
Book Review

The Geology of Chile. By Teresa MORENO and Wes GIBBONS (eds.) (2007). Geological Society. London (United Kingdom). 414 pages, 286 figures including maps, charts and pictures; 27, 5 x 21 cm, ISBN 978-1-86239-219-9 (hardback) and ISBN 978-1-86239-220-5 (softback).

Earth Science books or journals assembling review papers on the geology of a country are always welcome, since they usually provide updated “states-of-the-art” about the knowledge of the region considered. Sometimes, these paper assemblages focus on exceptional regions where the Earth system is especially active and alive. This is the case of **The Geology of Chile**, a book that deals with a region where active oceanic-continent subduction is giving rise to one of the most important ranges on Earth. The Andean orogen is a natural laboratory where the current mainstream of Earth Science research has been installed during the last decades, focusing on the study of the geological hard records (see for instance the sets of publications resulting from the *International Symposiums on Andean Geodynamics*- ISAG; and from the *GEOSUR* meetings: Menichetti and Tassone, eds. 2007 and 2008 and references therein), but also on the interplay between internal and external processes (i.e. tectonics –magmatism –atmospheric and oceanic circulation –basin evolution (Montgomery et al., 2001; Lamb and Davis, 2003; Dunai et al., 2005; Ghosh et al., 2006; Strecker et al. 2007)). The onshore and offshore domains of Chile include some of the most exciting and diverse geological features in the world. Most of Chilean territory, apart from its Pacific Islands, stretches from 18° to 56° of latitude south, between the backbone of the Andean Cordillera summits and the Pacific Ocean, in an up to a few hundred kilometres in wide fringe. The very changing landscapes and the visibly active geological processes taking place in the region attracted the admiring attention of foreign and local researchers since XIX century: Spectacular coastal cliffs and hyper-arid deserts to the north; glacier systems, lakes and fjords to the south; high mountains along the east including the world’s second largest plateau, active volcanoes and astonishingly well exposed and preserved volcanic and hydrothermal systems. Both volcanic eruptions and the very persistent and sometimes very intense earthquakes added to the spectacular geological features the feeling of continuous, endless geological activity. Moreover, the huge mineral

resources in Chile soon called the attention of local and foreign geologists who, challenging the sometimes very rigorous work conditions on the ground, contributed to build the present knowledge on its mineral deposits. As a consequence, a part of the geological knowledge of Chile is closely linked to the existence of these sometimes unique mineral deposits, which resulted from the widespread tectono-magmatic processes, in turn linked to long lasting subduction along this segment of the South America Pacific margin. So many subjects of interest put very soon the geology of Chile in the mainstream of Earth Science research and resulted in a close cooperation between Chilean and foreign research groups, a fact that has led to an increasing knowledge gathered in successive synthetic books (i.e., Bruggen, 1950; Ruiz et al., 1965; Muñoz Cristi, 1973; Frutos et al., 1986; Reutter et al., 1994). Nevertheless, from the end of the XXth century there has been a niche open for some time now that would hold a book on the general geological features of Chile that is more up to date than some of the above-mentioned contributions. **The Geology of Chile** goes some way toward satisfying this requirement and so, with some caveats to be addressed below, may confidently be recommended to earth scientists who wish an updated view of some major aspects of the Chilean Geology.

Everybody who has edited a compilation of papers on any subject knows how time consuming and long lasting may be this task. Therefore, to thank the book editors, Drs. T. Moreno and W. Gibbons, their effort to assembly and “interface” 13 contributions by 73 co-authors, which were reviewed by 22 referees, is a must. Also authors deserve deep acknowledgement and congratulations for writing these synthetic papers and gathering all the cited references to achieve their comprehensive contributions. We now have an enormously improved additional data base for thinking about the complexity of the Central and Southern Andes and its conceptual meaning.

On balance, this is a very useful and well-produced book although it does present some unavoidable difficulties and peccadilloes. The potential readers of this volume must be aware that it is not a homogeneous synthesis but overall this is a most valuable compilation of papers. The aim of covering all the country and a variety of subjects has been faced with ambition. Editors and authors tried their best, and this has not been an easy task, especially

for those contributions dealing with complex, multidisciplinary subjects and long time periods. The diversity of subjects and the diverse profiles of the contributing authors have resulted in diverse writing style and organization of the successive book chapters, although the efforts made by the editors solved most of potential discrepancies (see for instance Editorial acknowledgements in pg. vi). Given the more than considerable effort likely devoted to this volume, one is entitled to ask whether the philosophy of assembling papers from diverse authors and diverse subjects has paid off. Whether one answers yes or no, it is clear that this book includes an extraordinary wealth of data that should prove very useful for the researchers currently or in the future involved in the study of some of the described Chilean zones and their associated geological processes.

As usual in this kind of ambitious editorial projects, other minor formal flaws are conspicuous and easily detectable. Thus, illustration style is diverse and changing from one chapter to the others; maps, some of them in colour, display diverse formats and design and in some cases the size of publication is not the most suitable. On broad outline, the quality of edition and printing of this book (good paper and binding) is up to the Geological Society's usual high standards. Nevertheless, some of the drawn figures and pictures are poorly reproduced and, in a few cases, the dark grey shades may obscure them. On the other side, in some larger size drawn figures and pictures irregular stepped lines and "pixeling" occur.

The papers in the book cover key research and applied themes in the area including plate tectonics, tectonostratigraphic evolution, magmatism-vulcanism and metamorphism, mineral deposits and raw materials, water resources, seismology and Quaternary to Recent palaeoceanography and palaeoclimatology. The first chapter (**Introduction and overview**) by R.J. Pankhurst and F. Hervé (pgs. 1 to 4, 3 figures) opens by giving a short introduction to the major geographic, tectonic and morphostructural characteristics of Chile, as well as to the more than exceptional characteristics of the Chilean geology. Due to obvious reasons of origin and work experience, both authors have an excellent knowledge of the Andean geology and provide a very synthetic approach to the major geological features of the region and the driving forces that originated them. Moreover, they do not forget to homage to some pioneers of the XIXth century (Charles Darwin, Ignacio Domeyko) who carried out observations and works that were the seed of a still continuing fruitful research history. Also attention is paid to some of the previous books on the Geology of Chile as a whole (i.e., Bruggen, 1950; Ruiz et al., 1965; Muñoz Cristi, 1973; Frutos et al., 1986), as well to emphasize the fact that some advances in the knowledge of the Chilean geology

have been closely connected with the exploration of mineral deposits. The chapter finishes with some comments on the contents of the remaining 12 chapters, providing a tenuous thread to relate them each other.

Chapter 2 covers **Metamorphic and plutonic basement complexes** by F. Hervé et al. (pgs 5 to 19, 7 figures) and presents a synthetic description of the different units that constitute the Chilean geological basement. It offers a general view of the main metamorphic and plutonic complexes from Chile, although focusing mainly on the former. The provided information, although gathering commonly fragmentary evidence on the Pre-Andean record, is exhaustive and well framed following a terrane model proposed by Bahlburg and Hervé (1997). This model includes all the main metamorphic and plutonic complexes and goes through all of them, from older to younger and from north to south. This information is based on existing bibliography and includes geological setting, metamorphic characteristics and age. At the end, this contribution provides very synthetic information on the geodynamic setting of Chile and its evolution through Palaeozoic and Mesozoic. Graphical information includes two maps and graphs of metamorphic trajectories. All the basement complexes are located in a geological sketch of Chile, which can be used to follow the text. It may be considered that the scale of representation of this map is not appropriate, since the complexes are represented in a too small size and there is a lot of information included, so that the reading of this map is not straightforward. The southern complexes deserve a separate more detailed map, easier to read. On the other hand, PT graphs offer a useful compilation of PT paths of most of the metamorphic complexes. On the whole, this book section allows the reader to get a general idea on the evolution of the Chilean metamorphic and igneous complexes through geological history and on their geodynamic setting. It is a good up to date review in order to get introduced to this subject and to the more relevant bibliography of the Chilean basement.

Tectonostratigraphic evolution of the Andean Orogen in Chile is covered in Chapter 3 (pgs. 21 to 114, 70 figures including maps, cross sections, stratigraphic logs and chronostratigraphic charts) by R. Charrier et al. It is a real Geological History (93 pages!) of the Andean country, since all the stratigraphic formations in Chile are cited and described with diverse extent. This ambitious aim was obviously difficult to achieve and it must be acknowledged to the authors the "tour de force" that they carried out. The text of this section is necessarily long and complexly organized as shown by the several levels of heading used in it. Headings and subheadings refer to the description of evolutionary cycles and stages in the diverse sectors that the country was split into for descrip-

tion. A better design of these headings and its organization (i.e. using different kinds of lettering or numbers) might have helped readers, as well as the use of different letter sizes to emphasize which was the “first reading” significant information. The amplitude of the scope of this book section has resulted in some minor repetition (i.e. basin inversion is mentioned as a process developing at the end of “First stage of Andean Cycle”, but in fact this process characterizes the Second Stage of the Cycle). Despite these initial difficulties the authors manage to make clear the proposal of five major cycles (Pampean, Famatinian, Gondwana, Pre-Andean, Andean) as well as their characteristics and evolution. On broad outline, the second half of this contribution is more synthetic, interpretative and clearer for the not acquainted reader. Several sections of the chapter (Discussion, Tectonic evolution, Tectonic history, Summary and discussion, Final overview) provide a good summarized view of the tectonostratigraphic evolution of Chile and, combined with good, profuse illustration (chronostratigraphic charts, palaeogeographic sections and maps), make up the backbone of this contribution. Some figures have been taken from former publications and they show very diverse design (see for instance figures 3.1 and 3.2). Despite these minor inconveniences, the readers who expend their time connecting the huge amount of information will realize that quality and not just quantity characterizes this well documented and mature contribution.

The **Andean magmatism**, (pg. 115 to 146, 19 figures) is the subject of Chapter 4 by Parada et al., a dense synthesis the knowledge on this subject in Chile. Chile has been the place of widespread magmatism along an active orogenic margin since Palaeozoic times, and this activity has been developed as pulses in a number of geodynamic situations: arc magmatism, contractional tectonics leading to crustal thickening, subduction-related extensional tectonics with bimodal volcanism, obduction of ophiolite terranes, and so on. Both crust and mantle were the magma sources, with prevalence periods of either one or another, and also coexistence of both. Chile extends some 4000 km along the Central and Southern Andean orogen, and this fact has resulted in changing geometrical relationships between the subducting oceanic plate and the opposite continental margin, including subduction of oceanic ridges. Important variation of the Benioff zone inclination along this continental margin has resulted into changing longitudinal continuity and variation of igneous activity. Last but not least, a substantial part of the economy of the country during XX and XXI centuries has been or will be directly related to giant base- and precious metal deposits (mainly porphyry copper deposits) directly related to igneous bodies, a fact that was well understood by the country authorities and the private owners of metal deposits. This fact has been fostering a continuous flux of

studies (both fundamental and applied) on igneous rocks. Once given these premises, studies on the Chilean magmatism have been very important and largely developed during the last 30 years, and were performed with an adequate use of petrology knowledge and advanced tools, including extensive use of geochronology and radiogenic isotopy of petrogenetic interest. For this achievement, Chilean scientists have developed their work in parallel and frequently in close relation to international teams of research, and therefore have been in the middle of the mainstream petrologic developments over this period. The country is large, but most of the petrologic work has been performed in the central and northern sectors, a fact obviously related to the availability of excellent outcrops, the developing mining industry and the clustering of the main scientific structures of the country. This fact is also reflected in this chapter that is somewhat irregular but in any case also very interesting for a reader not just interested in Chilean geology, but also in understanding how to face the study of subduction related settings and the geology of accretion along continental plate margins. Therefore, one may keep in mind the learning acquired on this excellent, huge natural laboratory and not hesitating in suggesting careful reading and analysis of the integrative use made of trace element, geochronology and radiogenic isotopy in the study of igneous petrology in Chile. Those researchers interested in the development of orogen-related magmatism will find very stimulating ideas in this chapter, and may be a model to elucidate and improve understanding of magmatic processes in ancient Phanerozoic orogenic belts (i.e. Cadomian, Caledonian, Variscan).

Chapter 5 (**Chilean volcanoes**, by Stern et al., pgs. 147-178, 43 figures) is arranged in two parts: the initial one offers a geological setting of the three volcanic zones of the Andean cordillera placed in Chile: the Central Volcanic Zone (in the northern part of Chile, and mainly shared with Bolivia and Peru) and the Southern and Austral Volcanic Zones, mainly affecting to Chile but also disposed along upper mountain highs along the Chile-Argentine boundary, and in a minor extent in the latter country. This geological setting complements (but can easily be followed independently) the one in the chapter on **Andean magmatism**, and it is very clearly written to a reader not familiar with the Andean orogen in Chile. From a practical point of view, this geological setting is implemented in the text by subzones, and in each one is offered information on the most prominent volcano structures, in terms of main composition, eruptive mechanisms (in a very general view) and volcanic risk. The reader should not expect an exhaustive compilation on all Chilean volcanoes, since its great number precludes this possibility; but all the most significant are included. A greater detail is devoted to the Southern Volcanic Zone, since there is a great concentration of volcanoes with his-

toric activity, and overlaps in a great extent with the most populated areas of Chile. In fact, this reflects the surveying activity and intensive mapping research currently ongoing by the national geological survey SERNA-GEOMIN. The second part of the chapter is devoted to the petrogenesis of Quaternary Andean volcanoes of Chile and, in spite of the synthetic draft, offers an updated and intensive approach to this subject, and constitutes an excellent lesson of petrology for all people concerned with orogenic magmatism and plate tectonics. In this sense it is again a companion paper of the precedent chapter on **Andean magmatism**, mainly referred to the current state of the magma petrogenesis and plate tectonics relationships. Finally, a short reference to Chilean ocean-floor volcanism and oceanic islands closes this chapter.

Chapter 6 on **Metallic ore deposits** by Maksaev et al. (pgs 179-199, 12 figures) explores with a brief overview the mining history and metallogeny of Chile. The ore deposits are ordered according to their respective economic importance. Nine main deposit types are distinguished: i) porphyry copper-molybdenum deposits (the most abundant type of mineralization in the Chilean Andes), ii) epithermal precious metal deposits, iii) iron oxide copper-gold deposits, iv) iron oxide-apatite deposits, v) stratabound copper-(silver) deposits, vi) copper-silver-and gold-bearing veins, vii) sedimentary rock-hosted gold deposits, viii) gold-rich porphyry deposits, and ix) skarn deposits. Geology, mineralogy, radiometric ages and the processes involved in ore formation are discussed. Finally, the paper includes an overview of metallogenic evolution of the Chilean Andes. This chapter is a good review of the metallic ore deposits of Chile, and will be very useful to all geologists who wish to learn about an absolutely exceptional metallogenetical region developed along a convergent plate margin.

The Chapter 7 on **Industrial Minerals and Rocks** by Chong et al. (pgs. 201-214, 31 figures) deals with enlarging the information on the economic aspects of the Chilean geology. This text includes reports on non-metallic industrial minerals and raw materials including among the most significant salt, saline brines, clays, diatomites and nitrates. Nitrates, evaporites and evaporite-related resources, which were or are exploited in the Northern Chile deserts, are explained in more detail. This fact is clearly justified by the current economic interest of the evaporite-related resources and for the scientific interest and the historical importance of the nitrates. As a matter of fact, nitrates are world class deposits and were the most significant economic resource in Chile for more than 100 years. A well summarized synthesis is provided about some of the hypothesis proposed to explain their genesis that is still a matter of debate, although the gener-

al geological-palaeoenvironmental setting seems well understood (i.e. relation to the subduction setting and the very arid to hyperarid climatic regime that constrained the evolution of Northern Chile during Neogene and Quaternary times).

Chapter 8 by Muñoz et al. represents an attempt to summarize the salient points of the **Chilean water resources**. The chapter runs a total of 16 pages (215-230), which includes 9 well-prepared figures and 7 detailed tables. The chapter begins with an examination of the geographic background and its influence on climate. Then, it explores trends in climatic zones and hydrographical regions, and particular attention is paid to the hydrological patterns of surface and groundwater resources. Next, the chapter includes a section on water quality and related environmental issues. This section discusses the natural and anthropogenic controlling factors on water quality. It then concludes with a brief examination of the role of new environmental policy and regulations that will determine the future water resources management of Chile. This chapter is full of comprehensive information and will be a very useful summary for anybody interested in the water resources from Chile.

A comprehensive overview of the Neogene-Quaternary Nazca-South American plate interaction is introduced in the chapter 9 on **Neotectonics** by Cembrano et al. (pgs. 231 to 261, 29 figures). Active and passive ridge collision and migration and their connection with the flat-slab segmentation, and the role of plate coupling in the build-up of the Andes are discussed. The main body of the chapter is devoted to describe the setting of the region, its structural framework and its relation to the large-scale landscape configuration. Special attention is paid (10 pgs) to Pliocene-Pleistocene state of stress for the Central and Southern Chilean Andes based on the analysis of minor fault kinematics; a considerable number of local case studies illustrate the quality of the data. The authors outline (p. 256) the changes in regional stresses recorded by these data in contrast to the relatively constant plate kinematics. The convergence vector has not changed significantly during the past 6 Ma, and thus, plate kinematics can not account for these regional stress changes. The authors suggest different processes to explain the changes of the compressional direction in the Central and Southern Chile forearc. Finally, the former long term deformation data are compared with the short term data obtained from GPS measurements, which are only partly compatible (p. 260).

Chapter 10 by S.E. Barrientos on **Earthquakes in Chile** (pgs. 263-287, 31 figures) complements and extends the former one: it shows the current tectonic activity of the region. More than ten earthquakes with

magnitudes equal to or greater than magnitude 8 took place during the twentieth century, being the 1960 event the largest earthquake ever recorded since the beginning of instrumental seismicity. The author describes the general seismic characteristics of this seismic region with special attention to the large earthquakes, presenting a useful synthesis of the published seismological data, both historical and instrumental. The centroid-moment tensor solutions during a 26-year period (1980 - 2005), represented in four figures (22 to 25), illustrate the state of stress of the convergent margin, showing moment tensors compatible with low-angle thrusts earthquakes along the coast, whereas further inland these turn mainly into mechanisms of tensional type. The GPS efforts done during the last years are also reported. Finally, the author presents a short overview of the seismic hazard in Chile and discusses briefly the relationships between the seismicity and the plate interactions.

Chapter 11 focuses on **Marine Geology, oceanography and climate** (pgs. 289-308, 16 figures) and is a choral contribution coordinated by Dr. M. Marchant. Most of the co-authors are researchers who previously worked together and co-authored former papers. Therefore, the chapter content is well defined, coherent and focuses on the study of biogeochemical flows and their relation to the studies of palaeoceanography and palaeo-productivity, which are the research lines in which the authors have carried out their research, in the frame of a variety of cooperative Chilean - German oceanographic projects. It must be emphasized that the reader will miss some significant items in marine geology (i.e. geophysics of the continental margin, structural evolution, margin instability, and so on), a straightforward result of the research profiles of the authors. The chapter content is split into three parts, the first being an introductory *Tectonic and geomorphological setting*, which is written in a clear and plain way. This introduction deals with the current climatology, the descriptive oceanography and the subaerial and submarine physiography of the region, and provides the elements necessary to the better understanding of the remaining two parts. The second part (*Modern sedimentation*) shows the present distribution of the major sediment constituents (organic matter, carbonate organisms, siliceous phytoplankton and terrigenous material) with a modern approach to the importance of the particle transference from shallow sea to sea bottom. The extremely long latitudinal extent of the Chilean continental margin, together with the important associated oceanic circulation result in a distribution of the surface sediments that reveals a wide variety of physic and biological processes. These processes, combined with the physiography of the coast line (occurrence of upwelling and downwelling, counter-currents, fluvial contributions, deep fjords, extreme climatic situations, and so on) make the

Chilean continental margin one of the most singular ones in the world ocean. Finally, the third part (*Past sedimentation and palaeo-environmental implications*) focuses on the palaeoclimatic studies that the authors have been publishing during the last years. Thus, the studies of palaeo-productivity show the changing upwelling intensity, the shifting of the high biological productivity (eutrophic) zones from the Last Glacial Maximum until recent. The sharp rain gradient that occurs along the Chilean continental margin, from its southern maximum to its northern minimum, allows correlating the results of the sedimentological, mineralogical and geochemical studies of the terrigenous contributions with the palaeoclimatology on the continent and its influence on sedimentation along the continental margin. As a summary, this chapter (despite the mentioned omissions), is a very good and updated abstract of the developed subjects, mainly recent sedimentation and palaeoceanography along the Chilean continental margin.

Chapter 12 by C. Latorre et al. (pgs. 309-328, 11 figures) deals with **Late Quaternary environments and palaeoclimate of Chile**. Quaternary palaeoclimate is one of the most exciting and stimulating subjects of research in the Andean region, due to the formerly mentioned deep interrelationships between internal and external processes (i.e. mountain building and atmospheric and oceanic circulation). There is obvious linking between this chapter and chapter 11, since both of them share several aspects related to the palaeoclimate. Reading a review paper about this subject by the signing authors is a must, since it is largely well documented and the references are updated, showing the authors are fully aware of what is being published nowadays from Chile. The chapter begins with a very brief summary of what have been the main former reviews. As the authors state at the beginning of this chapter, providing a synthetic overview of the Quaternary evolution of the last 2 m.a. from different points of view is not a matter of a mere book chapter, but a book itself. Hence, they provide an overview of their research field and/or working area. Each author signs a section covering different aspects of the Late Quaternary evolution, such as palaeoceanography, palaeoecology, evolution of the vegetal cover, vegetal diversity, geomorphology, archaeology and palaeoclimatology. In this way, they achieve two main objectives: to ensure a high-quality overview and to provide a broad perspective of palaeoclimatic evolution of Chile. After reading this chapter, the reader has a good comprehensive synthesis of what has been the palaeoclimatic and palaeoenvironmental evolution of Chile since the Late Quaternary, and what research has been done up to now. At the end of the chapter, the authors provide what are, according to their opinion, the future challenges that the palaeoclimate and palaeoenvironment studies must afford. Most of the

researchers working in this region of the world will agree with their proposal.

Chapter 13 by W. Gibbons and T. Moreno (pg. 329 to 414, 5 figures) offers to the reader the opportunity of planning a long field trip from Santiago to the Atacama Desert, a snap-shot of Chilean geology ready to be tasted by everybody lucky enough for a rewarding and exciting experience.

An extensive list of references (pgs. 343 to 395) and an Index (pgs. 397 to 414) close the book, giving to the reader useful tools to search for the sources of the information used in the different chapters and extract its subjects of interest from the overwhelming amount of information. Although the book was published in 2007, some of the references correspond to 2006 papers, this fact being a guarantee of the as far as possible actualization of the provided list.

It would have been desirable that this book finished with a summary discussion by the editors and/or the authors with a more synthetic view of the geology of Chile. Although this is not the case, the book is still a lively, varied and argumentative contribution to modern knowledge of the Central and Southern Andes. For those who have had the chance and privilege of working on the Chilean Geology, this book will enable them to remember their experience, frame their observations and share other colleagues' contributions. For those who approach for the first time into the geology of this country, the book will be a discovery. Obviously, this paper assemblage will be submitted to reasonable criticisms from other authors who may consider either that some aspects are not developed enough (or at all), or that some of the ideas exposed are not correct. Let us remember Greek mythology: Sisyphus was a king punished by being cursed to roll a huge rock up a hill, only to see it roll down again, and to repeat this throughout eternity. Many earth-scientists might agree that this punishment reminds their hard (but in fact enjoyed) task to unravel Earth Evolution, task that needs permanent revision and revisiting once and again the rock record (their rolling rock) and using new views and technology. We must accept our knowledge is often provisory and that others after us will improve it. Nevertheless, the chapters of this book are solid contributions and will be essential reference during the near future for those interested in the Chilean regional geology and the general concepts derived from its study. The presence of this book is absolutely advisable on the shelves of Earth Science Departments and Libraries, as well as on the tables of teachers and researchers who are interested in some of the subjects the book deals with. Finally, we hope this book will be a stimulus for other South American colleagues to launch similar editorial projects to assemble the geologi-

cal knowledge treasured in other South America countries and regions. We trust they will find the most suitable support, coordination capacity and cooperation for this purpose.

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