Science Panel for the Amazon (SPA)

Working Group 1

GEOLOGY AND EVOLUTION OF THE AMAZON BASIN (GEOLOGICAL FORMATION OF THEAMAZON BASIN AND EVOLUTION OF TERRESTRIAL AND AQUATIC ECOSYSTEMS)

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CHAPTER 1: GEOLOGY AND GEODIVERSITY OF THE AMAZON: THREE BILLION YEARS OF HISTORY

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GEOLOGY AND GEODIVERSITY OF THE AMAZON: THREE BILLION YEARS OF HISTORY

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ACRONYMS AND ABBREVIATIONS

Early Eocene Climatic Optimum (EECO)

Great American Biotic Interchange (GABI)

Giga-annum (Ga)

Intertropical Convergence Zone (ITCZ)

Million years ago (Ma)

Middle Miocene Climatic Optimum (MMCO)

Water table depth (WTD)

World Reference Base (WRB)

Amazon Aquifer System (AAS)

Paleocene Eocene Thermal Maximum (PETM)

Platinum Group Elements (PGE)

Rare Earth Elements (REE)

Last Glacial Maximum (LGM)

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KEY MESSAGES

- Modern Amazonian landscapes can only be understood in the light of geological and climatic processes operating over immense time intervals of millions 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 surface and subsurface processes.
- It took hundreds of millions of years for the Amazon to develop the rich tapestry of landforms, soils, and ecosystems we see today, but it will only take a century or two for humans to destroy it. This sombre, deep time perspective should give us pause in making decisions that will affect the Amazon, for it will take a very long time for it to recover if it recovers at all.

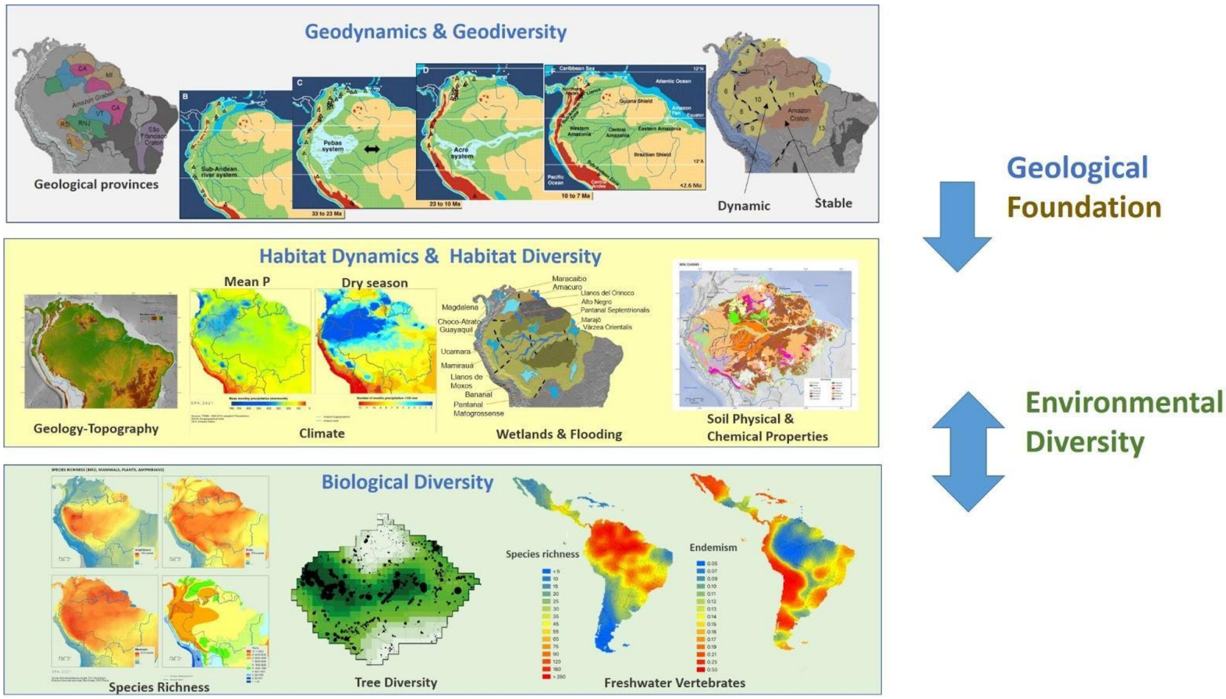
ABSTRACT

The Amazon hosts the most diverse tropical forest on Earth. But underneath, the Amazon also forms 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 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 (since c. 20 Ma) due to changes in Pacific plate motions. Together with a rise in global temperatures and sea level during the 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 completion 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, that is reflected in the geomorphology, lithology and geochemistry, and explains the 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 back to the geological subdivision of 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— translated into inundation of marine water into the Amazon, 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

resulting in 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 Andes and Amazon. When 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

GRAPHICAL ABSTRACT



GRAPHICAL ABSTRACT 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 (Macambira *et al.* 2020), and the uplifting Andes, sedimentary basins and the stable cratons (Fuck *et al.* 2008), landscape and drainage evolution sequence through the past 30 Ma (Hoorn *et al.* 2010b), dynamic Andes and sedimentary basins and stable cratons (Albert *et al.* 2018); middle panel, from left to right, topography from NASA Earth Observatory, precipitation and seasonality (Restrepo-Coupe *et al.* 2013), wetlands and flooding (Albert *et al.* 2018), soil (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 (Hoorn *et al.* 2010b), freshwater vertebrates (Albert *et al.* 2020)

1. INTRODUCTION

The Amazon is a globally unique region of exceptional **geodiversity** (**Glossary**; Gray 2008; Bétard and Peulvast 2019), arising from variations in underlying rocks and mineral resources, the emergent topography and surface relief, and the heterogeneous distributions of surface and subsurface water flows (hydrology) and soil types (edaphic conditions) (Fig. 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 are distinct: the Eastern Amazon is dominated by Precambrian **shields** with the Paleozoic sedimentary basin in between which occupy a relatively small area; the Western Amazon is largely dominated by Cenozoic sedimentary basins, while the Precambrian shields are spatially restricted towards the northern and southern limits. The landscapes reflect the geology well, with the shield areas generally being marked by plateaus (above c. 250 meters 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 meters elevation) which we nominate as the Amazon lowlands. The Western Amazon margin is marked by the Andean cordilleras 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, and groundwaters and soils that affect 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], climate change, and sea level fluctuations, extending over millions, even billions of years. The oldest Amazonian rocks were formed during the Meso to Neoarchean (3.0 – 2.5 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 Ma) and some still accumulate sediments today. Two other main geologic events fundamentally changed the Amazon region: the breakup of the final bridge between South America and the African continent (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 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 the modern west-to-east topographic gradients began to take form.

The Amazon is also wealthy in terms of its many mineral 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 locally 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 lowland Amazon, being most heavily exploited in the Alter do Chão Formation in the Eastern Amazon. These resources represent important potential sources of wealth for the Amazon; however their environmental and sociopolitical impacts 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 the modern landscapes. We use this geological narrative to explain the genesis of the 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.

Figure 1.1. Photographic overview of the geology and geodiversity of the Amazon (with photo credits). **Top row**: **2** - Chiribiquete (© Steve Winter); **3** - Monte Roraima (Paulo Fassina); **Bottom row**: **9** - Várzea near Manaus (Hans Ter Steege), **10** - Salobo Copper Mine in the Carajás Province (Gustavo Melo), **Left column**: **1** – The Andes in Ecuador (Esteban Suárez), **7** - Andean river (Esteban Suárez), **8** - Amboro Nat. Park (Pattrön), **Right Column**: **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), **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).

Box 1 - Earth and plate tectonics

The origin of Planet Earth is linked to the origin of our solar system, starting about 4.5 Ga (Ga = billions of years ago). Geologists divide the Earth's history in four major divisions they call "EON" or "AEON" inspired by the Greek word αἰών (*aiwṓn)* that bear the meaning for eternity. The four Eons are Hadean, Archean, Proterozoic and Phanerozoic. The hard shell of the Earth known as "Lithosphere" was formed by two processes over geological time. Initially magmatic differentiation prevailed, what, in simple words, is the solidification of a magma. Later on processes responsible for plate tectonics movements started. The rocks, which formed by magmatic differentiation, are the cores to which later other 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 consider that plate tectonics already started in the Mesoarchean (3.5 – 2.8 Ga), despite being different to present-day processes (Ernst 2009). For instance, during this Eon not much of the Earth surface was solid rock, therefore plate tectonics were not on a global scale like today but localized near to the solid cores formed by magmatic differentiation. Once plate tectonic movement started, so did the formation of continental assemblages and the congregation of cratons, supercratons, continents and supercontinents.

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 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 (Figuere 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.

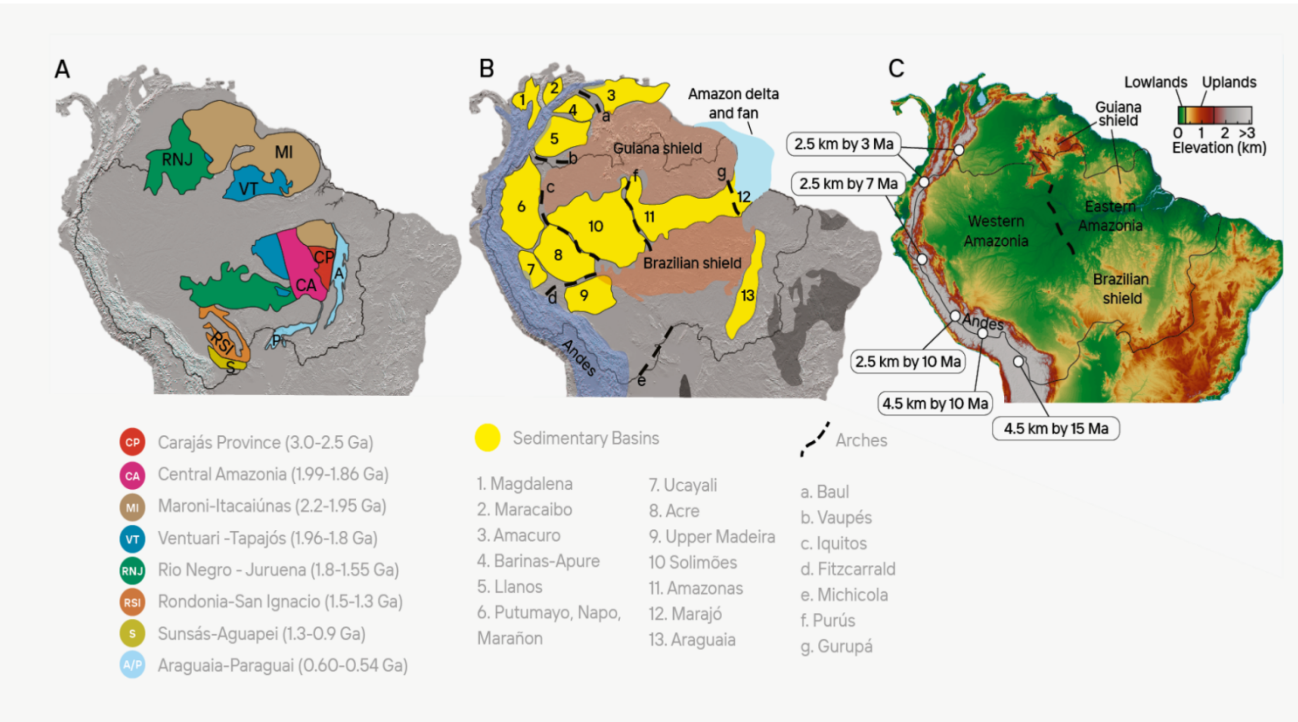


Figure 1.2. (A). Geochronological map of South America with the main provinces of the Amazon Craton (modified from Macambira *et al.* 2020). The location of the north Andean foreland basins is highlighted. The area enclosing the known extent of late Meso- to early Neoproterozoic basement in the Northern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

2.1.2. Amalgamation of terranes

The history of the Amazon Craton consolidation is linked with supercontinents assembly, particularly with Columbia and Rodinia (Zhao *et al.* 2004; Nance *et al.* 2014). 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 colided with the northeastern border of the proto-Amazon Craton, while the Central Amazon, 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 the Amazon had already been formed (Tassinari and Macambira 2004; Santos *et al.* 2008).

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 E-W 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; http://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 and through the intracratonic Amazon basin. 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 the 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).

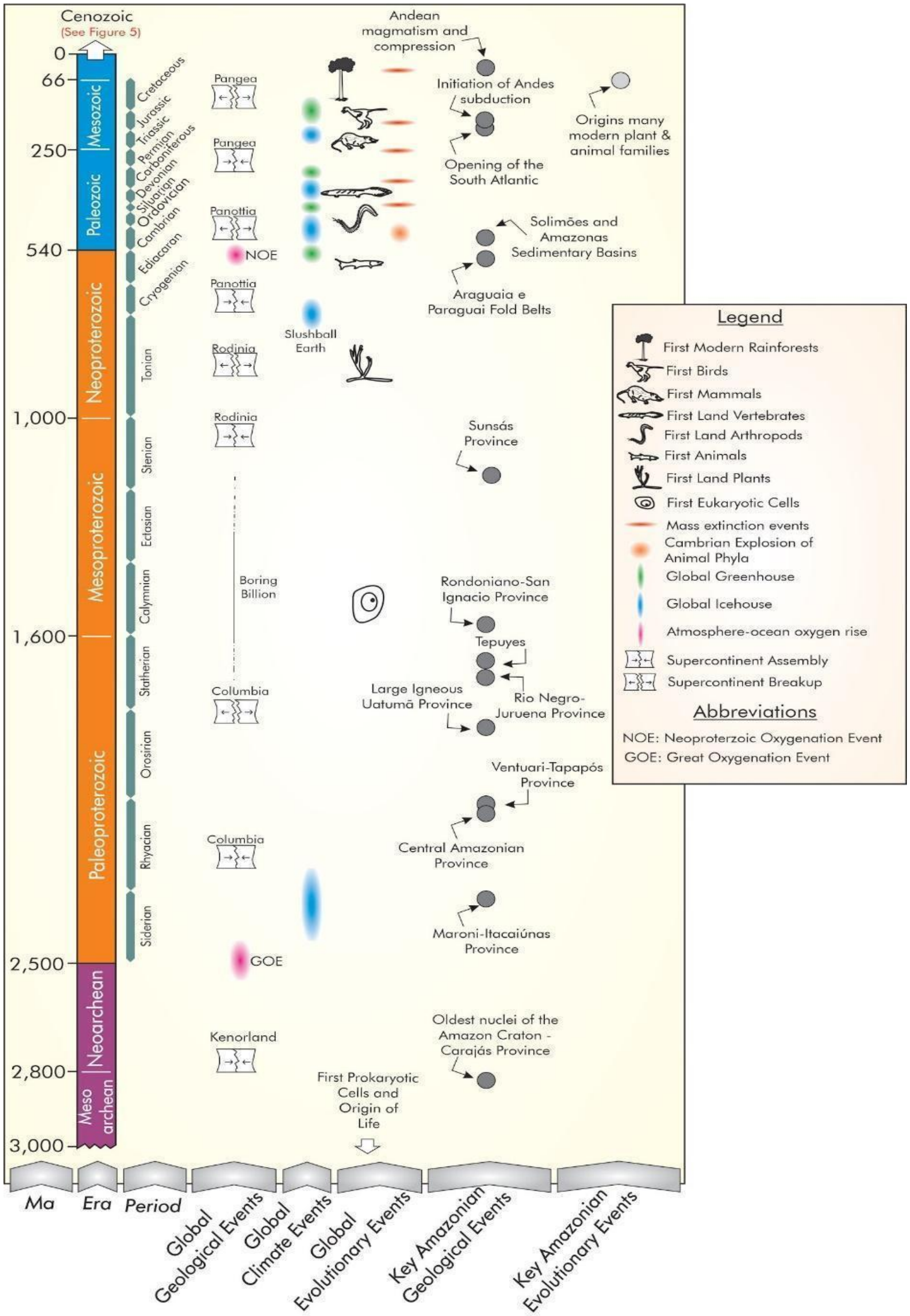


Figure 1.3. Geological time scale with the key global and Amazonian geological, climate and evolutionary events across time.

2.3.2. Westward drift of South America and Andes formation: forging 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 formation took place.

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. Here, during most of the last 100 Ma, South America had no significant mountains along its west coast. Despite this long history of westward drift of South America and tectonic convergence on its western edge, it wasn't until the last 40 ± 10 Ma that significant topographic expressions began forming (Capitanio *et al.* 2011; Garzione *et al.* 2017) but estimates are debated.

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 at 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). For a review of the Andes elevation through time across South America see Boschman (2021).

Evidence diverges on paleoelevations during the Miocene, but currently it seems that it was not until 4 – 5 Ma, that a 3 km high Andes flanked 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 Climate Chapter). 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 the 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 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, in the Eastern Amazon, 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 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, 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

The Andes formation 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, to make place for deltaic to 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 km^2, at a maximum reaching about 1500 km E-W from the Andean foothills to the

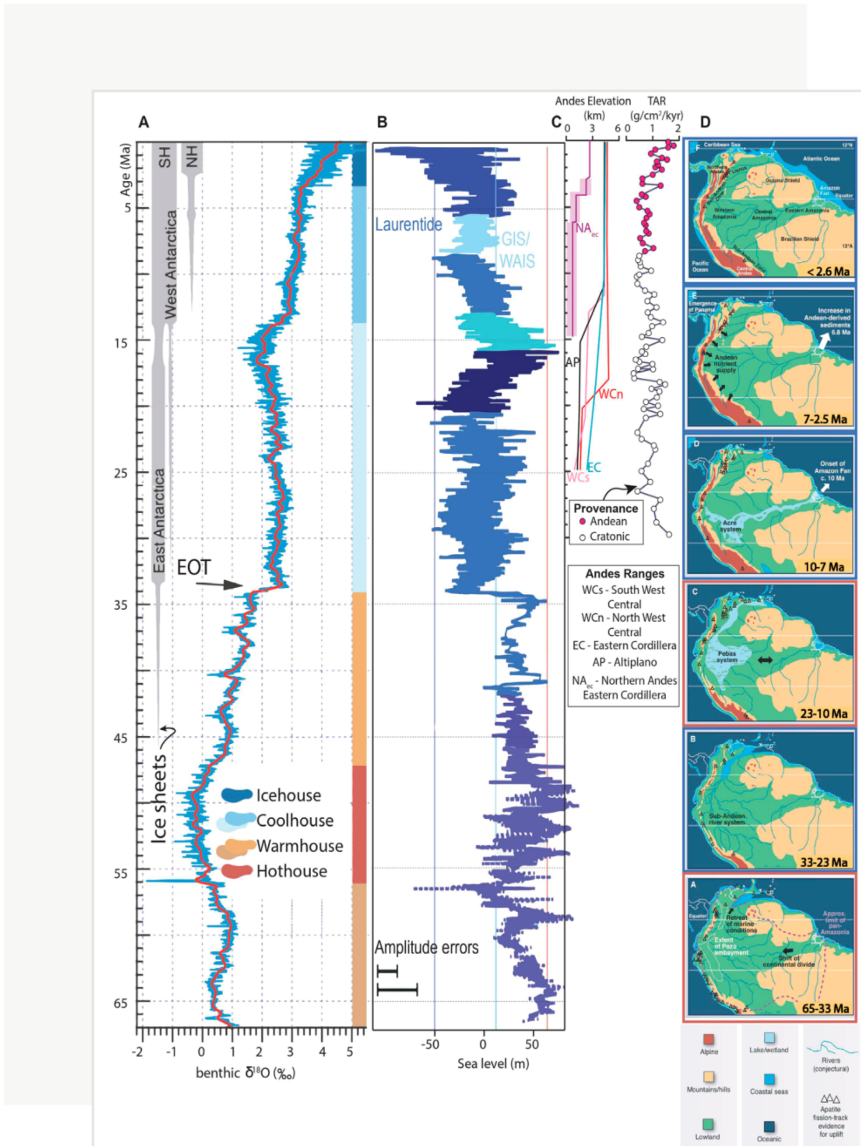


Figure 1.4. A) Global Cenozoic temperature curve (from Westerhold et al. 2020); **B)** Global Cenozoic sea level curve (from Miller *et al.* 2020) [Box 2]. **C)** Paleogeographic maps illustrating the transition from Amazon Craton to Andes-dominated landscapes. **D) (a)** Amazon once extended over most 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 Western Amazon. The Middle Miocene Climate Optimum and high sea level causes 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 Panama Isthmus and start of GABI. **(f)** Quaternary. Note that South America migrated northward during the course of the Paleogene.

Easternmost limit of the Western Amazon (near Manaus, Brazil). These wetlands also extended 1200 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) 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 Western Amazon also facilitated marine influence 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 or Solimões Formation, in Peru and Brazil respectively. In Peru, their nutrient-rich surface and associated soils harbour 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 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 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 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 source 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 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 as a result of the onset of glacial-interglacial fluctuations (Lisiecki and Raymo 2005, 2007) Box 2]. The climate dynamics of the Quaternary also substantially affected the abiotic (e.g. megafans, sedimentary deposits) and the biotic landscapes of the Amazon (Baker and Fritz 2015) (Figure 1.4.D.f).

In terms of precipitation, the Amazonian hydrological cycle is closely tied to the seasonal movements of intertropical convergence zone (ITCZ) over the Atlantic, which shapes the South American monsoon during the wet season. Additional precipitation forcing is caused by substantial rainforest transpiration playing a role in the onset of the monsoon system (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 Atlantic Convergence Zone (See chapter on climate). Our knowledge of precipitation patterns during the Quaternary is based on scattered archives from ice cores and lakes in the Andes to marine records along the Brazilian coast, and caves throughout the Amazon, but latest assessments hint at the complex history of shifting patterns of hydrological variation throughout the region (e.g. Thompson 1998; Sylvestre 2009; Novello *et al.* 2017, 2019; Hoorn *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). The effect of this precipitation dipole on biotic landscapes is poorly known, as fossil pollen sequences in 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). Paleo-records 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 Amazon. Andean temperature estimates during cool glacial periods, such as the Last Glacial Maximum at c. 21 ka, vary between 1 and 9°C cooler than the present (e.g. Mark et al. 2005). These temperature drops were accompanied by large changes in moisture availability linked to the South American monsoon system, causing substantial advances of high Andean glaciers in the Northern and Central Andes. Although temperatures were equally low during glacial periods in the Northern Andes, they were substantially drier than the Central Andes (Torres *et al.* 2013), creating an additional precipitation dipole of paleoclimate within the Andes.

The waxing and waning of glacial-interglacial cycles influenced Amazonian landscapes at all elevations. 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 elevation (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).

Box 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 the most recent several 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 white-water 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 rivers. 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.

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 and 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). Being that these high sediment loads come from nutrient-rich areas within the Amazon drainage basin (see Section 4), sediment provenance in the Amazon basin is extremely important for natural productivity and sets the stage for the types of aquatic and floodplain habitats (see

Section 5). Importantly, these mountains block atmospheric currents and produce steep local climatic gradients, the so-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 along with 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, these 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 of 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. Paleovárzeas 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 floodplains, 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 lowland rivers flow mostly over the Alter-do-Chão Formation (moderately resistant siltstones). Here, rivers are also low-relief (10 – 200 m), except for where resistant sandstones outcrop in the Pará state, 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 Negro River - Solimões confluence 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 the 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 – 1000 m elevation but reaching upwards to 2500 m in the northernmost Amazon of southern Venezuela and at the border with 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; see Section 2). This is where the deep-time geologic evolution of Amazon manifests itself on the current landscape the most. Whether these plateaus are uplifting and if so, how fast, is unknown, but likely orders of magnitude lower than in the Andes. Nonetheless, local **flexural uplift** due to the weight of the sedimentary pile 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 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 contrasts in geological settings 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 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 2], 3) river capture [Box 3], and 4) river avulsions [Box 3]. Lastly, erosion rates are largely unconstrained in the Amazon and only restricted to the largest tributaries of the Amazon River (Wittmann *et al.* 2011). There is essentially no published long-term erosion rate data in 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.

Box 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 arises 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 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 & 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 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 the Amazon with variable ages since the late Miocene (Wilkinson *et al.* 2010).

4. RICHNESS OF THE AMAZONIAN LANDSCAPE: GEODIVERSITY AND SOILS

Soils form at the interface between geology, biology, and water, and constitute an integral part of the physical environment for continental ecosystems and serve four main ecological functions. Soils provide the means for (i) storage, supply and purification of water, (ii) for plant growth, (iii) they modify the atmosphere and (iv) are the 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 affects 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 described in sections 2 and 3, have shaped the geographic distributions and physiographic coverage of **edaphic** conditions in 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 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 and are drivers of soil formation (Figure 1.5.).

The interactions of 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 section 2 and 3 resulted in large differences in the age and erosion rates of **parent material** (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 very old (Proterozoic) and highly weathered. Many shield soils developed over crystalline rocks instead of 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 Manaus in the **intracratonic basin**. During filling of the Amazon sedimentary basins, for example, Paleozoic-Mesozoic sediments originated from the already weathered Brazilian and Guiana shields over multiple cycles, this resulted in lower soil fertility (Quesada *et al.* 2010) (Figure 1.5. A and B).

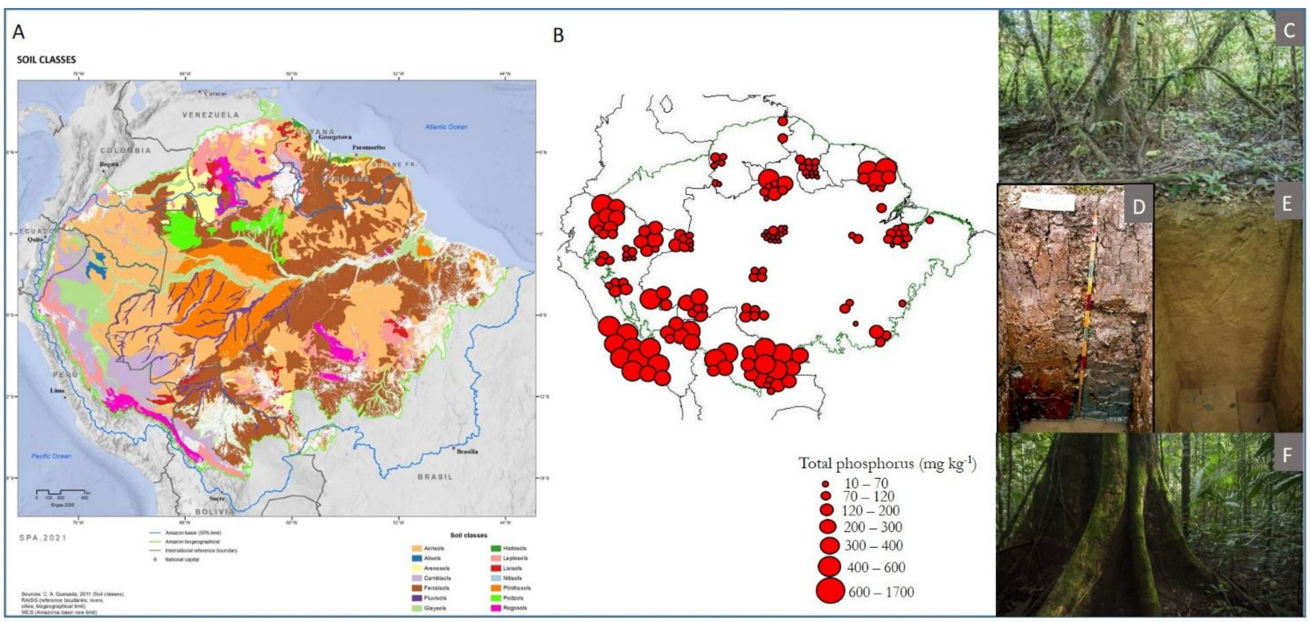


Figure 1.5. A) The complexity of soils across the Amazon; a majority is highly weathered, the rest varying from well-developed to young soil profiles. Parent material (geological substrate) and soils are directly related, but there is no relation with age of rocks. The E-W depression of the lower Amazon 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 the Amazon 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 Western Amazon; **E-F)** Ferralsols, weathered soil and biomass-rich forest in Eastern Amazon (photo credits: B. Quesada, João Rosa).

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 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 have only become significant from 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 can explain basin-wide variations in soil development and fertility, variations in parent material and geomorphology are the main factors influencing the variation of soil types locally. 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 resulted 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 the parent rock and regolith, and by nutrient enrichment from allochthonous sedimentary deposition and autochthonous organic decomposition. Chemical weathering processes (**carbonation, dissolution, hydrolysis, oxidation-reduction**) are accelerated in 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 mature forests but limitation by nitrogen occurs in forests that have been disturbed (e.g. logging, fires, large scale mortality events) and in 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, a high water storage capacity (Figure 1.5. E-F). This trade-off between physical quality and nutrient availability during soil development adds 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 for root growth in the subsoil, 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 thus 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) who 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 have reported that species richness was generally negatively correlated with soil nutrient status while others have reported 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 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, the topography and 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), the soils and rivers do not dry up quickly and the 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 5.1 illustrates the factors described above, which shape the hydrological plumbing of the system (cartoon in center).

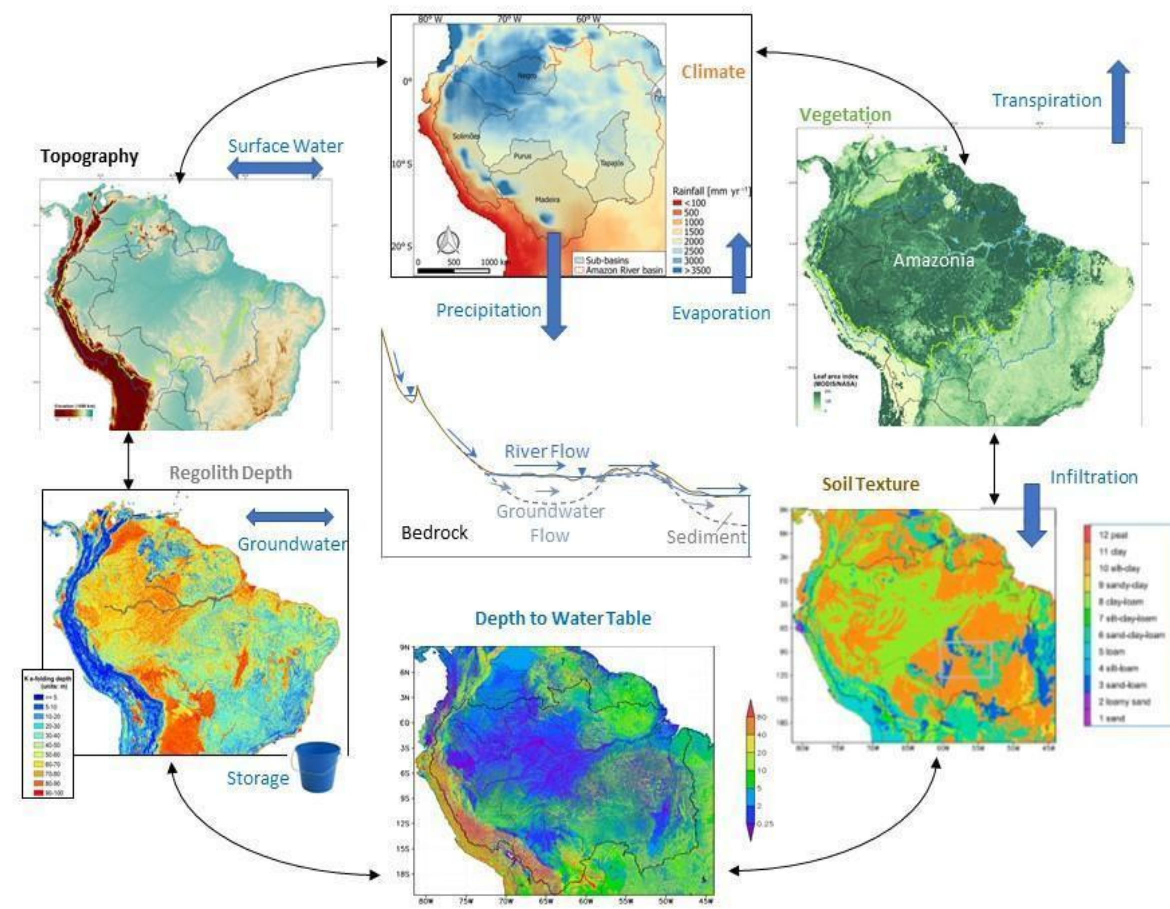


Figure 1.6. Drivers of modern-day Amazonian hydrology. Blue arrows indicate hydrologic effects. Climate (**top**) determines the precipitation supply and evaporative demand (**vertical fluxes**). Plant transpiration returns a large portion of the precipitation back into the atmosphere through transpiration (**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). [source: climate map from Maeda *et al.* (2017); vegetation index map from NASA (https://earthobservatory.nasa.gov/global-maps); topography map from SRTM/NASA (https://www2.jpl.nasa.gov/srtm/); regolith depth map from Fan *et al.* (2013); soil texture map (Miguez-Macho and Fan 2012b); depth to water table map (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 80m (see color bar in Figure 1.6) reflects both the climate (vertical fluxes) and the terrain (lateral fluxes above- and belowground). Shallow groundwater sustains streamflow and soil moisture in drought periods. Upland ecosystems over a deep WTD are solely rainfed and vulnerable to meteorological droughts, whereas lowland ecosystems on shallow WTD, 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 because surface slope directly 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 the 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 the 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 the 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). They give us glimpses of the large spatial variability and seasonal contrasts in the hydrologic conditions across the Amazon.

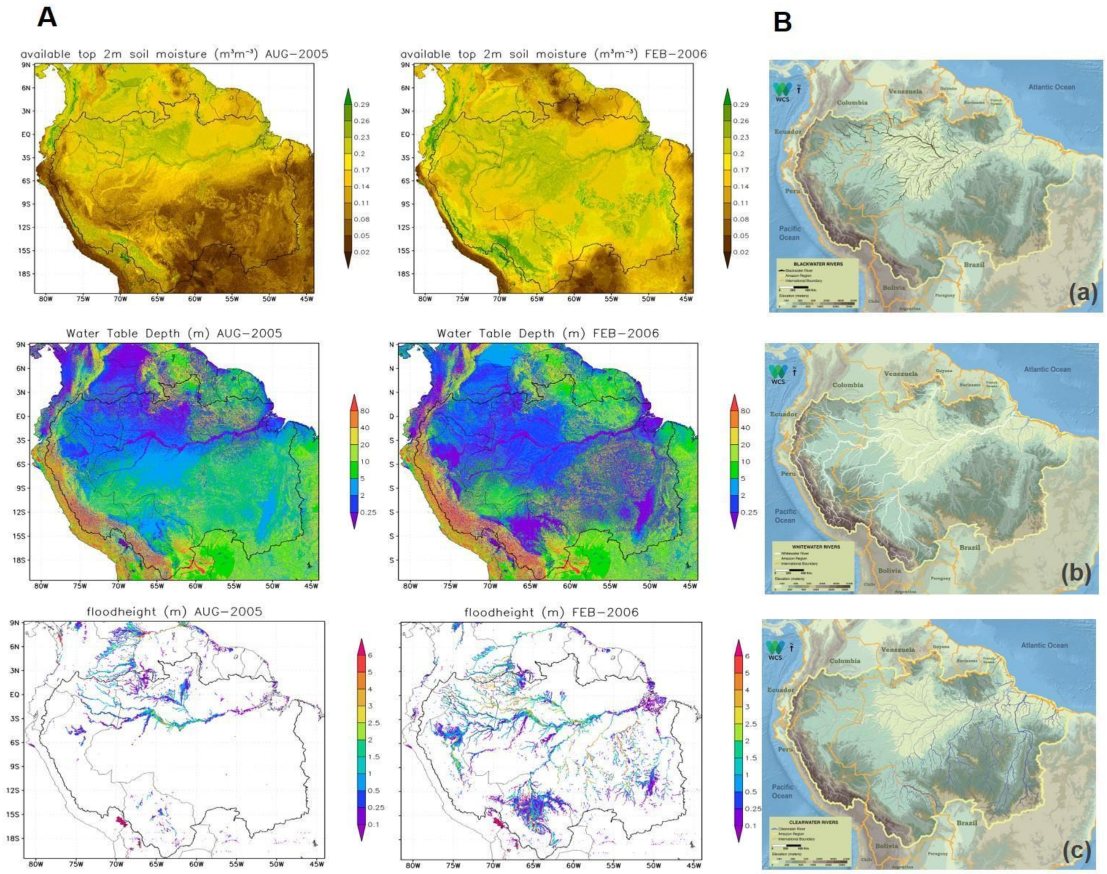


Figure 1.7. (A) Model simulated spatial distribution and seasonal contrast in top-2m soil moisture available to vegetation (**top panels**); water table depth (**middle panels**), and flood water height and floodplain connectivity (**bottom panels**) (Miguez-Macho and Fan 2012a) **(B)** the Amazon River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

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) the blackwater rivers originating from lowland forests with sandy soils that are nutrient poor and highly acidic (pH = 3.5 - 6.0), (b) the whitewater rivers sourced in the geologically young Andean cordilleras, which are sediment- and nutrient-rich, with 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 biota of aquatic plant and animal species (Stefanelli-Silva *et al.* 2019; Albert *et al.* 2020).

Some main hydrologic landscapes of the Amazon are periodically flooded wetlands such as **igapó** (black and clear water) and **várzea** (white water), which contrast with the **terra firme** that is never flooded (Figure 1.7.B). It is likely that this diversity of hydrologic landscapes had 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

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 >80m 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 the 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 1.8 gives four examples. In (a), summarizing decades of research in the white-sand ecosystems in Rio

Negro drainage, Terborgh (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 tolerating prolonged flooding) on the floodplains of 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.

Figure 1.8. (Requested permission to reproduce the figure under evaluation) Examples of hydrological influence on species distribution at landscape scales in the Amazon. Source: (a) Terborgh (1992); (b) Wittmann *et al.* (2010); (c) Schietti et al. (2014); (d) Rossatto *et al.* (2012).

6. MINERAL RICHNESS 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 the last decades, the region has been the locus of intense mining activities (exploitation) (Monteiro 2005; see chapters 9 and 11), including the districts of Carajás for Fe, Cu, Au, Mn and Ni; Pitinga for Sn, Nb and REE; Serra do Navio for Mn and Trombetas-Juruti for Al (See Table in Figure 1.9.). Exploitation of the Amazon had long been dominated by **garimpos (**i.e. small-scale largely unregulated mining operations. Starting in the 1990's large mining companies began employing modern technologies, such as those of the Carajás Province (Fe, Cu and Mn) and Juruti-Trombetas (Al) with large-scale mining operations (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 Venturari-Tapajós and Rio Negro-Juruena provinces (Juliani *et al.* 2016) The new 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 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.

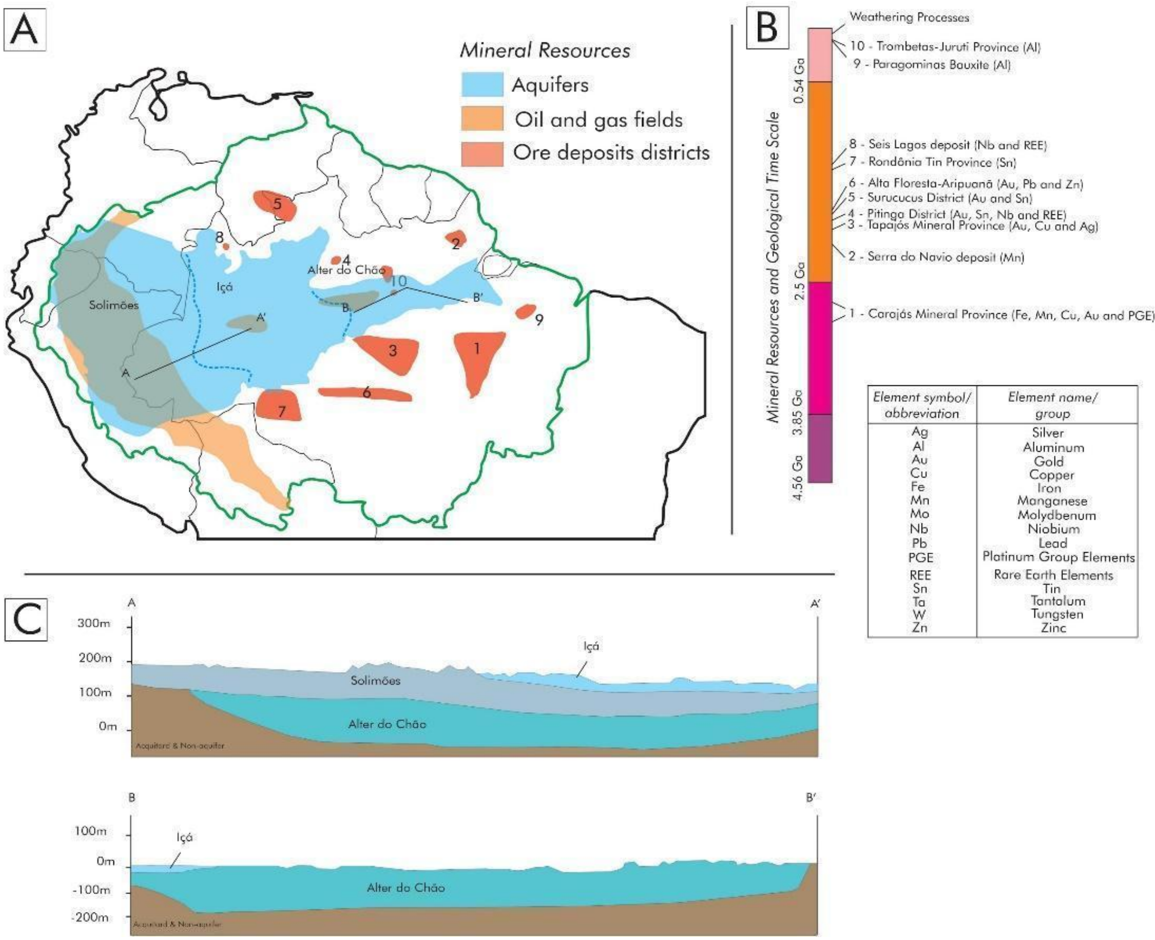


Figure 1.9. (A) Simplified tectonic-chronological map of northern South America with the distribution of the main ore deposits districts and oil and gas fields (Modified from Marini et al., 2016, and Klein et al. 2018). Also shown (A) are **major aquifer systems** with cross sections shown in (B) (modified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

The Amazon has been studied for hydrocarbon resources since the 1940's. Four countries have oil and gas reserves in their Amazonian territory: Colombia, Ecuador, Peru, and Brazil. So far, the largest proven reserves are in Colombia and in the western part of the Brazilian Amazon. 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 the 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 the Precambrian terranes, whereas hydrocarbon and aquifer resources are concentrated in the Phanerozoic sedimentary 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. At 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, one of the best-endowed mineral provinces in the world with a wide variety of ore deposits is found (Monteiro *et al.* 2014). The giant iron deposits associated with the banded iron formations of Carajás are globally recognized as the largest mining operations in the world. Manganese deposits, such as at the Azul Mine, also occur at Carajás. Additionally, in recent years Carajás also became a relevant copper (with associated gold) producer in Brazil (Juliani *et al.* 2016). Widespread **mafic- ultramafic rocks** host remarkable Ni and PGE (**Platinum Group Elements**, e.g. Pt and

Pd) ore 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 deposits (Klein *et al.* 2018).

Within the Paleoproterozoic terranes (2.1 – 1.6 Ga), it is common to find a wide variety of granite-related ore deposits associated with **paleo-subduction zones**. The Tapajós Mineral Province and the Alta Floresta Gold Province are the current frontiers of mineral exploration in Brazil for gold and base metals (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 Rare Earth Elements (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, southwestern portion of the Amazon Craton, remarkable Sn deposits were recognized and largely 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), and forms 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 at 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 Amazon, and to a lesser extent in the Central Amazon (Figure 1.9.). In Subandean sedimentary basins the search for oil and gas started during the 1940's, however, the first oil reserves were not discovered until the 1980's in the Llanos 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 1950's 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, and in 1986 a commercial reserve of Natural Gas and Oil was found in Solimões sedimentary basin, deep in the hinterland of the Western Amazon. From these remote areas pipelines laid through the forest have drained oil and gas.

6.3. Aquifers

Major aquifer systems in the Brazilian Amazon are shown in Figure 1.9. The largest aquifer systems are found in the sedimentary basins along the main stem of the Amazon River, comprising the Amazonas- to the east, and the Solimões sedimentary basin to the west. Here thick sequences of sand/clay deposits formed during the Mesozoic and Cenozoic allow for the accumulation of large and 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: the Alter do Chão (Amazonas sedimentary basin) to the east where it is exposed, and Tikuna aquifer (Solimões sedimentary basin) to the west, where it is buried. In the Solimões sedimentary basin in the Western Amazon, one can find three aquifers stacked vertically: the Iça, Solimões, and Tikuna (or Alter do Chão) aquifers. Together, these large sedimentary aquifers make up the Amazon Aquifer System, one the largest of such 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 by 2 - 4 degrees °C by 2100 (IPCC 2018). Anthropogenic global warming is already having dramatic environmental consequences for the Amazon, with the greatest future impacts resulting from sea level rise and pronounced shifts in rainfall patterns and intensities. Currently, the Earth's atmosphere has accumulated to an average of 416 ppm CO_2, a concentration 150% above the maximum amount measured during the Pleistocene (Ice Age - 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) 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 analogues for future scenarios of global warming, 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 ºC and 27 ºC. When assuming a pre-industrial temperature of c. 14 ºC, this makes the PETM and the EECO respectively c. 17.6 and 13 ºC 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 sq km of lowland Amazon rainforest to nearshore 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 an estimated 18.6 ºC high, which is c. 3 ºC 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.). Thus, the geological past can provide modern scientists with insights 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 rainfall, 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., Tapajos, Xingu, Tocantins) (Flores *et al.* 2019; Brando *et al.* 2020b, a). Regime shifts in landscape vegetation cover are already being observed in other parts of the world following a series of devastating fire seasons in Australia (Filkov et al. 2020), California (Wahl *et al.* 2019), and the Mediterranean (Camarero *et al.* 2019), among many others.

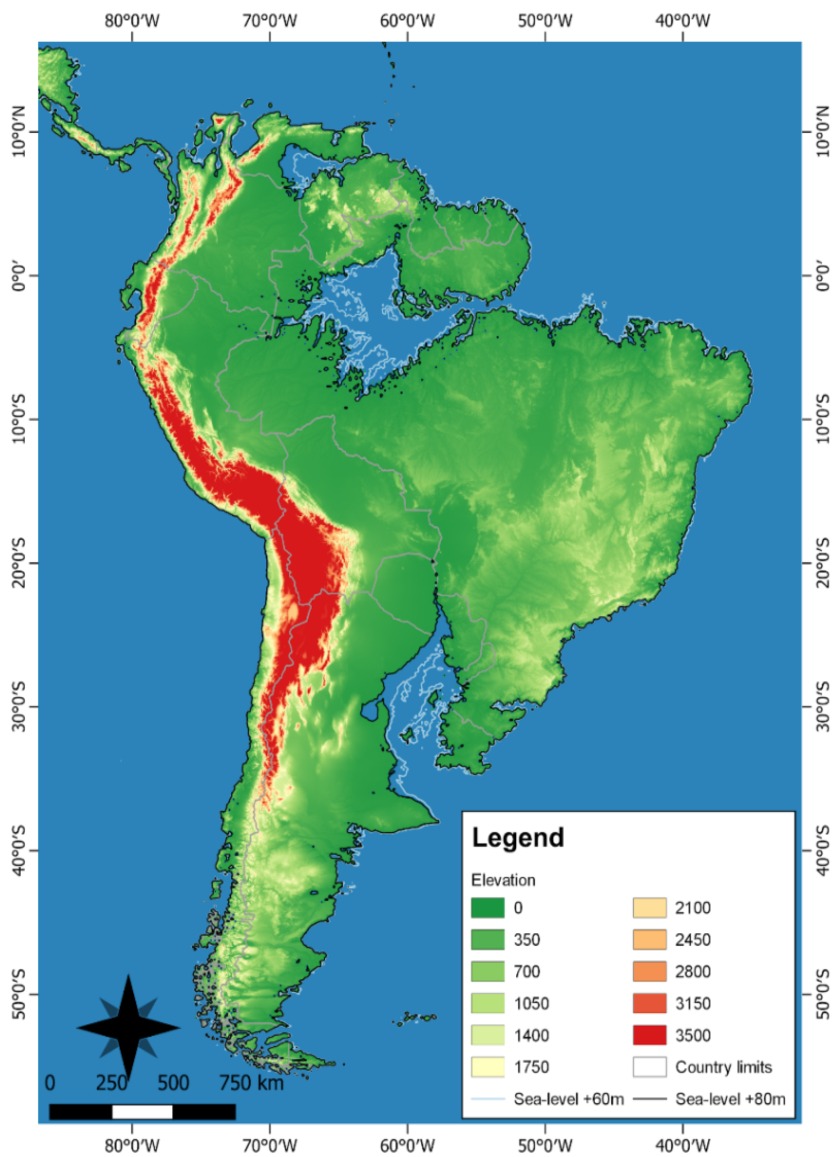


Figure 1.10. Projected coastline of South America after Earth's ice caps have melted (c. 2400 to 2700 CE) with shorelines anticipated at 60 and 80 m (216 and 262 ft) elevation. Image courtesy of Dr. João Marcelo Abreu, Universidade Federal do Maranhão, Brazil.

Facing so many environmental crises all at one, the Amazon is perched at 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

(Xu *et al.* 2020) Munroe et al. 2013. Future Amazonian landscapes may look very different from the vast tropical rainforests that have covered most of the region for the past c. 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 just 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, human societies, and global 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 coming perilous decades and centuries. 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 geodiversity in the Amazon. With the aim to unravel links between geological history, climate, geomorphology, soils, hydrology, and biodiversity, we found deep connections between these seemingly independent components of the region.

The most striking point that we convey through this multidisciplinary study is that Amazon history unfolded over the course of 3 billion years. During this time the Amazon 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 eastern Amazon and mountain building in 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 the soil types, which in turn create gradients in soil nutrients and, therefore, ecosystems. The overall distribution of rain in the Amazon is directly shaped by the heights of the Andes which, along with soil types, interconnect to affect hydrological conditions in the lowlands. Climate, soils, hydrology, mineral 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 in the offshore deposits. These records provide an incomplete, albeit consistent picture of how 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 deep time geological data help constrain 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. The unfortunate scarcity is matched with abundant need for more data. High-resolution records are crucial to constraining the Amazon's environmental response to extreme climatic fluctuations.

Only by understanding intricate connections like the ones summarized here we can provide a basis for future management plans of the Amazon. However, as demonstrated in this Chapter, constraining the intricate connections between the geological tapestry and the surface and biotic processes is not a trivial task. Historical archives of a dynamic past also constitute our guideline 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 IPCC become reality. Nevertheless, for current rates of soil and forest degradation there are no analogues and could trigger uncontrolled erosion of the landscape that is not easily rebuild.

The best strategy to reducing the impacts on the natural environment caused by human activities is undoubtedly based on scientific information. Our recommendations are, therefore, to cast a wide scientific net to produce a deeper understanding of the Amazon system (see below).

9. RECOMMENDATIONS

The global community must work closely and swiftly with national governments whose sovereignty includes Amazonian territory, 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 institutions that enable the study of Amazonian geodiversity at multiple spatial and temporal scales across social boundaries, and train 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., geosciences, climate sciences, biosciences), 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 challenges from human-built infrastructure and climate change.

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CORE GLOSSARY

Abiotic Landscape: topography + drainage network + rocks + soils

Active margin: boundary between two converging tectonic plates.

Alluvial fan: An alluvial fan is a sediment deposit formed by deposition of stream flows out uplands stemming from a single source point.

Alluvial megafans: a large cone or fan-shaped deposit built up by complex deposition patterns of stream flows originating from a single source point known as an apex. Megafans differ from Alluvial fans in their sheer size. Due to their larger size, they may be formed by different geomorphic processes. A megafan has an areal extent greater than 10,000 sq km.

Aquifers: a body of permeable rock which can contain or transmit groundwater.

Autogenic: Internally driven, spontaneous. Controlled by internal mechanisms, independent of external forcings.

Banded iron formation: chemical-sedimentary rocks composed primarily by iron oxides (magnetite and hematite)

Base metals: Cu, Pb, Zn, Sn and Ni

Baseflow: the portion of the streamflow that is sustained between precipitation events, fed to streams by delayed pathways. Baseflow (also called drought flow, groundwater recession flow, low flow, low-water flow, low-water discharge and sustained or fair-weather runoff) is the portion of streamflow delayed shallow subsurface flow". It should not be confused with groundwater flow.

Baselevel: limit below which rivers cannot erode.

Baselevel fall: a drop in the original base level, increasing the steepness in the lower reach. Also the lower limit for an erosion process.

Basement: undifferentiated complex of rocks that form the Earth crust below the sedimentary cover.

Biotic Landscape: vegetation + human landuse

Carbonation: reaction between water and carbon dioxide to create carbonic acid, which dissolves softer soil particles and lowers the pH of the water table.

Carbonatite intrusion: magmatic rock composed by more than 50% of carbonates with associated phosphates and oxides

Craton: A craton is an old and stable part of the continental lithosphere, which consists of the Earth's two topmost layers, the crust and the uppermost mantle. Regions where cratonic rocks outcrop are called **Shields.**

Dendritic fluvial system: Branching river network pattern, similar to trees.

Dissolution: removal of salt ions by water.

Greenstone belt: metavolcano-sedimentary rocks metamorphosed under greenschist facies

Equilibrium landscapes: unchanging landscape altitudes over time due to the balance between uplift and erosion. The balance between uplift and erosion is what dictates whether a landscape is in steady state. If this is the case, it is said static, unchanging in time. Equilibrium landscapes have generally uniform distributions of relief.

Foreland basin: a structural basin that develops adjacent and parallel to a mountain belt.

Geodiversity: The natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes

Geomorphic domains: areas containing landscape morphology specific to that region.

Geological provinces: Major geological areas with hundreds of kilometers that share a set of geological attributes, which can be types of rocks, ages of formation and/or geotectonic setting.

Greenstone belts: Zones of variably metamorphosed mafic to ultramafic volcanic sequences with associated sedimentary rocks that occur within Archaean and Proterozoic cratons between granite and gneiss bodies.

Hydrolysis: reaction between soil minerals and water, converting feldspar crystals into clays.

Igapó: black water flooded regions

Intracratonic basin: a sedimentary basin developed on top of a craton.

Lateritic cover: Al- and Fe-rich soils formed as a result of intense weathering in tropical regions

Long-wavelength: having spatial distribution over hundreds of kilometers

Mafic-ultramafic rocks: magmatic rocks composed by mafic minerals (amphibole, pyroxene and olivine) with low silica content (<52% SiO2)

Mantle flow: slow motion of mantellic, viscous rocks

Mantle parcels: moving regions of the Earth's mantle with different temperature and viscosities

Meiofauna: minute interstitial animals living in soil and aquatic sediments. Size between 40-500-µm

Metallogenesis: geology area that study the geological processes involved in the genesis of the ore deposits

Oil and Gas: naturally-occurring compounds and form the basis of crude oil, natural gas, coal, and other important energy sources

Oxidation-reduction: reaction between water and soil particles and oxygen to produce rust.

Parent material: underlying rock over which the soil profile developed

Paleo-subduction zones: subduction zones active in ancient geological time

Passive margin: continental boundary formed by rupture due to a divergent movement of plate tectonics

Plutono-volcanic rocks: intercalation of plutonic (or intrusive) and volcanic rocks

Physiographic: The subfield of geography that studies physical patterns and processes of the Earth. It aims to understand the forces that produce and change rocks, oceans, weather, and global flora and fauna patterns.

Precious metals: Au, Ag and Pt

Residual concentration ore deposits: ore deposits formed by intense weathering

Regolith: the layer of unconsolidated solid material covering the bedrock of a planet

River avulsion: the rapid and spontaneous abandonment of a fluvial channel and occupation of a new channel in a nearby area.

River capture: River capture occurs when a portion of one river drainage network is diverted into that of an adjacent drainage, thereby moving the watershed boundary between the two basins.

River incision - excavation of the rock substrate by rivers

Subandes: lowland areas in the vicinities of the Andes mountains

Shield: large regions where cratonic rocks are exposed on the surface.

Stream erosion power: the rate of erosion of a river into its bed, which is a function of river channel geometry (width-discharge scaling) and basin hydrology (discharge-area scaling).

Tectonic plate convergence: the motion of two tectonic plates towards each other, causing tectonic plate subduction, collision, and mountain building.

Tectonic regime: refers to the tectonic activity of a region, i.e. active or inactive, and style of deformation (compressive, distensive, strike-slip/transcurrent).

Tectonophysics: studies the physics of the Earth, in particular the forces responsible for movements in, and deformation of, the Earth crust.

Terra firme: in the tropical lowlands, the highlying ground that is not subject to fluvial flooding.

Weathering: physical and chemical processes that alters rock mineralogy at the earth surface

Várzea: white water flooded regions

Volcanic calderas: large depression in the central part of volcanoes caused by eruptions and collapse