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From coral reefs toward unveiling the deep geobiosphere in extreme rift settings: Afar Dallol Drilling (ADD-ON)

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Afar Dallol represents a world-class natural field laboratory where active rifting, volcanism and climate dynamics steer fast environmental change and complex geobiosphere interactions. Future drilling aims to understand the deep subsurface paleoenvironmental record, and its controlling factors during continental break-up.

The Afar Dallol: A spectacular science laboratory

Afar Dallol is located in the central Danakil Depression, Ethiopia, in the northern Afar rift system (Fig. 1) (Rime et al. 2023). The Danakil Depression is one of the hottest places on planet Earth, located 50 to 120 m below sea level, and forms an active salt pan today. This area is identified as one of the few exposed areas on Earth currently experiencing continental break-up on its way toward oceanization (Bastow and Keir 2011). As such, the area is an ideal field laboratory and analog to study rift processes through space and time.

Rapid subsidence rates in the central axis of the Danakil Depression resulted in the deposition of an exceptional and high resolution stratigraphic and sedimentary record (Foubert et al. 2018; 2024). Faulted, thinned and stretched continental crust is modified by hydrothermal fluid flow rich in volatiles, salt processes and mafic intrusions (e.g. Varet 2018).

The region includes the Dallol volcano, which is an active hydrothermal system associated with hydrothermal brine pools, fumaroles and hyperacidic to hypersaline springs rich in sulfur-iron mineralizations and active salt precipitation. This results in unique environmental and polyextreme settings, providing an ideal lab to study geobiosphere interactions at physicochemical limits. However, due to its remote location, detailed sedimentary, paleoenvironmental, paleoclimatic, and geobiological studies are only recently emerging.

Coral reefs, microbialites and salt as paleoenvironmental archives

The Afar Dallol area was flooded by the Red Sea during Pleistocene times, resulting in the growth and build-up of coral reefs along the western and eastern margin of the basin, following the paleoshoreline (Atnafu et al. 2015; Foubert et al. 2018). Coral-reef terraces developed as fringing reefs, patch reefs and coral carpets (Foubert et al. 2018). They host diverse coral-reef communities such as *Porites*, *Platygyra*, *Dipsastraea*, *Favites*, *Goniastrea*, *Goniopora*, *Diploastrea*, *Echinopora*, and *Pocillopora* (Fig. 1b, c).

The Pleistocene Danakil Depression is distinct in coral species composition and shows diversity change with time (Endeshaw et al. 2024). The coralgal-reef terraces are associated with ooidal and bioclastic grainstones. Terraces are often transitioning into hypersaline microbial build-ups (microbialites) and aragonitic crusts draped

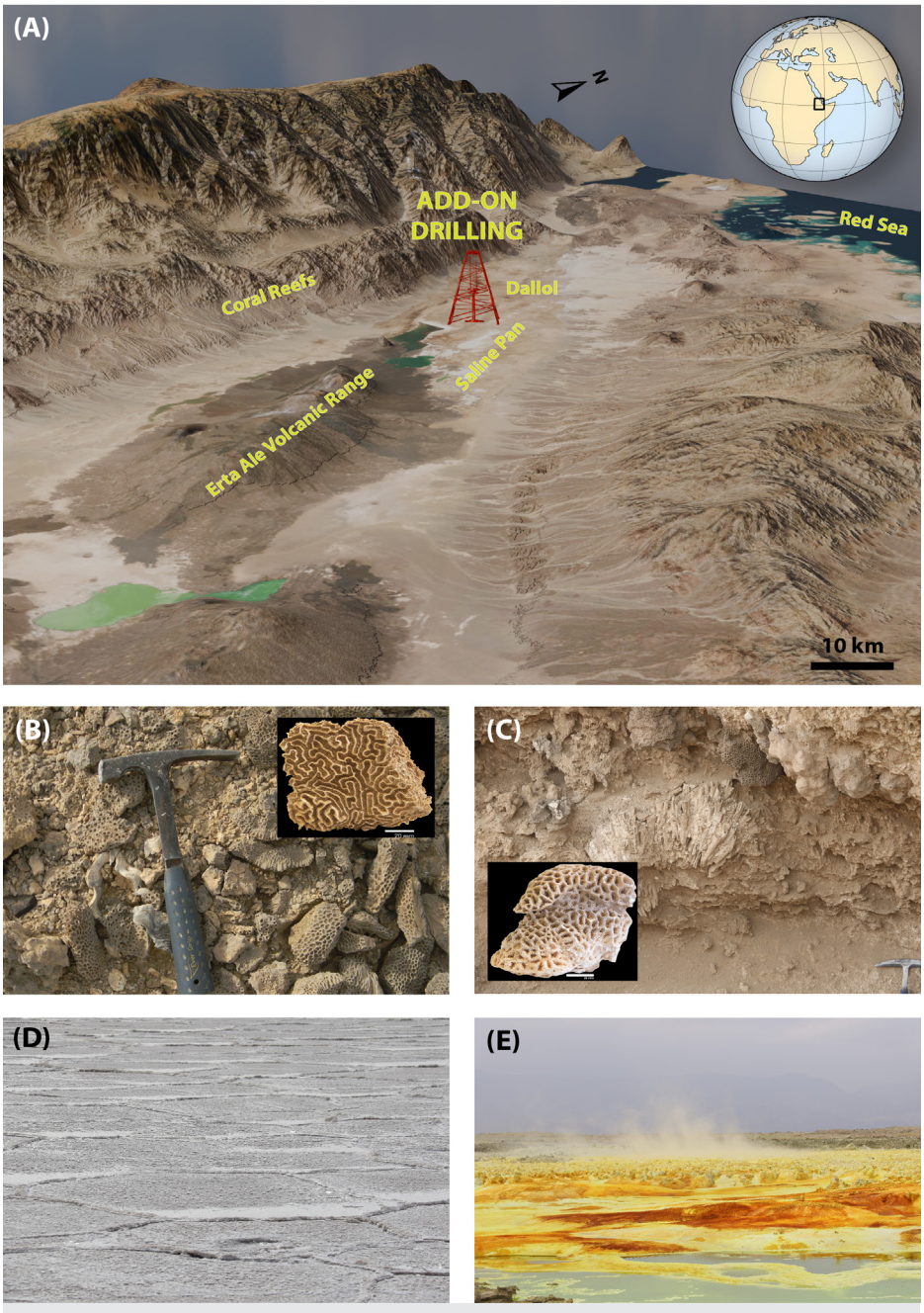

Figure 1: (A) Localization of the Afar Dallol area (Danakil Depression, Ethiopia) and the envisaged ICDP ADD-ON drill site. Pleistocene coral reefs and coral species exposed at the western margin of the Danakil Depression: **(B)** *Favites* and *Platygyra daedalea*; **(C)** *Goniastrea pectinata*, *Astraeosmilia* and *Porites*. **(D)** Active salt pan at the surface of the Danakil Depression. **(E)** Dallol geothermal brine pool.

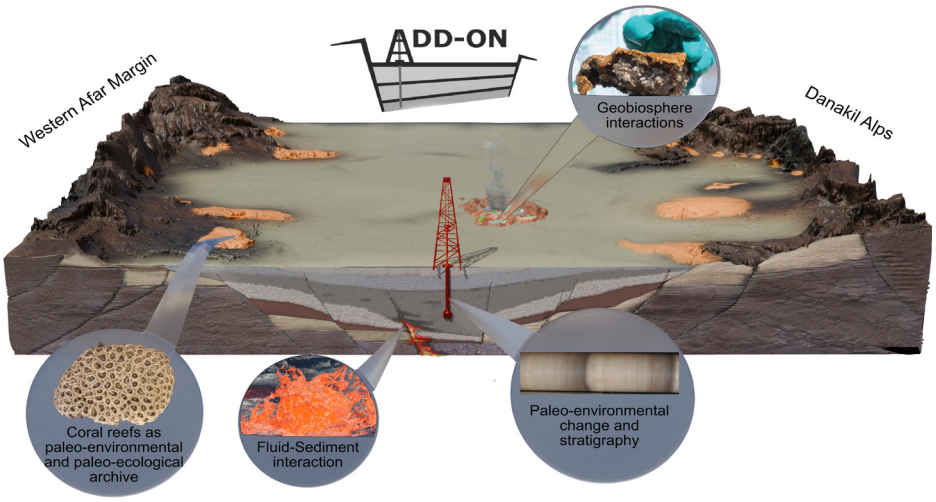

Figure 2: Synthetic profile through the Afar Dallol area highlighting the paleo-environmental and geobiological aim and objectives of the ADD-ON drilling project.

by gypsum deposits (Jaramillo-Vogel et al. 2019). Gypsum deposits witness closure of the basin from the Red Sea followed by desiccation. Successive episodes of coral growth, microbialite development and gypsum precipitation reveals the alternating and intermittent opening and closure of the Afar Dallol area with the Red Sea. Eustatic sea-level variations, in combination with tectonic uplift and subsidence patterns, control the gateway between the Afar Dallol area and the southern Red Sea regions (Rime et al. 2021). Overall, the Pleistocene coral-reef terraces and microbialites are excellent archives of multiple marine incursions and desiccation events in the Afar Dallol area.

The central part of the Afar Dallol area is characterized by the formation of thick evaporite deposits mainly consisting of halite successions, possibly representing a modern analog for Salt Giants, but also a high-resolution record of paleo-environmental and paleoclimatic change (Foubert et al. 2024). Evaporite facies show changes in the hydrological regime going from a restricted marine-fed seaway towards the evaporation of seawater in a restricted basin under arid conditions (Foubert et al. 2024). How previous phases of flooding and desiccation are expressed in the central part of the Danakil Depression, and how they impact the hydrological balance, ecosystems and biogeochemical cycling, is not known. In addition, the subsurface record of regional hydroclimatic change, and its potential link with global forcing mechanisms, remain to be unveiled, but may have had an important impact on human migration in the corridor between Africa and Eurasia.

Geobiosphere interactions in polyextreme environments

At, and around, the Dallol volcano, the interaction between evaporitic and hydrothermal processes results in the upwelling of polyextreme brines of contrasting hydrochemistry (e.g. Lopez-Garcia et al. 2020). Recent studies have revealed the presence and diversity of life, such as newly discovered hyperhalophilic archaea, in these polyextreme conditions (e.g. Belilla et al. 2019). This allows us to test the physico-chemical limits of life on Earth, experiencing polyextreme conditions. Whether microbial life, including new species, is present in the subsurface salt layers under anoxic conditions remains unknown. It is known that microbe-mineral interactions have resulted in microbialite formation in the Danakil Depression since the Pleistocene (Jaramillo-Vogel et al. 2019, 2023; Kotopoulou et al. 2019). Details on how metabolic activities in the deeper subsurface can mobilize metals and contribute actively to mineral precipitation and/or dissolution are not known. It is suspected that deeper hydrothermal fluid flow influenced the subsurface record resulting in biogeochemical processes analogous to early Earth. This may have important implications for origin-of-life research.

Toward the Afar Dallol Drilling (ADD-ON)

To unlock paleoenvironmental change in an active rift basin paced by volcanic events, tectonic processes and climate change, the ADD-ON project aims to drill in the central part of the Danakil Depression (Fig. 2) (Foubert et al. 2021; 2024). If successful, this will result in a 2.5 km long high-resolution stratigraphic and sedimentary archive covering the Pleistocene to Holocene in the Dallol area. Having access to this sedimentary archive and borehole data will allow us to:

(1) unravel complex paleoenvironmental changes in a rift basin,

(2) understand incipient and intermittent dynamics through punctuated volcano-tectonic events in a rift transitioning from continental rifting towards seafloor spreading, and adjacent rifted-margin development,

(3) test the origin and limits of life in the deep biosphere under polyextreme conditions,

(4) better understand fluid flow and fluid-sediment interaction in an active hydrothermal system.

Finally, we aim to use the drilling site to develop a Downhole Earth Observatory to improve hazard-related monitoring capacity (earthquakes, gas/fluid flux, ground motion). Last but not least, drilling in the Afar Dallol area is essential when it comes to the future exploitation of natural georesources (geothermal and hydrogen potential, critical metals, and CO_2 storage) and the mitigation of risk-related geohazards (seismic activity, volcanic hazards) in eastern Africa.

The ADD-ON drilling project was further developed and constrained during two International Continental Scientific Drilling Program (ICDP) funded workshops (June 2021 and August 2023) that brought together a very diverse and inclusive team, turning ADD-ON into a scientifically significant and highly relevant project to society, both at a global and regional scale.

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