

1 Introduction and overview

ROBERT J. PANKHURST & FRANCISCO HERVÉ

Chile is, geographically, an unusual and in many ways astonishing country (Fig. 1.1). It stretches north–south along the South American mainland for over 4000 km, from 18°S, where the Altiplano is shared with Peru, Bolivia and Argentina, to 56°S at Tierra del Fuego and the islands of Cape Horn, the next stop being Antarctica. Its western margin everywhere is the Pacific Ocean, and its eastern boundary is the summit of the Andes mountains, so that in a width of rarely more than 200 km, the topography rises from sea level to a maximum of almost seven thousand metres. Climatic variations reflect this extraordinary topography. The north is characterized by the Atacama Desert, considered to be the driest place on Earth. The south is in the temperate rainforest zone, with vegetation that struggles against the prevailing westerly gales. In this southern sector the land is moulded by recent glaciations that carved the coastal areas into fiords and archipelagos consisting of thousands of islands; the length of the Chilean coastline including these islands must exceed that of many other countries that have a larger surface area. It is the extreme variety represented by these factors that have led to Chile becoming such an attractive tourist destination, despite the isolation and comparative difficulty of access of many of its geomorphological treasures.

Figure 1.1 shows the distribution of the main tectonic and geomorphological features of Chile. The northern and central parts of the country can be reasonably divided into three north–south zones. The coastal zone (zone 1) is the Coastal Cordillera, consisting predominantly of Late Palaeozoic and Mesozoic igneous rocks, with paired belts of Palaeozoic metamorphic rocks cropping out south of Pichilemu (Fig. 1.1, zone 1a). The coastal batholith of Late Palaeozoic igneous rocks continues down to about 38°S, where it apparently passes eastwards into Argentina. In southern Chile the coastal zone (1b) is mainly represented by metasedimentary turbidites, once thought to be Palaeozoic in age but now known to be largely Mesozoic, apart from the Isla Madre de Dios area, which is interpreted as an accreted terrane with Permian limestones. The central depression (zone 2), or Central Valley, is a downwarp with a Mesozoic to Quaternary sedimentary fill; south of Santiago, this is the main agricultural zone and contains several major cities. In southern Chile the central valley is not recognized and the transition between the coastal turbidites and the Andes is dominated by the Mesozoic–Cenozoic calcalkaline igneous rocks of the Patagonian batholith – one of the longest continuous granitoid bodies in the world.

Overall, the geological evolution of Chile has resulted from the effects of east-directed subduction of Pacific (and proto-Pacific) ocean floor beneath the South American continent. This subduction is the force that generated the Andes, a chain of mountains (zone 3) whose primary uplift dates back to a Miocene event, but whose emergence continues today, as exemplified by major earthquake activity. Their elevation is accompanied by significant crustal shortening, principally accommodated by eastward thrusting. The mountain chain continues right down into Tierra del Fuego at the southern tip of Chile, albeit with continuous reduction in height. Subduction of the Nazca Plate (Fig. 1.1) is currently active, but in the southernmost sector, where the triple-junction with the

Antarctic Plate has steadily migrated northwards as far as the Taitao Peninsula (*c.* 47°S), it has slowed to about 2 cm/year.

Present-day and recent subduction is also evidenced by an almost continuous line of active and dormant volcanoes, mostly andesitic stratovolcanoes, that are studded along the entire length of the country, accounting for some 10% of the circum-Pacific ‘ring of fire’. They comprise the Central and Southern Andean volcanic zones, separated by a short volcanic gap between latitudes *c.* 27° and 31°S, due to a zone of subduction with unusually shallow dip (the so-called ‘flat slab’ zone), where the Central Valley is also absent. The northern volcanoes are built on the Altiplano, a high plateau area where the crust is up to 70 km thick, with a southern extension into the Puna of NW Argentina. Figure 1.2 shows the progress of a minor volcanic eruption in this zone. Significantly, this northern sector with thick continental crust is where the rich mineral wealth of Chile (Cu, Au, Ag) is prominently developed. The Southern Andean Volcanic Zone and the Main Cordillera reach the coast of the mainland, opposite the offshore archipelago, with the southernmost part sometimes being distinguished as the Austral Volcanic Zone due to the more basaltic composition of the volcanic products.

The pre-Andean (*sensu stricto*) geology, including the Coastal Cordillera and Patagonian batholiths, and the Palaeozoic igneous and metamorphic rocks, was also largely formed during east-directed subduction episodes, though in the latter case of a rather different character, with accretion of forearc and distal oceanic deposits, and even small exotic terranes. Chile is thus a most appropriate place in which to investigate models of crustal growth through magmatic and tectonic accretionary processes. The long-lived reworking of crustal material, especially where the continental crust is thickest, in a stable subduction environment is a major factor in the formation of the mineral wealth of the Chilean Andes.

The scenic diversity of this country, which lies directly above an ocean–continent subduction zone that has been continuously active since early Mesozoic times, is illustrated in Figure 1.3.

This book is intended to present a comprehensive picture of the evolution of Chilean geology, written by some of the most respected experts in the subject. However, it is appropriate to acknowledge the pioneering work of previous generations in revealing the essential background and describing features that we now have the luxury of interpreting from the standpoint of a modern state of knowledge.

One of the first to record aspects of the geology of Chile was the naturalist Charles Darwin (1809–1882), who travelled round Cape Horn and up the coast of southern Chile during the second such voyage of the *Beagle* in 1834/35. At the start, he made the first description of Cretaceous ammonites near Punta Arenas. Subsequently, he spent the best part of a year on land, travelling south as far as the Chonos Archipelago, where he first described the schists of the accretionary complex, and north to Copiapó, as well as crossing the Andes from Valparaíso to Mendoza. He saw Osorno in eruption and visited Concepción shortly after a major earthquake. His observations, first published in his diary (1836), show how



Fig. 1.1. Sketch map of Chile, showing the main topographical zones: 1, Coastal Zone; 2, Central Depression; 3, Main Cordillera; 4, Magallanes Basin. Active and dormant volcanoes, and the generalized location of eastward-dipping subduction zones are schematically illustrated. See text for further explanation.

thoroughly he had absorbed and applied the then revolutionary uniformitarian ideas of Charles Lyell, the first volume of whose *Principles of Geology* had been published just before the ship left Britain. In particular he remarked upon evidence for the uplift of land during earthquakes and deduced how over geological time this could explain raised terraces and, indeed, the uplift of the Andes themselves: he even noted earthquakes as the cause of tsunamis. His appreciation of geological processes extended to the volcanic activity associated with this 'upheaval' and the denudation by erosion of the uplifted crust to form the thick sedimentary deposits covering much of Patagonia.

Darwin's contemporary, Ignaz (Ignacio) Domeyko (1802–1889), was born in Polish Lithuania and was involved in his early life in the struggle against Russian domination. He was invited to Chile in 1838 and spent the next 30 years investigating the natural history and mineralogy of his second homeland. He was the first to demonstrate the presence of Jurassic rocks in the Andean cordillera; he discovered many economic deposits of coal and copper, but was also involved in the establishment of ethical and conservationist policies for their exploitation. In

1843 he was a founder member of the Faculty of Mathematical and Physical Sciences at the University of Chile, of which he became Rector in 1867. Chilean plants, fossils, minerals, and a mountain range now bear his name.

There have been previous books on the geology of Chile as a whole, most notably those of Hans Bruggen (1950), Carlos Ruiz *et al.* (1965), Jorge Muñoz Cristi (1973) and José Frutos *et al.* (1986). Naturally, each of these illustrates and builds on the progressive increase in knowledge of Chilean earth science with the passing decades, and a growing understanding of the tectonic processes that have forged this far edge of the Americas. Ruiz *et al.*'s *Geología y Yacimientos Metalíferos de Chile* was published in 1965 by the Instituto de Investigaciones Geológicas (IIG), of which he was director: this was the state organization which preceded the present Servicio Nacional de Geología y Minería (SERNAGEOMIN). It was the most comprehensive of these earlier books, and demonstrated the close connection between geological studies and mineral exploration, which has become a strong tradition in Chile, since the production of copper has always been the basis of the country's economy (except for fifty years at the end of the nineteenth

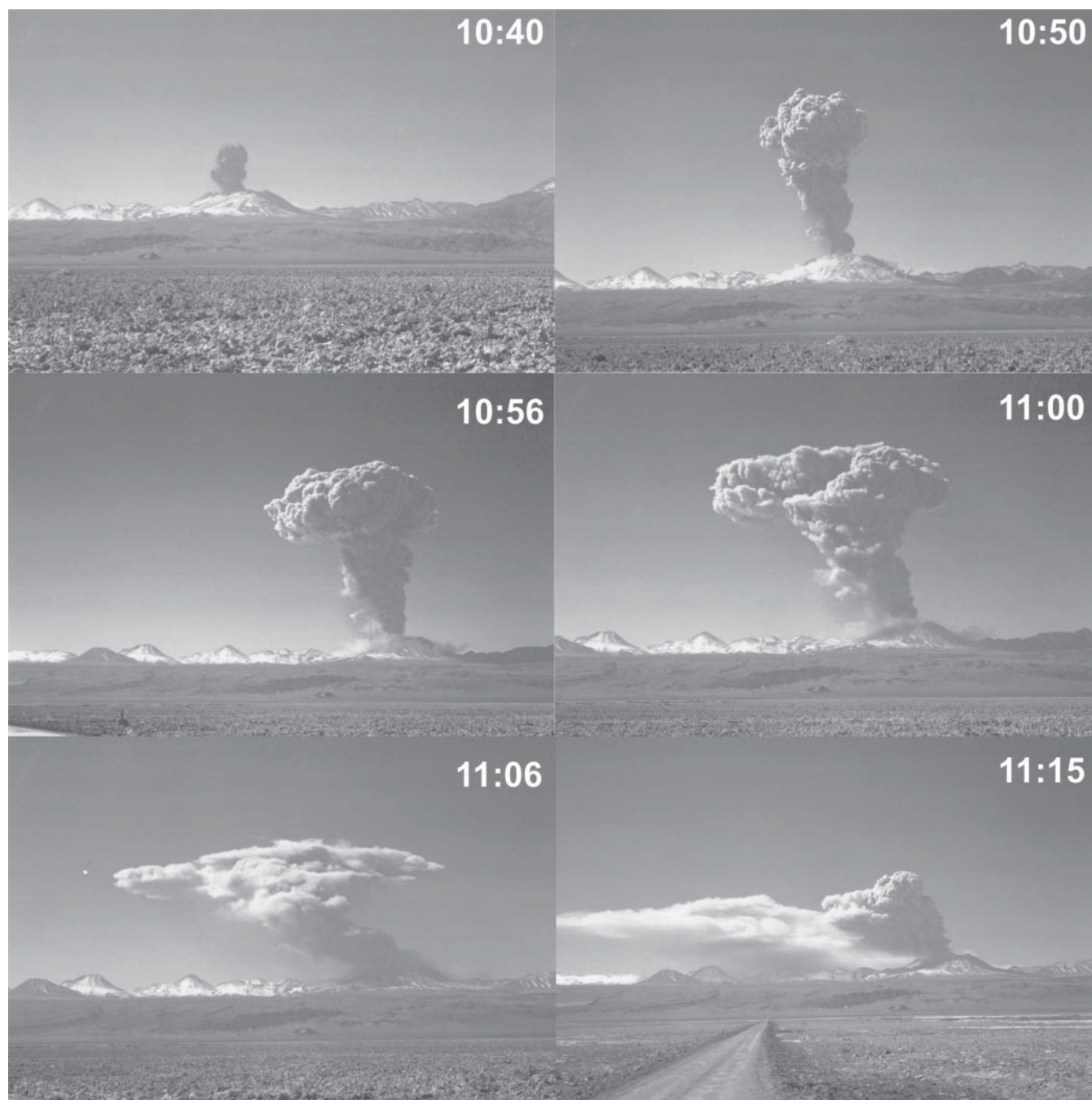


Fig. 1.2. Modern arc volcanism in Chile: ash eruption of Volcan Lascar on 20 July 2000 (see Chapters 5 and 13). View from the Quaternary evaporites of the Salar de Atacama to the west: each frame shows the approximate time during this short-lived eruption. The photographs show the flattening of the plume at the base of the stratosphere, and a second smaller pulse in the final frame. This volcano, at 23°22'S, 67°44'W, has been the most active of Chilean volcanoes in historic times, erupting over 15 times in the twentieth century; the largest eruption in 1993 when a subplinian eruptive column rose over 20 km rose above the crater. The most recent eruption (as at December 2005) was in May 2005 when a small explosion generated ash which dispersed towards Argentina. It is an andesite-to-dacite stratovolcano, 1400 m high, rising from the Chilean Altiplano to a summit elevation of 5592 m. The volcano erupts through the thickest continental crust in the world, in a zone of regional compression above the actively subducting Nazca Plate. The volcanic edifice has been built on Miocene dacitic ignimbrites erupted during the early evolution of the arc. Photo: Robert J. Pankhurst.

and beginning of the twentieth centuries, when the export of naturally occurring nitrates from the evaporitic deposits of the Atacama region was paramount). Because of its economic importance, the geology of the mining areas in northern Chile has always received much more attention, and was thus far better known, than that of the vast expanses of southern Chile, where very much less mineral wealth has been found.

Geological maps of the whole country at the scale of 1:1 000 000 were published in 1960, 1968 and 1980 by IIG, and in 2002 by SERNAGEOMIN. Significantly, this last issue is also available in digital format. Larger-scale maps have existed for many areas, but still do not cover the whole extent of Chilean territory, and are concentrated in the north, where mining is widespread.

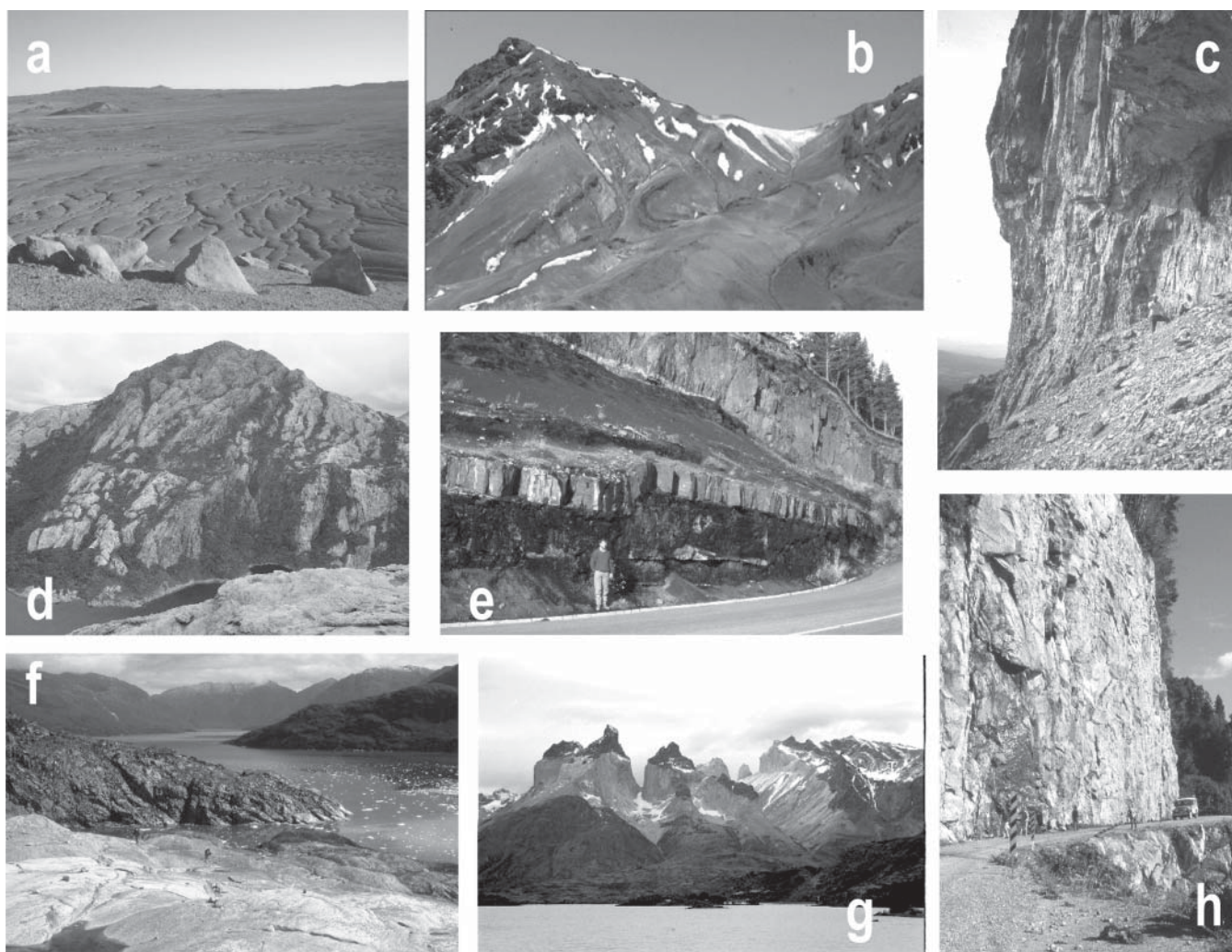


Fig. 1.3. (a) ‘Piel y camanchaca’ – a wind-sculpted feature of the Atacama Desert, where the hyperarid climate can result in the surface remaining undisturbed for thousands of years. (b) Carboniferous to Early Permian limestones in the Madre de Dios archipelago, part of an exotic terrane accreted to the southwestern margin of Gondwana (photo: Fernando Sepúlveda). (c) Thrust deformation in the Andes of Central Chile. The uppermost unit on the left (west) consists of Permo-Triassic volcanic rocks of the Pastos Blancos Formation, thrust over the overturned Miocene Tilito Formation. (d) Dolerite sills (?Tertiary) cutting Cretaceous black shales of the Katterfeld Formation, near Coyhaique. (e) Evidence of recent glacier recession in the South Patagonian Batholith, Seno Iceberg, where freshly exposed granite in the foreground lacks the otherwise dominant cover of lichen, grasses or shrubs. (f) Destruction of the city of Valparaíso by a major earthquake in 1906. (g) Torres del Paine, near Puerto Natales, a Late Miocene laccolithic body of pale granite emplaced in dark-coloured Cretaceous sedimentary rocks. (h) A 20-m thick ignimbrite flow of the Divisadero Formation (Cretaceous), Aysén.

The following 12 chapters firstly deal with the basement geology (Chapter 2), examining the commonly fragmentary evidence for Pre-Andean events. This is followed by accounts of Andean tectonostratigraphy (Chapter 3) and magmatism (Chapter 4), which together provide an encyclopaedic wealth of information on Chilean igneous complexes and sedimentary successions. Chapter 4 leads seamlessly into an account of the astonishingly active recent volcanic activity (Chapter 5) and the world-class metallic ore deposits which have proven to be so critical to the welfare of the country (Chapter 6). The economic theme continues with reports on non-metallic industrial minerals, including the famous and peculiar Atacama nitrates (Chapter 7), and by an overview of Chilean water resources (Chapter 8), many of which in arid northern Chile have been severely impacted by natural and anthropogenic metal pollution.

The subject then turns to geophysics with an examination of neotectonics (Chapter 9) and earthquakes (Chapter 10), the hazardous frequency of which is a daily fact of life for the Chilean population. Chapter 11 deals with the marine geology and oceanography of the offshore Pacific, a subject that continues to attract much research, not least from those seeking to understand world climatic variations. This marine Quaternary chapter is succeeded by one written from the perspective of land-based Quaternary scientists (Chapter 12), concluding with an account examining human colonization of southernmost America. Finally, the editors offer a geological description of a drive from the mediterranean landscapes of central Chile to the hyperarid Atacama Desert (Chapter 13). This last contribution is designed to give visitors a chance to experience for themselves the geology and scenery of this extraordinary country.