



Towards interactive global paleogeographic maps, new reconstructions at 60, 40 and 20 Ma

F. Poblete^{a,b,*}, G. Dupont-Nivet^{a,c}, A. Licht^d, D.J.J. van Hinsbergen^e, P. Roperch^a, M. G. Mihalynuk^f, S.T. Johnston^g, F. Guillocheau^a, G. Baby^a, F. Fluteau^h, C. Robin^a, T.J. M. van der Linden^{e,i}, D. Ruiz^c, M.L.J. Baatsen^j

^a Géosciences Rennes, UMR CNRS 6118, Rennes, 35042 Rennes Cedex, France

^b Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Chile

^c Universität Potsdam, Institute of Geoscience, 14476 Potsdam, Germany

^d Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (Cerege), UMR CNRS 7330, 13545 Aix-en-Provence, France

^e Department of Earth Sciences, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands

^f British Columbia Geological Survey, Vancouver, Canada

^g Department of Earth and Atmospheric Sciences, University of Alberta, Canada

^h Université de Paris, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France

ⁱ Thomas van der Linden – LinGeo, Berlin, Germany

^j IMAU, Utrecht University, Princetonplein 5, 3584CC Utrecht, the Netherlands

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ABSTRACT

Paleogeographic maps are essential tools for understanding Earth system dynamics. They provide boundary conditions for climate and geodynamic modelling, for analysing surface processes and biotic interactions. However, the temporal and spatial distribution of key features such as seaways and mountain belts that govern climate changes and biotic interchange differ between various paleogeographies that require regular updates with new data and models. We developed a reproducible and systematic approach to paleogeographic reconstruction and provide a set of worldwide Cenozoic paleogeographic maps at 60, 40 and 20 Ma. We followed a six-stage methodology that integrates an extensive review of geological data into a coherent plate tectonic model using the open source software GPlates. (1) We generated a global plate kinematic model, and reconstructed intensely-deformed plate boundaries using a review of structural, paleomagnetic and other geologic data in six key regions: the Andes, the North American Cordillera, the Scotia Arc, Africa, the Mediterranean region and the Tibetan-Himalayan collision zone. (2) We modified previously published paleobathymetry in several regions where continental and oceanic crust overlap due to differences in the plate models. (3) We then defined paleoshorelines using updated fossil and geologic databases to locate the terrestrial to marine transition. (4) We applied isostatic compensation in polar regions and global eustatic sea level adjustments. (5) Paleoelevations were estimated using a broad range of data including thermochronology and stable isotopes, combined with paleobotanical (mostly pollen and leaf physiognomy), structural and geomorphological data. We address ongoing controversies on the mechanisms and chronology of India-Asia collision by providing alternate reconstructions for each time slice. We finally discuss the implications of our reconstructions on the Cenozoic evolution of continental weatherability and review methodological limitations and potential improvements. Future addition of new data, tools and reconstructions can be accommodated through a dedicated interactive website tool (<https://map.paleoenvironment.eu/>) that enables users to interactively upload and download data and compare with other models, and generate their own plots. Our aim is to regularly update the models presented here with new data as they become available.

* Corresponding author at: Departamento de Geología, Universidad de Chile, Plaza Ercilla 803, Santiago Zip code: 8370450, Región Metropolitana, Chile.
E-mail address: ferpoble@uchile.cl (F. Poblete).

1. Introduction

Paleogeographic reconstructions relay the current understanding of geodynamic and plate tectonic processes that have shaped Earth's surface, influencing global climate and biotic evolution. Plate tectonics control the opening and closure of ocean gateways, modulating the development or decline of ocean currents, influencing water mass and heat transport between the oceans and the heat exchange between the ocean and the atmosphere (e.g. Barker, 2001; Munday et al., 2015; Scher et al., 2015). Collision and rifting generate mountain ranges providing rain-shadows, diverting trade and anti-trade winds, or as elevated temperature source modulating atmospheric circulation cells and monsoons (e.g. Ehlers and Poulsen, 2009; Licht et al., 2017; Si and Ding, 2013; Wheeler et al., 2016). Geodynamic and surface processes also play a fundamental role in the carbon cycle through modulation of CO₂ emissions, through atmospheric CO₂-consuming metamorphic or silicate weathering reactions, or through organic carbon sequestration with delivery of erosional nutrient to marine domains of high primary productivity (e.g. Berner and Kothavala, 2001; Godd ris et al., 2014; Karl and Trenberth, 2003; Larsen et al., 2014; Lasaga et al., 1985; Royer et al., 2004; Stephens et al., 2012; Sternai et al., 2014). In addition, the long-recognized impact of continental break-up, drift and collision on the radiation of species (e.g. Clyde et al., 2003; Dalziel et al., 2013; Wegener, 1929), has, owing to the increasing utilization of phylogenetic approaches, developed more recently into fields of research on understanding of the interplay between biotic evolution, climate and paleogeography (e.g. Lieberman, 2003).

This study focuses on the Cenozoic era for which reconstructing past environmental conditions has become crucial to constrain and calibrate model predictions of future climate and biodiversity changes. Indeed, continuously rising modern CO₂ levels necessitate exploration of deeper time to find analogous conditions and global response to high atmospheric CO₂ concentration scenarios (e.g. Karl and Trenberth, 2003; Lunt et al., 2017; Trenberth et al., 2009). It is critical to test these models by simulating paleoclimates in periods with high CO₂ concentrations (Baatsen et al., 2016; Baatsen et al., 2020) for which paleogeographic maps provide the necessary boundary conditions. The most recent greenhouse period was during Paleocene to Eocene times with 2× to 5× times preindustrial pCO₂ levels (i.e. 560–1400 ppm; Anagnostou et al., 2016; Heurreux and Rickaby, 2015). After reaching maximum temperatures during the Early Eocene Climate Optimum (~53–52 Ma), gradual cooling from greenhouse to icehouse conditions reached a threshold at the Eocene-Oligocene Transition (EOT, ~34 Ma; Zachos et al., 2001). Earth's climate changed abruptly with dramatic impacts around the globe: ice expansion in Antarctica, increasing aridity of continent interiors, drop in sea surface temperatures at high latitudes, and changes in atmospheric and oceanic circulation (Dupont-Nivet et al., 2007; Liu et al., 2009; Zachos and Kump, 2005).

The causes of the EOT and the longer-term fall into the Icehouse remain debated (e.g. Li and Elderfield, 2013). One explanation for the EOT invokes development of the Antarctic Circumpolar Current (ACC) that isolated the Antarctic Continent. The onset of the ACC is linked to the opening of the Drake Passage and the Tasman seaway during the Eocene, development of the Antarctic ice sheet, drop in CO₂ levels, and changes in ocean circulation (Barker, 2001; Barker and Burrell, 1977; Gill and Bryan, 1971; Kennett et al., 1975; Scher et al., 2015). Alternative models suggest that the EOT is related to diminishing global CO₂ atmospheric concentration during the Eocene, reaching threshold conditions for the development of the full Antarctic ice sheet at the EOT (e.g. DeConto and Pollard, 2003). An uncontested cause of dwindling atmospheric CO₂ during the Eocene remains elusive (e.g. Caves et al., 2016). Increase of continental weathering and denudation associated with global and Tibetan-Himalayan mountain uplift has been proposed (e.g. Hay et al., 2002; Herman et al., 2013; Raymo and Ruddiman, 1992; Schildgen et al., 2018; Shields and Mills, 2017), along with increased terrestrial and marine organic carbon burial due to enhanced runoff and

sediment transport into the deep ocean (e.g. France-Lanord and Derry, 1997; Galy et al., 2015; Galy et al., 2007). Other mechanisms include: contribution of arc volcanism to the CO₂ budget (Hoareau et al., 2015; Sternai et al., 2020), weathering of specific volcanic provinces such as ophiolite belts, island arcs (Jagoutz et al., 2016; Macdonald et al., 2019) and large igneous provinces (Kent and Muttoni, 2008; Lefebvre et al., 2013) at low latitudes, or decreasing global oceanic spreading and subduction rates (e.g. Lefebvre et al., 2013; van der Meer et al., 2014). A critical unknown on the long-term CO₂ budget is the respective contribution of weathering of various elevated regions compared to the alteration in lowlands during sediment transport with long residence time (e.g. Lefebvre et al., 2013; Caves-Rugenstein et al., 2019; van der Meer et al., 2014). Orogenesis along the North and South American Cordillera and along the Neo-Tethys subduction zones from the Mediterranean region to SE Asia, has been particularly important in driving Cenozoic climate evolution. To test these mechanisms, reproducible, systematic, and data-informed Cenozoic paleogeographic reconstructions have been essential (Baatsen et al., 2016; Blakey, 2011; Golonka et al., 2006; Herold et al., 2014; Scotese, 2001; Scotese and Golonka, 1997).

Exponential increases in computational power has made atmospheric general circulation models more accessible to the earth science community. Meanwhile, those models have improved, better simulating natural climate complexity, including atmosphere-ocean-sea ice-vegetation coupling, and they can be run at twice the resolution of early model generations. In addition, the variability of data that they can be input has also grown dramatically, including paleogeographic information, making reconstructions fundamentally relevant in the climate model space (Barron and Washington, 1984; DeConto and Pollard, 2003; Frigola et al., 2018; Huber and Sloan, 2001; Otto-Bliesner et al., 2002; Scotese and McKerrow, 1990; Sewall and Sloan, 2006; Sloan and Barron, 1992). Paleogeographic reconstruction involves a comprehensive search for evidence of past elevations, ocean depths, continental locations, ice sheet extents, and vegetation types in a specific time period (Blakey and Ranney, 2017; Scotese and Wright, 2018). These data are integrated to build a singular or suites of global reconstructions that are necessarily limited in the scope of data types and geographic coverage despite huge efforts (e.g. Bice et al., 1998; Fluteau et al., 1999; Hay and Wold, 1998; Markwick and Valdes, 2004; Sewall et al., 2000). It is a time-consuming and technically complex task, requiring both GIS expertise and the collaboration of scientists with specific geological and paleontological knowledge. This knowledge is not easily transferred into paleogeographic maps that need recurrent updates with incorporation of newer data sets. Thus, while climate models rapidly grow more sophisticated, paleogeographic reconstruction updates lag behind.

As part of a large collaborative effort between geologists and climate modellers, we present here a set of worldwide Cenozoic paleo-digital elevation models (paleoDEM) at 60, 40 and 20 Ma, to be used as boundary condition maps for the scientific community. Our paleotopographic reconstruction efforts have focused mainly on the review of geological literature and datasets to describe the evolution of six tectonically active regions during the Cenozoic (Fig. 1): 1) the Andes, 2) the North American Cordillera, 3) the Scotia Arc, 4) the Mediterranean region 5) the Tibetan-Himalayan collision zone, 6) Africa. We specifically account for the paleotopographic evolution of mountain ranges, the evolution of continental margins in response to terrane and micro-continent accretion and land-sea distribution. These three time slices at 60, 40 and 20 Ma aim to cover part of the Cenozoic and include the greenhouse to icehouse transition. They complement well paleogeographic maps published previously (e.g. Herold et al., 2014, at 55 Ma; Baatsen et al., 2016, at 38 Ma; Ruiz et al., 2020) allowing for comparison of different interpretations of paleotopographies, gateways and land sea distributions depending on various tectonic scenarios of major features such the Indo-Asia collision.

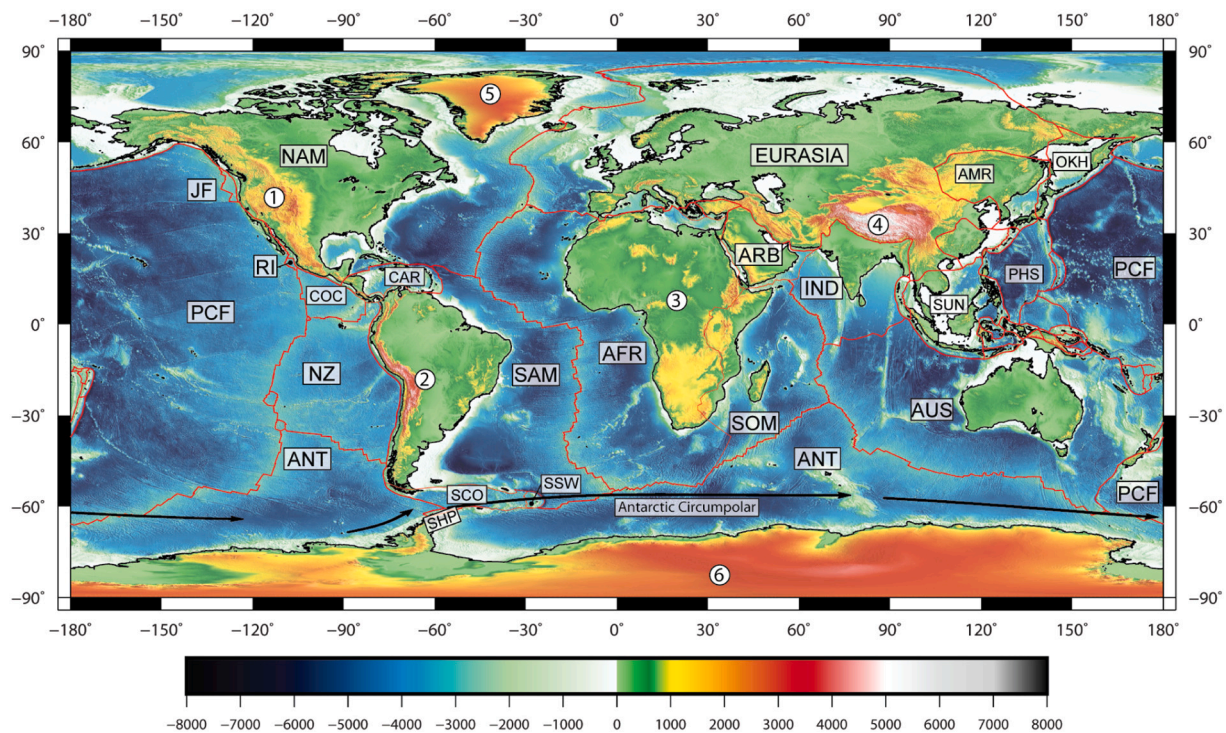


Fig. 1. Physiography of the world. Red lines show the present plate boundaries. Main plates are: AFR, African Plate; ANT, Antarctic Plate; ARB, Arabian Plate; AUS, Australian Plate; AMR, Amur Plate; CAR, Caribbean Plate; COC, Cocos Plate; EURASIA, Eurasian Plate; IND, Indian Plate; JF, Juan de Fuca Plate; NAM, North American Plate; NZ, Nazca Plate; OKH, Okhotsk Plate; PCF, Pacific Plate; PHS, Philippines Sea Plate; RI, Rivera Plate; SAM, South American Plate; SCO, Scotia Plate; SHP, South Shetland Plate; SOM, Somalian Plate; SSW, South Sandwich Plate; SUN, Sunda Plate. 1, North American Cordillera; 2, The Andes Cordillera; 3, African Topography; 4, Tibetan-Himalayan Orogen; 4–5, Greenland and Antarctic ice sheet (Modified from Bird, 2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methodology

Paleogeographic reconstruction requires integration of paleobathymetric, paleotopographic, and paleoshoreline data into a coherent and self-consistent plate tectonic model. We based our method essentially on that described by Baatsen et al., (2016) with some modifications, notably the integration of new kinematic and geological data sets.

Integration of disparate datasets was achieved using a combination of the Generic Mapping Tools (GMT) software (Wessel et al., 2013) to generate and modify paleobathymetric, paleotopographic, and paleoshoreline elements, and the open source software GPlates (www.GPlates.org; Boyden et al., 2011) to move these elements using an internally consistent plate rotation model. We also used a GIS software (such as QGIS or Global Mapper) as a bridge between GMT and GPlates, and for the creation of polygonal overlays (masks) for the manipulation of spatial databases. GMT provides a multiplatform open source collection of several tools that allow performing mathematical operations between raster grids, the interaction between vector masks and raster grid files, and several interpolation algorithms among other functions. GMT allowed generating and manipulating Network Common Data Format (netCDF) or similar file types for climate models requiring globally gridded elevation data (Herold et al., 2014). In the following subsections, we explain the successive steps that we undertook to develop our paleogeographic maps, following four key elements: (1) the plate tectonic model; (2) the paleobathymetry of the ocean crust; (3) paleoshorelines, and (4) the paleotopography (see also supplementary data).

2.1. Plate tectonic model

The fundamental framework of any paleogeographic map is the plate tectonic model that provides: (1) the kinematic model that describes relative motions between various tectonic blocks expressed as rotation

parameters (latitude, longitude, angle); and (2) the global reference frame for the plate circuit that can be either based on paleomagnetic data assuming a geocentric axial dipole (for paleoclimatic or biological purposes) or based on hotspot tracks assuming a fixed hotspot assumption or moving mantle (for geodynamic purposes; Boyden et al., 2011; van Hinsbergen et al., 2015b). In our reconstructions using GPlates, rotations of tectonic plates are expressed relative to South Africa so that changing global reference frames can be accomplished by simply changing the motion of South Africa (Torsvik et al., 2008) with respect to the preferred global reference frame. We use the paleomagnetic reference frame from Torsvik et al. (2012) although growing evidence suggests that this reference frame may be less robust for the Eocene than for the Paleocene time (Westerweel et al., 2019).

As per Baatsen et al. (2016), the global plate rotation model provided by Seton et al., (2012) is used as a first-order reconstruction of the main plates. We then modified this original model by integrating with GPlates a selection of previously published regional plate models providing detailed reconstructions of various orogenic zones (Fig. 2) including the Andes and the Caribbean (a, b and c in Fig. 2i, Arriagada et al., 2008, 2013; Boschman et al., 2014; Eagles and Jokat, 2014; Poblete et al., 2011, 2014, 2016; Schepers et al., 2017), the North American Cordillera (d, and e in Fig. 2i, Henderson et al., 2014; McQuarrie and Wernicke, 2005), the Mediterranean and Anatolia (f in Fig. 2i, Gürer and Van Hinsbergen, 2019; van Hinsbergen et al., 2020; van Hinsbergen et al., 2014; van Hinsbergen and Schmid, 2012), the Arabia-Eurasia and Tibetan-Himalayan collision zones (g, h in Fig. 2i, McQuarrie and van Hinsbergen, 2013; van Hinsbergen et al., 2019), and finally the Banda Arc zone (i in Fig. 2.i, Spakman and Hall, 2010; Tate et al., 2015, 2017). The combination of these models is referred to as the “Poblete rotation model” which extends back to 60 Ma and is provided in the supplementary data. In the N, NW, and SW Pacific regions we used the original plate model of Seton et al. (2012) without incorporating more recent

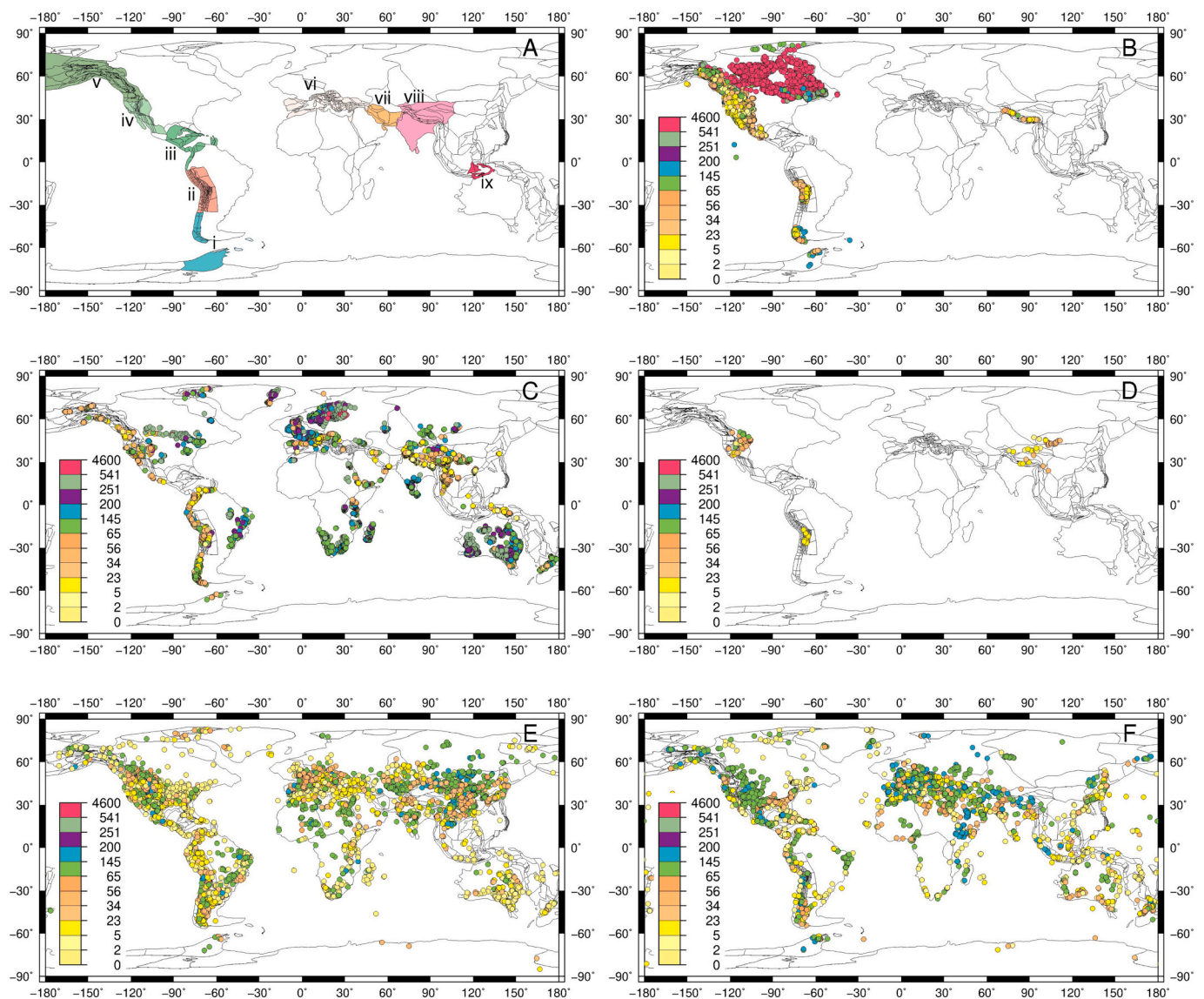


Fig. 2. Compilation of the different tectonic models and entire database integrated in GPlates. A) Compilation of tectonic models used in our reconstructions. i-ix are the location of the tectonic models (see section II.1 “Plate tectonic models” for more information). B) K/Ar, $^{39}\text{Ar}/^{40}\text{Ar}$ and U–Pb Geochronology compilation of magmatic rocks (Breitsprecher and Mortensen, 2004; Chapman and Kapp, 2017; Trumbull et al., 2006; <http://www.navdat.org>, Hervé et al., 2007, among others); the vertical colour scale is of time in Ma. C) Compilation of thermochronological data (Herman et al., 2013; this study). D) Paleoelevation compilation (Botsyun et al., 2016; Chamberlain et al., 2012; this study). E) and F) terrestrial and marine fossil database (www.paleobiodb.org, time span of data 160–0 Ma).

modifications addressing the complex subduction and deformation histories of the area, including the accretion of several terranes which are not depicted in our reconstructions (Domeier et al., 2017; Vaes et al., 2019; Van de Lagemaat et al., 2018).

Small continental blocks in orogenic regions are often depicted using polylines instead of polygons in previous reconstructions using GPlates, which simplifies changing their shape through time; or topological lines (Gurnis et al., 2018) which can be used to show lithospheric deformation parameters. A polygon overlay is the standard method used to “cut” raster topography in the process of creating paleotopography (see “Paleotopography” below). Müller et al. (2019) presented a global plate model where plate deformation is explicitly shown; however, this model cannot be used as a starting point for our approach because the deformed area is not constrained by static polygons and the topography cannot be cut and restored to past positions. We therefore created, for each considered age step, static polygon shapes that match as much as possible the lines in the original tectonic models and derived rotations for each of these static polygons using GPlates. For example, in the Basin

and Range we developed a simplified version of McQuarrie and Wernicke (2005) while in the Central Andes we used the tectonic model of Arriagada et al. (2008).

2.2. Paleobathymetry

To reconstruct the paleobathymetry we used the digital grids provided by Müller et al. (2008a) and available at <http://www.earthbyte.org>. These files are ASCII files in 1 Myr intervals and in the format of longitude, latitude, age, depth-to-basement and bathymetry. We extracted the paleobathymetry column from the original file in Müller et al. (2008a) and converted the ASCII file into a netCDF grid with a resolution of 6 min (GMT command xyz2grd). Combining the paleobathymetry reconstructions of Müller et al. (2008a) with our deformed continental polygons generated some overlaps. We erased these overlaps by cutting the paleobathymetry using a mask of the continental ocean boundaries (COBs, Seton et al., 2012), which correspond to the limit between the continental and oceanic crust. In the particular case of the

Greater Indian Basin (van Hinsbergen et al., 2012) we use the general depth-age relationship (Baatsen et al., 2016) to convert a set of created isochrons, by considering symmetric spreading between 120 and 60 Ma, into paleobathymetry; in the case of the Neo-Tethys we represented microcontinental blocks as submerged plateaus shown by the tectonic models (see sections IV to VI). We have also combined our paleotopographies at 60, 40 and 20 Ma, with the recently published paleobathymetry from Straume et al. (2020) (see supplementary data).

2.3. Paleoshoreline

Defining paleoshoreline maps is a crucial step in the construction of paleogeographic maps. Previous compilations (e.g. Heine et al., 2015), produced a set of Cretaceous and Cenozoic paleoshoreline maps from the two global paleogeographic atlases of Smith et al. (2004) and Golonka et al. (2006). We used the paleoshoreline maps from Golonka et al. (2006), based on their better global consistency as noted by Heine et al. (2015). Heine et al. (2015) provided each atlas as a shapefile in present day coordinates. In order to restore the paleoshoreline through time we have integrated these paleoshorelines in GPlates by dividing the shorelines into polygons, following the tectonic blocks defined in our plate tectonic model. At each time slice, we have then modified these paleoshorelines according to marine vs. terrestrial fossil data reported from www.paleobiodb.org. In some of the reconstructed regions, we have further constrained paleoshorelines, by comparing it with depositional environments (i.e. marine vs. terrestrial sediments) of the age at the time of the reconstruction provided by regional geological maps (e.g. Akhmetiev, 2007; Barrier et al., 2018; Caminos and González, 1997; Dercourt et al., 2000; Gómez et al., 2015; Kaya et al., 2019; Olivero and Malumián, 2008; Scotese et al., 1988; Sempere et al., 1997; SERNA-GEOMIN, 2003; Slattery et al., 2015; Swezey, 2009; Thiéblemont et al., 2016). Note that large lakes are not taken into account in our reconstructions. Resulting updated paleoshorelines are available in the supplementary data.

2.4. Paleotopography

2.4.1. Datasets

Paleotopographic datasets were integrated in GPlates (Fig. 2ii, iii, iv, v, vi; supplementary data) and include quantitative (stable isotopic, paleobotanical) and qualitative (thermochronologic, geochronologic, and geologic) data.

Analysis of stable oxygen isotope ratios in paleosols can be used to quantitatively estimate past elevation changes (e.g. Poage and Chamberlain, 2002; Quade et al., 2015; Rowley et al., 2001). Stable isotope paleoaltimetry is a mature technique based on the fractionation of oxygen isotopes in an air-cell with elevation gain (Botsyun et al., 2016; Rowley and Garzzone, 2007). Here we supplement such paleoaltimetry with estimates based on paleoflora and palynological data. Biotic paleoaltimetry relies on identifying past elevation and temperature based on nearest living relatives, or on paleoenvironmental data obtained from fossil plant physiognomy (Gregory-Wodzicki, 2000; Hoorn et al., 2012; Spicer, 2018; Utescher et al., 2014). The accuracy of these approaches varies depending on the orogen and are discussed for each region in Part III.

Quantitative thermochronologic methods record the thermal evolution of rocks based on estimating the time elapsed since the rock cooled below the closure temperature of various radio-isotopic systems (Lisker et al., 2009; Peyton and Carrapa, 2013; Reiners and Brandon, 2006). At a given geothermal gradient, temperatures are then converted to depth such that the age and rate of exhumation of a rock (rock uplift) through the closure temperature can be estimated. Thermochronology does directly not constrain surface paleoelevation; however, its integration with geomorphological and structural data (for example, with the extent of planation surfaces and tectonic activity) can be used to qualitatively estimate surface paleoelevations (e.g. Carrapa and DeCelles, 2015;

Japsen et al., 2012a; Rohrmann et al., 2012). We relied mostly on the database compiled by Herman et al. (2013) with additional thermochronological studies in various regions. When possible, we sought additional geomorphic information through inspection of the original publications and/or in additional references to better constrain paleoelevation estimates. Finally, we used an extensive compilation of geochronological data of igneous rocks that do not provide direct paleoelevation estimates but cover wide regions with no paleotopographic information. When associated with petrological and structural data, this compilation allowed us to reconstruct the location and magmatic style of past volcanic arcs, for which we made inferences on the elevation based on modern analogues. For example, geochronological and isotopic data from igneous rocks in southern Lhasa (Wen et al., 2008; Zhu et al., 2011) and Central Andes (Haschke et al., 2006) indicate the presence of a narrow and rectilinear Andean-type arc during late Cretaceous-Paleogene times. As there is no paleoaltimetry data for these two arcs, we attributed them paleoelevation similar to modern Andean-type arcs (with values around 500 to 2500 m) taking into account the tectonic setting and paleoelevation evolution.

2.4.2. Isostatic compensation in polar regions and global eustatic sea level adjustments

We considered a simplified model in which the topography at the poles only depends on the presence, extent, and thickness of ice sheets and their associated isostatic effects. We first created a modified modern topography for Greenhouse conditions (without ice-sheet; 60 and 40 Ma) by compensating isostatically the loss of the ice masses in Greenland, as done in Baatsen et al. (2016). Several recent studies have shown that additional vertical motion is induced on the margins of Greenland when glacial erosion is considered (Medvedev et al., 2018; Straume et al., 2020). The free-ice isostatic compensation used here should thus be considered as a first order approach of Greenland's paleotopography (a combination of our paleotopography at 60 Ma and 40 Ma, with the recent published Greenland paleotopography from Straume et al. (2020) can be found in the supplementary data). To obtain the topography for Icehouse conditions in Antarctica (with ice-sheets; 20 Ma), we used the same ice thickness as today, although we allowed the areal extension of the ice-sheets to vary (see section IV.3.1). The chronology of ice-sheet development in Greenland is debated (Bernard et al., 2016; Coxall et al., 2005; DeConto et al., 2008; Lear et al., 2008; Liu et al., 2009); we thus model no Greenland ice at 60 and 40 Ma and an ice sheet similar to today at 20 Ma.

Finally, we adjusted the topography for sea level changes using the eustatic sea-level curve of Müller et al. (2008b) so that the past topographies are given with respect to paleo-sea levels: +94.7 m at 60 Ma., +73.3 m at 40 Ma and +65.7 m at 20 Ma.

2.4.3. Topographic modifications

The next step was to reconstruct topographic data from their modern location to their paleogeographic location at a given age. This was achieved using GPlates to cut the modern topography using the polygons of tectonic blocks (as defined in section II.1 and Fig. 2A) and rotate these blocks including their topography at the desired time and position. Then, we exported this data into a netCDF file.

The following steps were applied to modify the topography of all regions and are illustrated in fig. 3 for South America. (A) The first step was to create a mask with "1" values inside the COB (the boundary between the oceanic and continental crust, Seton et al., 2012) and "NaN" values outside those limits, such that multiplying or dividing topographic values of any map with the mask values only yields values for locations within the COB. (B) We then used a surface interpolation implemented in GMT (Fig. 3B, "blockmean" and "surface" commands in GMT) to correct the gaps that arose from restoring shortening between individual polygons. (C) Then, we separated land and sea regions by creating a mask using paleoshorelines modified with updated fossil and geological data (blue line in Fig. 3C), which resulted in two areas, one

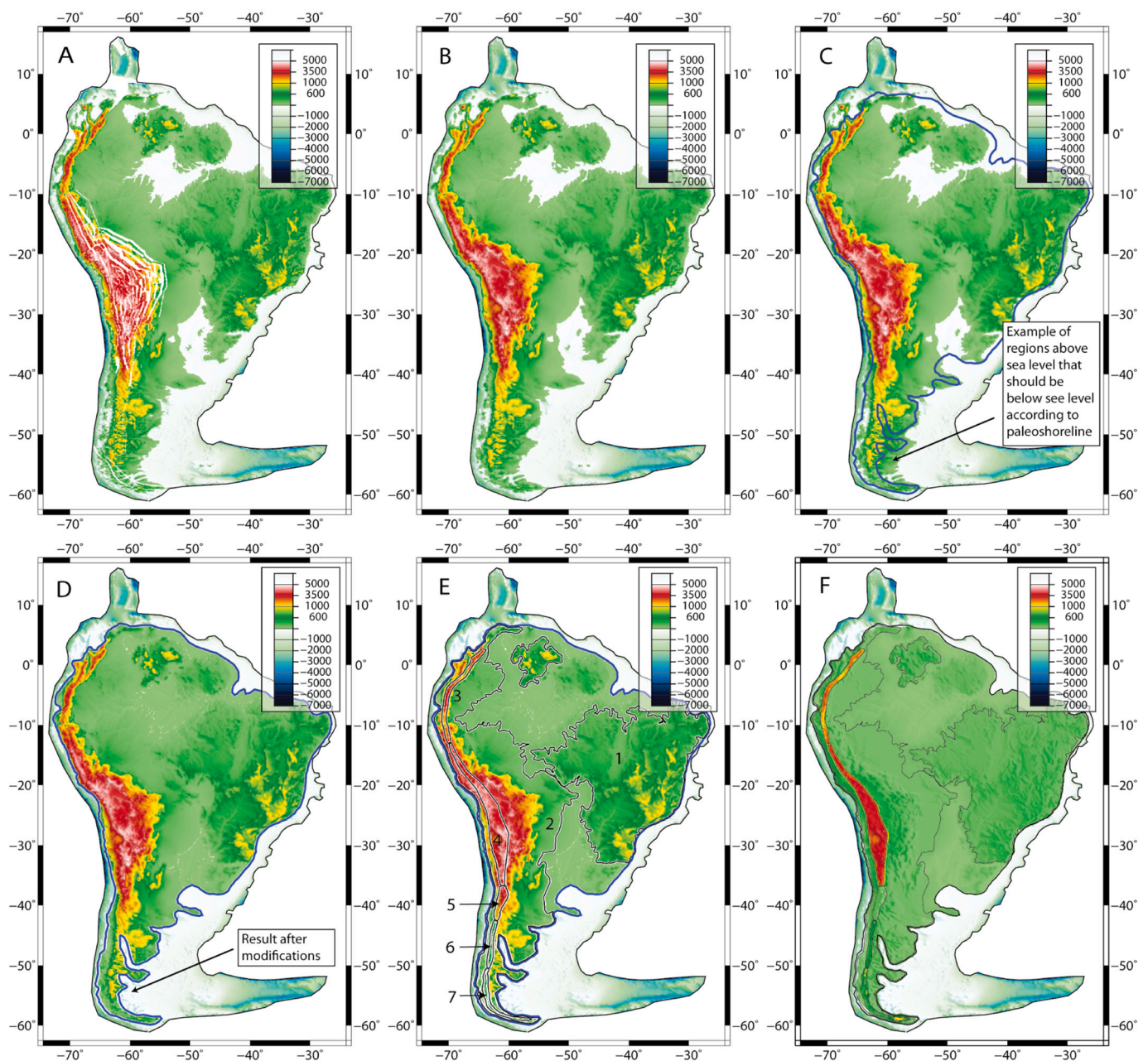


Fig. 3. Procedure for the topographic modification. (A) reconstructed South America at 40 Ma, black line denoted the COB; (B) resulting topography after fillings gaps; (C–D) first transformations in regions located seaward and landward of the paleoshoreline (blue thick line); (E) highlight individual masks (1–7) used to reconstruct the paleotopography; (F) final result. For more details, see text and supplementary data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that should be below sea level and one that should be above sea level (Fig. 3C). All emerged regions located seaward of the paleoshoreline (Fig. 3C) were transformed to end up below sea level using a linear equation defined by the initial minimum and maximum altitude (Z_{min} and Z_{max}) of these areas (obtained by using the ‘grdinfo’ command in GMT) and the final minimum and maximum altitude (Z'_{min} and Z'_{max}) defined by the user (see next step). Z values that were already below sea level are not modified. We used the same procedure for the region landward the paleoshoreline. We obtained a paleotopography in which all the values seaward/landward the paleoshoreline are below/above sea level, but with no major changes in the topography (Fig. 3D). (D) The next step was to modify the values above sea level according to geological constraints. To do that we first defined a set of masks in areas that were required to be modified with respect to the present day

topography (Fig. 3E, numbers 1 to 7). It is important to notice that the mask covered a much wider area than the data used to constrain paleoaltimetry, and in such masked areas there is a high degree of uncertainty (see section IV.2 for a discussion). To modify the topography over each region, we interpolated linearly between the initial minimum and maximum altitude (Z_{min} and Z_{max}) and the final altitudes (Z'_{max} and Z'_{min}), defined by our review of paleotopographic datasets, resulting in a linear equation in the form

$$Z' = f(Z) = A + m \cdot Z$$

in which Z represents any initial altitude value in the selected region and Z' is the final altitude at that point. m is defined by $(Z'_{max} - Z'_{min}) / (Z_{max} - Z_{min})$ and A by solving the equation for Z_{max} and Z'_{max} (or Z_{min} and Z'_{min}).

2.4.4. Final blend and change of reference frame

As stated above, our reconstructions are based on the rotation file of Seton et al. (2012) which uses the moving Indo-Atlantic hotspot reference frame of O'Neill et al. (2005) as an absolute reference frame. Various global mantle reference frames (e.g. Doubrovine et al., 2012; Torsvik et al., 2008; van der Meer et al., 2010) as well as paleomagnetic reference frames (e.g. Besse and Courtillot, 2002; Kent and Irving, 2010; Torsvik et al., 2012) are available and users may want to switch between frames. For instance, a paleomagnetic reference frame is appropriate for climate reconstructions since it includes true polar wander (Torsvik et al., 2012; van Hinsbergen et al., 2015a, 2015b). Switching between frames (Boyden et al., 2011; van Hinsbergen et al., 2015a, 2015b) is straightforward, since our GPlates reconstructions are all relative to southern Africa and changing the global reconstruction between frames only requires application of a global reference frame correction using the GMT command “grdrotation” (see supplementary data).

3. Paleogeographic reconstructions at 60, 40 and 20 Ma

We focused our work on the main cordilleras, critical zones for paleoclimate models. Other areas received less attention: Australia, Southeast Asia, the western Pacific rim, the Caribbean region, the Mediterranean region, and the NW Pacific and Aleutian basin. For these regions, we used recent tectonic models that were corrected for the paleoshorelines, but the regional paleotopography is mostly based on modern topography (see supplementary data for major data sources and masks used at each reconstruction time). Cenozoic paleogeographic history is marked by the formation of three main orogens: the Himalayan-Alpine system along the Eurasian Plate, and the Andes and the North American Cordillera along the western margins of the Americas. The Tibetan-Himalayan orogen and the Central Andes now include the highest plateaus on Earth, with elevations reaching more than 4000 m (Fig. 1). The Cenozoic also witnessed several episodes of oceanic gateway opening and closure, which exerted a major control on oceanic currents (Barker, 2001; Straume et al., 2020; Ladant et al., 2014, 2020). In particular, the connection between the Atlantic, Pacific and Indian parts of the Southern Ocean, through the Drake Passage (across the Scotia Arc) and the Tasman Gateway, allowed the development of the Antarctic Circumpolar and Subpolar currents (e.g. Barker and Thomas, 2004; Ladant et al., 2014; Lagabrielle et al., 2009; Scher et al., 2015; Williams et al., 2019). The formation of other gateways and straits had an important impact on past global climate, such as the Panama, Bering and Turgai Straits, and the Indonesian passage (Akhmetiev et al., 2012; Ladant et al., 2014, 2020; Lunt et al., 2008; Montes et al., 2015; Straume et al., 2020). We integrated these changes in a set of paleo Digital Elevation Models (DEMs) at 60, 40 and 20 Ma. These paleoDEMs (see supplementary data) are presented in three different reference frames: a paleomagnetic reference frame (Fig. 4, 5 and 6; Torsvik et al., 2012), a moving Atlantic hotspot (O'Neill et al., 2005), and a global moving hotspot reference frame (GMHRF, Doubrovine et al., 2012), as appropriate for paleoclimate or geodynamic studies respectively (van Hinsbergen et al., 2015a, 2015b). In the following sections, we review and discuss the tectonic setting of selected regions that underwent changes in the Cenozoic widely perceived as critical for global climate. We focused sequentially at 60 Ma, 40 Ma and 20 Ma on the Andes and the Scotia Arc, the Western North American Cordillera, the African and Brazilian shields and the Tibetan-Himalayan orogeny in which we developed different paleogeographies taking into account different models. We also explain how we dealt with ice caps on Antarctic and Greenland and we review the main modifications of paleoshorelines.

3.1. South America

South American Cenozoic tectonics are dominated by the build-up of the Andean cordillera in contrast with the limited evolution of the Brazilian shield. The Andean Cordillera can be followed uninterruptedly

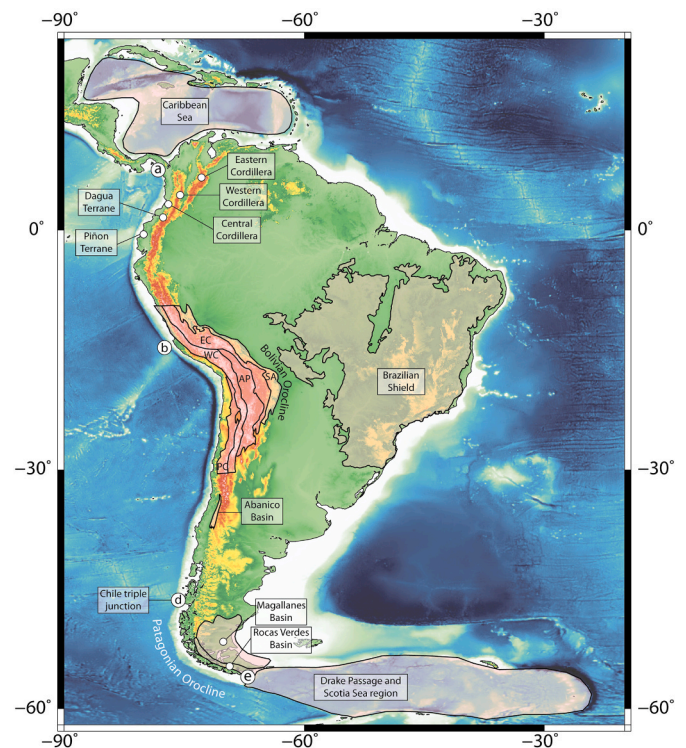


Fig. 4. Physiography of South America. a-b, Northern Andes segment; b-c Central Andes segment; c-d Southern Andes segment; d-e Austral Andes segment. PC, Precordillera; WC, Western Cordillera; AP, Altiplano Puna; EC, Eastern Cordillera; SA: Sub Andes. (Modified from Mpodozis et al., 2005; Poblete et al., 2016; Tassara and Yáñez, 2003;).

from the Caribbean Sea to the Drake Passage, where the Scotia Arc marks the consumptive plate boundary between southernmost Andes and the northern tip of the Antarctic Peninsula (Fig. 4, Dalziel et al., 2013). On a continental scale, the most outstanding feature of the Andean Cordillera are changes in its orientation that define the Bolivian and the Patagonian oroclines (Fig. 4, Arriagada et al., 2008; Carey, 1958; Isacks, 1988; Poblete et al., 2014; Rapalini, 2007). The Nazca Plate subducts beneath the western margin of central South America along most of its length. Along its northern margin, the South American Plate is juxtaposed with the Caribbean Plate (north) along a contact dominated by strike-slip and reverse faulting (Meschede and Frisch, 1998; Müller et al., 1999; Pindell and Dewey, 1982; Pindell and Kennan, 2001). Offshore of southern Chile, the Chile triple junction (Fig. 4) marks the northernmost point of the Antarctic Plate, where it subducts below Patagonian. From the Strait of Magellan, southmost Chile, to the Antarctic Peninsula, the Antarctic Plate is in contact with the Scotia Plate along both convergent and transform plate boundaries.

3.1.1. South America 60 Ma

From Peru to Colombia, the northwestern Andes include a collage of accreted terranes. For example, the Dagua and Piñon Terranes (Fig. 4), are thought to be pieces of an oceanic plateau, the Caribbean Large Igneous Province (CLIP), which collided in the Late Cretaceous (Pindell and Kennan, 2009; Ramos, 2009; Roperch et al., 1987; Villagómez and Spikings, 2013). Uplift and exhumation of the continental margin is attributed to this accretionary event (Villagómez and Spikings, 2013). In the Central Andes, shortening, basin inversion, and normal convergence have been documented during the Late Cretaceous-early Paleocene (Amilibia et al., 2008; Charrier et al., 2013; Henríquez et al., 2018; Herrera et al., 2017; Martínez et al., 2020, 2013; Sempere et al., 1997). This pulse of deformation was accompanied by calc-alkaline magmatism, suggestive of subduction-related arc petrogenesis (Trumbull et al.,

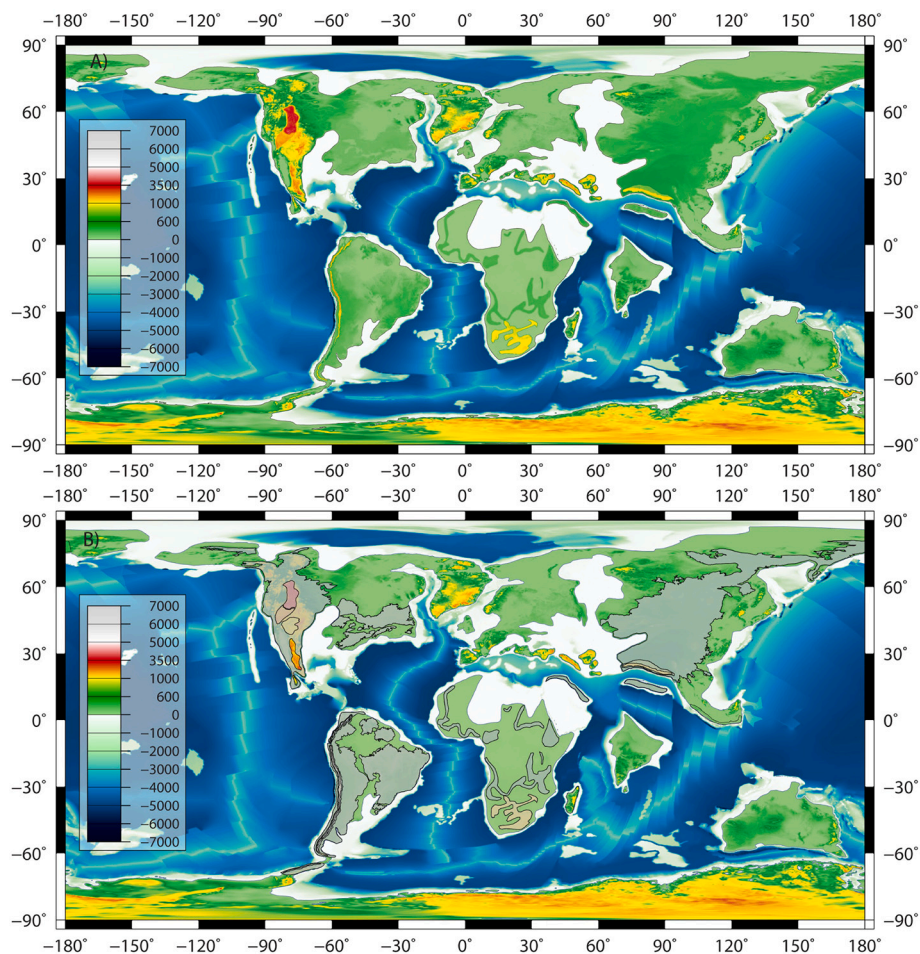


Fig. 5. (A) Paleogeographic reconstruction at 60 Ma. (B) Shaded regions show the location of modified regions (for more details see supplementary data).

2006). Both deformation and calc-alkaline magmatism were focused in the Precordillera and Western Cordillera (Fig. 4), and only began to migrate to the east during the Eocene (Canavan et al., 2014; Carrapa and DeCelles, 2015; Garzzone et al., 2014; Leier et al., 2013; Quade et al., 2015; Trumbull et al., 2006). Tectonic restoration of the Bolivian Orocline suggests that its construction began during the middle Eocene and the margin was more linear before that time (Arriagada et al., 2008; Eichelberger and McQuarrie, 2015; Roperch et al., 2006; Schepers et al., 2017). In the Southern Andes, low temperature thermochronology and field observations show that orogenic growth, associated with slab shallowing and arc migration, occurred between 100 and 60 Ma (Echaurren et al., 2016; Folguera et al., 2015). Further South, in the Fuegian Andes, closure of the Rocas Verdes Basin during the Cretaceous has been related to differential shortening and bending due to rigid block rotation around a vertical axis (Betka et al., 2015; Cunningham et al., 1991; Dalziel et al., 1973; Poblete et al., 2014, 2016; Rapalini et al., 2016). The closure of the Rocas Verdes Basin resulted in the collision of the Patagonian batholith against South America with the Río Chico Arch acting as a buttress (Calderón et al., 2012, 2007; Klepeis et al., 2010; Poblete et al., 2016; Torres Carbonell et al., 2016, 2014; Torres Carbonell and Olivero, 2019; Torres García et al., 2020) and in the thickening of the crust of Cordillera Darwin on the north western Scotia plate (Klepeis et al., 2010). In particular, deformation in the Cordillera Darwin was accompanied by denudation and uplift during Late Cretaceous-Early Paleocene (Gombosi et al., 2009; Kohn et al., 1993; Maloney et al., 2011; Nelson, 1982), creating a barrier that acted as a drainage divided since the Late Cretaceous (Barbeau et al., 2009). There are no direct paleoelevation constraints in the Andes for the Late

Cretaceous-Early Cenozoic, but evidence for shortening and calc-alkaline magmatism (Bruce et al., 1991; Hervé et al., 2007) is consistent with the presence of a rectilinear volcanic-dominated mountain range along the Pacific subduction margin, although probably narrower and lower than the modern Cordillera. Based on these considerations, we modeled paleoaltitudes at 2000 m for the northern and central Andes that decreased to the south, except in Cordillera Darwin where we suggest that it already formed a topographic high at that time, with a proposed elevation of 2000 m (Fig. 5).

For the Brazilian shield, thermochronological studies in different sectors of the Atlantic coast concluded that its current relief is the results of a series of cooling phases that took place between the Upper Cretaceous and late Neogene (e.g. Cogné et al., 2012, 2011; Japsen et al., 2012a; Karl et al., 2013). These studies suggest the eastern South American margin stood at altitudes not higher than 400 m, instead of 1000 m or higher as it is today in some areas. We thus used maximum altitudes of ~400 m, unchanged for our 60, 40, and 20 Ma reconstructions.

For paleoshorelines, an epicontinental sea incursion along the eastern edge of the Andes is indicated by geological and fossil data from 84 to 60 Ma (Sempere et al., 1997) but after 60 Ma that sea retreated from the northern part of South America (Gómez et al., 2015; Malumián and Ramos, 1984; Sempere et al., 1997). We have chosen to modify the paleoshoreline from Golonka et al. (2006) in the northern part of South America by eliminating the sea reentrant in the western Amazonas that was mostly gone by 60 Ma. In the area of the Scotia Arc region, we have adapted the paleoshorelines presented by Eagles and Jokat (2014).

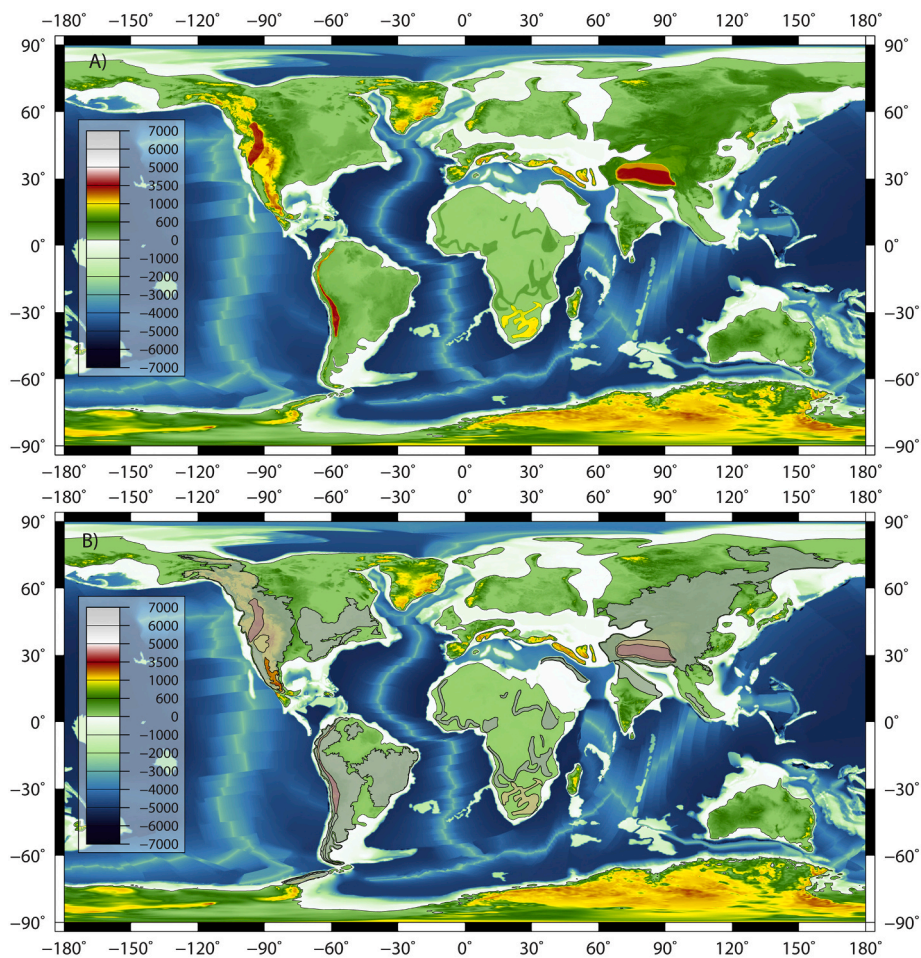


Fig. 6. (A) Paleogeographic reconstruction at 40 Ma. (B) Shaded regions show the location of modified regions (for more details see supplementary data).

3.1.2. South America 40 Ma

Thermochronological data indicates a second pulse of uplift in the middle Eocene which led to the onset of growth of the Western-Central Cordillera system (Villagómez and Spikings, 2013). This exhumation event is also recognized in the Ecuadorian Cordillera between 45 and 30 Ma (Spikings et al., 2010) and in the central Andes, where heterogeneous uplift gave rise to high altitudes in the Precordillera and Western Cordillera before 50 Ma and in the Puna Plateau by 35 Ma (Carrapa and DeCelles, 2015). Uplift is synchronous with shortening and basin inversion during the Incaic phase of the Andean orogeny (Charrier et al., 2009) and with the beginning of the rotation in the Bolivian Orocline (Arriagada et al., 2008). In the southern Central Andes, extension related to the Abanico Basin (Fig. 4) began by 40 Ma, suggesting that this region had a low elevation (Charrier et al., 2007). Further south, similar extension along the eastern side of the Cordillera is attributed to slab roll-back (Echaurren et al., 2016). In the Fuegian Andes, however, internal thickening and exhumation (Betka et al., 2015; Fosdick et al., 2011; Klepeis et al., 2010) indicates that shortening and contraction continued throughout the Eocene. Geochronological compilation of igneous rocks in the Central Andes (Trumbull et al., 2006) shows that the region was a magmatically active volcanic arc (Pindell and Tabbutt, 1995).

Paleoelevation data in the Cordillera are restricted to the Central Andes (Fig. 2D and supplementary data). There are, however, conflicting interpretations of these datasets, with two contrasting models. One model requires significant uplift only during the Miocene (~15 Ma), related to the latest stage of Bolivian Orocline development (Garzzone et al., 2006; Gregory-Wodzicki, 2000), whereas a second model entails

significant paleorelief in the Central Andes by 35 Ma with elevations higher than 4000 m (Canavan et al., 2014; Carrapa and DeCelles, 2015; Hartley, 2003; Quade et al., 2015). Paleoelevation data from fossil leaf physiognomy and oxygen isotopic values have been interpreted to show that the Eastern Cordillera and the Altiplano Plateau were rapidly uplifted during the Miocene (Garzzone et al., 2006, 2014; Ghosh, 2006; Gregory-Wodzicki, 2000; Rowley and Garzzone, 2007). However, these studies do not consider climatic variations during the interval of study (Ehlers and Poulsen, 2009) and may underestimate the paleoelevation. Paleoelevations corrected for climatic effects suggest a plateau elevation of ca. 3 km since at least 25 Ma (Ehlers and Poulsen, 2009). Moreover, paleoaltimetry studies in the area of the Puna Plateau and Western Cordillera, suggest that these regions (including the western side of the Altiplano Plateau) were already elevated at 35 Ma (Canavan et al., 2014; Quade et al., 2015). In the Brazilian region, thermochronological data do not indicate any major topographic change (Cogné et al., 2012; Japsen et al., 2012a).

We thus depict orogenic growth of the Andes at 40 Ma with a high degree of along strike variability (Fig. 6). We propose that the northern Andes were narrow, with maximum elevations around 3000 m, while the deformation front in the Central Andes was already farther east, in response to increasing elevation and width, and displaying a plateau-like configuration with maximum elevations reaching around 4000 m. Immediately to the south, a depression is related to the development of the extensional Abanico Basin (Charrier et al., 2007, 2009). In the Southern and Austral Andes, the Cordillera gained again in elevation, although with lower elevations than in the Central and Northern Andes (around 2000 m).

We adapted the paleoshoreline presented by [Eagles and Jokat \(2014\)](#) for the Scotia Arc region, similar to the 60 Ma reconstruction. We also made minor modifications to the reference paleoshorelines of [Golonka et al. \(2006\)](#) for consistency with marine and terrestrial fossil data.

3.1.3. South America 20 Ma

Thermochronological data do not show evidence of Oligocene exhumation in the Western and Central Cordillera of the Northern Andes ([Villagómez and Spikings, 2013](#)). However, in the Eastern Cordillera of Colombia, thermochronological and structural data suggest rapid orogenic propagation, basin inversion and shortening related to a plate reorganization and a related increase of plate convergence during early Miocene ([Mora et al., 2013](#); [Parra et al., 2009, 2012](#); [Spikings et al., 2010](#)). In the Central Andes, paleoelevation data show that surface uplift in the Eastern Cordillera had already started during the Oligocene ([Quade et al., 2015](#)) in agreement with thermochronological data ([Carrapa and DeCelles, 2015](#)) and the Eocene-Oligocene construction of the Bolivian Orocline showing shortening in the Eastern Cordillera ([Arriagada et al., 2008](#); [McQuarrie et al., 2008](#)). The Subandean zone only deformed after the mid-Miocene ([Arriagada et al., 2008](#); [Quade et al., 2015](#)). In the Southern Andes, extension was ongoing in the early Miocene (around 19 Ma), with orogenic contraction starting in the middle Miocene ([Echaurren et al., 2016](#)). By contrast, contraction was still active in the Austral Andes, with eastward migration of the deformation front ([Alvarez-Marrón et al., 1993](#); [Fosdick et al., 2011](#); [Klepeis et al., 2010](#)). We thus propose a Northern and Central Andes forming a wider mountain chain with elevations around 4000 m for the highest peaks in these regions. For the Southern and Austral Andes, we kept

paleoelevation similar to the previous 40 Ma reconstruction ([Fig. 6](#)). Paleoshorelines are the same as the reference paleoshorelines from [Golonka et al. \(2006\)](#), with only minor local modifications ([Fig. 7](#)).

3.2. North America

North American Cenozoic tectonic evolution is dominated by orogenic build-up and demise along the Western Cordillera orogenic belt, extending from Alaska in the north, to Central America in the south. It is characterized by an alternation of subduction and transform contacts between the North American Plate, the Pacific Plate and relicts of the conjugate Farallon Plate (Juan de Fuca, Gorda, Rivera, Cocos, Nazca; [Fig. 1](#)). The western margin of North America can be divided into several morphological units, among them: The Sierra Nevada, Cascades and Coast Belt mountains along the coast; the Basin and Range region and the Colorado Plateau; the Rocky Mountains, Alaskan and St. Elias Ranges ([Fig. 8](#), [Chamberlain et al., 2012](#); [Fenneman, 1931](#); [Mathews, 1991, 1986](#); [Ordóñez, 1936](#)).

3.2.1. North American 60 Ma

The Intermontane and Insular superterrane located westboard of the North American Cordillera traveled northward relative to North America during the late Cretaceous, but by how much is subject of a long-standing debate. Structural geological estimates give no more than ~700–900 km (e.g. [Gabrielse et al., 2006](#)), whereas paleomagnetic ([Enkin et al., 2006](#); [Kent and Irving, 2010](#)) and detrital zircon ([Garver and Davidson, 2015](#)) data suggest >2000 to 3200 km of coastwise translation, placing British Columbia (BC) adjacent to Baja California -

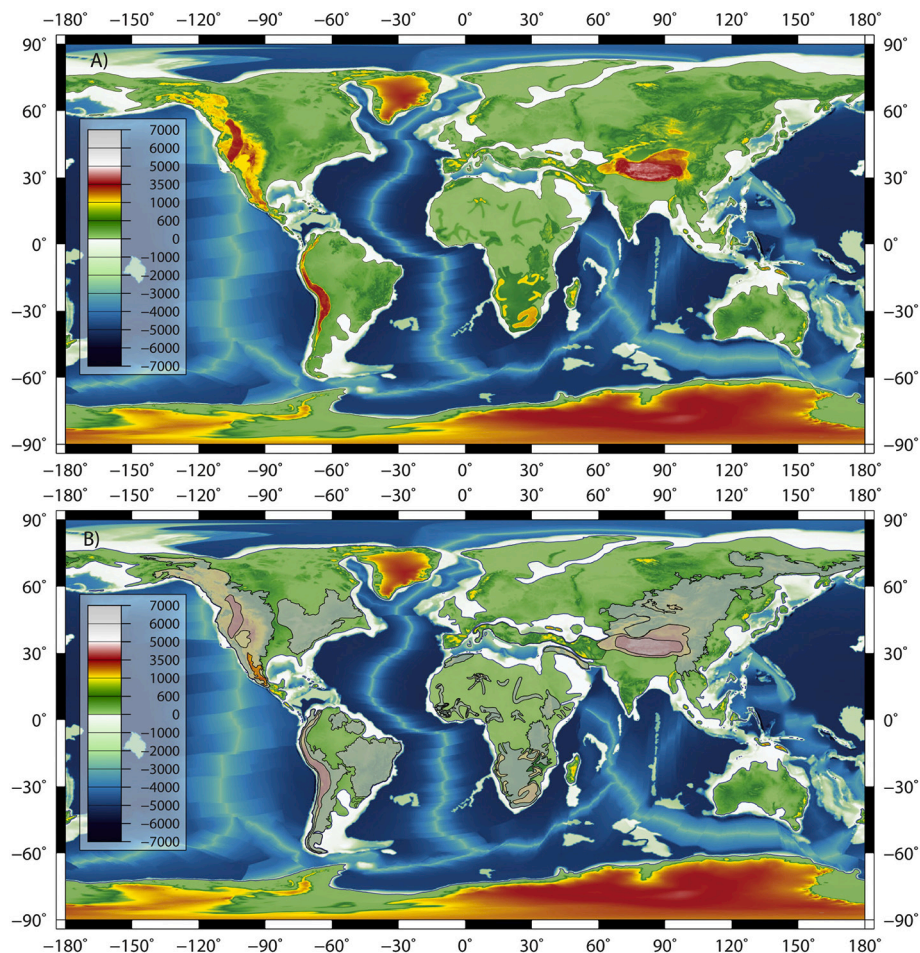


Fig. 7. (A) Paleogeographic reconstruction at 20 Ma. (B) Shaded regions show the location of modified regions (for more details see supplementary data).

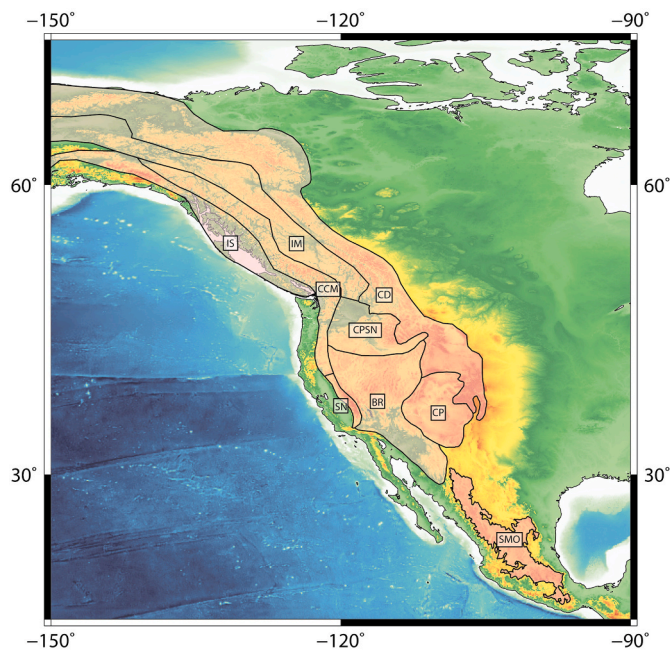


Fig. 8. Physiography of North America SMO, Sierra Madre Oriental; SN, Sierra Nevada; BR, Basin and Range; CP, Colorado Plateau; CCM, Coastal Domain and Cascades Mountains; CPSN, Columbian Plateau and Snake River plain; IS, Insular Domain; IM, Intermontane domain; CD, Continental Domain including the Rocky Mountains. (Modified from Chamberlain et al., 2012; Colpron et al., 2007; Silberling et al., 1992).

the so called “baja-BC” hypothesis (Irving et al., 1985). This dilemma has tantalized geologists for decades (Beck et al., 1981; Butler et al., 1989; Cowan, 1994; Irving and Archibald, 1990; Umhoefer, 1987). However, the blocks were essentially in place at 60 Ma (Cather et al., 2012; Coney, 1972; Dickinson and Snyder, 1978; English and Johnston, 2004; Ziegler et al., 1985). Post-60 Ma motion on major faults accounts for only a few hundreds of kilometers (Gabrielse et al., 2006), and are generally irresolvable using paleomagnetic methods (Enkin et al., 2006). The Laramide Orogeny, is a broad orogenic event responsible for the uplift of the Rocky Mountains, Sierra Madre and Laramide blocks (Armstrong, 1968; Coney, 1972, 1976; Copeland et al., 2017; Haxel et al., 1984). Major impacts of this orogeny on paleogeography includes the reactivation of the Rocky Mountains, the formation of a high plateau in central Nevada, called the “Nevadoplano” (analogous to the Altiplano in Bolivia), and the final regression of the Western Interior Seaway (Cather et al., 2012; DeCelles, 2004; Ziegler et al., 1985). Paleoelevation studies suggest a high Cordillera in the southern part of the Canadian Rocky Mountains (Chamberlain et al., 2012 and references therein; Mulch et al., 2007); elevations are thought to have been much lower further south in the Cordillera (Cather et al., 2012; Lechler et al., 2013; Licht et al., 2017), though past crustal thickness suggests that a 3 km high plateau may have extended as far south as northern Mexico in the latest Cretaceous (Chapman et al., 2020). We opted for a reconstruction that displays a North American Cordillera with the highest elevations in the Canadian Rocky Mountains at around 4000 m and decreasing elevation southward, reaching 2000 m in Nevada and around 800 m in Mexico (Fig. 5). Elevations in Sierra Madre were not modified.

For North American paleoshorelines, we used a modified version of Slattery et al. (2015) other minor modifications to the reference paleoshorelines of Golonka et al. (2006) were constrained by marine and terrestrial fossil data provided from the paleobiodb.org.

3.2.2. North American 40 Ma

The Laramide Orogeny was completed at ca. 40 Ma (Coney, 1976; Coney, 1972; Copeland et al., 2017; English and Johnston, 2004;

Henderson et al., 2014). Paleoelevation data suggest that the surface uplift was at its maximum expression and that the Nevadoplano reached elevations near 4000 m with a latitudinal extension of around 2500 km (Chamberlain et al., 2012; Fan and Dettman, 2009; Lechler et al., 2013; Sjostrom et al., 2006). To the southwest, contrasting models for the evolution of the Sierra Nevada mountains propose that elevations were attained either recently or in the early Cenozoic. Revised geomorphological observations have, however, shown that the Sierra Nevada has been at high elevations at least since the Eocene in agreement with stable isotope data (Gabet, 2014; Mix et al., 2016; Mulch et al., 2006). The high elevation in the Nevadoplano and Sierra Nevada contrast with elevations in the Colorado Plateau where stable isotopes are compatible with paleoelevations of around 1000 m (Cather et al., 2012; Licht et al., 2017). To the north, limited fission-track data suggest that the Coast Belt attained average elevations of ~2500 m that persisted until ~6 Ma (Densmore et al., 2007).

We thus propose a topographic reconstruction for which the Nevadoplano dominates the landscape of western North America with a north-south extent of ~2500 km and paleoelevations as high as 4000 m (Fig. 6). It also includes a modern-like Sierra Nevada and a Colorado Plateau at lower elevation, with altitudes around 1000 m, surrounded by mountains to the west, north and east. Paleoshorelines were reconstructed from the reference paleoshorelines from Golonka et al. (2006).

3.2.3. North America 20 Ma

A major change in the tectonic regime of Western North America took place during the Early Miocene with initial subduction of the Pacific-Farallon ridge and formation of the Mendocino triple junction (Atwater, 1970; Furlong and Schwartz, 2004; Silver, 1971). Northward migration of the Mendocino triple junction marks the long-term diachronous demise of the Farallon subduction zone, replaced by a new transform margin, part of which forms the modern-day San Andreas Fault (Atwater, 1970; Furlong and Schwartz, 2004; Silver, 1971). As North America rode over the growing slab window, a combination of thermal softening and coupling with the north-moving Pacific plate resulted in extension and formation of the Basin and Range province, starting ca. 36 Ma, with the most important pulse of deformation occurring after the mid Miocene (~14 Ma; McQuarrie and Wernicke, 2005).

Despite ongoing extension in the Basin and Range province, paleoelevation data suggests that during the Oligocene the Nevadoplano was still present from Central Nevada to Southern Canada (Chamberlain et al., 2012 and references therein), extending up to the Sierra Nevada (Chamberlain et al., 2012; Gabet, 2014; Wheeler et al., 2016). Paleoelevation estimates for the Colorado Plateau are debated ranging from elevations as high as today (e.g. Flowers et al., 2008) to less than 1000 m during the Oligocene (Sahagian et al., 2002). We opted for elevations similar to the 40 Ma paleotopography for the Nevadoplano and Colorado Plateaus, i.e., 4500 m and 1000 m, due to the lack of conclusive data showing significant topography change between 40 and 20 Ma (Fig. 7). Like previously, paleoshorelines were reconstructed from the reference paleoshorelines from Golonka et al. (2006).

3.3. Africa

The African realm, including Madagascar, comprises three major plates: The African-Nubian Plate, the Africa-Somalian Plate, and the Arabian Plate (Fig. 1; Bird, 2003; Stamps et al., 2018). These plates are surrounded by spreading ridges or rifts, except for the northern border of the African and Arabian plates, where they subduct below the Eurasian plate (Bird, 2003; Müller et al., 2016). Bimodal elevation distributions characterize the African topography (Fig. 9, Burke and Gunnell, 2008; Dauteuil et al., 2009) with high relief (900–1100 m) corresponding to domes, large plateaus (Kalahari, East African and Ethiopian Dome and Cameroon, Darfur, Tibesti, Hoggar and the Atlas, Guillocheau et al., 2018) and elevated passive continental margins (Japsen et al., 2012b),

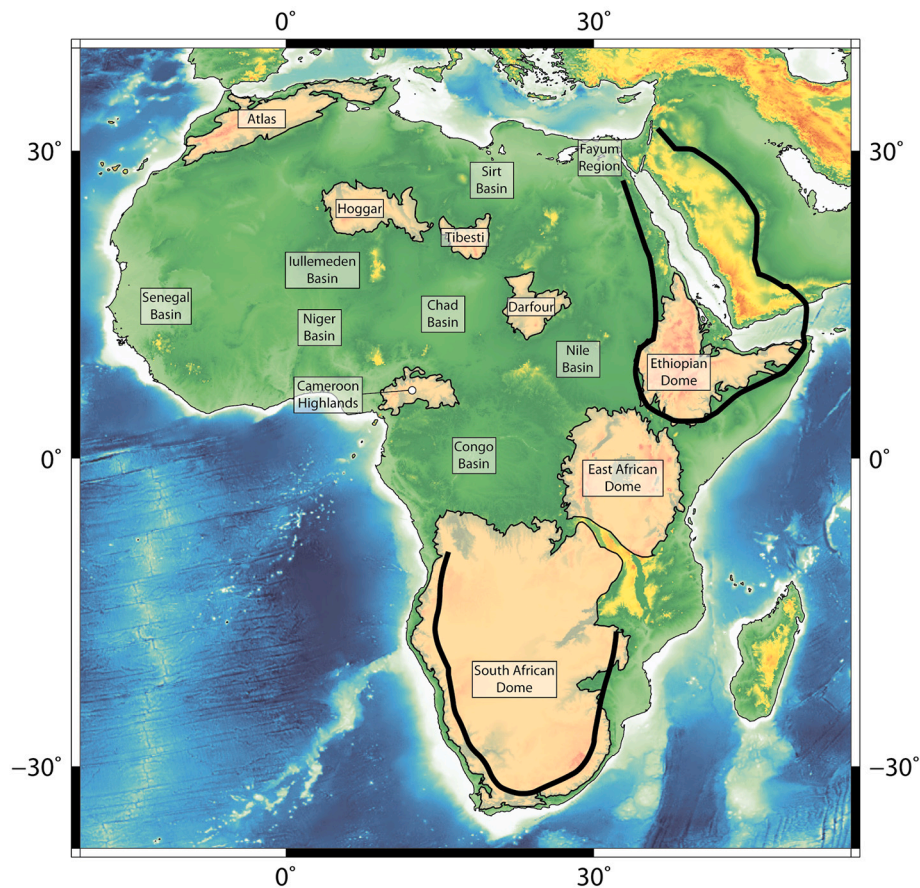


Fig. 9. Physiography of Africa. Thick black lines represent elevated passive margins. (Modified Burke and Gunnell, 2008).

and low relief regions (300–400 m) corresponding to the Sahara and the Congo Basin (Guillocheau et al., 2015) where most of the drainage basins are located (Senegal, Niger, Chad, Nile, Congo, among others, Burke and Gunnell, 2008). High relief regions have been argued to be related to isostatic compensation (Bechtel et al., 1987; Brown and Girdler, 1980) or dynamic topography related to vertical stresses generated by mantle flow (Burke and Gunnell, 2008; Gurnis, 1990; Lithgow-Bertelloni and Silver, 1998). New data, however, support the idea that the topographic evolution of the African surface is the result of a coupled interaction between mantle dynamic, lithospheric deformation and passive continental margin processes (Braun, 2010; Dauteuil et al., 2009; Guillocheau et al., 2018; Japsen et al., 2012b).

3.3.1. Africa 60 Ma

Elevated, passive continental margins (Japsen et al., 2012b) are a characteristic feature of the African continent that were first suggested to be long-lasting relict topographic features (Ollier and Pain, 1997; Weissel and Karner, 1989). Apatite fission track thermochronology, however, has revealed a more complex history in which denudation and surface uplift occurred long after break-up (Beauvais and Chardon, 2013; Gallagher and Brown, 1999; Tinker et al., 2008; Wildman et al., 2017).

The only area at 60 Ma in Africa with clear evidence for high topography is the southernmost part of the South African Plateau (or Kalahari Plateau), remnant of a late Cretaceous relief (Baby et al., 2020, 2018b, 2018a). Planation surfaces (etchplains and pediplains), used as geomorphological markers to identify vertical movements related to dynamic topography, indicate that during the late Paleocene-mid Eocene, an African-scale weathering surface (etchplain) known as the African Surface (Burke and Gunnell, 2008 for a review) was almost flat, with a faint drainage divide in central Africa (Guillocheau et al., 2018).

In northern Africa (Sahara) this etchplain was flooded by the sea during Late Paleocene times (Berggren and Hollister, 1974; Ye et al., 2017), confirming a flat topography near sea level. We thus propose a reconstruction with very low elevations on the African continent at 60 Ma (Fig. 5), including near sea level altitude for northern Africa, a curved drainage divide of elevations lower than 300 m in central Africa, and remnants of an early South African Plateau to the south. Our reconstructed paleoshorelines follow Golonka et al. (2006) with some modifications in northern Africa after Couvreur et al. (submitted).

3.3.2. Africa 40 Ma

Thermochronological data and paleogeographic maps (e.g. Burke and Gunnell, 2008) suggest that 40 Ma was the onset of a major change in the paleotopography of Africa that ended around 30 Ma (Fig. 5). For Northern Africa, thermochronological data in the Hoggar Dome (Rougier et al., 2013) indicate that the onset of exhumation occurred during the late Eocene (English et al., 2017), in agreement with Oligocene fluvial sedimentary rocks on top of the modern Hoggar (Rognon et al., 1983). The incipient growth of the Hoggar Dome initiated a divide in northwest Africa (Chardon et al., 2016) that might be extended until the Moroccan Atlas, and likely resulted from basin inversion related to the Europe-African collision responsible for the onset of surface uplift (e.g. Frizon de Lamotte et al., 2009). We thus changed the topography in Northern Africa in the area of the Hoggar Dome, with elevations between 200 m to 500 m (Fig. 6).

At 40 Ma, proposed paleoshorelines for northernmost Africa range between a large epicontinental sea (www.deepmaptimes.com; Blakey, 2008) to a paleoshoreline more similar to that of today (www.scotese.com; Golonka et al., 2006; Smith et al., 2004). Stratigraphic and sedimentological data indicate fluvial and lacustrine environments in the Chad (Genik, 1993) and Sudanese (e.g. Schull, 1988) Rifts and for the

Iullemeden Basin (Niger-Mali, e.g. Moody, 1997). The shoreline was therefore located northward of the Atlas-Hoggar-Tibesti-Darfur divide. The Late Eocene was a major period of emergence in the South Atlas, in Libya, and in Egypt (e.g. Mebrouk et al., 1997). The shoreline ran from central Tunisia (Merzeraud et al., 2016), through the southern Sirt Basin (Libya, Abouessa et al., 2014) to south Cairo (Fayum region, Underwood et al., 2013).

3.3.3. Africa 20 Ma

At 20 Ma, new domes and plateaus were initiated, and remnant topography from the 40–30 Ma uplift phase got more uplifted as a response of long wavelength deformation related to mantle dynamics (Guillocheau et al., 2018). The Southern African Plateau reached its modern elevation (Baby et al., 2018a). The Zambia-Malawi Plateau, East African Dome, Hoggar-Air-Tibesti-Darfur cluster, and Cameroon Volcanic Line started reaching significant elevations, attaining their modern elevations in the Late Miocene-Early Pliocene. Geological, thermochronological and structural data shows that the 1500-m high Atlas Mountains started growing in the late Eocene and must have reached significant elevation by the early Miocene (Balestrieri et al., 2009; Frizon de Lamotte et al., 2000; Missenard et al., 2008; Ruiz et al., 2011). We estimate paleoelevations for the Hoggar Dome and the Moroccan Atlas at around 1800 m and 1100 m respectively, and around 900 m for the Cameroon Volcanic Line and the East African dome (Fig. 7). Paleoshorelines are reconstructed following Golonka et al. (2006).

3.4. Eurasia

Eurasian Cenozoic tectonics are dominated by the development of the Alpine-Himalayan orogen at the boundary between the Eurasian Plate to the north and the African, Arabia, and Indian plates to the south. This orogen extends from the Mediterranean Sea in the West to the Sunda Arc in the East and is the classic example of an orogen constructed by accretion during continental underthrusting/subduction. In the following we present the paleogeographic evolution associated with the Tibetan-Himalayan orogen, and - more briefly - the Anatolian orogenic belt and the Alpine-Mediterranean region.

3.4.1. The Tibetan-Himalayan orogen

The Tibetan-Himalayan orogen (Fig. 1) is composed of various mountain belts and plateaus that resulted from the accretion of continental slivers originating from the northern margin of Gondwana against the southern margin of North China since the late Paleozoic (e.g. Kapp and DeCelles, 2019; Yin and Harrison, 2000). From south to north, the different accreted terranes and geological provinces include India, the Lhasa Terrane (referred here as “Southern Tibet”), the Qiangtang Terrane (referred here as “Central Tibet”), and the Songpan-Ganze accretionary complex overlain by the Hoh-Xil Basin (referred here as “Northern Tibet”). The orogen extends further north into the Qaidam and Tarim Basins, surrounded by the Pamir, Kunlun Shan, Tian Shan, Altyn Shan and Qilian Shan / Nan Shan mountain ranges (Fig. 10).

Tectonic models for the India-Asia collision remain debated. Recent

studies have narrowed the age of the collision to ca. 60–55 Ma based on the first input of Asia-derived material in the northernmost preserved continental rocks on the Indian Plate, in the Indian Foreland Basin (e.g. DeCelles et al., 2014; Garzanti, 2019; Garzanti et al., 2018; Hu et al., 2014). This age generates a dramatic difference between the amount of convergence of India and Asia since the collision — around 4000 km since 60 Ma — and the estimated amplitude of shortening in the Tibetan Plateau and Himalaya — totaling around 1500–2000 km (e.g. Dupont-Nivet et al., 2010; van Hinsbergen et al., 2011). Several models have been proposed to account for this mismatch. A first type of models invoke a “Greater India Basin” (Huang et al., 2015; van Hinsbergen et al., 2012, 2019). They propose that a terrane drifted off northern India in the Cretaceous, carrying ahead Greater Himalayan sequences, and was separated from mainland India by a wide oceanic basin. This small terrane collided with Asia at 60–55 Ma; the Greater India oceanic basin then subducted beneath Asia until the final India-Asia collision in the late Oligocene - early Miocene. Another family of models suggest a continuous subduction of the 2400 Km long Greater Indian continental crust below Asia (Ingalls et al., 2016; Searle et al., 2016). Arc collision models propose a first collision of India with an intra-oceanic arc at 60–55 Ma while subduction is kept along the Asian margin until a much later India-Asia collision. Various versions of this arc collision model have been proposed (Aitchison et al., 2007; Gibbons et al., 2015; Guilmette et al., 2012; Hébert et al., 2012; Jagoutz et al., 2015; Müller et al., 2016; Westerweel et al., 2019). These models invoke collision between India and Asia in the Late Eocene to Miocene, depending on the assumed magnitude of intra-Asian shortening. Finally, a set of “classic” models propose removal of continental lithosphere by lateral extrusion of continental blocks, wholesale continental subduction and very high estimates of overriding plate shortening (e.g. Cogné et al., 2013; Guillot et al., 2003; Molnar and Tapponnier, 1975; Replumaz and Tapponnier, 2003).

We propose here reconstructions following the different models. At 60 and 40 Ma, we have computed two different configurations of the Indian paleogeography, whereby we used the GPlates reconstruction of (van Hinsbergen et al., 2011, 2019) as basis: (1) the Greater India Basin model (Fig. 5, 6 and 7 and Fig. 11a; van Hinsbergen et al., 2012), and (2) a fully continental post 58 Ma Greater India collision with Asia, assuming wholesale continental subduction of several 1000s of km (Ingalls et al., 2016; see Fig. 11b). We have also explored the Arc collision model (Müller et al., 2016; Westerweel et al., 2019; see Fig. 11c) and the lateral extrusion model in which the Lhasa block is located further south (Replumaz and Tapponnier, 2003; Fig. 11d).

3.4.1.1. The Tibetan-Himalayan orogen 60 Ma. It has been proposed that topography in Tibet was already important before the India-Asia collision due to topographic build-up from previous terrane accretions and Cordilleran-style orogeny (Murphy et al., 1997), resulting in a high elevation “Lhasaplano” in southern Tibet as early as the Late Cretaceous (e.g. Kapp et al., 2007; Wen et al., 2008). This Lhasaplano would have built-up following increased India-Asia convergence, Gangdese and Kohistan-Ladakh magmatism, shortening and rapid exhumation in the

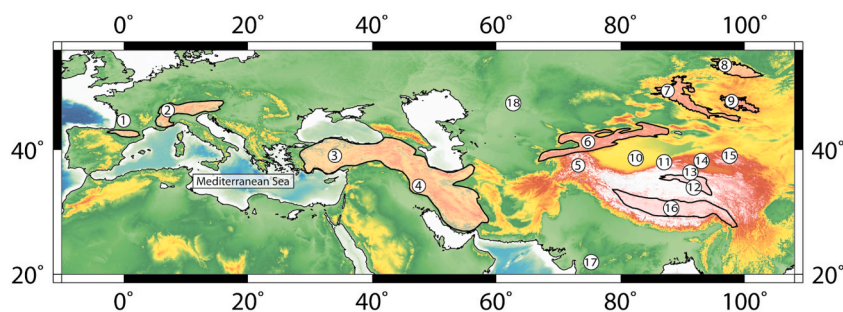


Fig. 10. Physiography of Eurasia. 1, Pyrenees; 2, Alps; 3–4, Anatolian, Zagros and other orogens; 5, Pamir; 6, Tian Shan; 7, Altai-Hangay-Sayan mountains; 8, Altai mountain; 9, Sayan mountain; 10, Hangay mountain; 11, Altyn Shan; 12, Hoh Xil Basin; 13, Kunlun Shan; 14, Qaidam Basin; 15, Qilian Shan and Nan Shan; 16, Lhasa Block; 17, Deccan Traps; 18, Turgai Region. (Modified from Choukroune, 1992; Dai et al., 2019; McQuarrie and van Hinsbergen, 2013; Schmid et al., 1996; Yin and Harrison, 2000).

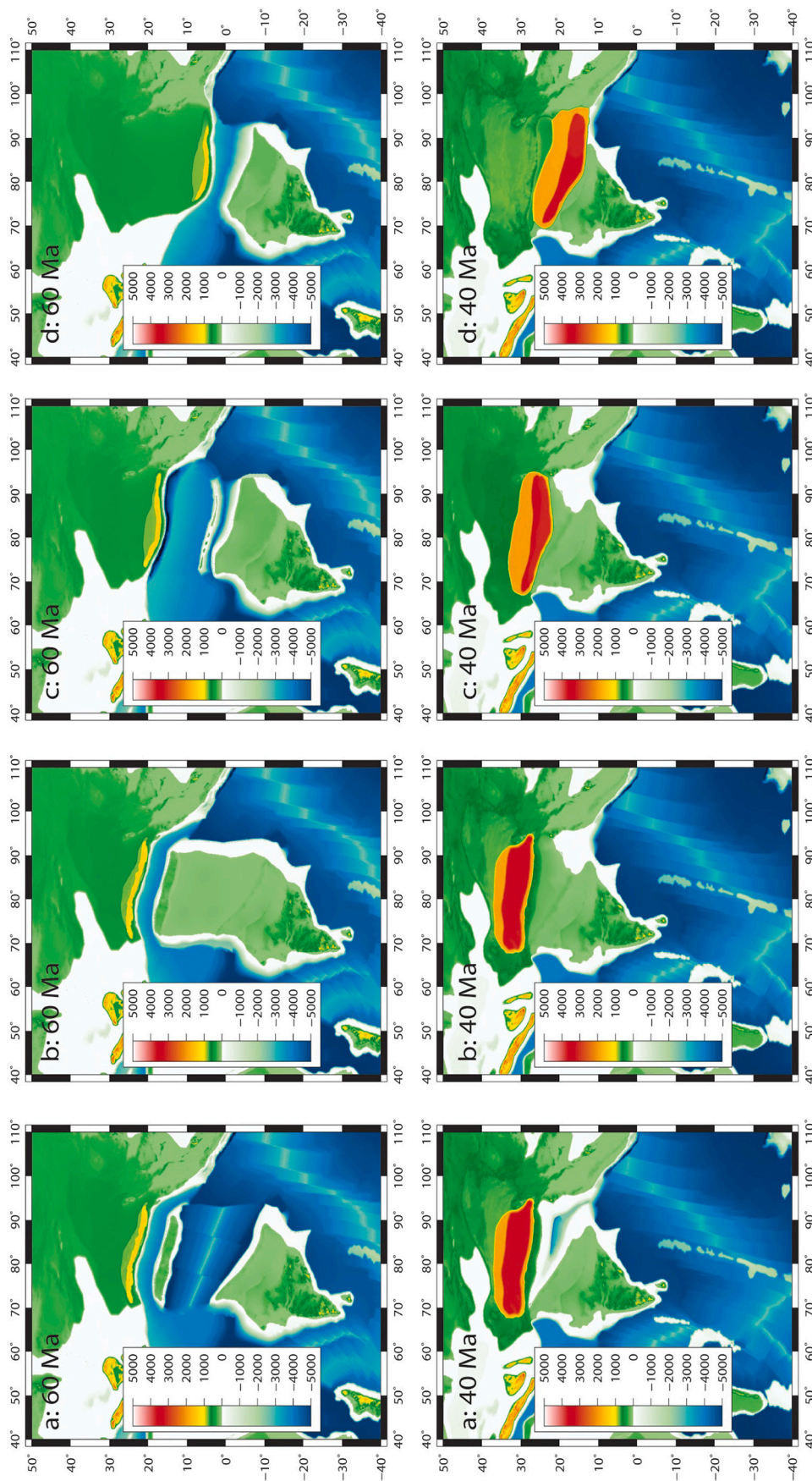


Fig. 11. Indo-Asia collision paleogeographies at 60 and 40 Ma according to various models: a) Double collision, first with an drifted fragment of Greater India, then with India after subduction of the Greater Indian Basin following van Hinsbergen et al. (2012, 2019); (b) Single India-Asia collision assuming collision age ca. 55 Ma; (c) India collision with a Trans-Tethyan arc and then with Asia (e.g. Jagoutz et al., 2015); and (d) India collision with Asia but with Lhasa block located at more southerly paleolatitudes (e.g. Cogné et al., 2013).

northern Lhasa Terrane and Qiangtang Terrane after 80–70 Ma (Chapman and Kapp, 2017; Kapp et al., 2007; Ravikant et al., 2009; Volkmer et al., 2014, p. 201; Wen et al., 2008). Further to the north in Central Tibet, it has been proposed that the Qiangtang Terrane formed a topographic relief since ca. 70 Ma, shedding detritus northward into the nonmarine Hoh-Xil Basin (Li et al., 2018; Staisch et al., 2014, 2016). Thermochronological data suggests that construction of the Central Tibetan Plateau began during the Late Cretaceous forming a conspicuous relief, but it was only later, during the Eocene, that the Tibetan Plateau formed a significant topographic high (e.g. Rohrmann et al., 2012; van der Beek et al., 2009; Wang et al., 2008). In northern Tibet, no major deformation is reported before the collision apart from local events possibly reactivating older structures (Jolivet et al., 2018; Morin et al., 2019; van Hinsbergen et al., 2015a, 2015b).

Paleoaltimetry data has suggested elevations ca. 4.000 m across the Lhasa and Qiangtang terranes near the time of initiation of the collision (e.g. Currie et al., 2016; Ding et al., 2014; Li et al., 2019) with relatively lower elevation to the north in the Hoh-Xil (Cyr et al., 2005; Miao et al., 2016; Polissar et al., 2009) and south in the proto-Himalaya (e.g. Ding et al., 2017; Leary et al., 2017). However, the interpretation of these data is still controversial. The primary nature of Eocene Tibetan oxygen isotopic records is questioned (Quade et al., 2020) and the use of modern isotopic lapse rates for paleoaltimetry estimates might significantly overestimate the actual topography (Botsyun et al., 2019). In addition, some stable isotopic records (Currie et al., 2016) are associated with fossils indicating lower elevation (Su et al., 2019) and their depositional age control has been revised to younger ages (e.g. Deng et al., 2019; Leary et al., 2018). These data overall suggest a more complex topographic development with pre-existing valleys and ranges instead a monotonic progression of plateau uplift (e.g. Laskowski et al., 2019). A precise description of paleotopography remains challenging to produce for this time slice.

Thus, we favored a conservative configuration in our reconstruction at 60 Ma with relatively low elevations (Fig. 5, Fig. 11a), with later, gradual uplift at 40 and 20 Ma, time slices for which pieces of evidence for high topography are more numerous. Our 60 Ma reconstruction displays a contiguous east-west trending volcanic arc located in the southern margin of Asia formed a relatively narrow mountain range at elevations between 500 and 1500 m. In central Tibet we also implemented an incipient plateau with elevations around 700 m. North of this, elevations are reduced to 500 m or less.

3.4.1.2. *The Himalayan-Tibetan orogen 40 Ma.* Structural evidence points to enhanced development of an elevated Central Tibetan Plateau in the Lhasa and Qiangtang regions during later Paleogene time (e.g. Kapp et al., 2007, 2005; van der Beek et al., 2009; Wang et al., 2014, 2008), although stable isotopic data yield contrasting results either suggesting complex topography combining low and high elevations and/or a more complex hydrological cycle affecting stable isotope paleoaltimetry (e.g. In northern Tibet, in the Hoh-Xil Basin and Kunlun Shan region, geological studies have shown late Eocene basin closure and exhumation, suggesting surface uplift) (Dai et al., 2019; Polissar et al., 2009; Staisch et al., 2016, 2014; Wang et al., 2017). Further north in the Qaidam and Tarim Basin, late Eocene increased subsidence and sea retreat is associated with tectonic activation along the Kunlun Shan (Bosboom et al., 2014b; Cheng et al., 2019; Kaya et al., 2019; Song et al., 2018), but apart from local ranges with elevations (e.g. Hoorn et al., 2012) significant surface uplift of those basins is not expected until later propagation of deformation in the Tian Shan and Qilian Shan in the Miocene (e.g. He et al., 2017; Zuzza et al., 2016).

We propose a 40 Ma reconstruction in which South and Central Tibet formed an incipient plateau with intermediate elevations at ca. 3500 m, and a moderate to low elevation paleosurface for Northern Tibet (Fig. 6, Fig. 11a).

3.4.1.3. *The Himalayan-Tibetan orogen 20 Ma.* Most thermochronology and paleoaltimetry studies indicates that the Central Tibetan Plateau attained high elevations by the early Miocene (e.g. Botsyun et al., 2019; Quade et al., 2011; Rowley and Currie, 2006; Wang et al., 2017). Important changes at this time include the growth of the Himalayas, enhanced since the early Miocene as suggested by a wide range of studies (e.g. Clift et al., 2008; Xu et al., 2018 and references therein), although some local lower elevation basins may have persisted in southern Tibet into the Miocene (e.g. DeCelles et al., 2018; Leary et al., 2017; Wang et al., 2013). To the north of Tibet, exhumation begins (or, in places, resumes) in the Tian Shan, Pamir, Kunlun, Altyn Shan, Qilian Shan, Nan Shan with infilling, uplift and closure of associated intermontane basins (Dai et al., 2019; Dedow et al., 2020; Sobel et al., 2013; Wang et al., 2017; Zuzza et al., 2016). We propose a 20 Ma reconstruction with wider and higher Tibetan Plateau than at 40 Ma, with elevations reaching beyond 4000 m. The Tian Shan, Pamir, Kunlun, Nan Shan and Qilian and intermontane basins north of Tibet are modeled at elevations around 1000–1500 m to reflect incipient range uplift before its further development later in the Miocene (Fig. 7).

3.4.2. *The central Eurasian proto-Paratethys Sea*

The extension of the proto-Paratethys epicontinental sea over Central Eurasia is particularly important for paleoenvironmental and biogeographic reconstructions, including the presence or absence of a N-S trending seaway (the Turgai Strait) that constituted the connection between the Neo-Tethys with the west Siberia interior sea (Akhmetiev et al., 2012) and through this, with the Arctic Ocean (Golonka et al., 2006). Although some paleogeographic maps have suggested that the Turgai Strait was closed at 40 Ma (www.deepmaptimes.com; Blakey, 2008), and terrestrial fossils are (mis?)placed in the strait at this time (Mihlbachler et al., 2004; www.paleobiodb.org). Geological data show three major sea transgressions in the proto-Paratethys in the Paleogene (Bosboom et al., 2017, 2014b, 2014a; Kaya et al., 2019). These studies suggest that the sea did not retreat sufficiently to close the Turgai Strait between the first and most extensive incursion (58–53 Ma) and the second one (46–41 Ma); however, the strait likely closed between the second (46–41 Ma) and the last (39–37 Ma) incursions, and remained closed after 37 Ma. Thus, we provide reconstructions with an open Turgai Strait at 60 Ma and closed at 20 Ma. At 40 Ma, we provide two maps, with an open or closed strait (see supplementary data).

3.4.3. *The Alpine-Mediterranean region and the Anatolian and Zagros orogens*

Cenozoic interaction between Africa, Iberia and Eurasia resulting in the orogenic growth in the Pyrenean-Alpine chain and basin segmentation and extension in the Mediterranean Sea which lead to the formation of several micro-basins (Choukroune, 1992; Dewey et al., 1989; Schettino and Turco, 2006; van Hinsbergen et al., 2014; Vissers and Meijer, 2012; Ziegler, 1987). Further East, the Anatolian and Zagros orogenic belts (Fig. 8), between the Eastern Mediterranean Sea and the Gulf of Oman, is within the collision zone between Arabia-Nubia to the south and Eurasia to the north (Bird, 2003). The current configuration results from the subduction of the Neotethyan Oceanic crust and collision between the Arabian and African Plates and the Eurasian Plate (Agard et al., 2007; Bird, 2003; Gürer and van Hinsbergen, 2019; Kuscus et al., 2010; McQuarrie and van Hinsbergen, 2013; Mouthereau et al., 2012; Reilinger et al., 2006; van Hinsbergen et al., 2020). The Arabian and Nubian Plates are being underthrust/subducted below the western Mediterranean, Anatolian, Aegean and Zagros orogens (Bird, 2003; McQuarrie, 2004; Reilinger et al., 2006; van Hinsbergen et al., 2020).

Our paleogeographic reconstructions of these regions are simplified from Barrier et al. (2018) and Popov et al. (2004), and follow the tectonic models of McQuarrie and van Hinsbergen (2013) and van Hinsbergen et al. (van Hinsbergen et al., 2014, 2020). Our paleogeographic reconstructions in this region are mainly restricted to the location of paleoshorelines and do not consider Late Miocene-Pleistocene uplift

(Cosentino et al., 2012; Fernández-Blanco et al., 2019; Ögretmen et al., 2018) which have been proposed to be a responses to lithospheric delamination (Bartol and Govers, 2014; Göğüş et al., 2017), slab breakoff (Portner et al., 2018; Schildgen et al., 2018), and to the arrival of the subducting African margin to the southern Taurides (McPhee et al., 2019).

4. Antarctica and Greenland

4.1. Antarctica and Greenland at 60 Ma and 40 Ma

The common approach to reconstruct past Antarctic landscape before ice-sheet spreading has been to use fossil databases (e.g. Lazarus and Caulet, 1993) and correct the present-day topography to account for the isostatic response to the ice mass removal (e.g. DeConto and Pollard, 2003). This approach results in a large part of the Antarctic continent being submarine before the EOT, particularly in West Antarctica (Fig. 12) around the West Antarctic Rift System (e.g. Blakey, 2008; DeConto and Pollard, 2003; Lazarus and Caulet, 1993). However, recent studies have suggested that most of the continent was above sea level before 34 Ma (Hochmuth et al., 2020; Wilson et al., 2012; Wilson and Luyendyk, 2009), by integrating erosion, thermal subsidence, shelf sedimentation and plate tectonic processes. In Antarctica, Hochmuth et al. (2020) presented a paleobathymetry, which could be complemented with the paleotopography from Paxman et al. (2019). However, their combination is made difficult by discrepancies. Paxman et al. (2019) suggests that the Ronne-Filchner and Ross Ice shelf were below sea level at 34 and 23 Ma as well as a sea interior that separates the Antarctic Peninsula from the Ellsworth Whitmore block, while Hochmuth et al. (2020) shows that both ice shelves as well as the west coast of west Antarctica (Antarctic Peninsula, Thurston island and Marie Byrd Land blocks) were above sea level at 34 Ma and the Ronne-Filchner and Ross Ice shelf were still above sea level at 21 Ma. Because of these differences resulting in an artificial internal basins at 34 Ma, we preferred keeping the paleotopography from Wilson et al. (2012). We use this Antarctic paleotopographic reconstruction with minor modifications in the South Shetland Islands to take into account the presence of Cenozoic

volcanism, fossilized trees and bird tracks in the archipelago (Birkenmajer and Zastawniak, 1989; Mansilla et al., 2012; Smellie et al., 1984; Torres, 1984) and the history of the Bransfield Strait which was closed at 60 Ma (Galindo-Zaldívar et al., 2014; Pelayo and Wiens, 1989; Solari et al., 2008). For Greenland, we have simply taken into account the isostatic rebound due to ice removal (Fig. 5, Fig. 6). We have also combined our paleotopographies at 60, and 40 Ma, with the recent published Greenland paleotopography from Straume et al. (2020) (see supplementary data).

4.2. Antarctica and Greenland 20 Ma

After the spread of Antarctic ice-sheet, and in the absence of data for 20 Ma, we use the current Antarctic topography. We use today's topography for Greenland as well, assuming it was glaciated at 20 Ma. For paleoshorelines, Golonka et al. (2006) suggested at 20 Ma a sea reentrant in the Ross Sea that extended up to 400 km in the interior of the Amundsen-Shackleton Coast. However, thermochronological and sedimentological data show that exhumation of the Transantarctic Mountains started before the Miocene (Fitzgerald, 2002; Olivetti et al., 2013; Zattin et al., 2010, 2014). Moreover, the drop in CO₂ at 23 Ma suggests that cold conditions predominated during the Early Miocene with ice-sheets expanding across the Antarctic continental shelf (McKay et al., 2016). The presence of the Transantarctic Mountains and the extension of the ice-sheet preclude the existence of the sea reentrant proposed by Golonka et al. (2006). In the Scotia Arc we have adapted the paleoshoreline presented by Eagles and Jokat (2014), while in other regions we have adjusted the paleoshoreline to be consistent with the fossil database (Fig. 7, paleobiodb.org). As for 60 and 40 Ma, we have also combined our 20 Ma paleotopography with the recent published Greenland paleotopography from Straume et al. (2020) (see supplementary data).

5. Discussion

5.1. Cenozoic topography, continent weatherability and climate

The most conspicuous result of our paleoreconstructions is a drastic increase in orography associated with the Cenozoic development of major mountain ranges (Fig. 13). The Cenozoic is also marked by one of the most dramatic decrease of atmospheric CO₂ and associated global cooling, starting at the end of the Early Eocene Climatic Optimum ~50 million years ago (Anagnostou et al., 2016; Zachos et al., 2001). Though many factors such as long-term volcanic degassing have been proposed as a driver for CO₂ drawdown over the period (Hoareau et al., 2015), most Cenozoic carbon cycle models require changes in continent and/or sea floor weatherability to explain this drop (Krissansen-Totton and Catling, 2017; Caves-Rugenstein et al., 2019). Two main mechanisms have been proposed to drive the increase of terrestrial weatherability after 50 Ma:

1. Increased fresh minerals exposure by tectonically-driven denudation along the Neo-Tethys margin, particularly in the Himalayas, where monsoonal dynamics enhanced denudation (Raymo and Ruddiman, 1992)
2. The emplacement of weatherable material through the equatorial belt, such as with the drift of the Deccan Taps of India (Kent and Muttoni, 2013) or the obduction of ophiolitic belts and volcanic arc material along the Neo-tethys subduction margin (Jagoutz et al., 2016; Macdonald et al., 2019).

Fig. 13a and b displays the percentage of emerged land (submerged land) and the percentage of emerged land per Myr per 10° latitudinal band. The distribution of emerged land surface significantly changed between 60 and 20 Ma at low latitudes. The northward motion of India redistributed emerged lands from the low southern latitudes to the low

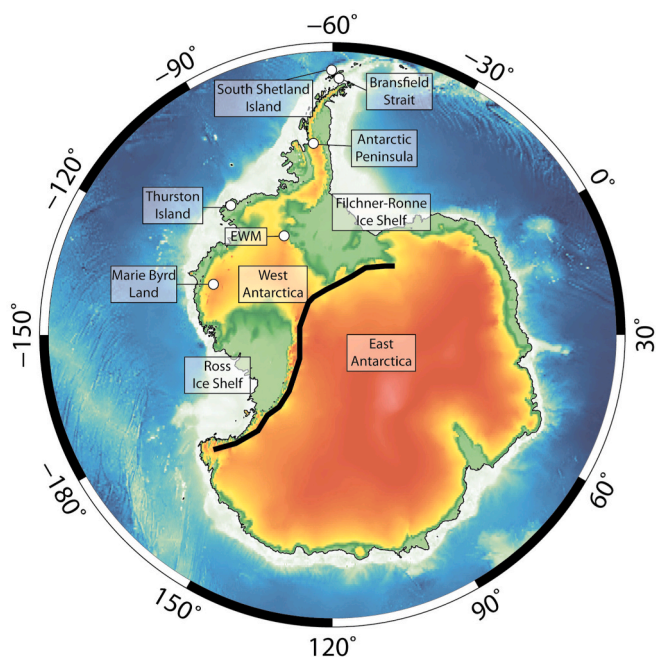


Fig. 12. Physiography of Antarctica. EWM, Ellsworth-Withmore Mountains. Thick black lines represent the Transantarctic Mountains. (Modified from Poblete et al., 2011).

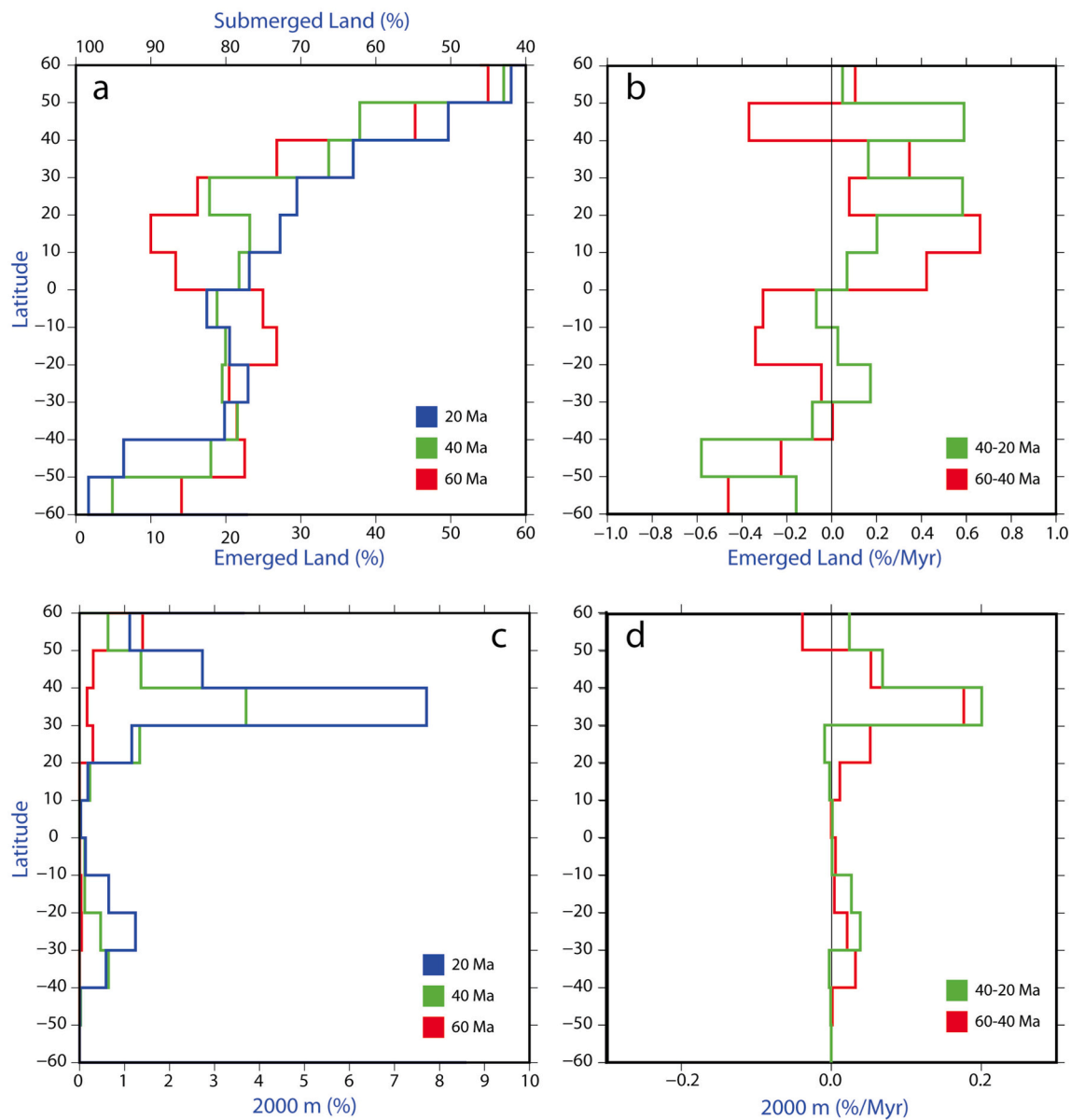


Fig. 13. a-b) Percentage of land above sea level and flux of emerged land (in %/Myr) per 10° latitudinal band c-d) Percentage of land above 2000 m flux of land above 2000 m (in %) binned for each 10° latitude band. Both figures are calculated following the Great India Basin tectonic scenario (see text for discussion).

northern latitudes, between 60 and 40 Ma, which itself should not have had much impact on weathering on the Indian Crust itself; however, the drying of the Northern Indian Seaway during this time window, covering most of North Indian Continental shelf, increased the amount of total land mass at low latitudes (Fig. 13). Two other events significantly increased the amount of emerged areas between 0 and 30°N: the long-term shrinkage of the Paratethys Sea, north of the Neotethyan Subduction zone, and the northward motion of Africa, associated with the retreat of its northern epicontinental seas, between 60 and 20 Ma. During this time window, the surface of emerged land masses increased by 50.4% between 0 and 30°N. This increase alone could have had a significant impact on weathering fluxes without evoking the presence of highly weatherable volcanic and ophiolitic rocks in this latitudinal band.

It is harder to evaluate potential changes of denudation through time with our approach as our model does not have the spatial resolution to reproduce steep gradients – where most denudation occurs at global scale (Larsen et al., 2014). Fig. 13b displays the percentage of areas above 2000 m, and shows a massive increase (90% between 60 Ma and 40 Ma and 42% between 40 Ma and 20 Ma) of high altitude areas

between 20 and 40°N during the period of reconstruction. Most of this altitude gain is associated with Tibetan Plateau growth in our reconstruction – a low relief orogen. However, increased uplift at its margin (Himalayas) and birth and growth of surrounding mountains ranges (Pamir, Tian Shan, Kunlun) during this time period can have had a major impact, potentially quantifiable by using our paleogeographic maps with GCM-coupled carbon models like GEOCLIM (Goddéris et al., 2017; Maffre et al., 2018).

5.2. Limitations and uncertainties

Limitation and sources of uncertainties in the reconstructions are obviously numerous. They are identified and organized below according to different features involved in the making of a paleogeographic map: 1) plate tectonic models; 2) paleobathymetry; 3) paleoshoreline; and 4) paleotopography.

The basis for any paleogeographic model is the plate tectonic model on which it is based and most reconstructions commonly use a set of rigid tectonic plates (Matthews et al., 2016; Müller et al., 2016; Seton

et al., 2012); this represents a first source of uncertainty because of the lack of rigidity of continental margins (e.g., the Patagonian bend and Bolivian Orocline in the Andes or the Basin and Range extension in North America). Including evolving shapes for plate margins (for example, Müller et al., 2019) adds uncertainties related to the shape restoration process. Latitudinal resolution of paleomagnetic data is around 5°. Uncertainties in shortening calculations have been calculated in the order of 20% in well constrained cross sections (Allmendinger and Judge, 2013; Pueyo et al., 2004). This is particularly critical in the restoration of the Central Andes and South Asian margin, where Cenozoic shortening and deformation have been significant. For example, in the Bolivian Orocline, 400 km of shortening has been calculated near the Arica bend, which led to uncertainties of at least 80 km of this part of the margin. In the case of the south margin of Asia before the Indo-Asia collision, a shortening estimation of around 1000 km has been calculated (van Hinsbergen et al., 2019), which leads to an uncertainty of at least 200 km. Ongoing work in these geodynamically active regions - and many others - consistently generates new data that will potentially improve these restorations (e.g. Boschman et al., 2019; Westerweel et al., 2019).

The paleobathymetry has intrinsic uncertainties due to differences between the observed age and gridded age, estimations of sediment thickness and the age-depth model used (see Müller et al., 2008a for details). The original paleobathymetry, however, does not consider the development of several small basins related to local tectonic features that were manually adjusted. For example, the Greater Indian Basin is not associated with any paleobathymetry estimate in the Müller et al. (2008a) reconstructions; we estimated depths from -5000 to -2600 m in this region, following a depth-age relationship formula (Baatsen et al., 2016). Maximum depths, however, could reach more than -6000 m if we consider other age-depth correlations (e.g. Chung-Hwa et al., 1990).

Determining the ancient paleoshoreline is also an important source of uncertainty. Our approach was to take Golonka et al. (2006) paleoshoreline presented in Heine et al. (2015), and then change it for each period accordingly to margin deformation, the fossil database, and geological data. The first source of errors here is the rotation and restoration of the paleoshorelines to their past position. Shorelines were originally drawn on reconstructed paleogeographies according to a previous kinematic rotation model (Golonka et al., 2006). We repositioned them to present day using another rotation model (Heine et al., 2015), and rotated them again into the desired time-slice (60, 40 and 20 Ma) with our own model. This required re-adjusting the shorelines to follow new continental positions, but also new continental boundaries defined in the rotation model. Another related source of error is that the paleoshorelines of Golonka et al. (2006) have a low temporal resolution because they were reconstructed per geological stage or Epoch. In addition, as pointed out by Heine et al. (2015), the information used for the construction of the different paleoshorelines available are sometimes proprietary, and it is difficult to check afterwards the accuracy of the reconstructions. A dramatic example of uncertainty in past reconstructions are the paleoshorelines of South America, which include a huge sea reentrant until the Eocene in previous reconstructions, although it was likely only present until the middle Maastrichtian (Sempere et al., 1997). Here, we adjusted paleoshorelines for each period of time in which the reconstruction was done.

The ultimate and most difficult task in creating a paleoDEM is evaluating the paleotopography. Stable isotope datasets, although still relatively rare, constitute promising quantitative estimations of paleoelevation. However, stable isotopes are sensitive to temperature changes, moisture source, relative humidity, post-condensational effects, changes in paleoclimate, and may be biased by diagenetic and/or tectonic effects, which results in high variability of results and complicates their interpretation (Botsyun et al., 2016, 2019; Ehlers and Poulsen, 2009; Licht et al., 2017; Rowley and Garzzone, 2007). Geological, structural and geochronological data are much more important and widespread, however they only constitute qualitative approximations

and cannot be used to directly determine paleoelevation estimations. These limitations are critical to correctly estimate the surface paleoelevation of the three main Cenozoic orogens: The Tibetan-Himalaya, the Andes and the North American Cordillera. As mentioned in the previous sections, in the Tibetan-Himalayan orogen, uncertainties are most important at 60 and 40 Ma with predicted maximum elevations between 1000 m to 4500 m for both periods. In Western North America, the existence of a Nevadoplano at 60 Ma with maximum elevations around 4500 m is better documented, although the southerly extent of the Nevadaplano remains poorly defined and recent work suggests controversial interpretations (see associated section above). There is more consensus that the Andes formed a low elevated range at 60 Ma, but more debate on the more recent evolution.

Finally, the combination of available data makes depicting uncertainties in a quantitative manner impractical. Although we provide means to assess the data we used, quantification of uncertainty remains a future frontier for paleogeographic research.

5.3. Potential improvements and expected progress

Potential improvements should focus on topographic reconstructions that are the biggest source of uncertainty. Our general approach following previous work (Baatsen et al., 2016) has been to rotate modern topography to its past position and modify it according to geological data. This implies that our reconstructions may bear features that should not be there, especially in areas that have not been worked on in detail or that are lacking relevant data. We have concentrated here on the main orogenic regions in the considered timeslices but still left out many that will require updates (e.g. Australia, Southeast Asia, the western Pacific rim, the Caribbean region, the Mediterranean region, and the NW Pacific and Aleutian basin). We hope our effort will spark collaborations with geologist experts in these regions that could provide valuable feedback. To stimulate this exchange we offer the reconstructions through a platform containing interactive paleogeographic tools associated with this publication (<https://map.paleoenvironment.eu/>). The tool consists currently of interactive maps, which can be zoomed, panned in different projections and downloaded in different formats (image or raster data). It is foreseen to be extended with other tools that aid constructing paleogeographic reconstructions (Ruiz et al., 2020).

In the areas we considered in detail, we generated new topography by simply increasing or decreasing linearly the modern digital elevations models (DEMs), sometimes radically to fully form or obliterate mountain ranges (e.g. in Africa). Resulting topographies usually yield unrealistic relief and drainage patterns, thus limiting the applicability of the reconstructions. This can be improved by developing more advanced tools enabling to generate various types of topographies (basins and mountains) with more realistic drainages based on simple governing physics such as the stream power laws (e.g. Braun and Willett, 2013; Cordonnier et al., 2019; Ruiz-Villanueva et al., 2019). Furthermore, rather than modifying modern DEMs, topographic features may be fully generated based on geodynamic setting and surface processes, in turn constrained by geologic data (e.g. Frigola et al., 2018; Sewall and Sloan, 2006; van der Linden et al., 2020).

As part of a continuous collaborative effort building paleogeographies and associated databases, we foresee that the addition and consideration of more and new data reconstructed to its past position with dedicated reconstruction tools (Baatsen et al., 2016; Ruiz et al., 2020; van der Linden et al., 2020) will certainly help to define more comprehensive, accurate and reliable paleoDEMs. The development and comparison of more reconstructions at different time slices, increasing the resolution in the Cenozoic and going further back in time, will necessarily add relevant data for a continuous and integrative overview of paleotopographies. In particular, the formation of features in the distant past that are potentially preserved 10^7 to 10^8 yrs. such as rift margins and orogenies. Another high potential approach, is using sedimentary budgets to estimate paleoreliefs (e.g. Baby et al., 2020; Roberts

and White, 2010; Yuan et al., 2019). A related aspect is the reconstruction of shelf and deep marine bathymetry and how they were influenced by terrestrial drainages. Considerable progress may be achieved with these additional constraints and tools acknowledging that they also require ground proofing from the sort of data provided in the present study.

6. Conclusion

We produced a set of global Cenozoic paleogeographic maps at 60, 40 and 20 Ma following a systematic approach based on a coherent plate tectonic model. These reconstructions are primarily designed to provide boundary conditions for regional and global climate models to test and explore Cenozoic paleoclimate. In particular, our paleogeographic maps show that emerged land surface areas increased by 30% and shifted from a low- to a high-relief regime in northern low latitudes between 60 and 20 Ma. These two processes are likely significant enough to partly contribute to the Cenozoic atmospheric CO₂ drawdown; our paleogeographic maps, in combination with carbon cycle models, provide key boundary conditions to test these mechanisms.

To take into account current paleogeographic controversies on the Indo-Asia collision, we provide four sets of reconstructions covering different tectonic scenarios at 60 and 40 Ma. Creating different paleoDEMs for competing tectonic models may contribute to resolve controversies by exploring their respective implications on climate, mantle dynamics, or paleobiodiversity that can be tested by field data and models. For example, climate models using various paleoDEM will result in different patterns of Asian monsoons and aridification that can be compared to paleoenvironmental proxy records. Thereby, paleoDEMs may ultimately improve our understanding of the underlying surface and tectonic processes that helped to build the past relief of the Earth.

This work builds on a wealth of previously published paleogeographic maps (e.g., Baatsen et al., 2016; Blakey, 2011; Golonka et al., 2006; Popov et al., 2004; Scotese, 2001; Scotese and Golonka, 1997) and an extensive review of geological constraints, with as a novelty to provide them as a consultable interactive database (<https://map.paleoenvironment.eu/>). Our global compilation approach is naturally bound to oversee important regions of the world, miss large portions of the literature, key datasets and even methods; we view this effort as another step of a long-term work to improve paleoDEMs through geological time. Paleotopographic maps are necessarily products of a collaborative effort, and these sets of maps are a starting point for future improvements. We plan to achieve this with regular updates on results and methods relayed on an interactive platform that will, hopefully, promote collaborations with regional experts and generate open source paleogeographic resources. We therefore do not consider the resulting paleoDEMs as comprehensive representations but rather as works in progress, especially given that this first publication will be revised and improved as new data comes available.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

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