Chapter 1

Geological History and Geodiversity of the Amazon

Pedro Val, Jorge Figueiredo, Gustavo de Melo, Suzette G. A. Flantua, Carlos Alberto Quesada, Ying Fan, James S. Albert, Juan Manuel Guayasamin, Carina Hoorn

THE AMAZON WE WANT

Science Panel for the Amazon

INDEX

Graphical Abstract

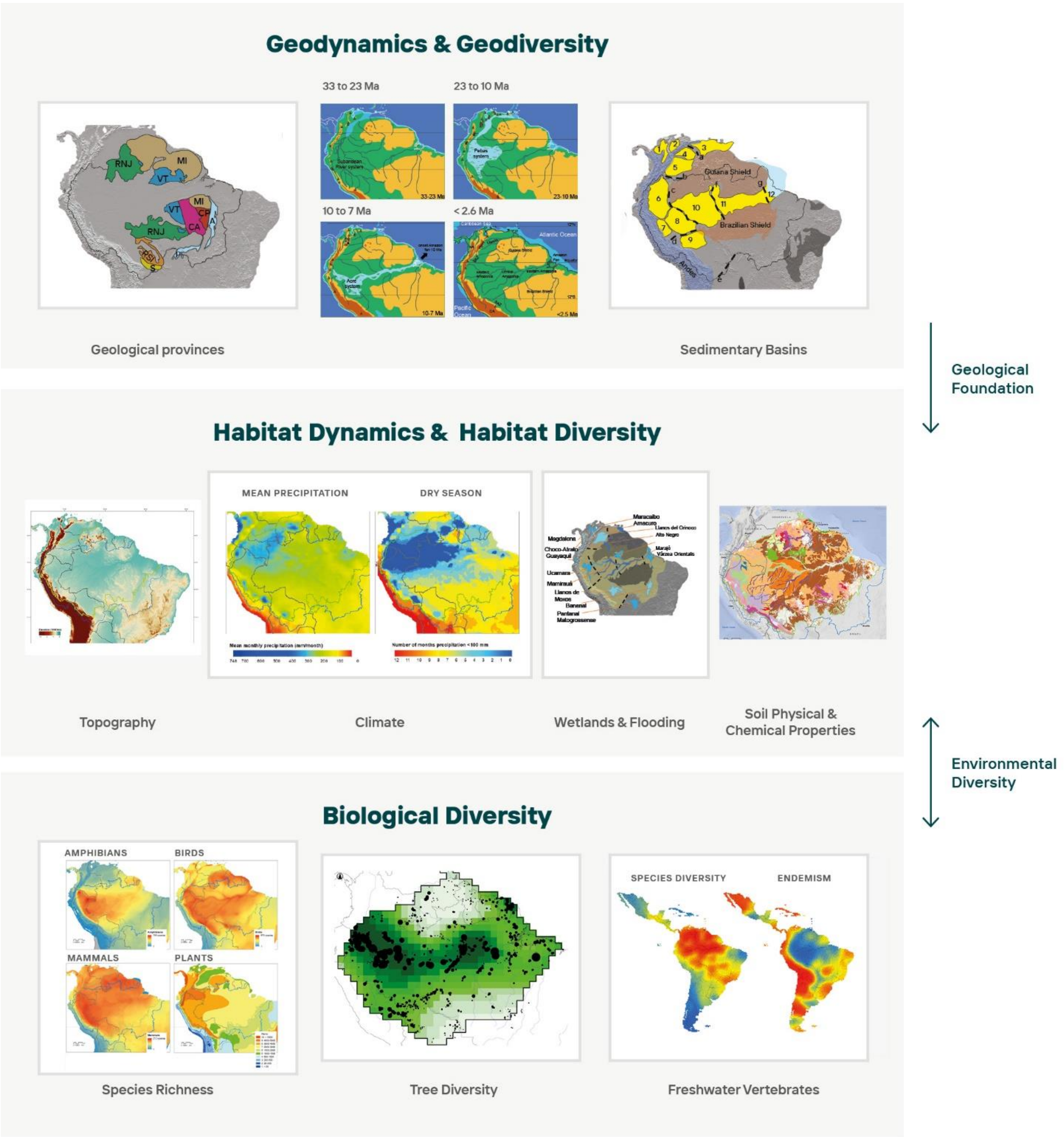

Figure 1.A Geodynamics and geodiversity (top panel) of the Amazon, which form the geological foundation for habitat dynamics and diversity (middle panel), and the environmental heterogeneity and gradients that drive biological diversity (bottom panel). Image sources: top panel, from left to right, geologic provinces from Macambira *et al.* (2020), and the uplifting Andes, sedimentary basins, and stable cratons from Fuck *et al.* (2008), landscape and drainage evolution sequence through the past 30 Ma from Hoorn *et al.* (2010b), dynamic Andes and sedimentary basins and stable cratons from Albert *et al.* (2018); middle panel, from left to right, topography from NASA Earth Observatory, precipitation and seasonality from Restrepo-Coupe *et al.* (2013), wetlands and flooding from Albert *et al.* (2018), soil from Quesada *et al.* (2011); bottom panel, from left to right, species richness from Plant-Talk.org (https://www.plant-talk.org/ecuador-yasuni-biodiversity.htm), tree diversity from Hoorn *et al.* (2010b), freshwater vertebrates from Albert *et al.* (2020).

Geological History and Geodiversity of the Amazon

Pedro Val[a], Jorge Figueiredo[b], Gustavo de Melo[a], Suzette G.A. Flantua[c], Carlos Alberto Quesada[d], Ying Fan[e], James S. Albert[f], Juan Manuel Guayasamin[g], Carina Hoorn[h]

Key Messages

- Modern Amazonian landscapes can only be understood in the context of geological and climatic processes operating over hundreds of thousands to billions of years.
- The subdivision of the Amazon into craton versus Andes-influenced landscapes and soils is the result of a unique geologic history that was determined by the interplay of plate tectonics, climate, dynamic topography, and sea level change. Together these factors created an exceptionally high geodiversity and diverse hydrological landscape.
- Amazonian geodiversity arises from the heterogeneous distribution of lithologies in the geological substrate and edaphic (soil) conditions at many spatial scales, under the perennial influence of varied hydrological and biological process, at the surface and subsurface.
- It took hundreds of millions of years for the Amazon to develop the rich tapestry of landforms, soils, and ecosystems we see today, but humans degrade these unique ecosystems at a much faster rate. Decisions should be made to avoid further degradation and consider the time necessary for the Amazon to recover, which, if at all, will not be on a human-relevant timescale.

Abstract

The Amazon hosts the most diverse tropical forest on Earth. But underneath, the Amazon also comprises an exceptionally geodiverse landscape, marked by the towering Andes in the west, highland plateaus with dramatic escarpments in the east, and the Amazon River traversing the region as a major artery. The region's exceptional geodiversity and biodiversity have shaped one another through time, as geological forces created the diverse soils, biotas, and hydrological landscapes of the modern Amazon. In this chapter we explore how these features evolved over a three-billion-year history, and show that periods of continental breakup followed by mountain building ultimately led to the characteristic subdivision of the western and eastern Amazon, while also generating a wealth of ore deposits, oil and gas reserves, and freshwater aquifers. The modern landscape was initiated after the supercontinental breakup that separated the continents of South America and Africa (c. 100 million years ago, or Ma), leading to the opening of the Atlantic Ocean and the gradual uplift of the Andes Mountains. However, the central and northern Andes only reached their present altitude after accelerated uplift during the Neogene (c. 20 Ma) due to changes in Pacific plate motions. Together with a rise in global temperatures and sea level during the

[a] Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, 35400-000, Brasil, pval@ufop.edu.br
[b] Departamento de Geologia, Universidade Federal Rio de Janeiro, Av. Athos da Silveira Ramos, 745/G04-49, 21.941-916 - Ilha do Fundão - Cidade Universitária, Rio de Janeiro, Brasil
[c] Department of Biological Sciences, University of Bergen, Postboks 7803, 5020 Bergen, Norway
[d] Instituto Nacional de Pesquisas da Amazônia (INPA), Av. André Araújo, 2936, Aleixo, CEP 69060-001 Manaus, Brasil
[e] Department of Earth & Planetary Sciences, Rutgers, The State University of New Jersey, Wright-Rieman Laboratories, 610 Taylor Road, Room 142, Piscataway, NJ 08854-8066, USA
[f] Department of Biology, University of Louisiana at Lafayette, 104 E University Ave, Lafayette 70503, Louisiana, USA
[g] College of Biological and Environmental Sciences, Universidad San Francisco de Quito, Diego de Robles y Vía Interoceánica, Quito, Ecuador
[h] Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, 1090 GE Amsterdam, The Netherlands, m.c.hoorn@uva.nl

middle Miocene (c. 17–15 Ma), the uplift of the Andes prompted radical changes in the Amazonian paleogeography, paleoclimate, and paleoenvironments, resulting in the creation of a large mega-wetland known as the Pebas System. The rise of the Andes further caused an eastward tilt in sedimentary basins that resulted in drainage changes and the formation of the transcontinental Amazon River (c. 10–4.5 Ma). These geological changes form the basis of the present west to east trending gradient, which is reflected in the geomorphology, lithology, and geochemistry, and explains contrasting weathering rates and nutrient composition across the Amazon. Conversely, the diverse hydrologic and geochemical regimes affect physical and chemical weathering, erosion, and deposition, feeding the geological subdivision of the Amazon. Global climate change also played a role by modifying Amazonian geomorphology and river base levels. Periods of global warming and high sea level, such as in the middle Miocene, inundated the Amazon with marine water, whereas global cooling, in the late Miocene (c. <11 Ma) and culminating in the Quaternary (c. <2.6 Ma), led to glacier formation in the high Andes and global sea level fall. The latter resulted in deep incised valleys and ria-like relict river patterns that are still visible in the Amazonian landscape today. During the interglacials, glacier melt also impacted the Amazonian landscape through megafan deposition at the interface between the Andes and Amazon. Looking into the future, and with knowledge of deep time history in mind, the anthropogenic effect of increasing atmospheric CO_2 on climate today may lead to an ice-free world in which renewed — fast rising — global sea level is likely and would result in an inundation of part of the Amazon, similar to the scenario last seen in the middle Miocene. In short, the geographic position of the Amazon, with its unique geological and climatic history, has created an unparalleled geodiversity, the foundation for the evolution of life and its unmatched biodiversity today. The rates of change induced by anthropogenic activity may outpace anything seen in geological and vegetation records and lead us to an uncertain future.

Keywords: Geodiversity, Amazon Craton, aquifers, Andean uplift, megafans, soils, hydrology, ores, Andes, Amazon River, mega-wetland, Pebas

1. Introduction

The Amazon is a globally unique region of exceptional geodiversity (Gray 2008; Bétard and Peulvast 2019), arising from variations in underlying rocks and mineral resources, emergent topography and surface relief, and heterogeneous distributions of surface and subsurface water flows (hydrology) and soil types (edaphic conditions) (Figure 1.1). Despite the lack of a formal consensus on the geographical division of the Amazon, we choose to separate the Amazon into the eastern and western Amazon based on their surface expressions. The geology of these regions is distinct; the eastern Amazon is dominated by Precambrian shields with Paleozoic sedimentary basin in between and occupy a relatively small area; the western Amazon is largely dominated by Cenozoic sedimentary basins, with Precambrian shields spatially restricted towards the northern and southern limits. These landscapes reflect the geology well, with the shield areas generally being marked by plateaus (above c. 250 m elevation), which we refer to as the upland regions in both the eastern and western Amazon. Instead, the landscapes across the Cenozoic sedimentary basins are generally marked by smooth, low-lying topography (below c. 250 m) which we nominate as the Amazon lowlands. The western Amazon margin is marked by the Andean cordillera and its foothills, which together rise upwards of 3–6 km in elevation. As we shall learn in this chapter, these distinct geographical regions also condition continental-wide patterns in the chemistry and nutrient content of surface waters, groundwaters, and soils, affecting hydrology, tree composition, forest growth rates, and biodiversity (ter Steege *et al.* 2006; Hoorn *et al.* 2010ab; Higgins *et al.* 2011;

Quesada *et al.* 2011; Hoorn *et al.* 2010a; Quesada *et al.* 2012).

The origins of these diverse Amazonian areas and landscapes need to be traced to a lengthy and dynamic history of geological evolution ruled by plate tectonics (Box 1.1), climate change, and sea level fluctuations, extending over millions to billions of years. The oldest Amazonian rocks were formed during the Meso to Neoarchean era (3.0–2.5 billion years ago [Ga]) (Macambira *et al.* 2020). This Archean core was reshuffled by plate tectonics through the amalgamation of several terranes from c. 2.1 to 1.0 Ga, which gave origin to the Amazon Craton (Macambira *et al.* 2020). On top of this craton, some intracratonic sedimentary basins recorded sedimentation since the Ordovician (c. 485 million years ago [Ma]) and some still accumulate sediments today. Two other main geologic events fundamentally changed the Amazon region: the breakup of the final bridge between the South American and African continents (c. 100 Ma) (Figueiredo *et al.* 2007) and the (re)connection with North America (c. 12–3.5 Ma) (Montes *et al.* 2015; O'Dea *et al.* 2016). It is important to emphasize that the shift from craton- to Andes-dominated processes, after the opening of the South and Equatorial Atlantic during the late Early Cretaceous (c. 120–100 Ma) is a fundamental part in this history (Wanderley-Filho *et al.* 2010; Mora *et al.* 2010). It was during this later stage that today's west-to-east topographic gradients began to take form.

The Amazon is also wealthy in terms of its many mineral and hydrocarbon resources, in particular metal ores, oil and gas, and freshwater aquifers. Metal ores such as iron (Fe), aluminum (Al), gold (Au), manganese (Mn), nickel (Ni) and tin (Sn) are common around the Precambrian shields and represent important export commodities. The genesis of these ores is closely related to the multibillion-year geological history of the Amazon (See section 2). Hydrocarbon reserves are abundant in the Subandean foreland basin of the western Amazon, with origins in the past 100 Ma. Freshwater aquifers underlie much of the lowland Amazon, being most heavily exploited in the Alter do Chão Formation in the eastern Amazon. These resources represent important potential sources of

Box 1.1 Earth and Plate Tectonics

The origin of Planet Earth is linked to the origin of our solar system, starting about 4.5 Ga. Geologists divide the Earth's history into four major divisions they call "EON" or "AEON," inspired by the Greek word αἰών (aiwṓn) that means eternity. The four Eons are Hadean, Archean, Proterozoic, and Phanerozoic. The hard shell of the Earth, known as the "Lithosphere," was formed by two processes over geological time. Initially, magmatic differentiation prevailed, or in simple words the solidification of magma. Later, the processes responsible for plate tectonics started. The rocks, which formed by magmatic differentiation, are the cores to which other, later geological terranes were added due to plate tectonics to form the cratons, supercratons, continents, and eventually, supercontinents (Harrison 2009; Hasui 2012; Hazen 2012).

Though no consensus exists, many authors propose plate tectonics had already started in the Mesoarchean (3.5–2.8 Ga), despite being different from present-day processes (Ernst 2009). For instance, during this Eon not much of the Earth's surface was solid rock; therefore, plate tectonics was not on a global scale like today but localized near the solid cores formed by magmatic differentiation. Once movement started, so did the formation of continental assemblages and the congregation of cratons, supercratons, continents, and supercontinents.

wealth; however, the environmental and sociopolitical impacts of their exploitation are highly contentious (See Chapters 10 to 15).

In this chapter we summarize the geological history of the Amazon, from its origins to the formation of contemporary landscapes. We use this geological narrative to explain the genesis of complex soils systems and hydrological regimes, as well as the distribution and abundance of the region's heterogeneous resources. A major objective of this chapter is to explain how geological, climatic, and hydrological processes have conspired over geological time to generate the geodiverse landscapes of the modern Amazon, and how these processes and landscapes ultimately set the stage for the evolution of the most species-rich biota on Earth.

2. Three Billion Years of Amazon History in a Nutshell

2.1. Assembling a Continent: Cratonization

2.1.1. The cratonic core The oldest core of the Precambrian shield of the Amazon is dated to between 3.0 and 2.5 billion years ago (Ga) and corresponds to the Carajás Province (Macambira *et al.* 2020; Figure 1.2.). The area of this core outcrops mostly in what today is the eastern Amazon, and is surrounded by younger crustal terranes, which were added from 2.1 to 1.0 Ga. The amalgamation

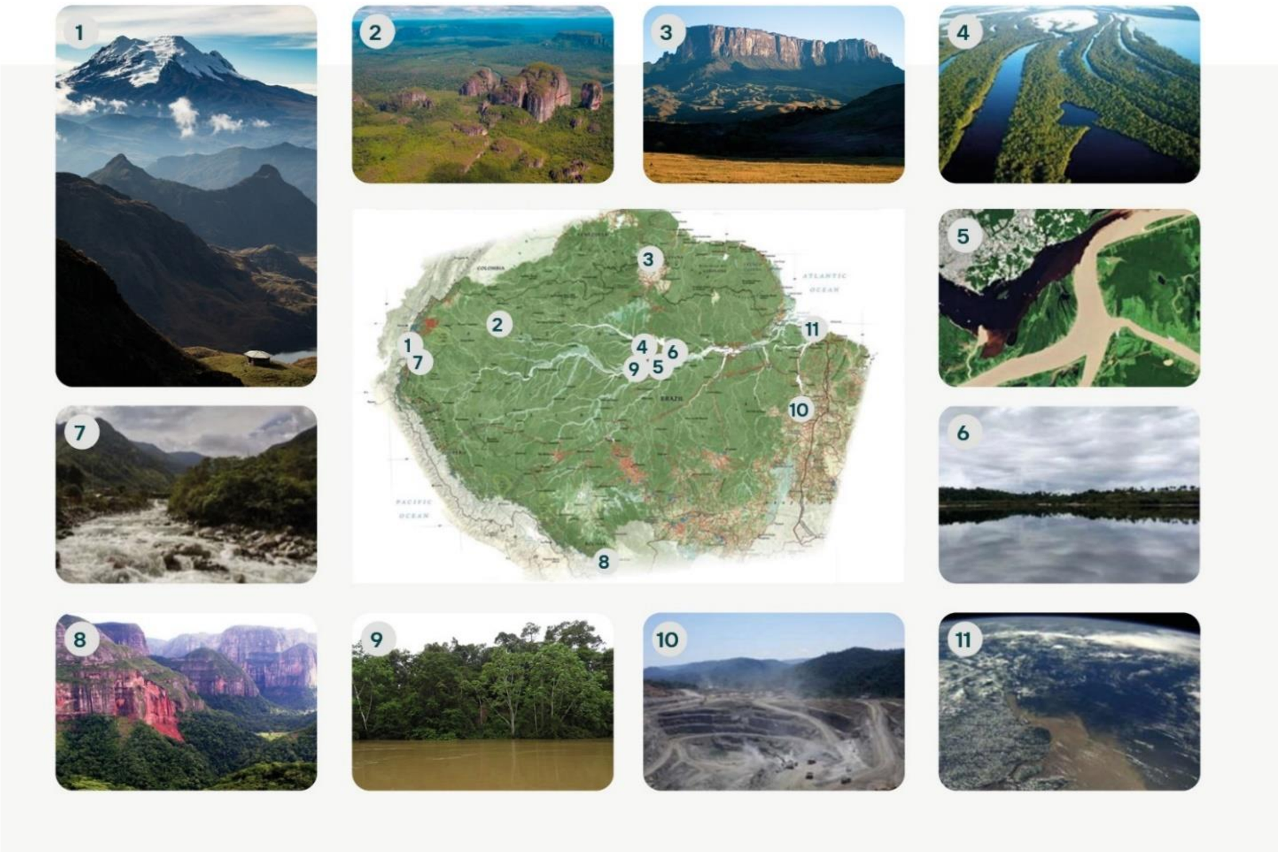

Figure 1.1 Photographic overview of the geology and geodiversity of the Amazon 1. The Andes in Ecuador (Esteban Suárez), 2. Chiribiquete (© Steve Winter), 3. Monte Roraima (Paulo Fassina), 4. Anavilhanas (Marcio Isensee e Sá / ((o))eco), 5. Negro-Solimões River junction, contains modified Copernicus Sentinel data (2018) processed by ESA, CC BY-SA 3.0 IGO (https://creativecommons.org/licenses/by-sa/3.0/igo/), 6. Lowland river (Pedro Val), 7. Andean river (Esteban Suárez), 8. Amboro National Park (Pattrön), 9. Várzea near Manaus (Hans Ter Steege), 10. Salobo Copper Mine in the Carajás Province (Gustavo Melo), 11. Mouth of the Amazon River (*Foz do Amazonas*) (European Space Agency https://www.uu.nl/en/news/amazon-river-impacted-eutrophication-of-atlantic-ocean).

of Paleo to Mesoproteroizoic terranes around the older Carajás Province Archean core consolidated the so-called Amazon Craton. It occupies most of western Brazil, covering almost half the size of the Brazilian territory, extending also into several other South American countries, and is larger than the modern Amazon drainage basin (Hasui 2012 and references therein).

The Amazon Craton is subdivided into two exposed areas, or 'shields', the Guiana Shield in the north and the Central Brazilian Shield in the south (Figure 1.2.). These shields are separated by sedimentary basins and cover about 40% of the Amazon. Alongside the Andes and associated sedimentary basins, the shields represent the most important geological setting of the continent, on which numerous geologic, surface, biologic, and climatic processes acted in parallel to produce the magnificent environmental diversity currently found in the Amazon.

2.1.2. Amalgamation of terranes The history of the consolidation of the Amazon Craton is linked with supercontinents assembly, particularly with Rodinia and Columbia (Zhao *et al.* 2004; Nance *et al.* 2014), the latter being different to the country 'Colombia'. During this time, the proto-Amazon Craton (i.e., the Carajás Province) was located at the southern margin of Columbia, while new terranes were accreted along its margins. The Maroni-Itacaiúnas Province collided with the northeastern border of the proto-Amazon Craton, while the Central Amazon, the Ventuari-Tapajós and Rio Negro-Juruena provinces, accreted to the southwestern margins (Figure 1.2.A). These new terranes expanded the areal extent of the craton, enhancing its mineral richness with rare metals like gold. By that time, at least half of the geological substrate of Amazon had already been formed (Tassinari and Macambira 2004; Santos *et al.* 2008).

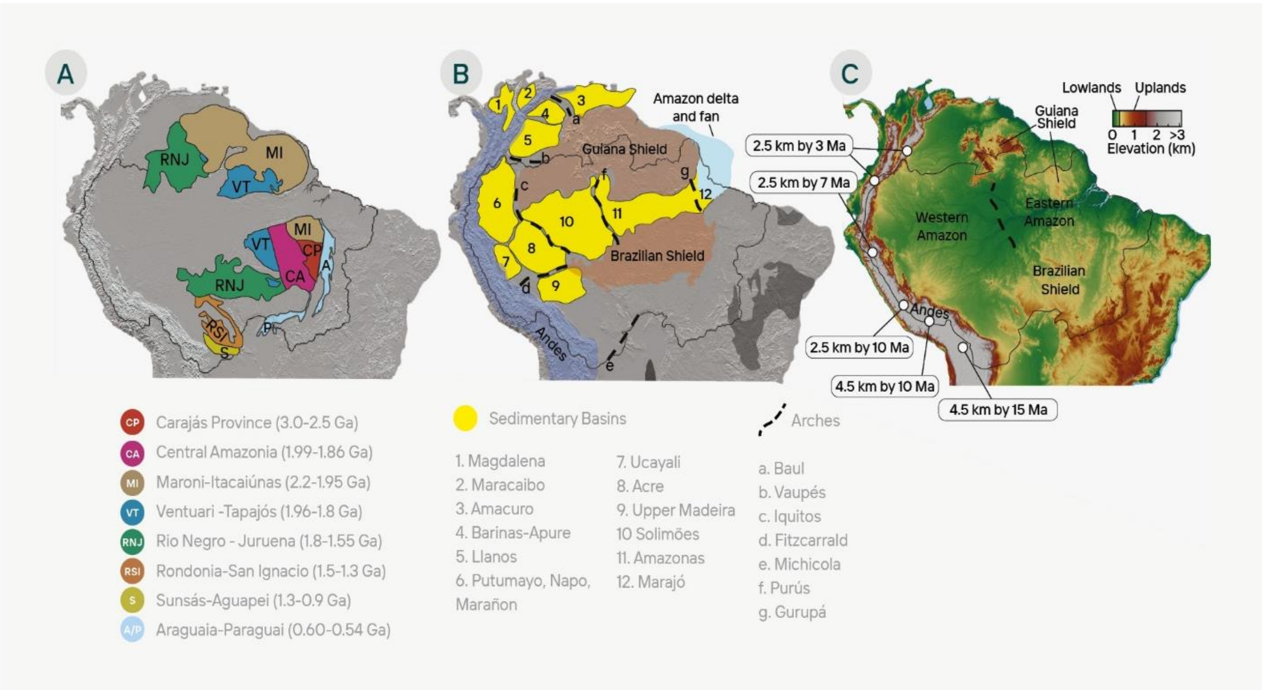

Figure 1.2 (A). Geochronological map of northern South America with the main provinces of the Amazon Craton (modified from Macambira *et al.* 2020). The area enclosing the known extent of late Meso- to early Neoproterozoic basement in the Northern Andes (fringing terranes). (B) Main foreland and intracratonic sedimentary basins of the Amazon (after Albert *et al.* 2018). The location of the north Andean foreland basins is highlighted. (C) Elevation map for the Amazon, with prominent highlands in the eastern Amazon standing out in red/yellow colors. The Andes uplift ages indicated are based on published literature (Mora *et al.* 2008; Garzione *et al.* 2017; Sundell *et al.* 2019).

Due to their geographic position on a stable continental platform, the Proterozoic sedimentary basins within the Amazon Craton were protected against subsequent continental collisions. Hence their sedimentary content remained relatively undisturbed over extended time. An example is the geomorphological province of table-top structures known as the "pantepui" (Figure 1.2). These sandstone platforms, such as Mount Roraima on the Guiana Shield, were formed by mostly fluvial braided with some coastal sediments that accumulated in an intracontinental sedimentary basin that extended over parts of the Columbia supercontinent.

The Columbia supercontinent fragmented at c. 1.9 Ga (Zhao *et al.* 2004), but no fragmentation was recorded at the proto-Amazon Craton. An attempted breakup resulted in the Large Igneous Uatumã Province, a widespread phase of granite magmatism along the craton. The assembly of the Rodinia supercontinent (c. 1.2–1.0 Ga) marked the end and final stabilization of the Amazon Craton with the accretion of the Rondoniano-San Ignacio and Sunsás provinces to the current western margin of the Amazon Craton. It was during this new tectonic cycle that the Amazon Craton assumed the configuration that we know today, behaving from then onwards as a single tectonic entity (Figure 1.2.A). Much later, during the assemblage of the Gondwana megacontinent at the end of the Neoproterozoic (c. 640 Ma), the Paraguai and Araguaia fold belts were amalgamated to the southeast and south portions of the Amazon Craton.

2.2. Building the Lowland Rock Substrate: Sedimentary Basins

2.2.1. Amazonian Sedimentary Basins After the breakup of Rodinia (c. 1.0 Ga) the Amazon Craton was embedded within the Gondwana supercontinent. At the beginning of the Paleozoic Era, an east-west rift developed across the middle of the Amazon Craton, almost splitting it into northern and southern portions (Wanderley-Filho *et al.* 2010). However, that rifting process did not persist, but instead resulted in the formation of an intracontinental depression that subdivided the craton into cores of what would become the modern Guiana and Brazilian Shields (Figure. 1.2). This depression formed the basement of the Solimões and Amazonas sedimentary basins. These E-W extending sedimentary basins in the middle of the Amazon Craton played a crucial role in forming present-day Amazonian landscapes. Over the past 400 million years, it was mostly a depression forming a seaway between the peripheral oceans and interior seas (e.g., the Paleomap Project by C. Scotese; www.scotese.com). This intracratonic depression now also forms the pathway of the Amazon River, with its tributaries in the surrounding uplands.

2.3. Setting the stage: Pangea breakup and birth of the Andes

The tectonic separation of South America and Africa led to the opening of the South and Equatorial Atlantic Ocean. This separation and the eventual uplift of the Andes along the western margin of South America fundamentally altered the geological, geomorphological, and climatic conditions of the entire continent, and led to the current geographic configuration (Figure. 1.3 and Fig. 1.4). The breakup of Pangea eventually transformed this supercontinent into multiple smaller continents, including South America, Africa, and the Indian subcontinent, with Antarctica and Australia breaking away from South America around 45 Ma (Seton *et al.* 2012). This paleogeographic rearrangement created new continental margins and large-scale drainage readjustments.

2.3.1. Creating an oceanic outlet for the proto-Amazon River (c. 100 Ma) The timing of onset and paleogeography of the Amazon River is a matter of much debate. Caputo and Soares (2016) proposed that during the Cretaceous the main direction of river flow was westward, away from the Atlantic margin

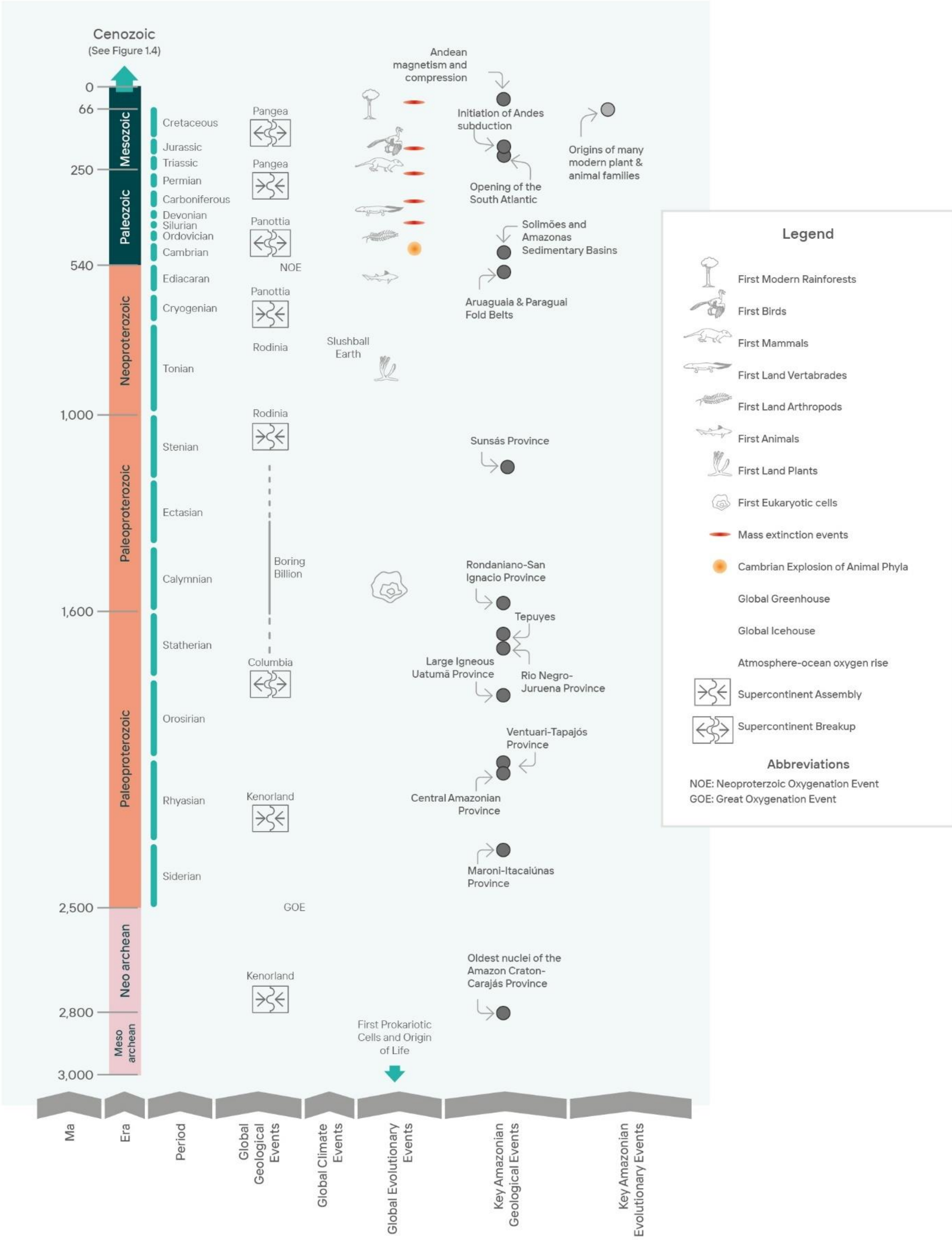

Figure 1.3. Geological time scale with the key global and Amazonian geological, climate and evolutionary events across time.

and through the intracratonic Amazon and Solimões basins. During this time the western margin underwent both passive and active margin phases, and had little topographic expressions except for isolated volcanoes (Ramos 2009; Martinod *et al.* 2020). Instead, Figueiredo *et al.* (2009) propose that the incipient Amazon River started flowing eastward soon after the initiation of the Equatorial Atlantic Ocean (c. 100 Ma). According to this hypothesis, during the Late Cretaceous (and after 100 Ma) the drainage system in Amazon was split into two basins. One basin was inherited from Pangea times, and continued flowing towards the west into the Pacific Ocean. The other newly-formed drainage basin flowed eastwards, draining the eastern Amazon and delivering cratonic sediments to the newly opened Equatorial Atlantic Ocean. The divide between the two basins would have been an elevated area conditioned by the tectonic complexity of the basement underneath, i.e., the Amazon Craton. This hypothesis is supported by the absence of Andean river sediments in the Atlantic Ocean until c. 10 Ma (Figueiredo *et al.* 2009; Hoorn *et al.* 2017), and by the progressive subsidence of the broken-up plate margin (McKenzie 1978). By this time, the paleo-Amazon drainage system was well developed in the eastern Amazon with an outlet in the Atlantic Ocean. To form its current transcontinental configuration, it needed to overcome a continental divide and connect with the western Amazon. However, this connection could not form until (i) the paleo-Amazon river could erode its westernmost headwaters and (ii) rivers could bypass the western Amazon. These necessary pieces of the puzzle fell into place when the Andes became an ~4 km-high mountain range and the Subandean foreland tilted eastwards (Dobson *et al.* 2001; Figueiredo *et al.* 2009; Shephard *et al.* 2010; Hoorn *et al.* 2010b; Sacek 2014).

2.3.2. Westward drift of South America and Andes formation: Forging the Amazon's westernmost boundary and eastward tilt The uplift of the Andes was fundamental to the formation of the Amazon we see today, with all the physiographic and climatic ingredients necessary to build its geologic and biologic diversity. Below we explain how the Andes formed.

As South America drifted westward during the opening of the Atlantic Ocean, the western margin of the South American plate experienced tectonic plate convergence, the driving force of mountain building. However, South America had no significant mountains along its west coast during most of the last 100 Ma. Despite the long history of westward drift and tectonic convergence on its western edge, it wasn't until the last 40 ± 10 Ma that the significant topographic expressions of the Andes began forming (Capitanio *et al.* 2011; Garzione *et al.* 2017). This delayed mountain building is puzzling and remains a matter of debate (e.g., Faccenna *et al.* 2017; Chen *et al.* 2019).

The Andes rose as high as 4 km in southern Peru by 10–15 Ma (Sundell *et al.* 2019). As uplift continued, the Andes also became wider, and by 7 Ma it reached 4–5 km elevation about 450 km away from Pacific Coast in southern Peru and northern Bolivia (Garzione *et al.* 2017). The southern Peruvian Andes became wider, while northern Peru, Ecuador, and Colombia had much less expressive topography (Figure 1.2.C).

Evidence diverges on paleoelevations during the Miocene, but it seems that it was not until 4–5 Ma that a 3 km high Andes flanked the Amazon's northwest (Mora *et al.* 2008). Importantly, when the Andes north of the Altiplano reached 2.5 km or more, atmospheric circulation was incrementally blocked, driving high orographic rainfall in the Andean foothills and fundamentally changing the climatic regime over South America (see Chapters 5 and 7). The Andean foothills got wetter, and parts of the eastern Amazon became drier (Ehlers and Poulsen 2009).

In the last 20 Ma, the rise of the Andes deformed the crust underneath the western Amazon, creating a large bowl-shaped terrain over which widespread wetlands could form, with occasional marine incursions (Hoorn *et al.* 2010b; Sacek 2014; See Section 3.2). Large sedimentary loads were exported from the uplifting and eroding Andes into the alluvial megafans, hinterland, and foreland basins (Wilkinson *et al.* 2010; Horton 2018). These processes also created the necessary conditions (i.e., thick and porous medium) to form the major groundwater aquifers (See section 6.3) in the region.

Mountain building, and the overfilling of wetlands by the large sediment loads, strongly controlled changes in the river network by pushing rivers further east. Together with the uplift of a lowland swell (i.e., Vaupés Arch), this was sufficient to interrupt the Orinoco River, formerly connected to the lowland western Amazon as far south as southern Peru, and a continent-wide river network began forming (Mora *et al.* 2010). At the same time, the paleo-Amazon River system in the eastern Amazon was growing westward by headwater erosion as suggested by Figueiredo *et al.* (2009). With the Andes continuously filling sedimentary basins in the western Amazon, the river network began bypassing the western lowlands, which flexed the lithosphere under the western Amazon and began forming an eastward tilt (Sacek 2014). Largely disconnected from the Orinoco system and potentially with an added push from the mantle underneath South America, the western and eastern Amazonian river systems connected and began draining eastward towards the Atlantic Ocean (Figueiredo *et al.* 2009; Shephard *et al.* 2010; Hoorn *et al.* 2010b; Eakin *et al.* 2014; Sacek 2014) (see Section 3).

3. Towards the Modern Landscape

3.1. Past environments that left their imprint on the modern Amazonian landscape

3.1.1 Transition from fluvial landscape to large wetland
Formation of the Andes dramatically reshaped the geography of northern South America in the Neogene (Garzione et al. 2008, 2017), with the marine seaway along the western margin of the Amazon gradually drying up, transitioning to deltaic and lacustrine settings (Hoorn et al. 2010b) (c. 66–23 Ma; Figure 1.4.D.a-b). From c. 23 to 10 Ma much of the western Amazon was covered by an immense mega-wetland known as the Pebas System (Wesselingh et al. 2001, 2006; Hoorn et al. 2010a, b) (Figure 1.4.D.c). This shallow, lake-dominated wetland system extended over c. 1 million km2, at a maximum reaching about 1,500 km E-W from the Andean foothills to the easternmost limit of the western Amazon near Manaus, Brazil. These wetlands also extended 1,200 km N-S along the Subandean foreland from the modern Ucayali River in Peru to the modern Caquetá River in southern Colombia (Figure 1.4.C.c). Associated with the Andean uplift, plate mantle/interaction, and global (eustatic) sea level high stands, the western Amazon faced subsidence (downwarping) and uplift of structural arches (*e.g.,* Fitzcarrald, Iquitos, Vaupés; see Figure 1.2.B), which formed the margins of sedimentary basins in the western Amazon today (Espurt et al. 2007; Shephard et al. 2010; Eakin et al. 2014; Sacek 2014; Jaramillo et al. 2017; Bicudo et al. 2019, 2020).

The sedimentary record of the Pebas mega-wetland system is archived in the Subandean sedimentary basins of Colombia, Ecuador, and Peru, and in the Solimões, Acre, and westernmost part of the Amazonas sedimentary basins of Brazil (Wesselingh *et al.* 2001; Mapes 2009; Hoorn *et al.* 2010a, b) (Figure 1.2.B). Pronounced subsidence along the Subandes and in the western Amazon also facilitated marine incursions into the region (Hoorn 1993; Hovikoski *et al.* 2010; Hoorn *et al.* 2010a, b; Jaramillo *et al.* 2017). The extent of marine influence is debated (Latrubesse *et al.* 2010; Gross and Piller 2020), but evidence is mounting that the Pebas wetland at times formed an estuarine embayment with tidal influence in the Llanos basin (Hovikoski *et al.* 2010; Boonstra *et al.* 2015; Jaramillo *et al.* 2017). The sedimentary units that represent the Pebas wetland are collectively called the Pebas, Curaray, or Solimões Formation, in Peru, Ecuador, and Brazil respectively. In Peru, their nutrient-rich surface and associated soils harbor a diverse and endemic-rich biota (Hoorn *et al.* 2010b; Higgins *et al.* 2011; Tuomisto *et al.* 2019).

The Pebas System was characterized by shallow, lake-dominated environments that deposited fine-grained sediments under frequently hypoxic (low oxygen) conditions. Such a system could form and maintain itself for over 10 millions years because subsidence and sediment input were kept in pace with one another (Wesselingh *et al.* 2001; Hoorn *et al.* 2010a, b). Most remarkable is the rich endemic fauna of molluscs and reptiles that inhabited its shores, but which went extinct after the disappearance of this environment (Wesselingh *et al.* 2006, Riff *et al.* 2010) (see chapter 2). The system was at its maximum extent during the Middle Miocene Climatic Optimum, from c. 17–15 Ma, coinciding with global sea level highstand (Miller *et al.* 2020; Westerhold *et al.* 2020; Methner *et al.* 2020) (Figure 1.4.).

3.1.2. From Wetland to Amazon River and Megafans By c. 10 Ma, the Pebas wetland system transitioned into alluvial megafans and the Acre fluvial system (Hoorn *et al.* 2010a, b). This change in sedimentary regime was caused by increased erosion and sediment output, possibly due to accelerated Andean uplift, and climate change from the late Miocene onwards (Figure 1.4.; Harris and Mix 2002). Together, these processes had a transcontinental effect, stretching from the Andes to the deep-sea fan system on the Atlantic margin. Evidence for this can be found both in the Subandean basins (e.g., Parra *et al.* 2009) and at the mouth of the Amazon River (*Foz do Amazonas*) (Figure 1.4.D.d,e). The latter has a sedimentary record that displays a clear change in sediment geochemistry, from cratonic to Andean sediment at c. 10 Ma (Figueiredo *et al.* 2009; Hoorn *et al.* 2017; van Soelen *et al.* 2017).

Other models propose a Pliocene (c. 4.5 Ma; Latrubesse *et al.* 2010; Ribas *et al.* 2012) or even Pleistocene (<2.6 Ma; Rossetti *et al.* 2015) age for the onset of the transcontinental Amazon River. Empirical data on the ages of *terra firme* surfaces along the Amazon River in the western Amazon show maximum ages of 250 ka (Pupim *et al.* 2019) suggesting that the most recent surfaces are relatively young (geologically speaking). Perhaps these different interpretations arise in part due to alternative definitions of the Amazon River, different dating methods, the longevity of geomorphic features, and data types used by different studies (see review in Albert *et al.* 2018).

3.1.3. Quaternary Climate & Landscape Changes in the Amazon The Quaternary covers c. 2.6 million years of history, during which the climate across the globe and in the Amazon drastically changed because of the onset of glacial-interglacial fluctuations (Lisiecki and Raymo 2005, 2007) (see Box 1.2). The climate dynamics of the Quaternary also substantially affected biotic and abiotic (e.g., megafans, sedimentary deposits) landscapes of the Amazon (Cheng *et al.* 2013; Baker and Fritz 2015; Govin *et al.* 2014, Hoorn *et al.* 2017) (Figure 1.4.D.f).

In terms of precipitation, the Amazonian hydrological cycle is closely tied to the seasonal movements of the intertropical convergence zone (ITCZ) over the Atlantic, which shapes the South American monsoon (e.g., Garreaud *et al.* 2009, Novello *et al.* 2019). Additional precipitation forcing is caused by substantial rainforest transpiration playing a role in the onset of the monsoon (Wright *et al.* 2017) and contributing large amounts of water vapor and precipitation to the Amazon drainage basin (Langenbrunner *et al.* 2019). The dry-to-wet transition season is additionally influenced by the significant amount of evapotranspiration from the Amazonian forest canopy landscape (Wright *et al.* 2017).

Quaternary climate changes affected both the intensity and mean latitude of the ITCZ, atmospheric convective systems, and the trade winds. Precipitation regimes over South America changed substantially following shifts in the intensity of the South American monsoon, the South American low-level jet, the Bolivian high, and the South Atlan

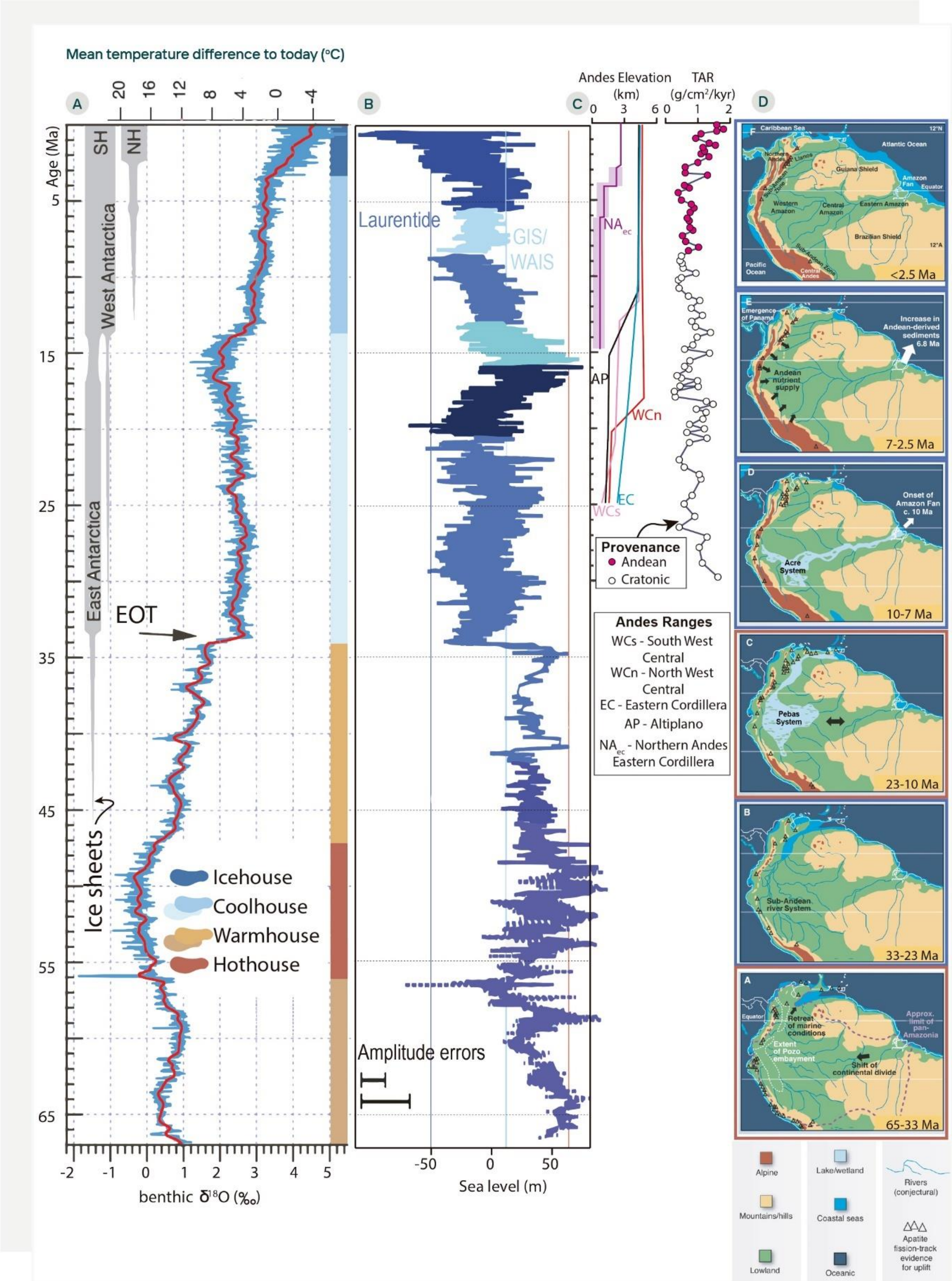

Figure 1.4 A) Global Cenozoic temperature curve (from Westerhold *et al*. 2020); B) Global Cenozoic sea level curve (from Miller *et al*. 2020) (see Box 1.2); C) Past elevation estimates for the Central Andes (after Sundell et al., 2019), and temporal variations in εNd in the Amazon submarine fan (red, after Figueiredo et al. 2009; Hoorn et al, 2017), Ceará Rise (black, after van Soelen et al, 2017) and Terrigenous Accumulation Rates (TAR) at the Amazon outlet near the Ceará Rise; D) Paleogeographic maps illustrating the transition from Amazon Craton to Andes-dominated landscapes: (a) The Amazon once extended over most of northern South America. Breakup of the Pacific plates changed the geography and the Andes started uplifting. (b) The Andes continued to rise with the main drainage toward the northwest. (c) Mountain building in the Central and Northern Andes (~30 Ma, specially from 12 Ma) and wetland progradation into the western Amazon. The Middle Miocene Climate Optimum and high sea level caused marine ingressions and estuarine conditions in the heart of the Amazon. (d) Uplift of the Northern Andes restricted "pan-Amazonia" and facilitated allopatric speciation and extirpation [e.g., (21)]. (e) The mega-wetland disappeared and *terra firme* rainforests expanded; closing of the Panama Isthmus and start of the Great American Biotic Interchange (GABI). (f) Quaternary. Note that South America migrated northward during the course of the Paleogene.

Box 1.2 Pleistocene Climate and Sea Level Fluctuations

Global climate fluctuations during the Pleistocene (c. 2.6–0.01 Ma) have driven multiple cycles of eustatic (or worldwide) sea level changes, with several of the most recent cycles exceeding 100 m vertical change from minimum to maximum sea stands. During warm interglacial periods, elevated sea levels slowed river discharges to the sea, allowing sediments to settle out and build up floodplains. During cool glacial periods, lowered sea levels allowed rivers to incise more deeply into their sediment beds as they approached their mouths, eroding floodplains and steepening the river gradient. This repeated formation and erosion of Amazonian whitewater floodplains (i.e., *várzeas*) during sea level high and low stands is referred to as the Irion Cycle (Irion and Kalliola, 2010).

Erosion during sea level low stands excavated the lower portions of rivers in the eastern Amazon, forming deep ría lakes near the mouths of large clearwater rivers like the Tocantins, Xingu, and Tapajós. Sea level rise after the LGM allowed sediments to fill the canyon that had formed in the lower portion of the Amazon-Solimões River, so that the bed of the modern Amazon is 10–50 m higher than that of the ria lakes of its adjacent tributaries. By lowering the topographic base-line for erosion, low sea levels also induced the formation of waterfalls and rapids in these upstream tributaries.

-tic Convergence Zone (see Chapters 5 and 7). Our knowledge of precipitation patterns during the Quaternary is based on scattered archives from ice cores and lakes in the Andes, marine records from the Brazilian coast, and caves throughout the Amazon. The latest assessments hint at the complex history of shifting patterns of hydrological variation throughout the region (e.g., Thompson 1998; Sylvestre 2009; Govin *et al. 2014*; Novello *et al.* 2017, 2019; Hoorn *et al.* 2017; Wang *et al.* 2017).

Evidence from paleorecords that cover the last two glacial-interglacial cycles (c. 250,000 years) reveals distinct climate profiles in the eastern and western Amazon, the so-called South American precipitation dipole (Cheng *et al.* 2013). This dipole consists of a differential precipitation pattern over the Amazon, where wet-dry conditions varied substantially in the eastern Amazon, while precipitation variability was much less in the western Amazon, including the Andes (Cheng *et al.* 2013; Baker and Fritz 2015, Wang *et al.* 2017). The effect of this precipitation dipole on biotic landscapes is poorly known, as fossil pollen sequences in the lowland Amazon often lack time series older than 50,000 yr (Flantua *et al.* 2015). However, records covering the last glacial period around c. 21 ka show different species composition and structures of lowland and Andean forests when compared to the present (Mayle *et al.* 2009), without necessarily a shift between biomes (Häggi *et al.* 2017). Paleorecords from the highlands, including glacier snowline reconstructions and fossil pollen records (e.g., Flantua *et al.* 2014, 2019), also indicate the persistent influence of Quaternary climate fluctuations on the Andean Amazon. Temperature ranges over a full glacial-interglacial cycle differed across the Amazon; current estimates are 2–5°C for the Amazonian lowlands and 5–10°C in the high Andes (above 2,500 m) (e.g., Klein *et al.* 1995; Mayle *et al.* 2004; Mark *et al.* 2005; Groot *et al.* 2011; Hooghiemstra and Flantua, 2019). Although temperatures were equally low during glacial periods in the northern Andes, they were substantially drier than in the central Andes (Torres *et al.* 2013), creating an additional precipitation dipole of paleoclimate within Amazonia but across the Andes. Cool temperatures during glacial periods were accompanied by large changes in moisture availability linked to the South American monsoon system, causing substantial advances of glaciers across the Andes (Palacios *et al.* 2020).

The waxing and waning of glacial-interglacial-cycles influenced Amazonian landscapes in many ways. The combination of global climate cooling during the Pliocene-Pleistocene (last 4 Ma) and the alterations of glacial processes are presumed to have increased glacial erosion globally (Herman *et al.* 2013). Increased precipitation accelerated erosion and sediment transport during interglacial periods, while extensive moraines paved valleys to elevations as low as 2,500 m (Angel *et al.* 2017; Mark *et al.* 2005). Erosion rates may have been highest during transitions to and from glaciated to ice-free conditions (Herman and Champagnac 2016), and sediment flux was disproportionately high during the high-amplitude climate oscillations of the last one million years (Robl *et al.* 2020). High denudation of the Andes during the Quaternary contributed to the formation of megafan alluvial piles in portions of the sub-Andean foreland (Wilkinson *et al.* 2010).

3.2. Modern landscapes in the Amazon

As reviewed in Section 3.1, modern landscape geodiversity from the continental scale down to river margin terraces is a cumulative function of tectonic, geomorphological, and climatic processes operating over millions of years.

Amazonian landscapes can be classified by the main features of their geologic settings, which affect all surface features from soils and rivers to species and ecosystems. Importantly, almost everything we know about the history of Amazonian landscapes comes from materials preserved in the geological record.

Landscape morphology is a description of the spatial distribution of elevations, resulting from the balance between uplift, erosion, and deposition. Thus, terrain steepness and sediment loads in rivers reflect how fast an area is uplifting (e.g., Hack 1960; Ahnert 1970; Milliman and Syvitski 1992; Montgomery and Brandon 2002; Portenga and Bierman 2011).

Tectonic compression uplifts mountain ranges in the Andes, while rivers remove all or part of that uplift just as fast, producing sediments and nutrients which are then transported downriver (e.g., Wittmann *et al.* 2011; Garzione *et al.* 2017). Thus, the Andes mountains have local amplitudes of elevation (i.e., range of elevation in a given radius, henceforth referred to as *relief*) upwards of 3 km within a 2.5 km window. These high relief areas are a testament to the forces driving uplift and produce high erosion rates (c. 100–1,000 m/Ma) at the westernmost edges of the Amazon, yielding 300–600 Mt/yr in the Lower Solimões River (Wittmann *et al.* 2011). These high sediment loads come from nutrient-rich areas within the Amazon drainage basin (see Section 4), which sets the stage for different types of aquatic and floodplain habitats (see Section 5). Importantly, these mountains block atmospheric currents and produce steep local climatic gradients, called orographic effects, focusing meters of rain on the eastern slopes of the Amazonian Andes (Bookhagen & Strecker 2008). Together, the high relief and sediment yield of the Andes and its local effects on climate and vegetation have been identified as key ingredients in generating and maintaining biodiversity (Antonelli *et al.* 2018).

In contrast, the lowland landscapes of the western and eastern Amazon have low relief (<200 m), mainly because of low uplift rates. Mostly, rivers flow over easily erodible sedimentary rocks from the sedimentary basins that form the substrate for most of the western and eastern Amazonian lowlands. Although the low relief and mostly uniform topography of the interfluves suggest these landscapes are at equilibrium with local uplift rates, the western Amazon lowlands are highly dynamic. Here, the low slopes pave the way for highly energetic and dynamic meandering rivers (i.e. Beni, Mamoré, Juruá, Purús, Madeira, Solimões), which migrate back and forth over their floodplains at rates from 10 m/year to >100 m/year, carving curved floodplain walls and even avulsing into new valleys (e.g., Mertes *et al.* 1996; Gautier *et al.* 2007). Compiled geochronologic data along the

Amazon whitewater floodplain suggest that active floodplain deposits are at most 20 ka (Pupim *et al.* 2019), placing a limit on the time for river channels to sweep across the active floodplain. *Paleo-várzeas* above the active floodplains are also preserved in some places (e.g., Lago Amanã), persisting through more than one glacial cycle of erosion and deposition of floodplain sediments (Irion and Kalliola 2010). These complex hydrogeomorphic dynamics generate high spatiotemporal heterogeneity on Amazonian lowlands, contributing to, for instance, exceptionally high local fish diversity (Saint-Paul *et al.* 2000; Correa *et al.* 2008; Goulding *et al.* 2019).

In contrast to the lowlands of the western Amazon, the eastern Amazon's lowland rivers flow mostly over the Alter-do-Chão Formation (moderately resistant siltstones and sandstones). Here, rivers are also low-relief (10–200 m), except for where resistant sandstones outcrop in the Pará state (Brazil), where local relief can reach 400+ m. Despite having a relatively uniform relief distribution which could indicate equilibrium landscapes, northern and southern tributaries to the Amazon River between the confluence of the Rio Negro and Solimões River are riddled with rapids and waterfalls, especially near the limits between the lowlands and uplands (i.e. João *et al.* 2013; Val *et al.* 2014; Val 2016). Also, the long-term stability of the Amazon River margins has allowed for the development of lateritic crusts (e.g Balan *et al.* 2005; Horbe and da Costa 2005), which are locally faulted (Silva *et al.* 2007). Together with evidence of fluvial incision and paleochannel features and deposits (e.g., Hayakawa *et al.* 2010), these landscapes are likely not equilibrated, which has led authors to argue for intracontinental faulting and glacio-eustatic sea level change as triggers of landscape change (Irion and Kalliola 2010; Val *et al.* 2014; Rossetti *et al.* 2015). Although these are all plausible interpretations, the true origin of knickpoints (waterfalls and rapids) in the eastern Amazon is not currently known but may be key to constraining the timing of landscape changes where river deposits are absent.

Where rivers flow over and out of cratonic areas (i.e. shields), spatial changes in relief are drastic and likely long-lasting. Extending over all the northern and southern edges of the Amazon's drainage basin, there are outcrops of cratonic rocks, which form wide plateaus mostly with 500 – 1,000 m elevation but reaching upwards to 2,500 m in the northernmost reaches of the Amazon in southern Venezuela and at the border between Brazil and Guyana (Figure 1.2.c). Here, the so-called *Tepui* form astounding table-top mountains which are supported by highly-resistant metamorphic rocks of the Amazon Craton and stand tall above the Amazon lowlands (e.g., Briceño and Schubert 1990; Rull *et al.* 2019, see Section 2). This is where the deep-time geologic evolution of the Amazon manifests itself on the current landscape the most. Whether these plateaus are uplifting, and if so, how fast, is unknown, but likely on orders of magnitude lower than in the Andes. Nonetheless, local flexural uplift due to the weight of the sedimentary and igneous (i.e. sills) piles in the Amazon sedimentary basin as well as in the deep-sea fan could contribute to maintaining some of these plateaus (Nunn and Aires 1988; Watts *et al.* 2009). These highly resistant, more than a billion-year-old rocks impede erosion and landscape lowering. Lateritic duricrusts 5 to 60 Ma in age are still preserved in the eastern Guiana Shield, suggesting <5 m/Ma erosion rates (Théveniaut and Freyssinet 2002; Balan *et al.* 2005; dos Santos Albuquerque *et al.* 2020). On millennial timescales, the shield areas erode at 10–40 m/Ma and contribute 9–20 Mt/yr of sediments via the Negro and Tapajós rivers (Wittmann *et al.* 2011). So far, erosion rates are scarce but highly important to determine how fast upland areas were integrated with the lowland basins through the geologic past. This is an important gap in knowledge as these plateaus harbor many range-restricted and endemic species (Albert *et al.* 2011; Cracraft *et al.* 2020; see also chapter 2).

In summary, the geological contrasts described above are 1) deeply entrenched rivers in the uplifting Andes with a mix of equilibrium and non-equilibrium landscapes; 2) low-relief, near-equilibrium landscapes in the western Amazon lowlands over relatively soft sedimentary rocks with textbook examples of dendritic and meandering fluvial patterns; 3) complex topographic forms in the shields with low-relief plateaus surrounded by intensified river excavations and anomalous river network configurations due to lithological contrasts. Importantly, low-relief drainage divides exist in many portions at the edges of the Amazon River, such as its divide with the Orinoco, Essequibo, and Paraná-Paraguay-Uruguay river basins, and indicate that the Amazon River basin is still undergoing transience (e.g., Albert *et al.* 2018; Stokes *et al.* 2018). Despite the absence of known active tectonic uplift, central and eastern Amazonian landscapes are prone to autogenic processes, and also to external base level perturbations that can ultimately lead to river network changes. These processes are 1) dynamic topography, 2) glacial-interglacial base level fluctuations (Box 1.2), 3) river capture (Box 1.3), and 4) river avulsions (Box 1.3). Lastly, erosion rates are largely unconstrained in the Amazon and only restricted to the largest tributaries (Wittmann *et al.* 2011). There is essentially no published long-term erosion rate data in the lowland Amazon and very few rates are available for the shield areas and for the Andes mountains. These are major data gaps. Constraining background sediment production will not only allow for constraining deeper links between landscape and species evolution. It is also of major importance to assess the impacts of anthropogenic activities such as agriculture as well as the effects of deforestation and wildfires on sediment yield and habitat degradation in a future of climate change.

4. Richness of the Amazonian Landscape: Geodiversity and Soils

Soils form at the interface between geology, biology, and hydrology, constitute an integral part of the physical environment for continental ecosystems, and serve four main ecological functions. Soils facilitate (i) the storage, supply, and purification of water; (ii) plant growth; (iii) atmospheric modifications; and (iv) habitats for organisms and microorganisms. Moreover, soils provide essential resources for primary production (i.e., photosynthesis) through the availability of essential mineral elements and water that support terrestrial and aquatic food webs. Soil transformations through time, therefore, control nutrient availability and profoundly influence the water chemistry in both terrestrial and aquatic ecosystems. The evolution, diversity, and geographic distribution of soil types affect all continental ecosystem functions. Here, we review aspects of the interaction between geological processes, time, and soil evolution in the Amazon, and how this regional geodiversity contributes to ecosystem functions.

4.1. Geodiversity has shaped Amazonian soils

Geological processes, such as those described in sections 2 and 3, have shaped the geographic distribution and physiographic coverage of edaphic conditions in the modern Amazon. Soil formation and evolution occur through the interactions of five major factors (Jenny 1941): parent material (e.g., rock type and minerals), geomorphology (local landscape relief), climate (hydrological and evaporative regimes governing water fluxes through sediments), interactions with organisms (e.g., soil and root-associated microfauna and meiofauna), and time. These factors act together to create the conditions where a given type of soil occurs. Soils are dynamic formations that reflect the inputs of many contributing abiotic (lithological, hydrological, climatic) and biotic factors, including chemical and physical modifications by bacteria, mycorrhiza, plants (e.g., roots, leaf litter) and animals (e.g., meiofauna, earthworms, arthropods).

Time changes both the morphological and chemical characteristics of soils in predictable ways. At the beginning of the soil forming process the flat

Box 1.3 Drainage modification through river capture and avulsion

River capture, sometimes referred to as stream piracy, is the process by which the tributaries of one river basin capture a fraction of a neighboring river network. River captures often arise from an imbalance in erosion rates between streams sharing a drainage divide. The transfer of tributaries among river basins moves the position of the drainage divide, and is often recognizable by abrupt changes in the thalweg or valley-line of river courses, such as characteristic hair-pin or U-shaped turns. In regions with rocky substrates, river capture results in the formation of narrow gorges or wind gaps, as well as topographic discontinuities represented as knickpoints in the longitudinal river profile. Such knickpoints are often the location of rapids or waterfalls, which are propagated upstream by progressive erosion. The upstream movement of knickpoints is a universal consequence of base level fall, stripping the landscape of its uppermost soil mantles. Base level fall resulting from river capture or lowered sea level is an understudied mechanism of landscape change in the Amazon, but likely to have been very important. Depending on several variables, landscape transience can persist for millions of years in the tectonically stable shield landscapes. Important variables driving river capture and watershed migration include the elevational magnitude of base level falls, differences in basin sizes on either side of a watershed divide, differences in precipitation and lithology on either side of a watershed divide, and the ensuing slope-driven stream erosion power.

River avulsions are changes in the position of active river channels that arise from hydrological and geomorphological processes. Avulsions are usually autogenic in nature and span timescales of years to thousands of years (Slingerland and Smith 2004). As rivers avulse into another channel, they leave fluvial "scars" behind, also called fluvial escarpments, as well as alluvial fans, which are kilometer-wide fan-shaped sedimentary deposits. Fluvial escarpments are widespread in the lowland Amazon and indicate that hundreds of kilometers of river avulsion are an intrinsic part of the lowland alluvial rivers, with important implications for biogeography and biodiversity (Albert *et al.* 2018; Tuomisto *et al.* 2019). The largest avulsions form alluvial megafans, and are also widespread in Amazon with variable ages since the late Miocene (Wilkinson *et al.* 2010).

surface develops a thin layer of unconsolidated material over the rock through the physical effect of climate (e.g., variations in temperature and moisture) and the pressure exerted by plant roots. Over thousands to millions of years, the soil will deepen and the effects of weathering (see section 4.2) will transform the structure of the soil minerals and their chemistry until a more stable, nutrient poor, and deeper soil is formed. Mature soils are resistant to further changes in the absence of pronounced landscape-scale transformations. If developed on a sloped surface, faster erosion might outpace the subsoil formation, keeping the soil young and shallow irrespective of how long it has been exposed. The continuous wet and warm climate and widespread presence of soil organisms across the Amazon imply that geological time, parent material, and geomorphology are the main factors controlling soil development. The influence of these factors, however, varies with spatial scale (Figure 1.5.).

Interactions between geological and climatic factors across scales have produced a complex mosaic of soil types and conditions across the Amazon, each with distinct physical, chemical, and biological properties. At basin-wide scale, the processes described in sections 2 and 3 resulted in large differences in the age and erosion rates of parent material (i.e., time since the substrate was exposed to weathering), forming different geological provinces (Figure 1.2A) with variation in soil nutrient status (Figure 1.5).

About 60% of soils in the Amazon drainage basin are highly-weathered, nutrient-poor ferralsols and acrisols, concentrated mainly in the eastern Amazon (Quesada *et al.* 2011). The parent material of the Guiana and Brazilian shields is Proterozoic in age and highly weathered. Many shield soils developed over crystalline rocks instead of sedimentary rocks or unconsolidated sediments, which have very low erosion rates (Section 3.2). Their weathering occurs at a slower pace and many shield soils have a somewhat higher nutrient status when compared to the comparatively younger soils occurring east of the Negro-Solimões river confluence in the intracratonic basin. During filling of the Amazon's sedimentary basins, for example, Paleozoic-Mesozoic sediments originating from weathered Proterozoic rocks resulted in lower soil fertility (Quesada *et al.* 2010) (Figure 1.5. A and B).

By contrast, soils in the western Amazon generally are more nutrient-rich, as they formed in recent sediments that eroded from the Andes (Quesada *et al.* 2010, 2011; Quesada and Lloyd 2016). Much of the sediments deposited in the western Amazon

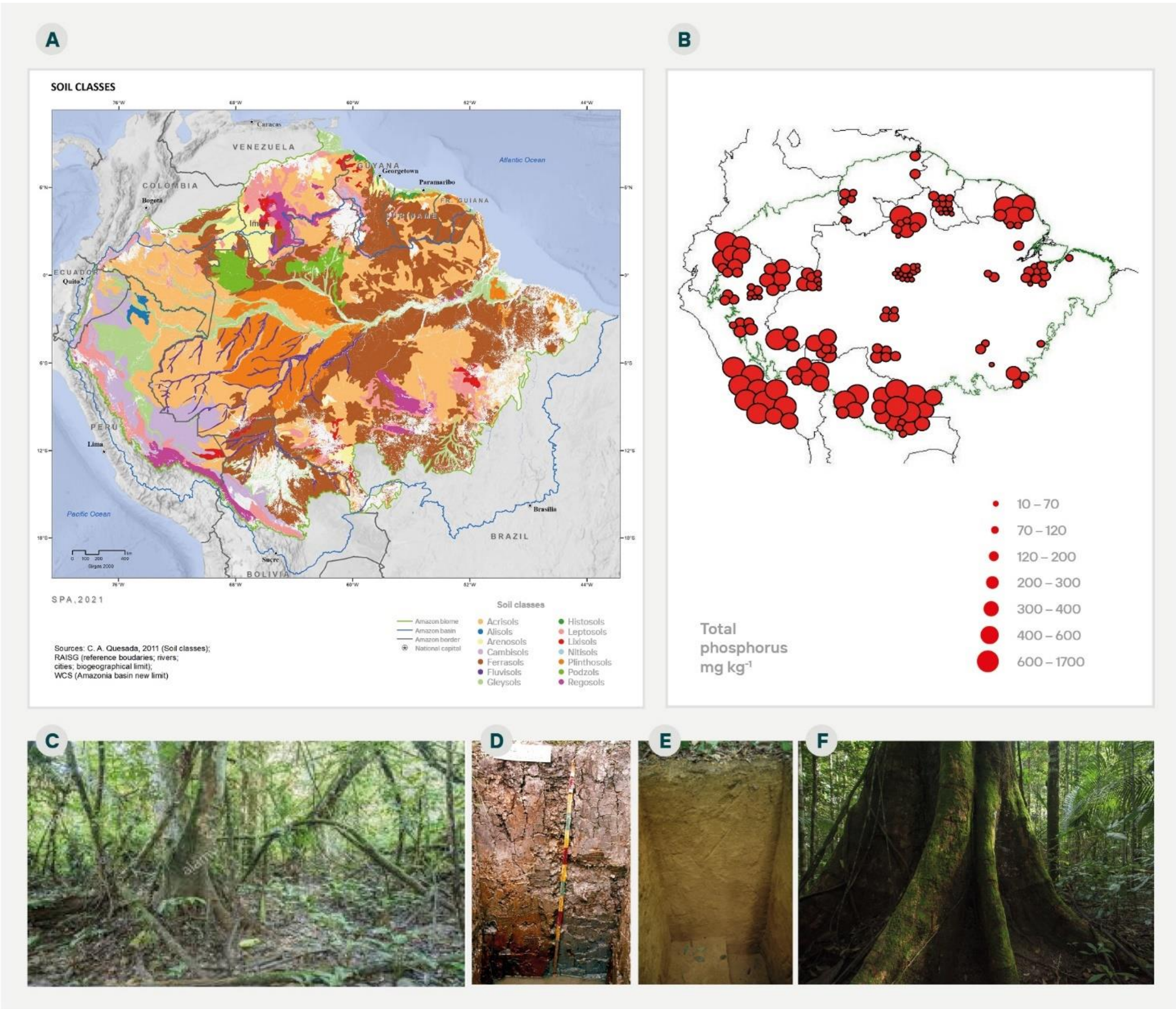

Figure 1.5 A) The complexity of soils across the Amazon; the majority are highly weathered, the rest varying from well-developed to young soil profiles. Parent material (geological substrate) and soils are directly related, but there is no relation with age of rocks. The E-W depression of the lower Amazon River has very poor soils; the crystalline rocks in the eastern Amazon are intermediate; the 'Andes-derived' substrates in the western Amazon have rich soils (Quesada *et al.* 2011). B) Phosphorus gradient in Amazonian soils, with a clear trend from phosphorus-rich soils in the west to phosphorus-poor soils in the east (Quesada and Lloyd 2016). C-D) Gleysols, non-weathered soil and biomass-poor soil in the western Amazon; E-F) Ferralsols, weathered soil and biomass-rich forest in the eastern Amazon (photo credits: B. Quesada, João Rosa).

during the Miocene were protected from weathering due to waterlogging during the Pebas mega-wetland phase (23-10 Ma, see Sections 2 and 3). Therefore, processes of soil formation in much of the western Amazon are significant only from the Pliocene (c. 5 Ma) onwards, with much of the region having soils that are less than 2 million years old (Quesada *et al.* 2011).

Although geological time and erosion rates explain basin-wide variations in soil development and fertility, variations in parent material and geomorphology are the main factors influencing local variations in soil type. Processes associated with geomorphology, such as topographic position (plateau, slope, and valley), drainage, and local erosion can influence soil formation strongly, resulting in different soils occurring at a scale of tens of meters, despite being formed on the same lithology (Catena Formation, Fritsch *et al.* 2007). The interaction of these factors results in an exceptionally high diversity of soils, with diverse physical and chemical properties. For example, at least 19 of the 32 World Reference Base (WRB) soil groups occur in the Amazon (Quesada *et al.* 2011), which only lacks soils associated with dry or cold environments.

4.2. Soil diversity influences ecosystem function and biodiversity

Soil development occurs because of physical and chemical weathering of parent rock and regolith, and nutrient enrichment from allochthonous sedimentary deposition and autochthonous organic decomposition. Chemical weathering processes (carbonation, dissolution, hydrolysis, oxidation-reduction) are accelerated in the hot and humid climates of lowland Amazonian rainforests, while physical weathering is more active in the high Andes. Physical weathering occurs through geomorphic processes that break soil particles into smaller sizes, whereas most chemical weathering of Amazonian soils involves reactions with water.

Weathering reduces the concentrations of many mineral elements essential for plant growth, such as phosphorus, calcium, magnesium, and potassium. Weathering also alters soil mineralogical composition and morphological characteristics (Quesada *et al.* 2010). This ultimately results in associations between major groups of soil classification and nutrient distribution (Figure 1.5.A). Soil phosphorus serves as an important indicator of soil development, as total phosphorus content decreases during soil weathering.

Because the phosphorus pool is gradually transformed to unavailable forms, phosphorus is the main nutrient limiting ecosystem productivity in ancient Amazonian soils (Quesada *et al.* 2012; Quesada and Lloyd 2016). On the other hand, nitrogen is mainly supplied to soils through atmospheric nitrogen deposition and microbial N_2 fixation, thus accumulating throughout soil development. Nitrogen is not limiting in mature forests, but nitrogen limitation does occur in disturbed forests (e.g., logging, fires, large scale mortality events) and white sand forests (Quesada and Lloyd 2016).

Forests are not solely affected by soils through nutrient availability. Younger soil types that have not suffered extensive weathering almost invariably show a lower degree of vertical development, often being shallow and with hard subsurface horizons that restrict root growth (Figure 1.5.C-D). Soil types that have resulted from many millions of years of weathering usually have favorable physical properties, such as well-developed soil structure, good drainage, and, due to their depth, high water storage capacity (Figure 1.5. E-F). This trade-off between physical quality and nutrient availability contributes strongly to the diversity of environments in the Amazon and causes deep effects on how the ecosystem functions.

Soil physical properties, such as shallow soil depth, poor drainage, and physical impediments to root growth, can be an important source of limitation to forest growth, directly or indirectly influencing tree mortality and turnover rates (Quesada and Lloyd 2016). Soil physical properties change patterns of above-ground vegetation biomass (Quesada *et al.* 2012), and how biomass is stored in individual trees (Martins *et al.* 2015). Physically constrained soils with high rates of tree mortality tend to be dominated by many small trees, while forests growing in favorable physical and low-disturbance soil conditions allow trees to live longer and accumulate more biomass. Soil physical properties are also related to the abundance of palms in the Amazon (Emilio *et al.* 2014), and to tree shape through their effects on the relationship between tree height and diameter (Feldpausch *et al.* 2011). Similarly, soil physical characteristics also influence forest demographic structure (Cintra *et al.* 2013) and dead wood stocks (Martins *et al.* 2015). On the other hand, forest growth rate (biomass production) is directly influenced by soil nutrient availability. Direct evidence of nutrient limitation on forest productivity has been reported by Quesada *et al.* (2012), which demonstrated that rates of biomass growth were correlated to variations in total soil phosphorus concentrations across the Amazon.

The importance of soils for tree species richness in the Amazon is controversial. Some studies report that species richness was generally negatively correlated with soil nutrient status, while others report a positive correlation (Faber-Langendoen and Gentry 1991; Phillips *et al.* 2003; Ruokolainen *et al.* 2007). In any case, tree species distributions are often associated with soil properties. Significant relationships between tree distribution and soil nutrient concentrations were found for at least a third of the tree species in the lowland forests of Colombia, Ecuador, and Panama (John *et al.* 2007). Higgins *et al.* (2011) show that floristic patterns in Amazonian forests were associated with soil variations across different geological formations, with this corresponding to a 15-fold change in soil fertility and an almost total change in plant species composition, suggesting that, to a large degree, floristic patterns may be related to underlying geological patterns (Quesada and Lloyd 2016).

5. Amazonian Hydrology: Rivers, Wetlands, Soil Waters, and Groundwaters

Water supports life directly, and indirectly modulates many processes essential to life. The varied distribution of water across the Amazon, at seasonal to geological time scales, provides the physiographic backdrop for both terrestrial and aquatic life. Below, we examine the modern-day Amazonian hydrological landscape as a product of geological and climatic gradients, and highlight the salient features relevant to understanding Amazonian biodiversity.

5.1. Geological and Climatic Diversity Shapes Hydrological Diversity across the Amazon

Under a given climate, topography, substrate, and vegetation cover, which could be even more important than geological substrates, control how much rainfall directly enters the surface drainage network (surface runoff), and how much infiltrates into the subsurface. While surface flow mobilizes sediments and nutrients into aquatic systems, the subsurface material stores the infiltrated water, promoting chemical weathering, and slowly releases water and solutes to streams as baseflow. Subsurface storage is also a source for root zone soil water for plants during rainless periods. Across the Amazon, substrate properties controlling this surface-subsurface partition (e.g., slope, permeability, and regolith or sediment thickness) vary dramatically. This creates a spatial mosaic in the landscape with hints on where water is shed or collected. Where there is substantial storage capacity in the subsurface (soils, regolith, fractured rocks), soils and rivers do not dry up quickly and ecosystems are more resilient to fast changing weather events and seasonal droughts (Hodnett *et al.* 1997; Cuartas 2008; Tomasella *et al.* 2008; Neu *et al.* 2011). Figure 1.6 illustrates the factors described above, which shape the hydrological plumbing of the system (cartoon in center).

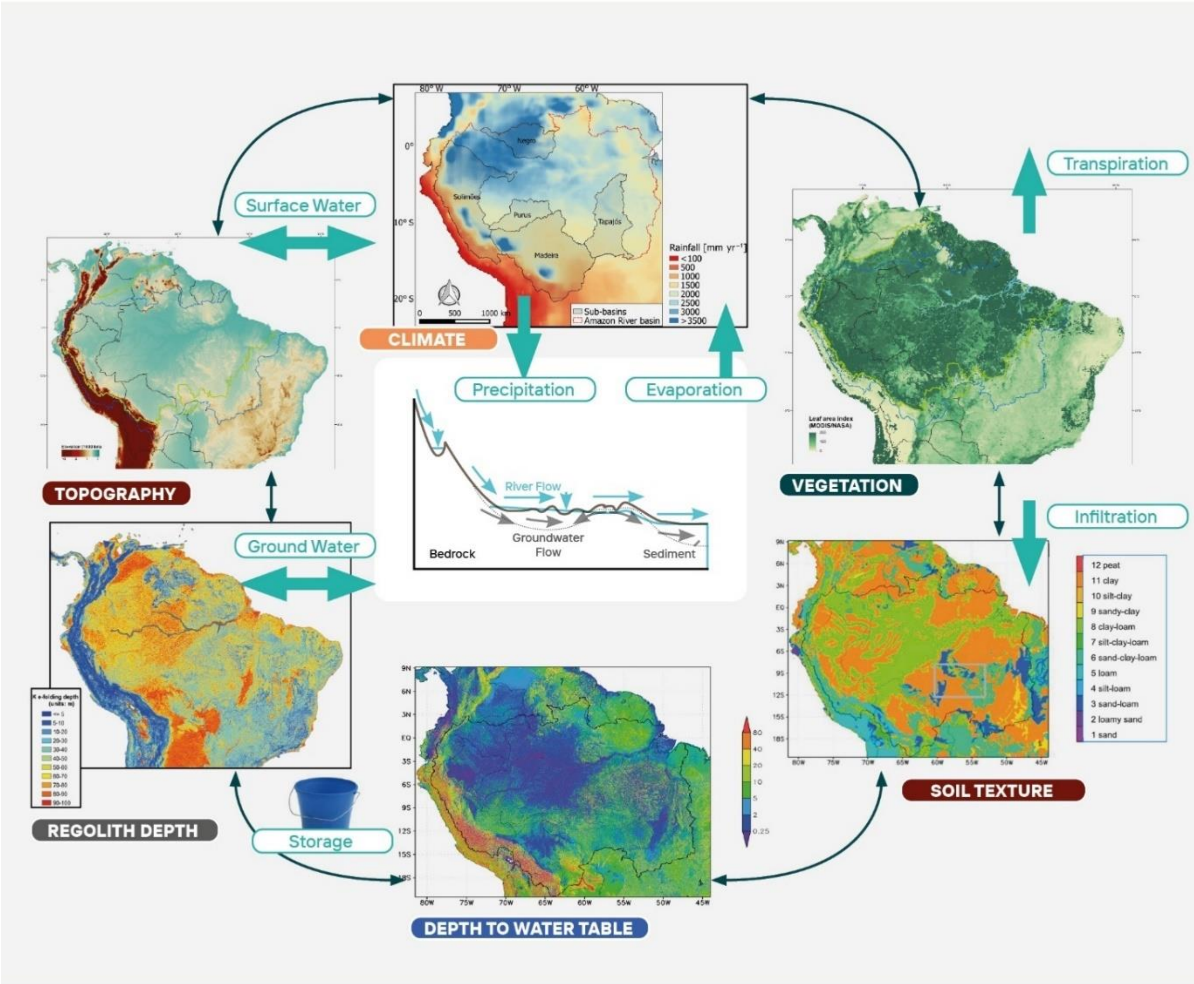

Figure 1.6 Drivers of modern-day Amazonian hydrology. Blue arrows indicate hydrologic effects. Climate (top) determines the precipitation supply and evaporative demand (vertical fluxes). Plant transpiration returns a large portion of the precipitation back into the atmosphere through transpiration (vertical flux), effectively reducing the amount of water to be moved on land laterally. The lateral fluxes are largely controlled by topography via the river network on the surface, and by the terrain-dependent regolith thickness and permeability via groundwater flow in the subsurface. The regolith also controls the storage capacity (the bucket) whereby wet-season surplus is stored and carried over to subsidize dry-season deficits. The soil physical properties control infiltration and hence subsurface storage. All factors influence the water balance of a location directly, but also indirectly via modulating other factors (indicated by double thin black arrows). Sources: climate map from Maeda et al. (2017); vegetation index map from NASA (earthobservatory.nasa.gov/global-maps); topography map from SRTM/NASA (www2.jpl.nasa.gov/srtm); regolith depth map from Fan et al. (2013); soil texture map from Miguez-Macho and Fan (2012b); depth to water table map from (Miguez-Macho and Fan 2012b).

The depth to the groundwater table (bottom map, Figure 1.6) is a good indicator of hydrologic conditions across the Amazon. Water table depth (WTD), ranging from zero (at land surface) to over 80 m (see color bar in Figure 1.6), reflects both the climate (vertical fluxes) and terrain (lateral fluxes above- and belowground). Shallow groundwater sustains streamflow and soil moisture in drought periods. Upland ecosystems over a deep water table are solely rainfed and vulnerable to meteorological droughts, whereas lowland ecosystems on shallow water tables, sustained by upland rain through downhill flow, enjoy a more stable water supply. Shallow WTD also causes waterlogging and anoxic soil conditions, excluding upland vegetation that is intolerant to waterlogging, and selecting wetland species well-adapted to waterlogging.

The spatial structure of WTD bears a strong signature of the topography, directly because surface slope controls drainage, and indirectly through its influence on climate (orography, lapse rate), regolith (weathering, erosion and deposition), and soil (substrate stability). These terrain features lay the physiographic foundation of diverse hydrologic features.

The strong climatic gradient across the Amazon, particularly in rainfall amount and seasonality, is another force shaping hydrologic diversity. The interaction of climate and topography results in a rich spatial-temporal pattern of water availability across the Amazon. However, except for the streamflow, hydrologic variables critical to ecosystems, such as root-zone soil moisture and WTD, are only sparsely observed across the vast Amazon, and here we use a model (Miguez-Macho and Fan 2012ab) to illustrate likely spatial and seasonal patterns in key hydrologic variables.

Figure 1.7. (A) shows the hydrological variability of Amazon; (i) soil water availability to plants mirroring seasonal rain (top), (ii) WTD showing areas of waterlogging (wetland conditions, purple) and root-accessible groundwater (blue) (center), and (iii) flood height showing inundation extent and the dynamic nature of lateral connectivity among streams (bottom). These inferred patterns give us glimpses of the large spatial variability and seasonal contrasts in hydrologic conditions across the Amazon. The chemical composition of the waters in the Amazon largely reflects the geologic substrates through which the water flows. The geochemistry of soil water, particularly soil nutrients for vegetation, which strongly depend on the bedrock (parent material) and geologic age, is discussed in Section 4. Here we highlight the geologic causes for the widely recognized river types across the Amazon (Figure 1.7.B); (a) blackwater rivers originating from lowland forests with sandy soils that are nutrient poor and highly acidic (pH = 3.5–6.0), (b) whitewater rivers sourced in the geologically-young Andean cordilleras, which are sediment- and nutrient-rich and have near neutral pH (6.8–7.0), and (c) clearwater rivers that drain the old cratonic shields, which are sediment- and nutrient-poor and slightly acidic (pH = 6.1–6.7). Each of these major water types hosts diverse and specialized aquatic plant and animal species (Stefanelli-Silva *et al.* 2019; Albert *et al.* 2020).

Some of the main hydrologic landscapes of the Amazon are periodically flooded wetlands such as *igapó* (blackwater and clearwater) and *várzea* (whitewater), which contrast with the *terra firme* that is never flooded (Figure 1.7.B). It is likely that this diversity has changed in the geologic past as the Amazon's drainage system evolved through millions of years (Section 2 and 3).

5.2. Hydrologic diversity shapes terrestrial and aquatic habitats and ecosystem diversity

The hydrologic variables that matter the most to life include water availability, water quality, temporal stability, and spatial connectivity. The high spatial diversity in water availability and stability is expressed in Figure 1.7.A.

The soil moisture available to vegetation (top row) varies from saturation to wilting point in one season. The water table depth (middle row) varies from 0 to >80 m with contrasting patterns across the season, hinting at seasonal distribution of wetlands, groundwater capillary reaching plant rooting depth, and the thickness and water storage capacity of the vadose zone to be filled in the wet season. The floodwater height (bottom row) is the most dynamic feature of the Amazon, filling and emptying massive floodplains, and seasonally connecting the many channels, enabling migration of aquatic life but hindering that of terrestrial.

At the landscape scale, under the same climate and over similar geology, hydrologic variations strongly align with hillslope gradients, with better-drained hills and poorly-drained valleys. This systematic variation in drainage is the foundation of the topo-sequence or soil catena notion (see Section 4). Along the catena, systematic changes in species distribution have been documented, encapsulated in the hydrologic niche concept (Silvertown *et al.* 1999, 2014).

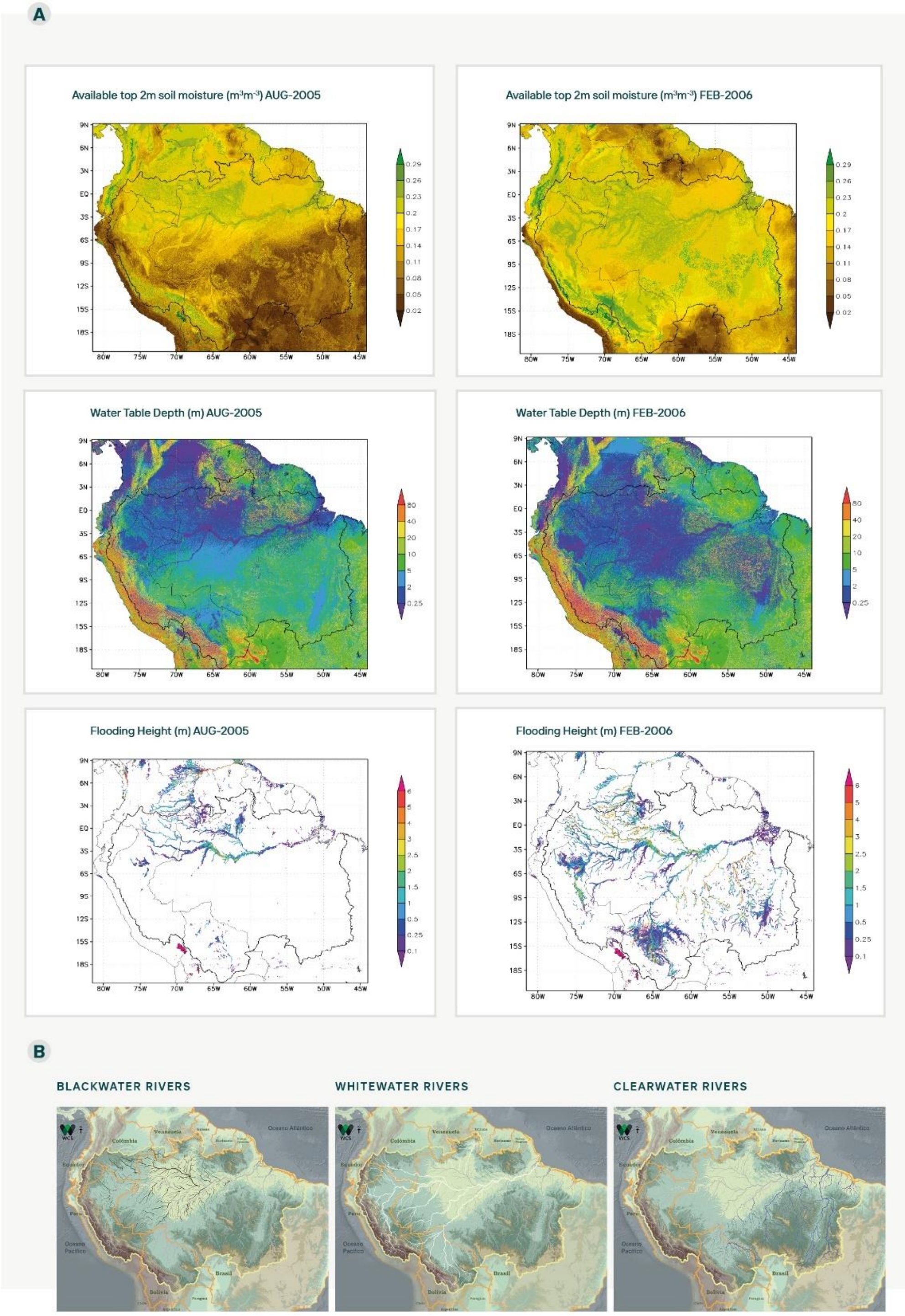

Figure 1.7 (A) Model simulated spatial distribution and seasonal contrast in top 2 m soil moisture (m^3m^{-1}) available to vegetation (top); water table depth (middle), flood water height and floodplain connectivity (bottom) (Miguez-Macho and Fan 2012a) (B) Amazon River water types: blackwater, whitewater, clearwater, based on water chemistry and sediment load, reflecting the geochemical nature of their source regions (https://amazonwater.org/waters/rivers-types).

Figure 1.8 gives four examples. In (a), summarizing decades of research in the white-sand ecosystems in Rio Negro drainage, Terborgh *et al.* (1992) notes that the slight undulations in topography, imperceptible on the ground, can dramatically influence vegetation structures, owing to selective vegetation response to water stress (excessively drained sand hills) and waterlogging (shallow water table in valleys), forming elevation zones from *igapó* to *terra firme* forests along a drainage gradient. In (b), the *várzea* forest, tree species richness is strongly zoned along flooding gradients (few species tolerate prolonged flooding) on the floodplains of the lower Solimões River (Wittmann *et al.* 2011). In (c), Schietti *et al.* (2014) found that species turnover corresponds to turnovers in water table depth, from uniformly deep under the plateaus (10% species turnover), to varying and fluctuating near the valleys (90% species turnover). In (d), along a hillslope in the Brazilian Cerrado, a denser and more complex woody canopy occupies the well-drained upper slopes, and the shallow water table under the lower slopes causes waterlogging and restricts species occurrence (Rossatto *et al.* 2012). The significance of hillslope drainage is greater in the parts of the Amazon with a strong dry season, when valleys remain moist and can sustain floristically different valley ecosystems.

6. Mineral Richness, Hydrocarbons, and Aquifers in the Amazon

The Amazon has long been known as an area of high potential for mineral resources and represents one of the last mineral exploration frontiers in the world (Cordani and Juliani 2019). In recent decades, the region has been the locus of intense mining activities (Monteiro 2005; see Chapters 9 and 11), including the districts of Carajás for Fe, Cu, Au, Mn, and Ni; Pitinga for Sn, Nb, and rare earth elements (REE); Serra do Navio for Mn; and Trombetas-Juruti for Al (See table in Figure 1.9). Mineral exploration of the Amazon had long been dominated by *garimpos* (i.e., small-scale, largely unregulated mining operations). Starting in the 1990s, large mining companies began employing modern technologies, such as operations in the Carajás Province (Fe, Cu and Mn) and Juruti-Trombetas (Al) (Monteiro 2005; Cordani and Juliani 2019). New frontiers for mineral exploration encompass the central area of the Amazon Craton on the Brazilian Shield, particularly in the Ventuari-Tapajós and Rio Negro-Juruena provinces (Juliani *et al.* 2016) The rush for precious and base metals has attracted many international mining companies to the Amazon. Nevertheless, the subsurface geology and mineral potential remains poorly known throughout much of the lowland Amazon and the Guiana Shield. These regions are difficult to access and have long experienced complex political and social issues related to industrial development.

The sedimentary basins of the Amazon contain large formations with significant porosity and permeability. A recent synthesis of multiple data sources in the western Amazon suggests that the Amazon Aquifer System (AAS) is potentially one of the largest aquifer systems in the world (Rosario et al. 2016) as discussed in Section 6.3.

6.1. Ore Deposits in the Amazon: A Diversity from the Archean to the Phanerozoic

Ore deposits are anomalous concentrations of an element of economic interest within the Earth's crust. Ore deposits may form as a result of (i) interaction of the lithosphere, hydrosphere, atmosphere, and biosphere; (ii) decrease in internal global heat production, and (iii) changes in global tectonics (Robb 2005). The great variety of Amazonian ore deposits is a consequence of the complex and protracted geological evolution described in this chapter.

Amazonian ore formation began as early as the Mesoarchean (c. 3.0 Ga), with geological processes during the Phanerozoic enlarging the mineral potential of the region. Most known Amazonian ore deposits are concentrated in Precambrian terranes, whereas hydrocarbon and aquifer resources are concentrated in Phanerozoic sedi-

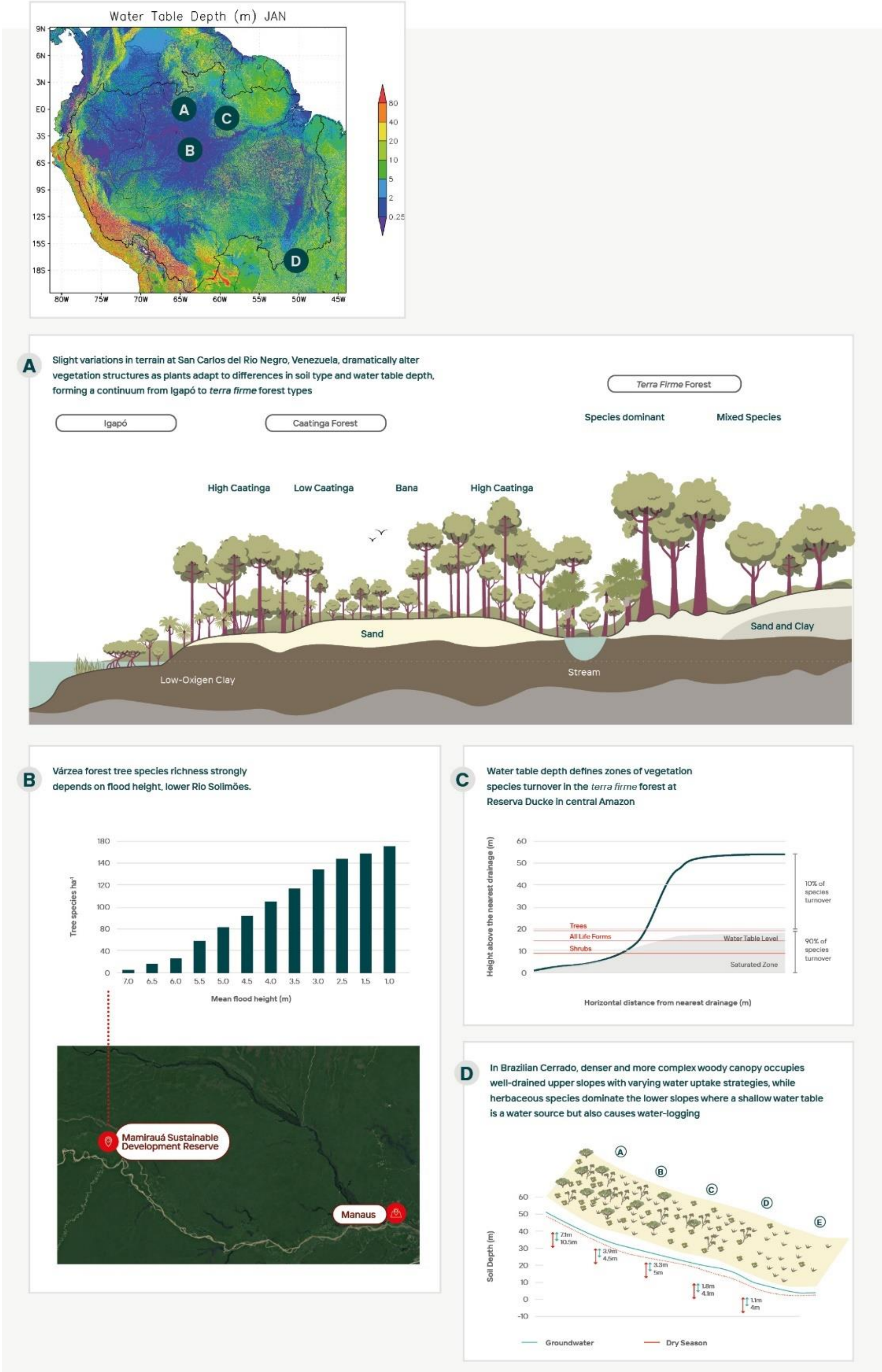

Figure 1.8 Examples of hydrological influence on species distribution at landscape scales in the Amazon. Source: (A) Terborgh *et al.* (1992); (B) Wittmann *et al.* (2010); (C) Schietti *et al.* (2014); (D) Rossatto *et al.* (2012).

-mentary basins (Figure 1.9, Figure 1.2A and B). One of the most prolific mineral provinces in the world is located within the oldest core of the Amazonian Craton, in the Archean Carajás Province. In the southern part, in the Rio Maria Domain, the metallogenesis of the terrain is marked by the occurrences of some gold deposits within Mesoarchean (3.2–2.8 Ga) greenstone belts (Monteiro *et al.* 2014). Conversely, in the northern part of the Carajás Province, the Carajás Domain is one of the best-endowed mineral provinces in the world with a wide variety of ore deposits (Monteiro *et al.* 2014). Iron deposits associated with banded iron formations in Carajás are globally recognized as the largest mining operations in the world. Manganese deposits, such as at the Azul Mine, also occur in Carajás. Additionally, in recent years, Carajás also became a relevant copper (with associated gold) producer in Brazil (Juliani *et al.* 2016). Widespread mafic or ultramafic rocks host remarkable Ni and PGE (Platinum Group Elements, e.g., Pt and Pd) deposits also in the Carajás Mineral Province. During the Transamazonian Orogeny (c. 2.05 Ga) substantial Mn deposit formed in the Maroni-Itacaiúnas Province, such as the Buritirama and the Serra do Navio.

It is common to find a wide variety of granite-related ore deposits associated with paleo-subduction zones within the Paleoproterozoic terranes (2.1–1.6 Ga). The Tapajós Mineral Province and the Alta Floresta Gold Province are the current frontiers of mineral exploration in Brazil (Juliani *et al.* 2016; Klein *et al.* 2018). In these settings, plutono-volcanic rocks hosting different styles of Au-Ag-Cu-Mo deposits of Paleoproterozoic age are encountered. Towards the northwestern portion of the Alta Floresta Gold Province, the Aripuanã mine is a rare example of a Paleoproterozoic Pb-Zn deposit associated with preserved volcanic calderas (Biondi *et al.* 2013).

In the northern sector of the Ventuari-Tapajós Province, in the Guiana Shield, granite-related ore deposits are also reported, including (i) the famous Pitinga deposit, a historical mine of Sn with large contents of Nb, Ta, F, and REE (Bettencourt *et al.* 2016); and (ii) the Surucucu district, a poorly investigated terrain with Sn and Au deposits (Klein *et al.* 2018). At the interface of the Rio Negro-Juruena and Rondoniana-San Inácio provinces, in the southwestern portion of the Amazon Craton, remarkable Sn deposits were discovered and exploited in the last 50 years (Bettencourt *et al.* 2016). The intrusion of granites from 1.31–0.97 Ga gave origin to great deposits of Sn, W, and Nb (Bettencourt *et al.* 2016). The Seis Lagos deposit represents one of the most important Nb and REE reserves in the world. This ore deposit is contained in a carbonatite intrusion and forms part of the northern Rio Negro-Juruena Province, with an age of about 1.3 Ga (Rossoni *et al.* 2017).

Aluminum deposits (bauxite ores) are quite common in the Amazon and encompass large reserves. The Trombetas-Juruti and Paragominas bauxite districts represent important sources of aluminum and are found in low relief plateaus within some of the Phanerozoic sedimentary basins (Costa 2016; Klein *et al.* 2018). These deposits are also a good example of ore deposits formed by extreme weathering and leaching of undesired elements, which concentrate metals in the sedimentary matrix. Mature lateritic cover is a common feature in the Amazon, which was formed by intense weathering processes due to climate conditions. These processes are thought to have begun at c. 80 Ma and remain active to the present (Monteiro *et al.* 2018). Importantly, these processes also enhance the quality of the Fe deposits of Carajás, the Mn deposits at Buritirama and Serra do Navio, and the Nb-REE deposits at Seis Lagos.

6.2. Oil and gas

Oil and gas are mainly concentrated in the Subandean region, along the western margins of the Amazon, and to a lesser extent in the western and eastern Amazon (Figure 1.9). In Subandean sedimentary basins, the search for oil and gas started during the 1940s; however, the first oil reserves were not discovered until the 1980s in the Llanos

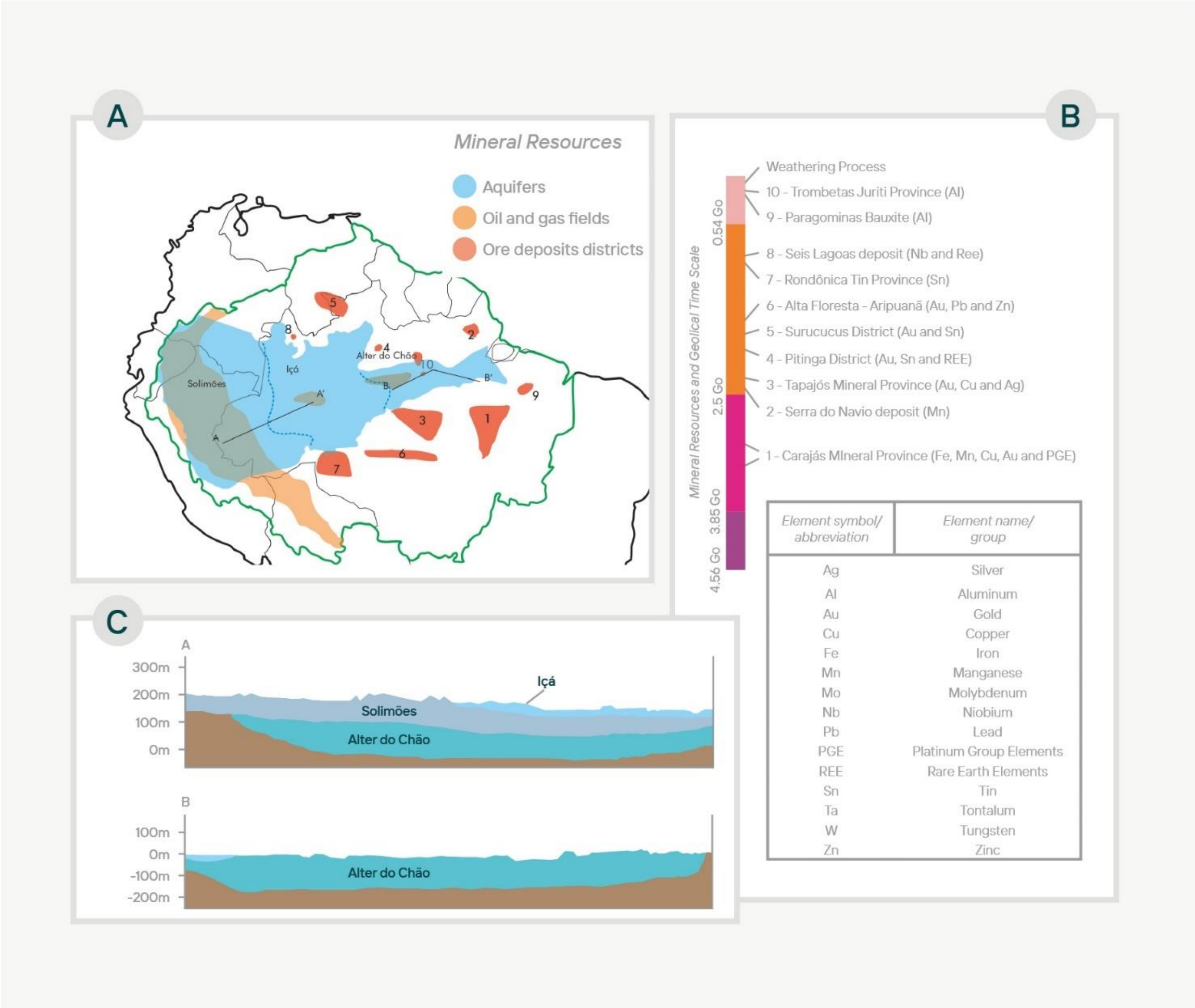

Figure 1.9 (A) Simplified tectonic-chronological map of northern South America with the distribution of the main ore deposits and oil and gas fields (Modified from Marini et al. 2016, and Klein et al. 2018). (B) Ore deposits of the Amazon and their location across the geological time scale. Also shown in (A) are major aquifer systems with cross sections shown in (C) (modified from Rosário et al. 2016; Hu et al. 2017).

region of Venezuela. Subsequently, hydrocarbon exploration expanded south from Colombia into Ecuador and Peru. The greatest proven hydrocarbon reserves are now known to occur in the westernmost Amazon, at the foothills of the Andes (de Souza 1997).

In the Brazilian Amazon, the search for oil and gas started during the 1950s in the intracratonic sedimentary basins, a very different type of geological and geographical setting. Initially, exploratory activity was focused on the banks of major rivers, such as the Solimões-Amazon, Tapajós, and Madeira. Later, exploration expanded into the forest. In 1978 the Juruá gas field was discovered by Petrobras (the state-owned Brazilian oil company). In the following years three appraisal wells were drilled in the Juruá field aiming to assess its potential, which was determined non-commercial. Nevertheless, at the beginning of the 1980s, Petrobras started a new exploratory campaign which eventually led to the discovery of the oil and gas field of Rio Urucu in 1986, deep in the hinterland of the western Amazon and in the Solimões sedimentary basin. As this new field contained oil in addition to gas, Petrobras redirected its exploratory efforts to this new area, leaving the development of the Juruá gas field for future demands, but conditioned to the potential of new discoveries and the commercial demand for dry gas. Following the Rio Urucu discovery, an even bigger oil and gas field named Leste de Urucu field was discovered. Other smaller oil and gas fields surrounding the Urucu oil and gas Province were discovered during the 1990s (Souza, 1997).

Initially, only the oil of the Urucu Province was exploited. At the very beginning it used barges, but in 1997 an oil pipeline was installed to transfer the oil to a harbor at the town of Coari (AM). From there, oil tankers transport it to Manaus (AM). During the 2000s, a gas pipeline connecting Urucu to Manaus was built and started operating in 2006. In association with other companies, Petrobras planned to connect the Juruá gas field to the Urucu Province via a gas pipeline. When it was finally approved, Petrobras had already discovered the giant oil province of the pre-salt and redirected its budget to explore and exploit it. Petrobras started a divestment program in which the Juruá gas field was offered, but there was no interest. Eventually, in 2018, the Brazilian Regulatory Agency for Oil and Gas (Agência Nacional do Petróleo, or ANP) acquired the Juruá gas field from Petrobras and, in 2020, ANP sold it to ENEVA. This company also bought the entire Urucu Province and Azulão gas field (east of Manaus, in Silves, AM) from Petrobras, also as part of the latter's disinvestment program. Today, a private company holds a monopoly over exploration and exploitation of the oil and gas in the Brazilian Amazon.

6.3. Aquifers

Major aquifer systems in the Brazilian Amazon are shown in Figure 1.9. The largest are found in sedimentary basins along the main stem of the Amazon River, comprising the Amazonas sedimentary basin to the east and the Solimões sedimentary basin to the west. Here, thick sequences of sand and clay deposits formed during the Mesozoic and Cenozoic allow for the accumulation of large, continuous aquifer systems (alternating aquifers and confining units) (Figure 1.9). In map view (A), they are from east to west the Alter do Chão, Içá, and Solimões aquifer systems (Rosário *et al.* 2016; Hu *et al.* 2017). The cross-section view (B) illustrates the aquifer types, where the surficial exposed (unconfined) aquifers are actively recharged by precipitation and discharge into the river drainage network, but the buried (confined, if buried under low-permeability strata) aquifers are isolated from the surface waters. Off the central axis of sedimentary basins, along the main stem of the Amazon River, are the small aquifers of Boa Vista and Parecis (not shown) in fractured Paleozoic sandstones/siltstones (Hirata and Suhogusoff 2019), which have limited groundwater storage capacity.

While the Alter do Chão aquifer is largely unconfined in the eastern Brazilian Amazon (section B-B', Figure 1.9.B), it becomes semi-confined in western Brazil under the Içá and Solimões aquifers (section A-A'). The Solimões aquifers in the western Amazon are unconfined, exchanging water with the river network (Rosário *et al.* 2016). Through a synthesis of multiple data sources, Rosário *et al.* (2016) also identified the confined Tikuna aquifer system, a large, continuous, Cretaceous sandstone unit in the Solimões Basin (see their Figure 10). The Alter do Chão Formation is exposed in the eastern Amazon and continues westward from the Amazonas to Solimões sedimentary basins, where it has been assigned two aquifer names: Alter do Chão (Amazonas sedimentary basin) to the east where it is exposed, and Tikuna (Solimões sedimentary basin) to the west, where it is buried. Three aquifers are stacked vertically: the Iça, Solimões, and Tikuna (or Alter do Chão). Together, these large sedimentary aquifers make up the Amazon Aquifer System, one the largest aquifer systems in the world (Rosário *et al.* 2016).

7. Outlook: The Future of the Amazon

Amazonian geodiversity faces grave and imminent threats from a broad range of human activities. These threats range from deforestation due to dam and road construction, mineral extraction, and associated land-use changes, to global climate change and sea level rise. Under "business as usual" models of carbon emissions, global temperatures are predicted to rise 6°C by 2100 (IPCC 2021), but regional changes in temperature and related ecosystem responses can differ spatially, especially in topographically-rich areas such as the Andes (IPCC 2021). Anthropogenic global warming is already having dramatic environmental consequences for Amazon, with the greatest future impacts resulting from sea level rise and pronounced shifts in rainfall patterns and intensities. Currently, the Earth's atmosphere averages 416 ppm CO_2, a concentration 150% above the maximum amount measured during the Pleistocene (Glacial - Interglacial) cycles of the past 2.6 million years, and representing a level not seen since the early Miocene c. 23 million years ago (Cui *et al.* 2020).

Paleoclimatic data and climate modelling indicate that high global mean surface temperatures previously occurred in earlier geological epochs (e.g., Inglis *et al.* 2020). For example, the Paleocene-Eocene Thermal Maximum (PETM, about 55 Ma) is an excellent analogue for our post-industrial fast-warming world (McInerney & Wing, 2011; Jones *et al.* 2019). Similarly, the Early Eocene Climatic Optimum (EECO c. 53–51 Ma) also represents a useful historical analogue for future scenarios, due to similarly high concentrations of atmospheric CO_2 (Inglis *et al.* 2020). Recent climate models by Inglis *et al.* (2020) suggest that during the PETM and EECO the Earth's global mean surface temperatures were respectively 31.6°C and 27°C. When assuming a pre-industrial temperature of c. 14°C, this makes the PETM and the EECO respectively c. 17.6°C and 13°C warmer than pre-industrial levels.

If carbon emissions continue unabated, Amazonian climates will be dramatically altered by 2100 (Sorribas *et al.* 2016). Melting polar ice caps will contribute to more than 13 m (c. 43 ft) global sea level rise by 2500 (DeConto and Pollard 2016), and complete loss of the Earth's ice caps is projected within the next 400-700 years (Winkelmann *et al.* 2015; Foster *et al.* 2017). In an ice-free world, global sea levels will be c. 60-80 m (c. 200-260 ft) above the present level (Winkelmann *et al.* 2015), higher than they have been for c. 56 million years (Foster *et al.* 2017; Tierney *et al.* 2020). These projections imply that marine waters would be driven deep into the Central Amazon, dramatically altering shorelines, habitats, microclimates, and regional rainfall patterns (Figure 1.10). Such a marine incursion would convert more than one million km^2 of lowland Amazonian rainforest estuarine and marine habitats, inundating the full geographic range of at least 1,030 plant species that are entirely confined the lowlands and the eastern Amazon, and possibly driving most if not all these species to extinction (Zizka *et al.* 2018).

During the Middle Miocene Climate Optimum (MMCO; c. 17–15 Ma) global mean surface temperatures were estimated to have been 18.6°C, which is c. 3°C higher than present (You *et al.* 2009). This makes the MMCO a realistic analogue for global temperatures and sea levels in the next century. During the MMCO, much of the western Amazon was covered by the Pebas mega-wetland system, with estuarine conditions caused by marine incursions related to the prevailing high sea level (Hoorn *et al.* 2010b; Jaramillo *et al.* 2017 Fig. 1.4.C.). Although basin dynamics in the western Amazon were different during the MMCO, overall, the geological past can provide modern scientists insight into how future landscapes may unfold under climate scenarios of global warming.

The scientific community is currently unable to accurately predict in detail how Amazonian landscapes and riverscapes will respond to all these simultaneous challenges. We simply do not have the data to forecast all the effects of encroaching shorelines, increased extreme flooding and rain-

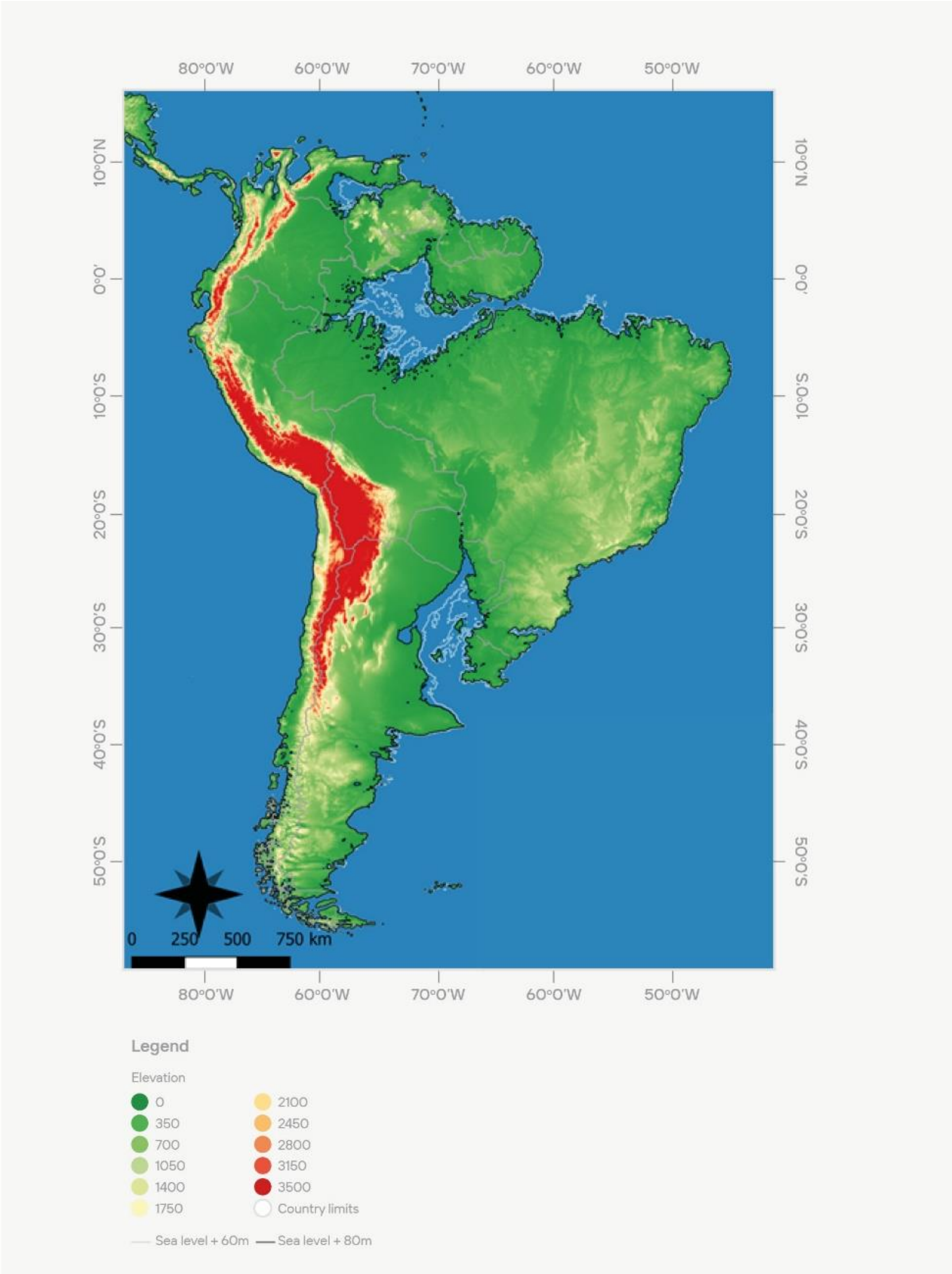

Figure 1.10 Projected coastline of South America after Earth's ice caps have melted (c. 2400 to 2700 CE) with shorelines antecipated at 60 and 80 m (216 and 262 ft) elevation. Image courtesy of Dr. João Marcelo Abreu, Universidade Federal do Maranhão, Brazil.

fall, severe droughts, and reduced vegetation. Nonetheless, we can expect intensified erosion of bare soils, increased debris in rivers, and erosion of river margins. Rivers will become even more prone to flash floods. Fires will increase these effects in a positive feedback loop, leading to higher fire probability due to diminished vegetation cover promoted by soil erosion and regional aridification, particularly in the headwaters of the main southeastern tributaries (e.g., Tapajós, Xingu, Tocantins) (Flores *et al.* 2019; Brando *et al.* 2020a, b). Regime shifts in landscape vegetation cover are already being observed in other parts of the world following a series of devastating fire seasons, such as those in Australia (Filkov *et al.* 2020), California (Wahl *et al.* 2019) and the Mediterranean (Camarero *et al.* 2019), among many others.

Facing so many environmental crises at once, the Amazon is precipitously on the edge of an evolutionarily unique climatic regime shift, an irreversible change from mostly forested to mostly open and environmentally degraded agricultural, marginal, and abandoned landscapes (Munroe *et al.* 2013; Xu *et al.* 2020). Future Amazonian landscapes may look very different from the vast tropical rainforests that have covered most of the region for the past 100 million years. Anthropogenic deforestation and habitat degradation in other parts of the world have already transformed large blocks of ancient forests into agricultural and marginal landscapes over the past few decades and centuries. These deforestations resulted in widespread soil erosion, aridification, and biodiversity loss, for example in the Mississippi and Yangtze river valleys. Immediate and sustained investments are required to support climate mitigation and landscape conservation policies, with coordinated actions at the local, national, and international levels (Albert *et al.* 2020).

To summarize, there is broad consensus within the geoscience and climate science communities that maintaining the Earth's polar ice caps is critical for the persistence of the relatively stable climates and shorelines that support modern ecosystems and human civilization (Sigmond *et al.* 2018; Vousdoukas *et al.* 2018; Westerhold *et al.* 2020, Lear *et al.* 2021). In the starkest of terms, we risk raising the concentration of CO_2 in the Earth's atmosphere above 450 ppm at our peril (Sherwood *et al.* 2020). Studies into the dynamics of Amazonian geodiversity are still in their infancy, and quantitative attention to Amazonian earth systems dynamics will be required to effectively manage Amazonian landscapes through the perilous decades and centuries to come. The projected dire impacts of climate change described here may be underestimated, as we do not have a robust understanding of the interlinks and cascading effects that rising global temperatures will have on the environment.

8. Conclusion

In this chapter, we explored the origins of the Amazon's geodiversity, with the aim to unravel links between geological history, climate, geomorphology, soils, hydrology, and biodiversity. We found deep connections between these seemingly independent components in the region.

The most striking point that we convey through this multidisciplinary study is that Amazonian history unfolded over the course of 3 billion years. During this time, the geological substrate of the Amazon region formed part of different continents, with the current configuration only taking shape in the past 100 million years. Key geographic features such as the Andes mountains at the western margin of the Amazon, and the connection between South and Central America were only completed in the past 20 million years. Conversely, the building blocks of the eastern Amazon were configured between 3 and 1 billion years ago. The timing of these configurations (west and east) and their legacy effects, such as the stability of the eastern Amazon and mountain building in the western Amazon, were largely dictated by the movement of tectonic plates. The interconnection between these 'old' and 'young' crustal regions is what makes the Amazon unique. For example, the east-west gradient of geological province ages is reflected in soil types, which in turn creates gradients in soil nutrients and, therefore, ecosystems. The overall distribution of rain in the Amazon is directly shaped by the Andes which, along with soil types, interconnect to affect hydrological conditions in the lowlands. Climate, soils, hydrology, mineral and hydrocarbon wealth, and biodiversity are either derived from or superimposed on this diverse geological tapestry crafted by geological time.

The Amazon's rich geological history can be partly gleaned from deep records in its intracontinental sedimentary basins and offshore deposits. These records provide a consistent, albeit incomplete, picture of what the environment looked like from millions to tens of millions of years ago, when sea levels and global climate were drastically different. These records demonstrate that, while part of the rich geological tapestry was set over billions of years, the environmental, climatic, and landscape changes in this region were dynamic and pervasive over tens of millions of years. While these data help us understand environmental and climatic changes over the million-year timescale in the Amazon, the feedbacks between geological and climatic processes which dynamically shape the environment require temporal resolutions of at least tens of thousands of years. Sedimentologic and paleoclimatic records with high temporal resolution are scarce and restricted to caves, lakes, and glacial cores high in the Andes. Their unfortunate scarcity is matched with abundant need for more data. High-resolution records are crucial to comprehending the Amazon's response to extreme climatic fluctuations.

Only by understanding intricate connections like the ones summarized here can we provide a basis for future management and conservation plans. However, as demonstrated in this Chapter, this is no trivial task. Historical archives of a dynamic past also constitute our guidelines for the future and are, therefore, paramount for drawing management strategies. Past changes in climate and sea level help us envision the future, if scenarios drawn by the IPCC become reality. Nevertheless, for many factors, such as rates of soil and forest degradation, there are no analogues and we could experience changes to the landscape that are not easily repaired.

The best strategies to reduce human impacts on the natural environment are undoubtedly based on scientific information. Our recommendations are, therefore, to cast a wide scientific net to produce a deeper understanding of the Amazon system.

9. Recommendations

The global community must work closely and swiftly with Amazonian governments to develop and enact the following scientific priorities.

- Decade-level financial investments and political support for geoscientific research in the Amazon, prioritizing research and education at institutions that enable the study of Amazonian geodiversity at multiple spatial and temporal scales and across social boundaries; this includes training the next generation of Amazonian geoscientists.
- Interdisciplinary studies of Amazonian earth systems, focusing on interactions among landscape, climate, and biological processes, and how complex feedback loops among these systems are affected by ongoing anthropogenic influences.
- Integrating "big data" from all of the environmental sciences (e.g., geoscience, climate, biology), with emerging tools and expert knowledge to develop new technologies for environmental characterization, including especially soil and aquatic (surface and subsurface) geochemistry.
- Establish a network of Critical Zone Observatories (*sensu* Brantley *et al.* 2017) in the Amazon

to advance study of landscape evolution processes, erosion rates, and sediment yield, over historical and geological timescales, crucial to predicting future geomorphic responses to accelerating environmental change and human-built infrastructure.

10. References

Ahnert F. 1970. Functional relationships between denudation, relief, and uplift in large, mid-latitude drainage basins. *Am J Sci* **268**: 243–63.

Albert JS, Val P, and Hoorn C. 2018. The changing course of the Amazon River in the Neogene: center stage for Neotropical diversification. *Neotrop Ichthyol* **16**.

Albert JS, Petry P, and Reis RE. 2011. Major biogeographic and phylogenetic patterns. *Hist Biogeogr Neotrop Freshw fishes* **1**: 21–57.

Albert JS, Tagliacollo VA, and Dagosta F. 2020. Diversification of Neotropical Freshwater Fishes. *Annu Rev Ecol Evol Syst* **51**: 27–53.

Angel I, Guzmán O, and Carcaillet J. 2017. Pleistocene Glaciations in the Northern Tropical Andes, South America (Venezuela, Colombia and Ecuador). *Cuad Investig Geográfica* **43**: 571–90.

Antonelli A, Kissling WD, Flantua SGA, *et al.* 2018. Geological and climatic influences on mountain biodiversity. *Nat Geosci* **11**: 718–25.

Baker PA and Fritz SC. 2015. Nature and causes of Quaternary climate variation of tropical South America. *Quat Sci Rev* **124**: 31–47.

Balan E, Allard T, Fritsch E, *et al.* 2005. Formation and evolution of lateritic profiles in the middle Amazon basin: Insights from radiation-induced defects in kaolinite. *Geochim Cosmochim Acta* **69**: 2193–204.

Bétard F and Peulvast J-P. 2019. Geodiversity Hotspots: Concept, Method and Cartographic Application for Geoconservation Purposes at a Regional Scale. *Environ Manage* **63**: 822–34.

Bettencourt JS, Juliani C, Xavier RP, *et al.* 2016. Metallogenetic systems associated with granitoid magmatism in the Amazonian Craton: An overview of the present level of understanding and exploration significance. *J South Am Earth Sci* **68**: 22–49.

Bicudo TC, Sacek V, and Almeida RP de. 2020. Reappraisal of the relative importance of dynamic topography and Andean orogeny on Amazon landscape evolution. *Earth Planet Sci Lett* **546**: 116423.

Bicudo TC, Sacek V, Almeida RP de, *et al.* 2019. Andean tectonics and Mantle Dynamics as a Pervasive Influence on Amazonian ecosystem. *Sci Rep* **9**: 1–11.

Biondi JC, Santos RV, and Cury LF. 2013. The paleoproterozoic aripuanã Zn-Pb-Ag (Au, Cu) volcanogenic massive sulfide deposit, mato grosso, Brazil: Geology, geochemistry of alteration, carbon and oxygen isotope modeling, and implications for genesis. *Econ Geol* **108**: 781–811.

Bookhagen B and Strecker MR. 2008. Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes. *Geophys Res Lett* **35**: L06403.

Boonstra M, Ramos MIF, Lammertsma EI, *et al.* 2015. Marine connections of Amazonia: Evidence from foraminifera and dinoflagellate cysts (early to middle Miocene, Colombia/Peru). *Palaeogeogr Palaeoclimatol Palaeoecol* **417**: 176–94.

Brando PM, Soares-Filho B, Rodrigues L, *et al.* 2020. The gathering firestorm in southern Amazonia. *Sci Adv* **6**: eaay1632.

Brando P, Macedo M, Silvério D, *et al.* 2020. Amazon wildfires: Scenes from a foreseeable disaster. *Flora* **268**: 151609.

Brantley SL, McDowell WH, Dietrich WE, *et al.* 2017. Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. *Earth Surf Dyn* **5**: 841–60.

Briceño HO and Schubert C. 1990. Geomorphology of the Gran Sabana, Guayana Shield, southeastern Venezuela. *Geomorphology* **3**: 125–41.

Camarero JJ, Sangüesa-Barreda G, Pérez-Díaz S, *et al.* 2019. Abrupt regime shifts in post-fire resilience of Mediterranean mountain pinewoods are fuelled by land use. *Int J Wildl Fire* **28**: 329.

Capitanio FA, Faccenna C, Zlotnik S, and Stegman DR. 2011. Subduction dynamics and the origin of Andean orogeny and the Bolivian orocline. *Nature* **480**: 83–6.

Caputo MV and Soares EAA. 2016. Eustatic and tectonic change effects in the reversion of the transcontinental Amazon River drainage system. *Brazilian J Geol* **46**: 301–28.

Chen Y, Wu J and Suppe J. 2019. Southward propagation of Nazca subduction along the Andes. *Nature* **565(7740)**: 331-338.

Cheng H, Sinha A, Cruz FW, *et al.* 2013. Climate change patterns in Amazonia and biodiversity. *Nat Commun* **4**: 1411.

Cintra BBL, Schietti J, Emillio T, *et al.* 2013. Soil physical restrictions and hydrology regulate stand age and wood biomass turnover rates of Purus--Madeira interfluvial wetlands in Amazonia. *Biogeosciences* **10**: 7759–74.

Cordani U and Juliani C. 2019. Potencial mineral da Amazônia: problemas e desafios. *Rev Estud Bras* **6**: 91–108.

Correa SB, Crampton WGR, Chapman LJ, and Albert JS. 2008. A comparison of flooded forest and floating meadow fish assemblages in an upper Amazon floodplain. *J Fish Biol* **72**: 629–44.

Costa M. 2016. Alumínio e bauxita no Brasil. In: Melfi AJ, Misi A, Diogenes C, Cordani UG (Eds). Potencial Mineral do Brasil, Capítulo I.

Cracraft J, Ribas CC, D'Horta FM, *et al.* 2020. The Origin and Evolution of Amazonian Species Diversity. In: Neotropical Diversification: Patterns and Processes, Fascinating Life Sciences.

Cuartas LA. 2008. Estudo observacional e de modelagem hidrologica de uma micro-bacia em floresta não perturbada na Amazonia central.

Cui Y, Schubert BA, and Jahren AH. 2020. A 23 m.y. record of low atmospheric CO2. *Geology* **48**: 888–92.

DeConto RM and Pollard D. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**: 591–7.

Dobson DM, Dickens GR, and Rea DK. 2001. Terrigenous sediment on Ceara Rise: a Cenozoic record of South American orogeny and erosion. *Palaeogeogr Palaeoclimatol Palaeoecol* **165**: 215–29.

Eakin CM, Lithgow-Bertelloni C, and Dávila FM. 2014. Influence of Peruvian flat-subduction dynamics on the evolution of western Amazonia. *Earth Planet Sci Lett* **404**: 250–60.

Ehlers TA and Poulsen CJ. 2009. Influence of Andean uplift on climate and paleoaltimetry estimates. *Earth Planet Sci Lett* **281**: 238–48.

Emilio T, Quesada CA, Costa FRC, *et al.* 2014. Soil physical conditions limit palm and tree basal area in Amazonian forests. *Plant Ecol |& Divers* **7**: 215–29.

Ernst WG. 2009. Archean plate tectonics, rise of Proterozoic supercontinentality and onset of regional, episodic stagnant-lid behavior. *Gondwana Res* **15**: 243–53.

Espurt N, Baby P, Brusset S, *et al.* 2007. How does the Nazca Ridge subduction influence the modern Amazonian foreland basin?: Reply. *Geology* **35**: 515–8.

Faber-Langendoen D and Gentry AH. 1991. The Structure and Diversity of Rain Forests at Bajo Calima, Choco Region, Western Colombia. *Biotropica* **23**: 2.

Faccenna C, Oncken O, Holt AF, Becker TW. 2017. Initiation of the Andean orogeny by lower mantle subduction. *Earth and Planetary Science Letters* **463**: 189-201.

Fan Y, Li H, and Miguez-Macho G. 2013. Global patterns of groundwater table depth. *Science* **339**: 940–3.

Feldpausch TR, Banin L, Phillips OL, *et al.* 2011. Height-diameter allometry of tropical forest trees. *Biogeosciences* **8**: 1081–106.

Figueiredo J de JP, Zalán PV, and Soares EF. 2007. Bacia da Foz do Amazonas. *B Geocience Petrobras* **15**: 299–309.

Figueiredo J, Hoorn C, Ven P van der, and Soares E. 2009. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin. *Geology* **37**: 619–22.

Filkov AI, Ngo T, Matthews S, *et al.* 2020. Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *J Saf Sci Resil* **1**: 44–56.

Flantua SGA, Hooghiemstra H, Boxel JH Van, *et al.* 2014. Connectivity dynamics since the Last Glacial Maximum in the northern Andes; a pollen-driven framework to assess potential migration. *Paleobotany Biogeogr A Festschrift Alan Graham His 80th Year Missouri Bot Gard St Louis*: 98–123.

Flantua SGA, O'dea A, Onstein RE, *et al.* 2019. The flickering connectivity system of the north Andean páramos. *J Biogeogr* **46**: 1808–25.

Flantua SGA, Hooghiemstra H, Grimm EC, *et al.* 2015. Updated site compilation of the Latin American Pollen Database. *Rev Palaeobot Palynol* **223**: 104–15.

Flores BM, Staal A, Jakovac CC, *et al.* 2019. Soil erosion as a resilience drain in disturbed tropical forests. *Plant Soil*.

Foster GL, Royer DL, and Lunt DJ. 2017. Future climate forcing potentially without precedent in the last 420 million years. *Nat Commun* **8**: 14845.

Fritsch E, Herbillon AJ, Nascimento NR Do, *et al.* 2007. From Plinthic Acrisols to Plinthosols and Gleysols: iron and groundwater dynamics in the tertiary sediments of the upper Amazon basin. *Eur J Soil Sci* **58**: 989–1006.

Fuck RA, Brito Neves BB, and Schobbenhaus C. 2008. Rodinia descendants in South America. *Precambrian Res* **160**: 108–26.

Garreaud RD, Vuille M, Compagnucci R, Marengo J. 2009. Present-day South American climate. *Palaeogeogr Palaeoclimatol Palaeoecol* **281**, 180-195

Garzione CN, Hoke GD, Libarkin JC, *et al.* 2008. Rise of the Andes. *Science* **320**: 1304–7.

Garzione CN, McQuarrie N, Perez ND, *et al.* 2017. Tectonic evolution of the Central Andean plateau and implications for the growth of plateaus. *Annu Rev Earth Planet Sci* **45**: 529–59.

Gautier E, Brunstein D, Vauchel P, *et al.* 2007. Temporal relations between meander deformation, water discharge and sediment fluxes in the floodplain of the Rio Beni (Bolivian Amazonia). *Earth Surf Process Landforms* **32**: 230–48.

Geological Survey of Brazil (CPRM). 2018. Atlas of mineral deposits and selected mineral occurences of continental Brazil.

Goulding M, Venticinque E, Ribeiro ML de B, *et al.* 2019. Ecosystem-based management of Amazon fisheries and wetlands. *Fish Fish* **20**: 138–58.

Govin A, Chiessi, CM, Zabel, M, Sawakuchi, AO, *et al.* 2014. Terrigenous input off northern South America driven by changes in Amazonian climate and the North Brazil Current retroflection during the last 250 ka. *Clim Past* 10: 843-862.

Gray M. 2008. Geodiversity: developing the paradigm. *Proc Geol Assoc* **119**: 287–98.

Groot MHM, Bogotá RG, Lourend, LJ, *et al.* 2011. Ultra-high resolution pollen record from the northern Andes reveals rapid shifts in montane climates within the last two glacial cycles. *Clim Past* **7**, 299-316.

Gross M and Piller WE. 2020. Saline Waters in Miocene Western Amazonia--An Alternative View. *Front Earth Sci* **8**: 116.

Hack JT. 1960. Interpretation of erosional topography in humid temperate regions. Bobbs-Merrill.

Häggi C, Chiessi CM, Merkel U, *et al.* 2017. Response of the Amazon rainforest to late Pleistocene climate variability. *Earth and Planetary Science Letters* **479**, 50-59.

Harris SE and Mix AC. 2002. Climate and tectonic influences on continental erosion of tropical South America, 0–13 Ma. *Geology* **30**: 447.

Harrison TM. 2009. The Hadean Crust: Evidence from >4 Ga Zircons. *Annu Rev Earth Planet Sci* **37**: 479–505.

Hasui Y. 2012. Evolução dos continentes. *Hasui Y, Carneiro CDR, Almeida FFM de, Bartorelli A(eds)*: 98–111.

Hayakawa EH, Rossetti DF, and Valeriano MM. 2010. Applying DEM-SRTM for reconstructing a late Quaternary paleodrainage in Amazonia. *Earth Planet Sci Lett* **297**: 262–70.

Hazen RM, Golden J, Downs RT, *et al.* 2012. Mercury (Hg) mineral evolution: A mineralogical record of supercontinent assembly, changing ocean geochemistry, and the emerging terrestrial biosphere. *Am Mineral* **97**: 1013–42.

Herman F and Champagnac J-D. 2016. Plio-Pleistocene increase of erosion rates in mountain belts in response to climate change. *Terra Nov* **28**: 2–10.

Herman F, Seward D, Valla PG, *et al.* 2013. Worldwide acceleration of mountain erosion under a cooling climate. *Nature* **504**: 423–6.

Higgins MA, Ruokolainen K, Tuomisto H, *et al.* 2011. Geological control of floristic composition in Amazonian forests. *J Biogeogr* **38**: 2136–49.

Hirata R and Suhogusoff AV. 2019. How much do we know about the groundwater quality and its impact on Brazilian society today? *Acta Limnol Bras* **31**.

Hodnett MG, Vendrame I, O. Marques Filho A De, *et al.* 1997. Soil water storage and groundwater behaviour in a catenary sequence beneath forest in central Amazonia: I. Comparisons between plateau, slope and valley floor. *Hydrol Earth Syst Sci* **1**: 265–77.

Hooghiemstra H and Flantua SGA. Colombia in the Quaternary: An overview of environmental and climatic change. 2019. In: Gómez J and Pinilla–Pachon AO (editors), The Geology of Colombia, Volume 4 Quaternary. Servicio Geológico Colombiano, *Publicaciones Geológicas Especiales* 38, 43–95. Bogotá

Hoorn C, Wesselingh FP, Steege H ter, *et al.* 2010a. Amazonia Through Time: Andean Uplift, Climate Change, Landscape Evolution, and Biodiversity. *Science* **330**: 927–31.

Hoorn C. 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. *Palaeogeogr Palaeoclimatol Palaeoecol* **105**: 267–309.

Hoorn C, Bogotá-A GR, Romero-Baez M, *et al.* 2017. The Amazon at sea: Onset and stages of the Amazon River from a marine record, with special reference to Neogene plant turnover in the drainage basin. *Glob Planet Change* **153**: 51–65.

Hoorn C, Wesselingh FPP, Steege H ter, *et al.* 2010b. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science* **330**: 927–31.

Hoorn C, Wesselingh FP, Hovikoski J, and Guerrero J. 2010. The Development of the Amazonian Mega-Wetland (Miocene; Brazil, Colombia, Peru, Bolivia). In: Amazonia: Landscape and Species Evolution. Oxford, UK: Wiley-Blackwell Publishing Ltd.

Horbe AMC and Costa ML da. 2005. Lateritic crusts and related soils in eastern Brazilian Amazonia. *Geoderma* **126**: 225–39.

Horton BK. 2018. Sedimentary record of Andean mountain building. *Earth-Science Rev* **178**: 279–309.

Hovikoski J, Wesselingh FP, Räsänen M, *et al.* 2010. Marine influence in Amazonia: evidence from the geological record. *Amaz Landsc species Evol a look into past* **143**: 161.

Hu K, Awange JL, Forootan E, *et al.* 2017. Hydrogeological characterisation of groundwater over Brazil using remotely sensed and model products. *Sci Total Environ* **599**: 372–86.

Inglis GN, Bragg F, Burls NJ, *et al.* 2020. Global mean surface temperature and climate sensitivity of the early Eocene Climatic Optimum (EECO), Paleocene–Eocene Thermal Maximum (PETM), and latest Paleocene. *Clim Past* **16**: 1953–68.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Irion G and Kalliola R. 2009. Long-term landscape development processes in Amazonia. *Amaz Landsc Species Evol A look into past*: 185–97.

Jaramillo C, Romero I, D'Apolito C, *et al.* 2017. Miocene flooding events of western Amazonia. *Sci Adv* **3**: e1601693.

Jenny H. 1941. Factors of soil formation. McGraw-Hill, New York. McGraw-Hill, New York.

João X da SJ, Teixeira SG, and Fonseca DDF. 2013. Geodiversidade do estado do Pará.

John R, Dalling JW, Harms KE, *et al.* 2007. Soil nutrients influence spatial distributions of tropical tree species. *Proc Natl Acad Sci* **104**: 864–9.

Jones MT, Percival LME, Stokke EW, *et al.* 2019. Mercury anomalies across the Palaeocene–Eocene Thermal Maximum. *Clim Past* **15**: 217–36.

Juliani C, Monteiro LV., and Fernandes CM. 2016. Potencial mineral. In: Melfi AJ, Misi, Arnoldo, Campos D de A, Cordani UG (Eds). Potencial Mineral do Brasil, Capítulo I. Rio de Janeiro.

Klein AG, Isacks BL, Bloom AL. 1995. Modern and Last Glacial Maximum snowline in Peru and Bolivia: Implications for regional climatic change. *Bull Inst Fre Estudes Andines* **24**, 607-617.

Klein EL, Matos DR, Santos dos, *et al.* 2018. Atlas of mineral deposits and selected mineral occurrences of continental Brazil. Servico Geologico do Brasil.

Langenbrunner B, Pritchard MS, Kooperman GJ, and Randerson JT. 2019. Why does Amazon precipitation decrease when tropical forests respond to increasing CO2? *Earth's Futur* **7**: 450–68.

Latrubesse EM, Cozzuol M, Silva-Caminha SAF da, *et al.* 2010. The Late Miocene paleogeography of the Amazon Basin and the evolution of the Amazon River system. *Earth-Science Rev* **99**: 99–124.

Lear CH, Anand P, Blenkinsop T, *et al.* 2021. Geological Society of London Scientific Statement: what the geological record tells us about our present and future climate. *J Geol Soc London* **178**: jgs2020-239.

Lisiecki LE and Raymo ME. 2007. Plio–Pleistocene climate evolution: trends and transitions in glacial cycle dynamics. *Quat Sci Rev* **26**: 56–69.

Lisiecki LE and Raymo ME. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography* **20**: n/a-n/a.

Macambira M, Teixeira W, and Vasquez M. 2020. O Cráton Amazônico e suas provínvias geocronológicas: o legado de Umberto Cordani. In: Bartorelli A, Teixeira W, Neves BB de B (Eds). Geocronologia e Evolução Tectônica do Continente Sul-Americano : a contribuição de Umberto Giuseppe Cordani. São Paulo, Brasil: Solaris.

Maeda EE, Ma X, Wagner FH, *et al.* 2017. Evapotranspiration seasonality across the Amazon Basin. *Earth Syst Dyn* **8**: 439–54.

Mapes RW. 2009. Past and present provenance of the Amazon River.

Marini O. 2016. Potencial mineral do Brasil. *Recur Minerais no Bras Probl e desafios* Rio de Janeiro: Academia Brasileira de Ciências. p. 18-31. URL: http://www.abc.org.br/IMG/pdf/doc-7006.pdf.

Mark BG, Harrison SP, Spessa A, *et al.* 2005. Tropical snowline changes at the last glacial maximum: A global assessment. *Quat Int* **138–139**: 168–201.

Martinod J, Gérault M, Husson L, and Regard V. 2020. Widening of the Andes: An interplay between subduction dynamics and crustal wedge tectonics. *Earth-Science Rev* **204**: 103170.

Martins DL, Schietti J, Feldpausch TR, *et al.* 2015. Soil-induced impacts on forest structure drive coarse woody debris stocks across central Amazonia. *Plant Ecol Divers* **8**: 229–41.

Mayle FE, Beerling DJ, Gosling WD, Bush MB. 2004. Responses of Amazonian ecosystems to climatic and atmospheric carbon dioxide changes since the last glacial maximum. *Phil Trans R Soc Lond B* **359**, 499-514.

Mayle FE, Burn MJ, Power M, and Urrego DH. 2009. Vegetation and fire at the Last Glacial Maximum in tropical South America. In: Past climate variability in South America and surrounding regions. Springer.

McInerney FA and Wing SL. 2011. The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future. *Annu Rev Earth Planet Sci* **39**: 489–516.

McKenzie D. 1978. Some remarks on the development of sedimentary basins. *Earth Planet Sci Lett* **40**: 25–32.

Mertes LAK, Dunne T, and Martinelli LA. 1996. Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil. *Geol Soc Am Bull* **108**: 1089–107.

Methner K, Campani M, Fiebig J, *et al.* 2020. Middle Miocene long-term continental temperature change in and out of pace with marine climate records. *Sci Rep* **10**: 7989.

Miguez-Macho G and Fan Y. 2012b. The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration. *J Geophys Res Atmos* **117**: 1–27

Miguez-Macho G and Fan Y. 2012a. The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands. *J Geophys Res Atmos* **117**: 1–30.

Miller KG, Browning J V, Schmelz WJ, *et al.* 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Sci Adv* **6**: eaaz1346.

Milliman JD and Syvitski JPM. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J Geol* **100**: 525–44.

Monteiro HS, Vasconcelos PMP, Farley KA, and Lopes CAM. 2018. Age and evolution of diachronous erosion surfaces in the Amazon: combining (U-Th)/He and cosmogenic 3He records. *Geochim Cosmochim Acta* **229**: 162–83.

Monteiro LVS, Xavier RP, Souza Filho CR, and Moreto CPN. 2014. Metalogenia da Província Carajás. *Met das Províncias Tectônicas Bras*: 43–84.

Monteiro M de A. 2005. Meio século de mineração industrial na Amazônia e suas implicações para o desenvolvimento regional. *Estud avançados* **19**: 187–207.

Montes C, Cardona A, Jaramillo C, *et al.* 2015. Middle Miocene closure of the Central American seaway. *Science* **348**: 226–9.

Montgomery DR and Brandon MT. 2002. Topographic controls on erosion rates in tectonically active mountain ranges. *Earth Planet Sci Lett* **201**: 481–9.

Mora A, Parra M, Strecker MR, *et al.* 2008. Climatic forcing of asymmetric orogenic evolution in the Eastern Cordillera of Colombia. *Geol Soc Am Bull* **120**: 930–49.

Mora A, Baby P, Roddaz M, *et al.* 2010. Tectonic history of the Andes and sub-Andean zones: implications for the development of the Amazon drainage basin. *Amaz Landsc species Evol a look into past*: 38–60.

Munroe DK, Berkel DB van, Verburg PH, and Olson JL. 2013. Alternative trajectories of land abandonment: causes, consequences and research challenges. *Curr Opin Environ Sustain* **5**: 471–6.

Nance RD, Murphy JB, and Santosh M. 2014. The supercontinent cycle: A retrospective essay. *Gondwana Res* **25**: 4–29.

Neu V, Neill C, and Krusche A V. 2011. Gaseous and fluvial carbon export from an Amazon forest watershed. *Biogeochemistry* **105**: 133–47.

Novello VF, Cruz FW, McGlue MM, *et al.* 2019. Vegetation and environmental changes in tropical South America from the last glacial to the Holocene documented by multiple cave sediment proxies. *Earth Planet Sci Lett* **524**: 115717.

Novello VF, Cruz FW, Vuille M, *et al.* 2017. A high-resolution history of the South American Monsoon from Last Glacial Maximum to the Holocene. *Sci Rep* **7**: 44267.

Nunn JA and Aires JR. 1988. Gravity anomalies and flexure of the lithosphere at the Middle Amazon Basin, Brazil. *J Geophys Res Solid Earth* **93**: 415–28.

O'Dea A, Lessios HA, Coates AG, *et al.* 2016. Formation of the Isthmus of Panama. *Sci Adv* **2**: e1600883.

Palacios D, Stokes CR, Philips FM, *et al.* 2020. The deglaciation of the Americas during the Last Glacial Termination. *Earth-Science Reviews* 203, 103113.

Parra M, Mora A, Sobel ER, *et al.* 2009. Episodic orogenic front migration in the northern Andes: Constraints from low-temperature thermochronology in the Eastern Cordillera, Colombia. *Tectonics* **28**.

Phillips OL, Vargas PN, Monteagudo AL, *et al.* 2003. Habitat association among Amazonian tree species: a landscape-scale approach. *J Ecol* **91**: 757–75.

Portenga EW and Bierman PR. 2011. Understanding Earth's eroding surface with 10Be. *GSA Today* **21**: 4–10.

Pupim FN, Sawakuchi AO, Almeida RP de, *et al.* 2019. Chronology of Terra Firme formation in Amazonian lowlands reveals a dynamic Quaternary landscape. *Quat Sci Rev* **210**: 154–63.

Quesada CA, Lloyd J, Anderson LO, *et al.* 2011. Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* **8**: 1415–40.

Quesada CA and Lloyd J. 2016. Soil–Vegetation Interactions in Amazonia. In: Nagy L, Artaxo P, Forsberg BR (Eds). Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin. Springer.

Quesada CA, Lloyd J, Schwarz M, *et al.* 2010. Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences* **7**: 1515–41.

Quesada CA, Phillips OL, Schwarz M, *et al.* 2012. Basin-wide variations in Amazon forest structure and function are mediated by both soils and climate. *Biogeosciences* **9**: 2203–46.

Ramos VA. 2009. Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. In: Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision. Geological Society of America.

Restrepo-Coupe N, Rocha HR da, Hutyra LR, *et al.* 2013. What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network. *Agric For Meteorol* **182**: 128–44.

Ribas CC, Aleixo A, Nogueira ACR, *et al.* 2012. A palaeobiogeographic model for biotic diversification within Amazonia over the past three million years. *Proc R Soc B Biol Sci* **279**: 681–9.

Riff D, R. Romano PS, Oliveira GR, and Aguilera OA. 2010. Neogene Crocodile and Turtle Fauna in Northern South America. In: Amazonia: Landscape and Species Evolution. Oxford, UK: Wiley-Blackwell Publishing Ltd Oxford.

Robb L. 2005. Introduction to ore-forming processes. Malden, MA: Blackwell Publishing Inc.

Robl J, Hergarten S, and Prasicek G. 2020. Glacial erosion promotes high mountains on thin crust. *Earth Planet Sci Lett* **538**: 116196.

Rosário FF, Custodio E, and Silva GC da. 2016. Hydrogeology of the Western Amazon Aquifer System (WAAS). *J South Am Earth Sci* **72**: 375–86.

Rossatto DR, Silva L de CR, Villalobos-Vega R, *et al.* 2012. Depth of water uptake in woody plants relates to groundwater level and vegetation structure along a topographic gradient in a neotropical savanna. *Environ Exp Bot* **77**: 259–66.

Rossetti DF, Cohen MCL, Tatumi SH, *et al.* 2015. Mid-Late Pleistocene OSL chronology in western Amazonia and implications for the transcontinental Amazon pathway. *Sediment Geol* **330**: 1–15.

Rossoni MB, Neto ACB, Souza VS, *et al.* 2017. U-Pb zircon geochronologycal investigation on the Morro dos Seis Lagos Carbonatite Complex and associated Nb deposit (Amazonas, Brazil). *J South Am Earth Sci* **80**: 1–17.

Rull V, Vegas-Vilarrubia T, Huber O, Señaris C. 2019. Biodiversity of the Pantepui. Academic Press/Elsevier, 452 pp.

Ruokolainen K, Tuomisto H, Macia MJ, *et al.* 2007. Are floristic and edaphic patterns in Amazonian rain forests congruent for trees, pteridophytes and Melastomataceae? *J Trop Ecol*: 13–25.

Sacek V. 2014. Drainage reversal of the Amazon River due to the coupling of surface and lithospheric processes. *Earth Planet Sci Lett* **401**: 301–12.

Saint-Paul U, Zuanon J, Correa MAV, *et al.* 2000. Fish Communities in Central Amazonian White- and Blackwater Floodplains. *Environ Biol Fishes* **57**: 235–50.

Santos Albuquerque MF, Horbe AMC, and Danišík M. 2020. Episodic weathering in Southwestern Amazonia based on (U Th)/He dating of Fe and Mn lateritic duricrust. *Chem Geol* **553**: 119792.

Santos JOS, Rizzotto GJ, Potter PE, *et al.* 2008. Age and autochthonous evolution of the Sunsás Orogen in West Amazon Craton based on mapping and U--Pb geochronology. *Precambrian Res* **165**: 120–52.

Schietti J, Emilio T, Rennó CD, *et al.* 2014. Vertical distance from drainage drives floristic composition changes in an Amazonian rainforest. *Plant Ecol |& Divers* **7**: 241–53.

Seton M, Müller RD, Zahirovic S, *et al.* 2012. Global continental and ocean basin reconstructions since 200Ma. *Earth-Science Rev* **113**: 212–70.

Shephard GE, Müller RD, Liu L, and Gurnis M. 2010. Miocene drainage reversal of the Amazon River driven by plate--mantle interaction. *Nat Geosci* **3**: 870–5.

Sherwood SC, Webb MJ, Annan JD, *et al.* 2020. An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Rev Geophys* **58**.

Sigmond M, Fyfe JC, and Swart NC. 2018. Ice-free Arctic projections under the Paris Agreement. *Nat Clim Chang* **8**: 404–8.

Silva CL, Morales N, Crósta AP, *et al.* 2007. Analysis of tectonic-controlled fluvial morphology and sedimentary processes of the western Amazon Basin: an approach using satellite images and digital elevation model. *An Acad Bras Cienc* **79**: 693–711.

Silvertown J, Araya Y, and Gowing D. 2015. Hydrological niches in terrestrial plant communities: a review (W Cornwell, Ed). *J Ecol* **103**: 93–108.

Silvertown J, Dodd ME, Gowing DJG, and Mountford JO. 1999. Hydrologically defined niches reveal a basis for species richness in plant communities. *Nature* **400**: 61–3.

Slingerland R and Smith ND. 2004. River avulsions and their deposits. *Annu Rev Earth Planet Sci* **32**: 257–85.

Sorribas MV, Paiva RCD, Melack JM, *et al.* 2016. Projections of climate change effects on discharge and inundation in the Amazon basin. *Clim Change* **136**: 555–70.

Souza RG. 1997. Petróleo: Histórias das descobertas e o Potencial Brasileiro. Muiraquitã.272p.

Stefanelli-Silva G, Zuanon J, and Pires T. 2019. Revisiting Amazonian water types: experimental evidence highlights the importance of forest stream hydrochemistry in shaping adaptation in a fish species. *Hydrobiologia* **830**: 151–60.

Stokes MF, Goldberg SL, and Perron JT. 2018. Ongoing River Capture in the Amazon. *Geophys Res Lett* **45**: 5545–52.

Sundell KE, Saylor JE, Lapen TJ, and Horton BK. 2019. Implications of variable late Cenozoic surface uplift across the Peruvian central Andes. *Sci Rep* **9**: 1–12.

Sylvestre F. 2009. Moisture Pattern During the Last Glacial Maximum in South America

Tassinari CCG and Macambira MJB. 2004. A evolução tectônica do Cráton Amazônico. In: Geologia do continente sul-americano: evoluçao da obra de Fernando Flávio Marques de Almeida. Beca.

Terborgh J and others. 1992. Diversity and the tropical rain forest. Scientific American Library., 61: 972:981.

Théveniaut H and Freyssinet PH. 2002. Timing of lateritization on the Guiana Shield: synthesis of paleomagnetic results from French Guiana and Suriname. *Palaeogeogr Palaeoclimatol Palaeoecol* **178**: 91–117.

Thompson LG. 1998. A 25,000-Year Tropical Climate History from Bolivian Ice Cores. *Science* **282**: 1858–64.

Tierney JE, Poulsen CJ, Montañez IP, *et al.* 2020. Past climates inform our future. *Science* **370**: eaay3701.

Tomasella J, Hodnett MG, Cuartas LA, *et al.* 2008. The water balance of an Amazonian micro-catchment: the effect of interannual variability of rainfall on hydrological behaviour. *Hydrol Process* **22**: 2133–47.

Torres V, Hooghiemstra H, Lourens L, and Tzedakis PC. 2013. Astronomical tuning of long pollen records reveals the dynamic history of montane biomes and lake levels in the tropical high Andes during the Quaternary. *Quat Sci Rev* **63**: 59–72.

Tuomisto H, Doninck J Van, Ruokolainen K, *et al.* 2019. Discovering floristic and geoecological gradients across Amazonia. *J Biogeogr* **46**: 1734–48.

Val P. 2016. The pace and timing of changing landscapes as viewed through cosmogenic radionuclides: Synthetic and real examples from the Central Andes and Amazonia.

Val P, Silva C, Harbor D, *et al.* 2014. Erosion of an active fault scarp leads to drainage capture in the Amazon region, Brazil. *Earth Surf Process Landforms* **39**: 1062–74.

Van-Soelen EE, Kim J-H, Santos RV, *et al.* 2017. A 30 Ma history of the Amazon River inferred from terrigenous sediments and organic matter on the Ceará Rise. *Earth Planet Sci Lett* **474**: 40–8.

Vousdoukas MI, Mentaschi L, Voukouvalas E, *et al.* 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat Commun* **9**: 1–12.

Wahl ER, Zorita E, Trouet V, and Taylor AH. 2019. Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. *Proc Natl Acad Sci* **116**: 5393–8.

Wanderley-Filho JR, Eiras JF, Cruz Cunha PR da, and Ven PH van der. 2010. The Paleozoic Solimões and Amazonas basins and the Acre foreland basin of Brazil. In: Amazonia: Landscape and Species Evolution: A look into the past. Wiley-Blackwell Publishing Ltd Oxford.

Wang X, Lawrence Edwards R, Auler AG, *et al.* 2017. Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature* **541**, 204-207.

Watts AB, Rodger M, Peirce C, *et al.* 2009. Seismic structure, gravity anomalies, and flexure of the Amazon continental margin, NE Brazil. *J Geophys Res* **114**: B07103.

Wesselingh FP, Anderson LC, and Kadolsky D. 2006. Molluscs from the Miocene Pebas Formation of Peruvian and Colombian Amazonia. *Scr Geol* **133**: 19–290.

Wesselingh FP, Räsänen ME, Irion G, *et al.* 2001. Lake Pebas: a palaeoecological reconstruction of a Miocene, long-lived lake complex in western Amazonia. *Cainozoic Res* **1**: 35–68.

Westerhold T, Marwan N, Drury AJ, *et al.* 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science* **369**: 1383–7.

Wilkinson MJ, Marshall LG, Lundberg JG, and Kreslavsky MH. 2010. Megafan environments in northern South America and their impact on Amazon Neogene aquatic ecosystems. *Amaz Landsc species Evol a look into past*: 162–84.

Winkelmann R, Levermann A, Ridgwell A, and Caldeira K. 2015. Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. *Sci Adv* **1**: e1500589.

Wittmann F, Schöngart J, and Junk WJ. 2010. Phytogeography, Species Diversity, Community Structure and Dynamics of Central Amazonian Floodplain Forests. In: Amazonian Floodplain Forests. Springer, Dordrecht.

Wittmann H, Blanckenburg F von, Maurice L, *et al.* 2011. Sediment production and delivery in the Amazon River basin quantified by in situ--produced cosmogenic nuclides and recent river loads. *Bulletin* **123**: 934–50.

Wright JS, Fu R, Worden JR, *et al.* 2017. Rainforest-initiated wet season onset over the southern Amazon. *Proc Natl Acad Sci* **114**: 8481–6.

Xu X, Jia G, Zhang X, *et al.* 2020. Climate regime shift and forest loss amplify fire in Amazonian forests. *Glob Chang Biol* **26**: 5874–85.

You Y, Huber M, Müller RD, *et al.* 2009. Simulation of the middle Miocene climate optimum. *Geophys Res Lett* **36**.

Zhao G, Sun M, Wilde SA, and Li S. 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. *Earth-Science Rev* **67**: 91–123.

Zizka A, Steege H ter, Pessoa M do CR, and Antonelli A. 2018. Finding needles in the haystack: where to look for rare species in the American tropics. *Ecography (Cop)* **41**: 321–30.