Exploring future scientific drilling targets in the Afar (Ethiopia)
ADD-ON
Afar **D**allol **D**rilling - **ON**set of sedimentary processes in an active rift basin

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1. Rationale

1.1 The northern Afar: a unique sedimentary field lab

Since the early days of the continental drift theory, the Afar triangle developed into an ideal field laboratory where the onset of continental and potentially future oceanic rifting can be studied in detail. The Danakil Depression is the northern portion of the Afar triangle, bordered to the west by the Nubian Plateau and to the East by the Danakil Horst, and characterized by active rifting since Oligocene times (Fig. 1). Research during the last decade, such as the EAGLE project (2000 – 2004) – Ethiopia-Afar Geoscientific Lithospheric Experiment – and in a second phase the AFAR Rift Consortium (2005 – 2013) funded by NERC (Natural Environment Research Council, UK), largely focused on tectonics, volcanology and geophysics to understand the underlying rift mechanisms in the Afar. Only a few studies dating back nearly half a century ago focused on the unique sedimentary deposits of the northern Afar. These first studies have been initiated within the light of the early potash exploration (Holwerda and Hutchinson, 1968; Bannert et al., 1971). Riding on the wave of the early potash exploration, coordinated studies by scientific teams of CNRS (France), CNR (Italy) and BGR (former BfB, Germany) resulted in the first structural and stratigraphic mapping of the area (Bannert et al., 1971; Brinckmann & Kürsten, 1971; Barberi et al., 1972; CNR, CNRS, Afar Team – Varet et al., 1975; Lalou et al., 1970; Bonatti et al., 1971). Under the umbrella of the ESF-coordinated COCARDE research networking programme, a first reconnaissance field action has been undertaken in 2013 in the northern Afar revisiting and exploring the carbonate sedimentary record at the basin margins. Recently, the SNF funded project SERENA (Sedimentary Record of the Northern Afar: Insights in the flooding history of the Danakil Depression) paved the way further for more detailed studies unveiling the unique Middle to Late Pleistocene and Holocene sedimentary archive (Atnafu et al., 2015; Foubert et al., 2015a, 2015b; Jaramillo-Vogel et al., 2019).

In the northern Afar, pre-rift series are discordantly overlain by Cenozoic syn-rift sediments intertwined with volcanic Afar Basalts (Paleogene- Neogene) and Aden volcanics going from basalts to alkaline rhyolites (Barberi & Varet, 1970). The Neogene Danakil Formation, composed of fluvial to lacustrine siliciclastic and marine carbonate rocks (Brinckmann & Kürsten, 1971), is followed by the deposition of the Pleistocene Zariga Formation. The Middle to Late Pleistocene sedimentary record bears witness of the past connection to the Red Sea. Multiple episodes of marine flooding and desiccation led to the deposition of successions of open marine coralgal reefs, calcarenites, coastal oolithes and hypersaline microbialites topped by gypsum deposits surrounding the margins of the Danakil Depression (Foubert et al., 2015a; Jaramillo-Vogel et al., 2019; Foubert et al., subm.). Late Pleistocene to Holocene fluvial sands and gravel separate the Zariga Formation from the lacustrine Holocene Afrera Formation characterized by lacustrine marls, carbonate, diatomites and evaporitic deposits locally interbedded with hot-spring build-ups representing respectively seasonal terminal saline lakes and geothermal pools. The sedimentary rocks deposited in the central part of the basin are represented by more than 1000 m thick evaporitic successions composed of halite intercalated with gypsum, anhydrite and potash-bearing deposits of economic significance. Seismo-stratigraphic interpretations based on industrial seismic sections, core and borehole data evidence the presence of evaporite units till the depth of about 900 m below the Dallol salt pan (Warren, 2016; Bastow et al., 2018). **However, to date not any sub-salt sedimentary core records** below those depths are **available from the central part of the rift basin** filled with more than 5 km of sediments.

1.2 Towards future scientific drilling: ADD-ON

The **ADD-ON workshop** aims bringing together junior and senior scientists from different disciplines to **fine-tune common scientific goals, specify drilling targets** and discuss technical and logistical issues in this extra-ordinary field lab to develop **an integrated full ICDP proposal**. Having future access to targeted drilling sites in the Danakil basin will provide a unique and continuous palaeoenvironmental record in an active rift setting paced by global environmental fluctuations. Such core records will give new insights into (1) the mechanical understanding of intermittent and incipient basin dynamics in an initial extensive continental rift basin: from rifting towards the development of passive margins, (2) East African climatic changes and Hominin evolution (i.e. continuous reference record going beyond 250 ka), (3) the limits of the deep biosphere in extreme hypersaline and high-temperature environments below the salt deposits, (4) natural fluid flow in an active geothermal system and (5) monitoring of active faults, earthquakes and volcanic events in remote areas. Thematically organized workgroups will reflect further upon those common drilling objectives. Future drilling in the Afar will significantly contribute to major scientific advances, and is timely complementary to previous accomplished ICDP drilling projects in the East African Rift (e.g. Hominin Sites and Paleolakes Drilling Project, Cohen et al., 2016; DeepCHALLA, Verschuren et al., 2017) and ocean drilling projects and initatives undertaken in the Red Sea and Gulf of Aden (e.g. DSDP Leg 23 Glomar Challenger; Gulf of Aden Drilling, IODP 724-Full, DeMenocal, P. et al.).

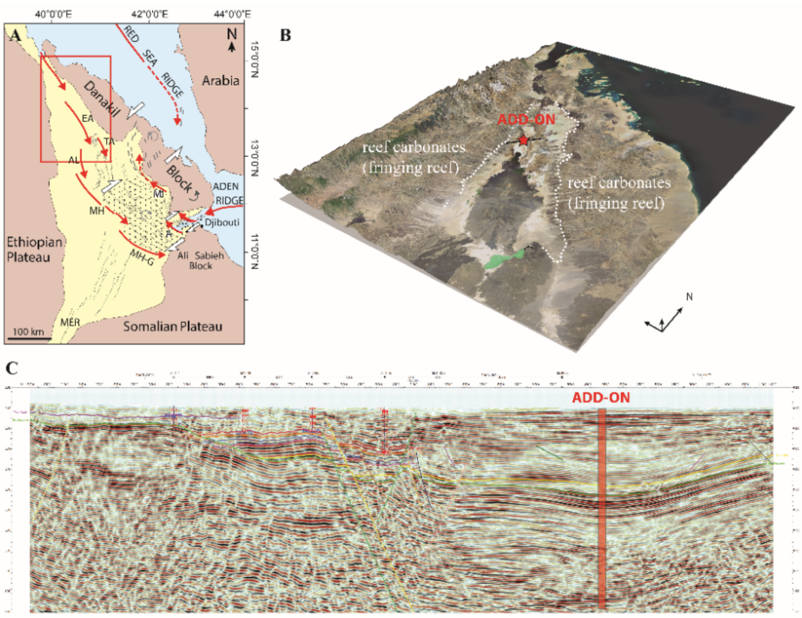

Figure 1

(a) *Overview Danakil Depression with major tectonic structures and study location (red rectangle). MER, Main Ethiopian Rift; EA, Eart'ale; TA, Tat'ale; AL, Alayta; MH, Manda Hararo; MH-G, Manda Hararo –Goba'ad; A, Asal; T, Tadjura; MI, Manda Inakir. Stippled area within the central Afar represent the major overlap between the Red Sea Rift and the Gulf of Aden Ridge.*

(b) *Satellite image of the Danakil depression superimposed on DEM (Aster GDEM product of METI and NASA Landsat 7 & Landsat ETM+) and potential drilling target.*

(c) *Seismic profile illustrating the sedimentary record in the Danakil Basin and potential drilling target.*

1.3 Societal needs: the triangle between academics, industry and society

The **ADD-ON workshop** will provide a **platform for open-minded discussions** between **industry, stakeholders and scientists** from different disciplines to identify how drilling can help in resolving urgent societal needs in remote areas often suffering from extreme natural hazards. Deep scientific drilling in the Afar will be necessary in the rapid assessment of local low-enthalpy versus high-enthalpy geothermal potential, the quest for ground water resource exploration and advanced Potash exploitation. Several local Potash mining companies are active in the northern Afar providing an important backbone for the ICDP ADD-ON project in terms of data support but also local logistical support. During the workshop, representatives of the Potash exploration and exploitation will be present to steer further common interest. Fresh water resources are a major concern and urgent need for further Potash exploration. The northern Afar has some great geothermal resources but exploitation and development is still on its way and questions still exist regarding natural fluid flow in such geothermal systems. Local initiatives are on their way to go towards sustainable energy development in this region. Important new players working on community-based geothermal development will be present at the workshop.

1.4 Education and outreach: the pillar for future success

The **ADD-ON workshop** will contribute to a **sustained flow of top-level junior Earth scientists** for **society and industry crossing boundaries and continents,** opening pathways for international collaboration and **providing hands-on training** through active participation in the ICDP discussion and proposal writing steps. During the workshop, training will be provided on successful ICDP proposal writing. Ethiopian scientists will be fully involved and communicate on any follow-up political steps to be taken with the Ethiopian government but also with local Afari communities. Initiatives are on their way to protect the Dallol area as world-heritage site. Group discussions will ensure synergies between the ADD-ON drilling project and any environmental protection initiatives in the area. Tight collaboration is currently existing between Addis Ababa University (Ethiopia) and the University of Fribourg (Switzerland) through an existing bilateral exchange and training programme which makes Fribourg an ideal and centralized place in Europe to organize the first ADD-ON workshop.

2. Scientific Objectives

The overarching scientific goal of this project is to get insights into the detailed sedimentary facies evolution in an active rift setting paced by global environmental fluctuations and their interplay with volcano-tectonic events. For the ADD-ON project, we have identified the following scientific objectives which closely relates to the goals identified in the ICDP Science Plan and should be further fine-tuned during the ADD-ON Workshop.

(1) Understanding intermittent and incipient dynamics in an extensional rift basin: from continental rift towards young ocean basin and passive margin development?

Since the early formulation of the continental drift theory (Wegener, 1929) and the early (Teilhard de Chardin, 1930) to extensive geological mapping during the late sixties and early seventies (e.g. Tazieff et al., 1971; Barberi et al., 1972), the Afar depression became and has remained one of the best field laboratories in the world where the evolution from the early stages of continental rifting to onset of oceanization can be analyzed in detail (e.g. Tazieff et al., 1971; Barberi et al., 1972). The rifting of the Arabian plate away from the Nubian Plate is thought to have begun ~30-35 Myrs ago around the same time as the mantle plume related eruption of the Ethiopian-Yemen traps (e.g. Baker et al., 1972; Hofmann et al., 1997; Rochette et al., 1998). The rifting formed the Gulf of Aden and the Red Sea, which link in Afar. The onset of seafloor spreading is thought to have occurred first in the eastern Gulf of Aden ~20 Myrs ago, with the mid-ocean ridge propagating westward towards Afar (Manighetti et al., 1997). Later at around 11 Ma, extension in the southernmost Red Sea migrated west and became focused in the current Danakil Depression (Eagles et al., 2002). This focusing of extension effectively created a new micro-continent (The Danakil Block) between the marine Red Sea to the east and the Danakil Depression to the west. Since ~11 Ma, extension in the Danakil Depression has been controlled by the progressive anticlockwise rotation of the Danakil Block away from Nubia (e.g. Eagles et al., 2002; McClusky et al., 2010). During this time extension has progressively become more localized to narrow (20-km-wide) axial volcanic segments, known in the Danakil Depression as the Erta'Ale, and Tat'Ale volcanic segments (Barberi and Varet, 1977). Recent studies have indicated these volcanic segments are currently the locus of active faulting, fissuring, dike injections and mostly basaltic lava flows (e.g. Pagli et al., 2012; Moore et al., 2020). Since the basalts flow up to 10-20 km away from the rift axis and interfinger with the sediments of the basin floor, the Danakil Depression has been cited as a potential modern analogue for formation of the enigmatic yet large thicknesses of high seismic reflectivity interbedded basalts and sediments (Seaward Dipping Reflectors – SDRs) that coat many previously rifted magmatic margins (Bastow and Keir, 2011).

The Danakil depression has especially been identified as a unique zone where processes associated with the transition from mechanical extension more typical of continental rifts (border faulting and ductile plate stretching) towards the magmatic rifting (dike intrusion and rift axial faulting), more typical of seafloor spreading can be studied in detail and subaerially (f.e. Keir et al., 2012; Bastow et al., 2018). A number of hypotheses and questions have been raised regarding the transition from continental break-up towards the evolution of a young ocean basin. Specifically, the timing and continuity of stretching and thinning of the continental lithosphere is poorly understood. Previous models suggested that dike intrusion progressively dominates the late stages of continental rifting (e.g. Wright et al., 2006), with diking continuing as the main deformation type during seafloor spreading. However, more recent studies in the Danakil Depression showing evidence for very recent rapid and significant subsidence, instead implying that renewed mechanical plate stretching may occur very late in the breakup process, potentially because the tectonic plate is very weak from previous phases of focused magma intrusion (Bastow and Keir, 2011). Combining those observations with new recent dating studies (Foubert et al., 2015a; Jaramillo-Vogel et al., 2019, Foubert et al., subm.), show that this process may happen in very short time scales and intermittent. This results in rapid subsidence and basin formation, creating accommodation space for the accumulation of unique sedimentary and volcanic records. Understanding the extensional and sedimentary processes is key for unravelling the origin of SDR's.

Deep drilling is key to constrain the subsidence history of the rift and interpret the amount and episodic nature of mechanical plate stretching and thinning. This provides insights in the existing models of continental drift and – especially – the formation of young oceanic basins prior to the onset of seafloor spreading. This may result in new and unique models for the understanding of the birth of oceans and passive margins with seaward-dipping reflectors worldwide.

(2) Unique and continuous sedimentary and stratigraphic reference record to constrain (1) East African Climate Change going beyond 250 ka and understanding its impact on (2) East African Hominin Evolution.

Despite the recognition of the unique sedimentary record associated with rapid basin development in the Afar and Danakil depression (e.g. Varet and Gasse, 1978), detailed analyses of the sedimentary record based on fieldwork but also core sections and seismic data, is emerging only recently (Atnafu et al., 2015; Foubert et al., 2015a; Jaramillo-Vogel et al., 2019; Rime et al., 2019; Foubert et al., subm.). The basement is composed of Paleozoic and pre-Cambrian gneiss, phyllites, carbonates, sandstones and conglomerates and is overlain by up to 300 m thick sandstone successions of the Adigrat Formation (Upper Triassic to Middle Jurassic) followed by marls and limestone of the Antalo Formation (Middle to Upper Jurassic) (Brinckmann & Kürsten, 1971). The Mesozoic series finishes with Jurassic to Cretaceous sandstones. Those pre-rift series are discordantly overlain by Cenozoic syn-rift series laterally interfingering with the volcanic Afar Basalts (Paleogene- Neogene) and Aden volcanic deposits going from basalts to alkaline rhyolites (Barberi & Varet, 1970). The Neogene Danakil Formation can be divided in the Lower and Upper Danakil Formation composed of fluvial to lacustrine siliciclastic and marine carbonate rocks intercalated with volcanic deposits (Brinckmann & Kürsten, 1971). The Danakil Formation is followed by the deposition of the Zariga Formation during the Pleistocene, through a transitional layer of siliciclastic fluvial sands and gravel. The sedimentary record of the Zariga Formation bears witness of the past connection to the Red Sea during middle-late Pleistocene times (Lalou et al., 1970; Bonatti et al., 1971). Multiple episodes of marine flooding and desiccation led to the deposition of diverse carbonate units surrounding the margins of the Danakil Depression and at most places directly overlying the volcanic substrates. The deposits are ranging from open marine coralgal reefs, coastal oolithes to hypersaline microbial reefs deposited in lacustrine environments (Atnafu et al., 2015; Foubert et al., 2015; Jaramillo-Vogel et al., 2019; Rime et al., 2019; Foubert et al., subm.). The marine to hypersaline units are intercalated with volcanoclastic layers and topped by gypsum deposits. On top of the gypsum deposits, late Pleistocene to Holocene fluvial sands and gravel separate the Zariga Formation from the lacustrine Holocene Afrera Formation characterized by lacustrine marls, carbonate, diatomites and evaporitic deposits locally interbedded with hot-spring build-ups representing respectively seasonal terminal saline lakes and geothermal pools. The sedimentary rocks deposited in the central part of the basin are represented by more than 1000 m thick evaporitic successions composed of halite intercalated with gypsum, anhydrite and potash-bearing deposits of economic significance. Recent seismo-stratigraphic interpretations based on industrial seismic sections, core and borehole data evidence the presence of evaporite units till the depth of about 900 m below the Dallol salt pan. Sedimentary studies and datings on the carbonate units at the basin margins and marls within the studied core sections evidence a record of 230 ka for the upper 600 m (Foubert et al., subm.; Rime et al., 2019).

However, not any sedimentary core records are available from the central part of the rift basin below those studied records.

Deep drilling through the central part of the Danakil Depression would allow to reconstruct a unique palaeoclimatic and palaeo-environmental record for East-Africa going beyond 250 ka.

Having access to high-resolution palaeoclimatic records may also elucidate new insights on the emergence and the out-of-Africa migration of *Homo sapiens*. Around 200 ka, Homo sapiens emerged in Africa (Tierney et al., 2017). Also Walter et al. (2000) supports an African origin for modern humans by 125 ka ago. However, still many questions remain open what is driving the evolution, expansion and diversification of *Homo sapiens* from the basal lineages and what was driving the human species out of Africa. The palaeoclimate history of northeast Africa and the gateway to migration remains to be further unveiled (Tierney et al., 2017). Probably the combined effects of climate change and the volcano-tectonic evolution of the Afar may have driven evolution of the biosphere and the out-of-Africa migration of *Homo sapiens*.

Deep drilling through the central part of the Afar will give new insights on the evolution of life and – especially - East African Hominin evolution.

(3) Understanding the limits of the deep biosphere in extreme hypersaline environments

The unique Dallol brines and associated hydrothermal field in the Danakil Depression have been recently the focus of several studies to understand (1) the limits of life in poly-extreme conditions (Belilla et al., 2019; Gomez et al., 2019) and (2) the potential of using those areas as analogues for Mars and – especially – the implications of habitability and life in extra-terrestrial environments (Cavalazzi et al., 2019). The biogeochemical conditions of the Recent Dallol salt brines vary across the different pools with pH ranging between <0 and 6.5, salinities ranging between 331 and 944 g/l and temperatures varying between 30 to 108 °C (Belilla et al., 2019; Gomez et al., 2019). Only in some of the brine pools, microbial communities, mostly archaea including taxa previously unknown to be halophilic, have been identified. Taxa were dominated by mainly Halobacteria and Nanohaloarchaeota (Belilla et al., 2019; Gomez et al., 2019). The geomicrobiological characterization of the Dallol-Danakil brines evidences the diversity of archaeal communities present and increases our understanding of the diversity and habitability of extreme brines at the surface. However, at this stage it is largely unknown how extremophiles, and especially halophiles have existed throughout Earth History and if they are also present in brines in the deep subsurface. Brines at the surface and the deep subsurface in the Dallol-Danakil region impose physicochemical, biophysical and biochemical stress on life that has not been experienced and studied before. It is likely that the complexity of many extreme brines has impacted halophile evolution, from growth phenotype and cellular adaptations to salt-induced stresses, to trophic interactions and ecosystem functioning (Hallsworth, 2019). Moreover, the interactions of this unknown deep halophilic biosphere with the geosphere is to be unveiled. Many studies evidence that archaea and bacteria play an important role in mediating mineral precipitation and/or dissolving other mineralogical products. Metabolic processes on their turn affect elemental and biogeochemical cycles. In the complex Dallol-Danakil environment the unknown deep biosphere likely interacts closely with complex brine circulation in a hydrothermal active system where the lithospheric crust is very thin and magmatic processes steer continental break-up. This unique set of geo-physico-chemical conditions may open a new window on the origin of life.

Drilling the deep Dallol-Danakil salt giant will help in understanding the limits of life in polyextreme and hypersaline environments not only at the surface but also in the deep subsurface below the Recent salt deposits.

(4) Understanding and characterization of active high-enthalpy geothermal systems

Afar is one of the best and most promising regions in the world with respect to high enthalpy geothermal resources (Nebro et al., 2016; Varet, 2018). Dallol and the Danakil Depression are the hotspot of fumaroles, hot springs, steam vents and hot grounds. Varet (2018) confirmed that all the conditions for the development of high-enthalpy geothermal fields are present in the northern part of the Afar: (1) significant and rather shallow magmatic heat sources, (2) high and active faulting crossing through the dominantly NNE-SSW normal and open fault pattern increasing fracture permeability, and (3) infiltration of meteoric water from the Ethiopian plateau into the faulted Proterozoic basement and its overlying Mesozoic sedimentary cover (Antalo limestones – Adigrat sandstones), Tertiary and Quaternary fluvio-lacustrine, evaporitic and marine units. Especially, the Danakil Depression might be an ideal case study if deeper Mesozoic and Tertiary Formations are present below the salt deposits which may act as a deep geothermal reservoir. However – no sedimentary record is available below the salt which is required for the further exploration of deep geothermal sites in the Danakil Depression. It should be mentioned that drilling active high-enthalpy systems is technologically very challenging but the deeper understanding of those challenges and developing those technologies will be necessary for geothermal energy production in the future. Scientific drilling into a deep high enthalpy geothermal reservoir will contribute to develop responsible management strategies for the sustainable use of geothermal resources in East Africa.

Deep drilling into the central part of the Danakil Depression will (1) contribute to the deep understanding and characterization of active high-enthalpy geothermal systems and (2) steer the exploration and exploitation of deep geothermal energy in East Africa.

(5) Downhole Earth Observatory: monitoring of active faults, earthquakes and volcanism

Previous monitoring of earthquake activity using temporary networks of passive seismometers in the Danakil Depression has provided initial constraints on the locus and timescales of faulting (e.g. Illsley-Kemp et al., 2018) and subsurface magma motion (e.g., Pagli et al., 2012). The seismic networks during 2007 to 2013 used relatively sparse station spacings (~20-30 km) with instrumentation suffering high noise levels due to them being installed in/near human settlements for security, and being on or within the unconsolidated surface deposits. As a result, these studies had earthquake location errors of +-2-3 km, and only recorded a complete record of earthquakes above ~M2, making it impossible to image the locus and shape of specific fault planes and impossible to see micro-fracturing associated with shallow hydrothermal fluid flow. We propose to take advantage of the new deep boreholes and populate them with strings of borehole seismometers. The borehole seismometers are likely to record much lower noise than surface deployment, which coupled with a tight station spacing for both the borehole and surface instruments (~5 km) will allow to detect and locate microseismicity with sub-100 m positional error bars for earthquakes down to magnitude 0 to 1. This will allow to image the subsurface shape of tectonically active faults, and also the fracture network associated with hydrothermal fluid flow at volcanic centres such as Dallol and Gada'Ale. The expected outcomes will closely link to objectives (1) and (4). The output earthquake catalog will be added to previous catalogs that will be fed into improved regional earthquakes hazard studies (e.g. Goitom et al., 2017). Through collaboration with the Addis Ababa University (who currently manage and run the Ethiopian permanent seismic network), such a downhole Earth observatory in combination with the addition of some permanent surface seismic stations will be integrated with the current real-time monitoring network. To facilitate this, training and exchange of knowledge between the ICDP consortium and local actors will be crucial. This will build on previous efforts (Afar Rift Consortium) to increase the number of permanent real-time seismic stations and required expertise for improved earthquake monitoring in Ethiopia.

Deep boreholes in Danakil Depression will provide a unique opportunity to image the tectonically active faults, and constrain for the first time the locus and timescales of subsurface fluid flow in the hydrothermal systems. The work will also improve permanent seismic monitoring of the region.

3. Towards a preliminary drilling strategy

<u>3.1 Site surveys and core site targets</u>

To address the overall goal and drilling objectives mentioned above, 3 drill holes on one ENE-WSW orientated Dallol core transect in the central part of the Danakil depression and 1 drill hole at the western flank of Erta'Ale are envisaged (Fig. 3). Taking this drilling approach will allow to characterize the western margin and the central part of the Danakil Depression. Drilling a ENE-WSW aligned transect will be necessary to allow correlating the discontinuous marginal deposits with the continuous sedimentary records in the central part of the basin. Industrial seismic sections and wells (max. depth 900 m) are existing for the western part of the Danakil Basin evidencing more than 900 m Quaternary evaporites interbedded with gypsum/anhydrite, shales, marls and sands (Fig. 2). The Potash Industry and Warren (2016) divided the sedimentary and the seismic units in resp. a lower (LRS) and upper rock salt (URS) unit (Fig. 2). Between the LRS and URS, the Houston Formation is present being the target horizon of the Potash Industry. The Houston Formation (present at a depth between 38 to 190 m) is enriched in kainite, carnallite, kieserite, sylvite, halite and some anhydrite. Regionally, the potash units and other beds dip towards the east. The LRS is about 300 to more than 500 m thick and characterized by bottom-growth aligned subaqueous halite textures organized as cm-scaled NCl-$CaSO_4$ couplets (Warren, 2016) most probably deposited in a marine-fed brine lake or seaway (Warren, 2016) shallowing upwards towards the Houston Formation. Sedimentary textures of the LRS are very comparable to the Messinian evaporites encountered in the Mediterranean region. Mineralogies and textures of the URS differ clearly from the LRS and define a separate hydrological association witnessing periodic and still ongoing clastic-rich sheet flooding and freshening alternated with saline pan deposits (Warren, 2016). The uppermost siliciclastic units intercalated with saline pan deposits have been interpreted as clastic overburden (Warren, 2016).

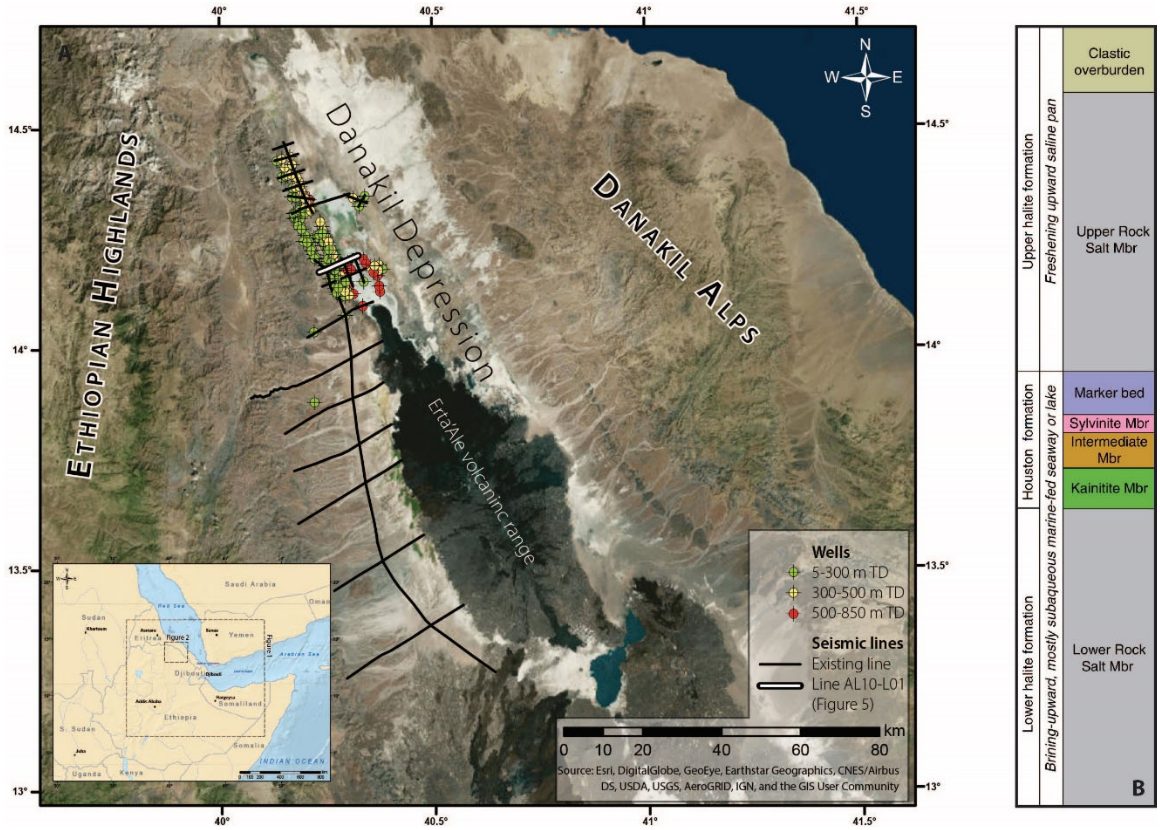

Figure 2 (a) *Satellite image of the Danakil depression superimposed on digital elevation model (Aster GDEM product of METI and NASA Landsat 7 and Landsat ETM+) with the indication of available industrial borehole data, wells and seismic sections. (b) Example of overview of lithology in core sections interpreted after Warren, 2016.*

Currently, the wells, geophysical downhole logs and seismic sections are studied in detail within the framework of the SNF-funded project SERENA (SEdimentary REcord of the Northern Afar – SNF 200021_163114, Foubert et al., 2015) evidencing several marine sea-fed incursions within the LRS and URS (Rime et al., 2019). For the purpose of this study, the proposed drill sites are located at the cross-sections of two existing seismic lines. The goal is to reach the units below the LRS and to have a detailed continuous core record through the LRS, URS, Houston Formation and previously defined clastic overburden which can be used for detailed palaeoenvironmental, palaeoclimatological and geomicrobiological studies. The max. depth of the envisaged drill holes on the Dallol Core Transects are resp. 2 km, 2.2 km and 1.5 km (Fig. 4). For the Erta'Ale Core Transect, one inclined drill hole with a max. depth of 2 km is envisaged following the stratigraphy perpendicular.

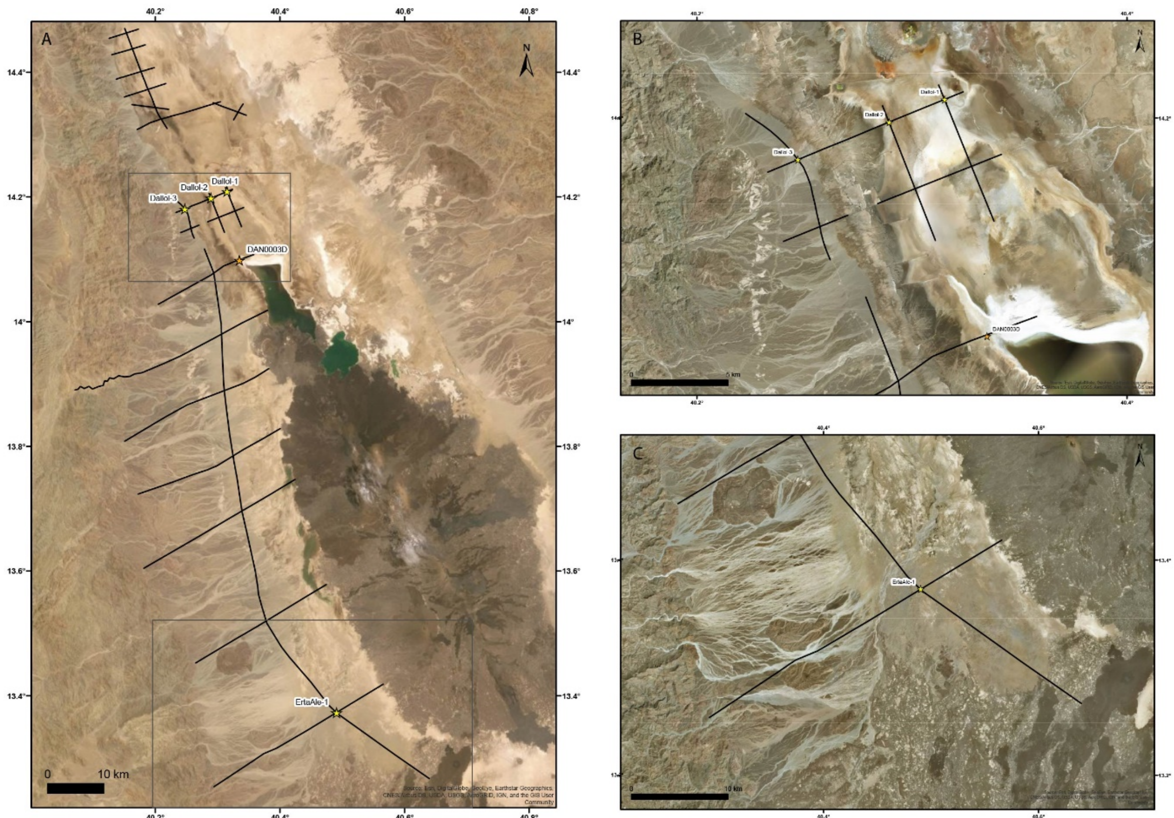

Figure 3 (a) *Overview map of envisaged ICDP core sections (resp. Dallol-1, Dallol-2 and Dallol-3 + ErtaAle-1).* (b) *Zoom on Dallol transect.* (b) *Zoom on Erta'Ale transect.*

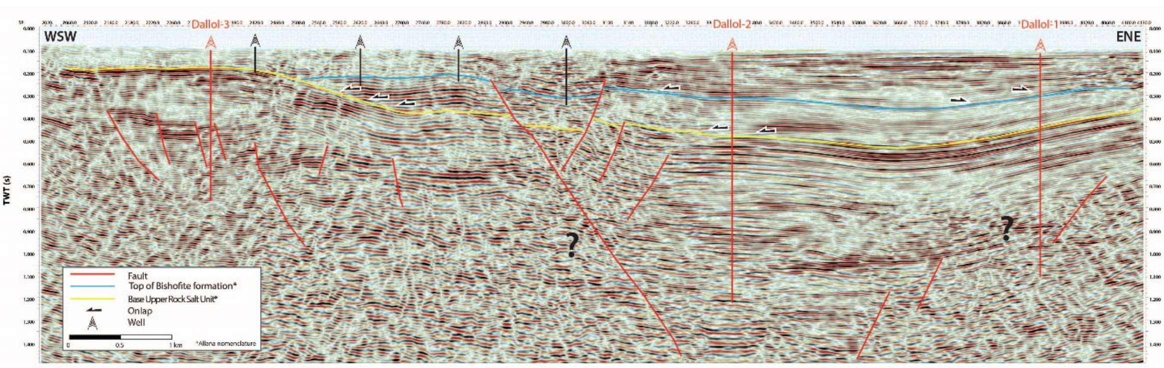

Figure 4 *Example of the Dallol Core Transect indicated on the seismic lines. Interpretation is modified after Allana Potash (2016). Drill holes indicated in black are available core sections. Drill holes indicated in red are potential ADD-ON Drill sites.*

3.2 Core recovery

Cores will be drilled using commercial or scientific drilling companies. It should be mentioned that high geothermal gradients are expected of which the technological and logistic challenges should be discussed during the ADD-ON Workshop. Due to the harsh desertic conditions of the Danakil depression, basecamps will be set-up on-site. Collaboration with Potash companies is existing. Additional logistical and technical drilling support on-site will be provided partially through the Potash companies. Cores will be stored in first instance on-site in containers. It should be envisaged to keep the cores in a dry and cool place to avoid alteration of the evaporites. Specific core sections containing brines and evaporites will be stored vacuum.

3.3 Borehole measurements and downhole Earth observatory

Wireline logging is planned at all drill sites to complete non-recovered core sections and allow precise core-to-seismic correlation. It is envisaged to place seismometers in the drill hole to allow seismic monitoring in this very active region. Details will be discussed at the workshop.

3.4 Core analysis

Full core sections will be scanned with traditional core logging techniques providing a first overview of the sedimentary record. Petrophysical parameters will be logged with a GEOTEK multisensor core logger (P-wave velocity, magnetic susceptibility, gamma-ray density). Standard sedimentological and geochemical measurements will be performed, incl. core photography, 3D visualization (medical CT-scanning), detailed sedimentological descriptions (macro-facies and microfacies analyses), XRF logging, XRD analyses, color spectrometry, grain-size analyses, micro-paleontological analysis, innovative dating techniques, amongst others. The full analytical suite to be measured will be discussed in detail when submitting the full drilling proposal. Pore waters will be extracted from the drill cores in order to understand pore water and brine chemistry. Pore waters will be sampled and monitored during coring operations. Unveiling the hidden terrestrial deep biosphere will be an important part of this ICDP drilling project. GFZ Potsdam has a mobile geomicrobiological laboratory (BUGlab) which might be envisaged to use during this ICDP ADD-ON project. Standard protocols for geobiological/geochemical sampling within ICDP projects are existing but should be adapted/modified for this project. This will be discussed during the workshop. Contamination during drilling should be monitored and drilling fluids should be selected to avoid any additional contamination. Issues with respect to in-situ sampling or double coring protocols will be discussed at the workshop.

3.5 Financial aspects

Potential funding sources are ICDP and the support of national research agencies through the different ICDP partners. It should be mentioned that existing collaborations are existing with the Potash mining industry and they have also expressed their sincere interest in contributing to this ICDP drilling proposal (cfr. support letters in attachment).

3.6 Tentative time planning and milestones

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