­­­Central Afar: An analogue for oceanic plateau development

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# Abstract

The structure, composition and evolution of oceanic plateaus is poorly understood and strongly debated. Here, we compare 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: 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 afterwards. 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, ultra-thick igneous crust, and repeated re-organisation of the extension locus during rift/ridge jumps, which delays the onset of oceanization and Penrose-style crustal production. This differentiates 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 as normal oceanic crust.

# Introduction

Rifting and the formation of new oceanic crust is a fundamental part 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 the Earth’s crust (Mooney et al., 2023), play a major role in palaeoceanography (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 been reached (e.g. Campbell, 2007; Foulger et al., 2020).

The Afar region (Figs 1, 2A, 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, and has a rift morphology and 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 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 an example of conventional magma-rich breakup (Wolfenden et al., 2005; Bastow and Keir, 2011; Chauvet et al., 2023), shows differences with 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). Here, 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.

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, suppl. mat. 2), questioning 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 can therefore not be compared to Afar. Oceanic plateaus are thus divided in two broad categories (fig. 1 and suppl. mat. 1). Some of them developed exclusively on oceanic crust, with no evidence for ever having been connected to a continent (e.g. the Shatsky Rise), are referred to as “*Oceanic Magmatic Plateaus”* or “*OMP”* and will not be discussed in the present paper. Others that started forming during the rifting stage and were originally connected to a continent and a *Continental Flood Basalt* *province* (CFB) are referred to as “*Rifted Oceanic Magmatic Plateaus”* or “*ROMP”*.

Here, we aim to test the hypothesis that Central Afar represents the birth of a ROMP. We establish 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, which we then test against 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 suppl. mat 2.

# Characteristics of fully developed ROMPs

By definition, all ROMPs originated as a CFB and are all associated to a hotspot (Fig. 1; suppl. mat. 2; Koppers et al., 2021). The GIFR is linked to the *North Atlantic Igneous Province* (~56 Ma), and to the Iceland hotspot (Storey et al., 2007; Fig. 1). ROMPs form positive topography above the surrounding oceanic basins, linked to the significantly thicker crust than classic (6-8 km thick) Penrose-like oceanic crust, reaching 40 km in Iceland (Fig. 3B, suppl. mat. 2.2). 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 (suppl. mat. 2). 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 neighbouring oceanic basins (Fig. 3D, suppl. mat. 4). This difference is most simply explained by crustal magmatic additions significantly more voluminous than normal oceanic spreading processes (suppl. mat. 4). Most ROMPs, including 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; Phethean et al., under review) and several are associated with microcontinents (e.g. Jan Mayen; Fig. 1, suppl. mat. 2). The thick crust of ROMPs is often referred to as *Icelandic-type crust*, featuring a 3-10 km magmatic upper crust, displaying 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 re-organisations in the locus of extension by rift/ridge jumps, which can bound and isolate continental fragments offshore (Fig. 1, suppl. mat. 2). Iceland currently features two main overlapping rift/ridge segments (Fig. 2C), and both onshore and offshore geology shows that the GIFR experienced at least seven rift/ridge jumps during its history. (Fig. 2C-D; Harðarson et al., 1997; Hjartarson et al., 2017). This tectonic architecture is reflected in cross-sectional view with large Seaward Dipping Reflector wedges (SDR) at the basin margins and multiple synclinal structures along the ridge marking the location of abandoned rift/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 continental flood basalts (~30 Ma Ethiopian Flood Basalts found in Ethiopia and Yemen, Figs 1, 2A) caused by a hotspot which is part of a plume imaged by a broad-scale low seismic velocity anomaly centred beneath Afar (e.g. Civiero et al., 2022; suppl. mat. 2.1). The Central Afar region forms a 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, suppl. mat. 2). It is heavily intruded by new mafic igneous rock and covered by several kilometres of lavas (suppl. mat. 2.1). Like the GIFR, Central Afar features approximately 7’000 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 duration of extension (Fig. 3C; suppl. mat. 4; Rime et al., 2023). Magmatic additions to the crust might reach 40% of the total crustal volume (suppl. mat. 5). This contrasts with conventional magma-rich rifted margins, which recent studies suggest to 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, suppl. mat. 2), several continental fragments have been identified in Central Afar (Hammond et al., 2011; Rime et al., 2023; Fig. 2A), 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 (suppl. mat. 2), Central Afar shows several active and extinct overlapping rift segments (Figs 2A-B, 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, 3A).

Central Afar thus features several distinctions from conventional magma-rich margins, including the neighbouring 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 (magma-ultra 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 OMP, 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. These mechanisms are illustrated by balanced cross-sections representing the evolution of RMOP (Fig. 4A-E) and conventional magma-rich margins (Fig. 4F-I), 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 which continues long after continental breakup, 3) the important and long-lasting instabilities in rift localisation. These three characteristics strongly points towards elevated mantle melt production throughout the rifting history and can be explained by the presence of a hotspot that provides thermo-chemical conditions for the protracted production of large volume of melt. Central Afar and older ROMPs show that magmatism predates the early rifting stage, forming CFB, and adds significant volume to the crust before this crust has been significantly thinned (i.e. still >30 km, Fig. 4A-D). Fig. 3C, 3D, and suppl. mat 4 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 neighbouring oceanic crust. Magma-compensated plate thinning starts early in the evolution of a ROMP (Bastow and Keir, 2011; La Rosa et al., 2024) Figs 3C; 4B-D suppl. mat 4). 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 causing 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 (Fig. 4A-E). Conversely, conventional magma-rich margins have relatively stable extension locus throughout the rifting history (Fig. 4H-I).

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 a 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 is 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 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 allows 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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# Figure caption

Figure 1. Bathymetric map of the Atlantic and Indian ocean showing the position of potential ROMPs and OMPs, CFBs, hotspots and recovered continental material on ROMPs. Underlined labels indicate potential microcontinent. More information in suppl. mat. 1, 2, 3 and 6.1.

Figure 2. Geological maps (A, C) and cross-sections (B, D, 20x vertical exaggeration) through the Afar and GIFR regions. They highlight the important magmatic cover, the overlapping rift/ridge segments and the numerous extinct rift/ridge segments. Sources in suppl. mat 6.2.

Figure 3. Moho depth map of the GIFR region (A) and Afar region (B). The crustal area in cross-section is calculated for different lines represented on (A) and (B) and is plotted in (C) and (D). It highlights a clear excess in crustal material in the GIFR and Central Afar compared to neighbouring basins that experienced comparable extension. More information in suppl. mat. 4 and 6.3.

Figure 4. Conceptual and schematic crustal evolution model of ROMPs (A-E) and comparison with conventional magma-rich margins (F-I). As opposed to classical magma-rich margins, ROMPs fail to focus extension and produces large amount 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. 2x vertical exaggeration. More information in suppl. mat 6.4.

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