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Central Afar: An analogue for oceanic plateau development

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ABSTRACT

The structure, composition, and evolution of oceanic plateaus are poorly understood and strongly debated. Here, we compared the magmatic history and crustal structure of Afar with the Greenland–Iceland–Faroe Ridge and other oceanic plateaus. Key similarities indicate that Central Afar represents the early stage of development of a specific type of oceanic plateau: a rifted oceanic magmatic plateau (ROMP). These features begin their formation before continental rifting and develop into wide magmatic rift systems capable of isolating slivers of continental crust within the new igneous crust. Importantly, the anomalous magmatism continues through breakup and for several tens of millions of years afterward. The recognition of Central Afar as a precursor of this type of oceanic plateau allows us to better understand their formation. Increased melt production causes early and voluminous magmatism, ultrathick igneous crust, and repeated reorganization of the extension locus during rift/ridge jumps, which delay the onset of oceanization and Penrose-style crustal production. These factors differentiate ROMPs from many magma-rich rifted continental margins and from other types of oceanic plateaus, highlighting that Central Afar and other ROMPs should neither be considered as conventional magma-rich margins nor be considered as normal oceanic crust.

INTRODUCTION

Rifting and the formation of new oceanic crust are fundamental processes of plate tectonics. While the evolution of conventional continental rifted margins is relatively well known, special cases where rifting interacts with hotspots for a protracted period to form oceanic plateaus, instead of Penrose-like oceanic crust, are poorly understood due to the lack of exposure, geophysical data, samples, and modern analogues in the early stages of development (Coffin and Eldholm, 1992). Yet, oceanic plateaus form 3% of Earth's crust (Mooney et al., 2023), play a major role in paleoceanography (Pindell and Heyn, 2022) and species dispersal (Nilsen, 1978), and are fundamental building blocks of continents (Nur and Ben-Avraham, 1982). Several aspects of oceanic plateaus, including their structure, composition, evolution, and the role of plumes, are strongly debated in the literature, and no consensus has yet been reached (e.g., Campbell, 2007; Foulger et al., 2020).

The Afar region (Figs. 1, 2A, and 3A) is often presented in the literature as a textbook example of continental rifting near the point of breakup (e.g., Bastow and Keir, 2011). Afar sits spatially between the East African rift system and the mid-ocean ridges of the Red Sea and Gulf of Aden; it has a rift morphology and a crustal structure that is broadly between continental and oceanic in character (Bastow and Keir, 2011; Hammond et al., 2011; Rime et al., 2023). Within Afar, spatial variations in styles of extension have traditionally been interpreted within a framework of progressive evolution from rifting to seafloor spreading (e.g., Mohr, 1970; Hayward and Ebinger, 1996; Bastow and Keir, 2011). However, as our knowledge of the crustal structure and rift chronology of the area improves, these hypotheses about the evolution of Afar can be challenged. Central Afar (Fig. 2A), traditionally considered to be an example of conventional magma-rich breakup (Wolfenden et al., 2005; Bastow and Keir, 2011; Chauvet et al., 2023), shows differences when compared to most conventional magma-rich passive rifted margins, including the early onset of voluminous magmatism, limited crustal thinning, and evidence for changes in the locus of rifting (Rime et al., 2023). We therefore challenge these traditional interpretations and propose that Afar displays spatial variations in rift style that are controlled by long-lived variations in magma productivity, and that Central Afar represents an extreme end member of magma-rich rifted margins and the early stage of oceanic plateau development.

An "oceanic plateau" mainly refers to extensive, topographically elevated areas of volcanic origin that rise above the surrounding oceanic basins (e.g., Coffin and Eldholm, 1992). While these plateaus were previously considered to be purely magmatically thickened oceanic crust, continental material has been found in several of them (Fig. 1; Text S2 in the Supplemental Material[1]), raising questions about their mechanisms of formation and evolution. Oceanic large igneous provinces are usually classified based on their morphology (e.g., Coffin and Eldholm, 1992), but some of these features developed exclusively in the oceanic realm far from continental processes such as rifting, and they can therefore not be compared to Afar. Oceanic plateaus are thus divided into two broad categories (Fig. 1; Text S1). Some of them developed exclusively on oceanic crust, with no evidence for ever having been connected to a continent (e.g., the Shatsky Rise), and these are referred to as "oceanic magmatic plateaus" (OMPs) and will not be discussed in this article. Others started forming during the rifting stage

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[1]Supplemental Material. Additional discussion on the definition of oceanic plateaus, literature review of the characteristics of other ROMPs and other oceanic features, details on crustal balancing, calculation of the fraction of magmatic addition in Central Afar, and references used to construct the figures. Please visit https://doi.org/10.1130/GEOL.S.26276239 to access the supplemental material; contact editing@geosociety.org with any questions.

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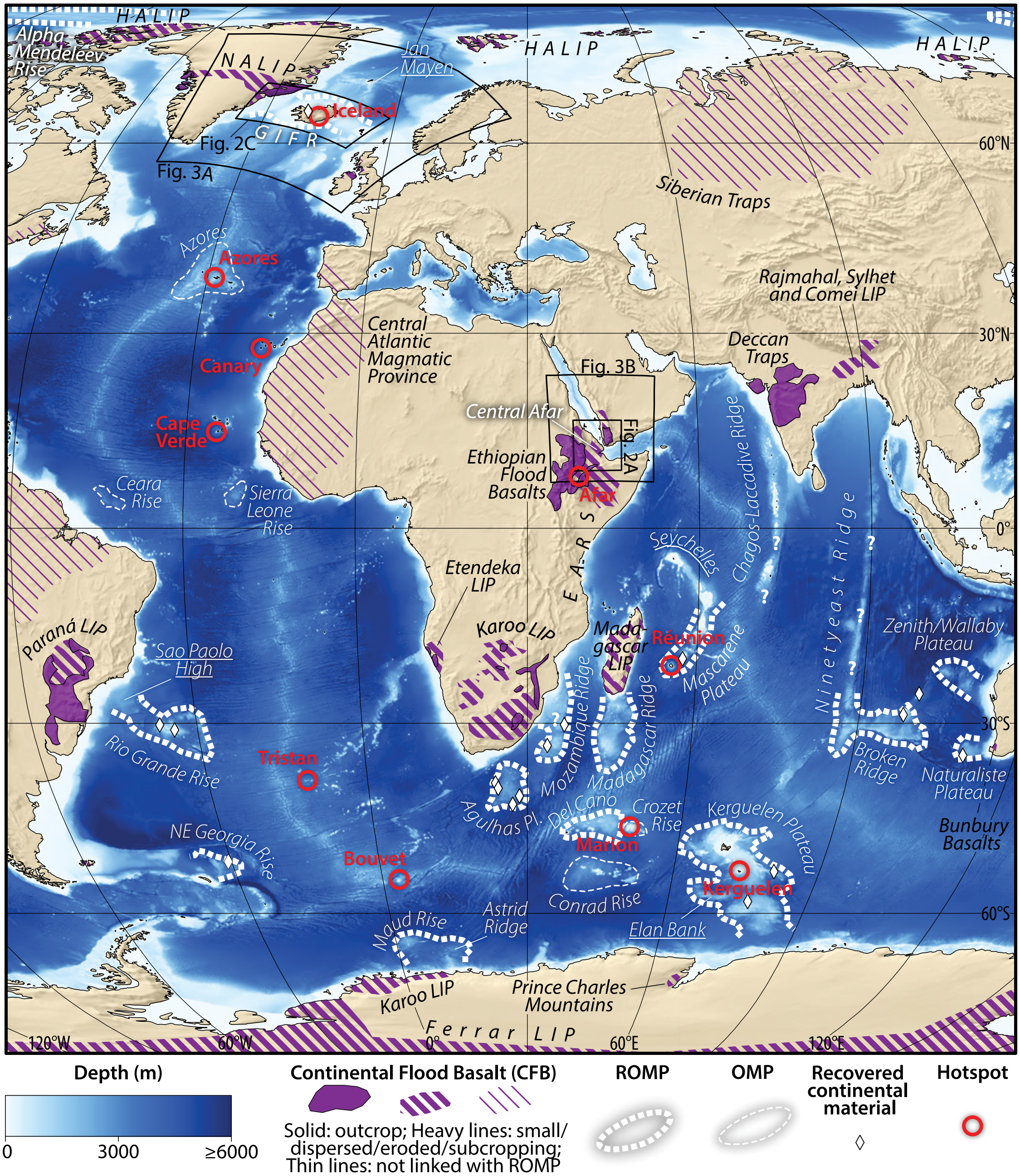

Figure 1. Bathymetric map of Atlantic and Indian Oceans showing positions of potential rifted oceanic magmatic plateaus (ROMPs) and oceanic magmatic plateaus (OMPs), continental flood basalts (CFBs), hotspots, and recovered continental material in ROMPs. Underlined labels indicate potential microcontinent. EARS—East African Rift System; GIFR—Greenland–Iceland–Faroe Ridge; HALIP—High Arctic large igneous province; LIP—large igneous province; NALIP—North Atlantic large igneous province; OMP—Oceanic Magmatic Plateau; Pl—Plateau; ROMP—Rifted Oceanic Magmatic Plateau. More information is given in Text S1, S2, S3, and S6.1 (see text footnote 1).

and were originally connected to a continent and a continental flood basalt (CFB) province, so these are referred to as "rifted oceanic magmatic plateaus" (ROMPs).

Here, we aimed to test the hypothesis that Central Afar represents the birth of a ROMP. We established the primary characteristics and processes responsible for ROMP formation using the well-studied Greenland–Iceland–Faroe Ridge (GIFR), where plateau formation is clearly linked to protracted hotspot activity through continental rifting and well after breakup, and then we tested these observations against features in Central Afar. Other ROMPs (Rio Grande Rise, Georgia Rise, Maud Rise, Agulhas Rise, Madagascar Ridge, Del Cano Rise, Mascarene Plateau, Kerguelen Plateau, Broken Ridge, Wallaby/Zenith plateaus, Naturaliste Plateau, and Alpha-Mendeleev Ridge) are described and compared to Central Afar in Text S2.

CHARACTERISTICS OF FULLY DEVELOPED ROMPS

By definition, all ROMPs originated as a CFB and were associated with a hotspot (Fig. 1; Text S2; Koppers et al., 2021). The GIFR is linked to the North Atlantic Igneous Province (ca. 56 Ma) and to the Iceland hotspot (Fig. 1; Storey et al., 2007). ROMPs form positive topography above the surrounding oceanic basins, linked to the significantly thicker crust than classical (6–8-km-thick) Penrose-like oceanic crust, reaching 40 km in Iceland (Fig. 3B; Text S2.2). For ROMPs, the formation of Penrose-like oceanic crust was either never reached (such as on the GIFR) or strongly delayed (e.g., Rio Grande Rise) compared to the adjacent oceanic basins, despite having experienced similar amounts of extension.

The crust of ROMPs systematically comprises large volumes of extrusive, intrusive, and underplated magmatic rocks (Text S2). Lavas are ubiquitous over the GIFR (Fig. 2C), and crustal cross sections show an excess crustal area of ~20,000 km² in the GIFR compared to neighboring oceanic basins (Fig. 3D; Text S4). This difference is most simply explained by crustal magmatic additions significantly more voluminous than normal oceanic spreading processes (Text S4). Most ROMPs, includ-

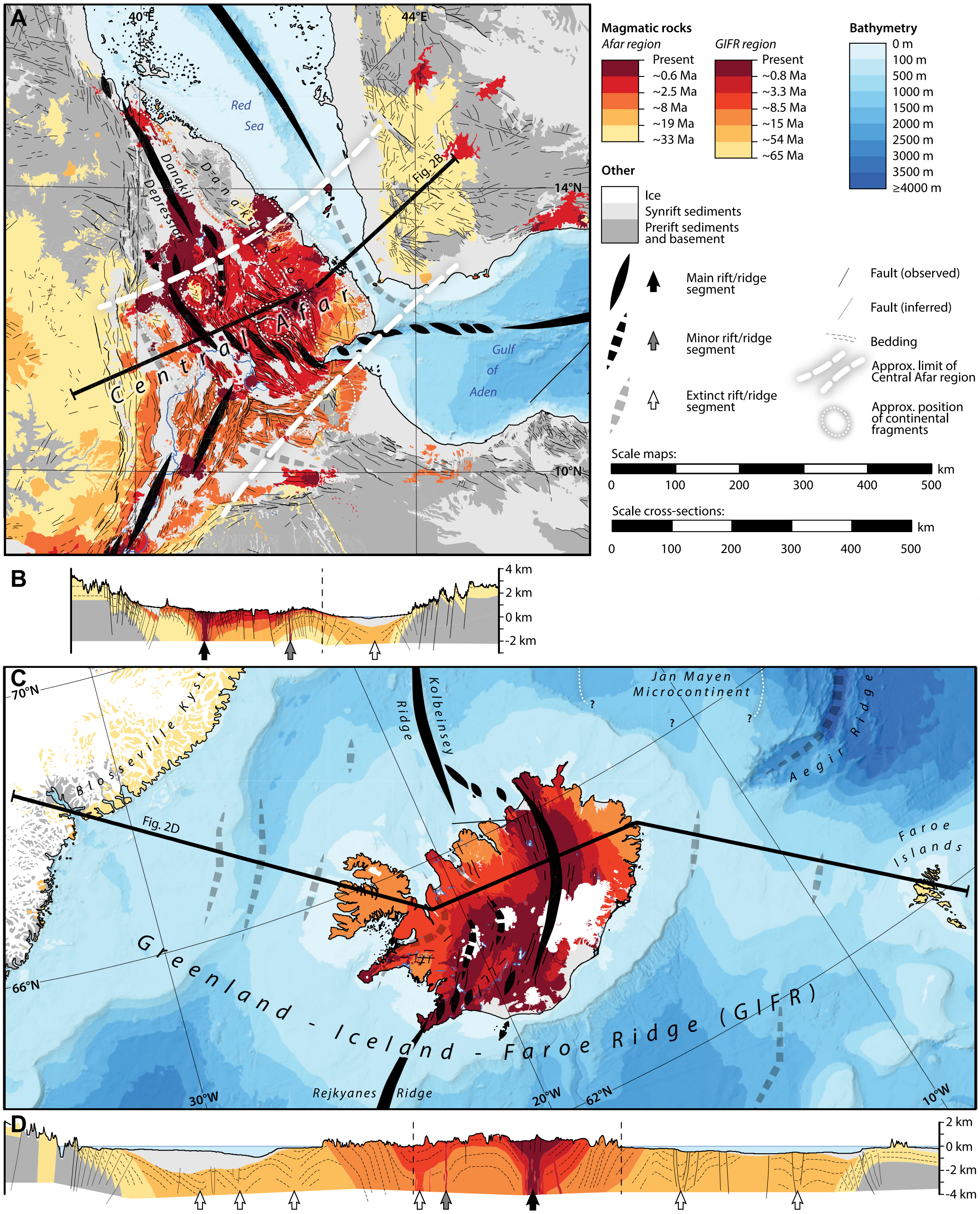

Figure 2. (A, C) Geological maps and (B, D) cross sections (20× vertical exaggeration) through Afar and Greenland–Iceland–Faroe Ridge (GIFR) regions, highlighting important magmatic cover, overlapping rift/ridge segments, and numerous extinct rift/ridge segments. Sources are given in Text 6.2 (see text footnote 1).

ing the GIFR, have geophysical, geochemical, and/or geological indications that they contain fragments of continental crust (Fig. 1; Torsvik et al., 2015; Foulger et al., 2020; Yuan et al., 2020), and several are associated with microcontinents (e.g., Jan Mayen; Fig. 1; Text S2). The thick crust of ROMPs is often referred to as Icelandic-type crust, featuring a 3–10-km-thick magmatic upper crust that displays sharply increasing seismic velocity with depth, and a 10–30-km-thick lower crust (Vp 7.0–7.3 km/s) dominated by mafic intrusive rocks and remnant blocks of continental material (Foulger et al., 2003, 2020).

ROMPs have a recurrent tectonic architecture indicating repeated reorganizations in the locus of extension by rift/ridge jumps, which can bound and isolate continental fragments offshore (Fig. 1; Text S2). Iceland currently features two main overlapping rift/ridge segments (Fig. 2C), and both onshore geology and offshore geology show that the GIFR experienced at least seven rift/ridge jumps during its history (Figs. 2C and 2D; Harðarson et al., 1997; Hjartarson et al., 2017). This tectonic architecture is reflected in cross-sectional view as large seaward-dipping reflector (SDR) wedges at the basin margins and multiple synclinal structures along the ridge marking the locations of abandoned rifts/ridges (Fig. 2D; Hjartarson et al., 2017). One of them isolated the Jan Mayen microcontinent (Fig. 3B). As such, ROMPs lack persistent focused rifting compared to classical rifting models, even after continental breakup has occurred in adjacent basins.

CENTRAL AFAR AS THE BIRTH OF A NEW OCEANIC PLATEAU

Similar to other ROMPs, Central Afar is linked to CFBs (ca. 30 Ma Ethiopian flood basalts found in Ethiopia and Yemen; Figs. 1 and 2A) caused by a hotspot that is part of a

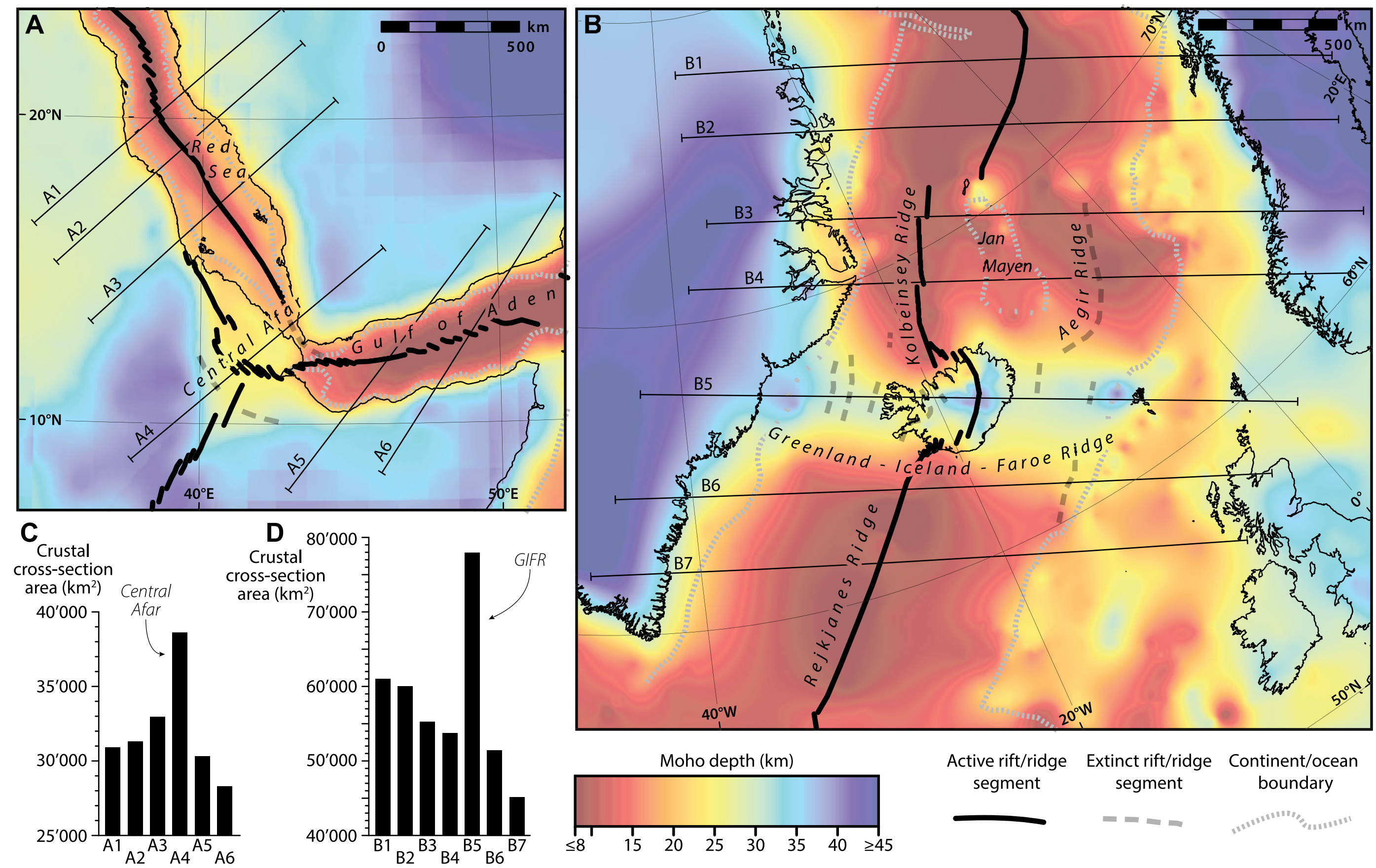

Figure 3. (A–B) Moho depth maps of Greenland–Iceland–Faroe Ridge (GIFR) region (A) and Afar region (B). (C–D) Crustal area in cross section calculated for different lines represented on A and B, respectively. It highlights clear excess in crustal material in GIFR and Central Afar compared to neighboring basins that experienced comparable extension. More information is given in Text S4 and S6.3 (see text footnote 1).

plume imaged by a broad-scale low-seismic-velocity anomaly centered beneath Afar (Text S2.1; e.g., Civiero et al., 2022). The Central Afar region forms positive topography relative to the Red Sea and Gulf of Aden (Fig. 2A). It similarly lacks normal oceanic crust, being the only part of the Red Sea (south of 24°N)–Gulf of Aden system that does not feature oceanic crust (Fig. 3A). Like other ROMPs, the crust beneath Central Afar is not thinner than ~20–30 km thick (Fig. 3A; Text S2). It is heavily intruded by new mafic igneous rock and covered by several kilometers of lavas (Text S2.1). Like the GIFR, Central Afar features ~7000 km² of excess crustal material (interpreted as magmatic additions) compared to the surrounding magma-rich southern Red Sea and western Gulf of Aden, which experienced similar amounts, rates, and durations of extension (Fig. 3C; Text S4; Rime et al., 2023). Magmatic additions to the crust might reach 40% of the total crustal volume (Text S5). This contrasts with conventional magma-rich rifted margins, which recent studies suggest do not require excessive magmatism, but simply the somewhat early onset of magmatism during rifting (compared to magma-poor passive margins) when the continental crust has been thinned to ~20–10 km (Tugend et al., 2020; Sauter et al., 2023; Chenin et al., 2023).

As in several ROMPs (Fig. 1; Text S2), several continental fragments have been identified in Central Afar (Fig. 2A; Hammond et al., 2011; Rime et al., 2023), including the Danakil Block (Fig. 2A), which was isolated from the Nubian plate during a major rift jump (Mohr, 1970; Rime et al., 2023). Like many ROMPs (Text S2), Central Afar shows several active and extinct overlapping rift segments (Figs. 2A, 2B, and 3A; Hammond et al., 2011; Rime et al., 2023). In cross section, this structure very much resembles the GIFR, with thick SDRs on the rift margins and synclinal structures evidencing major rift segments (Fig. 2B). Conversely, the western Gulf of Aden, the southern Red Sea, and the Danakil Depression show evidence for focused extension throughout rifting (Figs. 2A and 3A).

Central Afar thus features several distinctions from conventional magma-rich margins, including the neighboring southern Red Sea and western Gulf of Aden margins, and features several similarities with ROMPs. We therefore interpret it as an extreme end member of magma-rich rifted passive margins (ultra–magma rich and very wide) and as a ROMP in the early stages of development. In this sense, one might even see more mature ROMPs as extreme types of rifted passive margins—separating continental and oceanic domains with a transitional crust that is neither completely continental nor purely (Penrose-like) oceanic. However, the distal parts of ROMPs are probably very similar to OMPs, featuring fewer and fewer characteristics of a rifted passive margin.

THE FORMATION OF ROMPS

The consideration of Central Afar as a ROMP in the early stages of development allows a better understanding of its early evolution and mechanisms of formation to be ascertained. These mechanisms are illustrated by balanced cross sections representing the evolution of a ROMP (Figs. 4A–4E) and the evolution of conventional magma-rich margins (Figs. 4F–4I), represented by the nearby southern Red Sea and Danakil basins.

Three important characteristics of ROMPs are: (1) the high volume of magmatic addition to the crust, (2) the early onset of excess magmatism, preceding the main rifting phase and continuing long after continental breakup, and (3) the important and long-lasting instabilities in rift localization. These three characteristics

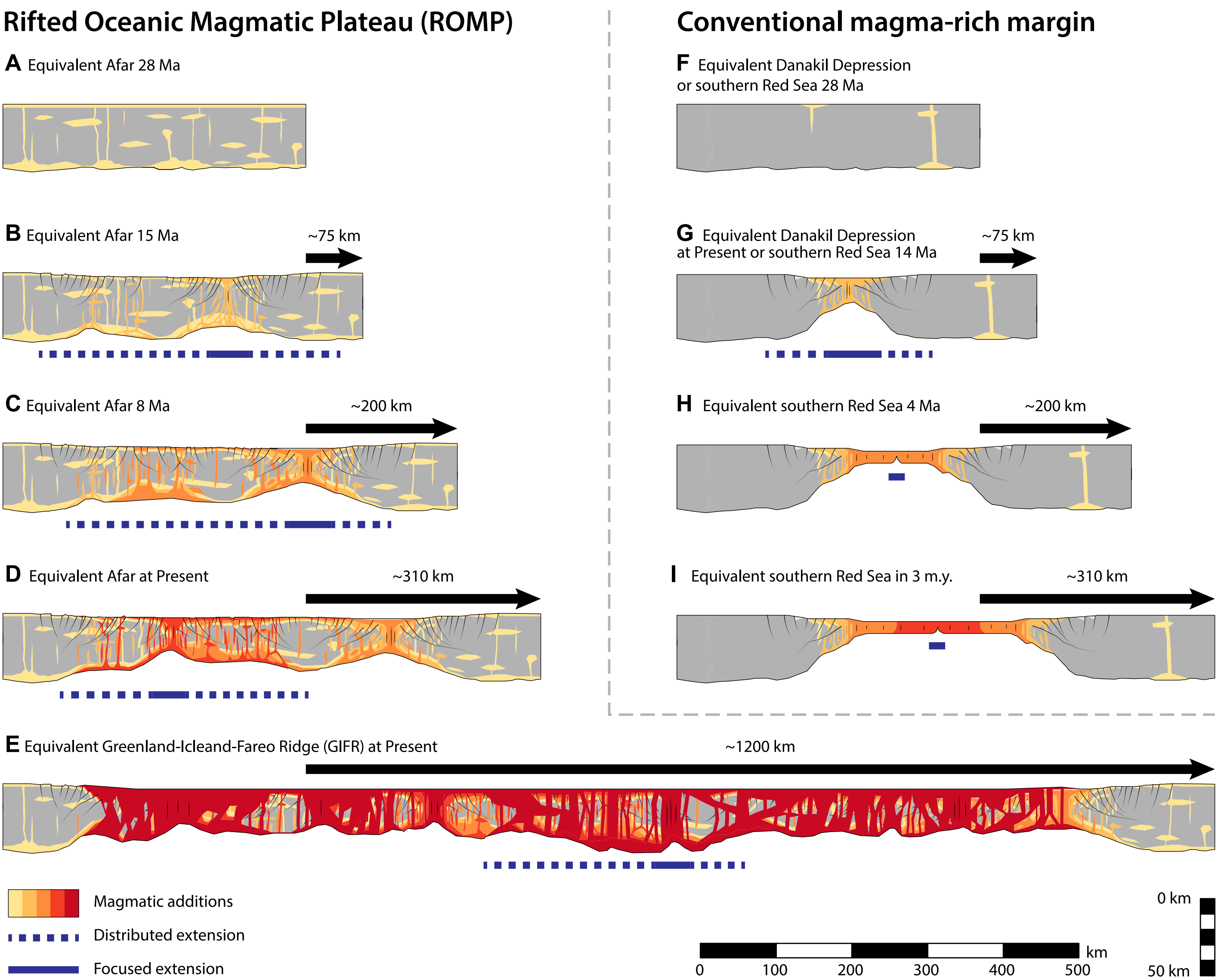

Figure 4. (A–E) Conceptual and schematic crustal evolution model of rifted oceanic magmatic plateaus (ROMPs) and (F–I) comparison with conventional magma-rich margins. As opposed to classical magma-rich margins, ROMPs fail to focus extension and produce large amounts of magmatic material, leading to thicker crusts and dragging of continental material very far from continental margins. Cross sections are all area-balanced. Arrows indicate magnitude of extension; 2× vertical exaggeration. More information is given in Text S6.4 (see text footnote 1).

strongly point toward elevated mantle melt production throughout the rifting history and can be explained by the presence of a hotspot that provides the thermo-chemical conditions necessary for the protracted production of large volumes of melt. Central Afar and older ROMPs show that magmatism predates the early rifting stage, forming CFBs, and adds significant volume to the crust before this crust has been significantly thinned (i.e., still >30 km; Figs. 4A–4D). Figures 3C and 3D and Text S4 show that both Central Afar and the GIFR require the accretion of approximately three times more magmatic material than the 6–8 km melt thickness forming the neighboring oceanic crust. Magma-compensated plate thinning starts early in the evolution of a ROMP (Figs. 3C and 4B–4D; Text S4; Bastow and Keir, 2011; La Rosa et al., 2024). The relative lack of crustal thinning, together with dynamic topography (Gvirtzman et al., 2016), leads to reduced subsidence of the rift, protracting subaerial rifting, and reduced bathymetry after breakup compared to conventional passive margins.

Rifting above hot and buoyant mantle has also been proposed to foster rift/ridge jumps (Müller et al., 1998, 2001; Mittelstaedt et al., 2008, 2011; Whittaker et al., 2015; Lavecchia et al., 2017), thus linking the magmatic and tectonic properties of ROMPs. The examples of Central Afar and GIFR show that overlapping rift segments and frequent rift/ridge jumps play a long-lived role during the geological history of ROMPs and can isolate continental material far offshore (Figs. 4A–4E). Conversely, conventional magma-rich margins have a relatively stable extension locus throughout the rifting history (Figs. 4H–4I).

The protracted accretion of a ROMP is thus a self-sustained mechanism where increased melting in the upper mantle promotes rift/ridge jumps and keeps the location of extension above the productive mantle melting zone. In turn, this maintains voluminous (and often subaerial) magmatic accretion of crust, delaying the formation of Penrose-like oceanic crust for tens of millions of years. However, if melt production decreases, then the ROMP ceases to further evolve. This may have been the case with the Rio Grande Rise, where there was a temporal coincidence between the change from plateau to seamount formation (indicating a lower magmatic budget), the change from on-ridge to off-ridge hotspot magmatism, and the creation of Penrose-like oceanic crust along the entire south Atlantic mid-ocean ridge (O’Connor and Duncan, 1990).

Our analysis therefore suggests that the Central Afar portion of the Red Sea–Gulf of Aden rift system will possibly not reach normal oceanic spreading while under the influence of the hotspot beneath Afar.

CONCLUSION

Central Afar features several similarities with the GIFR and other ROMPs. It is therefore interpreted as an oceanic plateau in the early stages of development. This provides a better understanding of the formation and evolution of ROMPs. Increased melt production causes early and voluminous magma input, which hinders crustal thinning and leads to rift jumps that retain tectonic extension over the productive melt region. This shapes the crustal structure and morphology of ROMPs from the early stages of their development and prevents the formation of Penrose-like oceanic crust. Rift jumps further isolate continental blocks within the developing magmatic rift, ultimately isolating continental material far offshore. Central Afar should thus not be considered a conventional rift or magma-rich rifted margin, just like Iceland should not be considered a conventional mid-ocean ridge.

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