The Atlantic Jigsaw Puzzle and the geoheritage of Angola

Louis L. Jacobs[1], Stefan Schröder[2]*, Nair de Sousa[3], Richard Dixon[2], Edoardo Fiordalisi[2], Arthur Marechal[4,5], Octávio Mateus[4,5], Pedro Claude Nsungani[6], Michael J. Polcyn[1], Gustavo do Couto Ramos Pereira[2], Nathan Rochelle-Bates[2], Anne S. Schulp[7,8], Christopher R. Scotese[9], Ian Sharp[10], Carlos Gaudari Silvano[4,5], Roger Swart[11] and Diana P. Vineyard[1]

[1]Roy M. Huffington Department of Earth Sciences, Southern Methodist University, Dallas, Texas 75275, USA

[2]Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK

[3]Department of Geosciences and Technology, African Circular Business Alliance, Comuna de Camama, No C-2-1, Luanda, Angola

[4]Museu da Lourinhã, 2530-158 Lourinhã, Portugal

[5]GEOBIOTEC, Department of Earth Sciences, NOVA School of Science and Technology, Universidade NOVA de Lisboa, Campus de Caparica, 2825-149 Caparica, Portugal

[6]Departamento de Geologia, Faculdade de Ciências, Universidade Agostinho Neto, 374J + R8F, Luanda, Angola

[7]Naturalis Biodiversity Center, Darwinweg 2, 2333 CR Leiden, The Netherlands

[8]Faculty of Geosciences, Utrecht University, Princetonlaan 8A, 3584 CB Utrecht, The Netherlands

[9]Department of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois 60208, USA

[10]Equinor ASA, PO Box 7200, Bergen, Norway

[11]BlackGold Geosciences cc, PO Box 24287, Windhoek, Namibia

LLJ, 0000-0002-7735-3678; SS, 0000-0001-5464-0108; ASS, 0000-0001-9389-1540; CGS, 0000-0003-4998-797X

*Correspondence: stefan.schroeder@manchester.ac.uk

Abstract: The jigsaw-puzzle fit of South America and Africa is an icon of plate tectonics and continental drift. Fieldwork in Angola since 2002 allows the correlation of onshore outcrops and offshore geophysical and well-core data in the context of rift, sag, salt, and post-salt drift phases of the opening of the central South Atlantic. These outcrops, ranging in age from >130 Ma to <71 Ma, record Early Cretaceous outpouring of the Etendeka–Paraná Large Igneous Province (Bero Volcanic Complex) and rifting, followed by continental carbonate and siliciclastic deposition (Tumbalunda Formation) during the sagging of the nascent central South Atlantic basin. By the Aptian, evaporation of sea water resulted in thick salt deposits (Bambata Formation), terminated by seafloor spreading. The Equatorial Atlantic Gateway began opening by the early Late Cretaceous (100 Ma) and allowed flow of currents between the North and South Atlantic, creating environmental conditions that heralded the introduction of marine reptiles. These dramatic outcrops are a unique element of geoheritage because they arguably comprise the most complete terrestrially exposed geological record of the puzzle-like icon of continental drift.

The purpose of this contribution is to emphasize a well-known observation realized by authors even before Wegener (1966): the puzzle-like fit of the western coast of Africa with the eastern coast of South America. Our approach is to view the southern coast of Angola (Figs 1 & 2) as a unique region of geoheritage due to its remarkable documentation of the major phases of opening and growth of the central South Atlantic Ocean, defined originally by marine geophysical models and well-core analysis (Fig. 2). To our knowledge, the Angolan coast is the only place that preserves relatively easily visited

From: Clary, R. M., Pyle, E. J. and Andrews, W. M. (eds) *Geology's Significant Sites and their Contributions to Geoheritage*. Geological Society, London, Special Publications, **543**,
https://doi.org/10.1144/SP543-2022-301

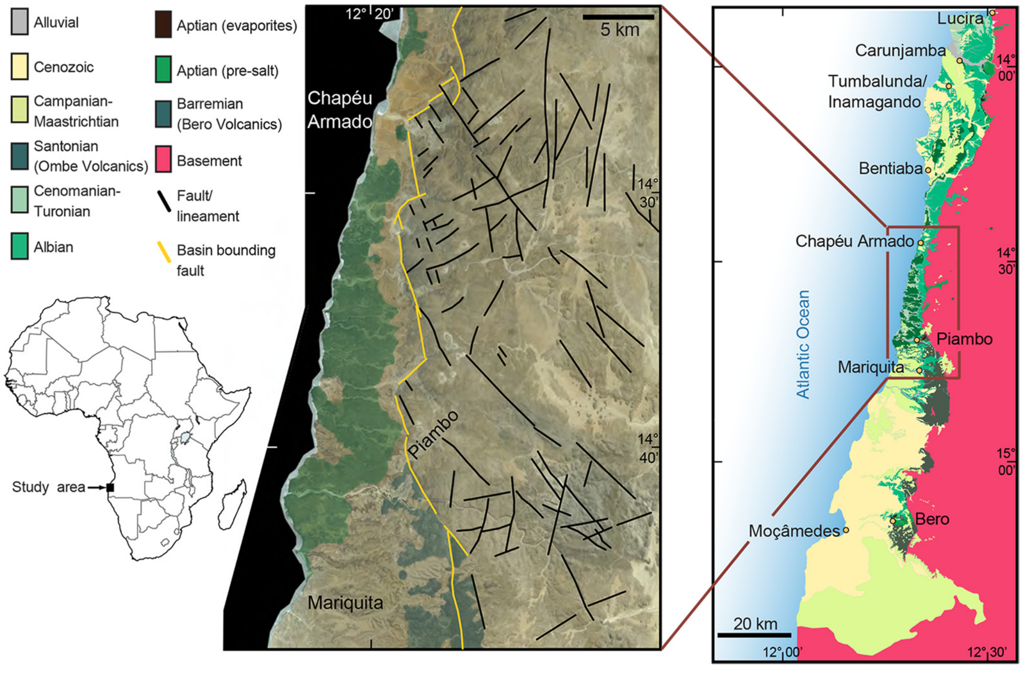

Fig. 1. Geological map of the Namibe Basin (right) with key localities mentioned in the text indicated. The satellite image (left) shows detail from the Piambo–Chapéu Armado–Bentiaba area, highlighting the trace of the basin-bounding fault and the distribution of volcanics in the area. A selection of faults, fractures and lineaments is shown in the basement in the east. These are selected from over 500 such structures determined through detailed satellite imagery mapping. Source: Satellite imagery from Google Earth.

onshore outcrops that reflect this geologically significant chapter in Earth history.

J. Tuzo Wilson (1963) popularized plate tectonics by using the descriptive and easily visualized term ‘jigsaw-puzzle fit’ to describe the Atlantic coasts of Africa and South America (Fig. 2). Angola is at the centre of this jigsaw puzzle, and the geology of Namibe Province in southern Angola has geohistorical and geoheritage significance. The study of geology and of fossils in Angola has been reinvigorated in recent years, following the end of the civil war. Fossils are portable elements of geoheritage, and therefore worthy of perpetual care, so we include them here for their evolutionary, environmental, ecological, and palaeobiogeographical geoheritage value as it relates to the opening of the South Atlantic.

Opening of the central South Atlantic Ocean

A useful framework for the opening of the central South Atlantic was presented by Quirk *et al.* (2013). The sequence of events began with the eruption of huge amounts of lava while Africa and South America were still conjoined (Figs 2–4). These flood basalts are part of the Etendeka–Paraná Large Igneous Province (LIP) and date from about 134 to 131 Ma (Fig. 3; Valanginian–Hauterivian, Renne *et al.* 1996; Jerram *et al.* 2019). Volcanic outpouring, crustal extension, and rifting formed extensional fault basins filled with alluvial, fluvial, and lacustrine deposits interbedded with basalt. With the cessation of rifting at approximately 121 Ma (Quirk *et al.* 2013; Quirk and Rüpke 2018), faulting ceased and the nascent ocean basin isostatically sagged, creating an early Aptian subaerial unconformity (Figs 2–4). Shallow-water lacustrine carbonates and siliciclastics were deposited (Fig. 3). Later in the Aptian, ocean water began to leak in to fill the subsiding basin, and then evaporated in extensive saline lakes to leave behind a great thickness of salt (2 to more than 6 km; Figs 2–4; Tedeschi *et al.* 2017; Quirk and Rüpke 2018). Following the cessation of salt deposition, the development of more open ocean conditions began about 113 Ma (Norton *et al.* 2016). Seafloor spreading began at the nascent Mid-Atlantic Ridge (Fig. 4). As the ocean basin widened through seafloor spreading it became fully flooded. The final phase was the sundering of the Equatorial Atlantic Gateway (EAG), separating the easternmost portion of what is now Brazil from the Bight of Benin and Gulf of Guinea. New ocean currents formed in

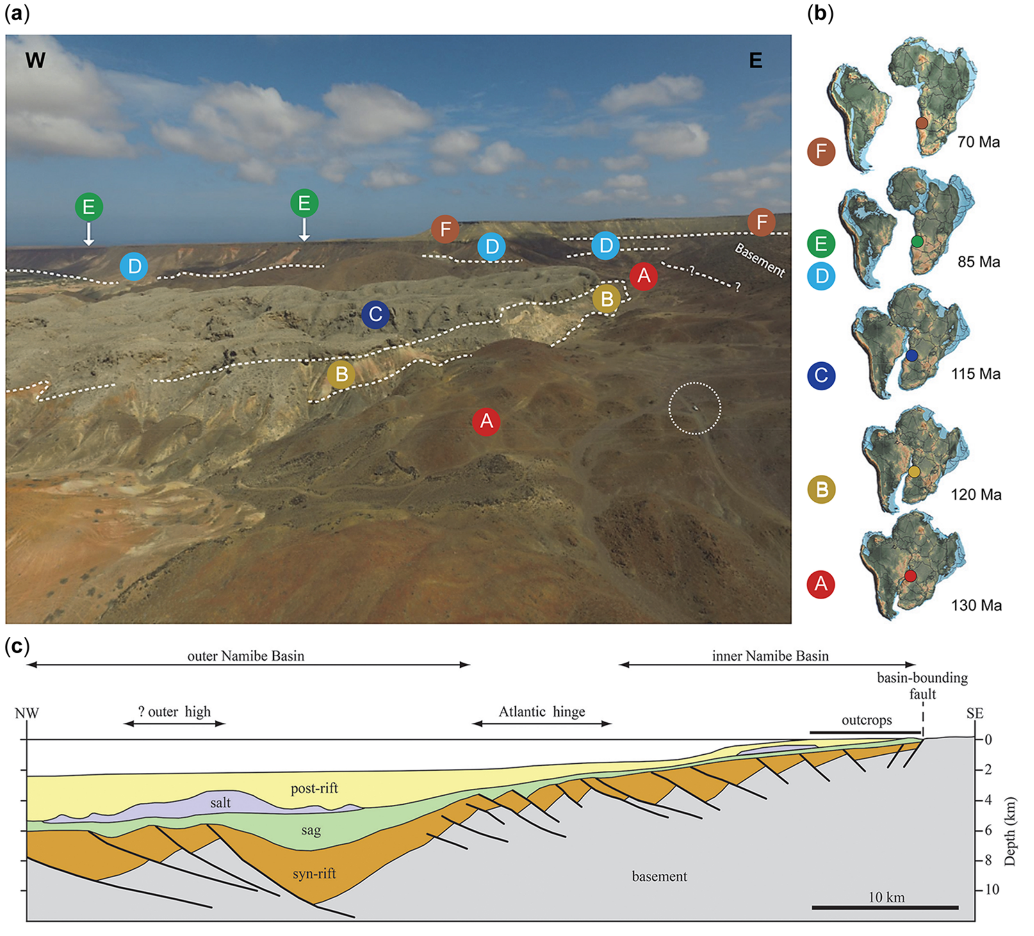

Fig. 2. (**a**) Outcrops near Piambo showing syn-rift basal volcanics of the Bero Volcanic Complex (A), unconformably overlain by sag phase carbonate and siliciclastic deposits of the Tumbalunda Formation (B), followed by the Bambata Formation salt (C). Overlying the salt are the marginal-marine Binga Member and the conglomeratic Giraul Member of the Piambo Formation, followed by the marine Salinas Formation (D), then by the volcanic Ombe Formation (E), dated to 88 Ma at Piambo, but younger to the north. Atop the Ombe, marine siliciclastics of the Baba and Mocuio formations (F) containing fossil reptiles and other vertebrates are correlated with similar Campanian and Maastrichtian fossiliferous beds at Bentiaba (83–72 Ma). Note that Baba and Mocuio formations overstep Precambrian basement (upper right of photograph). Truck (white speck in circle) for scale. (**b**) Palaeogeographical maps (colour keyed by letter) show the position of South America and Africa during the syn-rift phase (130 Ma; Bero Volcanic Complex, A), and the pre-salt sag phase (120 Ma; Tumbalunda Formation, B). The 115 Ma palaeogeographical map depicts the continental arrangement a few million years after Bambata salt (C) deposition ceased and seafloor spreading began (Giraul Member of the Piambo Formation and Salinas Formation, D). 85 Ma falls within the post-salt volcanic interval (Ombe Formation, E). By 70 Ma, the central South Atlantic Ocean had grown to approximately half the width of the modern Atlantic Ocean (Mocuio Formation, F). (**c**) A diagrammatic seismic line through the central part of the Namibe Basin to illustrate the onshore and offshore structure of the basin. The Namibe Basin outcrops are landward of the Atlantic hinge zone (necking domain). Rotation along this hinge created a westward-thickening wedge of sag and post-rift sediments. The outer Namibe Basin is located on hyperextended continental crust, which passes further west to oceanic crust. Seaward-dipping reflectors of proto-oceanic crust (SDRs), if present, would lie seaward of this diagram. Only the uppermost portions of the sag deposits are preserved onshore. The onshore salt thickness (some 30 m) is exaggerated to show its presence. Source: (a) drone photograph by Roger Swart; (b) palaeogeographical maps modified from C.R. Scotese (2021); (c) redrafted from Moragas *et al.* (2023).

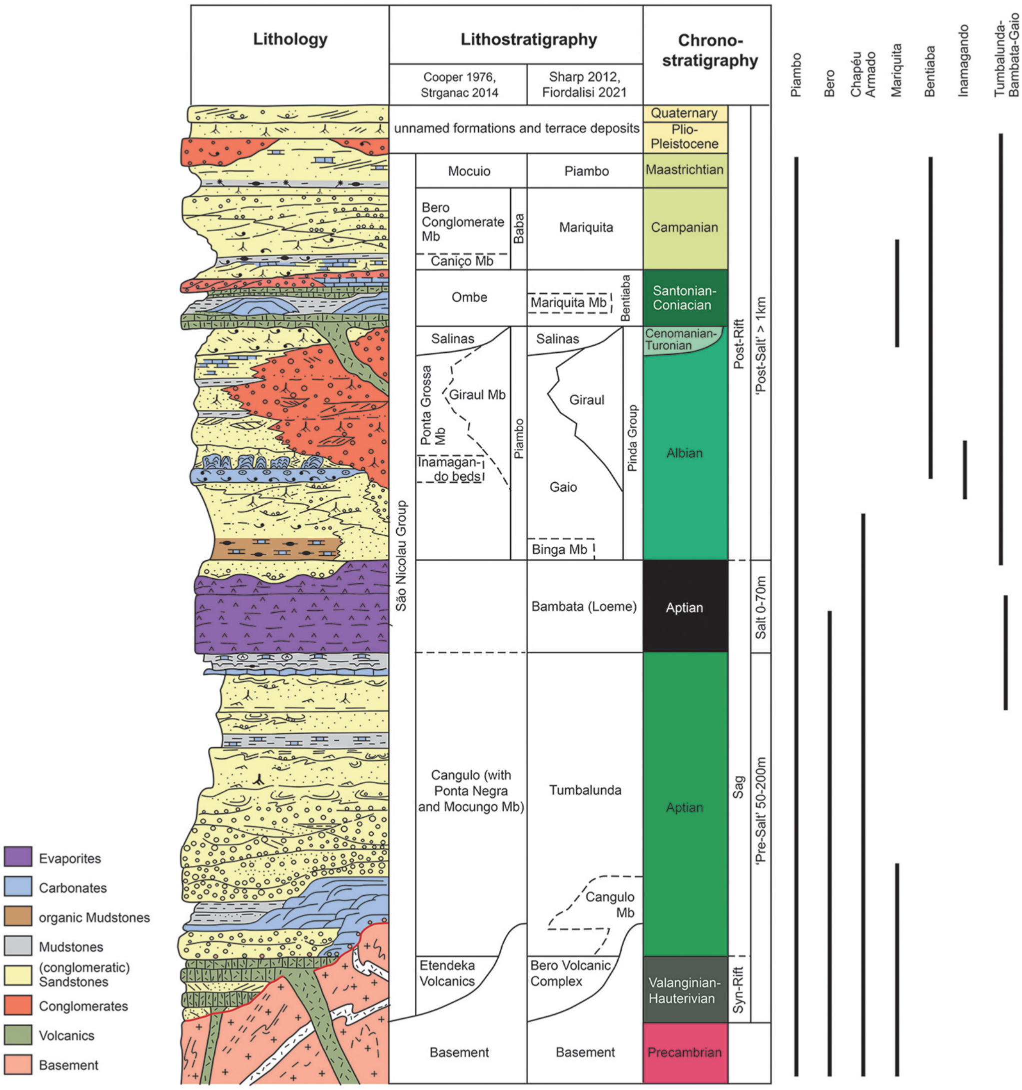

Fig. 3. Generalized stratigraphy of the Namibe Basin. Lithostratigraphy was first established by Cooper (1976), modified by Cooper (2003, 2018) and followed by Strganac *et al.* (2014*a*). For comparison, the stratigraphy of Sharp *et al.* (2012), followed by Fiordalisi *et al.* (2021), is shown. Colours in chronostratigraphy column match mapped units shown in Figure 1. Stratigraphic range of significant localities described in text is shown on right.

the now conjoined North and South Atlantic oceans, transforming the water column and its ecology.

The geological model as seen on land

Piambo (Fig. 2)

This discussion of onshore exposures begins at Piambo, near the south end of the study area. The salient observations here are the basal volcanic complex (Bero Volcanic Complex, part of the Etendeka–Paraná LIP; Fig. 3). The eroded irregular surface of these volcanic rocks represents the 121 Ma subaerial unconformity of the central South Atlantic basin. It is locally covered by metre-scale domal carbonate build-ups (Fig. 3; Fiordalisi *et al.* 2021). These and similar carbonate buildups are common throughout the Namibe Basin (see Bero and Chapéu Armado localities below) and represent precipitation of carbonate around groundwater resurgences and

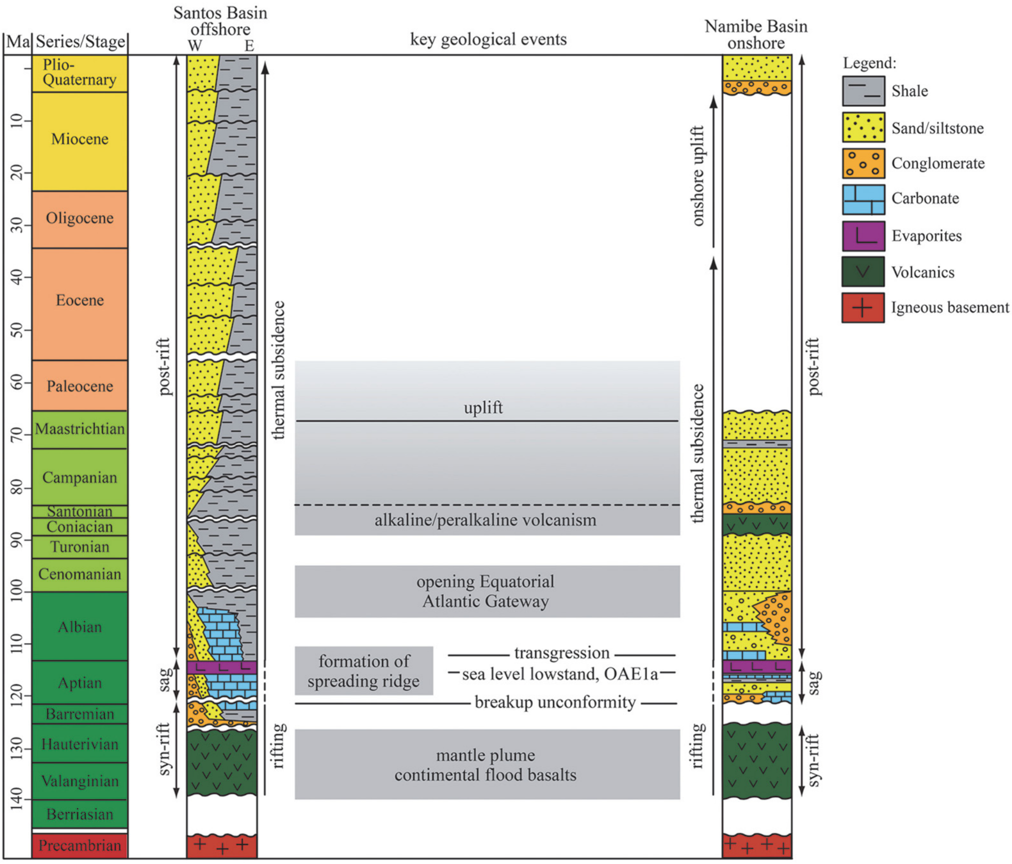

Fig. 4. Depositional records in the conjugate basins of Namibe and Santos, together with key geological events recorded in these rocks. Note that the Namibe Basin record is onshore only, and very proximal relative to the offshore Santos Basin record. Whereas the records are very similar in the early stages of South Atlantic opening, they diverge later, due to the different palaeogeographical positions represented. Source: Santos Basin record was redrafted from Moreira *et al.* (2007).

springs (tufa and travertines; Pentecost 2005), typically within heavily faulted transtensional zones along the basin-bounding fault. Such carbonates are common in volcanic and rifted areas (e.g. East African Rift or Italy; e.g. Renaut *et al.* 2002, 2013), where elevated (volcanic) heat flow drives a system of hydrothermal water circulation and metal leaching in the subsurface. Reduced pressure and temperature at the surface cause mineral precipitation, which will mainly include carbonates and silica, but metal (iron and manganese) oxides, and sulfates (barite, $BaSO_4$, and celestine, $SrSO_4$) were also observed in Angola (Carvalho 1961).

Overlying fine-grained siliciclastics and dolomitic carbonates at Piambo represent the uppermost sag phase (Fig. 2). The sag succession thickens dramatically from Piambo westwards to the offshore and the syn-rift and lower sag are only preserved offshore (Fig. 2). These observations reflect increased accommodation space offshore due to tilting of the proximal margin and thermal subsidence (Moragas *et al.* 2023). The salt phase is represented by the Bambata Formation, which is in turn overlain by the Albian marginal-marine Binga Member and terrestrial Giraul Conglomerate (Figs 2 & 3). This is followed by the marine Salinas Formation and then the Ombe Formation, which includes volcanic flows dated at Piambo to 88 Ma (Coniacian; Fig. 3; Gindre-Chanu *et al.* 2015; Jerram *et al.* 2019). These units are faulted against crystalline basement, and capped by the Campanian–Maastrichtian fossiliferous marine siliciclastic and calcareous Baba and Mocuio formations, which overstep the fault on to granitic basement (Fig. 2). The last phase of activity on the fault is thus Late Cretaceous in age. The basin-bounding fault at Piambo can be traced northwards some 50 km to Bentiaba, and then another approximately 50 km to Lucira (Fig. 1). Along that combined stretch, on the seaward side of the fault, outcrops show the broader expression of rock units representing the opening of the South Atlantic to the end of the Cretaceous. The upper units at Piambo contain marine reptiles that are correlated with the Campanian–Maastrichtian marine reptile fauna farther north at Bentiaba.

Bero (Fig. 5a)

In the Giraul and Bero valleys, 20 km east of Moçâmedes, Precambrian basement granitoids and metasediments (Pereira *et al.* 2011) are abruptly juxtaposed against the rift fill along the NNW–SSE-trending basin-bounding master fault and NE–SW-trending linking faults. In the Bero valley, the rift fill starts with the basal Bero Volcanic Complex, which is intersected by a dense network of NE–SW- and NW–SE-trending conjugate normal faults parallel to the linking fault. This fault network creates a series of tilted blocks that form <1 km wide half-graben. The half-graben are filled by sag siliciclastics and carbonates of the Tumbalunda Formation (Fiordalisi *et al.* 2021). The most striking observation is the occurrence of boulder conglomerates, with clasts up to the size of vehicles and small houses, that abut the faults and overlie the volcanics (Fig. 5a). Clasts are made up of volcanics and basement, and testify to the dramatic erosion of the tilted blocks, and the high-energy deposition in alluvial fans that started to infill the nascent rift basin. Conglomerates pass laterally and upwards into finer-grained sandstones and travertine and lacustrine carbonates, which reflect quieter, fluvio-lacustrine environments as well as mineral precipitation from carbonate-rich fluids circulating along the faults. The succession is capped by erosive remnants of the Bambata Formation gypsum (<50 m thick), which forms a distinctive hardcap. The Bero small half-graben are analogous to tilted blocks in the modern East Africa Rift, for example around Lakes Asal and Magadi in Djibouti and Kenya, respectively, and provide a snapshot of the geomorphology in early volcano-sedimentary rifts.

Chapéu Armado (Fig. 5b–e)

Sag-phase carbonates are exposed near Chapéu Armado (Rochelle-Bates *et al.* 2021; Fig. 5b). They rest directly on faulted granitic basement rocks. The carbonates form a series of travertines up to several tens of metres high (Fig. 5c). Fabrics include small circular vents precipitated around orifices, as well as a series of terraces and connecting cascades where water flowed over steps in the substrate. About 12 m of sag phase siliciclastics overlie and interfinger with the travertines at this locality.

Another striking feature at this locality is the nephelenite/basanite volcanic plug called Chapéu Armado itself (Fig. 5b), meaning ‘armoured hat’ due to its distinctive cap of weathered volcanic rocks. In contrast to the basal volcanic complex, it has been dated to 91–88 Ma (Jerram *et al.* 2019; Rochelle-Bates *et al.* 2021), and thus represents a distinct post-rift phase of alkaline volcanism in Angola. Near the plug are some shallow galleries that were dug manually into soft Albian sandstones and mudstones of the Binga Member. These adits contain a fine network of veins filled with bitumen. Possibly the bitumen was mined by artisans for local consumption in heating, lighting, and lining the base of fishing boats, indicating the recognition of its significance (Fig. 5d, e). The source of the bitumen is from the mudstone itself – these contain a high amount of organic matter that accumulated in saline lakes at the end of Bambata Formation deposition in the Aptian (Binga Member of Piambo Formation; Fig. 3). The eruption of Chapéu Armado volcano some 30 million years later then produced enough localized heat to transform this organic matter into the tar-like bitumen (Fiordalisi *et al.* 2023).

Mariquita (Fig. 5f, g)

The Mariquita valley traverses a north–south-trending graben structure that is parallel to the rift axis. Pre-salt Bero Volcanics constitute the footwall to the east, whereas Albian to Campanian rocks form the western footwall (Strganac *et al.* 2014*a*; Fiordalisi *et al.* 2021). In the west, Santonian basanite volcanics of the Ombe Formation are intercalated (Fig. 5f; Jerram *et al.* 2019; Fiordalisi *et al.* 2021). These are equivalent to the volcanics at Chapéu Armado. Deposits inside the graben belong to the Santonian Ombe Formation (Strganac *et al.* 2014*a*), and contain a mix of lava flows, volcaniclastics, carbonates and mudstones (Fiordalisi *et al.* 2021; Fig. 5f). Closely associated with the bounding faults and minor faults are spring-related carbonates (tufa, travertines) that appear as metre- to decametre-scale buildups. They commonly have a central steep vent where carbonate precipitated around the orifice, surrounded by more gentle slopes where spring water drained off the main orifice and precipitated carbonate. The carbonates on the distal parts of the slope contain numerous gastropod and ostracod casts. Surrounding the build-ups are horizontally bedded lacustrine clays and carbonate muds, locally containing silicified tree stumps (Fig. 5g). The build-ups are eventually overlain by the same clays and carbonates. Modern erosion of

Fig. 5. (**a**) Bero locality, looking NW. Faulted contact between Bero Volcanic Complex (left) and boulder conglomerate of the basal Tumbalunda Formation. Several boulders are indicated by arrows. Car for scale (circled). (**b**) Chapéu Armado locality, looking north. The volcanic cone of Chapéu Armado, Santonian age (Ombe Formation). (**c**) Chapéu Armado locality, looking west. Prograding carbonate travertine (white dashed lines) in contact with basement (black dashed line). Similar thermal spring deposits are developed on Bero Volcanic Complex at Piambo. (**d**) Chapéu Armado locality. Short gallery dug into Albian sandstones to mine bitumen. (**e**) Detail from (d) illustrating the black bitumen blebs in sandstone (arrows). (**f**) Mariquita locality, looking NNW. Stratigraphy in the Mariquita graben. The fault is the western graben bounding fault, bringing the Cenomanian–Turonian Salinas Formation in contact with the sedimentary-volcanic Santonian graben fill (Ombe Formation). Arrows indicate several carbonate spring mounds with conical shape (left buildup is about 10 m high). The graben and graben shoulders are overlain conformably by the Campanian Baba Formation. (**g**) Mariquita locality. Silicified tree trunk in the Mariquita valley (Ombe Formation). (**h**) Inamagando locality, looking east. Albian marine carbonate buildups (between arrows) interbedded with shallow marine and coastal sandstones. Two persons circled for scale. Source: photographs by Stefan Schröder and Luz Gomis Cartesio.

these clays has exhumed the palaeo-landscape of a depression dotted with carbonate spring mounds, surrounded by what were likely small lakes where the spring water accumulated. The lower reaches of mounds and the lakes teemed with gastropods, bivalves and ostracods, while the shoreline was colonized by trees. Positions of spring mounds were controlled by fault-related water resurgences, with heat provided by the post-salt volcanics immediately underlying the succession. A possible connection of these continental systems to the sea is indicated by the presence of brackish/marine *Teredolites* shipworm borings in the silicified trees (Fiordalisi *et al.* 2021).

Bentiaba (Fig. 6a–c)

The section along sea cliffs in the region of Bentiaba from north of Salinas to the Bentiaba River begins with coarse, pebbly red sands, the finer-grained facies of the Albian Giraul Conglomerate (Fig. 6a). The overlying Salinas Formation is rich in invertebrates, indicating a late Cenomanian age (~100 Ma) near its base, progressing through the Turonian. The Salinas Formation is capped by the Ombe Formation, correlative of the distinct Mariquita Member (84.6 Ma, Santonian; Fig. 6c; Strganac *et al.* 2014*a*). The Ombe is succeeded by the Campanian Baba Formation (Fig. 6c; Cooper 2003), overlain by the late Campanian and Maastrichtian Mocuio Formation. Both the Baba and Mocuio formations produce vertebrate fossils, with the Bench 19 vertebrate fauna from the Mocuio Formation being arguably the richest marine reptile locality in Sub-Saharan Africa (Fig. 6b; Jacobs *et al.* 2006, 2016; Strganac *et al.* 2014*a*, *b*, 2015; Mateus *et al.* 2019). In addition to sharks and bony fish, four genera of turtles, at least seven mosasaur taxa (Schulp *et al.* 2006, 2008, 2013; Polcyn *et al.* 2010, 2023), two plesiosaurs (Araújo *et al.* 2015*a*, *b*; Marx *et al.* 2021), two taxa of pterosaurs (Fernandes *et al.* 2022), and rare indeterminate dinosaur bones (Mateus *et al.* 2012, 2019) have been recognized. A magnetostratigraphic section anchored by the Ombe Formation constrains the age of the Bench 19 fauna to chron 32n.1n (71.4–71.64 Ma; Husson *et al.* 2011; Strganac *et al.* 2014*a*). Stable carbon and oxygen chemostratigraphy is consistent with magnetostratigraphy (Strganac *et al.* 2014*a*), and the $\delta^{18}O$ palaeotemperature estimate at Bench 19 is around 18°C (Strganac *et al.* 2015). The Agostinho Neto University Geological Museum in Luanda (UANMG) displays some fossils from Bentiaba and other Angolan sites. A Smithsonian

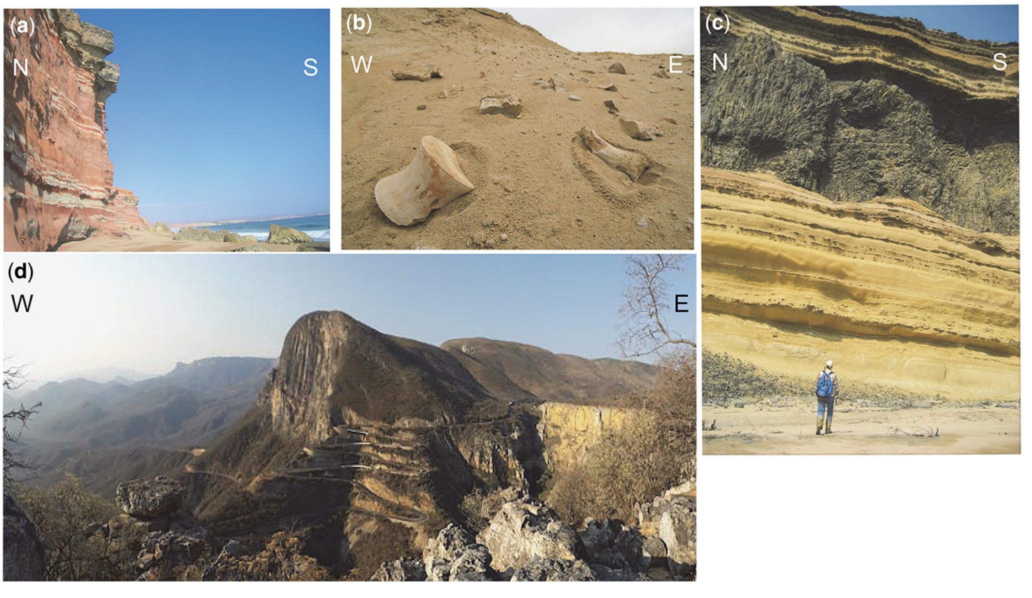

Fig. 6. Late Cretaceous section from Salinas to Bentiaba. (**a**) Base of Bentiaba section: Piambo Formation (red, Albian), capped by Salinas Formation (tan, Cenomanian), looking south. (**b**) Bench 19 level at Bentiaba, surface of Mocuio Formation (Maastrichtian, 71.5 Ma), littered with plesiosaur bones. (**c**) Salinas Formation (yellow), overlain by dark-coloured volcanic Ombe Formation, in turn overlain by Baba Formation (Campanian). Beds dipping south along shore (person for scale). (**d**) Photograph looking north along the Serra da Leba escarpment, rising above the coastal desert plain (left of image). Source: photographs by Christopher Strganac, Anne S. Schulp, Louis L. Jacobs, Stefan Schröder.

Institution exhibition developed around the Bench 19 fauna has been on display in the US National Museum of Natural History since 2018. It will ultimately return to its home in Angola.

The rich Cretaceous vertebrate fossil deposits at Bentiaba, dominated by diverse apex predators, are indicative of a highly productive ecosystem. Palaeolatitude derived from geomagnetism of the Ombe Formation, and corrected for minor variation among models of palaeolatitude estimation (Jacobs *et al.* 2009, 2011, 2016; van Hinsbergen *et al.* 2015; Scotese 2021) was between about 26° and 22°S, or by modern analogy, between the latitudes of Lüderitz and Walvis Bay, Namibia. Compared to its present latitude of 14°S this indicates northward drift of approximately 10° through latitudes expected to produce upwelling. Today, from far southern Angola through Namibia and into South Africa, nutrient-rich coastal waters are brought to the surface by the Benguela Upwelling System (BUS). The position of the BUS relative to the continent is based on trade winds generated by the descending limb of the atmospheric Hadley Cell and Earth's rotation. The palaeolatitudinal setting of Bench 19 suggests the possibility of coastal upwelling and ecosystem productivity that supported the Cretaceous vertebrate fauna. Turonian (91.1 Ma, early Late Cretaceous) and Maastrichtian (68 Ma, late Late Cretaceous) palaeoupwelling maps by Scotese and Moore (2014) show upwelling progressing towards the southern extent of Africa as the continent moved northwards. Wagner *et al.* (2013), in their study of geochemical distribution patterns and Hadley Cell dynamics, support upwelling at the appropriate latitudes during the early Late Cretaceous (Cenomanian and Turonian stages). Thus, the proto-Benguela Current has had a long history. Its more modern iteration was attained in the Neogene, likely initiated by Antarctic glaciations and enhanced by uplift of the African continent (Siesser 1980; Heinrich *et al.* 2011; Jung *et al.* 2014).

Sedimentary evidence for a proto-Benguela current along the coast of Angola in the Albian has been reported (Quesne *et al.* 2009), but there is no evidence of marine reptiles in the central South Atlantic until after the completion of the EAG. Sea turtles and plesiosaurs, which are known to have occurred in Jurassic and Early Cretaceous seas elsewhere, first occur in the central South Atlantic in the Late Cretaceous. Mosasaurs have their evolutionary origin at ~100 Ma, probably in the Middle East (Polcyn *et al.* 1999, 2014). The first records of mosasaurs, plesiosaurs, and sea turtles in Angola are ~88 Ma (Jacobs *et al.* 2006; Mateus *et al.* 2009, 2011, 2012). The two earliest genera of mosasaurs are related to taxa first seen in the northern hemisphere. By 71.5 Ma, the Bentiaba Bench 19 mosasaur fauna indicates dispersal from North African and Trans-Saharan Seaway localities. In contrast, the plesiosaurs are related to southern hemisphere forms (Polcyn *et al.* 2014; Araújo *et al.* 2015*b*).

Thus, it appears that South Atlantic occurrences and the later biogeography of mosasaurs and sea turtles is intimately related to the opening of the EAG. Prior to its complete opening, Setoyama and Kanungo (2020) documented Coniacan (90 Ma) anoxic to dysoxic waters between the Walvis Ridge in the south and the EAG in the north. The initiation of well-ventilated bottom waters in the central South Atlantic heralded the appearance of marine reptiles and likely encouraged their dispersal. Moreover, the completion of the EAG was an event with global reach. The widening and deepening of the gateway allowed the flow of intermediate and deep water. The result of this reorganization of ocean currents may have been global cooling and the decline of the Cretaceous greenhouse (Granot and Dyment 2015).

Tumbalunda, Bambata, Gaio and Inamagando

The Tumbalunda area is the type locality for the sag-phase Tumbalunda Formation, resting directly on basement (Sharp *et al.* 2012). It consists of an overall fining-upwards succession of siliciclastics and carbonates deposited in alluvial fans, braided rivers, deltas, and lakes (Sharp *et al.* 2012). The Tumbalunda clastics transition upwards through a marginal-marine and tidal sabkha succession of evaporites, algal carbonates, and siliciclastics into the Bambata Formation evaporites (Gindre-Chanu *et al.* 2015, 2016; Moragas *et al.* 2023). The evaporites are overlain by fine-grained marginal-marine facies of the Binga/Gaio Member before being overstepped by alluvial fan conglomerates of the Giraul Member (Piambo Formation). Several Albian alluvial fans of 40–200 km^2 in area can be mapped through their distinct radial weathering pattern. The fans were sourced through westward-flowing palaeovalleys that cut through the basin-bounding fault and can be traced west towards the basin edge. Near the coast, in the Inamagando Valley, the Albian conglomerates pass laterally to fluvio-deltaic siliciclastics that sit conformably above lagoonal micrites of the Binga Member. They are overlain by a distinctive, regionally extensive transgressive metre-thick carbonate interval (Fig. 5h; Inamagando beds, Cooper 1976). This carbonate comprises a basal bed of oyster- and gastropod-rich limestone and is overlain by pillar-like build-ups rich in red algae, oncoids and microbial structures (Fig. 5h; Schröder *et al.* 2016). These carbonates represent a short-lived marine transgression into the marginal-marine depositional system, establishing brackish-water lagoons (Schröder *et al.* 2016). Only a limited set of higher organisms and microbes were able to colonize these lagoons due to the variable salinity and continued siliciclastic input.

Serra da Leba (Fig. 6d)

Serra da Leba is a kilometre-high escarpment about 120 km east from Moçâmedes on the Atlantic coast. The escarpment runs broadly north–south, parallel to a regional fracture and fault network, and is part of the much more extensive Great African Escarpment that separates the coastal plains from the central plateau of southern Africa. East of Moçâmedes, the coastal desert plain is dotted with basement granitoid inselbergs that record Eburnean (Paleoproterozoic) to Pan-African (Neoproterozoic) orogenic activity (~2.1–0.5 Ga; Pereira *et al.* 2011). At Serra da Leba, the basement is disconformably overlain by flat-lying Mesoproterozoic quartzites and limestones of the Chela Group (~1.9 Ga; Pereira *et al.* 2011). These sediments form a prominent cliff at the edge of the Humpata Plateau that provides spectacular views over the Namibe desert plain below. Caves in the stromatolitic limestone of the Chela Group contain Mesolithic archaeological assemblages (de Matos and Pereira 2020) and Plio-Pleistocene mammal fossils, including cercopithecid primate remains concentrated by eagle predation (Gilbert *et al.* 2009). The Serra da Leba escarpment, due to its scenery, preserved geological record, and local cultural significance, is a tourism hotspot in SW Angola, and is recognized as a potential geoheritage site (Henriques *et al.* 2013; Tavares *et al.* 2015).

The origins of the Great African Escarpment are still poorly understood. One hypothesis sees the escarpment as an erosional remnant of the Lower Cretaceous rift shoulder (King 1951), whereas alternative hypotheses postulate repeated uplift events of the margin through the Cretaceous to Neogene (e.g. Green and Machado 2017). Either way, the presence of such topography and its possible rejuvenation via uplift increased erosion rates and delivered sands to offshore regions, constituting potential petroleum reservoirs. Increased offshore subsidence could have aided in maturation of organic-rich source rocks (Green and Machado 2017). Thus, the dynamic history of the Angolan continental margin was a key component in developing the petroleum systems offshore Angola, which are important for Angola's economic development.

Pliocene–Quaternary deposits along coastline

The Cretaceous section is unconformably truncated by flat-lying conglomerates, boulders, and marine shells. This is considered a Pliocene highstand terrace as elsewhere in South Africa (Hearty *et al.* 2020). Post-Pliocene sediments include Pleistocene marine terraces (Sessa *et al.* 2013) and palaeosols with occasional mammal fossils and ostrich shell fragments, topped by younger silt with local shell middens, stone tools, hand axes, and hut circles, dating back to the Paleolithic (de Matos *et al.* 2021). Strikingly, cherty tools such as axes and blades cluster near outcrops of silicified rift and sag-phase carbonates.

Geoheritage in Angola

Henriques *et al.* (2013) outlined the legal framework for protecting geoheritage and biodiversity in Angola. In 2019, the Declaration of Antananarivo on Geological Heritage and its Conservation in Africa was issued (PanAfGeo 2019). Among the signatories was a representative of the Organization of African Geological Surveys, of which Instituto Geológico de Angola Igeo is a member. The Declaration presented six principles, including a fundamental link between geoheritage and biodiversity, and seven recommendations, which acknowledge that 'the value of African geological heritage [should be] brought to the attention of the greatest number of persons'. Neto and Henriques (2022) reviewed the status of geoconservation across Africa, pointing out that most geoheritage studies in Africa reviewed by them involve inventory and assessments of geoheritage value of specific locations. Such inventories showcase the wonder and beauty of Earth at varying levels of detail. Its audience is all people, all ages. Its benefits accrue to all – residents, students, tourists, industry geologists, or scholars, through economic development, aesthetic appreciation, or learning. It is science for development. This report conforms to that characterization.

In terms of bringing attention of Angola's geoheritage to the greatest number of persons, fossils from the locality of Bentiaba form the core of a temporary museum exhibit, *Sea Monsters Unearthed: Life in Angola's Ancient Seas*, in the Smithsonian Institution's National Museum of Natural History in Washington, D.C. Since its opening on 18 November 2018 through 2023, the museum had 14 614 718 visits (Smithsonian Institution 2024). Ten percent of museum visitors live in countries other than the United States; thus, the exhibit provides a far-reaching educational experience based on Angolan geoheritage. As the exhibit returns to Angola, the planning, construction, and visitation of the exhibit at the Smithsonian can further inform decision makers in Angola as to possible applications and conservation of Angola's geoheritage.

Conclusions

Geoheritage is the appreciation of geological and geomorphological features and processes as natural heritage, including their role in ecosystem function and cultural heritage. We have alluded to each of these aspects in the context of the Atlantic Jigsaw Puzzle, and to Angola specifically. However, the Atlantic Jigsaw Puzzle is not simply an Angolan or South America–African, or even southern hemisphere example of geoheritage. It is geoheritage on a global scale because it is an example of a fundamental paradigm in geology and its meaning is recognized by young and old the world over. The significance of the Angolan geological record is that it is the first place where a relatively complete sequence of geological events leading to the Atlantic Jigsaw Puzzle has been recognized in outcrop.

Acknowledgements An international palaeontological consortium referred to as Projecto PaleoAngola has conducted field research in Angola since 2005. Projecto PaleoAngola acknowledges the encouragement of ISEM and Southern Methodist University. Since the inception of Projecto PaleoAngola, Universidade Agostinho Neto in Luanda has been its host institution. Sincere thanks are due Maria Luísa Morais, A. Olímpio Gonçalves, André Buta Neto, Tatiana da Silva Tavares, and the numerous students and friends who worked with us in all phases of field work. Sonangol and Statoil (now Equinor) staff were involved in the 2010–14 onshore Namibe Basin mapping project. Sonangol EP supported museum exhibit development.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Author contributions **LLJ**: conceptualization (equal), investigation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **SS**: conceptualization (equal), investigation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **NDS**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **RD**: investigation (equal), writing – review & editing (supporting); **EF**: investigation (equal), writing – review & editing (supporting); **AM**: investigation (supporting), writing – review & editing (supporting); **OM**: investigation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **PCN**: project administration (equal), writing – review & editing (supporting); **MJP**: conceptualization (equal), investigation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **GDCRP**: investigation (equal), writing – review & editing (supporting); **NR-B**: investigation (equal), writing – review & editing (supporting); **ASS**: conceptualization (equal), investigation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **CRS**: visualization (supporting), writing – review & editing (supporting); **IS**: investigation (equal), writing – review & editing (supporting); **CGS**: investigation (supporting), writing – review & editing (supporting); **RS**: visualization (equal), writing – review & editing (supporting); **DPV**: project administration (equal), visualization (equal), writing – review & editing (supporting).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

Araújo, R., Polcyn, M.J., Schulp, A.S., Mateus, O., Jacobs, L.L., Gonçalves, A.O. and Morais, M.-L. 2015*a*. A new elasmosaurid from the early Maastrichtian of Angola and the implications of girdle morphology on swimming style in plesiosaurs. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, **94**, https://doi.org/10.1017/njg.2014.44

Araújo, R., Polcyn, M.J. *et al*. 2015*b*. New aristonectine elasmosaurid plesiosaur specimens from the Lower Maastrichtian of Angola and comments on paedomorphism in plesiosaurs. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, **94**, https://doi.org/10.1017/njg.2014.43

Carvalho, G. Soares de 1961. Geologia do deserto de Moçâmedes (Angola). Uma Contribuição para o Conhecimento dos Problemas da Orla Sedimentar de Moçâmedes. *Memórias da Junta de Investigações do Ultramar Lisboa, Segunda Série*, **26**, 1–227.

Cooper, M.R. 1976. The mid-Cretaceous (Albian–Turonian) biostratigraphy of Angola. *Annales du Muséum d'Histoire Naturelle de Nice*, **IV**, xvi.1–xvi.22.

Cooper, M.R. 2003. Stratigraphy and paleontology of the Upper Cretaceous (Santonian) Baba Formation at São Nicolau, Angola. *Annals of the South African Museum*, **110**, 147–170.

Cooper, M.R. 2018. *Cretaceous Fossils of South-Central Africa*. CRC Press.

Fernandes, A.E., Mateus, O., Andres, B., Polcyn, M.J., Schulp, A.S., Gonçalves, A.O. and Jacobs, L.L. 2022. Pterosaurs from the Late Cretaceous of Angola. *Diversity*, **14**, 741, https://doi.org/10.3390/d14090741

Fiordalisi, E., Marchegiano John, C.M. *et al*. 2021. Late Cretaceous volcanism and fluid circulation in the South Atlantic: insights from continental carbonates in the onshore Namibe Basin (Angola). *Marine and Petroleum Geology*, **134**, 105351, https://doi.org/10.1016/j.marpetgeo.2021.105351

Fiordalisi, E., van Dongen, B. *et al*. 2023. Magmatically driven hydrocarbon generation and fluid flow in the Namibe Basin of Angola. *Geological Society, London, Special Publications*, **547**, https://doi.org/10.1144/SP547-2023-44

Gilbert, C.C., McGraw, W.S. and Delson, E. 2009. Brief communication: Plio-Pleistocene eagle predation on fossil cercopithecids from the Humpata Plateau, southern Angola. *American Journal of Physical*

Anthropology, **139**, 421–429, https://doi.org/10.1002/ajpa.21004

Gindre-Chanu, L., Warren, J.K. *et al*. 2015. Diagenetic evolution of Aptian evaporites in the Namibe Basin (southwest Angola). *Sedimentology*, **62**, 204–233, https://doi.org/10.1111/sed.12146

Gindre-Chanu, L., Perri, E. *et al*. 2016. Origin and diagenetic evolution of gypsum and microbialitic carbonates in the late sag of the Namibe Basin (SW Angola). *Sedimentary Geology*, **342**, 133–153, https://doi.org/10.1016/j.sedgeo.2016.06.015

Granot, R. and Dyment, J. 2015. The Cretaceous opening of the South Atlantic Ocean. *Earth and Planetary Science Letters*, **414**, 156–163, https://doi.org/10.1016/j.epsl.2015.01.015

Green, P.F. and Machado, V. 2017. Pre-rift and synrift exhumation, post-rift subsidence and exhumation of the onshore Namibe Margin of Angola revealed from apatite fission track analysis. *Geological Society, London, Special Publications*, **438**, 99–118, https://doi.org/10.1144/SP438.2

Hearty, P.J., Rovere, A., Sandstrom, M.R., O'Leary, M.J., Roberts, D. and Raymo, M.E. 2020. Pliocene-Pleistocene stratigraphy and sea-level estimates, Republic of South Africa with implications for a 400 ppmv CO_2 world. *Paleoceanography and Paleoclimatology*, **35**, e2019PA003835, https://doi.org/10.1029/2019PA003835

Heinrich, S., Zonneveld, K.A.F., Bickert, T. and Willems, H. 2011. The Benguela upwelling related to the Miocene cooling events and the development of the Antarctic Circumpolar Current: evidence from calcareous dinoflagellate cysts. *Paleoceanography*, **26**, PA3209, https://doi.org/10.1029/2010PA002065

Henriques, M.H., Tavares, A.O. and Bala, A.L.M. 2013. The geological heritage of Tundavala (Angola): an integrated approach to its characterization. *African Journal of Earth Sciences*, **88**, 62–71, https://doi.org/10.1016/j.jafrearsci.2013.09.003

van Hinsbergen, D.J.J., de Groot, L.V. *et al*. 2015. A paleolatitude calculator for paleoclimate studies. *PLoS ONE*, **10**, e0126946, https://doi.org/10.1371/journal.pone.0126946

Husson, D., Galbrun, B., Laskar, J., Hinnov, L., Thibault, N., Gardin, S. and Locklair, R. 2011. Astronomical calibration of the Maastrichtian (Late Cretaceous). *Earth and Planetary Science Letters*, **305**, 328–340, https://doi.org/10.1016/j.epsl.2011.03.008

Jacobs, L.L., Mateus, O., Polcyn, M.J., Schulp, A.S., Antunes, M.T., Morais, M.L. and Tavares, T.da S. 2006. The occurrence and geological setting of Cretaceous dinosaurs, mosasaurs, plesiosaurs, and turtles from Angola. *Journal of the Paleontological Society of Korea*, **22**, 91–110.

Jacobs, L.L., Mateus, O. *et al*. 2009. Cretaceous paleogeography, paleoclimatology, and amniote biogeography of the low and mid-latitude South Atlantic Ocean. *Bulletin of the Geological Society of France*, **180**, 333–341, https://doi.org/10.2113/gssgfbull.180.4.333

Jacobs, L.L., Strganac, C. and Scotese, C.R. 2011. Plate motions, Gondwana dinosaurs, Noah's Arks, ghost ships, and beached Viking funeral ships. *Anais da Academia Brasileira de Ciências*, **83**, 3–22, https://doi.org/10.1590/S0001-37652011000100002

Jacobs, L.L., Polcyn, M.J., Mateus, O., Schulp, A.S., Gonçalves, A.O. and Morais, M.-L. 2016. Post-Gondwana Africa and the vertebrate history of the Angolan Atlantic coast. *Memoires of Museum Victoria*, **74**, 343–362, https://doi.org/10.24199/j.mmv.2016.74.24

Jerram, D.A., Sharp, I.R. *et al*. 2019. Volcanic constraints on the unzipping of Africa from South America: insights from new geochronological controls along the Angola margin. *Tectonophysics*, **760**, 252–266, https://doi.org/10.1016/j.tecto.2018.07.027

Jung, G., Prange, M. and Schulz, M. 2014. Uplift of Africa as a potential cause for Neogene intensification of the Benguela upwelling system. *Nature Geoscience*, **7**, https://doi.org/10.1038/NGEO2249

King, L.C. 1951. *South African Scenery*, 2nd edn. Oliver and Boyd, White Plains, N.Y.

Marx, M.P., Mateus, M., Polcyn, M.P., Schulp, A.S., Gonçalves, A.O. and Jacobs, L.L. 2021.The cranial anatomy and relationships of *Cardiocorax mukulu* (Plesiosauria: Elasmosauridae) from Bentiaba, Angola. *PLoS ONE*, **16**, e0255773, https://doi.org/10.1371/journal.pone.0255773

Mateus, O., Jacobs, L.L., Polcyn, M.J., Schulp, A.S., Vineyard, D.P., Antunes, M.T. and Neto, A.B. 2009. The oldest African eucryptodiran turtle from the Cretaceous of Angola. *Acta Paleontologica Polonica*, **54**, 581–588, https://doi.org/10.4202/app.2008.0063

Mateus, O., Jacobs, L.L. *et al*. 2011. *Angolatitan adamastor*, a new sauropod dinosaur and the first record from Angola. *Anais da Academia Brasileira de Ciências*, **83**, 221–233, https://doi.org/10.1590/S0001-37652011000100012

Mateus, O., Polcyn, M.J. *et al*. 2012. Cretaceous amniotes from Angola: Dinosaurs, pterosaurs, mosasaurs, plesiosaurs, and turtles. *V Jornadas Internacionales sobre Paleontología de Dinosaurios y su Entorno*, 75–105, Salas de los Infantes, Burgos.

Mateus, O., Callapez, P.M., Polcyn, A.S., Schuilp, A.S., Gonçalves, and Jacobs, L.L. 2019. The fossil record of biodiversity in Angola Through time: a paleontological perspective. *In*: Huntley, B.J., Russo, V., Lages, F. and Ferrand, N. (eds) *Biodiversity of Angola, Science & Conservation: A Modern Synthesis*. Springer, 53–76 [also in Portuguese].

de Matos, D. and Pereira, T. 2020. Middle Stone Age lithic assemblages from Leba Cave (Southwest Angola). *Journal of Archaeologica Science: Reports*, **32**, 102413, https://doi.org/10.1016/j.jasrep.2020.102413

de Matos, D., Martins, A.C., Senna-Martinez, J.C., Pinto, I., Coelho, A.G., Ferreira, S.S. and Oosterbeek, L. 2021. Review of archaeological research in Angola. *African Archaeology Review*, **38**, 319–344, https://doi.org/10.1007/s10437-020-09420-8

Moragas, M., Baqués, V. *et al*. 2023. Paleoenvironmental and diagenetic evolution of the Aptian Pre-Salt succession in Namibe Basin (Onshore Angola). *Marine and Petroleum Geology*, **150**, 106153, https://doi.org/10.1016/j.marpetgeo.2023.106153

Moreira, J.L.P., Madeira, C.V., Gil, J.A. and Machado, M.A.P. 2007. Bacia de Santos. *Boletim de Geociências da Petrobras*, **15**, 531–549.

Neto, K. and Henriques, M.H. 2022. Geoconservation in Africa: State of the art and future challenges.

Gondwana Research, **110**, 107–113, https://doi.org/10.1016/j.gr.2022.05.022

Norton, I.O., Carruthers, D.T. and Hudec, M.R. 2016. Rift to drift transition in the South Atlantic salt basins: a new flavor of oceanic crust. *Geology*, **44**, 55–58, https://doi.org/10.1130/G37265.1

PanAfGeo 2019. Declaration of Antananarivo on geological heritage and its conservation in Africa, http://www.progeo.ngo/assets/declaration_of_antananarivo.pdf

Pentecost, A. 2005. *Travertine*. Springer, Berlin.

Pereira, E., Tassinari, C.C.G., Rodrigues, J.F. and Van-Dünem, M.V. 2011. New data on the deposition age of the volcano-sedimentary Chela Group and its Eburnean basement: implications to post- Eburnean crustal evolution of the SW of Angola. *Comunicações Geológicas*, **98**, 29–40.

Polcyn, M.J., Tchernov, E. and Jacobs, L.L. 1999. The Cretaceous biogeography of the eastern Mediterranean with a description of a new basal mosasauroid from 'Ein Yabrud, Israel. *In*: Tomida, Y., Rich, T.H. and Vickers-Rich, P. (eds) *Proceedings of the Second Gondwanan Dinosaur Symposium*. National Science Museum, Monograph, Tokyo, **15**, 259–290.

Polcyn, M.J., Jacobs, L.L., Schulp, A.S. and Mateus, O. 2010. The North African mosasaur *Globidens phosphaticus* from the Maastrichtian of Angola. *Historical Biology*, **22**, 175–185, https://doi.org/10.1080/08912961003754978

Polcyn, M.J., Jacobs, L.L., Schulp, A.S. and Mateus, O. 2014. Physical drivers of mosasaur evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **400**, 17–27, https://doi.org/10.1016/j.palaeo.2013.05.018

Polcyn, M.J., Schulp, A.S. and Gonçalves, A.O. 2023. Remarkably well-preserved in-situ gut-content in a specimen of *Prognathodon kianda* (Squamata: Mosasauridae) reveals multispecies intrafamilial predation, cannibalism, and a new mosasaurine taxon. *In*: Lee, Y.N. (ed.) *Windows into Sauropsid and Synapsid Evolution: Essays in Honor of Louis L. Jacobs*. Dinosaur Science Center Press, Hwaseong City, South Korea, 66–98.

Quesne, D., Buta-Neto, A., Benard, D. and Guiraud, M. 2009. Distribution of Albian clastic deposits in the Benguela basin (Angola): evidence of a Benguela palaeocurrent? *Bulletin de la Société géologique de France*, **180**, 117–129, https://doi.org/10.2113/gssgfbull.180.2.117

Quirk, D.J. and Rüpke, L.H. 2018. Melt-induced buoyancy may explain the elevated rift-rapid sag paradox during breakup of continental plates. *Scientific Reports*, **8**, 9985, https://doi.org/10.1038/s41598-018-27981-2

Quirk, D.J., Hertle, M. *et al*. 2013. Rifting, subsidence and continental break-up above a mantle plume in the central South Atlantic. *Geological Society, London, Special Publications*, **369**, 185–214, https://doi.org/10.1144/SP369.20

Renaut, R.W., Morley, C.K. and Jones, B. 2002. Fossil hot-spring travertine in the Turkana Basin, northern Kenya: structure, facies, and genesis. *SEPM Special Publications*, **73**, 123–141.

Renaut, R.W., Owen, R.B., Jones, B., Tiercelin, J.-J., Tarits, C., Ego, J.K. and Konhauser, K.O. 2013. Impact of lake-level changes on the formation of thermogene travertine in continental rifts: Evidence from Lake Bogoria, Kenya Rift Valley. *Sedimentology*, **60**, 428–468, https://doi.org/10.1111/j.1365-3091.2012.01347.x

Renne, P.R., Glen, J.M., Simon, S.C. and Duncan, A.R. 1996. Age of Etendeka flood volcanism and associated intrusions in southwestern Africa. *Geology*, **24**, 659–662, https://doi.org/10.1130/0091-7613(1996)024<0659:AOEFVA>2.3.CO;2

Rochelle-Bates, N., Roberts, N.M.W. *et al*. 2021. Geochronology of volcanically associated hydrocarbon charge in the pre-salt carbonates of the Namibe Basin, Angola. *Geology*, **49**, 335–340, https://doi.org/10.1130/G48019.1

Schröder, S., Ibekwe, A., Saunders, M., Dixon, R. and Fisher, A. 2016. Algal-microbial carbonates of the Namibe Basin (Albian, Angola: implications for microbial carbonate mound development in the South Atlantic. *Petroleum Geoscience*, **22**, 71–90, https://doi.org/10.1144/petgeo2014-083

Schulp, A.S., Polcyn, M.J., Mateus, O., Jacobs, L.L., Morais, M.L. and Tavares, T.da S. 2006. New mosasaur material from the Maastrichtian of Angola, with notes on the phylogeny, distribution and paleoecology of the genus *Prognathodon*. *Maastricht Museum, Publicaties van het Natuurhistorisch Genootschap in Limburg*, **45**, 57–67.

Schulp, A.S., Polcyn, M.J., Mateus, O., Jacobs, L.L. and Morais, M.L. 2008. A new species of Prognathodon (Squamata, Mosasauridae) from the Maastrichtian of Angola, and the affinities of the mosasaur genus *Liodon*. Proceedings of the Second Mosasaur Meeting, Fort Hays State University, Kansas, 1–12.

Schulp, A.S., Polcyn, M.J., Mateus, O. and Jacobs, L.L. 2013. Two rare mosasaurs from the Maastrichtian of Angola and the Netherlands. *Netherlands Journal of Geosciences*, **92**, 3–10, https://doi.org/10.1017/S001677460000024X

Scotese, C.R. 2021. An atlas of Phanerozoic paleogeographic maps: the seas come in and the seas go out. *Annual Review of Earth and Planetary Sciences*, **49**, 679–728, https://doi.org/10.1146/annurev-earth-081320-064052

Scotese, C.R. and Moore, T.L. 2014. *Atlas of Phanerozoic Upwelling Zones (Mollweide Projection)*. PALEOMAP Project PaleoAtlas for ArcGIS, Evanston, IL. 1–6.

Sessa, J.A., Callapez, P.M., Dinis, P.A. and Hendy, A.J.W. 2013. Paleoenvironmental and paleobiogeographical implications of a Middle Pleistocene mollusc assemblage from the marine terraces of Baía das Pipas, southwest Angola. *Journal of Paleontology*, **87**, 1016–1040, https://doi.org/10.1666/12-119

Setoyama, E. and Kanungo, S. 2020. Mesozoic biochronostratigraphy and paleoenvironment of the South Atlantic: a revised framework based on 20 DSDP and ODP deep-water sites. *Journal of South American Earth Sciences*, **99**, https://doi.org/10.1016/j.jsames.2020.102511

Sharp, I., Verwer, K. *et al*. 2012. Pre- and post-salt nonmarine carbonates of the Namibe Basin, Angola. AAPG Annual Convention and Exhibition, 22–25 April 2012, Long Beach, California.

Siesser, W.G. 1980. Late Miocene origin of the Benguela upwelling system off northern Namibia. *Science (New York, NY)*, **208**, 283–285, https://doi.org/10.1126/science.208.4441.283

Smithsonian Institution 2024. Visitor stats, https://www.si.edu/newsdesk/about/stats

Strganac, C., Jacobs, L.L. *et al*. 2014*a*. Carbon isotope stratigraphy, magnetostratigraphy, and $^{40}Ar/^{39}Ar$ age of the Cretaceous South Atlantic coast, Namibe Basin, Angola. *Journal of African Earth Sciences*, **99**, 452–462, https://doi.org/10.1016/j.jafrearsci.2014.03.003

Strganac, C., Jacobs, L.L. *et al*. 2014*b*. Geological setting and paleoecology of the Upper Cretaceous Bench 19 marine vertebrate bonebed at Bentiaba, Angola. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, **94**, https://doi.org/10.1017/njg.2014.32

Strganac, C., Jacobs, L.L. *et al*. 2015. Stable oxygen isotope chemostratigraphy and paleotemperature regime of mosasaurs at Bentiaba, Angola. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, **94**, https://doi.org/10.1017/njg.2015.1

Tavares, A.O., Henriques, M.H., Domingos, A. and Bala, A. 2015. Community involvement in geoconservation: a conceptual approach based on the geoheritage of South Angola. *Sustainability*, **7**, 4893–4918, https://doi.org/10.3390/su7054893

Tedeschi, L.R., Jenkyns, H.C., Robinson, S.A., Sanjinés, A.E.S., Viviers, M.C., Quintaes, C.M.S.P. and Vazquez, J.C. 2017. New age constraints on Aptian evaporites and carbonates from the South Atlantic: implications for Oceanic Anoxic Event 1a. *Geology*, **45**, 543–546, https://doi.org/10.1130/G38886.1

Wagner, T., Hofman, P. and Flogel, S. 2013. Marine black shale deposition and Hadley Cell dynamics: a conceptual framework for the Cretaceous Atlantic Ocean. *Marine and Petroleum Geology*, **43**, 222–238, https://doi.org/10.1016/j.marpetgeo.2013.02.005

Wegener, A. 1966. *The Origin of Continents and Oceans*. Dover [Biram, J., transl. of Wegener A. 1929. *Die Entstehung der Kontinente und Ozeane*. Friedrich Vieweg & Sohn, Braunschweig, Germany].

Wilson, J.T. 1963. Continental drift. *Scientific American*, **208**, 86–103, https://doi.org/10.1038/scientificamerican0463-86