Chapter 1 In Brief

Geology and geodiversity of the Amazon: Three billion years of history

Vista aérea da Terra Indígena Yanomami (Foto: Bruno Kelly / Amazônia Real)

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Geology and geodiversity of the Amazon: Three billion years of history

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Key Messages & Recommendations

1) The Amazon is a complex region composed of multiple lithologically, topographically, and chemically distinct geological provinces, each with diverse landforms, riverscapes, and soilscapes. These subdivisions are the result of a unique geologic history involving interactions between plate tectonics, climate, dynamic topography, and sea level change. Together, these factors created an exceptionally high geodiversity, from rock substrates to the hydrological, edaphic, and biophysical landscapes.

2) It took hundreds of millions of years for the Amazon to develop the rich tapestry of landforms, soils, and ecosystems we see today, but humans degrade these unique ecosystems at a much faster rate. Decisions should be made to avoid further degradation and consider the time necessary for the Amazon to recover, if it recovers at all.

Abstract This chapter explores how geodiversity evolved over three billion years of history. It shows that periods of continental breakup followed by mountain building ultimately led to the fundamental physiographic subdivisions of the Amazon, and a wealth of landscapes, soils, ore deposits, oil and gas reserves, and freshwater aquifers. Data on the Amazon's geodiversity support a central theme of the environmental sciences, that the formation of most natural resources (like rare-earth ores, hydrocarbons, freshwater aquifers, and fertile soils) requires natural processes to operate undisturbed over immense periods of geological time and across broad spatial domains.

The modern Amazon: Geodiversity and soil diversity 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. The modern Amazonian geomorphology is formed by the Andes mountains, which have local amplitudes of elevation (i.e., relief) upwards of 3 km within a 2.5 km window, and the lowland landscapes of the Western and Eastern Amazon exhibiting low relief (< 200 m), mainly because of low uplift rates. Across the majority of its area, meandering rivers flow over easily erodible sedimentary rocks from the sedimentary basins that form the substrate for most of the Amazon's lowlands, dynamically migrating back and forth across floodplains. Extending over the northern and southern edges of the Amazon's drainage basin are extensive outcrops of cratonic rocks, which form wide plateaus averaging 500–1000 m in elevation but reaching 2,500 m in the northernmost parts of the Amazon, such as in southern Venezuela and at the border of Brazil and Guyana. On millennial timescales, the shield areas erode at 10–40 m/Ma and contribute 9–20 Mt/yr of sediments to shield-draining rivers, whereas rivers draining the Andes erode at 100-1,000 m/Ma and contribute 300–600 Mt/yr to the sediment loads of the Amazon River[1].

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Geological and biological processes together created an exceptionally high geodiversity and diverse hydrological landscape. As a result, the Amazon holds a complex mosaic of soil types and conditions, each with distinct physical, chemical, and biological properties which are related to the above-mentioned rates of geomorphic change. About 60% of soils in the Amazon drainage basin are highly weathered, nutrient-poor ferrasols and acrisols, concentrated mainly in the slowly eroding Eastern Amazon[2]. Soils in the Western Amazon are generally more nutrient-rich, as they formed in sediments that recently eroded from the Andes[2-4]. Differences in these sediments affects the chemical composition of the waters, distinguishing three river types, namely blackwater, whitewater, and clear water rivers. Added to this geomorphic and geochemical complexity is the periodicity of flooding, such as *igapó* (black and clear water) and *várzea* (white water), in contrast with *terra firme* that is never flooded.

The physical properties of soils, such as shallow soil depth, poor drainage, and physical impediments for root growth in the subsoil can be an important limitation to forest growth, directly or indirectly influencing tree mortality and turnover rates[4]. The depth of the water table is a good indicator of hydrologic conditions across the Amazon and soil water availability to plants. Shallow groundwater sustains streamflow and soil moisture in drought periods. Upland ecosystems over deep water tables are solely rainfed and vulnerable to meteorological droughts, whereas lowland ecosystems on shallow water tables enjoy more stable water supplies sustained by upland rain through downhill flow. Shallow water tables also cause waterlogging and anoxic soil conditions, excluding intolerant upland vegetation and selecting well-adapted wetland species.

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[5]; for example, iron, copper, and manganese are found in Carajás Province and aluminum in Juruti-Trombetas (Brazil)[5,6]. Oil and gas reserves are found in the Amazonian territory of four countries: Colombia, Ecuador, Peru, and Brazil. Related to its significant porosity and permeability, the Amazon contains one of the largest aquifers in the world, the Amazon Aquifer System (AAS), which extends along the main stem of the Amazon River, through the Amazon sedimentary basin to the east and the Solimões sedimentary basin to the west[7].

Assembling the continent The oldest rock formations in the Amazon are dated to 3–2.5 billion years ago (Ga) and correspond to the Carajás Province (Brazil)[8] (Figure 1.1A). These formations can be found at the surface mostly in the Eastern Amazon, surrounded by younger crustal terranes dating to 2.1–1.0 Ga. Together, the amalgamation of these Paleo- to Mesoproterozoic terranes and the older Archean core of the Carajás Province make up the so-called Amazon Craton[i]. This craton covers almost half the territory of Brazil and extends into several other South American countries, over an area larger than the modern Amazon drainage basin[9]. The consolidation of the Amazon Craton is further linked with supercontinent assembly, particularly Columbia at c. 1.9 Ga and Rodinia at c. 1.2–1.0 Ga[10,11].

Building the lowland rock substrate: Sedimentary basins After the breakup of supercontinent Rodinia the Amazon Craton was embedded within the Gondwana supercontinent. At the beginning of the Paleozoic Era (c. 541 Ma), an east-west rift developed across the middle of the Amazon Craton, almost splitting it into northern and southern portions[12]. The rifting process did not persist but resulted in the formation of an intracontinental depression that subdivided the craton into two 'shields', the Guiana Shield in the north and the Brazilian Shield in the south, which extend over about 40% of the Amazon (Figure 1.1B). The intracontinental depression also formed the

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[i] 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.
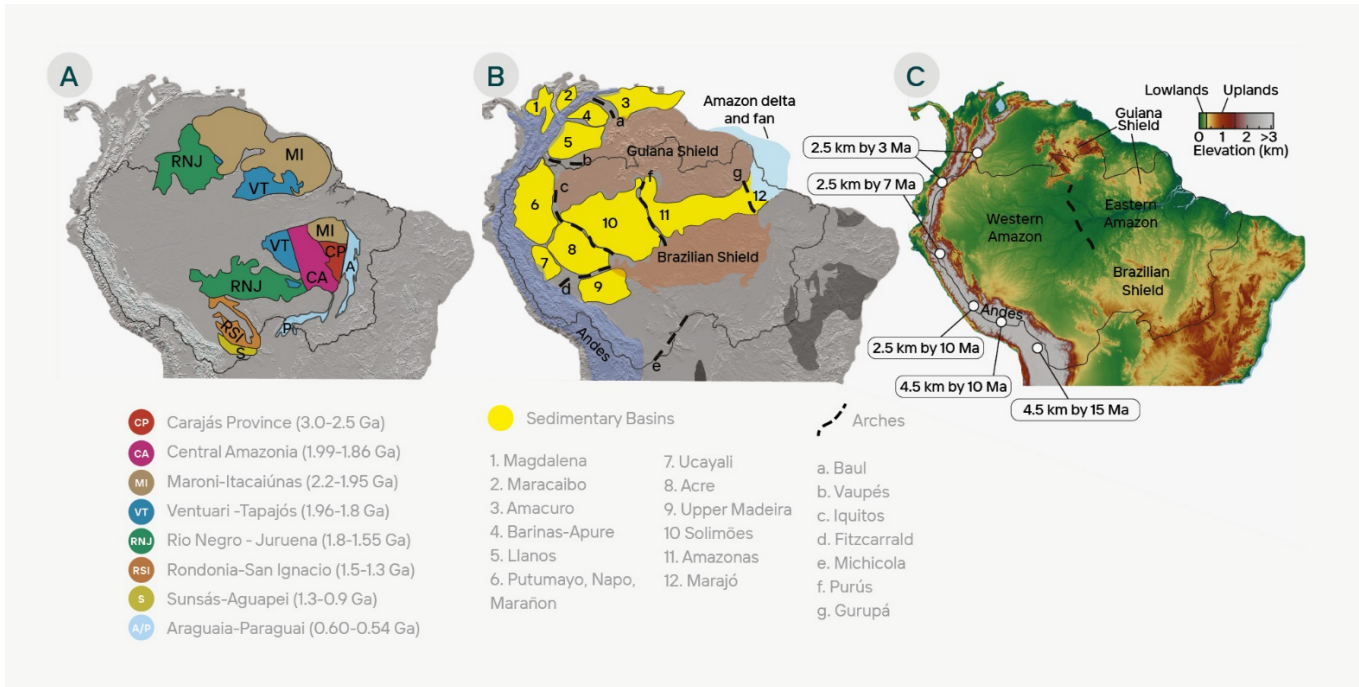
Figure 1.1 (A). Geochronological map of South America with the main provinces of the Amazon Craton (modified from Macambira et al. 2020[8]). (B) Foreland and intracratonic sedimentary basins of the Amazon (after Albert et al. 2018[24]). (C) Contemporary elevation map. The Andes uplift ages are indicated based on published literature[14–16].

foundation of the Solimões and Amazonas sedimentary basins, and the channel of the modern Amazon River.

Alongside the Andes and these sedimentary basins, the shields represent the most important geological feature of the continent on which numerous geologic, surface, biologic, and climatic processes acted in parallel to produce the Amazon's magnificent environmental diversity.

Pangea breakup and the birth of the Andes The Gondwana supercontinent formed the southern half of the Pangea supercontinent c. 250 Ma. Since then, rifting of Pangea and the tectonic separation of South America and Africa led to the opening of the south and equatorial Atlantic Ocean (c. 100 Ma). 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 its current geographic configuration. The breakup

of Pangea formed multiple smaller continents and created new continental margins. Consequently, there was a continent-wide drainage readjustment derived from this paleogeographic rearrangement.

The westward drift of South America and formation of the Andes As South America drifted westward during the opening of the Atlantic Ocean, the western margin of the South American plate experienced tectonic plate convergence, but it wasn't until the last 20±10 Ma that significant topographic expressions along its west coast began forming[13,14]. However, estimates of this timeline are still debated. By 10–15 Ma[15] the Andes rose as high as 4 km close to the Pacific Ocean in southern Peru. As uplift continued, the Andes widened, and by 7 Ma reached 4–5 km elevation about 450 km away from the Pacific coast in southern Peru and northern Bolivia[14]. The southern Peruvian Andes continued to widen, while northern Peru, Ecuador, and Colombia had much less expressive topography (Figure 1.1C). In these northern Andean ranges, evidence diverges

on paleoelevations during the Miocene, but most agree that it was not until 4–5 Ma that a 3 km high Andes flanked the Amazon's northwest[16]. When the Andes — north of the Altiplano plateau — reached 2.5 km or more, atmospheric circulation was incrementally blocked, driving high orographic rainfall in the Andean foothills of southern Peru and northern Bolivia. Here, the Andean foothills got wetter, and parts of the Eastern Amazon became drier[17]. In the last 20 Ma, the rise of the Andes and other processes (see next section) deformed the crust underneath the Western Amazon, creating a large bowl-shaped terrain over which widespread wetlands could form with occasional marine incursions[18–20] and large, Andes-derived sediment accumulation in alluvial megafans, hinterland, and foreland basins[21,22]. These processes also created the necessary conditions (i.e., thick, porous substrate) to form the major groundwater aquifers in the region, such as the Içá and Solimões aquifer systems, and controlled changes in the river network by pushing rivers further east. Together with the uplift of a lowland swell (i.e., Vaupés Arch), this was sufficient to interrupt the Orinoco River, formerly connected to the Western Amazon lowland as far south as southern Peru, and a continent-wide river network began forming[23].

Transition from fluvial landscape to large wetland Formation of the Andes gradually led to the drying of the marine seaway along the western margin of the Amazon, giving way to delta and lake systems[18,19] (c. 66–23 Ma; Fig. 1.2C.a-b). From c. 23–10 Ma much of the Western Amazon was covered by a mega-wetland known as the Pebas system[18,19,24,25] (Figure 1.2C), that extended over c. 1 million km² at its maximum and reached about 1,500 km east-west from the Andean foothills to the easternmost limit of the Western Amazon. These wetlands also extended 1,200 km north-south along the Subandean foreland, from the modern Ucayali River in Peru to the modern Caquetá River in southern Colombia (Figure 1.2Dc).

Andean uplift, interactions between the continental plates and the mantle caused a pronounced subsidence along the Subandes and in the Western Amazon and, along with changes in the eustatic sea level, facilitated the marine influence into the region[18,19,26–28]. The extent of marine influence is debated[29,30], but evidence is mounting that the Pebas wetland at times formed an estuarine embayment with tidal influence in the Llanos sedimentary basin[27,28,31]. The sedimentary units that represent the Pebas wetland are collectively called the Pebas, Curaray or Solimões Formation, in Peru, Ecuador and Brazil respectively. In Peru, their nutrient-rich surfaces, and associated soils, harbor a diverse, endemic-rich biota[19,32,33].

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 million years because subsidence and sediment input kept pace with one another[18,19,24]. Most remarkable is the rich endemic fauna of mollusks and reptiles that inhabited its shores, but which went extinct with the disappearance of this environment[25,34]. The system was at its maximum extent during the Middle Miocene Climatic Optimum, from c. 17–15 Ma, coinciding with global sea level highstand[35–37] (Figure 1.2).

Birth of the Amazon River The incipient Amazon River started flowing eastward soon after the initiation of the equatorial Atlantic Ocean (c. 100 Ma). According to Figueiredo et al.[38], during the Late Cretaceous (c. 100–66 Ma) drainage in the Amazon was split into two basins, one inherited from Pangea that continued flowing towards the west into the Pacific Ocean, and a newly formed basin flowing eastwards, draining the Eastern Amazon and delivering cratonic sediments to the newly-opened Equatorial Atlantic Ocean. This hypothesis is supported by the absence of Andean river sediments in the Atlantic Ocean until c. 10 Ma[38,39]. 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 drainage divide and connect with the Western Amazon. However, this connection could
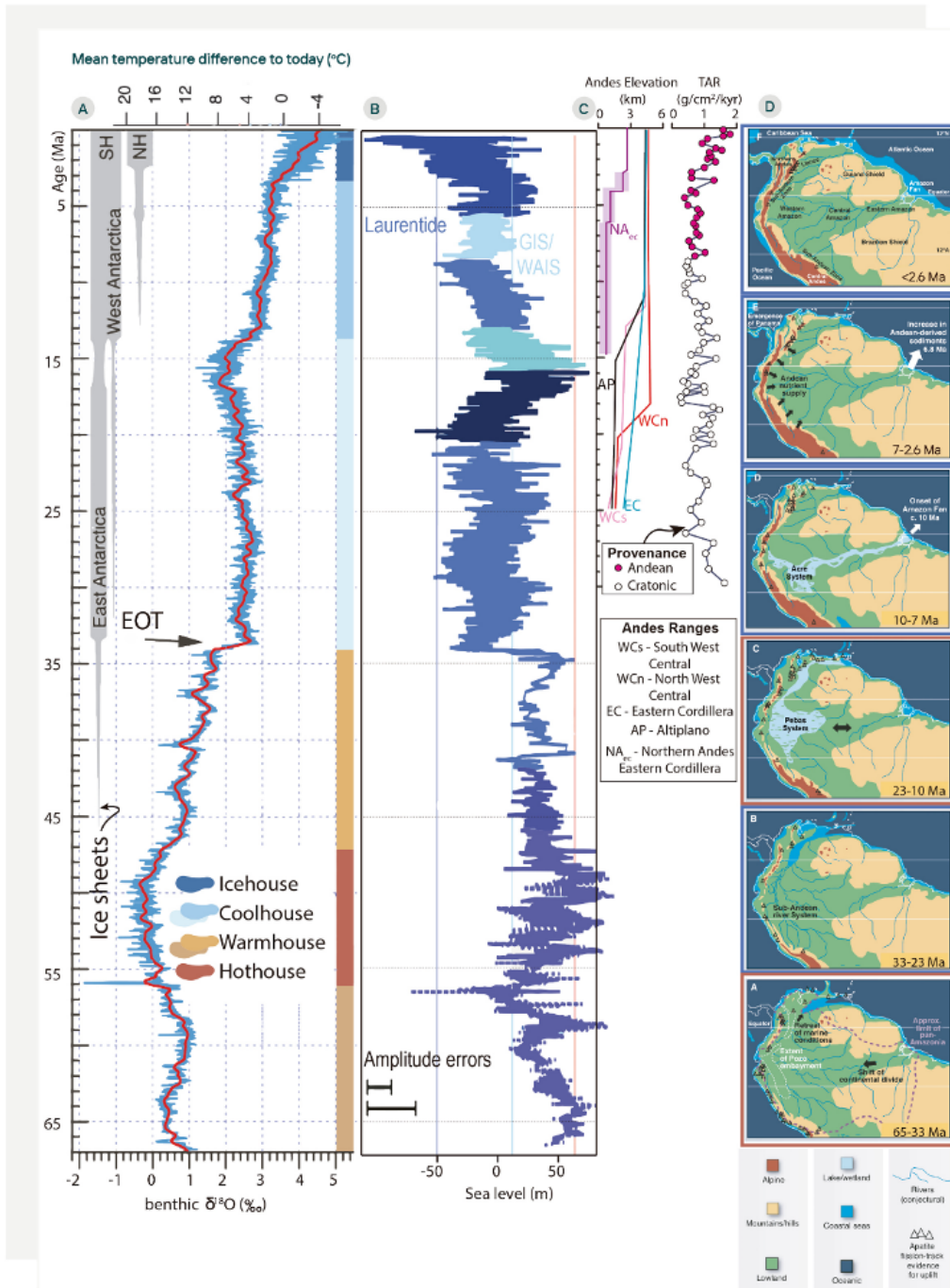
Figure 1.2 A) Global Cenozoic temperature curve (from Westerhold et al. 2020[35]). B) Global Cenozoic sea level curve (from Miller et al. 2020[34]). C) Transition from Amazon Craton to Andes-dominated landscapes. D) (a) Andes started uplifting. (b) The Andes continued to rise with the main drainage toward the northwest. (c) Mountain building in the Central and Northern Andes (specially from 12 Ma), wetland progradation into the Western Amazon, and marine ingressions and estuarine conditions in the heart of the Amazon; closing of Panama Isthmus. (d) Uplift of the Northern Andes restricted "pan-Amazon" and facilitated allopatric speciation and extirpation. (e) The mega-wetland disappeared and *terra firme* rainforests expanded; start of GABI. (f) Quaternary. Note that South America migrated northward during the course of the Paleogene.

not form until (i) the paleo-Amazon River in the east could erode its westernmost headwaters and (ii) rivers in the west could bypass the Western Amazon. These necessary pieces of the puzzle fell into place when the Andes formed and the Subandean foreland tilted eastwards[19,20,38,40,41].

By c. 10 Ma, the river systems in the Western and Eastern Amazon connected, transitioned into a transcontinental the Amazon river system, and Andean sediments began reaching the Atlantic Ocean[38,39]. This change in paleogeography and the sedimentary regime was caused by increased erosion and sediment output, possibly due to accelerated Andean uplift, and climate change from the late Miocene onwards[42]. Evidence for this can be found both in the Subandean basins[43] and at the mouth of the Amazon River[38,39,44].

Other models propose a Pliocene (c. 4.5 Ma)[29,45] or even Pleistocene[46] (<2.6 Ma) age for the onset of the transcontinental Amazon River. Perhaps these different interpretations arise in part due to alternative definitions of the Amazon River, different dating methods, the longevity of geomorphic features, and the different data types used by different studies (see the review in Albert *et al.* 2018[48]).

Quaternary climate and landscape changes in the Amazon The waxing and waning of glacial-interglacial cycles influenced Amazonian landscapes at all elevations. The onset of global climate cooling from c. 15 Ma onwards (Figure 1.2A), and particularly the climate oscillations from c. 3 Ma related to glacial processes, are presumed to have increased glacial erosion globally[49]. Increased precipitation accelerated erosion and sediment transport during interglacial periods, while extensive moraines paved valleys to elevations as low as 2,500 m elevation[50,51]. High denudation of the Andes during the Quaternary contributed to the formation of megafan alluvial piles in portions of the sub-Andean foreland[21]. In the Western Amazon lowlands, the ages of *terra firme* surfaces along the Amazon River show maximum ages of 250 ka[47], suggesting that the most recent surfaces are relatively young and that they expand and contract in response to Quaternary climate dynamics.

Conclusions Modern Amazonian landscapes from the continental scale down to river margin terraces can only be understood as a cumulative function of tectonic, geomorphological, and climatic processes operating over 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.

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