Geoenvironmental Disaster Reduction

Vít Vilímek
Bryan Mark
Adam Emmer *Editors*

Geoenvironmental Changes in the Cordillera Blanca, Peru

Springer

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This book is dedicated to Marco Zapata and Alejo Cochachin Rapre

Foreword

The editors invited me to write the prologue to this book because I am undoubtedly the oldest of the Peruvian scholars who have studied the Cordillera Blanca comprehensively in its broader context, including its geology, its glaciers, its geodynamics, its vulnerability, its catastrophes, and its diverse inhabitants. Moreover, I have been fortunate to have not only witnessed and survived major geophysical events that have impacted so many lives in our region—like the 1970 earthquake—but also to have served a leading role in studying and mitigating potential hazards in this glaciated environment. My commentary below includes both general reflections on the book content and anecdotes from my personal experiences in the region.

First, like any other prologue author, one of my aims is to comment on this book's content and invite those interested in mountain research to read it. Indeed, this book will certainly be of great interest due to the diversity of topics it covers, both from the point of view of geosciences and the climate and the social sciences addressing the uncertain dimensions of the vulnerability within the Cordillera Blanca. Such vulnerabilities are complex and multidimensional, stemming from the diverse catastrophes of glacial origin that have occurred already, along with the fear and uncertainties that awaken within the inhabitants about their ongoing and future vulnerability to continued geohazard risks, decreases in water resources and agricultural challenges that cause social conflicts.

The Cordillera Blanca and the Santa and Conchucos valleys that channel its drainage have been of great interest for centuries due to the abundance and variety of natural resources they contain. It has also been the ideal place in the world to study the secrets of tropical mountains, given that it contains the highest and most extensively glacierized of all tropical mountains globally, exposed to dynamic geophysical forces. For this reason, many scholars from around the world have written extensively about the Cordillera Blanca. Likewise, this book stands out for bringing together a large group of specialists from various countries to contribute as authors to the diverse topics contained within these 15 chapters. Each chapter amplifies the details and current scientific understanding of many specific themes that have great importance for the general knowledge of this special region. Furthermore, the conclusions reached can be applied to serve the good of diverse populations inhabiting it through the public and private organizations informed by this book.

Second, having personally had the good fortune and opportunity to actively participate for more than 65 years in a multiplicity of actions related to each of the topics in the 15 chapters of this book, I will now take this opportunity to complement the enlightened opinions of the authors by sharing a few reflections from my own experiences.

Much research has been carried out on the Cordillera Blanca geology, yet little has been said about the structural events of the Quaternary, especially the implications of the longitudinal fault—the Cordillera Blanca Normal fault (CBNF). This is such a prominent feature of the landscape that evidences the dramatic tectonic forces of the region, which demand to be respected by any engineering projects. In fact, I recall three important projects that were proposed but ultimately not carried out in the 1960s and 1970s due to the presence of the CBNF trace.

The first case was the Recreta Dam project in Conococha, where we carried out a series of geotechnical and hydrological investigations to build an 1800 m long dam that would impound more than 200 million cubic meters of the Santa River at its headwaters. This would have served as a great water regulator for the Cañón del Pato Hydroelectric Power Plant and for the large irrigation projects of Chavi—Mochic on the right bank of the Santa River and Chinecas River on the left bank. After three years of investigations, including preliminary design constructions that remain relict on the landscape, the project was scrapped because the active CBNF crossed the projected dam.

The second case was the Querococha Dam, another potential reservoir idea which was discarded because it would have been too close to the fault line and raised similar concerns for the potential vulnerability of any structure to tectonic displacement.

The third case was the project of the Chorro Hydroelectric Power Plant downstream of the Cañón del Pato, a project that was also discarded due to the CBNF that crossed the proposed route of the tunnels. Interestingly, the confirming evidence of potential destruction was that some pre-Incan walls had been displaced by fault motion. Furthermore, there were large areas of landslides that were observed in the exact place where the electrical infrastructure was planned.

Regarding the regional geomorphology, in addition to all the beautiful features found at local scales within the glacial ravines that are described in this book, we have long recognized three distinct zones that can be identified from south to north within the Cordillera Blanca based on progressively greater relief:

(1) The southern zone spans from Conococha to Olleros in the Negro River and features wide plateaus 4000 m high over which glacial peaks rise to summits below 6000 m.
(2) The central zone that extends between Olleros and the Ulta ravine is where the relief increases, deepening the distance from the bottom of longer glacial ravines to higher peaks reaching over 6000 m.
(3) The northern zone features the greatest relief and largest differences in elevation between the Santa River and the summit of the snow-capped peaks. This zone includes the highest summit of the range, the Huascarán massif, and extends northward to encompass the valleys of Parón, Santa Cruz, Los Cedros, and the Quitaracsa stream, ending with the snow-capped Champara as the northern limit.

Regarding the retreat of glaciers, I have witnessed and documented profound evidence of climate change during my life in the formation of new lakes as glaciers have melted. The increase in the number of glacial lakes that have been inventoried from 1950 to the present date is visible proof of the increasing melting of the glaciers. According to the National Glacier Inventory prepared by INAIGEM in the year 2016, the Cordillera Blanca has lost 38.20% of its total ice mass between 1960 and 2016, and it has been predicted that by the early twenty-second century the Cordillera Blanca glaciers could completely disappear.

These are shocking transformations, and it can often be difficult to consider as just numbers. But I have witnessed specific lakes take form over time that provide a much more vivid point of reference for how rapidly this phase change can occur. For example, I only must remember the formation of the glacier Lake 513 above Carhuaz under the Hualcan massif. It was there that we observed directly as a large lake formed from a glacier. First detected by us in 1966, the lake became a risk for the city of Carhuaz in less than 20 years. Similarly, Lake Safuna below the snowy Pucahirca Norte Mountain in the northern Cordillera Blanca zone emerged from the melting glacier tongue and grew to more than 1500 m long and more than 100 m deep in only 18 years. In 1967, to predict how deep the Safuna Lake might become, we in the Peruana Del Santa Corporation drilled through the glacier tongue. The rotational drilling was carried out for over 72 hours and reached a depth of 150 m, very near the bedrock, indicating that the lake could continue to grow and deepen to fill the trough. It should be emphasized that this glacier drilling was the first such perforation carried out on any tropical glacier worldwide. Most prominent recently, Lake Palcacocha is an example of accelerated melt-induced lake growth that, despite being carefully recorded and monitored, continues to present an imminent danger for the city of Huaraz.

Without a doubt, one of the most important factors determining the susceptibility of these glacial lakes to outburst floods is related to landslides, rockfalls, and collapses of the lateral slopes of moraines bounding them. Obvious evidence of these are the landslides on the left slope of Lake Safuna Alta that caused a wave more than 50 m high that overtopped the moraine dam, leading to the lake overflow. In the same way, the slide from the left slope of the moraine bounding Lake Palcacocha produced overflows over its reinforced dams.

In my opinion, a priority topic to be investigated in greater detail is related to detecting the potential for rock slope collapses on the west and north faces of the Huascaran that are like the type that occurred on the North summit of Huascaran in 1970. This remains an unresolved challenge in evaluating hazard potential. Ongoing scientific efforts as documented in this book and others will surely provide more detailed information that can be used to build upon our earlier work.

While science understanding progresses within its own community of scholars and engineers, it has been my experience that the participation of local Andean residents living near or within glacial landscapes presents an extremely delicate social issue. Those of us who have lived and worked alongside these people for decades have seen examples of how their way of acting and thinking has changed over time. In our first decades of work, we more often encountered friendly local inhabitants with whom we could coordinate and exchange products and labor. Currently, some of these same residents have become distrustful and even intractable about sharing access to glacier valleys, and repeated efforts to talk or agree with public officials have failed.

Prominent examples of this breakdown in communication are what has happened with the residents of the Quebradas Honda and Parón, where residents have even completely taken over the entry and control of the discharge gates from potentially dangerous lakes below glaciers that were originally built for their safety. Even glaciology specialists have found it difficult to enter the Parón Valley to access and make routine observations on the Artesonraju glacier.

Another unfortunate case occurred on the dam of Lake 513 under the snowy Hualcan where the Swiss Cooperation installed sophisticated equipment for an early warning system that would alert downstream residents of a glacier lake outburst flood. However, given local issues of distrust stemming from cultural sensitivities expressed by local residents, the equipment was removed to prevent it being forcibly destroyed, thus preventing this important service from being useful to the larger city of Carhuaz.

Moreover, it is my opinion that the residents of cities, such as Huaraz, Caraz, or Carhuaz, are rather too passive in the face of these potential hazards and do not act in defense of their own interests. People have to participate in the civil processes to demand better services from public officials overseeing the organizations that are often underfunded or inadequately prioritizing the execution of hazard prevention operations and security infrastructure construction.

Lima, Peru Benjamín Morales Arnao

Preface

In compiling this book, we collectively acknowledge that our scientific efforts over multiple decades in the Cordillera Blanca have all been facilitated and elevated by close friendships, and we dedicate this book to the memory of two friends: Ing. Marco Zapata Luyo ("Marco") and Ing. Justiniano Alejo Cochachin Rapre ("Alejo"). Both served at different times as directors of the office in Huaraz that had charge of monitoring glaciers and lakes in the Cordillera Blanca. While this office has changed names and been transferred between different overseeing organizations over the years, many of the same people worked together, dedicated to the same important tasks. Each of us, in turn, has collaborated with many of them to conduct our research projects over the years, and all the work presented here has in some way or another been influenced by the observations, measurements, and careful maintenance of instrumentation carried out by the office. Below we share some brief biographical details to memorialize their lives and impactful service in stewarding information and expanding our understanding of this incredible mountain range.

Although he was born in the northern coastal city of Piura, Marco (Fig. 1) spent most of his life in Huaraz, working with the study of glaciers and lake security in the Cordillera Blanca. He was trained as a geological engineer at the National University of San Marcos. His studies were dedicated to cataloging and surveying the relative risk of proglacial lakes to dangerous outflow events. Our first encounters with Marco date to the mid-1990s, when he was working in Huaraz at the office known as the "Unidad de Glaciología y Recursos Hídricos" (UGRH), then under the auspices of Electroperú, the Peruvian state-owned hydropower company. What stands out in our minds was the warm welcome Marco extended, along with his characteristically broad smile and desire to work together cooperatively. The office was then under the directorship of Benjamin Morales Arnao, who had initiated the group in 1966 within the Corporación Peruana del Santa to monitor changes in glacier mass balance, survey lakes, and plan construction projects to prevent or mitigate flood disasters caused by glacier lake outbursts. Many of these efforts ended at the end of the twentieth century when the UGRH office was closed after Electroperú was privatized during the term of national Peruvian President Fujimori. Unfortunately, this meant that many of the previous precipitation and discharge gauging stations were abandoned during the 1997–98 El Niño event. Nevertheless, despite a few years of dormancy, the office reopened under the administration of the Peruvian National Institute of Natural Resources (Instituto Nacional de Recursos Naturales del Perú, INRENA), under the Agricultural Ministry. It was then in the early to mid-2000s that Marco served as office coordinator. In this capacity, Marco fostered expanded international research collaboration, often formalizing inter-institutional work agreements ("convenios" in Spanish). Such formalized convenios facilitated invaluable logistical support and collaborative fieldwork carried out by international research teams of faculty and students with the UGRH personnel, often leveraging federal funding for synergistic outcomes. For example, under Marco's oversight, Ohio State University researchers in collaboration with Canadian partners carried out an aerial LiDAR survey of glaciers in the Cordillera Blanca with funding from NASA and National Geographic. Such new data combined with NASA satellite imagery aided in a comprehensive inventory of glaciers and lakes led by INRENA. Marco shepherded multiple additional international research agreements with other groups from mostly Europe. After stepping down from active service at UGRH, Marco remained keenly interested in glacier and lake studies and was a devoted husband, father, and friend to many. He died in 2022.

Alejo (Fig. 2) likewise devoted his professional career to studying glaciers throughout Peru and beyond. He lived and worked in Huaraz, where, upon his death in 2023, he served as director of the office that by that time had its current denomination as the Sector for Evaluating and Monitoring Glaciers and Lakes ("Área de Evaluación y Monitoreo de Glaciares y Lagunas") within the National Water Authority of Peru (Autoridad Nacional del Agua, ANA). Alejo's soft-spoken and reserved personality were different than Marco's, but his working style was equally impactful. He was deeply committed to service in guiding applied glacier studies and hydrologic engineering, for which he was well trained. He earned his engineering degree in Agricultural and Civil Engineering, a master's degree in Environmental Management, and obtained an International Diploma in Glaciology, Climate Change and Disaster Risk Management via an International Internship at the University of Zurich-Switzerland. He gained competency with the numerical modeling of avalanches and floods, mapping of glacier-originated hazards, and early warning system. Beginning at the office in 2003, he gained extensive experience in the study of glaciers and high Andean lakes, carrying out field studies of lake bathymetry, hydrology, and the execution of hydraulic works. His scientific work took him to many international glacierized mountains, including Nepal, the European Alps, and Antarctica. Over his term as Director, the ANA office featured a broadening of research collaborations as many more international scientists became involved in projects in Peru.

No scientific effort ever stands completely alone, and all research progress depends upon the efforts of many other people and projects that went before. Hence, in dedicating this book to our close friends and colleagues Marco and Alejo, we also acknowledge all those scientists and engineers, technical staff, and administrators in Huaraz who have endured social, political, and climatic changes to maintain the study of this special Cordillera Blanca.

Fig. 1 Marco Zapata during his visit to European Alps (image: Marlene Torres de Zapata)

Adios queridos amigos Marco y Alejo; estimados colegas de estudios en Huaraz, avanzamos juntos!

This book, published as part of the book series entitled, “Geoenvironmental Disasters Reduction,” focuses on Peru’s highest and most glacierized mountain range—the Cordillera Blanca. Due to its prominence among the glacierized tropical mountains around the globe, the Cordillera Blanca has attracted many Peruvian research institutes as well as international research teams over the last few decades to conduct research projects tackling various aspects of rapid developments associated with climate change, water security, population expansion and abundant occurrence of natural hazards and disasters. Likewise, this expansion of research studies and reports focusing on the broad theme of geo-environmental changes in the Cordillera Blanca has motivated us to prepare a comprehensive overview of the state-of-the-art knowledge in monograph form.

Fig. 2 Alejo Cochachin Rapre during his research in Cordillera Blanca (image: Adam Emmer)

The 15 chapters of the book span from broadly thematic topics of geology, geomorphology, climate, hydrology and hydrogeology, lakes, glaciation, and environmental settings to more specific topics and emergent themes of relevance for the Cordillera Blanca. While most of the chapters focus on biophysical processes of the natural environment, several chapters explore the complex interactions between humans and environmental factors, providing insights and perspectives from social science and the humanities. A final chapter provides a concluding summary of the individual chapters.

We invited contributions from a diversity of Peruvian and international scholars to reflect some of the multidisciplinary science conducted in the Cordillera Blanca over recent decades. Our authors have a range of experience and include multiple young and emerging scholars. We acknowledge there are many more research groups from around the globe who have worked in the region, as reflected in the bibliographies. There are also other relevant books addressing mountain geohazards that include this region. Notable is the Elsevier book series on Hazards, Risks and Disasters, where large numbers of international experts provide comprehensive reviews on the topic, including examples from the Cordillera Blanca in Peru (i.e., Haeberli and Whiteman 2021). Thus, we offer this compendium with professional appreciation for the dedication of many colleagues from many nations. Our own research has been completed collaboratively with many Peruvians, and we have dedicated this book in honor of two colleagues who sadly recently passed away. Finally, we gratefully acknowledge that this book has been reviewed by Professor Wilfried Haeberli (University of Zurich, Switzerland) and Professor Jan Kalvoda (Charles University, Czechia).

We are confident that the Cordillera Blanca remains an area of interest for future research and individual chapters outline open research questions while emerging research methodologies open new possibilities and pave the way to new insights. Our book is recommended to anyone interested in learning more about this fascinating part of the world.

Prague, Czech Republic — Vít Vilímek
Columbus, USA — Bryan Mark
Graz, Austria — Adam Emmer

Reference

Haeberli W, Whiteman C (eds) (2021) Snow and Ice-related hazards, risks and disasters, 2nd edn. Elsevier, 754p

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Vít Vilímek (*1959 in Mariánské Lázně, Czechia) is a full professor at Charles University in Prague. He studied Physical Geography and Cartography at his home university and has worked as the Head of Department and Vice-Dean of the Faculty of Science in the past. His teaching and research interests are mainly in geomorphology and natural hazards. He is the author or co-author of 60 publications listed on the Web of Science. He has worked in Central Asia, the Ethiopian Highlands, and for more than 25 years in the Peruvian Andes. He has worked in Peru, in Cordillera Blanca since 1996 and in Machu Picchu since 2001. His current interests are focused on the European Alps and the use of remote sensing data in other high mountains around the world. He was recognized for an award by the International Consortium on Landslides (ICL) for landslide research in developing countries in 2023. He has held the position of Assistant to the President and later the Vice-President of ICL. In the International Consortium on Geo-disaster Reduction (ICGdR), he works as treasurer and together with Prof. Fawu Wang he established the book series of Geoenvironmental Disaster Reduction (Springer).

Bryan Mark (*1969 in New Mexico, USA) is a full professor of geography at the Ohio State University where he leads the Glacier Environmental Change research group at the Byrd Polar and Climate Research Center and also serves with the State Climate Office of Ohio. He earned his Ph.D. in Earth Sciences from Syracuse University in 2001 and was a postdoctoral fellow with the Max Planck Institute of Biogeochemistry from 2001 to 2003. His teaching is focused on climate change and physical geography, as well as special topics in mountain geography. His research focuses on changes in glaciers, water, and climate in globally diverse mountain environments. In the tropical Andes, he investigates modern glacier recession as well as Late-Glacial to Holocene climate and environmental variability. He combines modeling and remote sensing with fieldwork using various methods of hydrology, hydrochemistry, paleoclimatology, and terrain analysis. As a founding member of the Transdisciplinary Andean Research Network (TARN), he collaborates internationally with social scientists, biogeographers, and hydrogeologists to examine hydrologic transformations and social resilience below melting glaciers. He has over 90 peer-reviewed publications and has (co)led expeditions to the Cordillera Blanca for over 25 years, including two Fulbright Scholarships.

Adam Emmer (*1989 in Jablonec nad Nisou, Czechia) is a physical geographer with expertise in high mountain geomorphology and natural hazard science. He earned his Ph.D. at Charles University in Prague, Czechia (2017), and completed his habilitation at the University of Graz, Austria (2022). He has worked for Charles University (2013–2020), the Czech Academy of Sciences (2015–2020), and the University of Graz (2020–present). His university teaching, at both bachelor and master levels, covers topics ranging from geomorphology and regional physical geography to statistics and data visualization. In his research, he focuses on the hazardous consequences of retreating glaciers, the dynamics of deglaciated areas, the evolution of glacial lakes and lake outburst floods, their characterization, and patterns of occurrence in space and time. To better understand these processes, he integrates fieldwork, the analysis of remotely sensed images, and the analysis of documentary data sources. He conducted most of his work in the Peruvian Andes, Austrian Alps, and Sikkim Himalaya. Since 2012, he has organized nine field campaigns in the Peruvian Andes. He has participated in recent inventories of Peruvian lakes and lake outbursts and has (co-)authored over 50 scientific papers addressing various aspects of geo-environmental changes in the world's mountain regions.

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Geology and Tectonic Setting of the Cordillera Blanca

Sarah R. Hall, Alba M. Rodríguez Padilla, Keith R. Hodson and Laurence Audin

Abstract

The Cordillera Blanca is situated in the northern Peruvian Andes and hosts some of the highest elevations in the Andean Range. Cored by a—granitic pluton and flanked by Mesozoic metasedimentary rocks and Cenozoic volcanics, the range harbors a portion of Andean geologic history spanning the last ~200 Ma. While the region is dominated by igneous rocks, this part of the Andes has not experienced active magmatism since ~5 Ma. One of the most striking features of the range is the active Cordillera Blanca Normal Fault, a ~200 km long fault accommodating extension and strike-slip deformation and enabling the high elevation glaciated peaks of the footwall block. While this region shares a similar geologic history with the rest of the Andean Range, including long-lived subduction and mountain building since the Mesozoic, the Cordillera Blanca is situated above a flat slab section of the downgoing Nazca Plate, which adds a complexity to the tectonic history of this region. Understanding the connection between the initiation and kinematics of this extensional crustal-scale fault set within and parallel to a contractional margin is an area of active research. The Quaternary geologic record preserves a rich record of Pleistocene glaciations and associated post-glacial landscape processes. The striking topography, geology, landforms, and active Earth processes that make this region an important archeological zone and modern tourist destination as well as a resource-rich location (e.g. hydroelectric power generation, metal mining, water resources for coastal agriculture) also expose the highly populated Callejón de Huaylas valley to geohazards such as mass wasting events, floods, and earthquakes.

Keywords

Cordillera Blanca · Extension · Geology · Tectonics · Geohazards

1 Introduction

Tracing the western edge of the South American continent, the Andean Mountain Range hosts active volcanoes, modern glaciers, and the

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world's second largest high plateau. The Cordillera Blanca (CB) makes up the crest of the Andean Range in northern Peru and supports the tallest peak in northern South America, Huascarán (6768 m), surpassed in the Andes only by three higher peaks in Patagonia. Like other regions of the American Cordillera, the continuous ribbon of mountains extending from Alaska to the tip of Patagonia, the Andean topography has its genesis in long lived convergence of tectonic plates. For the last ~200 million years, subduction of the Nazca Plate beneath the western edge of the South American Plate has resulted in a long history of tectonic and magmatic activity along the plate boundary. Millions of years of crustal deformation have thickened the continental crust, producing a deep "keel" of crustal material that extends to depths of more than 60 km below sea level along the Andean Range. As it grew, the thickening crust raised the mountain range to higher elevations, leading to repeated glaciations that sculpted the range and lifted peaks to the elevations in excess of 6 km that we observe today.

Active volcanism is a classic characteristic of Andean landscapes, with new crust added along the entire western margin of South America related to ongoing subduction since the Jurassic (James 1971; Jaillard and Soler 1996). However, in contrast to other parts of the Andean Range, the northern Peruvian Andes have not been volcanically active since the Pliocene. The absence of volcanism is due to the low angle of the Nazca Plate as it subducts along this portion of the Range since ~15 Ma (Isacks 1988; James and Sacks 1999). The implications of this flat slab segment, coupled with subduction of aseismic ridges and the convergence obliquity, are the subject of many recent studies in this region.

While the entire Andean margin is recognized as a classic example of a non-collisional convergent margin featuring archetypal characteristics of compressional landscapes, the Cordillera Blanca is notable for its active crustal-scale normal fault, the Cordillera Blanca Normal Fault (CBNF), parallel to the range and bounding the western side of the high peak region. Ongoing continent-scale compressional deformation coupled with localized relief generation in the footwall block has resulted in high elevations and high relief in the Cordillera Blanca (Fig. 1). The range currently hosts the world's largest volume of tropical glaciers and preserves a very rich record of Pleistocene glaciation. Making up an important storage component to the regional water budget, these modern shrinking glaciers clinging to the high peaks also present mass wasting hazards, "aluviones", especially when coupled with regional seismic hazards associated with both the CBNF and the nearby subduction zone.

To appreciate the unique modern landscapes of the Cordillera Blanca and Earth processes currently active in this region, we will begin by describing the geography of the broader Andean Range and situate the characteristic morphologies in the context of the geologic and tectonic history of the orogen. We follow with a description of current morphologic, geologic, and tectonic settings of the Cordillera Blanca region and consider their connections to ongoing surface processes, resources, geohazards, and human societies. Readers are directed to other chapters within this volume that address some of these topics, especially: Chap. 2 on geomorphology; Chaps. 4 and 5 on hydrology and lakes; Chap. 6 on glaciation; and Chap. 15 on landscape changes.

2 The Andes

2.1 A Segmented Range

We find many of the classic features of a characteristic subduction zone setting along the Andean margin: a forearc basin, andesitic magmatic arc, and a foreland fold and thrust belt (Dewey and Bird 1970; James 1971). Viewed from west to east through the Central Andes we observe—north–south trending geographic provinces associated with this archetypal subduction margin running roughly parallel to the subduction trench: the Coastal Plain, the Western Cordillera, the Altiplano-Puna Plateau,

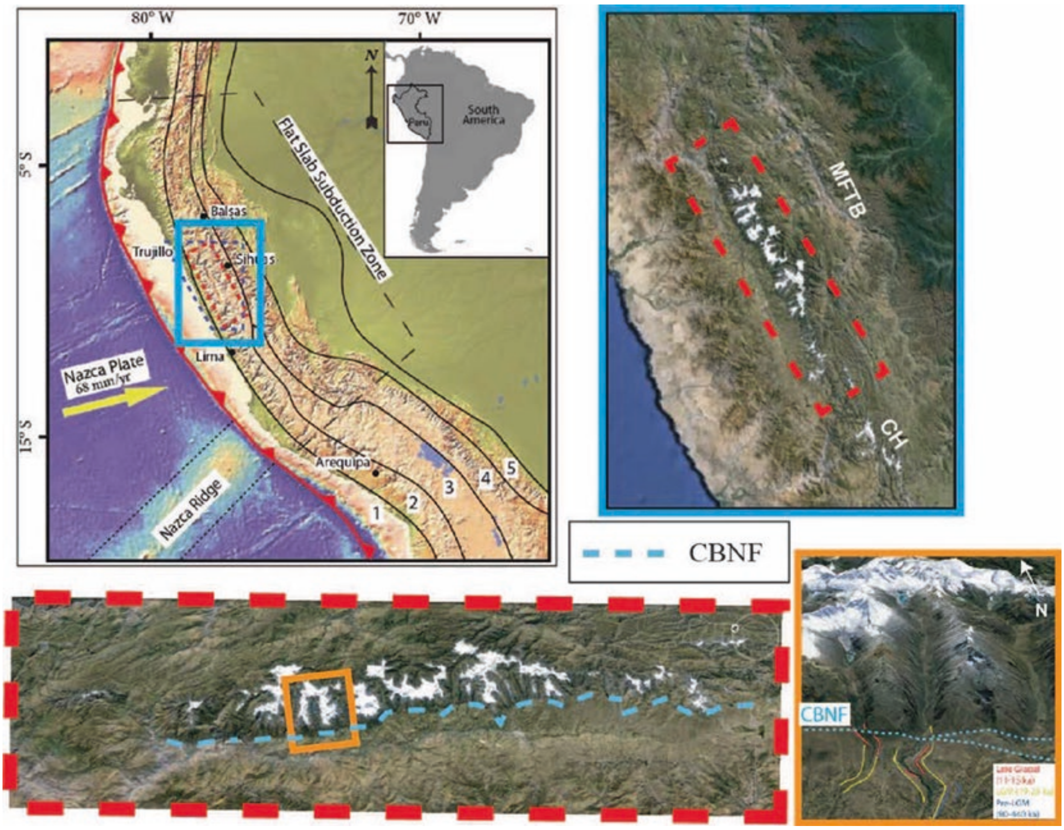

Fig. 1 Upper left: Tectonic setting of northern Peru. Ongoing subduction of the Nazca Plate beneath the South American Plate accommodates uplift and maintenance of the Andean Range along the strike of the continent. Locally, the 200 km long Cordillera Blanca Normal Fault (CBNF), is an active crustal-scale fault bounding the western side of the in the Cordillera Blanca (CB) Range (modified after Hodson 2012). Upper Right: Aerial image of the northern Peruvian Andes. The CB hosts the largest volume of glaciers in the tropics. To the south, the Cordillera Huayuash (CH) also hosts modern glaciers. The Marañón Fold and Thrst Belt (MFTB) structures to the east is currently incised by the Rio Marañón. Note the visible vegetation differences in the region reflecting the east–west precipitation gradient (wet Amazon Basin in the east, dry coastal forearc region). Lower: Red dashed box shows CB region along the strike of the range. The orange box highlights the glacially carved Llanganuco valley where LGM moraines are cut by the active CBNF (modified after Farber et al. 2005)

the Eastern Cordillera, the Sub-Andean zone, and finally, east of the Andean Range lies the Amazon Basin (Fig. 2). While this general structure can be observed along the length of the Andes, variations in range morphology, subduction style, crustal structure, and geology exist along and across the modern margin (e.g. Isacks 1988).

Morphologically, the Andean range width varies along the strike of the margin with narrow portions at the northern and southern ends bounding a wider portion between ~13 and 27°S that hosts the Altiplano-Puna Plateau (e.g. Gephart 1994; Montgomery et al. 2001). Zones of flat-slab subduction in northern Peru (~5 to 15°S) and central Chile (~27 to 33°S) illustrate the *tectonic segmentation* of the margin resulting in discontinuous zones of active magmatism along the margin (e.g. Stauder 1975; Barazangi and Isacks 1976). *Structural segmentation* is apparent at the continental scale with major deflections mapped in Peru at approximately 6°S, 13.5°S, and 18°S (e.g. Megard 1984). *Geologically*, the amount and composition of

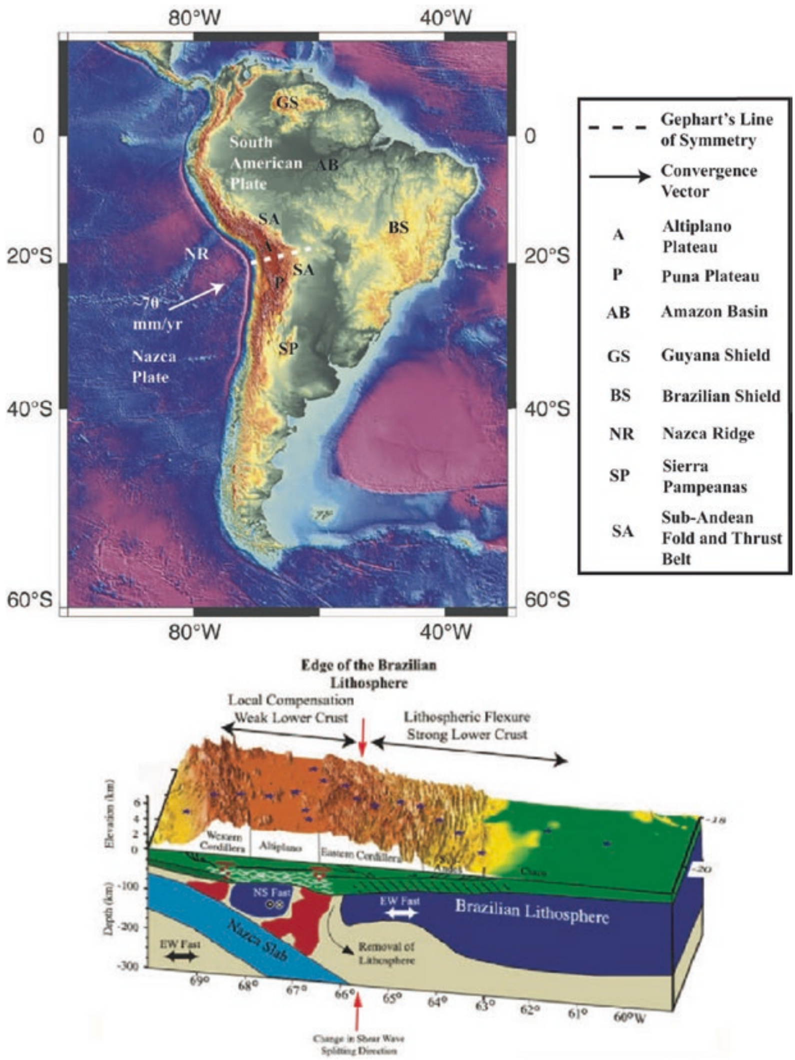

Fig. 2 Top: South American Topography (SRTM Digital Elevation Model). The dashed line shows the Gephart (1994) symmetry axis. A topographic profile along this line is shown in the lower right corner. Bottom: Generalize plate tectonic cross-section at 19°S (near line of symmetry) modified after Beck and Zandt (2002). Dark blue and red sections indicate fast and slow seismic wave velocities, respectively. Note wide thin-skinned Sub-Andean Fold and Thrust belt in the Subandean Zone (SZ) along the gently sloping eastern flank and the narrow steeply dipping thrust belt in the steep western foothills. Thick-skinned deformation occurs in the Sierra Pampeanas (SP)

plutonic igneous rocks varies along strike suggesting a dynamic history of margin segmentation (e.g. Kono et al. 1989; James and Sacks 1999). Segmentation is apparent at the scale of the lithosphere (James 1971; Allmendinger and Gubbels 1996; Whitman et al. 1992, 1996; Allmendinger et al. 1997) providing additional clues about the lithologic evolution of the region.

While set within a context of compressional tectonics during the last ~200 million years, we find evidence of changing plate geometries, plate motions, and variations in the topography of the downgoing slab due to the periodic subduction of aseismic ridges (Dalmayrac and Molnar 1981; Gutscher et al. 1999; Margirier et al. 2015; Ramos 2021). These first-order plate tectonic changes have resulted in morphologic variations that, coupled with climate change through the late Mesozoic and Cenozoic, have influenced the biosphere (e.g. Strecker et al. 2007; Hoorn et al. 2010; Martinez et al. 2020). On-going plate tectonic processes and inherited geologic features continue to influence modern Earth processes active throughout the range, and within the Cordillera Blanca region. As these first-order processes directly impact and, especially now in the Anthropocene, are entangled with local, regional, and global human societies, a brief discussion of the spatial and temporal geologic and tectonic settings of the Andes and specifically, the northern Peruvian Andes, provides context for consideration of the present-day Cordillera Blanca region biosphere (e.g. Byers 2000), cryosphere (e.g. Farber et al. 2005), and hydrosphere (e.g. Baraer et al. 2012).

2.2 Andean Morphology: Connections to Tectonic, Geologic, and Climatic Settings

The iconic curvature of the western South American margin, known as the Bolivian Orocline, harbors a topographic symmetry that reflects roughly symmetrical subduction of the downgoing Nazca Plate (Gephart 1994). This curvature necessarily imposes variations in the geometry of the subducting plate along the margin leading to spatial and temporal segmentation within this broadly symmetrical Andean morphology (Fig. 3). Situating the continent-scale topography within a climatological context, the segmentation of the margin is reflected in the variations in Andean topography and mass distribution as a function of climate factors such as glaciation, precipitation, and aridity (e.g. Lamb and Davis 2003; Barnes and Pelletier 2006; Montgomery et al. 2001).

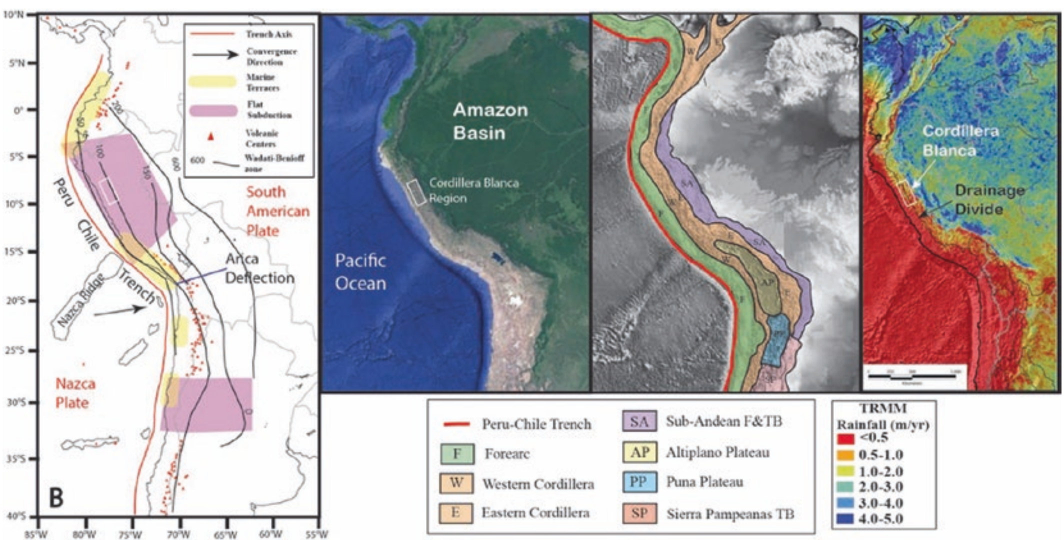

Fig. 3 Left: Tectonic Setting of the Andean margin. Note the areas of flat slab subduction correlate with locations lacking an active volcanic arc and marine terraces (modified after James and Sacks 1999). Left Center: Google Earth imagery of northern south America. Note the arid west coast and elevated topography compared to the vegetated Amazon Basin in the east. The location of the Cordillera Blanca is shown in the white rectangle. Right Center: Morphostructural provinces of the Andean margin. Note the bifurcated cordilleras around plateaus in the Central Andes. The subduction trench is indicated with a red line. Right: Average Annual Rainfall from the TRMM satellite (Bookhagen and Strecker 2008). Note the greatest precipitation gradient is along the eastern slope of the range, not along the drainage divide (black line)

2.2.1 Andean Morphology: North to South

In southern Peru and extending southward into Chile and Bolivia, the Andean Range has two distinctive spines, the Western Cordillera and the Eastern Cordillera, flanking the ~300 km-wide and ~4 km high Altiplano Plateau. Glaciated peaks reaching above 5 km bound the high internally drained basins of the Altiplano Plateau. Extending north from the Central Andes, the Western and Eastern Cordilleras converge forming a—NW–SE trending spine of high topography with a range width of ~150 km. North of ~6°S, in northernmost Peru and extending northward into Ecuador and Columbia, the single spine of the Range narrows further to only ~60 km wide. Similarly, south of ~33°S the range narrows to a single spine ranging in width from 60 to 100 km. The largest volume of glaciers is found within the single-spine regions of the northern Peruvian Andes and the Patagonian Andes of southern Chile and Argentina.

Within the double-spine region where the range widens, ~6°S to ~33°S, a relict and dissected low-relief surface of concordant peaks exists around 4 km with the highest peaks rising above, made jagged by glaciation or active volcanism. This relic surface, known in northern Peru as the Puna Surface, was mapped by early workers. It was thought to have been formed by the mid-Miocene uplift of a low relief landscape that was subsequently abandoned and incised into by streams, potentially in relation to the initiation of subduction of the Nazca Ridge (McLaughlin 1924; Coney 1971). Additional incised low-relief surfaces throughout the western Andean margin suggest younger phases of uplift and erosion since the mid-late Miocene (Myers 1976; Noble et al. 1990). Closer to the coast, marine terraces record Plio-Pleistocene surface uplift and sea level changes along much of the western margin (e.g. Freisleben et al. 2021). The existence and extent of marine terraces vary along the length of the coast, reflecting the continent-scale tectonic segmentation of the margin.

North–south variations in the subducting plate geometry and the presence of subducting aseismic ridges cause regional differences in the surface geometry along the strike of the Range (c.f. Fig. 3). Active volcanoes dot the Western Cordillera of the Central Andes (~14°S to ~27°S) as well as north of ~3°S and south of 35°S where the subducting plate angle is steeper. In the areas of flat-slab subduction, 2–15°S and 28–33.5°S, the plate descends at an angle of about 30° for about 100 km before shallowing to near horizontal. Both flat slab sections are also associated with subducting aseismic ridges, which have been proposed to contribute to the formation of the shallowing slab and localized tears in the downgoing plate (Gutscher et al. 2000; Gerya et al. 2009; Manea et al. 2012). The northern flat slab section currently underlies the Cordillera Blanca region and is bound to the south by the Nazca Ridge, currently positioned at ~15°S along the subduction trench.

2.2.2 Andean Morphology: West to East

Along a west–east transect in northern Peru, the ribbon of NW–SE striking high topography of the Cordillera Blanca is situated in the middle of the Andean Range with the arid Pacific coast ~100 km to the west and the edge of the Amazon Basin ~100 to 150 km to the east. The Cordillera Blanca serves as a boundary between tectonically and climatically contrasting landscapes. Within the steeper western margin, some high-angle active faults accommodate transpression related to slightly oblique subduction. However, little of the convergence-related shortening is attributed to active surface-breaking faults, despite geomorphic evidence of surface uplift in this region. In contrast, the eastern Andean margin hosts the tectonically active Sub-Andean Fold and Thrust Belt which accommodates about ~30% of modern convergence related shortening. Active thrust faults of the orogenic wedge thicken the crust, build relief, and contribute to widening the Andean Range over the old dense crust of the Brazilian Shield (c.f. Fig. 2).

This eastern edge of the Andes is the location of one of the largest precipitation gradients on the planet with the wet regions of the Amazon Basin receiving over 4 m/year of precipitation while regions in the western Andean margin near the arid Pacific Coast receive <0.5 m/year (Tropical Rainfall Measurement Mission (TRMM) data; Huffman et al. 2007). The highest precipitation gradient is located along the major break in slope at the Sub-Andean front where moist air masses carried westward from the Atlantic by easterly winds of the Tropics are forced to rise, condense, and produce precipitation. The Cordillera Blanca also acts as an orographic barrier causing around 2–3 times more moisture to fall on the eastern side of the range compared to the west. However, the precipitation gradient at the range crest is less prominent than the gradient further east in the Sub-Andes (Bookhagen and Strecker 2008).

2.3 Geology and Geologic History of the Northern Peruvian Andes

While some accreted terranes exist in the northernmost Andes of Ecuador and Colombia, none are known in the Peruvian Andes or further south (Goossens and Rose 1973). Eastern South America is underlain by two ancient cratons, the Guiana Shield and the Brazilian Shield, blanketed by the Quaternary sediments of the Amazon Basin. The western South American bedrock tells a story of closing ocean basins, island arcs, and a thickening continental margin. Characterizing the Andean Orogen are sub-parallel structural zones roughly coincident with the geographic zones described in Sect. 2.2 (c.f. Fig. 2). Within the forearc and Western Cordillera, Precambrian metamorphic rocks that were intruded by the Mesozoic-Cenozoic batholiths are overlain by Cenozoic continental sediments and volcanic rocks. Progressing eastward, on the eastern slope of the Western Cordillera and into the Eastern Cordillera are deformed low-grade metamorphic marine and continental sediments of Precambrian-Paleozoic age, with minor intrusive rocks. Folded and faulted Mesozoic-Cenozoic marine and continental sedimentary deposits are typical of the Subandean zone (Steinmann 1929; James 1971, Jordan et al. 1983; Megard 1984; Sebrier et al. 1988; Lamb and Hoke 1997; McQuarrie 2002).

The stratigraphy and localization of different types of bedrock reveal periods of deformation and suggest the eastward migration of both the magmatic arc and deformation front during the last ~100 Ma. Deformation was focused in the Western Cordillera in the late Mesozoic and early Cenozoic and migrated to the Eastern Cordillera by ~40 Ma, and then to the Sub-Andean zone by ~10 Ma. During the latest Mesozoic, Precambrian bedrock is folded and faulted in the Hercynian and Peruvian deformation phases while marine deposition occurred along a continental margin with active volcanism, producing the Coastal batholithic rocks. By the early Cenozoic, the zone of active deformation had migrated eastward and the Inca phase of deformation resulted in the uplift and erosion of the Mesozoic sedimentary sequences. During the last ~40 Ma, repeated phases of magmatism, shortening, and uplift have resulted in the formation of batholiths, volcanic sequences, folded bedrock, thickened crust, stratigraphic unconformities, relict low-relief surfaces and the high topography of the Andean Range. These Cenozoic Quechua phases of deformation affected a wide swath of the Andean range including the forearc, Western Cordillera, Eastern Cordillera, and most recently since the late Miocene, the Sub-Andean Zone.

Like the eastward migration of crustal deformation, the location of the active magmatic arc also moved eastward in the Cenozoic, likely due to changes in the geometry of the down-going subducting plate (James 1971). Parallel to the coast and the Peru–Chile trench, the granodioritic and tonalitic Coastal Batholith of Peru reaches about 50 km wide along much of the forearc. Mainly emplaced in the Cenozoic, pluton ages span the Cretaceous-Eocene (~100–40 Ma) growing younger to the east with a chemical signature suggesting mantle wedge melts, subducting slab, or deep crustal melts generated at ~5–10 km. The melts ascended to ~2–3 km depth where they cooled rapidly (Giletti and Day 1968; Atherton and Petford 1996; Haederle and Atherton 2002; Wipf 2006). East of the Coastal Batholith, the chemically distinct Miocene-Pliocene Cordillera Blanca Batholith, has evolved from the partial melting of thickened mafic crust without slab contributions (Petford and Atherton 1996; McNulty et al. 1998; Coldwell et al. 2011; Fig. 4).

While convergence-related mountain building has resulted in high topography along the western South American margin, modern elevations were only reached quite recently. Paleobotanical and carbonate isotopic signatures yield paleo-elevation estimates indicating that only ~30% of the present elevation was attained before 20 Ma and no more than 50% before 10 Ma (Gregory-Wodzicki 2000; Garzione et al. 2006). Despite active Cenozoic volcanism throughout the range, magmatic additions alone are not enough to explain crustal thicknesses observed in the Andes. Tectonic shortening (Isacks 1988; Schmitz 1994; Lamb and Hoke 1997; Allmendinger et al. 1997; Kley et al. 1999), lithospheric delamination (Kay and Mahlburg Kay 1993; Kay et al. 1994; Beck and Zandt 2002; McQuarrie et al. 2005; Sobolev and Babeyko 2005; Garzione et al. 2006), material additions through sedimentation, lower- and mid-crustal ductile flow (Lamb and Hoke 1997; Beck and Zandt 2002; Husson and Sempere 2003), and plate coupling or magmatic underplating (Haschke and Gunther 2003; Sobolev and Babeyko 2005), have all potentially contributed to growth of topography and thickening of the Andean crust.

3 Cordillera Blanca

3.1 Cordillera Blanca Geography

The Cordillera Blanca Mountain Range is a geomorphologically and tectonically distinct portion of the Western Cordillera from ~8° to 10°S. Like the broader Andean Range, the Cordillera Blanca is morphologically segmented, mainly due to variations along the CBNF and the geomorphic processes modifying the tectonically active and glacierized landscape (Schwartz 1988; Giovanni 2007; Hodson 2012). Extending 200 km along the crest of the Andes, the Cordillera Blanca hosts 27 peaks over 6000 m a.s.l. (Ames 1998). Range morphology features north–south trends in peak elevation, catchment relief, and mean slope (Giovanni 2007). Peak elevations reach a maximum in the central portion of the range near Huascarán and decrease to the north and south. This contrasts with topographic relief and slope, which both decrease along the range from north to south, possibly related to southward fault propagation (Schwartz 1988; Giovanni 2007). The high topography is bound on the west by the CBNF and Callejón de Huaylas, a broad north–south trending down-dropped basin containing the Rio Santa and many of the region's larger towns and cities. The western side of the basin is bounded by the similarly trending Cordillera Negra range (c.f. Fig. 4).

3.2 Cordillera Blanca Geology and Geologic History

The prominent high elevation and high relief portion of the Cordillera Blanca (CB) is composed mainly of granitic-granodioritic rocks of late Miocene-Pliocene age (Fig. 5). The bulk of the granitic rocks are associated with the Cordillera Blanca Batholith, with an emplacement age of 8.2–5 Ma (McNulty et al. 1998; Petford and Atherton 1992; Giovanni 2007). The less voluminous Carhuish Stock of the southern portion of the range are older granitic rocks with an age of ~13.7 Ma (McNulty et al. 1998; Petford and Atherton 1992; Hodson 2012). Thought to have been emplaced along a regional lineament during a period of normal subduction just before the flattening of the subducting slab and cessation of volcanism, the plutonic rocks were emplaced under high pressure conditions,

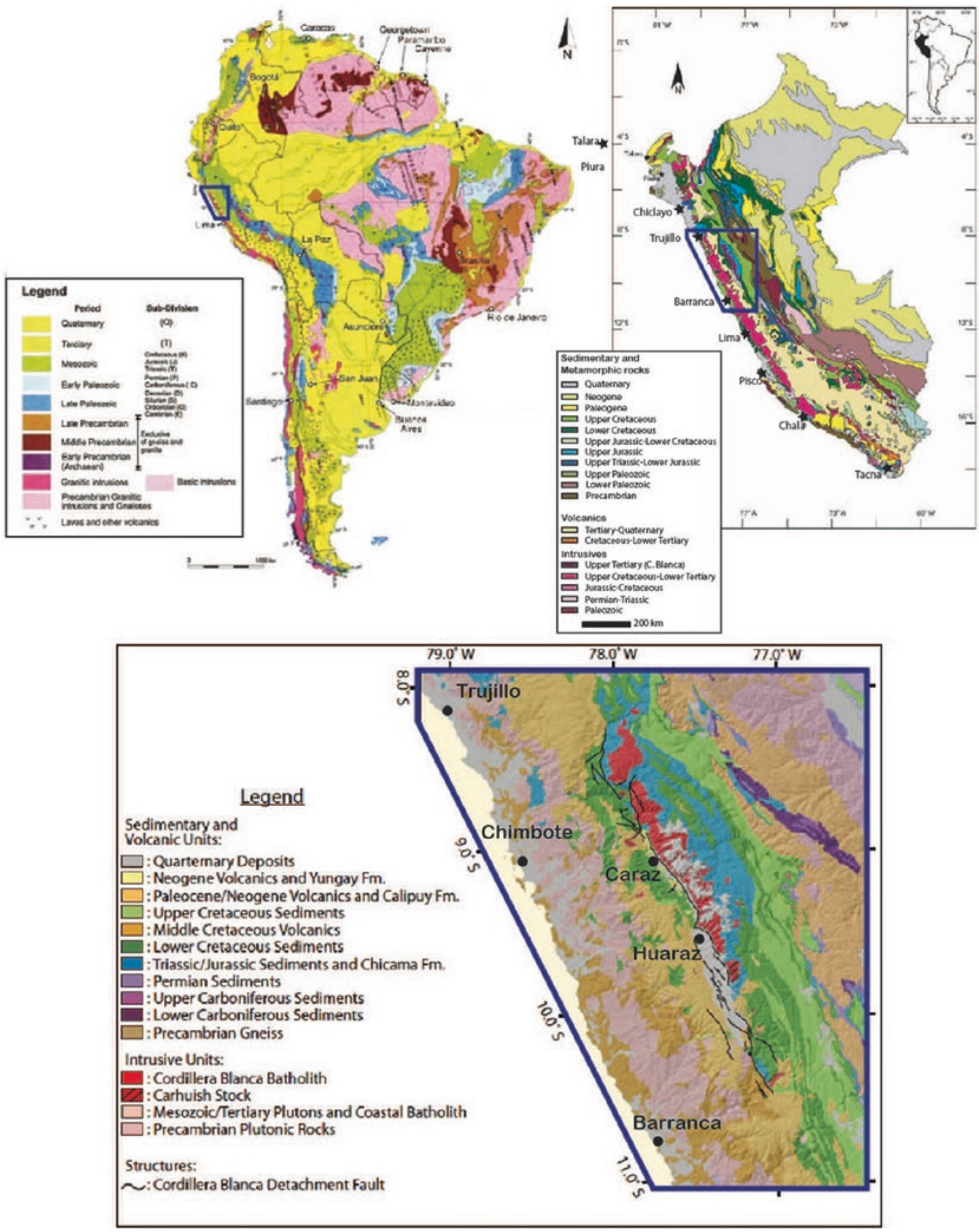

Fig. 4 Bedrock Geologic Maps. On all maps, the dark blue polygon indicates northern Peru. Top Left: Geology of South America (modified after Acevedo et al. 2015). Top Right: Geology of Peru (modified after Wipf 2006). Bottom: Geology of the northern Peruvian Andes (modified after Hodson 2012). The Cordillera Blanca region hosts the cities of Huaraz and Caraz. The black line delineates the CBNF