

Evaporites reveal Pleistocene basin dynamics in the Danakil depression (northern Afar, Ethiopia)

**Valentin Rime^{1,*}, A. Foubert¹, R. Fentimen¹, H. Negga¹, A. El Korh¹,
T. Adatte², I. Hajdas³, B. Atnafu⁴ & T. Kidane⁵**

¹ Department of Geosciences, University of Fribourg, Ch. Du Musée 6, Fribourg, Switzerland.

² Faculty of Geosciences and Environment, University of Lausanne, Switzerland

² Department of Physics, ETH Zürich, Switzerland

⁴ School of Earth Sciences, Addis Ababa University, Ethiopia.

⁵ School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal Durban, South Africa.

* valentin.rime@unifr.ch

Welcome!

Welcome to my COVID-type presentation!

- If you like to know the **summary** of this study, jump to the next slide.
- If you are only interested in the **results**, jump to page 8.
- If you are only interested in the **discussion**, jump to page 12.
- If you are only interested in the **conclusion**, jump to page 22.

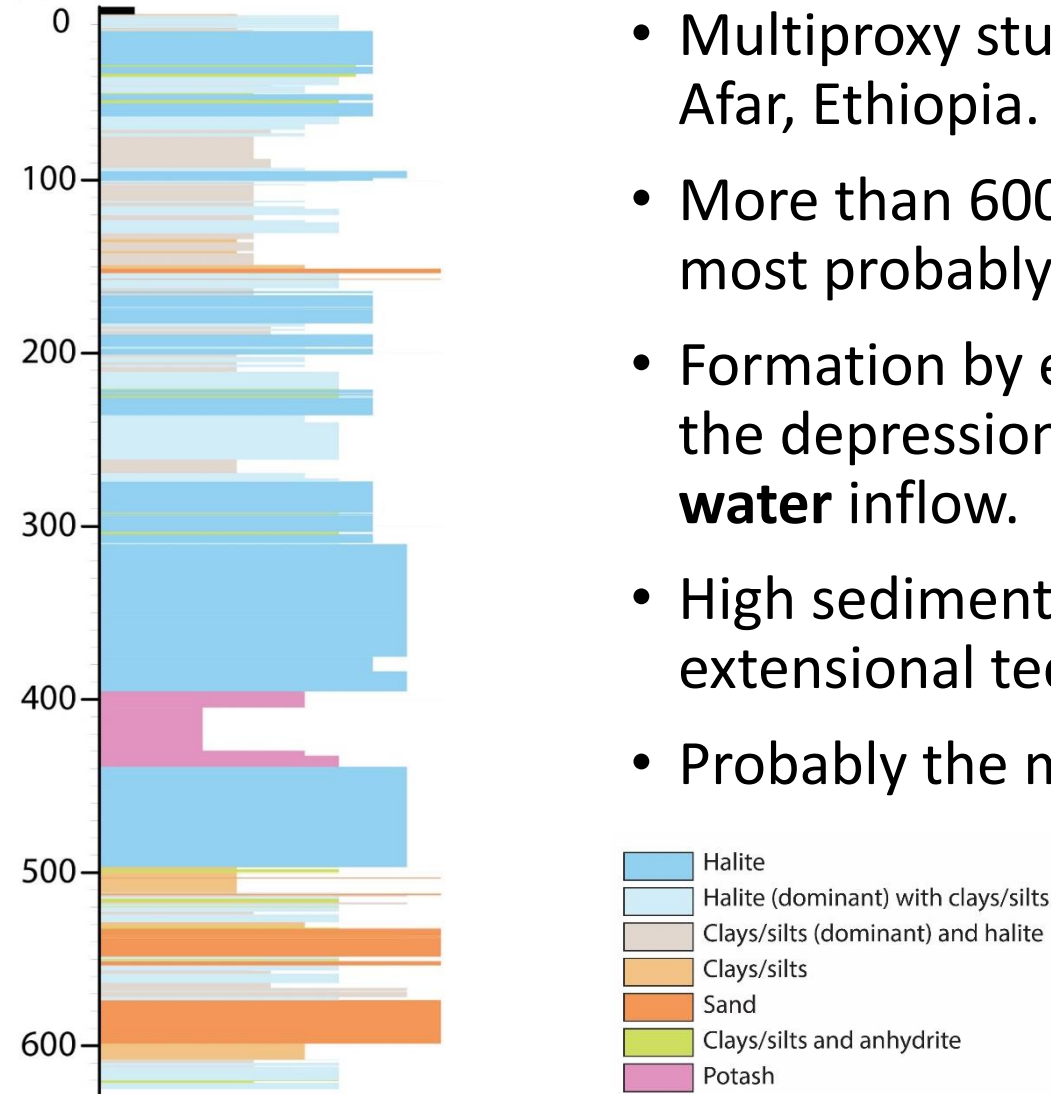
Don't hesitate to comment, ask questions, or make any suggestions to this study!



Highlights

Depth

(m)



- Multiproxy study of a drillcore in the **Danakil depression**, Afar, Ethiopia.
- More than 600m of sediments dominated by **evaporites** most probably formed during the last 130ka.
- Formation by evaporation of **seawater** after flooding of the depression and by remobilization through **meteoric water** inflow.
- High sedimentation rates, important subsidence and rapid extensional tectonics.
- Probably the most Recent analogue of Past **Salt Giants**.

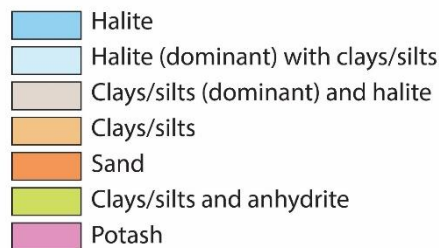


Fig. 1: Lithostratigraphic log of the core record

Introduction: Geological setting (1)

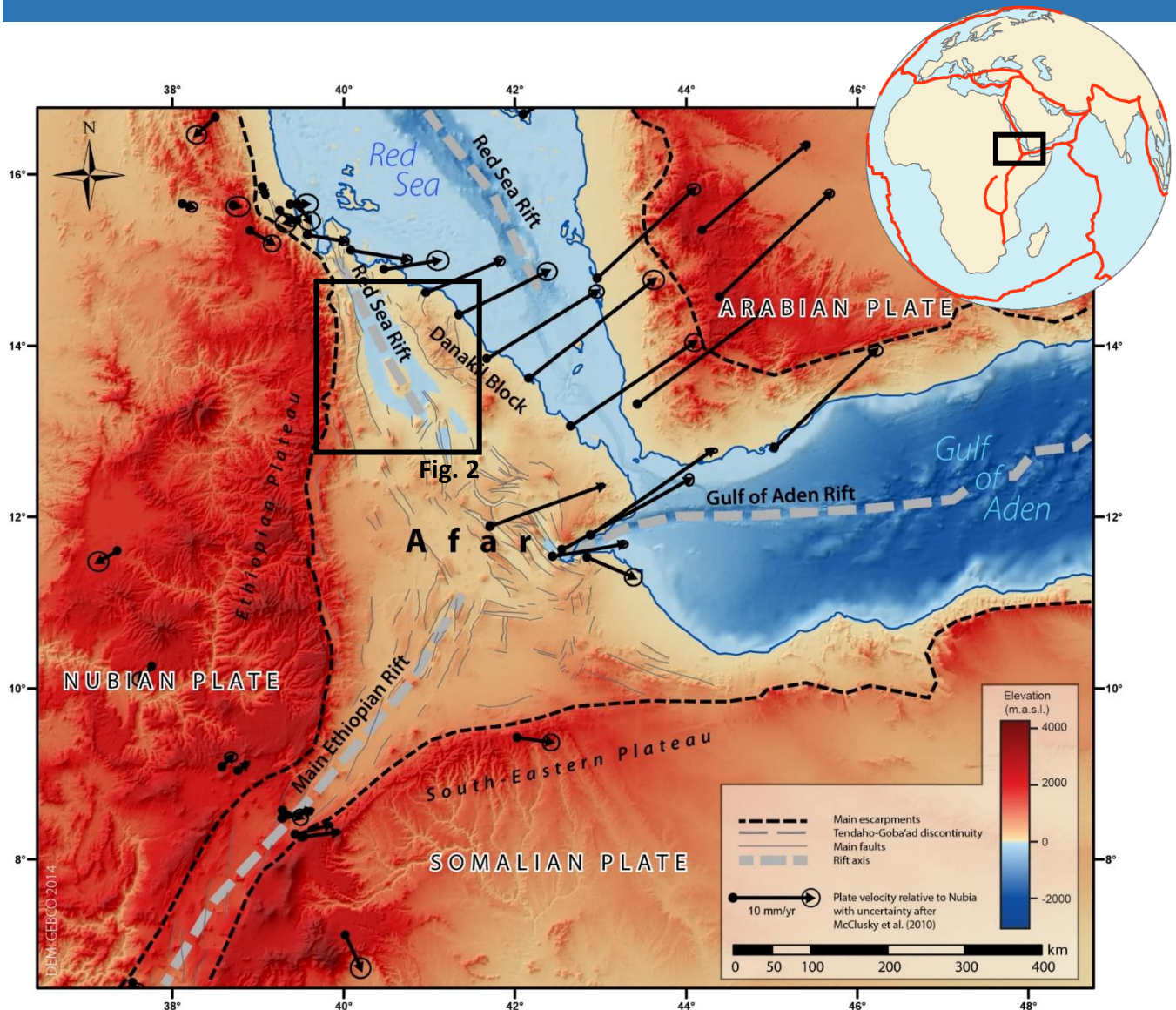


Fig. 2: Topographic and tectonic map of the southern Red Sea

The **Danakil depression** (Afar, Ethiopia) is a **rift valley** forming the southernmost part of the Red Sea rift. It is situated between the Ethiopian plateau and the Danakil block and represents an advanced stage of rifting, characterized by important tectonic and volcanic activity. Its floor is situated 120 meters below sea level and is covered by Recent saline pans.

Introduction: Geological setting (2)

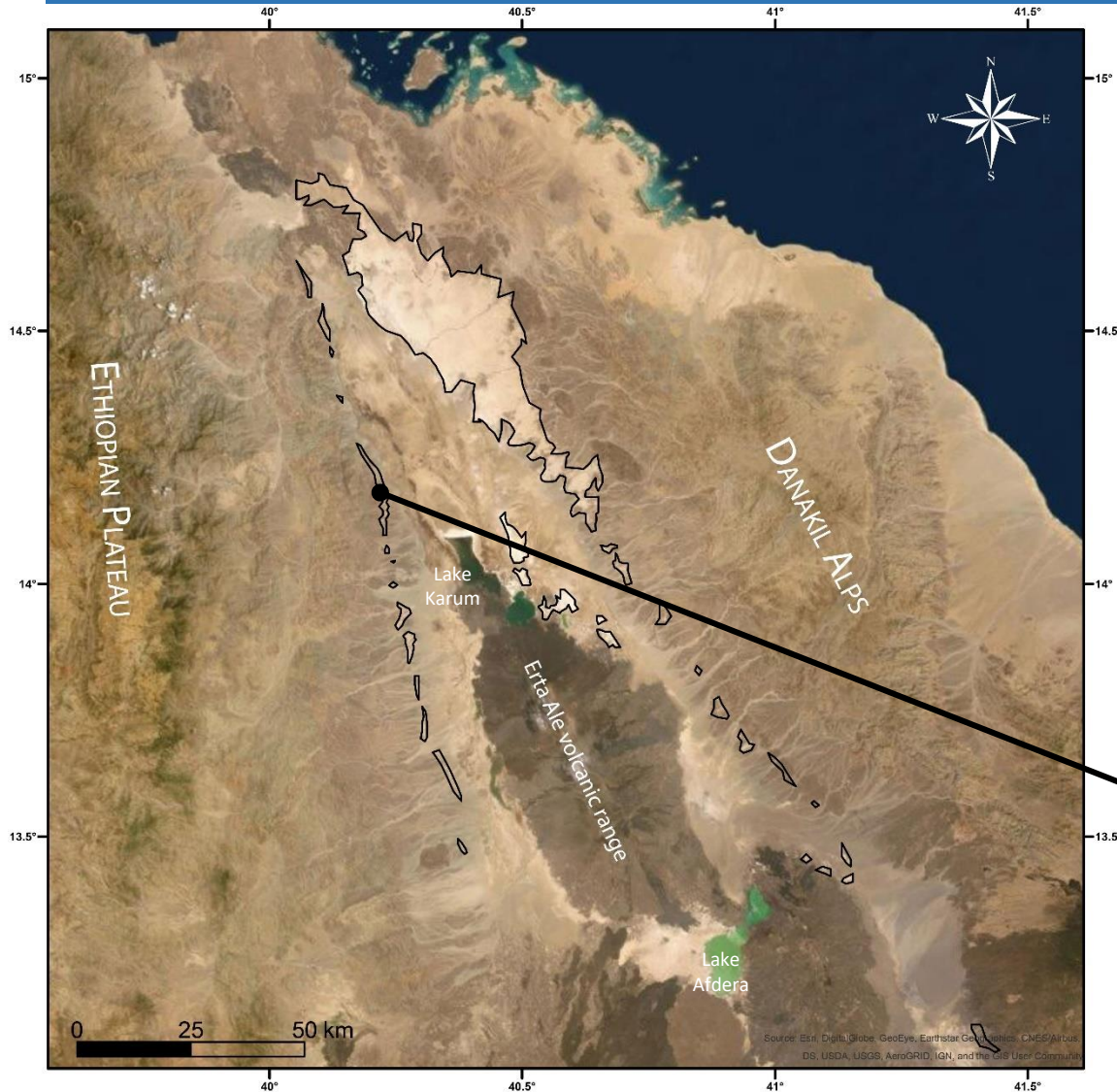


Fig. 3: The Danakil depression. The lighter coloured areas outlined in black represent the Pleistocene marine deposits.

The depression shows up to four different generations of corallal reef deposits (Fig. 3), indicating **Red Sea floodings** during the middle and late Pleistocene interglacials.



Fig. 4: Four fringing corallal reef terraces can be distinguished on this outcrop. The two most recent were dated as MIS5 and MIS7 (Jaramillo-Vogel et al., 2018).

Introduction: Aim of the study

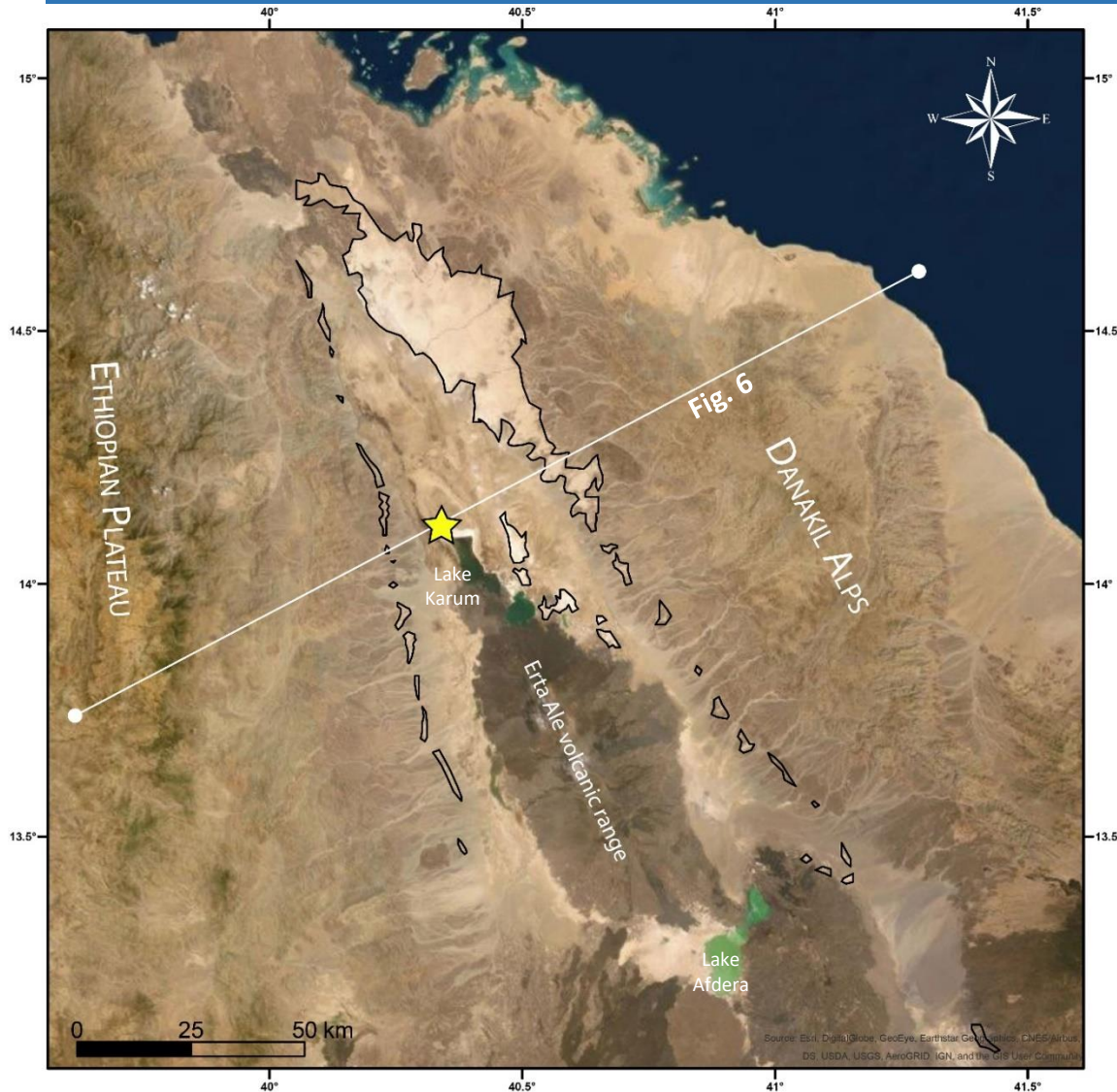


Fig. 5: The Danakil depression. The yellow star represents the studied core. The lighter coloured areas represent the Pleistocene marine deposits.

- This study focuses on a **625 m deep borehole** drilled in the central part of the basin.
- The aim of the study of this core section is to better understand the stratigraphy at basin-scale. Moreover, studying the lithostratigraphic variations at core-scale results in the better understanding of the palaeo-environmental and palaeoclimatological setting, as well as the basin dynamics.

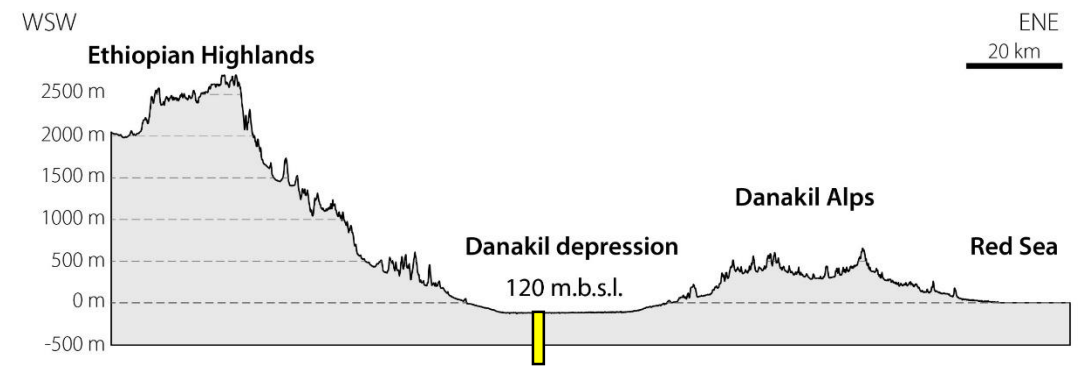


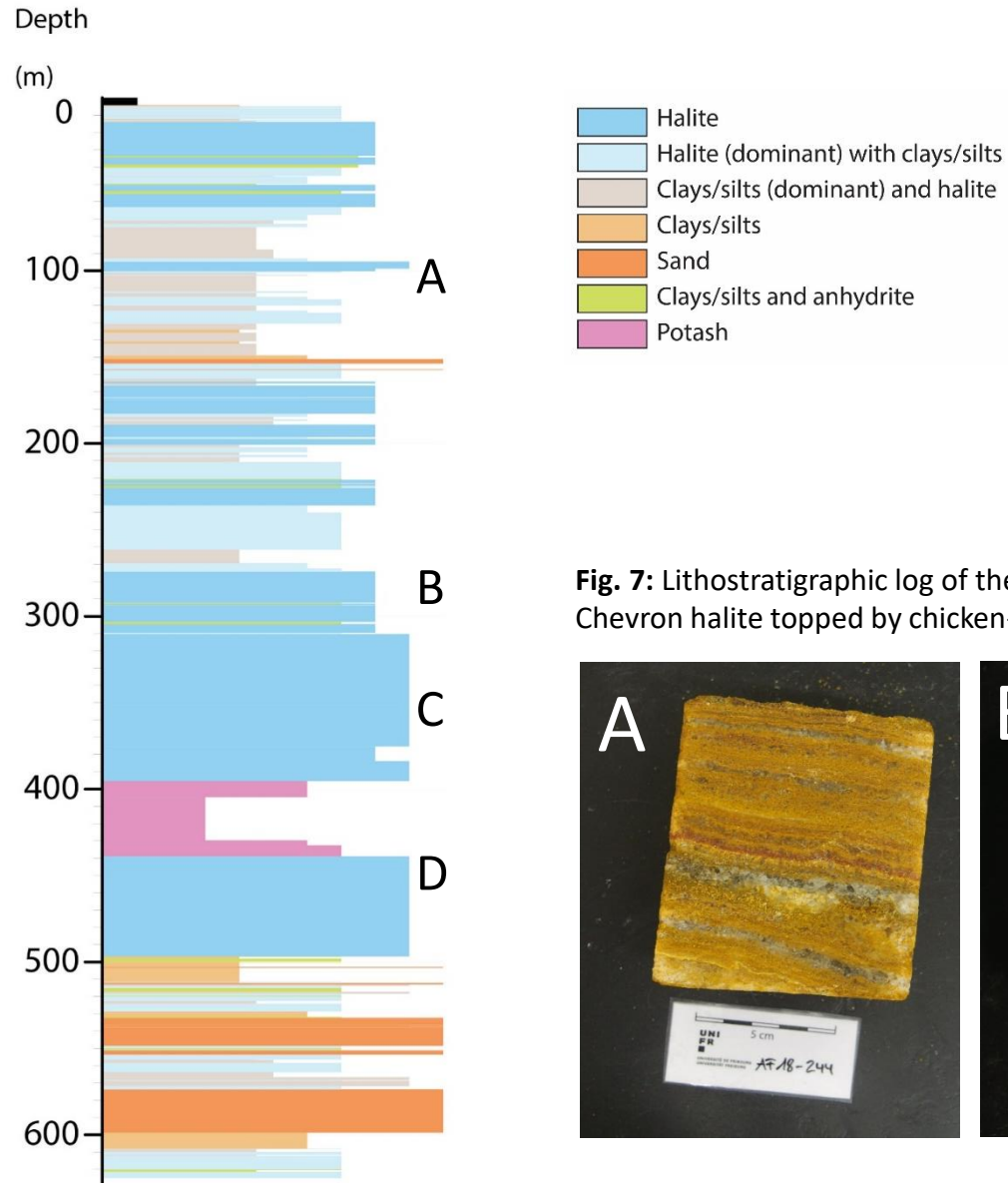
Fig. 6: Topographic cross-section through the depression. The yellow line represents the studied core. See fig. 5 for the position of the cross-section.

Methods and results

An integrated multi-proxy approach is used to characterize the core sediments:

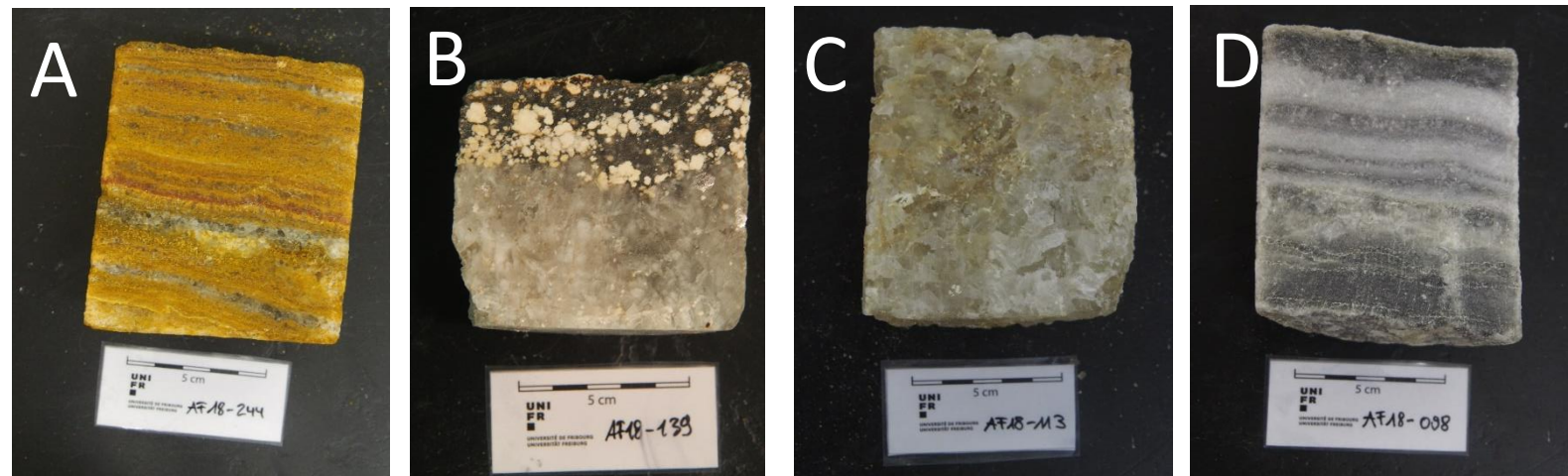
- Lithostratigraphic and facies analysis
- Elemental XRF analysis
- Mineralogical XRD analysis
- Micropaleontological analysis
- Organic matter analysis (RockEval)
- ^{14}C datings
- U/Th datings (not completed)

Methods and results: Lithostratigraphy

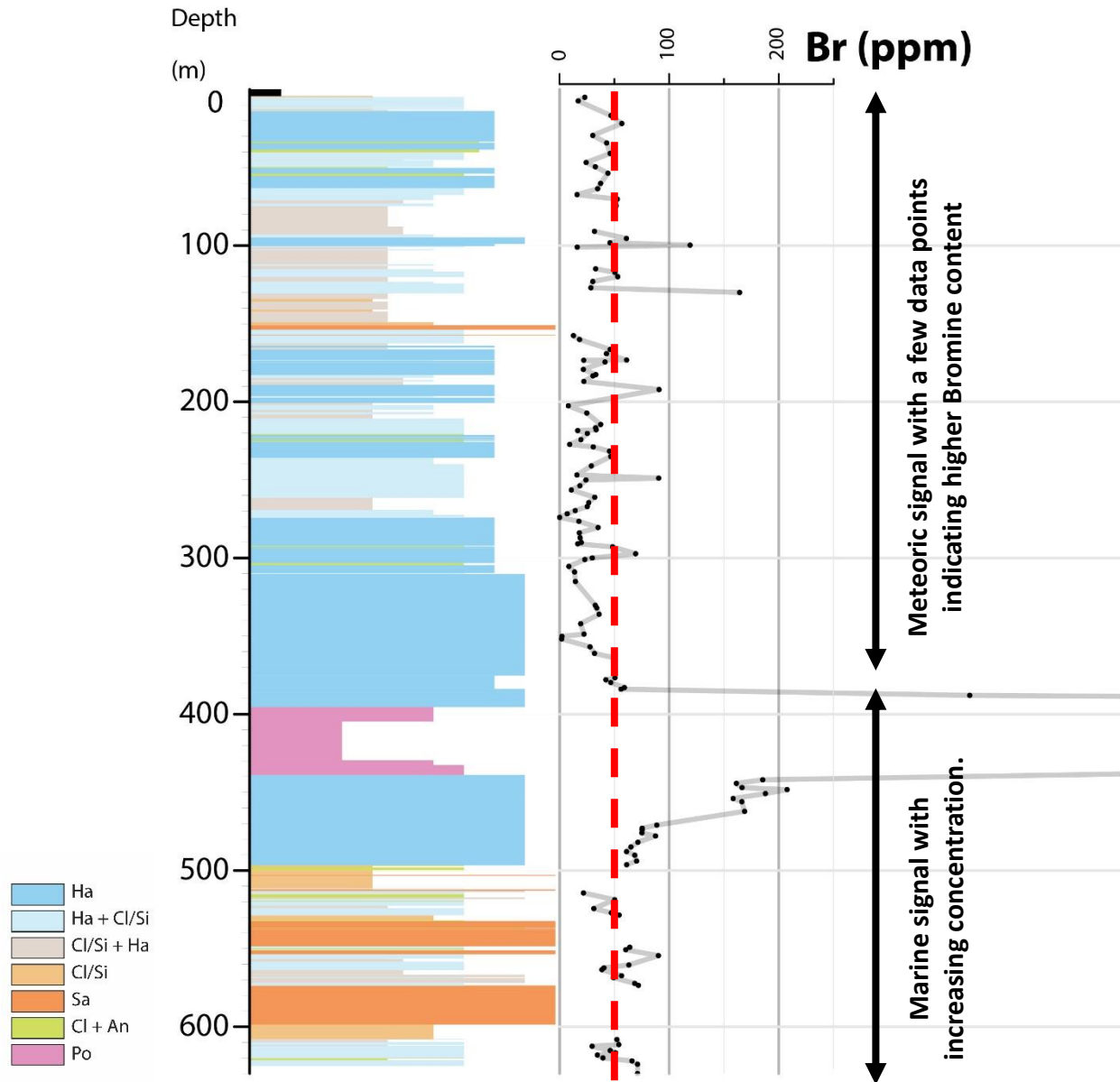


- Core formed by **evaporites** dominated by halite intercalated with clastic and carbonate sediments.
- One horizon of potash salt (kieserite, polyhalite, sylvite, kainite, bischofite) between 395 and 440m depth.

Fig. 7: Lithostratigraphic log of the core record with examples of halite and anhydrite. A) layered coloured halite; B) Chevron halite topped by chicken-wire anhydrite; C) Coarse chevron halite D) Layered halite.



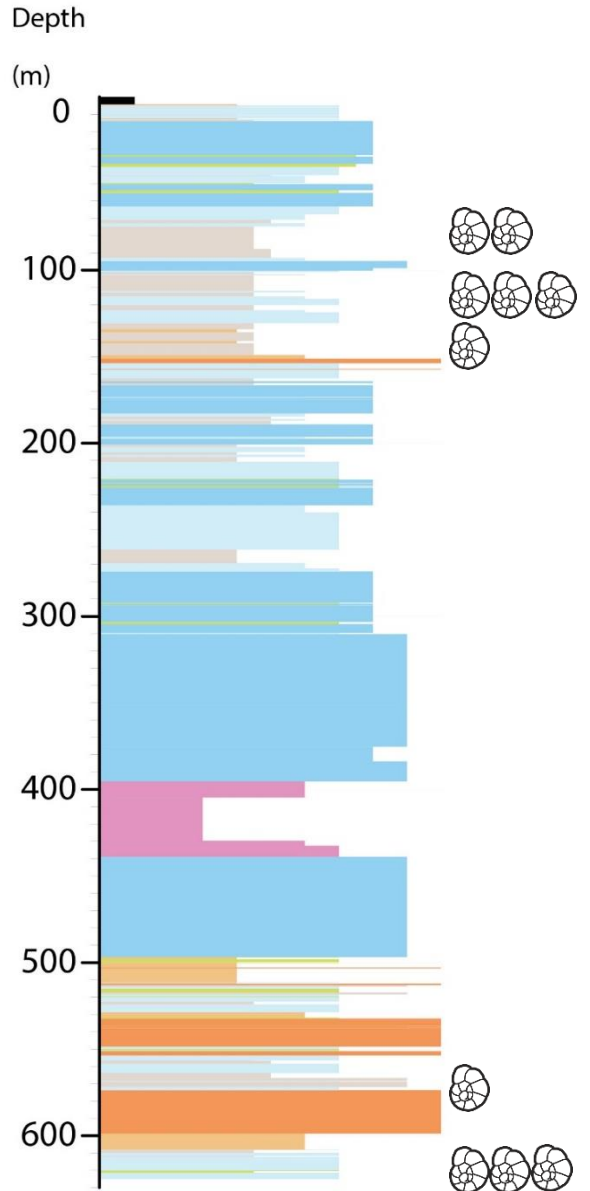
Methods and results: Elemental analysis



- XRF analysis focused on the **bromine content**, a proxy for brine origin and the degree of evaporation.
 - Concentration < ~50 ppm = evaporation of meteoric water
 - Concentration > ~50 ppm = marine water and degree of evaporation.
- Lower part: high and increasing bromine content
- Upper part: lower bromine content

Fig. 8: Bromine content (XRF analyses).

Methods and results: Micropaleontology



- Two horizons containing microfossils in small quantities and size.
- Dominance of foraminifera.
- Sporadic presence of ostracods and diatoms.

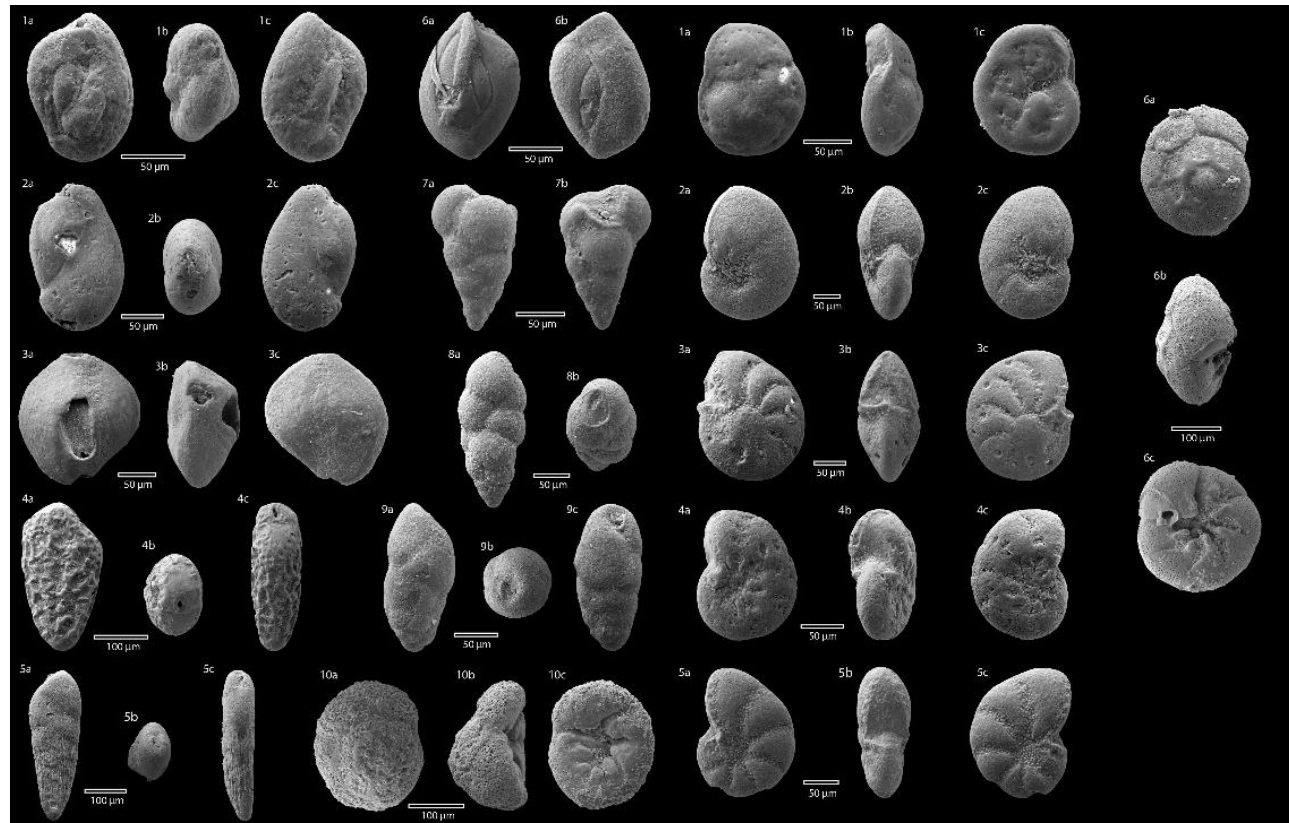
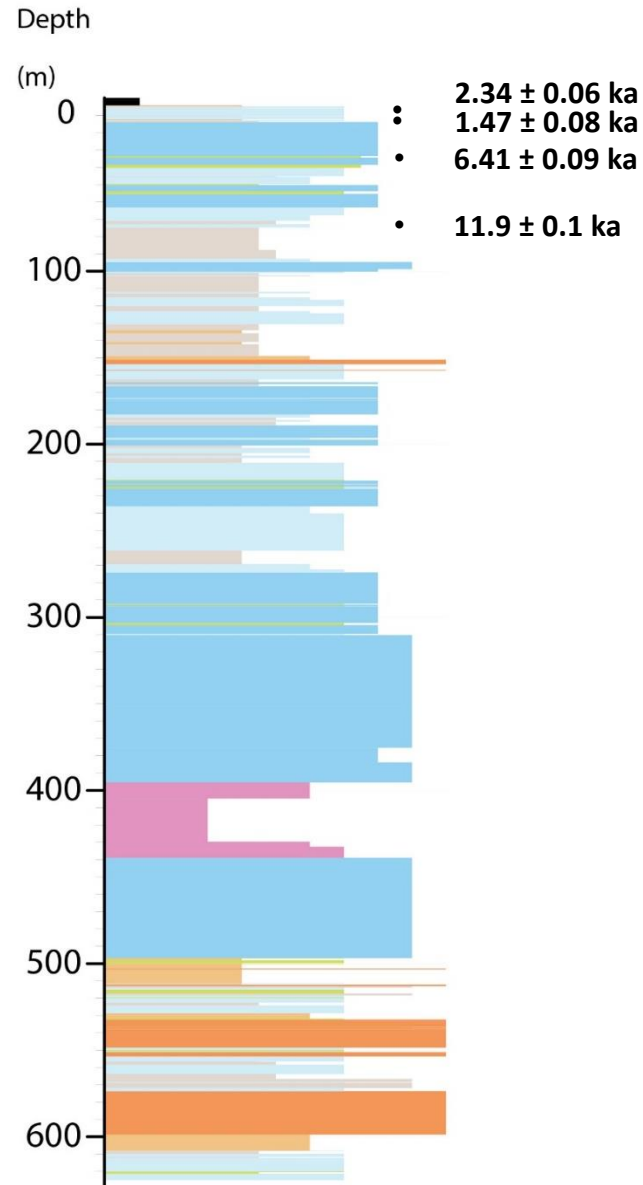


Fig. 9: Few foraminifera species observed in specific horizons within the core.

Methods and results: ^{14}C datings

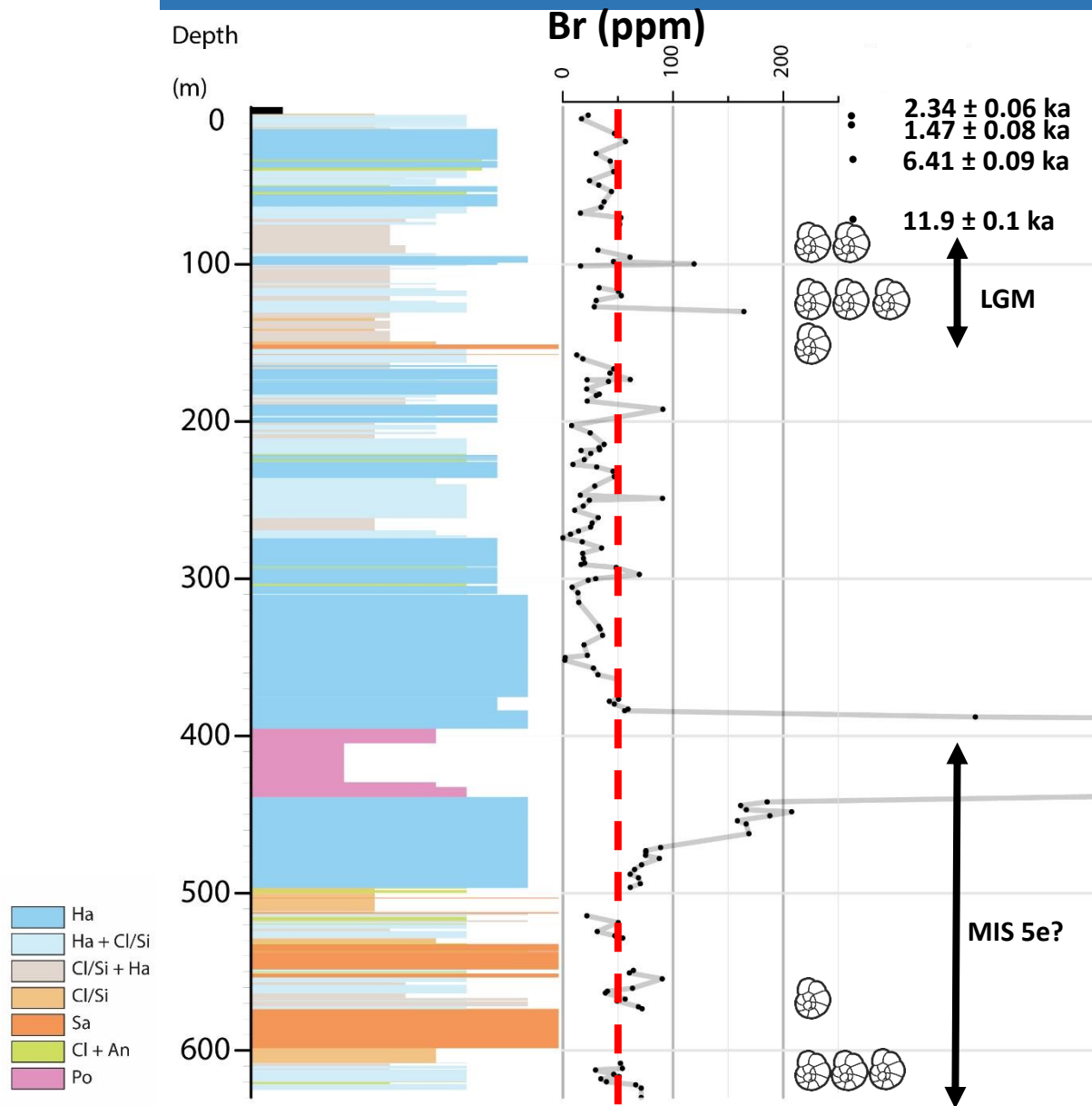


- Radiocarbon dating of 4 samples of wood fragments
- The upper 70 m of the core is Holocene in ages.



Fig. 10: Wood fragments dated by ^{14}C dating techniques.

Discussion: Chronostratigraphy



- Uppermost 70 m **Holocene** in age (^{14}C).
- The uppermost horizon rich in foraminifera specimen is present below the Holocene unit, and corresponds most probably to the **LGM**. Those specimen have been interpreted as living in a saline lake and being imported by birds in those settings. The possibility of a Red Sea incursion is discarded by the very low sea level at that time.
- The lowermost fossiliferous interval corresponds to a unit with higher Bromine content and is topped by units rich in marine potash salts. Through correlation with the marginal deposits, this interval is interpreted as being **MIS5e** (130 ka).
- Further U/Th datings are on-going to constrain further the chronostratigraphic framework.

Fig. 11: Chronostratigraphic framework.

Discussion: Paleoenvironment (summary)

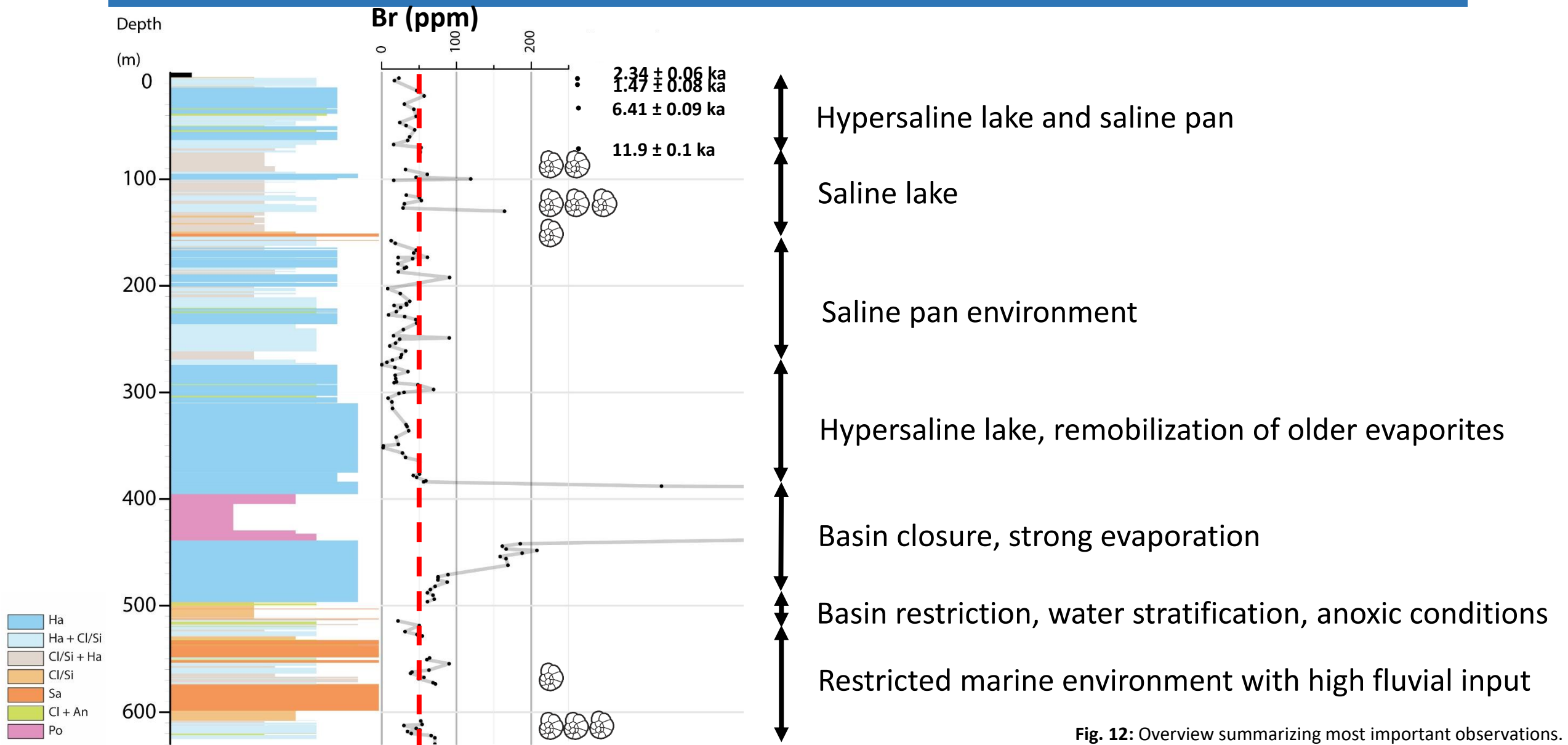
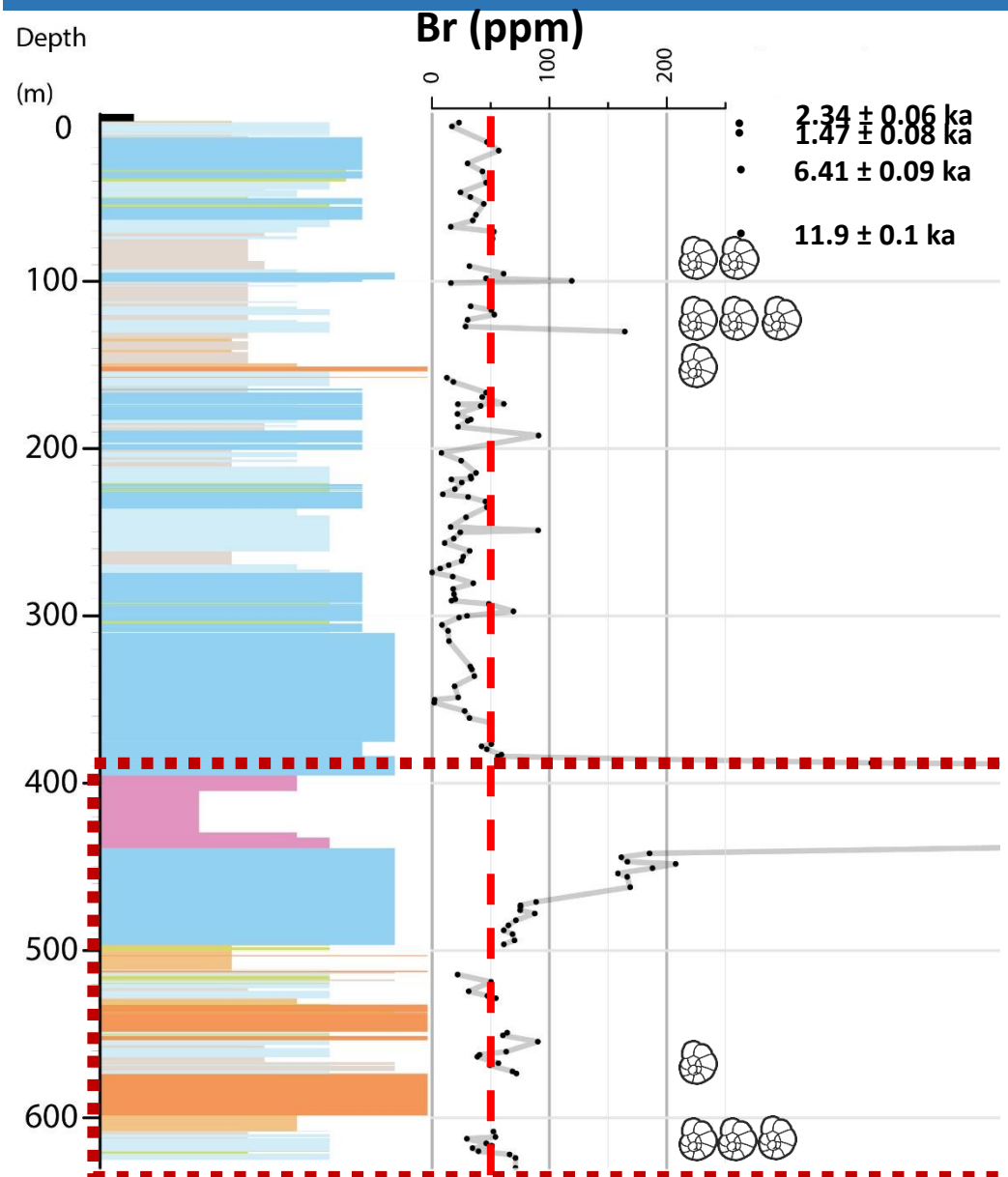


Fig. 12: Overview summarizing most important observations.

Discussion: Paleoenvironment (1)



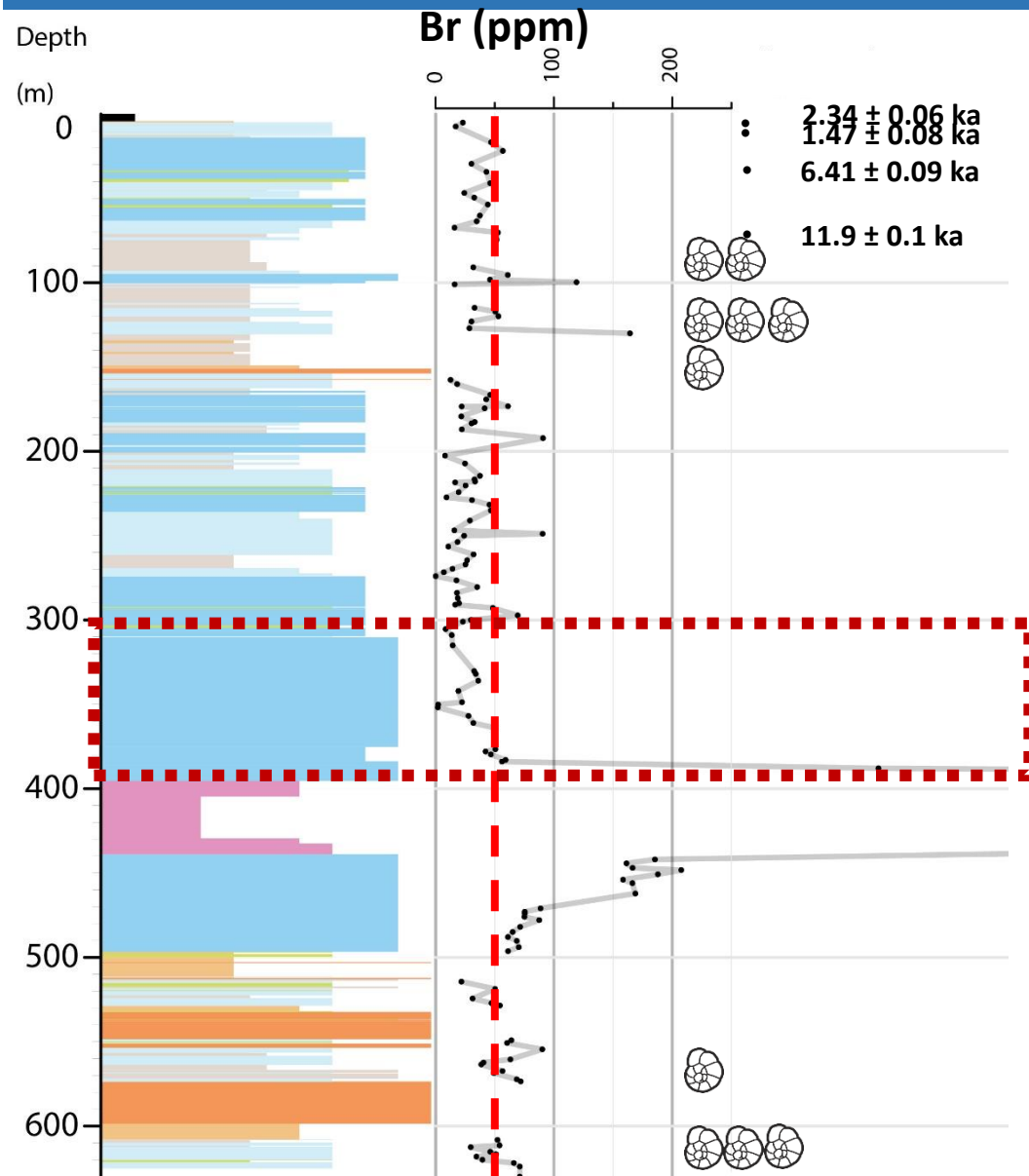
The lowermost part of the core (from 500m till 625m) is interpreted to represent a **marine environment**, as indicated by the presence of foraminifera and the high bromine content. Fluvial input was also important as indicated by the sandstone intervals, suggesting a wet climate.

The upper part of this interval (500-520m) is characterized by the dominance of magnesite ($MgCO_3$), high TOC level and type I (sapropelic) kerogen. This indicates water stratification, anoxic conditions and **basin restriction**.

The interval between 500 and 400m is formed exclusively by evaporites. The increasing bromine content and the appearance of potash salts indicates a gradual **closure of the basin** and concentration of the seawater.

Fig. 13: Overview of the most important observations. The red square indicates the discussed palaeo-environmental setting.

Discussion: Paleoenvironment (2)

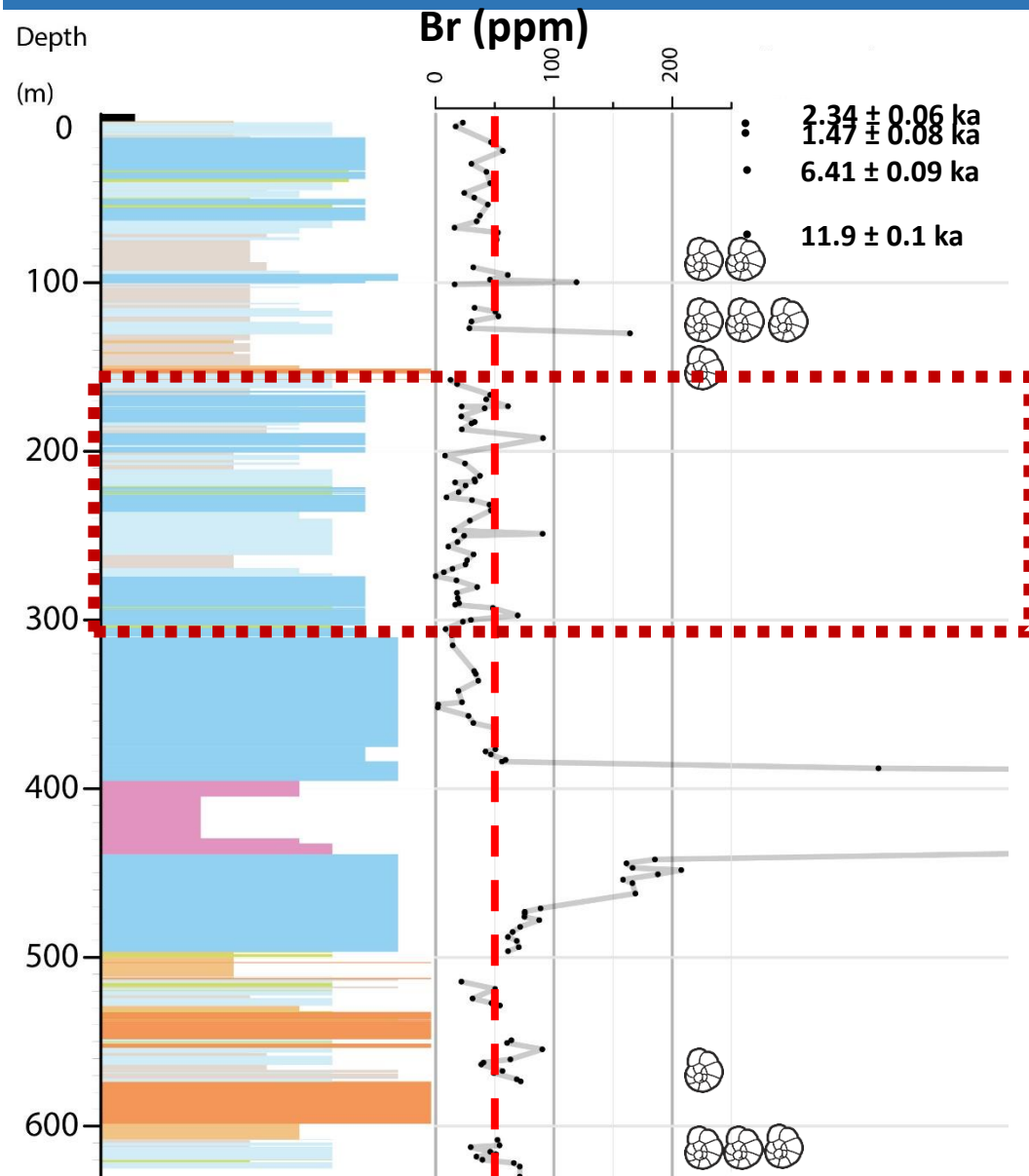


Above the potash interval (400-300 m), a thick package of pure halite with low bromine content indicate a drastic change in environment. The halite probably comes from the remobilization of the marine halite deposited on the margins by meteoric water inflow. The absence of siliciclastic material and the laminated and bottom-growth halite facies points towards the presence of a **hypersaline lake**.



Fig. 14: Present-day hypersaline lake Karum. The hypersaline paleo-lake was probably significantly deeper. Location on figures 3 and 5.

Discussion: Paleoenvironment (3)

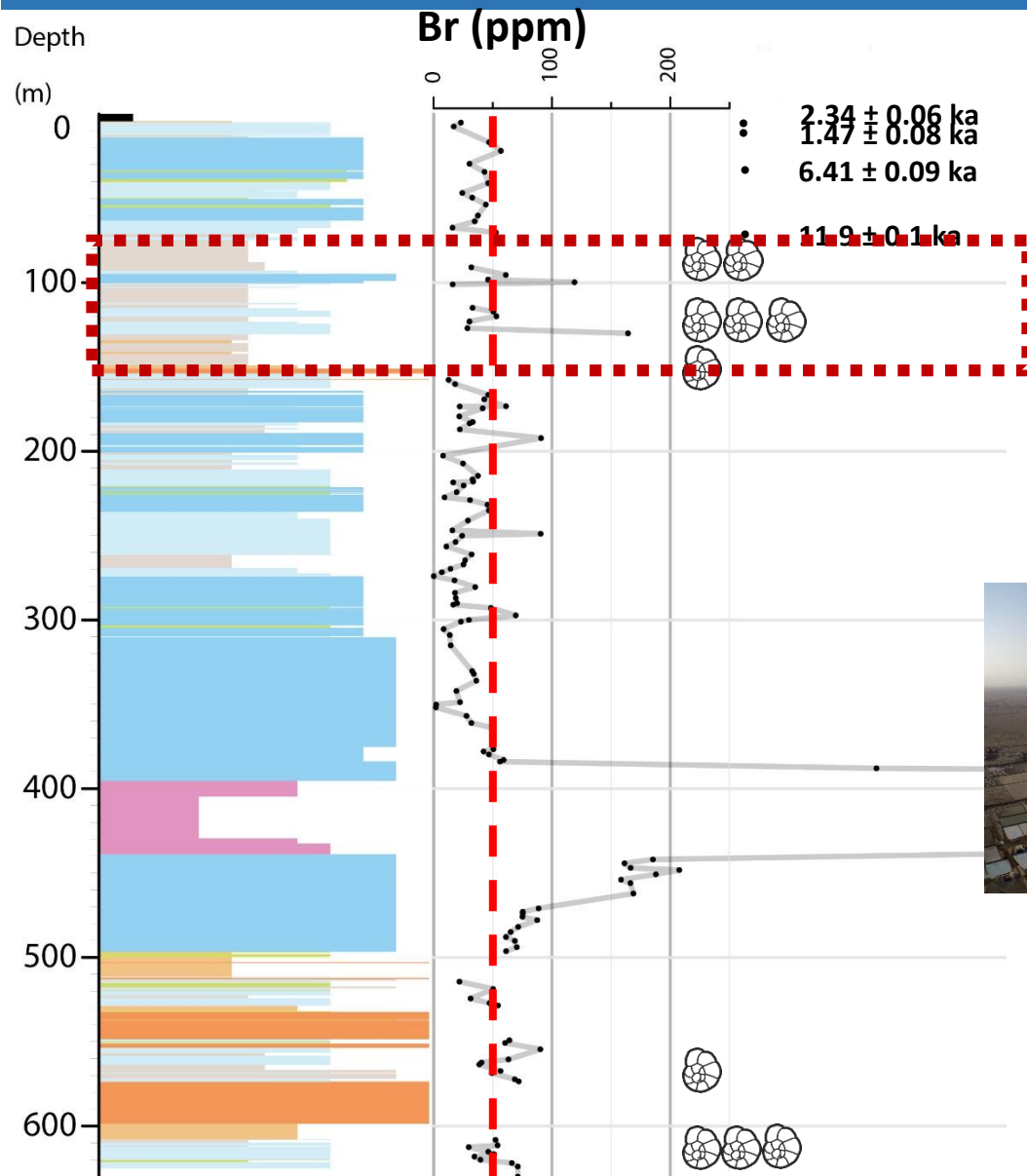


Between 300 and 150 m, the alternation of fine grained sediments and halite suggest the transition to a **saline pan** environment, comparable to the present-day conditions at the Danakil depression. The climate was dry and the salt probably comes from the recycling of older evaporites, as observed today.



Fig. 15: Present-day salt flat environment on the floor of the depression.

Discussion: Paleoenvironment (5)

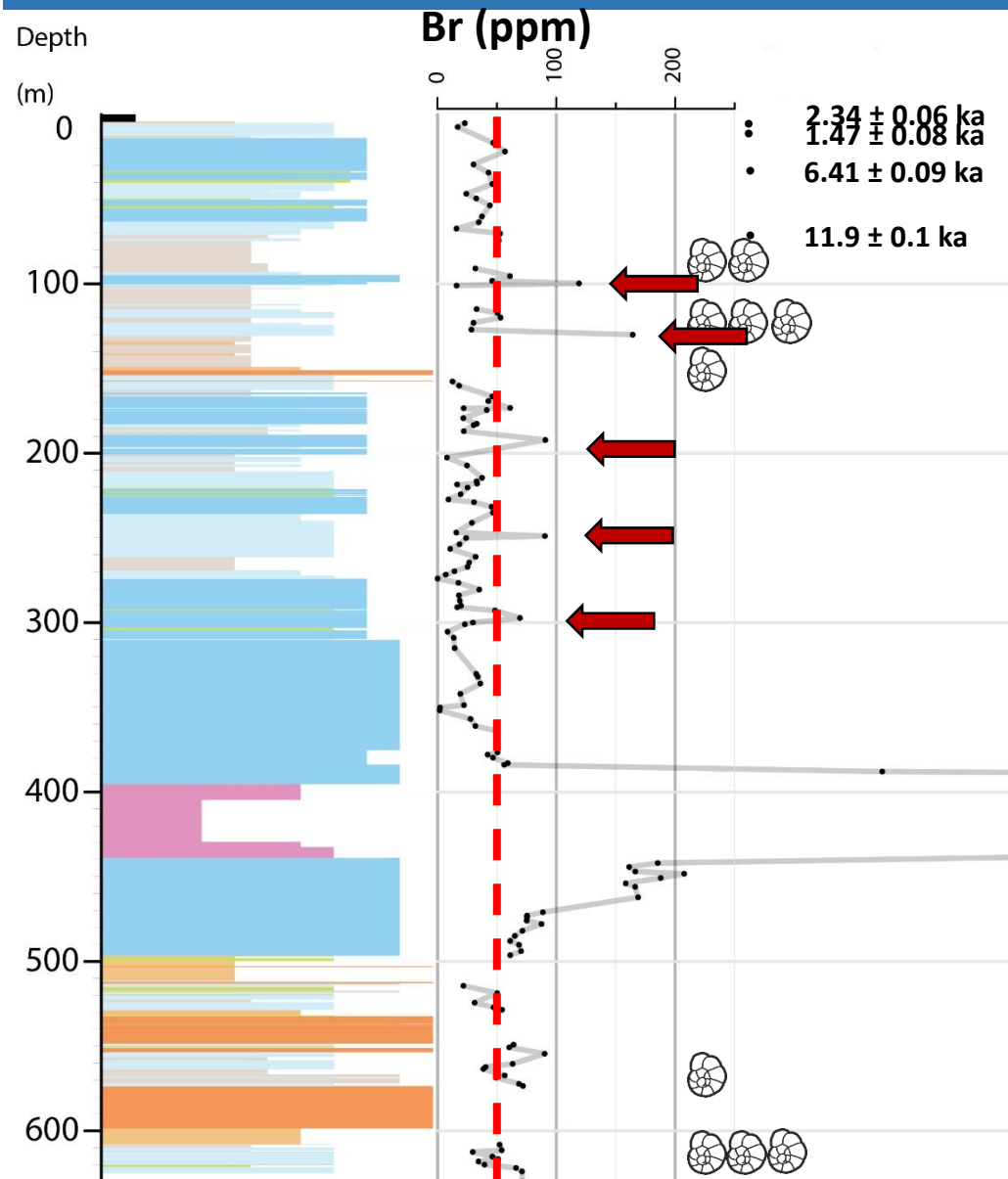


The interval between 150 and 70m shows the dominance of fine grained sediments with minor layers of halite. Foraminifera, ostracods and diatoms are present in the studied marly sediments. Those sediments are interpreted as representing a **saline lake**, related to an early phase of the *African Humid Period*.



Fig. 16: Lake Afdera, an example of a present-day saline lake in the Danakil Depression. In contrast to Lake Karum, the water is saline but does not precipitate salt unless processed in evaporation ponds as widely exploited by the local population. Location on figures 3 and 5.

Discussion: Paleoenvironment (6)



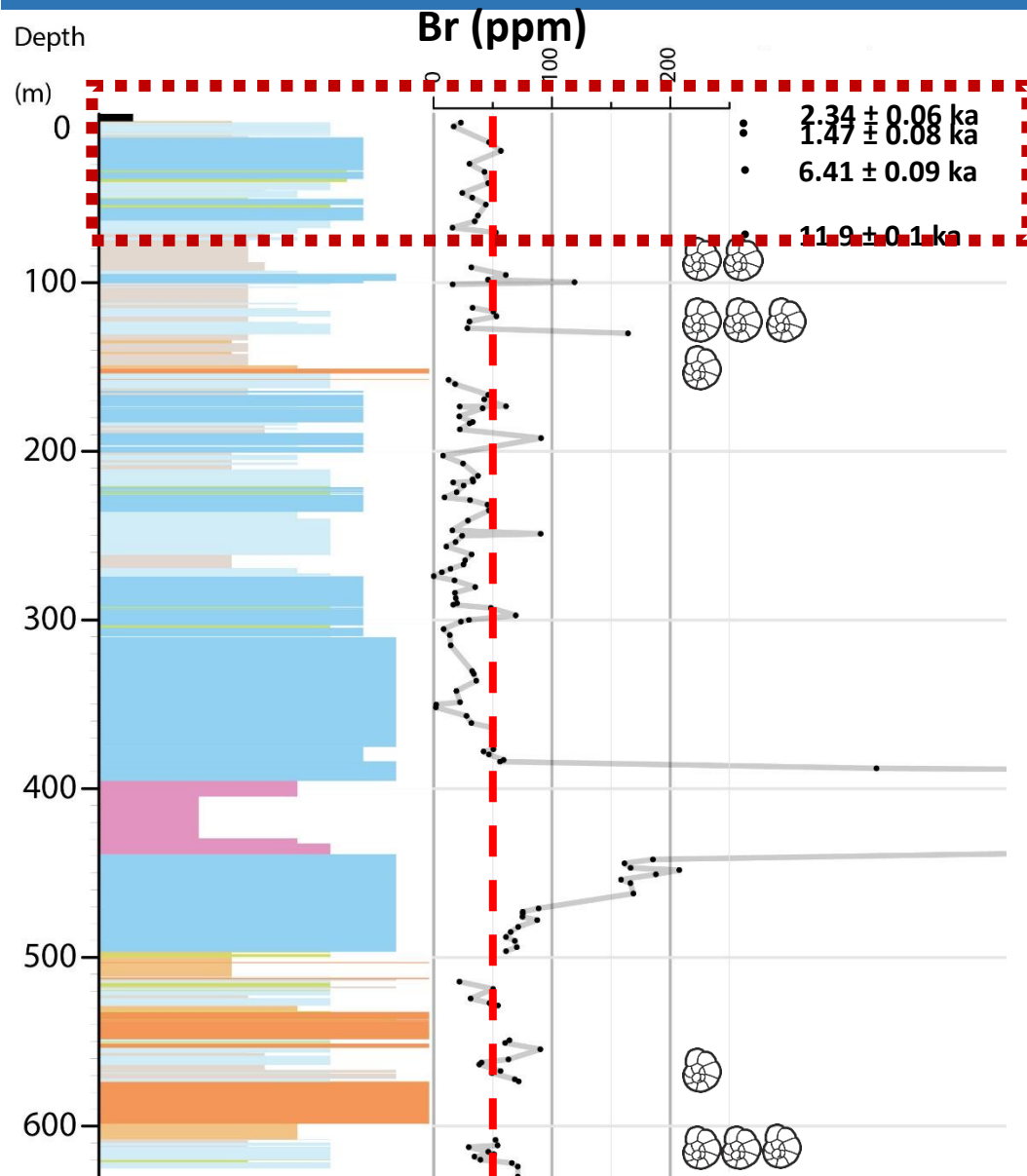
Distinct peaks in bromine content visible between 300 and 70 m probably represent a process still observed today. Halite forming nowadays from water coming from the eastern side of the depression also evidence elevated bromine values.

This can be interpreted either as **seepage of seawater** through the escarpment (possibly with hydrothermal interaction with the basalts as indicated by elevated values of Fe, Mn, Zn and Ba correlated with some of these peaks) or as **leaching of the bromine-rich potash** layer which is situated at shallower depth on the eastern margin of the depression.



Fig. 17: Red waters coming from the eastern margin precipitating halite with bromine values between 120 and 220 ppm.

Discussion: Paleoenvironment (7)



The last interval (above 70 m depth) is well constrained by the ^{14}C datings and was formed during the Holocene. The deposits are interpreted as a succession of **hypersaline lakes** and **salt flats**. The presence of extended lake in the Danakil depression during the early and middle Holocene has already been evidenced by Gasse (1974). This change from saline to hypersaline conditions can be linked to an increase in temperature during the early Holocene.

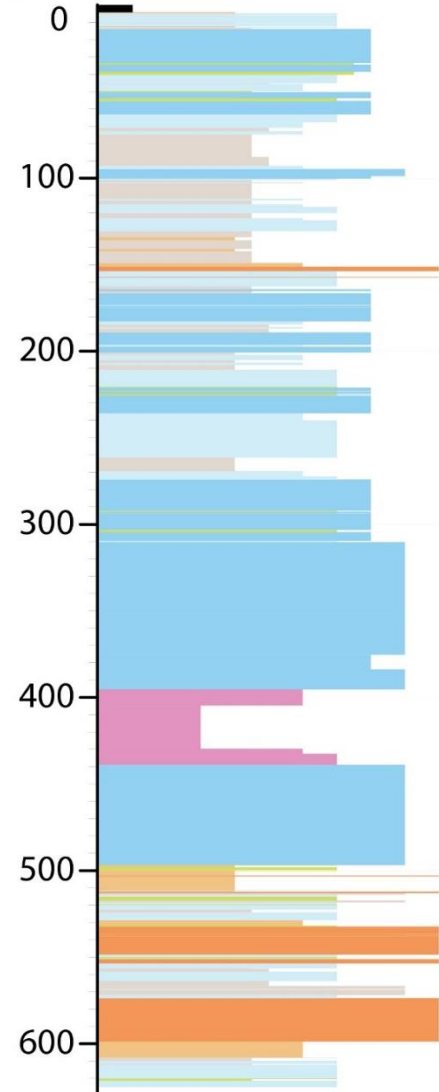


Fig. 18: Present-day salt flat environment on the floor of the depression.

Discussion: Basin dynamics

Depth

(m)

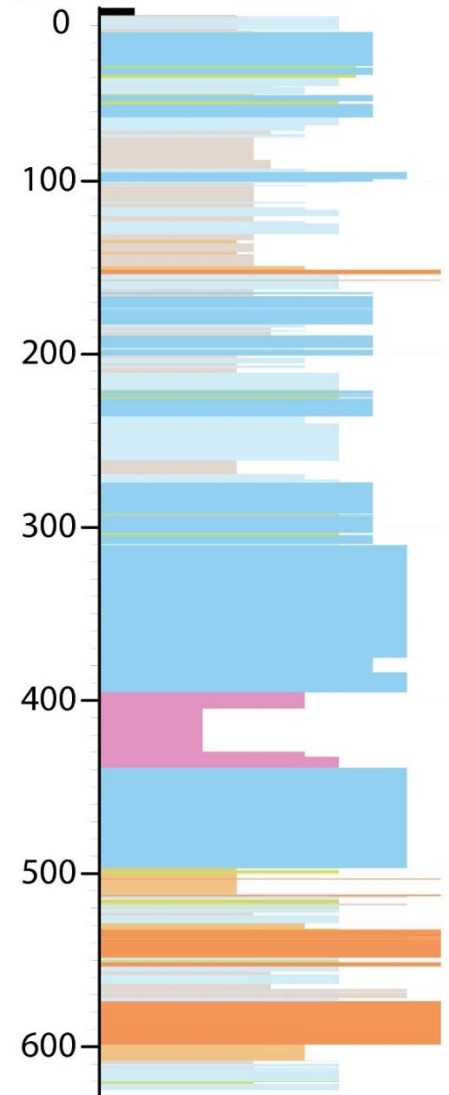


- The successive flooding and desiccation events are resulting from Rea Sea-level variations but also important tectonic activity. Rift margin uplift prevented flooding during the Holocene resulting in the restriction of the Danakil basin (Foubert et al., in prep.; Rime et al., in prep.).
- High basin subsidence rates created enough accommodation space for voluminous sedimentary basin infill. The preliminary interpretation of the microfauna seems to indicate a relatively shallow depositional environment, implying more than 500m of subsidence in 130ka, i.e. more than 3mm/yr.
- This subsidence cannot be explained by flexural isostasy only, implying active extensional tectonics at least since the late Pleistocene.

Discussion: Formation of a “mini salt giant”

Depth

(m)



- Marginal deposits indicate at least 3 more marine cycles, implying the presence of a significant amount of evaporites below the studied core sections. This is coherent with geophysical interpretations of Behle et al. (1975) who calculated a salt thickness of 2.2 km and with the study of Holwerda & Hutchinson (1968) mentioning a second potash layer at 930 m depth.
- The deposition of large amount of evaporites can take place in short times by cyclic flooding of the rift, evaporation of the seawater and recycling of older evaporites by meteoric water under hot and arid climate.
- The Danakil depression is probably the closest Recent analogue to some older *salt giants* (e.g. in the south Atlantic) which cover wider areas, but show similar thickness and tectonic settings. The Danakil salt basin can help better understand the formation of its older counterparts.

Conclusions

- The Danakil basin is filled by sediments dominated by evaporites (mainly halite) alternating with clastics and carbonates sediments.
- The upper 625m of the studied core section probably corresponds to the late Pleistocene and the Holocene (129 ka till present day). Sediments were formed by the marine flooding of the depression, followed by its closure and desiccation. The uppermost part of the core section corresponds to a period of continental sedimentation dominated by hypersaline lakes and saline pans.
- The stratigraphy indicates high subsidence rate implying active extensional tectonics.
- The Danakil depression is probably the closest recent analogue to some of the older *salt giants* on earth and can help us to decipher the formation of those past evaporite deposits.



Fig. 19: Eruption on the flank of the Erta Ale in February 2020.

Aknowledgments

- This study has been funded through the **Swiss National Science Foundation** (SNF-project SERENA 'SEdimentary REcord of the Northern Afar' 200021_163114).
- We thank the **Ethiopian Geological Survey** and the **Ethiopian Ministry of Mines** that have granted us access to the core sections.
- **Geraldine Zimmerli, Janine Sturny, Xenia Haberditz, Stephanie Hayman, Ermias Filfilu, Samuel Getachew, Bernard Grobety, Alexandre Salzmann** are also thanked for their precious help on the field and in the labs.
- We also acknowledge **Circum Minerals, Yara Dallol** and former **Allana Potash Ltd.** for accommodation and field logistics.



Fig. 20: The western margin of the depression with white-coloured sediments of the MIS5 marine incursion

Bibliography

Behle, A., Makris, J., Baier, B., & Delibasis, N. (1975). Salt thickness near Dallol (Ethiopia) from seismic reflection measurements and gravity data. In A. Pilger & A. Rösler (Eds.), *Afar Depression of Ethiopia: Proceedings of an International Symposium on the Afar Region and Related Rift Problems* (pp. 156–167). Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Gasse, F. (1974). Les Diatomées des Sédiments Holocènes du Bassin du Lac Afrera (Giulietti) (Afar Septentrional, Ethiopie). Essai de Reconstitution de l'Évolution du Milieu. *Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie*, 59(1), 95–122.

Holwerda, U. G., & Hutchinson, R. W. (1968). Potash-bearing Evaporites in the Danakhil Region, Etiopia. *Economic Geology*, 2(63), 124–150.

Jaramillo-Vogel, D., Foubert, A., Braga, J. C., Schaegis, J. C., Atnafu, B., Grobety, B., & Kidane, T. (2019). Pleistocene sea-floor fibrous crusts and spherulites in the Danakil Depression (Afar, Ethiopia). *Sedimentology*, 66(2), 480-512.