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Workshop report: Afar Dallol Drilling – ONset of sedimentary processes in an active rift basin (ADD-ON)

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Abstract. Rifts and rifted margins form when continents break apart and shape the continent-to-ocean transition on much of our planet. The sedimentary basins that result from continental rifting host unique sedimentary archives of palaeo-environmental and palaeo-climatic change required to understand complex natural processes. Rifts and rifted margins are key sites for natural resources (e.g. geothermal and hydrogen potential, critical metal resources, and CO_2 storage) and have an important societal relevance in the mitigation of geohazards such as earthquakes and volcanic activity. However, knowledge on the tectonic structure, sedimentary architecture, rapid palaeo-environmental change, fluid flow and hydrothermal circulation, deep subsurface biosphere, and their impacts on biogeochemical fluxes in rift basins remains poorly understood. Considering their large scientific potential and societal relevance, understanding the formation and architecture of rifts and rifted margins is now critical. The Afar rift is a world-class natural field lab where continental breakup can be directly observed. The northern part of Afar, the Danakil Depression, especially represents a unique snapshot in space and time when the continent ruptures and new seafloor and adjacent rifted margins form. However, deep subsurface records are missing in the basin. The ADD-ON project aims at deep drilling in the Danakil Depression to provide a unique sedimentary record in an active rift basin paced by global environmental fluctuations and their interplay with volcanic and tectonic events. To explore drilling targets and address scientific drilling objectives, an International Continental Scientific Drilling Program (ICDP) workshop was organized in Addis Ababa, Ethiopia, in August 2023. In total, 64 participants from 10 countries and all career stages respecting diversity and inclusion joined the workshop. They represented a wide range of scientific disciplines including government agencies, industry, local universities, and communities to discuss the overall ADD-ON science plan during several workshop sessions. One target drilling site has been flagged, covering the unique Pleistocene full syn-rift sedimentary record in the Danakil Depression. This unique sedimentary archive will allow us to (1) unravel complex palaeo-environmental change 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 poly-extreme conditions, (4) better understand fluid flow and fluid–sediment interaction in an active hydrothermal system, and (5) use the drilling site to develop a downhole Earth observatory to improve hazard-related monitoring capacity (earthquakes, gas/fluid flux, ground motion).

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1 Introduction

Since the early days of the continental drift theory, the Afar Triangle developed into the archetypal field lab where the breakup of continents and potential future ocean spreading can be subaerially observed and studied. The Afar Depression is situated at the boundaries of the Nubian, Arabian, and Somalian plates and forms a triple junction related to the opening of the Afro-Arabian rift system (McKenzie et al., 1970; Viltres et al., 2020). The Danakil Depression is the northern portion of the Afar Depression, bordered by the western plateau and the Danakil Horst to the east. Rifting in the region started in the Oligocene, with extension localizing in the Danakil Depression since Middle to Late Miocene times due to the rotation of the Danakil Block (Arrata Microplate) (Rime et al., 2023) (Fig. 1).

Kinematic modelling supported by geological and geophysical observations suggest the Danakil Depression has formed in faulted, stretched, and thinned continental crust that has been heavily modified by mafic intrusions and flow of volatiles (Bastow and Keir, 2011; Rime et al., 2023). This, in combination with the potentially thick, young syn-rift evaporites and basaltic lava flows in a near-sea-level basin, makes it one of the few modern analogues for the development of a classic magma-rich rifted margin (Bastow et al., 2018; Rime et al., 2023). Accelerated subsidence rates in the central axis of the Danakil Depression over at least the last 120 kyr, resulted in the accumulation of an exceptional stratigraphic and sedimentary record (Foubert et al., 2018; Rime et al., 2024). Several cycles of marine flooding with transgression of the Red Sea into the Danakil Depression resulted in the formation of kilometre-thick evaporite successions in the subsurface of the depression composed of halite intercalated with gypsum, anhydrite, and potash-bearing deposits of economic significance (Warren, 2016; Rime et al., 2024). With that, the Danakil Depression is one of the youngest salt giants on planet Earth. The central part of the Danakil Depression hosts the Dallol volcano formed through the direct interaction between magmatism and sedimentary processes. The associated hydrothermal brine pools, sulfuric acidic springs, and fumaroles form an ideal test case to understand the limits of life in poly-extreme conditions (Belilla et al., 2019). This unique set of geo-physico-chemical conditions may open a new window on the origin of life and function as an analogue for potential extra-terrestrial life. As such, the Danakil Depression is a unique setting in which the interplay between tectonic, sedimentary, volcanic, fluid flow, and environmental processes during the formation of a magmatic rifted continental margin can be studied.

1.1 Historical backbone

Research during the last 2 decades largely focused on tectonics, volcanology, and geophysics to understand mechanisms and controls of rifting. Only a few studies dating back nearly half a century ago focused on the sedimentary deposits and mostly on the rich record of northern Afar. They were initiated as a result of early potash exploration (Holwerda and Hutchinson, 1968; Bannert et al., 1971) and resulted in the first structural and stratigraphic mapping of the area (e.g. Bannert et al., 1971; Brinckmann and Kürsten, 1971; Barberi et al., 1971; Varet et al., 1975; Bonatti et al., 1971). Then, little was done until 2013, with the start of reconnaissance field actions in northern Afar exploring the carbonate sedimentary record at the basin margins (COCARDE research networking programme) (Atnafu et al., 2015). Recently, projects such as SERENA ("Sedimentary Record of the northern Afar: Insights in the flooding history of the Danakil Depression", 2016–2022) and CONNECT ("Paleo-Connectivity and Paleo-Hydrological change in an initial rift basin", 2023–2027) started to focus on the unique Middle to Late Pleistocene and Holocene sedimentary archive (Atnafu et al., 2015; Foubert et al., 2021, 2018; Jaramillo-Vogel et al., 2019) and have resulted in new geological maps of the wider Afar region and the Danakil Depression (Rime et al., 2022a, b, 2023). More recent exploration and exploitation surveys led by the potash industry during the last decade resulted in an additional set of subsurface data, which have been further scientifically explored within the framework of the above-mentioned research projects (e.g. Rime et al., 2024; Bastow et al., 2018; Hurman et al., 2023).

1.2 Unique syn-rift sedimentary record: the need for drilling

In the Danakil Depression, pre-Cambrian, Palaeozoic, and Mesozoic pre-rift series are diachronously overlain by Palaeogene to Neogene Afar flood basalts or trap volcanics ranging from basalts to alkaline rhyolites (Barberi and Varet, 1970; Watts et al., 2020), followed and intertwined with Cenozoic syn-rift sediments (Fig. 2a). Syn-rift sediments are characterized by fluvio-lacustrine siliciclastic sediments since the Neogene (Belekiya and Sabba formations). The Middle to Late Pleistocene record witnessed episodic marine flooding and desiccation resulting in the deposition of marine carbonate sediments at the margins (Zariga Formation) and evaporites in the centre of the depression (Dallol Formation) (Atnafu et al., 2015; Foubert et al., 2018; Jaramillo-Vogel et al., 2019). Currently, the surface of the Danakil Depression, featuring elevations as low as 120 m b.s.l., is covered by lacustrine sediments, seasonal terminal saline lakes, saline pans and geothermal pools.

Available industrial core sections provide relatively good constraints on the expected lithologies and allow for correlations with carbonate outcrops at the margin of the depression (Rime et al., 2023, 2024) (Fig. 2b). Seismo-stratigraphic interpretations, based on industrial seismic section, core, and borehole data, evidence the presence of evaporite units until the depth of about 800 m below the Dallol salt pan (e.g. Bastow et al., 2018; Foubert et al., 2018; Hurman et al., 2023).

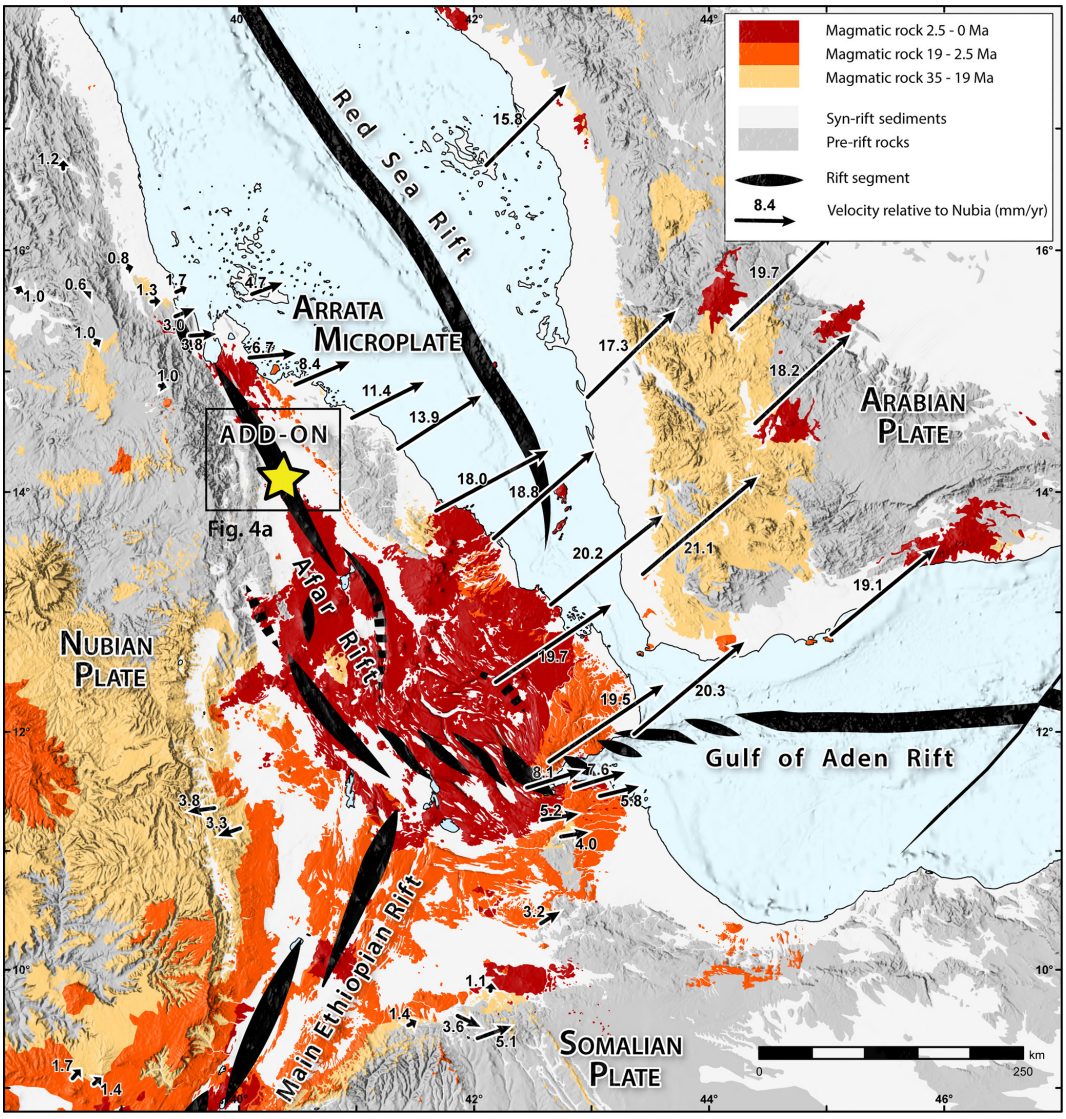

Figure 1. Afro-Arabian rift system with indication of the Red Sea Rift, Gulf of Aden Rift, Main Ethiopian Rift, and the Afar Rift. The central Afar domain is mainly characterized by magmatic rocks, while the northern Afar represents a unique archive of syn-rift sediments. Yellow star represents ADD-ON drilling location. Modified after Rime et al. (2023).

However, to date no sedimentary records are available from the central part of the rift basin filled with more than 2.2 km of sediments which record the basin evolution.

2 Workshop structure

After funding was granted in 2020, a first online International Continental Scientific Drilling Program (ICDP) ADD-ON workshop was initiated from 29 to 30 June 2021 with 70 participants from 10 countries and representatives from the ICDP Operational Support Group (OSG). This workshop resulted in a first set of scientific ADD-ON drilling objectives and a selection of drilling scenarios that served as a base for subsequent discussions. To keep momentum during the COVID-19 era, a European Geosciences Union (EGU) splinter meeting was held on 25 May 2022. The in-presence ICDP ADD-ON workshop was finally organized from 28 to 31 August 2023 in Addis Ababa, Ethiopia, at the Ambassador Hotel and at Addis Ababa University (Fig. 3). The workshop was attended by 64 participants from Ethiopia, Germany, United Kingdom, USA, Switzerland, France, Italy, Belgium, Israel, and Japan. More than half of the participants were from Ethiopia, including scientists and delegates from Addis Ababa University, Addis Ababa Science and Technology University, Mekelle University, and Semera University. There were representatives from the potash, geothermal, and petroleum exploration sectors; the national and regional government; and a number of non-government agencies active

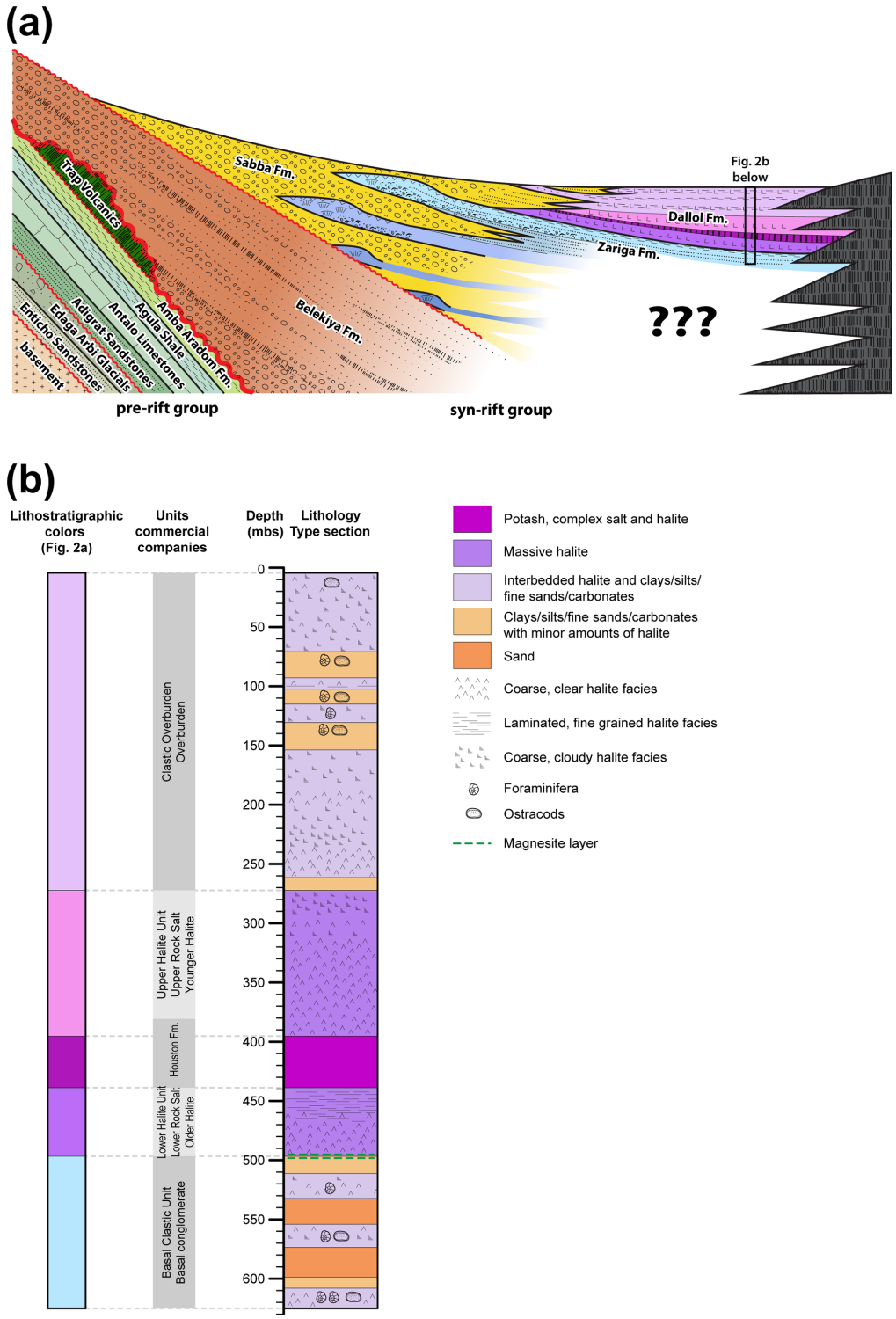

Figure 2. **(a)** W–E cross-section through the Danakil Depression indicating pre-rift and syn-rift sediments (Belekiya Formation, Sabba Formation, Zariga Formation, and Dallol Formation). Please note that this schematic cross-section only represents the lithostratigraphy. Structural features (faults, fractures) are not represented. **(b)** Lithology of the upper syn-rift sedimentary record. The upper units are mainly consisting of an alternation of halite and clay/silt ("Clastic Overburden"), below which there is a thick unit of mainly halite ("Upper Halite Unit"). This is followed by a layer of potash-bearing minerals ("Houston Formation"), another major halite unit ("Lower Halite Unit"), and then sandstones locally enriched by anhydrite ("Basal Clastic Unit"). Those sandy units can be correlated, based on seismic sections, with the carbonate outcrops (Zariga Formation) at the margins of the depression and identified as belonging to the Middle to Late Pleistocene (Foubert et al., 2018; Rime et al., 2024).

in the Afar region. The principal investigators (PIs) encouraged the participation of early-career scientists by inviting around 20 post-graduate (both local and international MSc and PhD) students. A wide range of disciplines was represented and included sedimentology, stratigraphy, structural geology, volcanology, geochemistry, geophysics, hydrology, palaeo-climate, biology, biogeochemistry, and engineering.

The official workshop opening started with a meet-and-greet event and an ice-breaker event on 28 August 2023. Formal sessions started on 29 August with welcome addresses by the ADD-ON PI team, delegates from the Ethiopian Ministry of Mines, and Addis Ababa University, as well as an introduction to the ICDP from the ICDP executive director. The first scientific session set the state of the art for geological, sedimentological, basin dynamics, and biological background of the Danakil Depression. The afternoon sessions opened with lightning talks on research background and interests by workshop attendees, followed by talks on industrial drilling experience in Ethiopia from the potash, geothermal, and petroleum industries. The day concluded with a presentation by the ICDP OSG on guidelines for writing a full drilling proposal, followed by an open discussion around the 25 posters presented by workshop attendees.

The 30 August started with presentations by the PI team on the draft science plan and three potential drilling strategies followed by discussions on science objectives and drilling strategy by all workshop participants during break-out sessions of three groups with a balanced mix of disciplines, background, and experience. The second half of the morning was devoted to discussions on the societal relevance of the drilling project and opened with a presentation on the hydrogeology in Afar and an overview of the permanent seismic monitoring network managed by Addis Ababa University. Further talks included local Afar community-based schemes that promote education about, and sustainable development of, geothermally sourced energy compatible with their lifestyle and culture (the green geothermal village concept). After an introduction on core, sample, and data handling; ICDP geophysical downhole logging capability; and gas/fluid monitoring, a second break-out session was organized in the afternoon. Groups that were organized by broad discipline (stratigraphy, biology, palaeo-climate, tectonics, volcanology) discussed required sampling material, analyses, and datasets. A geophysics/monitoring group discussed post-drilling downhole and surface geophysical monitoring infrastructure. The day finished with a final discussion on matching funds, funding resources, and time plan for the compilation of the full drilling proposal. Future avenues were explored for an integrative cross-border regional seismic monitoring initiative and a LEAP (Ocean Drilling Legacy Assets Project) initiative for including existing Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) core records in the Red Sea and Gulf of Aden.

On 31 August, the full ICDP ADD-ON team made a trip through Addis Ababa with a visit to Unity Park and the National Museum of Ethiopia. The day finished at Addis Ababa University with a session on education and public outreach as well as possible links with local education activities inside and outside the academic environment. Key delegates in the discussion were from Addis Ababa University, Semera University, and Mekelle University (Ethiopia). Local MSc and PhD students from Addis Ababa University were invited to join the session and participate in the discussion. Different ideas on how to actively involve local Afar communities and Afar authorities in the drilling project were levered, as well as the potential of recognizing Danakil as a national heritage site.

3 Drilling site

The ADD-ON project aims at deep drilling in the Danakil Depression to provide a unique sedimentary record in an active rift basin paced by global environmental fluctuations and their interplay with volcanic and tectonic events. During the ADD-ON workshops, different drilling sites have been discussed along a basinal transect going from west to east (Fig. 4). Due to financial and technical constraints, it has been decided to only focus on one drilling site in the central part of the Danakil Depression between the Dallol volcano and the Erta Ale volcanic range, i.e. Dallol-01A. This strategic choice avoids major faults and fault zones, as well as gas pockets. The target depth is 2.2 km, aiming to intercept the full syn-rift sedimentary record through continuous coring until the rift basement (Fig. 4). Available site survey data at the potential drill site show the presence of four distinct seismo-stratigraphic units covering the Middle-to-Upper Pleistocene to Holocene ($\sim$ 500 kyr) (Fig. 4). After drilling, we aim to keep the hole open for seismic monitoring and develop a downhole Earth observatory.

4 ADD-ON project strategy

During the workshop discussion, five thematic challenges were flagged, covering the major aim and objectives of the ADD-ON drilling project: the understanding of rapid palaeo-environmental change in rift settings, unravelling the complex interaction between basin dynamics and volcanics, unveiling the deep geo-biosphere in poly-extreme environments, characterizing hydrothermal systems and mineral resources in active rift settings, and developing a downhole Earth observatory to monitor seismic and volcanic hazards (Fig. 5). These are outlined below.

4.1 Rapid palaeo-environmental change in rift settings

Rift basins are characterized by heterogeneous sedimentation patterns varying at very short temporal scale, resulting in complex palaeo-environmental change. The interaction and feedback between tectonics, surface processes, volcanic events, climate variations, and eustasy on sediment

Figure 3. Impressions from the workshop discussions, presentations, and group picture of the workshop participants at Addis Ababa, Ethiopia.

flux, sediment deposition, and basin dynamics explain their complex stratigraphic architecture. Drilling in the Danakil Basin will provide keys to understand the complex palaeo-environmental change in a rift basin near breakup and how this is modulated by climate, tectonic, and volcanic events.

Until now, only the more recent desiccation record has been recovered from the central part of the basin, while outcrops at the basin margin witnessed at least four flooding cycles during which the Red Sea transgressed into the basin. It is hypothesized that the four flooding cycles represent a high-resolution record of approximately 500 kyr. However, how these cycles of flooding and desiccation are expressed in the central Danakil Basin is not known. Having the full syn-rift sedimentary record will help to understand complex sedimentation patterns since the onset of rifting, including the complex transitional phase from continental sedimentation towards the first marine incursion events.

Sedimentation rates in the Danakil Depression are not well constrained due to the lack of deep subsurface data. Detailed stratigraphy will allow for calculating sedimentation rates and their variability through time. This will help to constrain and quantify the non-linear sedimentation rates in an active rift setting.

The last desiccation cycle in the Danakil Depression resulted in the formation of thick halite units (Rime et al., 2024). However, the formation mechanisms of these evaporites as well as the palaeo-hydrological balance of the basin are poorly constrained. Understanding how the Danakil evaporites may form a deep subsurface salt giant remains debatable. Understanding the formation of those evaporites will also help us to understand other salt giants on planet Earth, e.g. the Messinian.

Finally, having access to the high-resolution palaeo-environmental record in the Danakil Depression may also elucidate new insights into regional palaeo-climatic change, especially precipitation patterns, in northeast Africa, influenced by global monsoonal variations and Atlantic driven oscillations. Palaeo-climatic records in northern Afar are lacking – despite it being a critical zone in the corridor between Africa and Eurasia. The combined effects of climate change and the volcano-tectonic evolution of the Afar may have had an influence on the out-of-Africa migration of *Homo sapiens*.

4.2 Interaction between basin dynamics and volcanism

The Danakil Depression is a unique zone where the final transition from continental rifting to seafloor spreading is well

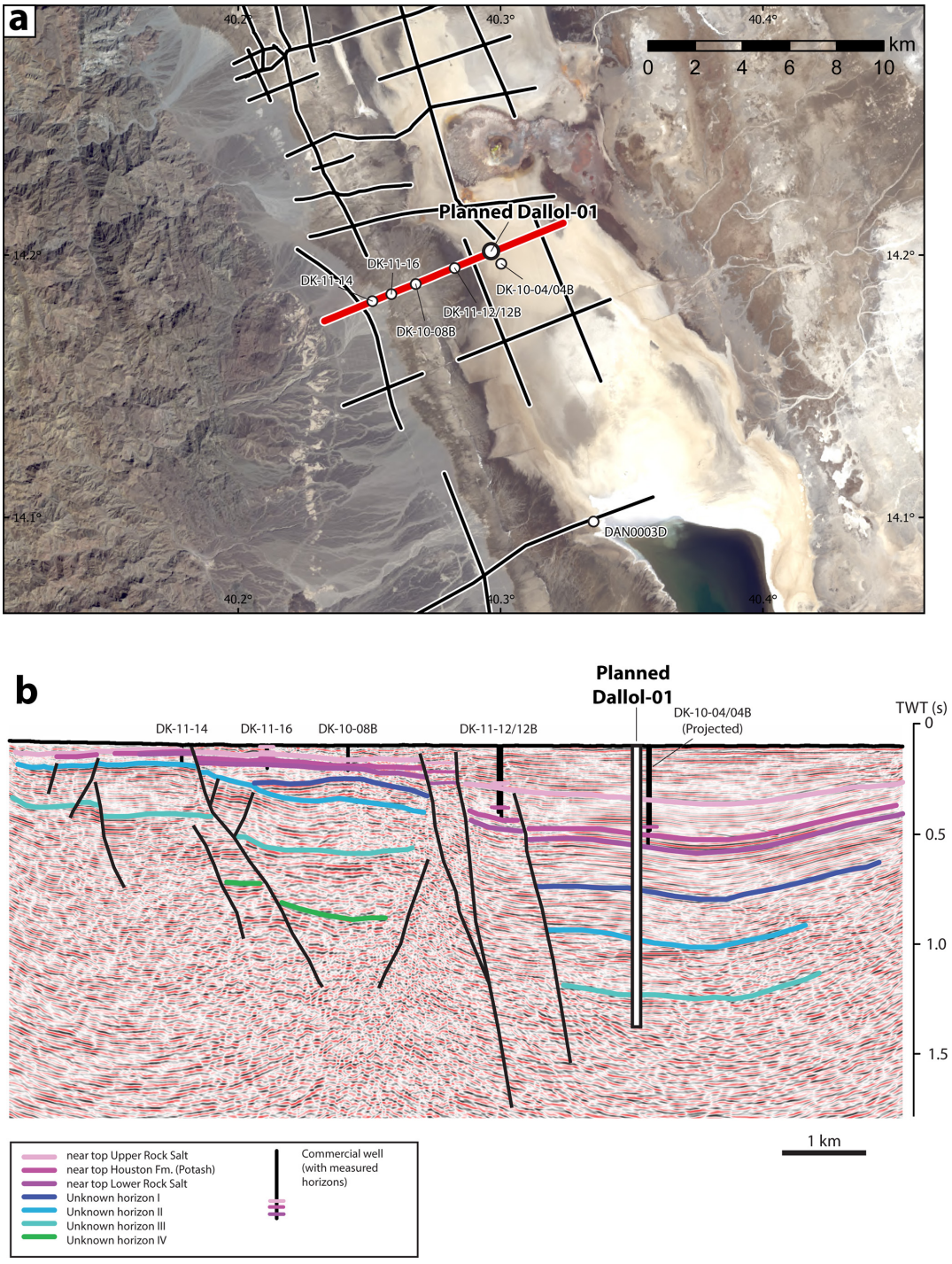

Figure 4. **(a)** Location of the ADD-ON drilling site Dallol-01 (Landsat-8 image). Red line indicates the location of the seismic profile presented in panel **(b)**. **(b)** Seismic section with an indication of the planned drilling site Dallol-01. Seismic profile provided by former Allana Potash Ltd.

exposed subaerially. Constraints from the drill core will significantly aid the interpretation of other datasets such as the surface geology and subsurface seismic images of the basin. Combined datasets will show a 4D picture of how the tectonics and magmatic/volcanic processes unfold in space and time during the final stages of splitting a continent. This will provide key insights to interpret the structure and processes that form magmatic rifted passive margins flanking much of the oceans.

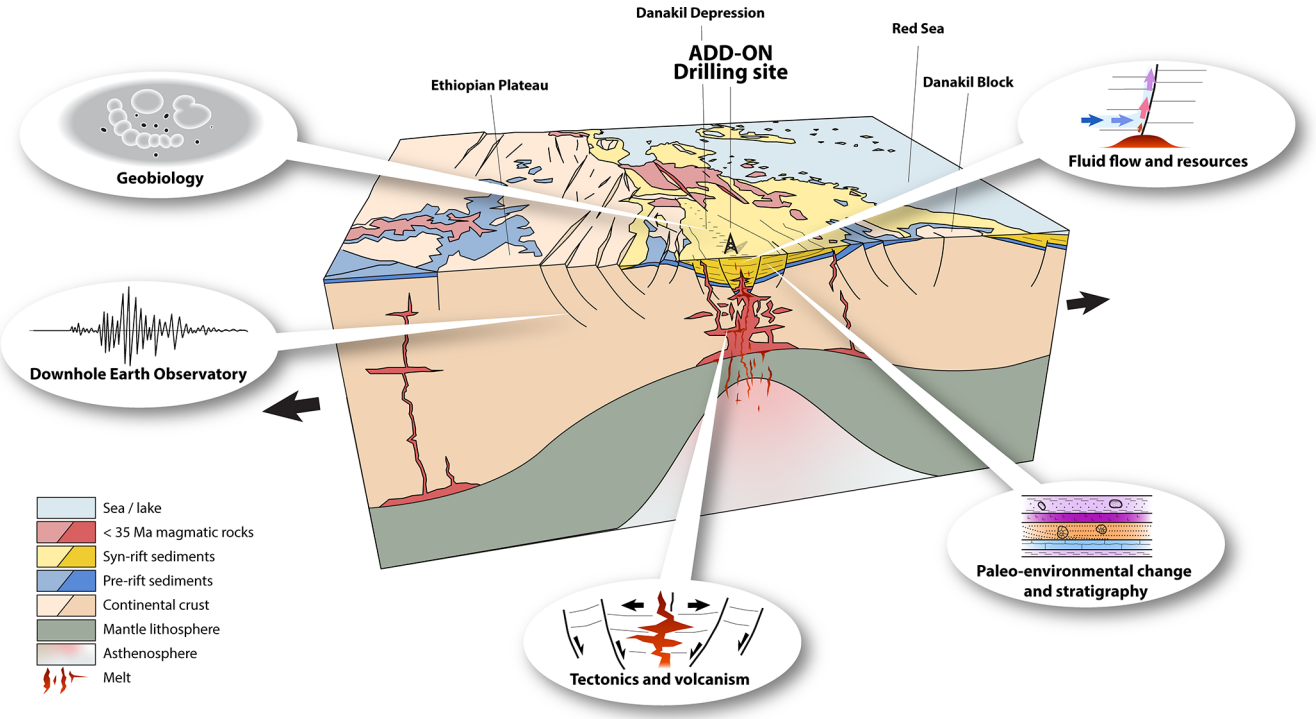

Figure 5. ADD-ON block diagram synthesizing the main objectives of the ADD-ON project.

Traditionally, it was thought that extension via magma intrusion increases during the breakup process (e.g. Ebinger, 2005). However, recent studies of the Danakil Basin show evidence of significant subsidence caused by plate thinning and faulting and thus contradicting standard models (Bastow and Keir, 2011; Rime et al., 2023). A well-dated core record will directly constrain subsidence rates and enable quantitative interpretation of fault slip rates from subsurface seismic images, as well as modelling of associated plate thinning. We will address when did rapid subsidence and fault slip rates initiate and how do these processes vary in space and time.

In addition to the longer-term evolution of basins during the rift to drift transition being uncertain, the short-term interaction between faulting, subsidence, volcanism, sea level, and the sedimentary environment is not well understood. The development of a unique sedimentary record will enable us to develop conceptual and numerical modelling schemes to address what is the sedimentary record of short-term episodic events (volcanic eruptions, earthquakes, flooding) and how do these interact with long-term rift processes.

4.3 Geo-biosphere in poly-extreme environments

The unique Dallol brines and associated hydrothermal fields in the Danakil Depression are ideal natural labs to (1) understand the limits of life in poly-extreme conditions; (2) discriminate biotic from abiotic signatures, using those areas for deriving implications for habitability and life in extra-terrestrial environments; and (3) study the role of archaea and bacteria in mediating mineral precipitation and dissolution. At this stage, it is not yet fully deciphered how extreme halophiles evolved their unique adaptations and if they are also present in brines in the deep anoxic subsurface. Brines and evaporites in the Dallol–Danakil region impose physicochemical, biophysical, and biochemical stress on life that has not been experienced and studied in detail before. Moreover, the interactions of the deep halophilic biosphere with the geosphere are to be unveiled, as well as how metabolic processes affect elemental and biogeochemical cycles.

Having access to the core records will allow us to understand the deep unknown biosphere experiencing poly-extreme conditions, testing the limits of life and opening up a window on the origin of life and/or life in extra-terrestrial environments. Moreover, the recovered pristine records will allow us to study how the deep biosphere interacts with brine circulation in an active rift hydrothermal system.

4.4 Hydrothermal systems and resources

The Danakil Basin has one of the most vigorous hydrothermal systems globally (e.g. Varet, 2017), with fumaroles, hot springs, steam vents, and hot grounds common in the rift and on its flanks. Previous studies suggest the region has all the key component conditions for the development of high-enthalpy geothermal fields, including shallow magmatic heat sources, fault and fracture permeability, and po-

tential aquifers from infiltration of meteoric water from the Ethiopian Plateau into the basement and Mesozoic to Quaternary sediments. However, we lack subsurface petrophysical observations including rock, microfracture, fluid properties, and heat flow data to build realistic models of ground water and hydrothermal fluid flow. The data from the core will constrain how fluid flow in the basin impacts the sedimentary record and fracture/fault evolution. Data from the core should also be combined with other datasets (such as surface gas/fluid flux and chemistry, microseismicity, and surface deformation), along with surface geology, as key inputs to 3D models of fluid and heat flow and geochemical exchanges. The active hydrothermal circulation through evaporites also raises the possibility of commercially viable concentrations of metals such as lithium that are required for global society to transition to renewable green sources of energy. Overall, drilling will allow us to understand better active high-enthalpy geothermal systems and associated green-energy-related resources and directly determine whether there is a major deep aquifer in the basin.

4.5 Hazards: towards a downhole Earth observatory

The Danakil region is seismically and volcanically active, and it experiences ground deformation caused by tectonic, magmatic, hydrothermal, and anthropogenic processes (Pagli et al., 2012; Battaglia et al., 2021; La Rosa et al., 2023). Specifically, we aim to understand where and when earthquakes, ground deformation, and fluid flow occur and what controls these processes, gaining a better understanding of controls and links between these processes to improve forecasts and manage the associated hazards.

After the drilling phase is complete, we aim to use the new borehole site as a platform for a downhole Earth observatory for improved capacity in Ethiopia for short and permanent long-term monitoring of seismic activity, ground deformation, and gas/fluid flux. To this end, a permanent broadband borehole seismometer should be installed in the borehole, combined with a surface GPS station, which will use real-time data transfer into the national monitoring centre at the Addis Ababa Geophysical Observatory. During drilling, we plan to populate the basin with temporary dense networks of these instruments for improved spatial mapping.

5 Societal relevance and public outreach

A major component of the workshop involved presentations and open discussions about the societal relevance of ADD-ON; who the stakeholders in the project are; and how to effectively engage with them before, during, and after the project. Potential stakeholders such as the Energy Office of the Afar National Regional Government; the Afar Geothermal Alternative Power (AGAP) company; representatives from the potash and geothermal sectors; and representatives from the universities of Addis Ababa, Mekelle, and Semera universities led the conversation.

ADD-ON is a research project led by academics with a strong desire and need to engage with local communities. Opportunities were identified to link with ongoing community-based projects to exploit geothermal systems in ways not normally pursued by traditional large-scale commercial projects. The intensive time required to develop and implement the project in the field has offered and offers opportunities to invest in sustainable-geoscience-related educational activities/material for local government, schools, and commercial activities including geo-tourism. The universities expressed a strong desire to use the links, knowledge, data, and drill site developed through ADD-ON to strengthen student training in subsurface characterization as well as using the drill site as a future focus for a field camp, along with archiving core samples and downhole data locally. Using the borehole post-drilling to permanently house a downhole seismometer, linked real-time to the national earthquake monitoring system, provides a mechanism to help support ongoing maintenance of the drill site and also aids hazard and risk assessment for the Afar region.

ADD-ON will further deliver knowledge directly relevant to the wider economic and societal development in Afar and Ethiopia. Deep drilling offers an opportunity to identify and better quantify potential water aquifers, and it also informs on the hydrothermal fluid flow needed for commercial-scale development of geothermal energy. Deep drilling is of direct interest to potash exploration, since the project aims to characterize past marine flooding cycles and therefore potentially identify deeper potash deposits or tap into metal resources key for the global green transition.

Data availability. The map data used in this paper are available at https://doi.org/10.5281/zenodo.7351643 (Rime et al., 2022a) and https://doi.org/10.5281/zenodo.7351765 (Rime et al., 2022b). The seismic profile and core data presented in the paper are courtesy of former Allana Potash Ltd and the Ministry of Mines, Ethiopia.

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