal Range (slope 6–12 %) have developed cambic and argillic horizons, although rock outcrops and surface stones are common. Despite being granitic residual soils, the complete profiles described are probably influenced by colluvial processes and marine sedimentation. Sandy loam and sandy clay loam textural classes have been described in surface, B_w or B_t horizons and are fine-textured (clay loam to clay) and strongly structured (subangular blocks and prismatic). Soil pH varies between 6.1 and 7.7, OC content reaches 2.0 % at the surface and 0.3 % at depth. Soils with a cambic horizon have been classified as Camborthids or Haplocambids (Mincha soil series) and those with an argillic horizon as Paleargids (Luzio et al. 2010).

In conclusion, in the western Hyper-arid to Semi-arid zone, only two continuous longitudinal morphological units are recognised: the Coastal Plain and the Coastal Range. In the majority of the north of Chile, the Great Coastal Escarpment separates the Coastal Cordillera from the Coastal Plain. The Coastal Plain, with 3 km average width, contains sedimentary deposits and abrasion marine terraces, partially covered by alluvial fans, which extend from the present coastline to 300 m a.s.l. (Paskoff 1989). However, between the cities of Arica (18°S) and Iquique (20°S), virtually no marine terraces are preserved. In many places south of Iquique, there is a narrow coastal plain, 1–3 km wide, that extends south beyond Chañaral (~26°S, Region III). This plain broadens to the north of Antofagasta, at the structural block of the Mejillones Peninsula.

2.2.1.5 Soils of the Coastal Plains

The northern coast of Chile includes the most emerged parts of the Southern Central Andes forearc closest to the Pacific Ocean trench. The pervasive Hyper-arid climate conditions along with the good preservation state of the morpho-stratigraphic (i.e. marine terraces) and morphostructural (i.e. fault scarp) records allow studies in neotectonics. However, southward of La Serena (Coquimbo), the morphological signs are more difficult to interpret, probably as a

Fig. 2.36 Characteristics of a northern Coastal Range soil profile with colluvial coarse fragments comprising almost 80 % (Luzio et al. 2010)

result of the combined effects of greater complexity and greater dissection by the wetter climate (Regard et al. 2010).

Morphogenetic inheritance of plate tectonics and of the marine cycles associated with the Holocene highstands has been important, generating a coastline of bays which have marine terraces and beach-ridge plains. Paskoff (1989) in a sectorisation of Chilean coastal plains in the Hyper-arid to Semi-arid zone, describes their littoral features from 18 to 25°S and from 25 to 33°S, which are denoted as desert and semi-arid coast, respectively.

The escarpment of the Coastal Range (18–25°S), which is 700 km long and 700 m a.s.l. on average, is largely inactive from Iquique city (20°13′S, Region I) to the south with Pleistocene marine terraces exposed at the foothills attesting to formerly intense marine degradation of the coastal cliff profile, which is the result of marine erosion acting on an actively uplifting coastline since the Pliocene (González et al. 2003). North of Antofagasta (23°38′S, Region II), cliffs are cut into horizontally bedded Tertiary sandstone (Fig. 2.37).

Over the terraces, large alluvial fans were formed during the rainy Quaternary by streams of the Coastal Range. Although the escarpment is from the end of the Miocene, a recess as a result of marine erosion during a major transgression occurred in the Upper Miocene/Lower Pliocene. A narrow continental platform borders an aligned coast with a marked N–S orientation. Only the Mejillones peninsula (23°15′S) which is 55 km in length and 20 km in width breaks this regularity. It consists of N–S orientated uplifted and downfaulted blocks, with a tectonically emerged coastal platform developed on sandstones, shales and coquinas. Flores-Aqueveque et al. (2010), characterising wind erosion processes over the flat geomorphology of the northern portion of this peninsula, also observed marine terraces of Pleistocene age (highest terraces) and mineralogical composition of moving particles similar to that of the soils, with quartz, feldspar and calcite as the most important minerals, followed by clay minerals, gypsum and amphibole. The ages reported indicate that substantial uplift has affected the peninsula.

From 25 to 33°S, the coastline is mainly rocky and lower (150–200 m a.s.l.), behind which extend abrasion marine terraces, stepped up to the first spurs of the Coastal Range. Resulting from the interference between sea eustatic fluctuations and the upthrust trend of the coast, there is general recognition of the Quaternary marine terraces along 110 km of the coast between 27 and 28°S. Uplift of these terraces, within the Chilean flat-slab sector, has been attributed to subduction of the oceanic Juan Fernández ridge beneath this continental section (Le Roux et al. 2005, 2006).

Detailed studies by various authors (Martínez et al. 2011; Pfeiffer et al. 2011; Saillard 2008; Quezada 2007; Marquardt et al. 2004) have been carried out in bays such as Caldera (Region III), Coquimbo-La Serena and Tongoy (Region IV) and Con Con (Region V). Talinay and Huentelauquen, both in Region IV of Chile, are the locations where different levels of marine terraces (Fig. 2.38) have been studied (Saillard et al. 2009; Aburto et al. 2008b; Le Roux et al. 2006).

Pedological studies on marine terraces are concentrated mainly in Region IV (Luzio et al. 2010), where it is possible to establish some general differences between soils. Lower and intermediate marine terraces include (a) soils without profile development, (b) indurate soils (tertel and petrocalcic horizon), (c) soils with natric horizons and (d) sedimentary soils. More pedogenetic development is observed at some intermediate and higher terraces, as evidenced by cambic horizons, and in some cases, argillic horizons.

Undeveloped Soils

Although dunes are present along the coast of Chile, between 30°00′ and 31°45′S (Los Vilos) and near La

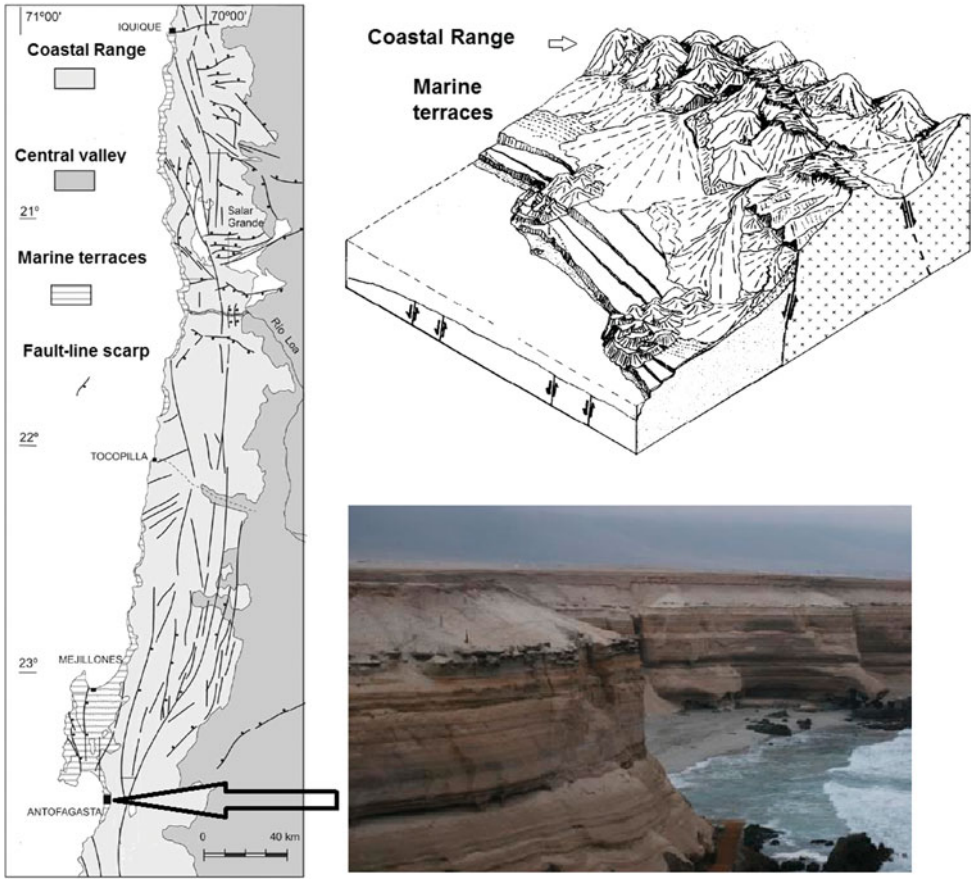

Fig. 2.37 Marine terraces and coastal cliffs in Region II of Chile

Serena city, stabilised dunes that have resulted in very scarce soil development can be distinguished by the absence of diagnostic horizons. Slope gradient is <6 % with some rock outcrops, but without stoniness at the surface or in the profile. The A–C horizon sequence is coarse-textured (sandy, loamy sand until sandy loam) on deep profiles (~150 cm) and is common, in some cases, over marine terraces (Aburto et al. 2008b). With an assumed granitic origin, these sandy soils are characterised by a pH between 6.3 and 8.0 and surface organic matter content <2 %, which suggests soil stability. Some pedons show relict redoximorphic features (iron nodules and laminar concentrations) formed on depressive positions or by probably more humid conditions than today's climate (Fig. 2.39). Classified as Torripsamments, LCC varies between II and III, but some soil phases correspond to Class IV due to complex slopes (5–8 %). A characteristic pedon of this soil group found near La Serena city is La Compañía soil series.

However, in the southern part of this Hyper-arid to Semi-arid zone, other stabilised dunes (paleodunes) displaying more advanced development occupy the highest marine terraces (CIREN 1997a). The Longotoma soil series, an Entic Haploxeroll (32°23′S), is a good example of this pedogenic evolution.

Indurate Soils

These limitative soils can be found on marine terraces and at colluvial positions and coastal piedmonts. They are slightly deep and thin soils, with a substrate consisting of a layer of hard/extremely hard consistency which in some cases consists almost entirely of carbonates and in others material, but the cementing agent is a mixture of silica and manganese without reaction to HCl, so that locally in both cases, a *tertel* denomination is used.

Nevertheless, for soils with calcareous tertel it is necessary to distinguish between those with a calcareous substratum pedogenically not related to formed soil and soils with a petrocalcic horizon (e.g. B_{km} or C_{km}) directly vinculated to soil formation processes. Soil pH is high (>8) along profiles, OC decreases regularly with depth (1.5–0.3 %) and EC is maintained below 1 dS m^{-1}. These soils belong to LCC, commonly III and IV, but exceptionally are classified as VI or VII. The Cerrillos de Elqui (Calcid Petrocalcid) soil series includes pedons representative of this soil group.

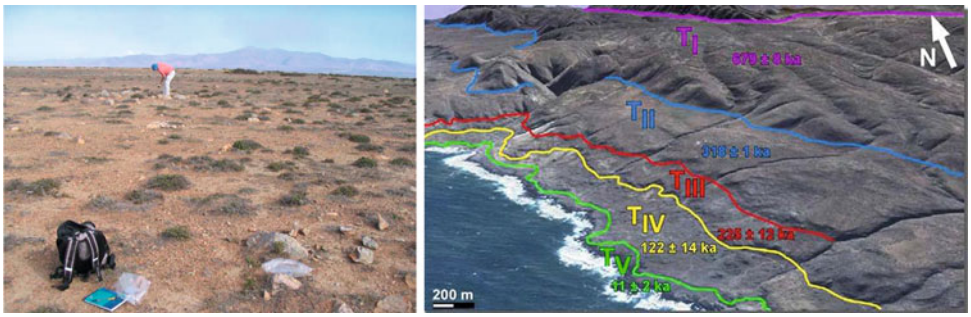

Fig. 2.38 Distribution of abrasion marine terrace levels at the coast of Region IV of Chile (Saillard 2008)

Fig. 2.39 Stabilised dune (Typic Xeropsamment) with certain pedogenic development at Los Vilos (Region IV)

Recently, Pfeiffer et al. (2011) described an aeolian sand cover deposit that also underwent pedogenic processes overlying calcrete. Aburto et al. (2008a) reported similar soils in the same paleobay (Tongoy), but classified these as Xeric Petrocalcids (Fig. 2.40).

Soils with Natric Horizons

Natrargids, characterised by the occurrence of a natric horizon but lacking a duripan or petrocalcic horizon within a metre of the ground surface, have been observed over marine terraces at Huentelauquén (31°34′S). These soils are present from a slight slope gradient (2–5 %) to gently rolling topography (5–8 %), where sodicity features include a strong prismatic or columnar soil structure and surficial spots of dispersed organic matter (Fig. 2.41). Fine-textured soil profiles can show cutans and redoximorphic features (Fe–Mn concretions). Within the natric horizons, exchangeable sodium percent (ESP) varies between 21 and 65 %. Pedon Huentelauquén, classified as a Typic Natrargid (CIREN 2005a), represent this group but other profiles have been characterised later as Xeric Natrargids (Aburto et al. 2008a).

Sedimentary Soils

These soils on marine terrace positions occur at the transition of the Hyper-arid to Semi-arid zone with the Mediterranean zone, at Region V. In general, they are classified as Alfisols and are coarse-textured at the surface and fine-textured at depth. Most soils show a drainage class depending on topography and resting over different substrates (granite/quartzite sandstones cemented or partially cemented with silica, or gravels with a clayey matrix). The Tabolango soil series is an example of this soil group. Other members of this group have been classified as an Ochreptic Haploxeralf (Mantagua soil series), Udollic Albaqualf (Catapilco soil series) and Ochreptic Haploxeralf (Chilicauquén soil series).

2.2.1.6 Soils of the *Serranías*

Serranías is the local physiographical denomination for a portion of Chilean territory where the characteristic geomorphic continuity (Andes Range—Longitudinal Central Valley—Coastal Range) is broken and active volcanism does not exist, and which coincides with the tectonic Chilean flat-slab sector.

Knowledge of soils in this sector is very limited, because most soil surveys have been conducted in valleys where agriculture activities first developed, but today are occupied by intensive fruit production (Fig. 2.42). The *serranías* sector, 800–1,000 m a.s.l., is interrupted by some plains of rolling topography and by some of those valleys with permanent watercourses (principally Copiapó, Elqui, Limarí, Choapa and Aconcagua) described above.

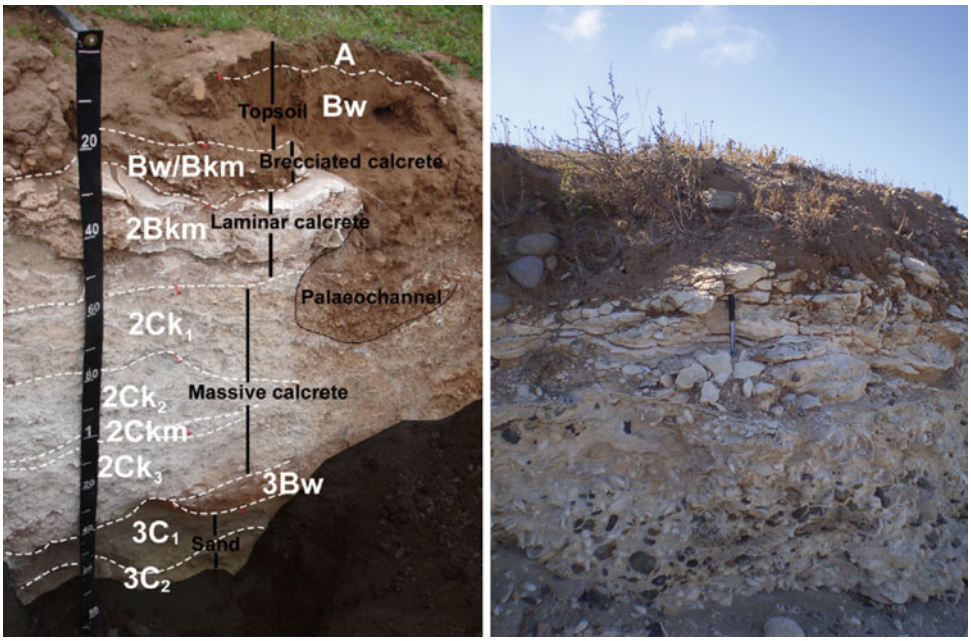

Fig. 2.40 Pedons on marine terraces at Tongoy paleobay (Pfeiffer et al. 2011; Aburto et al. 2008a), Region IV of Chile

Characteristic relief includes moderately hilly (8–15 %) and hilly (20–30 %) sectors, among which depressions are not enough to constitute valleys in a geographical-geomorphologic sense.

Residual soils from granite with diverse degrees of weathering are normally developed. Although it is common to find cambic horizons, few profiles develop argillic horizons and it is possible to observe soils derived from calcareous materials only locally (A–C_k profiles).

Granite-derived soils reach between 60 and 130 cm depth, depending on erosion process rates, which in these sectors are moderate to severe. Upper horizons present a variable textural class and varying gravel content, but clay content increases with depth, so clay loam or clayey B horizons have been described (Fig. 2.43). However, this clay content increase is associated with in situ transformation without illuviation processes. Most soils described in these situations present a cambic horizon (B_w), so the soil group has been classified as Haplocambids, and a pedon of the El Tambo soil series is considered representative.

More developed soils, classified within the Haplargid and Paleargid Great Groups, coexist with less developed soils. Piedmonts or alluvio-colluvial positions, with slope gradients from 2–5 % up to 8–15 %, and reaching between 50 and 90 cm in depth, rest over gravel to boulder substratum or granite weathered to different degrees. Illuviation features (cutans) and the presence of B_t horizons indicate advanced pedogenesis. Morphologically, these constitute a very homogeneous soil group, because they are fine- and very fine-textured, with strong and coarse blocks or prisms. The Combarbalá soil series is characterised here (see Appendix) as a representative pedon of this soil group. Figure 2.44 shows the landscape and soil profile of the Pintacura soil series, which also belongs to this soil group.

Another group of soils in this sector is those overlying calcareous materials (Fig. 2.45). Due to the absence of pedogenic studies, it is not possible to accurately define the processes that have occurred in these soils, and thus determine whether subsurface calcareous materials have served as parent material. These soils are observed at slope gradients that can reach 30 –50 %, particularly in places such as Vicuña (30°02′S) and Punitaqui (30°50′S). Very incipient soil profile development is observed and generally A–C (C_k) horizons have been described with only in few cases a B_w horizon. These Typic Haplocalcids have medium-textured profiles and are not suitable for agriculture. The Marquesa soil series is presented as an example of this soil group.

Southward of this wrinkled (*serranías*) landscape, morphological and geological features change abruptly at Santiago city (33°27′S). As the dipping of the subduction zone again reaches higher values, volcanism and forearc alluvial basins (the Chilean Central Longitudinal Valley) reappear and extend to latitude 41°28′S at Puerto Montt city, where the sea has entered into the Central Valley.

2.2.2 Soils of the Mediterranean Zone

During the Quaternary, the relief was defined in the current zone, disappearing the transverse valleys and defining the physiography in a north–south direction, from the Andes, the Longitudinal Central Valley, the Coastal Range and the Coastal Plains in an east–west direction.

Fig. 2.41 Sodicity features of the Huentelauquén pedon on marine terraces of Region IV

Fig. 2.42 *Serranías* in Region V (La Ligua, *left*) and Region IV (San Lorenzo, *right*)

The crestal elevation of the Andes and Coastal Range in this zone decreases significantly. The latter reveals a gradual elevation decrease from approximately 5,000 m at 33°S to only 2,000 m at 42°S. The materials brought from the mountains, either by ice, lahars or alluvial fans, were deposited mainly in the Central Valley, defining broad valleys where the current rivers flowed out and giving rise to the parent materials of soils. The geology of the Coastal Range south of 33°S is marked by abundant, primarily low-grade metamorphic rocks (especially from ~38°S to the south).

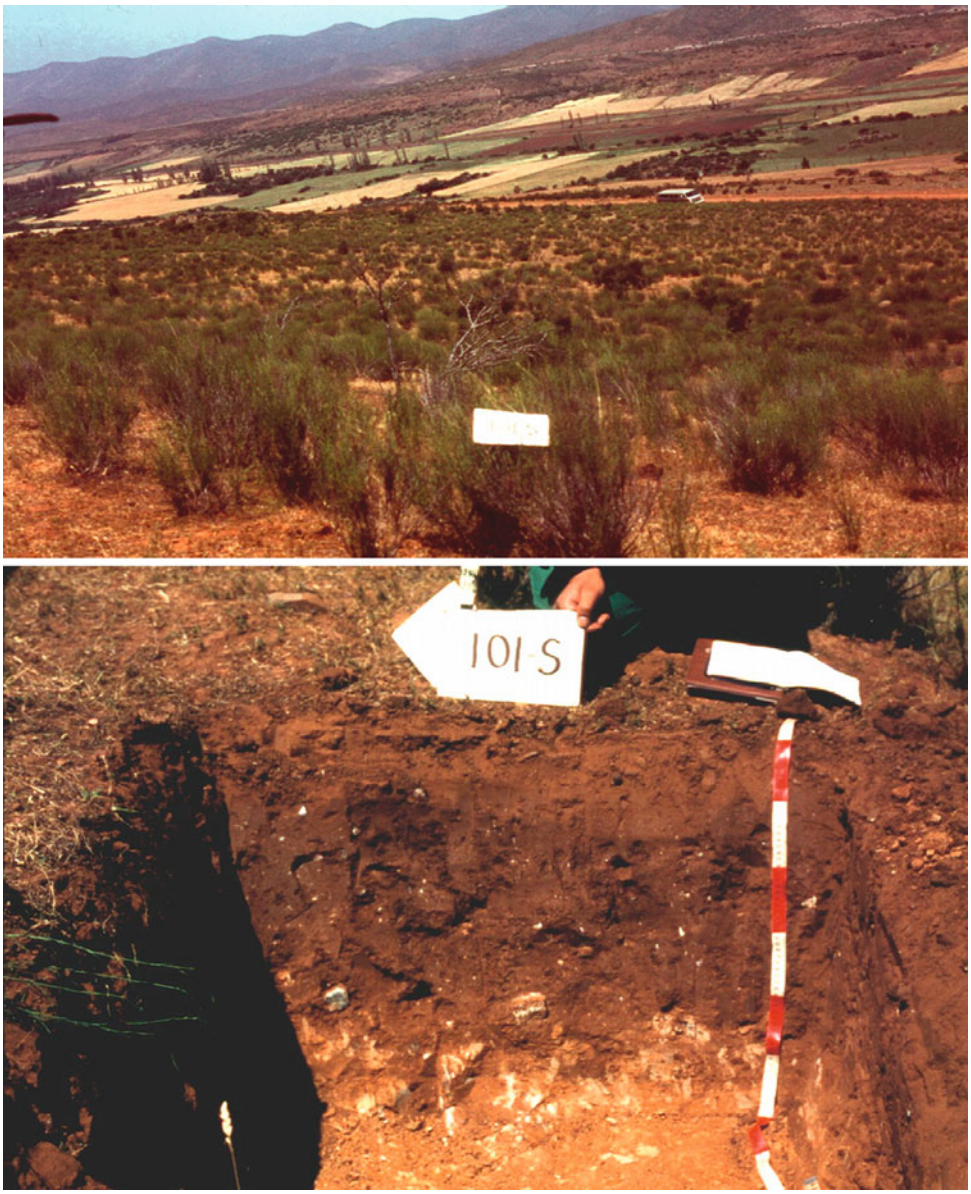

Fig. 2.43 Landscape and pedon of granite-derived soil in the inner *serranías* (Region IV). A B_w horizon developed without illuviation can be seen (Luzio et al. 2010)

2.2.2.1 Soils of the Andean Mountains

Geographically, this sector comprises an area bounded by an imaginary line from north to south, roughly along the 72° meridian. There are few references of these soils, usually due to low agricultural use and the limited accessibility of most sectors.

Non Volcanic Soils

North of parallel 36°S there have been no detailed soil surveys, but overall pedogenic processes have not been strong enough to give rise to soils with a clear differentiation of horizons. Coarse-textured skeletal soils with abundant angular stones and an andesitic and basaltic origin dominate. The best taxonomic approach to these soils is to consider them Entisols (Luzio et al. 2010).

The steep slopes (>30 %), the low vegetation cover (dominated by *Stipa* spp. and *Festuca* spp.) and the irregular regime of rainfall lead to these soils being considered to fall within VIII LCC.

Volcanic Soils

According to Moreno and Varela (1985) there was intense volcanic activity in the Andes of Chile during the Quaternary, with considerable volumes of materials ejected at the surface (Fig. 2.46). Much of the finer pyroclasts (volcanic ash and dust) were transported to Argentinian territory by the action of winds from the west (Bertrand and Fagel 2008). However, it is necessary to consider that this area has a large influence of easterly winds (locally called *Puelche*), which had the effect of depositing tephras in the valleys and

Fig. 2.44 The Pintacura soil series, a Typic Haplargid, in Region IV of Chile (Luzio et al. 2010)

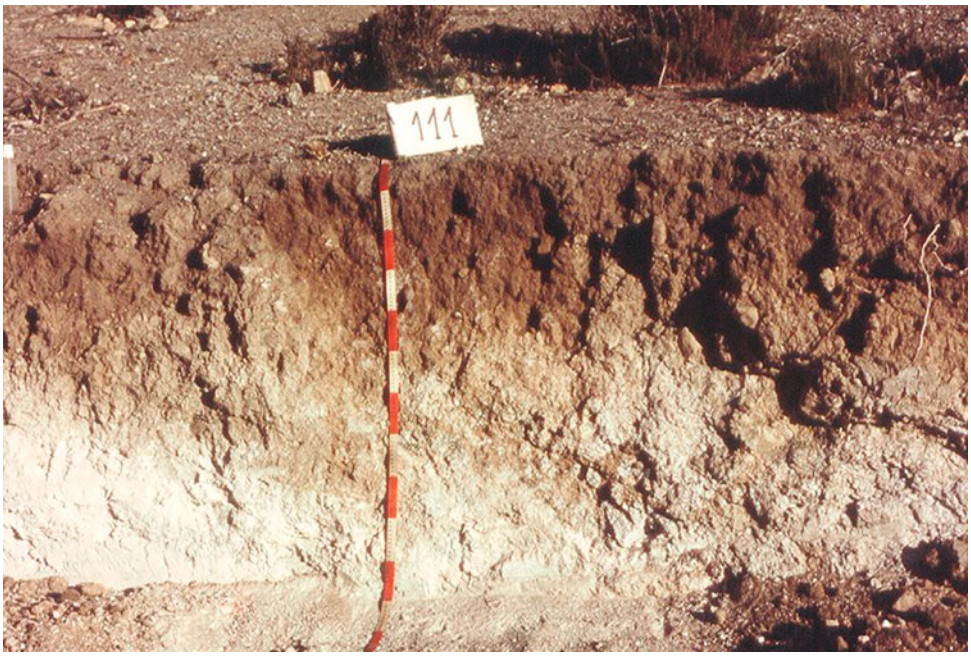

Fig. 2.45 Soil over limestone near Punitaqui, Region IV (Luzio et al. 2010)

flanks of the Chilean Andes, from where the deposits extended to the Central Valley in the south.

From, approximately, Chillán city to the south (37°S), between 600 and 1,400 m a.s.l., there is a dominance of soils derived from coarse and medium grain size tephras (pumice, cinder and fragmental material), with ages ranging between 600 and 14,000 years (Pino et al. 2004). These soils are deep and moderately deep, with textural class varying between coarse sandy loam and silty loam. At the surface the colour is often brown, of 10YR hue, and can reach a yellowish brown of 7.5YR hue at depth. Most of the soils have scoriaceous volcanic gravel as substrate and an abrupt boundary, with particle size varying between 2 and 6 cm in diameter. The slope is between 30 and 50 %. Permeability is moderate to fast and drainage is good to excessive.

Even though not all the soils derived from volcanic materials have evolved to Andisols, the 36°S parallel marks a natural limit beyond which rainfall has allowed this evolution. In southern parts of xeric-thermic and udic-mesic areas, the evolution of the volcanic material has been enough to qualify some of these soils as Andisols, with bulk density (Db) <0.9 Mg m^{-3}, P retention >85 % and $[Al_{ox} + ½\ Fe_{ox}] > 2$ %. The OC content is elevated at the surface, reaching values of 9.5 %, with a gradual decrease to approximately 2.3 % at 120 cm depth. In some soils, the effective cation exchange capacity (ECEC) is <2 $cmol_c$ kg^{-1}, indicating a low availability of exchangeable cations and a low amount of Al^{3+} (KCl).

The use of these soils is limited due to P retention and slope (20–30 %), even though the soil may be deep (Fig. 2.46). Their agricultural potential is limited by susceptibility to

Fig. 2.46 Sequence of paleo-soils in a deep and steeply sloping deposit of volcanic ash close to the Lanin volcano

erosion, being classified within IV, VI and VII LCC, predominantly suitable for forestry, especially native species. Areas with slope gradient >50 % are considered within VIII Class. Los Nevados soil association (Acrudoxic Hapludand), is considered representative of the soils in this area.

In udic-isomesic areas, it is possible to find a first group of soils (among 900–1,200 m a.s.l.) with steep relief and coarse particle size distribution, all belonging to cinder and pumice families, which are alternating layers of pumice and sand. Most of these soils, because of the steep slopes, are only suitable for forestry and present a dense cover of native forest.

A second group of soils, also in steep positions, are characterised by their marked thixotropy. The tephras have been deposited in discordance on basaltic rocks without weathering (Fig. 2.47). With a particular disruption, such as an earthquake, the soil behaves like a liquid, causing landslides that are facilitated by the steep slopes and the discordant contact with the underlying rock.

When landslides occur due to thixotropy, vegetation cover is not able to sustain the soil, which is considered extremely susceptible to erosion and classified in VII and VIII LCC. Los Riscos soil series (Acrudoxic Hydrudand) is representative of this group of soils.

A third group of soils in the udic-isomesic area of the Andes Mountain are Andisols without thixotropy. These are moderately deep to deep soils, some of them over pumice substrate with different degrees of weathering. All are well drained, with slopes varying from 15 to 30 %. Textural classes are medium and fine, but some soils show stratification with coarser materials, as a result of successive tephra deposition. They correspond to Hapludands, with ECEC <2 $cmol_c\ kg^{-1}$, which are identified into the Acrudoxic sub-group. The main limitation of these soils is the steep slope, so the LCC may vary between IV and VII.

2.2.2.2 Soils of the Pre-Andean Mountains

Like soils of the Andean Mountains, the soils in this sector can be classified as not volcanic and volcanic, the former predominantly Mollisols (36°S to the north) and the latter sufficiently developed to satisfy the central concept of Andisols.

Non Volcanic Soils

These correspond to soils situated on hills, piedmonts and alluvial-colluvial deposits with pedogenic development which allowed the formation of subsurface diagnostic horizons and mollic epipedons. Slopes vary from 2 to over 30 % (Fig. 2.48), with substrates constituted by andesitic and dioritic rocks and depths that can exceed 1 m. Textural classes are highly variable, and OC content can reach values of 3 % in the surface horizon.

The deeper soils located at low slope can be classified as I and II LCC, but those less than 50 cm deep and at slopes over 30 % are classified as VI and VII. Challay soil association is considered representative of this group of soils.

From 35°S, the soils are located in high terraces and undulating hills of the pre-Andean Mountains which derive from Holocenic volcanic ash. The slopes vary between 1 and 15 % and the soils are deep, loam to silty loam, with surface OC content close to 5 %, pH between 6.0 and 6.5 and BS < 50 %.

Recent studies (Stolpe et al. 2008) concluded that these soils have evolved to such a level that they cannot be considered Andisols, since the bulk density exceeds the boundary value of 0.9 $Mg\ m^{-3}$ and the mineralogy is dominated by halloysite, which is the result of loss of silicon in allophane (Tan 2000). Bramadero soil series (Andic Haploxeroll) is characteristic of this group of soils, originally classified as Humic Haploxerand by CIREN (1997b).

Soil physical properties and the well-drained conditions give these soils a high productive capacity that is only limited by the slope, with LCC between I and III. In some cases (udic-isomesic zone), it is possible to identify a group of soils located between 300 and 900 m a.s.l. with weak

Fig. 2.47 Lithic contact between soil and basaltic rock in an abrupt limit (*left*). Landslide processes favoured by steep relief and thixotropic behaviour (*right*)

profile development, moderately deep, in hill positions and with slopes that vary from 15 to 50 %. These soils are derived from volcanic ash with varying grain size, which were deposited on coarse sand and cinder sediments, mostly of basaltic origin. Although the parent material is volcanic, these soils have not developed andic properties in their fullness.

Because of the coarse grain size dominance, the position in the Andes Mountains and the steep slopes, it can be assumed that the absence of andic properties results from lack of evolution of the original tephra to short-range order minerals (MORC), being classified as Andic Dystrudepts and within VI and VII LCC. Choshuenco soil series (Andic Dystrudept) represent this group of soils.

Volcanic Soils

Closer to the Central Valley, but always within the concept of pre-Andean Mountains, these soils reach the Andisol central concept, being classified as Haploxerands and Hapludands in the southern part of the xeric-thermic zone and the udic-mesic zone, and as Fulvudands in the udic-isomesic zone. They are deep and moderately deep soils located on alluvial terraces as a result of the alluvial re-transport of volcanic ash, on fluvio-glacial remnant terraces or on compacted and cemented volcanic conglomerates.

The soils located on alluvial terraces present a substrate of gravel and usually rounded and subrounded stones at depths of around 100 cm, with a soil matrix that can range from sandy to clay loam. When the slope gradient is <3 %, the soil may have a moderate to imperfect drainage class, even when it has moderately rapid permeability. Slightly undulating (2–5 % slope) soil phases generally have good drainage.

In the case of soils classified as Haploxerands, the OC content ranges between 3.6 and 7.7 % at the surface and 0.7 % at 100 cm depth, but is very variable through stratification. In the case of Hapludands, the OC content is high (>5.5 %) in the surface horizon and decreases regularly with depth, except for those soils with buried soil below 50 cm depth, where the OC content increases again. Other soils may have higher OC content in the surface horizons (10–14 %), where a melanic or similar epipedon is dominant.

The pH is in the range from weakly acidic to strongly acidic, ECEC remains between 3 and 10 $cmol_c\ kg^{-1}$ and Al saturation is <5 % for most soils in the sector. The water content retained at 33 kPa is maintained above 50 % for all horizons of most soils and, in some cases, can reach 80 %, which is consistent with andic properties.

Soils located closer to the Central Valley have the best productive potential, mainly because of more appropriate topographic position, for example alluvial terraces, remnant terraces or fluvio-glacial deposits with low slope gradient. It is possible to find soils in II and III LCC, with 1–3 % slope, such as the Cunco soil series (Acrudoxic Hapludand), representative of the soils in this area.

Fulvudands are characterised by their very dark brown to black colour (Munsell chroma <2) in deep deposits, which can be up to 2 m in depth above the substrate. These soils are formed from the weathering of fine tephras deposited on flat lacustrine conditions or alluvial fans, with gravelly and rounded stony substrate. The upper horizon has OC content >6 % and textural class ranges from loam to silty loam and silty clay loam, with well-developed structure and excellent radical penetration. Despite the typical constraints of the Andisols and BS usually <10 %, they are very productive soils with good agricultural potential and can have II LCC. Their main constraints are the imperfect drainage and the slope, making them slightly to moderately undulating.

A special case of volcanic soils are those derived from volcanic sands on alluvial positions in the pre-Andean Mountains of Region VIII, which have a fine fraction that

Fig. 2.48 General view of landscape in the pre-Andean Mountains at Santiago and soil profiles of the Challay soil association (Lithic Haploxeroll, *left*) and the Santa Sara soil series (Haplic Palexeroll, *right*), after Valle (2012)

has andic properties. These soils are slightly deeper, up to 75 cm, resting on a substrate of sand and gravel of volcanic origin. Textural class ranges from sandy loam to silty loam, but the substrate is always sandy and structureless. The pH is maintained close to 6.0 and BS is <40 %. See in Appendix, the properties of the Antuco soil series (Humic Vitrixerand).

The soils are well drained, but of limited agricultural suitability, ranging between IV and VII LCC depending on depth, gravel content and textural class.

2.2.2.3 Soils of the Longitudinal Central Valley

Geographically, this valley covers a large area located between the western flank of the Andes Mountains and the eastern flank of the Coastal Range, ranging between 50 and 100 km. However, these limits are somewhat fuzzy, due to the intervention of landscape-altering agents such as alluvial sediments, aeolian volcanic ash, alluvial lahar flows and some glacial sediment all of which generated deposits of up to 500 m thick (Araneda et al. 2000). The Central Valley is crossed by numerous water courses in an east–west direction, which is of great agricultural importance and has resulted in intense productive activity.

In this whole area, between 50 and 400 m a.s.l., there are differences in topography, ranging from alluvial terraces with flat or nearly flat surfaces to rolling hills with up to 15–20 % slope gradient. This variability gives rise to a wide range of soils with different characteristics, although most soil surveys have established that there is a predominance of soils derived from Holocene and Pleistocene tephra, so most of the soils would have volcanic sediments originating from different geological times.

Soils are associated here into six groups, according to their soil moisture and temperature regimes, considering morphological properties, geomorphic features and pedogenic development. The first group, in the xeric–thermic zone, includes soils with BS > 50 % throughout the soil profile and dark-coloured epipedons, mostly classified as Mollisols, and in few cases as Inceptisols or Vertisols. A second soil group is of higher age (Pleistocene) and more profile development, showing an illuviation horizon (B_t). A third soil group has BS < 50 % and less evolution, although it is possible to distinguish a B horizon with no evidence of translocation of components (B or B_w). The fourth group is represented by Holocene volcanic soils with umbric or melanic epipedons, which correspond to the typical Andisols and are locally called *trumaos*. The fifth group includes poorly drained Andisols in an aquic soil moisture regime, locally called *ñadis*. The last group, concentrated in Region VIII and also found in alluvial terraces of the Coastal Range, is a group of holocenic sandy soils of volcanic origin, locally called *arenales*.

Soils with High Base Saturation

This group includes a large number of soils with variations in origin, parent material and transport agent, but the common feature is their intense productive activity. The soils are in positions of alluvial terraces, piedmonts and lacustrine sedimentation basins. The landscape is flat to nearly flat, with slopes ranging from 1 to 5 %. The depth and texture class are very variable, but in the case of alluvial soils the substrate is typically rounded stones (Fig. 2.49). Base saturation is greater than 65 %, with some exceptions; the pH varies between 6.8 and 8.2 in the Maipo river basin, due to the contributions of carbonate in irrigation water, but decreases towards the south to between 5.6 and 7.6. See in Appendix the main properties of a profile of the Maipo soil series (Fluventic Haploxeroll).

Most of these soils have good permeability and good drainage, which determines their inclusion in LCC between I and IV, depending on the depth to the rocky substrate. While most of them are Mollisols (Haploxerolls), some cases are classified as Inceptisols (Haploxerept).

Fig. 2.49 The Central Valley of the Mediterranean zone is the main base for agricultural production. Walnut trees on Maipo soil series (Fluventic Haploxeroll)

Another soil group with high BS values originates from lacustrine sediments. The Metropolitan Region (33°S) defines the limit for soils with presence of pedogenic carbonate and high EC values reaching 18 dS m^{-1} (Fig. 2.50). Dominant slopes are in the range 1–3 %, the soil is fine-textured and the depth is limited by a cohesive dense horizon (by clay or cemented by carbonates) or a permanent watertable, the latter imparting black colour in surface horizons and grey colour at depth.

The OC content ranges between 1 and 8 % in the surface horizon and decreases regularly with depth, while depending on carbonates and salinity, the pH ranges between 7.0 and 9.3 around Santiago city and between 5.3 and 7.9 to the south, increasing with depth. The drainage conditions determine II–VI LCC for these soils, but with artificial drainage the soils improve their productive potential. Agua del Gato soil series (Petrocalcic Calciaquoll) is representative of this group.

A special group of soils with high BS are those derived from volcanic materials, but as a consequence of the climate conditions (xeric-thermic soil regime, mainly from Chillán city to the north) did not form Andisols. They are located in flat positions within the landscape or sloping up from 15 to 20 %, depending on transport agent. The soils have a variable depth, usually resting on a cemented or consolidated material. Base saturation increases with depth, the pH ranges between 5.2 and 7.9 and the OC in the surface horizon ranges between 0.6 and 3.5 %. Quillayes soil series (Aquic Haploxerept) is representative of this group.

Because the substrate is cemented or consolidated, drainage restrictions are normal, so it is possible to find common to abundant redoximorphic features. Thus LCC ranges from II to VI, depending on depth and drainage.

In the Central Valley from the udic-mesic zone to the south, it is possible to find a group of soils characterised by high BS. These are classified as Mollisols but with a low areal representation. This soil group includes deep pedons, medium and fine-textured, located in alluvial terraces and flat deposits of fluvio-glacial origin, with topography ranging from flat to gently undulating. The dominant colours are in the 10YR hue, with low chroma value (Munsell), i.e. dark brown, dark greyish brown and black in some cases. The OC content is not particularly high, as would be expected, and in some soils is even close to the lower limit for the presence of a mollic epipedon. The BS is over 50 % across all profiles and the CEC varies from 12 to 27 $cmol_c$ kg^{-1}, which is an important factor in concluding that the soil mineralogy is mixed, with dominance of 1:1 clay minerals. Only a few pedons (Santa Rosario soil series) contain evidence of Holocene volcanic ash inputs, because P retention reaches 78 % and bulk density is less than 1 Mg m^{-3} in the epipedon and about 1 Mg m^{-3} in the whole profile. In general, these soils have good productive potential, with II and III LCC dominating, although some soil phases show low potential due to a watertable close to the surface, excessive slopes and erosion risks.

Soils with Argillic Horizons

These soils are located in hillocks with slopes from 2–5 % to 20–30 % and are moderately deep to deep and medium to fine-textured. There are two dominant soils, those located closer to the Andes Mountains in fluvio-glacial sediments, and those located close to the Coastal Range. The former dominate between 34 and 36°S, approximately, with a highly variable BS (38–83 %), pH between 5.0 and 6.6 and OC values close to 2.2 %. At contact with the fluvio-glacial substrate, soil redoximorphic features are common, classified from II to IV LCC, but with good potential for crops (Fig. 2.51). Talca soil series, a Pachic Palexeroll (Stolpe et al. 2008), represent this soil group.

Close to the Coastal Range, these soils are deep and moderately deep (Fig. 2.52), resting over fluvio-glacial conglomerates, are variable and partially weathered from andesitic-basaltic material or volcanic breccias. Located at

Fig. 2.50 A drained Petrocalcic Calciaquoll (Agua del Gato soil series, *above*) with Ckm horizon and *gley colour* persisting at depth. A Sodic Haploxerert (Batuco soil series, *below*)

positions on hillocks with gentle to moderate undulating topography, with slopes predominantly 8–15 % but 20–30 % in some soil phases. Although slowly permeable, the soils are well-drained and only few soil phases in concave positions may have imperfect drainage. The upper horizons are clay loam or silty clay loam, whereas the subsoil (B horizon) is always clayey; i.e. there is a clear increase in the fine fraction with depth, so that the clay content of B horizons varies between 40 and 65 %. The strong erosion that these soils have suffered because of inappropriate farming on slopes has led to most of the profiles being currently described are incomplete because of the beheading of the surface horizons (Fig. 2.52).

Another feature that distinguishes this soil group is the colour of the horizons, ranging from the hues 2.5 and 5YR, from dark reddish brown to dark red. The clay content and the colours are the reason why these soils are known as *Red Clayey Soils* (*Suelos Rojo Arcillosos*).

Weakly to strongly acidic (6.2 and 5.3) soil pH is observed, with low Al saturation in the exchange complex. At the same time, BS varies between 31 and 65 % through the profile. The highest BS values found in deeper horizons allow these soils to be classified as Alfisols. The CEC is variable among pedons and horizons within the same profile (13–31 $cmol_c\ kg^{-1}$), which may be associated with the original stratification of parent materials, in addition to the translocation of components to which the soils have been subjected.

South of Temuco city (39°S) the andic properties begin to appear, which could be considered evidence that these soils originated from old volcanic ash deposits (Besoaín 1958). The bulk density is usually slightly higher than 1 $Mg\ m^{-3}$ but in some horizons may be less than that, P retention is over 50 % in all soils and can reach 66 % in some horizons, and $[Al_{ox} + ½\ Fe_{ox}]$ is always less than 1 %, but close to this value. According to these data, it seems logical to deduce that the original amorphous materials have evolved into some form of crystalline minerals (Besoaín and González 1978) and that it is still possible to find some features that identify them. The productivity of these soils is largely associated with the topography and the current and potential soil erodibility. Slightly undulating soil phases (slope 2–5 %) are classified as III and IV LCC and show slight

Fig. 2.51 General view of the Mariposa soil series (Ochreptic Haploxeralf) and redoximorphic features of the fluvio-glacial deposit

erosion, but phases with 15–20 % slope gradients show severe sheet erosion and frequent gullies, being included on VII LCC and destined for permanent grassland or forest, excluding tillage crops. Representative soils of this group are Collipulli (Typic Rhodoxeralf), Mininco (Typic Rhodudalfs) and Metrenco (Typic Paleudults) soil series.

Soils with Cambic Horizon

There are soils with different origins and positions in the landscape, but that share the common feature of development of a cambic horizon. One group corresponds to deep and moderately deep soils on alluvial terraces, with 1–3 % slope and well drained. Another important group corresponds to thin soils over a duripan formed by volcanic breccias, conglomerates or gravels with varying degrees of weathering, that inhibit rooting. Finally, there are also soils on hillocks and hills with slopes greater than 30 %.

The soils, deep and moderately deep developed on alluvial terraces, have moderately fine to fine textures, silty loam and silty clay loam in the surface horizon, clay loam and clayey in the B horizon. The colours are in the hues 7.5 and 10YR, with low chroma values (Munsell). The normal sequence of horizons for these soils is an umbric epipedon over a cambic horizon with BS < 50 % throughout the profile. In some cases, there may be a duripan under 100 cm. In some soil phases, the redoximorphic features are abundant, showing current conditions of poor and imperfect drainage. These restricted drainage conditions determine that these soils are classified as III and IV LCC.

Fig. 2.52 Eroded (*left*) and non-eroded (*right*) Collipulli soil series (Typic Rhodoxeralf) in Region VIII of Chile

Soil bulk density is over 1.0 Mg m^{-3} in all horizons and all soils, although occasionally some horizon can have a value of 0.9 Mg $m^{-3.}$ The retention of *P* may be unusually high (80 %) for this type of soil, thus indicating some source or contamination with volcanic material. The OC content reaches 4.7 % in the epipedon, decreasing regularly with depth, and soil pH is maintained in the range of weakly acidic throughout the profile. The CEC is very variable from one soil to another and from one horizon to another within the same profile (13–34 $cmol_c$ kg^{-1}). Nueva Imperial soil series (Typic Humaquept) is representative of these soils.

The slightly deep and thin soils are restricted by a duripan at depth, cemented by silica and manganese, always in abrupt boundary with the overlying soil. The boundary layer has been described as lying between 50 and 60 cm depth, restricting the possibilities for use, even though the other properties remain more or less similar. The dominant textural classes are silty loam, clay loam and clayey, with a slight increase in the clay fraction to the subsurface horizons. All these soils occupy alluvial terraces in flat or nearly flat topography, with some phases poorly drained in more depressed positions. They are classified as III and IV LCC.

The soils located on hills with 30–50 % slope are deep, formed from ancient volcanic ash deposited in the Central Valley between 300 and 400 m a.s.l. These soils have a high clay content (40–55 %) with amounts increasing towards the B horizons, are reddish brown and dark reddish brown (5 and 2.5YR), well structured and can rest on a conglomerate very weathered under 120 cm depth. Their origin from ancient tephra is related to some properties associated with andic properties of Holocene volcanic soils, i.e. Db < 1.0 Mg m^{-3} and P retention 60 %, values too high to ignore a possible influence of volcanic deposits. Because of their topography on hillocks and hills and their suitability for forest, these soils are classified within VI and VII LCC.

From the udic-mesic regime zone to the south, it is possible to distinguish two kinds of Andisols through their position in the landscape. These are locally called trumao and ñadi and correspond to the deep and well-drained Hapludands (trumao) in softly-steeply higher positions of landscapes and the moderate to slightly deep and poorly drained Placaquands (ñadi) in flat and depressed positions in the landscape (Fig. 2.53), commonly associated with outwash from glaciers.

Typical Andisols (*Trumaos*)

In the Central Valley from Chillán city to the south, soils derived from Holocene volcanic ashes are widely represented and satisfy all requirements to be considered Andisols. As deep and moderately deep soils, they have no restrictions on rooting in most soil series and their respective soil phases. Located in recent or older remnant alluvial terraces, where the original volcanic ash has been redeposited by water, the substrate of most of these soils is composed of rounded gravel with interstitial sand. In some soils, the substrate can be less than 1 m depth, without limitations to root penetration (Fig. 2.54).

Dominant textural classes are silty loam in the surface and silty clay loam or clay loam in the deeper horizons. The most common colours are hues 7.5 and 10YR, and only in rare cases are there reddish brown and red soils (2.5 and 5YR). The OC content varies between 3 and 11 % in the epipedon, with a gradual decrease with depth, but is not less than 1 % even at 120 cm depth. In soils that have a marked alluvial influence, the OC has an irregular decrease, clearly marking the stratification of materials. The BS is particularly low, <25 % in all soils, reaching 2 % in some horizons, as in the Toltén soil series.

Except for the restriction common to all these soils (high *P* retention), they are very suitable for agriculture, with most soil phases classified into II and III LCC due to slight limitations on drainage in the lowest sectors of the relief. See properties of the Toltén soil series (Acrudoxic Hapludand) in Appendix.

A second group of Andisols includes deep soils, dark brown and black coloured, with a high content of OC throughout the profile (Fig. 2.55), with values between 8 and 6 % to 60 cm, and in some soils, 3 % at 140 cm depth. They commonly contain an umbric epipedon, a melanic epipedon or a horizon that meets the requirements of the melanic epipedon, except for the chroma value (Munsell). The water content can vary from 64 to 80 % at 33 kPa and 38 to 61 % at 1,500 kPa. The CEC can reach values of 57 cmol kg^{-1}, indicating dominance of short-range-order minerals. Like all the soils of this sector, BS remains under 17 % and in some horizons may reach values as low as 2 %.

These soils have good potential from the agricultural point of view and most have been classified as II and III LCC, with only a few soil phases included within IV and VI LCC, mainly due to the increase in slope or drainage restrictions (Osorno and Paillaco soil series, respectively). Corte Alto soil series (Typic Hapludand) is a very deep and stratified Andisol, which occupies remnant terraces and slightly steep positions, with very well-expressed andic properties.

Aquic Andisols (*Ñadis*)

In addition to their andic properties, these soils share the common feature of restricted drainage that in some stages can reach very poor conditions. This constraint is created both by the topography and soil morphological features. Generally, they occupy flat and depressed positions in the landscape (Fig. 2.53) and a fluvio-glacial deposit consisting of gravel and sand has been described as the substrate.

Above this deposit, a duripan and/or a placic horizon (locally named *fierrillo*) is present which prevents the passage of water and plant roots (Luzio et al. 1989). The

Fig. 2.53 In the foreground, a *trumao* and in the low relief, a *ñadi*, volcanic ash-derived soil developed over a glacial substrate with drainage restrictions creating a Bhsm horizon (*red arrow*). *Ñadi* soils can be moderately deep, e.g. the Frutillar soil series (Typic Placaquand, *above*) or thin, e.g. the Alerce soil series (Histic Placaquand, *below*)

Fig. 2.54 Loncoche soil series (Acrudoxic Hapludand) with natural prairie and detail of soil profile

fierrillo is very thick (<2 cm), extremely strong and cemented with Fe and Al, with mixed black (N 2/0) and yellowish red (5YR 5/8) colours. This diagnostic horizon is moderate to strongly acid, with an OC content too high for this type of horizon. Palma (1993) reported OC contents from 1.1 to 5.6 % and found that Fe is the most abundant element in the fierrillo, particularly Fe extracted with oxalate. Al is present too, but to a lesser extent, so Palma (1993) concluded that Fe is an essential element in cementing these horizons.

The depth of these soils is very variable depending on the position of the fierrillo within the profile and they range from very thin to deep soils. The dominant slopes range from nearly flat (1–3 %) to slightly undulating (2–5 %), so surface runoff is slow. In some soils, the watertable can be found near the surface in winter and drops below 1 m in summer, but other soils remain saturated throughout the year. These characteristics are maintained in the soils of Chiloé Archipelago, in particular, and have a wide distribution in the core of the Big Island of Chiloé.

The topsoil is usually an O horizon, consisting of a bed of *Sphagnum* sp., roots and leaves, and depending on its thickness can be a histic epipedon. The most frequent colour is black, from 5 and 10YR. At depth, there is always good development of the profile which implies the presence of a cambic horizon. In field descriptions, it is possible to note an increase in the clay fraction with depth, as the textural class ranges from loam or silty clay loam at the surface to silty clay loam or even clay loam in the B horizon.

In general terms, these soils have potential use for pasture and in most cases there is a dominance of imperfect to very poor drainage. However, some soil phases (Frutillar soil series) are moderately well drained and classified as IIw LCC. All soils are considered Duraquands, Endoaquands or

Fig. 2.55 The Puerto Octay soil series, a Typic Hapludand on morrenic deposits at Llanquihue Lake, and detail of the soil profile

Placaquands. Maullín soil series (Hydric Endoaquand), is an example of this soil group.

Holocene Sandy Soils (*Arenales*)

A special soil group corresponds to those derived from volcanic sands deposited in alluvial fans and terraces of the Laja River (Region VIII), corresponding to basaltic-andesitic materials, coarse textured, stratified and developed in a xeric-thermic regime (Mella and Khüne 1985). Moreover, some of these materials have been mobilised to the valleys of the Coastal Range and deposited in alluvial terraces (Fig. 2.56).

The main geomorphologic positions in which these soils are disposed correspond to alluvial fans, terraces and flat fluvio-glacial deposits. The substrate may be gravel and rocks with a sandy matrix, located deeper than 160 cm. Textural classes are particularly homogeneous, ranging from sandy loam to sandy, as in the Coreo and Arenales soil series.

In general, the soils are deep and very deep (150–160 cm depth) with elevated permeability, but through topographical position they may contain drainage restrictions. The root system is well developed, so roots are reported even up to 160 cm depth.

In the Arenales and Coreo soil series, the OC content is 1.0 and 1.8 %, respectively, and BS increases with depth (from 20 to 85 % in some soils). The pH remains uniform in all soils, with values between 5.4 and 6.7. The LCC varies between IV and VI, mainly as a consequence of the coarse soil texture. Arenales soil series (Dystric Xeropsamment) is considered representative of this group.

2.2.2.4 Soils of the Coastal Range

The delimitation of this sector is based on geological and geomorphologic features, which means the Coastal Range, rising gradually in some sectors and more sharply in others west of the Central Valley, until it reaches 800 m a.s.l. Two main parent materials are recognised, which together with the climate determine the properties of these soils. There is a continuity of the northern Coastal Range to the Mediterranean zone, with igneous (granitic) materials, but about from 37°45′S to the south metamorphic rock begins to appear.

Igneous Parent Materials

Angular gravels, especially of quartz, have been described on all these soils with a dominant hilly topography, with slope gradients from 8–15 % up to >50 % (Fig. 2.57), although some alluvial fans and piedmonts can have lower slopes. The dominant textural classes are medium to fine, but at depth the sand content increases through the presence of quartz. As a result of geomorphic position, all soils are well drained.

The chemical and biological properties correspond to a climate gradient from 33 to 37°S, thus BS ranges from 65 to 95 %, the pH is slightly acid (between 6.0 and 6.6) and OC content can reach 1.5 % in the upper soil horizons at 33°S. However, in soils from 37°S to the south, pH can decrease to 5.0, BS can be lower than 50 % and OC can reach values of 3.0 % in upper soil horizons. The most important constraint is given by the position of hills and steep slopes, so that soils are between IV and VII LCC. Lo Vásquez soil series represent clearly this important group of soils.

Metamorphic Parent Materials

South of 37°45′S, on the eastern side of the Coastal Range, between 250 and 300 m a.s.l., deep soils are developed from volcanic ash deposited on a metamorphic complex.

The most evolved pedogenic soils have developed from metamorphic rocks of the Coastal Range, in hillock and hill positions. Some of them (Correltúe and Araucano soil series) are considered to be derived from old volcanic ash deposits. In the case of the Nahuelbuta (Rhodic Palehudult) soil association, its origin would be directly in the

Fig. 2.56 The Quillón soil series, a Dystric Xerorthent derived from Holocene volcanic sands in alluvial deposits of Region VIII (*left*). From Concepción city to the south, the parent material of the Coastal Range begins to change from igneous (*right* Cauquenes soil association, an Ultic Palexeralf) to metamorphic rock

weathering of metamorphic rocks such as phyllites and mica schists. One characteristic of these soils is that they occupy relief that goes from softly to strongly undulating hills (Fig. 2.58). Andic properties for several of these soils are very close to the limit to be considered Andisols and therefore the influence of volcanic materials in their evolution is undeniable. An example of these soils is Correltúe soil series (Andic Haplohumult), described as resting on mica-schist at 130 cm depth.

Soils derived from metamorphic rock, where no influence of holocenic tephras is detectable, are deep and B_t horizons can reach 150 cm, with dominating fine textural classes (silty clay loam to clay). Although eluviation horizons morphologically are not obvious, either by colour or textural class (very homogeneous), the soils are well evolved because of the presence of argillic horizons. The clay fraction varies between 35 and 73 % in the B_t horizons and soil structure is generally strong, varying from medium and coarse subangular blocks to coarse prisms. The dominant colour varies from dark reddish brown to dark red, in the hues 2.5 and 5YR. Only the high OC content of some surface horizons imparts a brown colour in the hue 10YR.

The CEC, although it is highly variable among soils (14–36 $cmol_c\ kg^{-1}$), shows a decrease with depth, following a trend similar to OC content. In the same way, the BS may vary considerably from one soil to another, but is always <40 %. Only some soil phases with low slope (2–5 % and 5–8 %) are suitable for agriculture, particularly grasslands and cereals, but the best use of these soils is forestry, with VII and VIII LCC.

A second group of soils, located in the areas of flat topography between the metamorphic massifs of the Coastal Range, has been described. These soils have intermediate pedogenic development with a cambic horizon (B_w), mostly occupying recent or remnant alluvial terraces. Materials of these terraces come largely from sediments that have been transported from the highest parts of the relief due to the severe erosion affecting these sectors. Therefore, the soils are rich in mica and quartz minerals from the weathering of metamorphic rocks (Fig. 2.59).

These soils are deep and fine-textured, generally clay loam to clay (27–50 % clay). The dominant colour is dark reddish brown, in 2.5 and 5YR hues, inherited from parent materials. The flat or nearly flat soils (1–3 % slope) have moderately slow permeability and imperfect drainage; the deeper horizons (100 cm) have abundant redoximorphic features (concretions of Fe and Mn and grey colours in 2.5 Y hue).

The OC content is low, not exceeding 2.3 % in the surface horizons, and decreases with depth to 0.1 %. Base saturation remains under 30 % in all horizons and CEC does not exceed 17 $cmol_c\ kg^{-1}$, indicating an abundance of kandites. Soils in depressed positions have imperfect drainage, with concretions and nodules of Fe and Mn occurring in the horizons below 85 cm depth and imparting an olive brown colour in the hue 2.5 Y. Soils are classified according to the imperfect drainage (IIIw LCC) and excessive slopes, as in the case of soils located in colluvial or piedmonts (IVe and VI LCC). Los Copihues soil series (Oxiaquic Dystrudept) is considered representative of this group.

From Valdivia city (~40°S) to the end of the udic-isomesic zone, metamorphic rock is the dominant parent material, determining the existence of Inceptisols with andic properties. In soils that have been described in this formation, it has been shown that the rocks are more weathered, and therefore, have less recognisable petrographic structure. Soil substrate consists of gravel deposits of multicoloured gravels, rounded and subrounded, with different degrees of weathering, very weathered tuff and/or metamorphic phyllites and mica schists, generally very weathered. The depth of the soil is determined by erosion occurrence, giving slight to moderately deep soils (Fig. 2.60).

Complex slopes dominate (20–50 % slope gradient) and only some soil phases show 8–15 % slopes, with moderate

Fig. 2.57 The Lo Vásquez soil series (Ultic Haploxeralf) in a steeply sloping position (*above*). The La Lajuela soil association (Ultic Haploxeralf) with productive activity on the low position of the alluvio-colluvial deposits (*below*). Despite the great depth of weathering of granite, soil depth depends on the degree of erosion to which the soil has been submitted

Fig. 2.58 Landscape of the Correltúe soil series (Andic Haplohumult) and the respective profile

to severe erosion, so they have been assigned to VI and VII LCC, i.e. suitable for forestry. Some sectors (5–15 % slopes) have a better aptitude and are used with annual crops, being classified within II, III and IV LCC. Hueñi soil series (Andic Dystrudept) is very representative of these soils.

2.2.2.5 Soils of the Coastal Plains

This group includes a wide variety of soils not deeply studied, developed on marine terraces, gentle rolling hills, stabilised dunes and remnant terraces, both alluvial and marine (Fig. 2.61). The position in the landscape determines that the slopes are less than those of the Coastal

Fig. 2.59 General view of soil distribution in the Coastal Range of Region IX and detailed profiles of the Los Copihues (*left* Oxiaquic Dystrudept) and Lumaco (*right* Oxic Dystrudept) soil series

Fig. 2.60 General view of a deforested landscape of the La Pelada soil series (Oxic Dystrudepts) and detail of soil profile resting on a weathered fluvio-glacial deposit

Range (>15 %) and the gradient of chemical properties influenced by climate persists as in the case of Coastal Range soils.

The most common substrate is sandstone, often mixed with gravel of mixed composition. Coarse-textured upper horizons are without a definite trend in depth, varying from sandy to clay, but more or less homogeneous in each soil. The depth to the substrate is variable (50–120 cm) and drainage is good to imperfect. As expected, there is a gradient of chemical properties from north to south, with BS between 60 and 90 % in the north and 20–70 % in the south, pH values decreasing from 5.6 to 7.8 in the north down to 4.6–6.5 in the south, and OC content ranging from 1.5 to 3.4 % in the same climate gradient. Matanzas soil association (Oxic Haplustoll) developed from limonite in a marine terrace position, is a good example of these soils.

Although soil analyses and taxonomic classification require updating, in general these soils belong to the orders Alfisols, Mollisols and Inceptisols. Aqueveque (2008) indicates that soils derived from Holocene dunes correspond to Ustipsamments. On the other hand, LCC varies from III to VI, depending on drainage conditions and depth.

2.2.3 Soils of the Rainy and Patagonian Zone

Most of northern Rainy and Patagonian zone has a climate that does not strictly respond to latitude, because of the topographical effects of the Andes Mountains, and then precipitation diminishes towards the Atlantic Ocean. However, in the southern part of this zone the precipitation trend follows latitudinal bands, again diminishing from south to north. This zone includes Region XI (Aysén) and Region XII (Magallanes), where the geomorphology is dominated by overlapped volcanic and glacial processes, which make it complicated to interpret the distribution of soils. Fluvio-glacial deposits have greater representation in the northern sector of Region XI due to the less steep topography of the area, probably by intense glacier activity, leaving large areas of sediments of different natures. In the southern sector of Region XI, it is difficult to distinguish these fluvio-glacial deposits, due to more steep topography and active fluvial erosion processes determined by narrow river valleys.

In the Province of Palena (43°S), glacial valleys are filled with different kinds of materials such as moraines or alluvial deposits. Above them, volcanic materials from the Michimahuida, Apagado, Hornopirén and Chaitén

Fig. 2.61 Soils developed on the coastal plains have an origin that may be alluvial, marine or aeolian, which result in large soil variability, but similar chemical properties (Photo: Aqueveque C)

volcanoes were deposited, which would be the starting materials for most soils of the area (Ahumada et al. 2004).

Díaz et al. (1959–1960) show that during the Lower Cretaceous, the sea invaded the continent gradually, from about 43°S to the south, which resulted in the formation of marine sandstones. Later, during the Tertiary, great volcanic activity began and was responsible for the formation of Paine and Balmaceda clumps. At the end of the Tertiary, there was a new period of volcanic activity that deposited ash, lava and pumice on extensive areas, which were then redistributed by watercourses. During the Quaternary the area was covered by ice which was responsible for major erosive activity and the formation of various channels, lakes and bays. This glacial activity also left a complex system of moraines that act as dams, giving rise to large glacial lakes with varved sediments on the banks of the Strait of Magellan (53°S). At the end of the last glacial period, there was activation of extrusive volcanism, resulting in extensive deposits of basaltic lava and ash.

In the area of Puerto Edén (49°S), Calderón et al. (2007) describe a sequence of schists, gneisses, migmatites and granitoids, biotite and biotite–hornblende granitoid derived from Puerto Edén Igneous and Metamorphic Complex, belonging to the South Patagonian batholith. The authors attribute these formations to the Late Jurassic.

In Magallanes in Region XII (*Tierra del Fuego*), in particular the east sub-Andean foothills, Gerding and Thiers (2002) describe a flat-shaped area with mountain ranges of low altitude, whose peaks rarely exceed 1,200 m a.s.l. There are deep valleys carved by the effect of Quaternary ice and postglacial phenomena, filled with glacial, fluvio-glacial, fluvial and lacustrine deposits and the latest volcanic ash.

Díaz et al. (1959–1960) observed close coincidence between the distribution of Great Groups of soils and systems of moraines that have been described as glacial deposits of Quaternary advances. For example, the substrate of the Castaños soil series is highly weathered and partly disintegrated, while Podzolic soils show a massive clay substrate, known locally as *masacote*, which allows the accumulation of organic matter and the presence of peatlands in the area.

The volcanic deposits correspond to thin materials (ash) and sand-sized particles, but it is also possible to find medium and coarse particles (lapillis). Pumice fragments, most with intermediate degrees of weathering, are widely distributed in soil, either as strata in lithological discontinuities or mixed with the soil matrix. The volcanic materials were deposited covering different types of formations such as alluvial terraces, moraines, colluvial deposits and rocks (Fig. 2.62), so that soils developed from these materials are derived from contemporary events from the same volcanic centres. Therefore, the tephra have led to similar soils, even when the substrate on which they are developed can be of a different nature. Because volcanic events have been sporadic, soils show a marked stratification, and not all possess andic properties, differentiating the soils from Puerto Montt to the north, where the tephras have been more homogeneous in both particle size and composition (Luzio et al. 2010).

As a result of volcanic origin and steep slopes, most soils in this zone are thixotropic. This phenomenon is associated with the presence of gels, in this case derived from volcanic materials (such as allophane, imogolite and ferrihydrite), which change their behaviour from solid to liquid on physical alteration (such as an earthquake). Due to these minerals of low crystallinity, which have a large surface area, the soils have the capacity to absorb an enormous amount of water, which can reach over 100 % at wilting point, so that slopes over 60 % can easily produce landslides.

The forms due to alluvial processes are mainly alluvial terraces, usually 1–3 % and 2–5 % slope, in low positions within the landscape, over rounded gravel substrate and always associated with numerous rivers in the area. Many of

Fig. 2.62 Volcanic soils over different deposits or rocks. Sequence of ash deposited from the Hudson volcano over basaltic rock (*left*), mixed layers in alluvial deposits (*centre*) and volcanic soil over moraine (*right*)

these soils are formed from volcanic ash, with similar properties to the soils of the highest positions, which suggests that the volcanic ash deposits are relatively recent (Holocene). Close to Coyhaique city alluvial terraces can reach great dimensions, constituting potential areas for agriculture and livestock (Fig. 2.63).

Between 42 and 50°S, the soil landscape can be subdivided into two sectors without clearly defined boundaries. The first group corresponds to the Andisols, taxonomically well expressed, but the substrate can be glacial (moraines), fluvio-glacial, alluvial and even rock (Fig. 2.62). These soils are found in the central sector of the zone, approximately between 71°45′ and 72°30′W. On the other hand, there are intermediate developed soils (presence of a cambic horizon) that are found on alluvial terraces or fluvio-glacial sediments, which do not exhibit sufficiently well-expressed andic properties to be considered Andisols.

From 71°45′W to the east (soils of the East of North Patagonia), there is a change in the landscape: forests disappear and are replaced by a dense cover of *Stippa* spp. bunchgrass (Fig. 2.64). The soil properties also change, particularly in relation to BS in the soils described, assuming a xeric soil moisture regime. Agriculture activity is more intense in these areas, including crops impossible to grow in the western sector.

Between 50 and 55°S (South Patagonia) there are few detailed studies of soils. Physiographically, three important forms have been identified in this area: The Magellan Mountains, the pre-Mountains (Precordillera) and the Magellan Pampa. The Magellan Mountains consists of a granitic batholith as a crystalline basement and volcanic rocks of different ages. This formation raises an aspect of wall, with the highest peaks over 3,000 m. Petrographically, schists, phyllites and gneiss of the lower Paleozoic or Precambrian dominate. The present relief is completely influenced by Quaternary glacial action (IREN 1967). The pre-Mountains show a relief softer than the Mountains and are composed of sedimentary and metamorphic rocks such as sandstones and shales, attributed to the Cretaceous and Tertiary. Volcanic materials in contact with the Magellan Mountains have also been described. To the east the landscape is softer, slightly undulating to flat (IREN 1967). The Pampa extends from the foothills (Precordillera) to the Atlantic Ocean with a flat relief composed of Tertiary sediments (sandstones and clay) over Quaternary fluvial-glacial deposits.

Finally, the *mallines* and *vegas* are sectors that generally occupy the lowest positions of the Patagonian relief, and are therefore imperfectly to very poorly drained (Fig. 2.65). Soils in these positions include mineral soils and organic soils, with huge stratiographic variability. In the case of organic soils, the variability is related to the content and degree of humification of organic materials and the depth they achieve. They are found in lake sedimentation basins, terraces and alluvial plains lacking natural drainage. They can also be found in areas of steep slopes breaking from the hills to the alluvial terraces. The *mallines* of Cisne River (Queulat soil series) show moderately flat topography and microrelief (2–5 % slope) and are permanently saturated.

In a broad separation, the area is divided here simply into North and South Patagonia (*Tierra del Fuego*), corresponding in general to Administrative Regions XI and XII, respectively.

2.2.3.1 Soils of the West of North Patagonia

Andisols

In this sector, the Holocene tephras have been widely spread, covering large areas of shapes and different origins. This means that the slopes that dominate in each soil are also quite variable, ranging between 1–3 % and 5–8 % in

Fig. 2.63 Sequence of alluvial terraces near Coyhaique city. Volcanic ash was deposited over alluvial substrate, defining the Pollux soil series (Typic Hapludand)

Fig. 2.64 A typical landscape in a possible udic-isomesic area where Andisols are well developed (*left*). From 71°45′W to the east, xeric conditions allow the existence of soils with high base saturation and in some cases with drainage restrictions (*right*)

alluvial terraces, 5–8 % and 8–15 % in moraines and 15–50 % in hills and mountains.

The textural classes of surface horizons are medium and coarse (silt loam, sandy loam and loamy sand) that, practically as a rule, become fine-textured towards the deeper horizons, so there are frequent silty clay and silty clay loam classes. Most of the soils described are deep and moderately deep, with only Murta soil series described in detail as being 67 cm deep. All soils have good root penetration, usually reaching to the substrate.

One characteristic property of these soils is their strong stratification (Fig. 2.66), where strata of pumice lapillis are inserted between layers of ash (Besoaín et al. 2000). Another property common to most of these soils is the thixotropy, which does not manifest itself uniformly throughout the profile, but appears in some layers of ash, which facilitates the occurrence of differential slip processes.

With BS < 50 %, OC content can reach high values in the upper horizons (13 %) followed by an irregular decrease with depth, which is associated with marked stratification. The pH is maintained in the acidic range (6.3 and 4.7) and redoximorphic features are mainly represented by Fe segregations, which have been translocated by organic matter in *trumaos* and *ñadis (*Luzio et al. 1989). The bulk density is low because of the volcanic ash origin and the low intensity of use, and the water retention is highly variable, in some upper horizons exceeding 100 % at field capacity and wilting point (Besoaín et al. 2000). Pollux soil series (Typic Hapludand) a wide area in Region XI.

Because of the slope, stratification and thixotropy phenomena are common in these soils, the VI and VII (VIII in

Fig. 2.65 Depressed sites where mallines and vegas are found, near to Caleta Tortel (Region XI, 47°47′S)

special cases) LCC dominate. The volcanic ash soils in alluvial terrace positions have better suitability because of their lower slope, high depth and good drainage, so they are classified frequently as II and III LCC.

Other Soil Orders

Near Coyhaique city (45°34′S), a deep Andic Distrudept is reported by CIREN (2005b) in an alluvial terrace position with a substratum of glacial clay.

2.2.3.2 Soils of the East of North Patagonia

Although no detailed data are available for moisture and temperature regimes of the soils in this area, it is assumed that they have conditions close to a xeric moisture regime and thermic temperature regime, based on higher agricultural activity and chemical analyses.

A recent study (Pfeiffer et al. 2010) reported relationships between soil Great Groups and the glacial geomorphology of the Pascua River and Baker River basins (Table 2.5), observing only Entisols, Inceptisols and Histosols. Exceptionally, in the east and close to the Andean Mountains, some Andisols are developed (Murta soil series, a Typic Hapludand) according to CIREN (2005b).

A pristine landscape is characteristic of this eastern portion of Chilean Patagonia, where the Chapel of Marble and Baker River emerge as two emblematic pictures (Fig. 2.67).

Soils with High Base Saturation

The most significant feature of this soil group is that in contrast to the other soils of Region XI, BS is usually >50 % throughout the profile.

Most soils in this area are developed in a position of lake terraces, glacial plains, glacial moraines and alluvial deposits (Fig. 2.68). The alluvial areas show gentler slopes, with topography flat and nearly flat (0–1 % and 1–3 %) to gently undulating (5–8 %). In the case of soils developed on plains and glacial moraines, the relief is more pronounced, dominating complex slopes from gently undulating (5–8 %) to strongly undulating (15–20 %).

Soils in this group are moderately deep and deep on a substratum that can be variable: a succession of strata of sand mixed with layers of finer textural classes such as sandy loam, or angular gravel with coarse interstitial material and glacial clays. As might be expected in soils of sedimentary origin, textural class is highly variable, of indistinct origin (alluvial or glacial), but it has been observed that there is some textural uniformity within each profile. The soils are well drained, with the exception of some soil phases of alluvial soils (Chile Chico and Fachinal soil series) that have imperfect drainage, and all have good root penetration to the depth of description.

In almost all soils BS is >85 %, although in the Puesto Viejo soil series it is 67 %. The pH is more acidic in the upper horizons with values between 6.3 and 6.8, whereas in

Fig. 2.66 Glacial landscape and profile of the Pollux soil series (Typic Hapludand). The soil phases are indistinctly located in the base of the valley (2–5 % slope) or on the hills (up to 20–30 % slope). *Right* stratification, with a buried soil at 77 cm depth

Table 2.5 Classified pedons in the Baker and Pascua river basins (Pfeiffer et al. 2010)

Geomorphology	Baker River basin	Pascua River basin
Alluvial	–	Fluvaquentic Dystrudept;Typic Dystrudept
Alluvial fan	Aquic Cryofluvent	Typic Dystrudept
Colluvial	Typic Udorthent	Typic Udorthent; Humic Lithic Dystrudept; Typic Dystrudept; Lithic Udorthent; Lithic Dystrudept; Typic Fragiudept
Fluvio-glacial terrace	Hydric Cryohemist Typic Cryaquent; Typic Cryorthent; Typic Cryosaprist	Aquertic Udifluvent; Fluventic Dystrudept; Humic Psammentic Dystrudept; Oxyaquic Dystrudept; Oxyaquic Udifluvent; Typic Dystrudept; Typic Endoaquent; Typic Fragiudept; Typic Udifluvent; Typic Udipsamment; Typic Udorthent
Fluvial terrace	Typic Cryaquent; Aquic Udipsamment	Typic Dystrudept; Typic Udorthent; Vitrandic Udorthent
Moraine	Fluvaquentic Sphagnofibrist	Lithic Dystrudept; Lithic Udorthent; Typic Dystrudept; Typic Fragiudept
Stoss and lee topography	Hydric Cryofibrist; Lithic Cryofibrist	Humic Dystrudept; Lithic Dystrudept; Lithic Udorthent; Oxyaquic Dystrudept; Typic Dystrudept; Typic Udorthent
Esker	–	Vitrandic Udorthent
Kame terrace	–	Typic Dystrudept
Kettle	–	Terric Sulfihemist; Typic Udifolist
Loess	–	Typic Dystrudept
Outwash plain	–	Typic Dystrudept; Typic Udorthent

the deeper horizons it is more basic (8.3–8.6). Carbonate filaments have been described under 13 cm depth, but only in the Fachinal soil series.

The agricultural aptitude of these soils is rather limited: most of the soil phases are included between IV and VII LCC. Only some soil phases of the Fachinal and Chile Chico soil series are classified as III LCC. From a taxonomic point of view, these soils are classified as Haploxerolls and Palexerolls and only the Puesto Viejo soil series is classified as a Haploxerept. Chile Chico soil series (Oxyaquic Haploxeroll) is considered representative of the soils in this group.

Figure 2.69 shows the landscape at Chile Chico in Region XI (46°34′S).

Soils with Low Base Saturation

These soils, with BS usually <50 %, are distributed in the udic moisture regime, here represented by the Cochrane soil series (Andic Oxyaquic Dystrudept), i.e. a soil with moderate depth in hill positions (20–30 % slope gradients), coarse-textured in upper horizons and fine-textured at depth. Fluvio-glacial deposit is a more common substratum, less frequently they occur over glacial clays, moraine deposits or rocks. Soil permeability is moderate and soils are well

Fig. 2.67 *Chapel of Marble* (*left*) and beginning of the Baker River (*right*) at General Carrera Lake, Region XI of Chile

Fig. 2.68 Landscape of the Puesto Viejo soil series (Typic Haploxerept) and the respective soil profile east of the Andean Mountains (Region XI)

drained. The Land Capability of these soils is limited both by stratification and by slope, classes VI and VII are common. The landscape at Cochrane is shown in Fig. 2.70.

2.2.3.3 Soils of South Patagonia (*Magallanes*)

According to Filipová et al. (2010) the most frequently recorded soil groups here are Histosols and Fluvisols. Gleysols, Vertisols, Regosols, Solonchaks and Solonetzs are detected with much less frequency. There is also considerable variability in soil properties among and within the soil groups. The principal differences between the Histosols and the Fluvisols are the content of organic matter (often peat), pH level (related to the absence/presence of carbonates) and associated soil properties. Fluvisols are more susceptible to salinisation under conditions of aridity, whereas the main threat to Histosols is artificial drainage.

Mineral Soils

The soils described in this area are located on alluvial terraces, with flat to gently undulating relief. The slopes are frequently 1–3 % and 2–5 %, with only few phases of the Última Esperanza soil series being described as having slopes of 5–8 % and exceptionally of 8–15 %. In some soils, the relief is flat to concave which contributes to creating poorly drained soils with a watertable that can fluctuate between 50 and 90 cm depth (Fig. 2.71). In addition, several of these soils have formed organic horizons at the surface (could correspond to histic epipedon) that can reach 25 cm thick.

The soil substrate is variable, even when the soils occupy similar positions in the landscape. Thus, substrates have been described with rounded gravel and interstitial sand, compacted sandstone, cemented clay and a compacted glaciolacustrine material, very hard, clayey or silty clay, with some degree of cracking, locally known as *masacote*.

Grey (5Y 5/1) and olive grey (5Y 4/2) colours are common at depth, associated with poor to very poor drainage. The textural class of the surface horizon ranges from silty clay loam to silty loam and in some cases can be fine sandy loam. However, at depth the textural class is highly variable.

Many soils have been described as deep and very deep (100–130 cm); soils with limited depth (thin, 25–50 cm, and slightly deeper, 50–75 cm) correspond to soils with high watertable or its depth was defined by the presence of partially cemented sediments. Drainage is poor to imperfect

Fig. 2.69 Landscape of Chile Chico city (46°34′S, 71°40 W') in Region XI of Chile, on the shores of General Carrera Lake

in all the soils described; the exceptions are the Tres Pasos and Última Esperanza soil series, with slopes ranging from 5 to 8 % and 8 to 15 %. Some soils, such as the Las Chinas soil series, have a high content of Na, with sodium adsorption ratio (SAR) of 59 and 76 for horizons from 0 to 20 and 20 to 50 cm, respectively. LCC is assigned based on drainage, depth and slope, ranging from III to VII, with V being the most frequent.

According to Douglass (2005), who studied glacial deposits from 1 Ma old to the present, OC, CO_3 and clay content increase with the age of soil at a decreasing rate, while the Ca and Mg increase linearly with age. The presence of CO_3 in soils would be the result of both deposition of aeolian dust originating from evaporation from lakes and pedogenic redistribution from parent material.

South of 50°S, in the Province of Magellan, soils have undergone various processes of landscape modelling, so soil substrates are varied, such as glacial and fluvio-glacial sediments, fresh and weathered rounded gravel with sandy matrix and the aforementioned masacote.

Most soils in this area have been described as having abundant gravel in the profile. The dominant structure through the profile is subangular blocky, changing to massive in deeper horizons. In those soils with an organic surface horizon, it is possible to distinguish a granular structure. Depth to the substrate is variable, between 60 and 120 cm. The drainage is related to the position in the landscape soil, so poorly drained soils are associated with flat or nearly flat positions with IV, V and VI LCC; instead soils in gently undulated positions are well drained, with III and IV LCC.

In this area, it is possible to find Podzolic soils (Fig. 2.72) which present a profile with a surface layer formed by peat or a layer rich in organic matter and roots. At depth, there is a mineral horizon, fine sandy loam, sandy silt loam or sandy, grey-coloured (between 2.5Y 7/1 and 10YR 6/1), ending in a silty loam to silty clay loam horizon. The soils are been described as moderately deep to thin over a substrate of glacial sediments with gravel and stones or Cretaceous shale.

However, the current concept of Spodosols (Soil Survey Staff 2006) is based on the presence of an illuviation horizon (B_{hs}), which would not be clearly identified in the descriptions above. Gerding and Thiers (2002), in the area of Bueno River in *Tierra del Fuego*, identified soils to be included in this group, characterised by young soils, thin to very thin, influenced by volcanic activity, topography and climate, pH between 4 and 5.5 with high Al saturation (>60 %). Below the topsoil there is a grey (10YR 5/1), silty loam and structureless horizon, but the formation of this horizon could be influenced by the deposition of volcanic ash and by podsolisation processes.

Certainly, given the continued action of transport agents on the contribution of new parental material, Inceptisols should be an important group, more precisely Dystrustepts. However, soils with coarse textural classes throughout the profile should be considered rather within the concept of Entisols, probably Cryorthents.

Fig. 2.70 Landscape at Cochrane city (47°15′S, 72°34′W) in Region XI of Chile

Organic Soils

Knowledge of organic soils is more limited than that of mineral soils for the area, because there are few studies on recognition and identification of these ecosystems. The few studies that exist have focused on description and identification of plant species that make up each system, but not the soil in which these species are growing.

According to Clausen et al. (2006), there would be nine *major types of wetlands* in Patagonia, considered unique in South America, mainly in terms of plant species that dominate in each wetland. Three of these major types are considered closer to the concept of organic soils.

One of these wetlands is described as *Carex-Nothophagus* (called *mallines*), found mainly in depressions within glacial moraines and slopes that can reach 28 % on hillsides. A second type is similar to peat, described in the vicinity of Grey Lake, and corresponds to the concept of marsh or swamp in which the dominant species is *Sphagnum magellanicum*. The third type of wetland, considered the most important in Magellan, is called *vega*, occupying depressions in the landscape due to glacial processes that have created an impermeable clay layer very close to the surface and slopes lower than 1 % (Fig. 2.73). They are considered more like moist meadows than wetlands, because they constitute an

Fig. 2.71 Landscape near Puerto Natales (52°30′S) city

Fig. 2.72 Soil morphologically similar to a Spodosol. The limited surveying in the area and the lack of analysis result in uncertainty regarding soil classification (Luzio et al. 2010)

essential habitat for the guanaco (*Lama guanicoe*) during spring and summer.

Filipová et al. (2010) identified within the Histosols some Ombric Histosols (Haplohemists), Folic Histosols (Haplohemists) and Episalic Histosols (Sulfihemists).

2.2.4 Soils of the Insular (Easter–Juan Fernández) and Antarctic Zone

2.2.4.1 Insular Territory

Chilean oceanic islands are fragile ecosystems, with few and incomplete soil information available today, that have been modified by humans since prehistoric times and more severely in recent centuries. Therefore, only two inhabited territories in central Chile (Region V) are characterised here: Easter Island and Juan Fernández Archipelago.

Easter Island

An island in the south Pacific Ocean belonging to Chile, Easter Island has different names (Polynesian: *Rapa Nui* or Great Island, *Te Pito te Henua* or navel of the world, *Mata-ki-te-rangi* or the eyes that look to the sky; Spanish: *Isla de Pascua*). It is located 3,515 km west of continental Chile (27°09′S 109°25′W), has an area of 163.6 km^2 and is roughly triangular in shape, with a maximum ground elevation of 560 m a.s.l. It occupies an exceptionally isolated position in the South Pacific Ocean, where the nearest island is Pitcairn Island, located 2,075 km to the west. Only a few soil surveys have been carried out on Easter Island, and although some of these are very old, they represent the only reference available. The origin of the island is volcanic, and it is still possible to see three volcanoes located in each corner of the island (Fig. 2.74): Poike, an older (3 Ma) strato-volcano; Rano Kau, a caldera and the fissure complex of Terevaka and its associated cones (Baker et al. 1974).

Over a small submarine platform of 560 m high, this island presents a hilly landscape, with altitude from sea level to 70 m a.s.l. Average slope ranges between 1 and 15 %, with steep slopes (10–20 %) occurring on volcanic cones. The relief has been described as a sequence of terraces with a nearly level slope (1–3 %) descending down from the volcanic cones, which were probably formed by erosion.

Baker et al. (1974) carried out a comprehensive geological study on Easter Island and found that the lava showed a wide compositional spread, from tholeiites and olivine tholeiites to hawaiites, mugearites, benmoreites, trachytes and rhyolites (comendites). They also determined that hawaiite is by far the most abundant rock type and trachytes and rhyolites are relatively rare, whereas intermediate and acid rocks are concentrated in the south-western part of the island.

The recent geomorphologic evolution of Easter Island has been dominated by volcanic and marine events. The age of the geomorphologic forms defines the interrelationships among these, as is evident in the dense drainage net which is found in Hiva Hiva, which is a maximum of 5,000-years old (Muñoz 2004).

The state of the cliff in coastal areas is directly related to the low weathering processes over the parent material. For instance, there are differences between the north and south side in the fissure complex of Terevaka, but these have been related to differences in height between the cliffs and coastal areas.

In general, soils are very shallow and shallow, frequently with lava outcrops. As the slope increases, the soils are shallower than in flatter areas. Deeper soils are located at the bottom of volcanic cones and in lower areas with sediment accumulations.

The soil factors that determine the soil depth and properties are topography (height and slope) and parent material (type and age) (Wright and Díaz 1962). In the island soil, parent materials are volcanic materials, such as andesitic lavas, volcanic scoria, volcanic tuff, and basaltic and andesitic volcanic ash. Moreover, it is possible to find a mix of old volcanic ash and scoria from the volcanic cones in some areas. These volcanic materials are very fine and the scoria weathered, so therefore it is usually very difficult to identify new and old volcanic materials (Wright 1965). Volcanic eruptions have generated a high amount of basaltic rock, which is named Terevaka basalt, mainly in the central part of the island, covering approximately two-thirds of the total area. Therefore, it is considered that the parent material of the soils is tephras, either volcanic ejecta moved and deposited by wind or lava flows (Louwagie et al. 2006).

Louwagie et al. (2006) noted that in Easter Island the main soil limitations include (i) extensive areas with

Fig. 2.73 General view of landscape with evidence of aeolian erosion and at the *bottom* of the valley, a typical wetland with damp meadows important for feeding auchenids (*Lama guanicoe*)

shallow soils and basaltic rock on the surface; (ii) scarce soil water due to a long dry season with irregular precipitation distribution; (iii) soils excessively drained with low water holding capacity and (iv) soils with low values of available P and K.

Although different authors (Díaz 1949; Wright 1965; Alcayaga and Narbona 1969) agree that the soils in Easter Island are developed from volcanic materials, they disagree on the type of volcanic material and geological processes which created these soils. Díaz (1949) concluded that the soils are derived from intemperised volcanic ash and that the island is composed of andesitic lava over basaltic lava at the bottom. Wright (1965) considered the soils of the island to be tropical volcanic soils, together with nonvolcanic soils, similar to the young latosolic soils described in Western Samoa. Alcayaga and Narbona (1969) concluded that the soils in Easter Island developed from volcanic ash and weathered lava. Mikhailov (1999) added that in addition to Pleistocene volcanic activity in the island, there were intensive hydrothermal processes that generated red-clay deposits in the fault lines, where these clays were deposited in undulating slope positions. Moreover, this author noted that east winds were the source of loess deposits, by transporting fine particles from abrasion zone to plateau, and that the red deposit in the upper soil horizons was caused by hydrothermal metasomatism of volcanic rocks and the only product of soil formation processes would be a humic horizon. Horrocks and Wozniak (2008) claimed that the soils in the island are Oxisols, but they did not report any analytical data or taxonomic characteristics.

On Easter Island the weathering of tephras has generated soils with andic soil properties, with significant amounts of short-range-order compounds, such as allophane, imogolite, ferrihydrite, or aluminium-humus complexes in soils (Louwagie et al. 2006). Thus, soils in the island present low bulk density, high amounts of OM and high P retention. In addition, the soils have loamy textures at the surface and fine textures at the bottom of the profiles, which is similar to volcanic soils in the Mediterranean zone of central continental Chile (Honorato and Cruz 1999).

The main controllers of the soil cover mosaic are altitude, slope, the nature of the parent material (e.g. lava flow or tephra deposit) and the age of these deposits, and only small pockets of arable soils occur, scattered across the rest of the island (Mann et al. 2008). Only soil surveys that include a detailed description are reported here, which in chronological terms include Díaz (1949), Wright (1965) and Alcayaga and Narbona (1969).

Díaz (1949) grouped the soils according to its LCC and identified seven soil series. Although this is a very old soil survey that omits many soil properties included nowadays, it is the primary work used by national and foreign researchers for studies on Easter Island. The author classified the soils in different slope gradients: <6 %, 5–10 %, 10–15 %, and >30 %. The dominant soil colour in surface soils is brown, ranging between light brown, dark reddish brown and light reddish brown with only one white soil, providing details about the parent material, whereas deeper horizons have yellowish brown as the dominant colour. Soil textural class varies between silt loam and sandy loam in all soils. It is assumed that with the actual soil structure types, soil may present no visible structure (massive). In general, the soils are described as deep, ranging from 80 to 200 cm, with a stony surface layer, whereas no stones are found in the soil profiles. Some chemical analyses have been carried out and show that soil pH ranges between 5.5 and 6.6 and CEC between 28 and 60 $cmol_c\ kg^{-1}$.

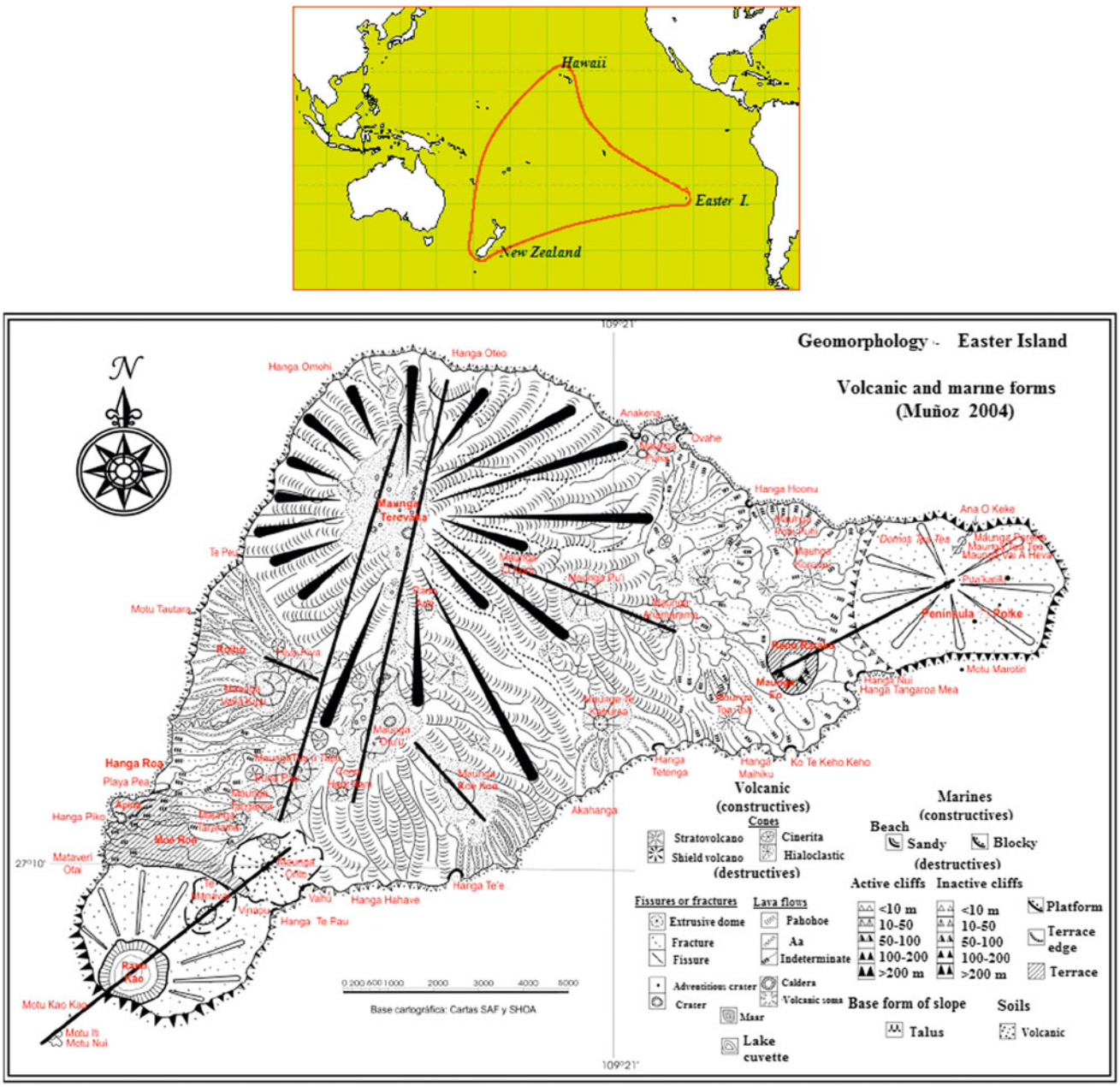

Fig. 2.74 Geomorphology map of Easter Island and its relative location (*below*) in the Pacific Ocean (*above*) modified from Muñoz (2004)

Wright (1965) described the soils on hills, plateaus and gently sloping areas in the volcanoes and grouped these into three soil series, Rano Kao, Vinapu and Poike. Slopes ranged from 7 to 14 %, with the substratum identified as scoria or weathered volcanic tuff. Soils are deep, between 125 and 175 cm to the substratum. The colour in topsoil is dark brown, whereas in deeper horizons it ranges from dark reddish to yellowish red. Textural classes are finer than the soil described by Díaz (1949), such as sandy loam, silty clay loam and silty clay in all horizons. Soil structure is sub-angular blocky. In that study, the soil pH was found to range between 5.1 and 5.9 at the soil surface, whereas in deeper horizons it was more acid, reaching 4.8. Although unfortunately the soil survey by Wright (1965) did not provide enough data either to compare with those of Díaz (1949) or to classify the soil according Soil Taxonomy, it is clear that the parent materials of the soils of the island are volcanic materials.

Alcayaga and Narbona (1969) carried out a detailed soil survey in the entire island at scale 1:40,000 and described soils on volcano hills, piedmonts and floodplains, generally with slopes level (0–1 %), nearly level (1–3 %), gently (3–8 %) and strongly sloping (15–20 %). In particular, a very stony soil surface was found in soils on volcano hills

Table 2.6 Correlation between World Reference Base and Soil Taxonomy for some soils in Easter Island (Louwagie et al. 2006)

Soil	World Reference Base	Soil Taxonomy
TP3 and VA4	Hyperdystri-SILANDIC (aluandic) Andosol	Typic Hapludand
Akahanga: AK1, AK2 and AK3	(Silti-Pachic) (Silti-Endosonic) (Silti-Hiposodic) Phaeozem	Andic Hapludoll
La Pérouse: LP4	Silti-Pachic Phaeozem	Typic Hapludoll
LP6	Silti-Luvic Phaeozem	Typic Argiudoll
LP1 and VA3	(Hyperdystri-Silandic) (Ferrali-Silandic) Cambisol	Andic Dystrudept
Vaitea: VA2 and LP3	(Hyperdystri-Humic) (Hyperdystri-Umbrihumic) Cambisol	Andic Dystrudept–Humic Pachic Dystrudept
VA8	Humi-Episkeletic Leptosol	Lithic Udorthent

and piedmont positions. The soil substratum was lava flows with different stages of weathering processes, with the exception of the Vaitea soil series, which had a mix of ash and lava flows. Although the authors found that the dominant soil texture class was clay, ranging from dense clay to less dense clay in whole soil horizon, it is not in agreement with volcanic soils (Andisols) in the southern Mediterranean zone. Soil colour in surface soils is generally dark brown to very dark brown, whereas in subsurface horizons it is closer to reddish. The survey found no poorly drained soils, and these soils colours were related to the parent material (tephras). The dominant soil structure is subangular blocky in surface and subsurface horizons, with some cases of no visible structure such as massive at the bottom of the soil profiles. The soils are usually shallow (<50 cm depth), with the exception of the Rano Kao soil series, which is deep (>100 cm depth). All the soils are well drained, with soil restriction to root growth at depth resulting in commonly occurring very fine roots in surface horizons and scarce roots in deeper horizons. Some data showed that SOC at the surface ranges from 1.8 to 4.2 %, decreasing in deeper horizons to values around 0.5 %. A broad range of soil reaction was found in all soil horizons, with soil pH values between 6.3 and 4.9. Cation exchange capacity was found to be medium to high, ranging from 44 $cmol_c\ kg^{-1}$ in surface horizons to 18 $cmol_c\ kg^{-1}$ at the bottom. These authors defined the soils from moderate to extremely limited for agricultural use, with LCC between IV and VI, with the exception of the Orito soil series, which is II.

On the other hand, Louwagie et al. (2006) reported that soils in Easter Island are derived from tephras, clearly show andic soil properties and can be classified as Andisols. Table 2.6 shows the correlation between World Reference Base and Soil Taxonomy for some soils in Easter Island according to Louwagie et al. (2006).

Juan Fernández Archipelago

This archipelago includes raised areas from submarine volcanoes at a depth of 1,000 m bsl, in an extension of 402 km from 74 to 83°W. This submarine volcano series is part of a submarine mountain range that runs north parallel to the continental Chilean coast, related with the Juan Fernández ridge of the Nazca plate. This archipelago is located 670 km west of continental Chile (33°36′S–33°66′S and 80°47′W–78°47′W), and has three main islands: *Más a tierra* or Robinson Crusoe Island, *Más afuera* or Alejandro Selkirk Island and Santa Clara Island. Stuessy et al. (1984), using K–Ar dating of five basalts, found ages of 1.01 ± 0.12 and 2.44 ± 0.14 Ma for Alejandro Selkirk Island, 3.79 ± 0.20 and 4.23 ± 0.16 Ma for Robinson Crusoe Island, and 5.8 ± 2.1 Ma for Santa Clara Island.

Robinson Crusoe Island has an area of 48 km^2 with a maximum ground elevation at 922 m a.s.l. and is long in shape. It has many volcanic centres, which have extended to peripheral structures (Baker et al. 1987). Approximately 180 km west of Robinson Crusoe Island lies Alejandro Selkirk Island, with an area of 52 km^2, which has a cupola shape, very cliffy, with a maximum ground elevation of 1,650 m a.s.l. Alexander Selkirk Island is the youngest and highest of these islands and exhibits strong ecological zonation, with many species associated with particular environments. Santa Clara Island is the smallest, 2.2 km^2, and is located 1.2 km south-west of Robinson Crusoe Island (Fig. 2.75).

The only information available regarding the soil properties of this archipelago were reported by IREN (1982) and updated by Cereceda et al. (1996). Figure 2.76 shows the distribution of three general soil groups according to natural zones defined for Robinson Crusoe and Santa Clara islands. Figure 2.77 shows a more detailed portion of Robinson Crusoe Island.

In general, Rici (2006) reported that soils on all three islands are volcanic in origin, and thus highly susceptible to erosion, particularly in areas where vegetation cover has been overgrazed or removed. There are few permanent surface streams and no lakes, as the soils are very porous and the steep slopes cause rapid runoff. The islands have a maritime climate, with a high average relative humidity of 77 % and mean annual precipitation of 1,181 mm.

Robinson Crusoe Island is composed of basaltic material with different stages of weathering and morphological relationships, where IREN (1982) concluded that cinerite deposits are not related with rock weathering. Similarly, Cereceda et al. (1996) noted that the soils in the islands are volcanic.

IREN (1982) described geomorphologically at least four altitudinal areas: (i) high mountains in the eastern zone of the island, where basaltic basalt dike occupies the top areas; (ii) hilly zones in a medium position in boundaries of watershed in the north side, where slopes range from 35 to 60 %, with continuous outcrops of rocks of different hardness; iii) low hill areas with slopes between 35 and 40 % that have suffered intensive landslide processes due to natural and anthropogenic causes, such as forest clear-cutting and overgrazing, which have formed even depth gullies; and (iv) deposition zones of material transported by alluvial, wind and landslide processes. Alluvial cones and landslides are associated with developed valleys, which are not connected to actual fluvial dynamics, whereas active wind deposition areas have been found around the island but mainly close to the airport in the west zone of the island.

Nowadays, the soils show the effects of different soil formation factors, such as topography, vegetal cover and anthropic activity, but soil erosion has had a great impact on soil characteristics. Thus, IREN (1982) defined three soil types associated with relief:

i. Soils of mountains of new origin and derived from volcanic ash, classified as Andepts of new origin according Cereceda et al. (1996). These are located in the central part of the island covering 1,356 ha, approximately 29 % of the total area of the island. Soils are located between 250 and 300 m a.s.l., where slopes may reach 80 %. In these areas, vegetation includes indigenous forest. Soils are thin and characterised by A–C horizons and have loam to coarse texture, usually with basaltic outcrops. Some measured soil properties show that soil pH is slightly acid to neutral (6.0–6.8), soil organic matter levels are high (17–25 %), and CEC is also high (70–100 $cmol_c\ kg^{-1}$). The Yunque and Chifladores soil series are characteristic of these positions (IREN 1982).
ii. Soils of intermediate level, located in hilly zones in a medium position, where slopes range from 20 to 40 % and colluvial material has been deposited. According to Cereceda et al. (1996), these soils may correspond to more evolved Andepts. They occupy 705 ha, approximately 16 % of the total area of the island. These soils are more evolved than the Andepts of new origin and present an A–B–C soil horizon distribution, while in some soils there is an argillic horizon (B_t). Some measured soil properties show that soil texture class ranges from loam to clay, usually with fine gravel, soil organic matter levels between 4 and 9 %, and that CEC

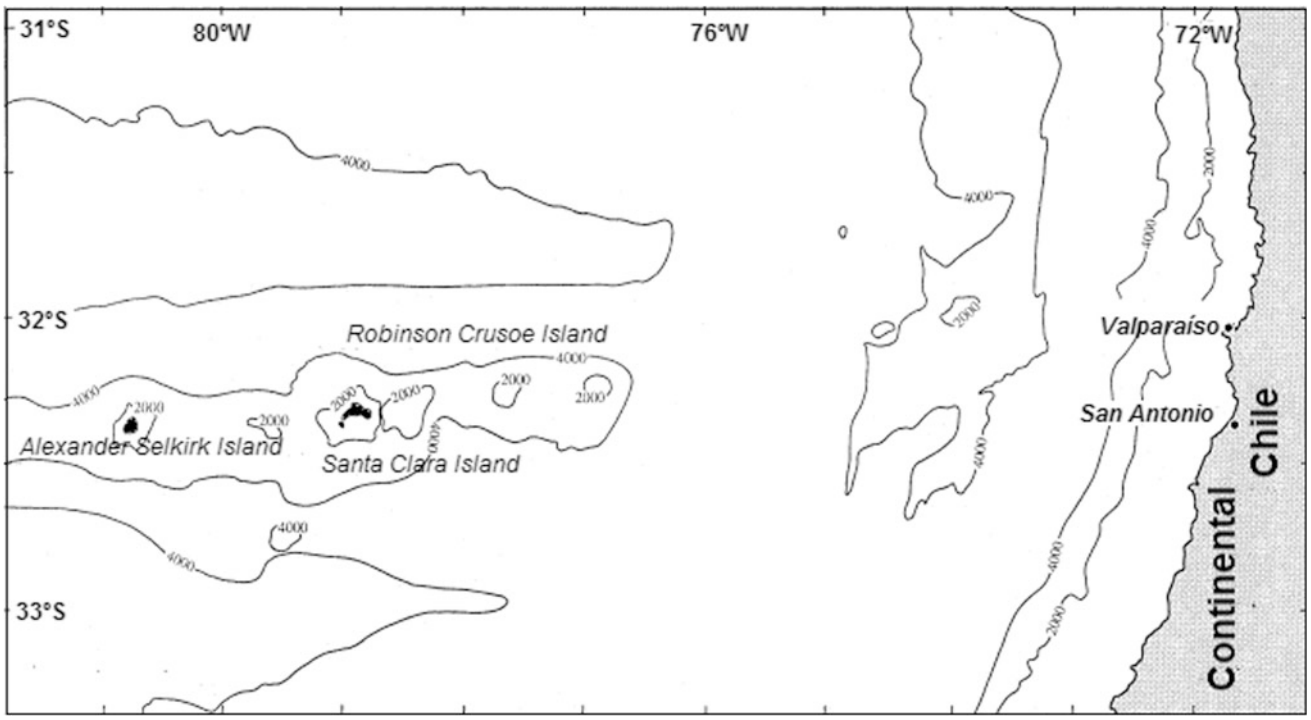

Fig. 2.75 Juan Fernández Archipelago in relation to the Chilean coast

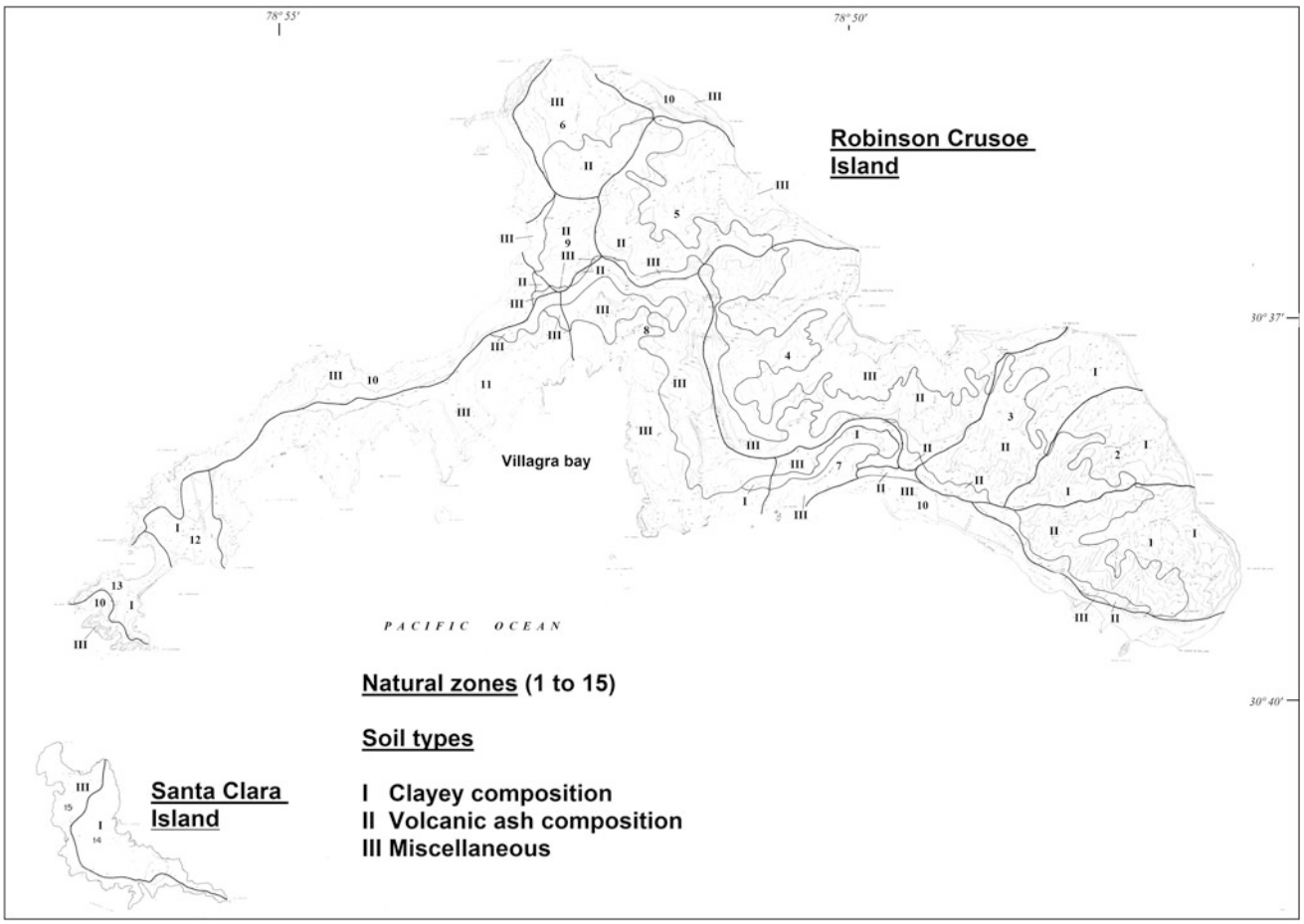

Fig. 2.76 General soil group distribution on Robinson Crusoe and Santa Clara islands. Adapted from IREN (1982)

is high (>40 $cmol_c\ kg^{-1}$). According to IREN (1982) the Vaquerías, Puerto Inglés, Puerto Francés and San Juan Bautista soil series are some examples of the soil groups occurring in these positions.

iii. Soils in depositional positions located in flat to slightly sloping areas, fine textured and with a moderate degree of evolution, displaying in some cases an A–B–C soil horizon distribution. According to Cereceda et al. (1996), these soils may correspond to Fluvents. They occupy 204 ha, approximately 4 % of the total area. Some of these soils in the area close to the airport, in the west zone of the island, show evidence of wind erosion processes.

Finally, the Land Capability of the two islands is illustrated in Fig. 2.78 which gives a general view of the soil and topographical constraints common in this territory.

2.2.4.2 Antarctic Territory

Lagabrielle et al. (2009) provided an integrated review of plate tectonic models of the evolution of the Antarctica-Patagonia connection and robust correlations of seaways and tectonic events along the Scotia and South America plates, and concluded that the opening of Drake Passage (Fig. 2.79) was not steady state since ca. 30 Ma.

Rather, the regions forming the present-day northern limit of this gateway experienced important paleogeographic changes, from deep marine basins to shallow ridges and emerged regions during the late Oligocene and early-mid Miocene. Geological data show that emergence along the North Scotia Ridge and *Tierra del Fuego* was achieved at 23–22 Ma, and has been followed by elimination of the Patagonian Sea in Patagonia. This transition towards more continental sedimentation in southern South America is correlated with more shallow marine conditions in the Austral Basin. This succession of events had a strong influence on the general geometry of Drake Passage, corresponding to a constriction of its northern limit.

A general description of Antarctic soils is included here, extracted from Campbell and Claridge (2009). Coarse fragments (>2 mm) in Antarctic soils are abundant, typically exceeding 50 %. Horizon development is weak, and mostly restricted to colour changes that diminish in intensity with

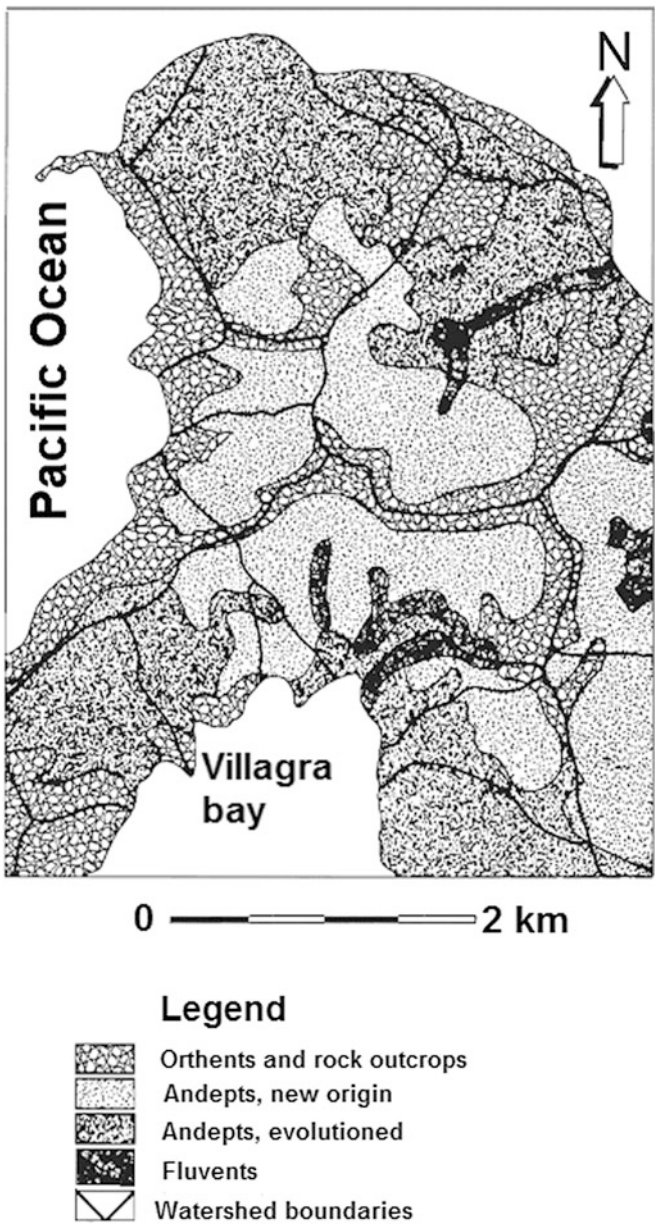

Fig. 2.77 Soil types on the Robinson Crusoe Island (Cereceda et al. 1996)

increasing depth, to lithologically related textural changes, or to salt accumulation. The soil surface is usually a stone pavement including loose material derived from fragmentation of surface clasts. On younger surfaces, clasts are mainly angular, coarse and unweathered, while on older surfaces, clast rounding, rock pitting, ventifaction, oxidation and disaggregation may be prominent. Weakly developed structure may be present in upper horizons as a result of freezing when the soil is moist. Where there is an increased proportion of fine material, a thin surface crust may be present. Below the surface, the soil is usually structureless and dusty, except where salt concentrations occur, when the soil material may be firmly cohesive. In older soils, the disaggregation of coarse grained clasts by salt weathering results in rock ghosts that indicate a highly stable soil environment.

The permafrost is generally ice-cemented (Fig. 2.80), but in older and drier soils may be loose. Because of the extreme aridity, the soils accumulate salts derived from precipitation and weathering, the composition and amount of the salts being a function of soil age, composition of the parent material and distance from the coast. Chemical weathering processes are assisted by the salts, which allow unfrozen saline solutions to be present on grain surfaces and cracks in rock particles, even at very low temperatures. Weathering comprises the breakdown of ferromagnesian minerals, releasing Fe and cations to the soil solution. The Fe oxidises and is precipitated on grain surfaces, giving rise to the red colouring of older soils (Fig. 2.81). The cations, especially Ca and Mg, combine with nitric and sulphuric acids arriving in precipitation to make up part of the thick salt

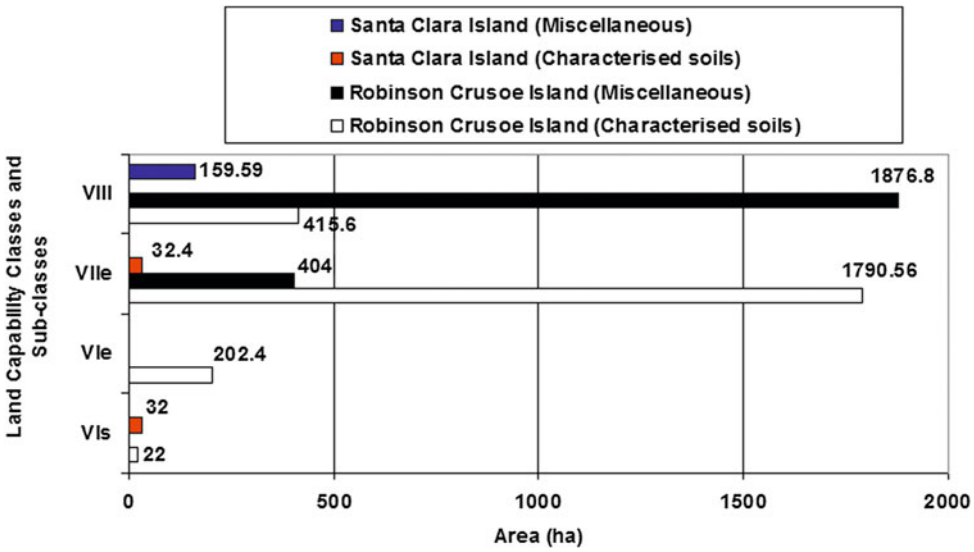

Fig. 2.78 Land Capability of Robinson Crusoe and Santa Clara islands from IREN (1982)

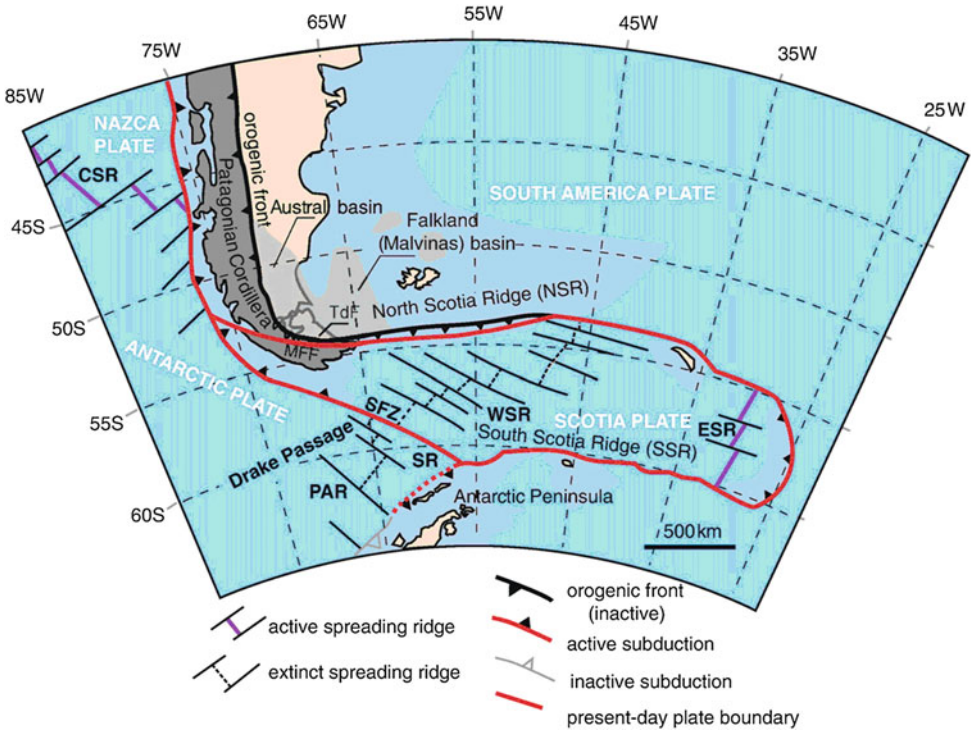

Fig. 2.79 Present-day setting of the Antarctica-South America connection and tectonic environment of Drake Passage (Lagabrielle et al. 2009)

horizons which are found in older soils. The concentrated salt solutions react with silica, also released by weathering, to form secondary clay minerals, and in some cases, zeolites.

Soil surveys carried out during the early 1990s by researchers at the Soil and Engineering Department, University of Chile, in the Antarctic islands are presented is this section, particularly those works carried out in the South Shetland Islands, including Robert (Haberland 1992, Álvarez 1993), Livingston (Henríquez 1994) and King George islands (Luzio et al. 1990). Figure 2.82 indicates the relative geographical position of these islands.

It is important to note that the soil characteristics of the Antarctic islands and the Antarctic continent are different due to dissimilar precipitation and temperature regimes. In particular, climate conditions in the Antarctic islands are more favourable for vegetal growth than those in the Antarctic continent, giving rise to higher soil OM accumulation in the Antarctic islands and having a great impact on soil formation processes.

In the Robert and Livingston islands, Haberland et al. (2008) suggested that the landscape and topography are the main factors affecting soil distribution pattern, whereas

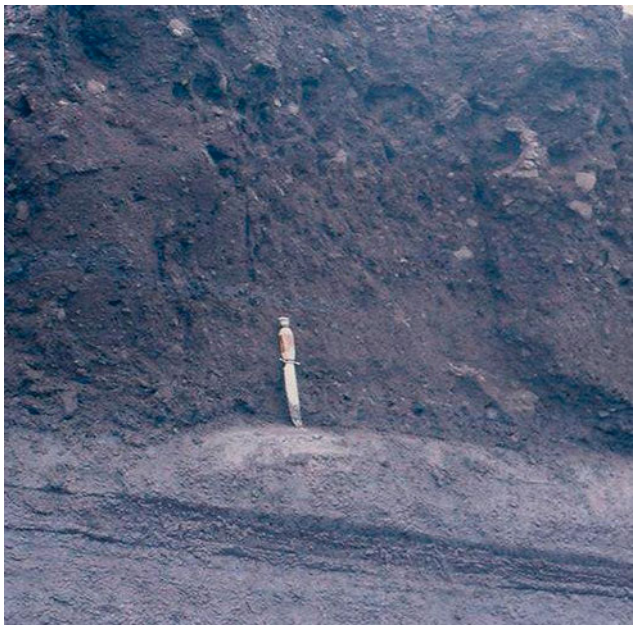

Fig. 2.80 Permafrost under (1 m) a colluvial Antarctic soil (Luzio et al. 2010)

cryoturbation is a major soil-forming process which induces continuous physical weathering. Similarly, Luzio et al. (1990) reported that thawing/freezing cycles have caused haploidisation in soil profiles on King George Island (Fig. 2.83). Soil water content is also an important soil formation factor in these Antarctic islands, as evidenced through gleyisation and clay eluviation processes. Vera (1990) added that there is also permafrost from 40 to 70 cm that influences the dynamics of soil formation processes.

Hervé and Araya (1965) suggested that climate conditions are not favourable for the formation of clay minerals. Thus in these soils, fine soil materials are produced by mineral and rock grinding. Campbell and Claridge (1987) concluded that in the Antarctic there is a lack of significant soil development, with weathering and the action of living organisms having been directly conditioned by climate conditions (Fig. 2.84).

According to soil surveys carried out in the South Shetland Islands, the soils can be broadly divided into mineral and organic (ornithogenic) soils.

Mineral Soils

Figure 2.85 shows a typical poorly developed Antarctic mineral soil. On Robert Island, Haberland (1992) and Álvarez (1993) described 10 profiles, from very thin to moderately deep (17–70 cm), overlying a basaltic rock substratum. In some cases, between 50 and 100 cm, permafrost was described. Deeper soils were found in areas where the permafrost was between 90 and 110 cm. Soils occupy different positions in the landscape with varying slopes, including steep slope areas (30–35 %), drumlins (10–15 %), slightly hilly areas (7–10 %), high terraces (6 %) and marine terraces (2 %).

On Livingston Island, Henríquez (1994) described five profiles and found thin to moderately deep soils, ranging from 37 to 80 cm. These soils occupy high terraces, steep slope areas, marine terraces and hilly areas inside an outwash plain (Fig. 2.86). The soils usually have gentle slopes (–5 %), and in some cases steep slopes (>20 %).

Some results of measured soil properties for Robert and Livingston islands are shown in Appendix. The soils on these islands are coarse textured, generally without structure (massive), with acid to slightly alkaline reaction and an exchange complex dominated by Ca^{2+}, Mg^{2+} and H^{+}. Although the soil colloids are present in low quantities, the CEC is high, mainly due to the presence of zeolite minerals. This shows that soil properties in the South Shetland Islands are similar. Navas et al. (2008) also found that soil properties such as pH, EC, carbonates and soil organic matter content had the same patterns. They added that in these soils, the main differences lie in soil particle size distribution.

Originally, the soils on Robert and Livingston islands were classified as Pergelic Cryorthents and Pergelic Cryochrepts (Haberland 1992; Álvarez 1993; Henríquez 1994), and those on King George Island as Cryochrepts (Luzio et al. 1990), according to Soil Taxonomy and before Gelisols were

Fig. 2.81 Soil profile and landscape at King George Island (Luzio et al. 2010), where coarse texture and structureless soils have been described (single grain or massive)

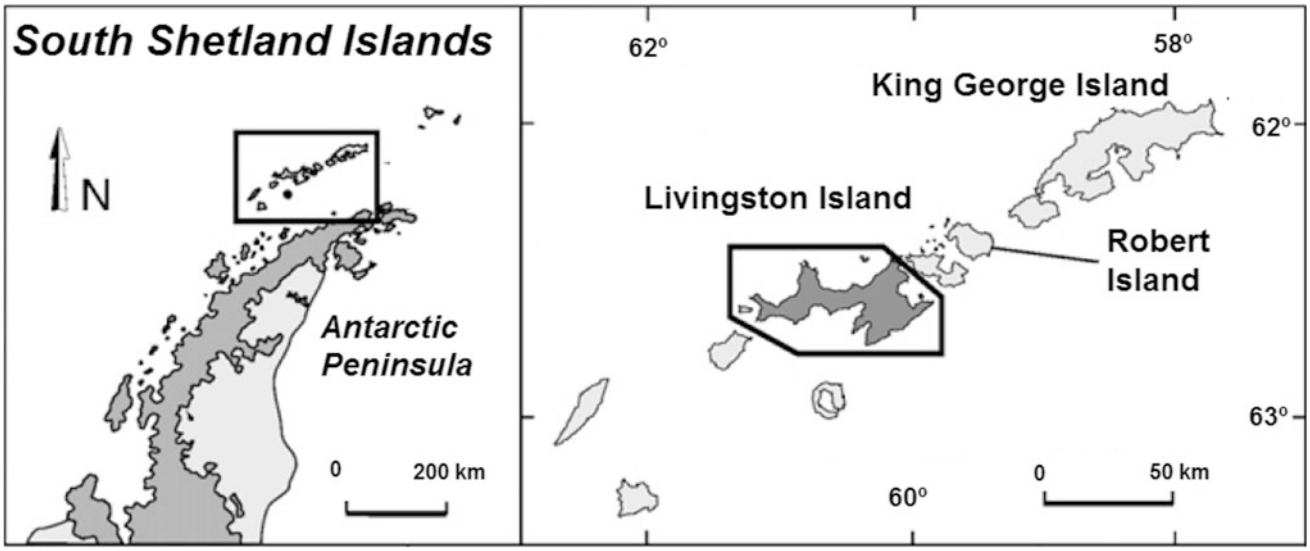

Fig. 2.82 Location of South Shetland Islands and Antarctic Peninsula

Fig. 2.83 Weathering processes (freezing/thawing) occurring at the surface of Antarctic soils (Luzio et al. 2010)

established as a soil order. As regards WRB (IUSS Working Group WRB 2006), Pergelic Cryorthents and Pergelic Cryorthents correlate to Glacic, Cryosols (Dystric) and Glacic, Cambic, Cryosols (Eutric). For these soils, Haberland et al. (2008) suggested that the best approximation according to the Key to Soil Taxonomy (2006) is Typic Haplorthels.

Ornithogenic Soils

These soils are an interesting organic soil group of cold regions, particularly of coastal continental Antarctica, where penguins play an important role in soil nutrient cycles, by during the breeding season bringing huge amounts of organic materials from the sea to the land. These organic materials accumulate to considerable thickness in the form of a friable layer of droppings, feathers, shells, bones and dead penguins. Most soils show cryoturbation features such an organic and organic horizon mixture, displaying particular forms such as wedges and contorted horizons (convoluted). According to Michel et al. (2006), soil organic matter accumulation and associated phosphatisation are marked soil-forming processes in ice-free areas once colonised by penguins. Ugolini and Bockheim (2008) concluded that phosphatisation is the main pedogenic process in these ornithogenic soils, causing acidity and weathering, showing that chemical weathering in maritime Antarctica is more intense than expected.

The ornithogenic soils are distinguished from non-ornithogenic soils by several features such as the presence of

Fig. 2.84 Organism soil formation factor, restricted to weak lichens, mosses and seaweed cover, affecting only few centimetres of upper soil horizons (Luzio et al. 2010)

Fig. 2.85 A typical A–C soil horizon sequence in the Antarctic zone (Luzio et al. 2010)

continuous vegetation cover, lower pH and lower BS. Their chemical properties change rapidly after the abandonment of the rookeries by the penguins. Processes such as CO_2 evolution and N and P release in the sea, formation of oxalic acids in upper horizons and simultaneous concentration of recalcitrant soil compounds (chitin, urates, and phosphate minerals) are indicated by Finkl (2005) and Zhu et al. (2009) in these organic soils.

On King George Island, Michel et al. (2006) describe this organic type of soil, where parent material is composed of moraines covered by weathered volcanic rocks, mainly andesitic basalts and gravels from an upper outwash. Ornithogenic Gelisols are deep and present a coarse active layer with gravel reaching 30 cm in depth and a brown humified histic epipedon. Deeper soils occur along gentle slopes and stable sites abandoned by penguins, where vegetation reaches a maximum height and diversity.

An ornithogenic soil on King George Island is reported by Michel et al. (2006), as a developed, uniform (texture and colour) Lithic Fibristel located on a flat ground moraine, near a present-day penguin rookery.

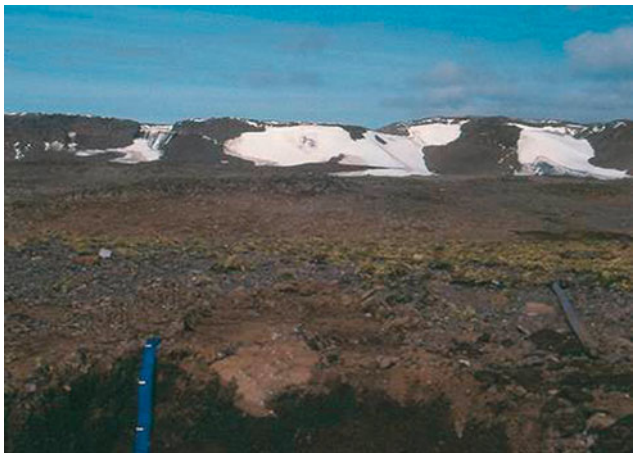

Fig. 2.86 Antarctic landscape including high terraces and other features within an outwash plain (Luzio et al. 2010)

The upper horizon is formed from fibric remains of mosses, whereas in brownish-coloured deeper horizons organic matter is partly humified. The soil is almost exclusively colonised by mosses due to its poor drainage, although no clear gleying is noticed. Another example is a Lithic Umbriturbel, located on a former lateral moraine covered by debris from an upland nesting bird area, with permafrost at 70–75 cm depth. Topsoil is formed by a thin layer of fibric remains of dead mosses mixed with loose rock fragments, but from 10 to 40 cm it is composed of a stony layer with hydromorphic gleying features, followed by dark humified material mixed with pebbles at 40–60 cm, with fibric material.

Several ornithogenic soils are reported by Simas et al. (2007), also on King George Island (Table 2.7).

Table 2.7 Ornithogenic pedons on King George Island described by Simas et al. (2007)

Pedon	[a]Altitude	Vegetation	ST/WRB	General description
A10	147	Absent	Typic Haploturbel; Turbic Cryosol	Subpolar desert without any ornithogenic influence. Desert pavement overlying oxidised basaltic till. Virtually no horizonation. Single-grain conditions and medium granular structure
A9	87	D > C	Lithic Haplorturbel; Turbi-Leptic Cryosol	Skua nest in subpolar desert with weak ornithogenic influence. Discontinuous vegetation with occurrence of higher plants (*Deschampsia antarctica*) and green algae (*Prasiola crispa*). Formation of a shallow, incipient A horizon. Single-grain condition and medium granular structure
A4	72	D > C	Typic Psammoturbel; Hapli-Turbic Cryosol	Abandoned rookery on the highest and most ancient level of ornithogenic influence. Continuous vegetation cover. Well defined A, B and C horizons, with crumbs in A and medium granular structure in B. Ice-cemented from 45 cm
A3	69	D > M > C	Typic Psammoturbel; Skeleti-Turbic Cryosol	Abandoned well-drained penguin nesting area. Well-defined A horizon below a continuous vegetation cover. Phosphatisation evidenced by whitish discontinuous B horizon starting at 20 cm. Crumbs in A horizon. Single-grains condition and medium granular structure in B horizon. Ice-cemented permafrost at 50 cm
A6	50	D > M > C > L	Andic Umbriturbel; Umbri-Turbic Cryosol	Close to pedon A5 but with a longer time of abandonment as evidenced by the well-developed vegetation cover and presence of A horizon. Ice-cemented permafrost at 60 cm
A1	45	D > L	Andic Umbriturbel; Umbri-Turbic Cryosol	Well-drained uplifted terrace, at the lower part of a slope. Continuous vegetation cover and well defined A horizon. Indirect penguin influence through lateral percolates from former rookeries
A5	45	P	Typic Haploturbel; Andi-Turbic Cryosol	Represents the most recently abandoned rookery, adjacent to the current penguin nesting area. Incipient A horizon, below a well-developed *P. crispa* cover. Ice-cemented permafrost at 65 cm
A2	32	M > D	Psammentic Aquiturbe; Oxyaqui-Turbic Cryosol	Similar to A1 but poorly drained, with predominance of mosses. This site receives a high amount of leacheates from upslope rookeries
A7	23	M > D	Terric Fibristel; Turbi-Histic Cryosol	Moss peat on uplifted marine terrace. Fibric, 50 cm deep, O horizon overlying a mineral horizon. Ice-cemented permafrost at 70 cm from the soil surface
A8	5	D > M > C	Andic Cryofluvent; Gelic Fluvisol	Marine terrace under strong influence of nutrient-rich leacheates from upslope penguin rookeries. Frequent occurrence of phosphatic, white precipitates on rock surfaces. Single grain

M mosses, *L* lichens, *D D. antarctica, C C. quietensis*, *P P. crispa.* [a] (m a.s.l.)

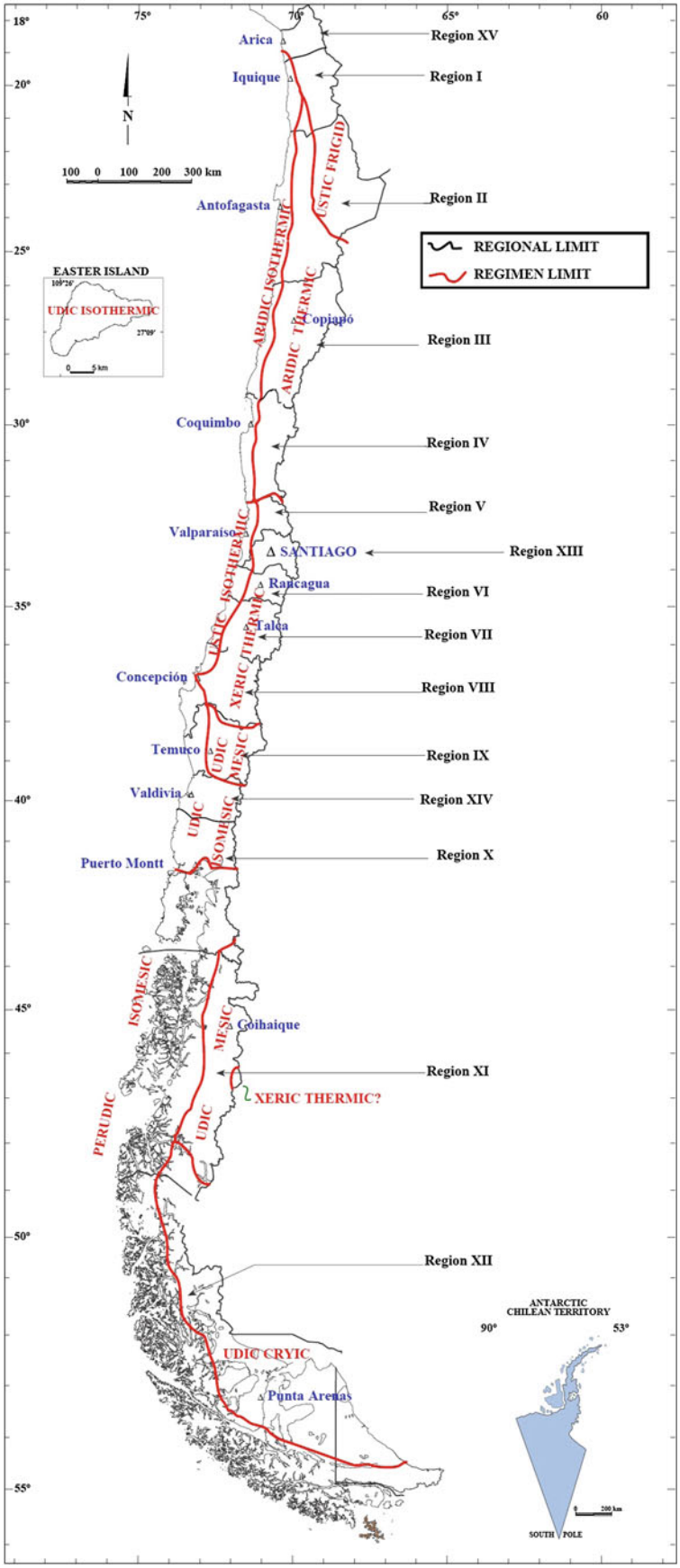

Fig. 2.87 Actual soil temperature and soil moisture regimes for Chile (Luzio et al. 2010)

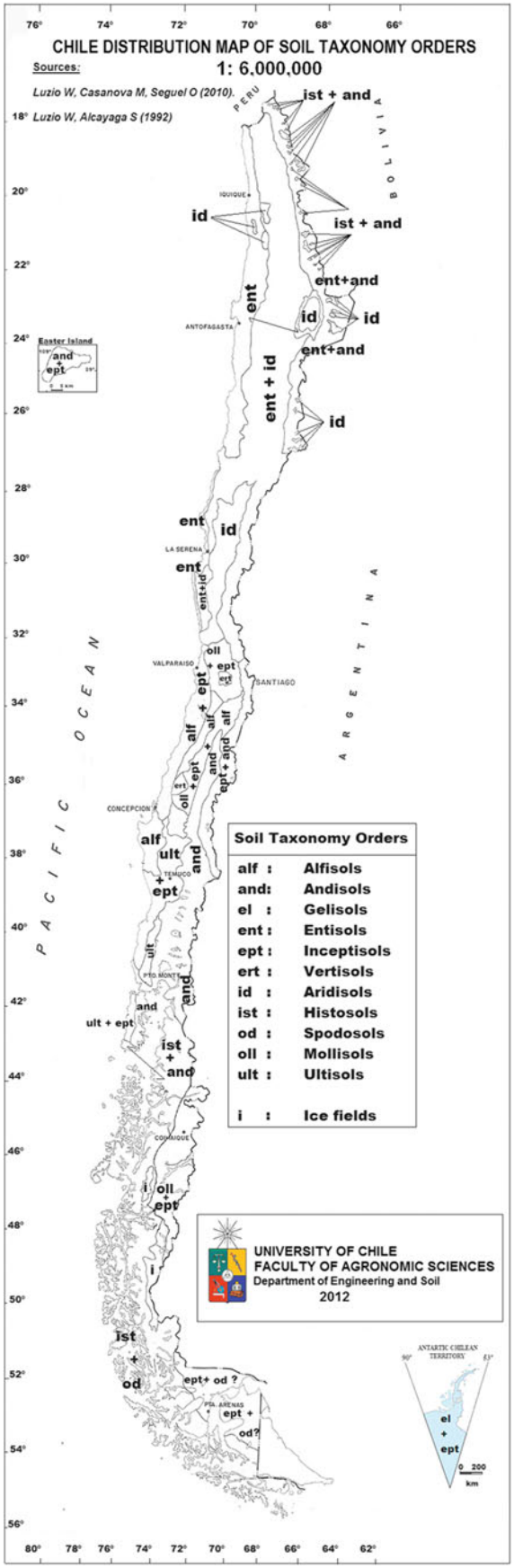

Fig. 2.88 Distribution of current Soil Taxonomy orders in Chile

2.3 A Soil Map of Chile

Although high soil variability is probably present in any particular major soil zone, there are at least two elements that can be considered relatively constant; moisture and temperature regimes in the control section of the soils are studied when soil mapping is the objective (Luzio et al. 2010). Figure 2.87 summarises the soil moisture and temperature regimes for Chile proposed by van Wambeke (1981) and van Wambeke and Luzio (1982) reported by Luzio et al. (2010).

Finally, we present a map showing the distribution of Soil Taxonomy system (USDA) orders observed in Chile (Fig. 2.88). It consists of a broad-based inventory of soils that occur in a repeatable pattern on the landscape, including the probable classification and extent of the soils. The map shows at least 14 different soil mapping units described in the legend at the level of soil orders, represents the state of current knowledge. Each polygon shows the dominant soil order present and identifies the soil order possessing the largest summed component percentage (largest land area) for each map unit. However, this soil distribution map should only be used to compare the general distribution of different soil orders.

Scaled to 1:6,000,000, it is the first informative level for a soil map of Chile, and is also a tool for soil correlation at the continental level. Soil regions are a regionally restricted part of the soil cover characterised by a typical climate, geomorphology and parent material association.

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