

# Geochemistry, Geophysics, Geosystems®



## RESEARCH ARTICLE

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### Key Points:

- The African-Arabian plate boundary in the northern Red Sea is marked by a transtensional, left-lateral strike-slip fault system
- Transtension began after the Miocene, leading to oblique continental rifting without seafloor spreading, unlike the southern Red Sea
- The Mabahiss Deep opened as a pull-apart basin at an overstep of this shear zone and is part of the Zabargad Fracture Zone

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## Post-Miocene Transtensional Opening of the Northern Red Sea

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**Abstract** The mechanism of opening, as well as the crustal characteristics of the northern Red Sea are subject of ongoing controversial scientific debate. With the objective of elucidating the nature of rifting in this area, a grid of 2D multi-channel reflection seismic data was acquired off the Al Wajh carbonate platform (AWCP), and supplemented by high-resolution bathymetric data. Along the previously proposed rift axis, a major meandering graben system is identified trending NNW-SSE that exhibits characteristics indicative of a strike-slip zone. The observed slip is left-lateral with a predominant extensional component. At the Mabahiss Deep, the fault zone bends to the south and steps over. Consequently, the basin functions as a pull-apart basin and is supposed to be a part of the Zabargad Fracture Zone. Bathymetric data highlight the complex seafloor topography in the study area today, which is caused by various subsurface salt structures. Their surface expression reflects the prevailing tectonic regime. Three distinct domains have been identified. The first encompasses the AWCP and its surrounding slopes. The second domain comprises the distal part of the rift, where salt structures trend NNW–SSE in line with the inferred rift axis. In the third, proximal domain, salt structures trend obliquely to the rift axis in places. This is attributed to intrinsic extension and normal faulting transverse to the strike-slip zone. Our results suggest that the NRS is in a transitional phase from continental rifting to seafloor spreading. The observed magmatic intrusions and submarine volcanoes are precursors to continental breakup.

**Plain Language Summary** The creation and destruction of ocean basins is a continuous and fundamental process in Earth system dynamics. This process is often associated with extensive volcanism and large earthquakes that can pose risks to human infrastructure and populations. Understanding how continents begin to separate and give rise to new ocean basins, such as the Red Sea, is therefore of significant scientific interest. Using an acoustic source along designated ship tracks, we transmitted sound waves that penetrated the seafloor and were reflected at boundaries where the physical properties of the rocks changed. The recorded echoes provide vertical images of the subsurface geology, allowing us to map the Earth's layering, the occurrence of faults, and magmatic as well as salt structures. We were able to identify a major shear system at the Red Sea rift axis, northeast of the Mabahiss Deep, along which the African and Arabian plates are moving apart and also sliding past each other. The results also show that the Mabahiss Deep is a fault-bounded basin located at the northern end of the Zabargad Fracture Zone and is part of this shear system. The mapped fault system triggers earthquakes and is a site of submarine volcanism.

## 1. Introduction

The Red Sea is regarded as the type location for an ocean basin in the incipient phase of its formation. However, there are markedly contrasting opinions regarding its opening mechanism, as evident in the variety of rifting models developed, reflecting different rifting modes. The Red Sea has been interpreted as a pure-shear symmetric rift system characterized by limited crustal stretching and attenuation (e.g., Almalki et al., 2015; Buck et al., 1988), while others have associated it with simple-shear rifting and highly asymmetric rift margins resulting from low-angle normal faults (e.g., Cochran & Martinez, 1988; Gaulier, Villemin, & Colletta, 1988; Wernicke, 1985). Regarding the nature of the crust along the axis of the Red Sea, there are two main schools of thought: one stating that the entire basin is underlain by oceanic crust (e.g., Augustin et al., 2021; Delaunay

et al., 2023; El Khrepy et al., 2021; Gaulier, Le Pichon, et al., 1988; Girdler & Underwood, 1985), whereas the other argues that the southern and central sectors are rifted margins that have reached or approached the oceanic stage, but the northern Red Sea (NRS) is underlain by hyper-extended continental crust (e.g., Almalki et al., 2015; Cochran, 2005; Le Magoarou et al., 2021; Ligi et al., 2018; Stockli & Bosworth, 2019).

In the NRS, a thick mobile salt layer of Miocene age (Bosworth et al., 2020; Torfstein & Steinberg, 2020) complicates the reconstruction of the structural patterns of the rift basin. Location and kinematic evolution of basement faults are masked or obscured by the salt layer, which hinders the faults penetrating and deforming the overlying stratigraphy. In other cases, deformation of the overburden might be detached from the basement by the mobile salt layer, producing thin-skinned tectonics. Several studies in the Red Sea document how salt mobilization such as salt withdrawals and diapirism overprint the original basement morphology and shape of the present seafloor (Augustin et al., 2014; Ligi et al., 2018; Mitchell & Augustin, 2017; Orszag-Sperber et al., 1998; Petrovic, Lüdmann, et al., 2023; Tubbs et al., 2014). However, although salt masks subsurface structures, it can also provide diagnostic features for the prevailing tectonic regime (Jackson & Hudec, 2017). For the northern Egyptian Red Sea margin, Ali, Koyi, et al. (2023) identified salt walls and ramp-synclines as diagnostic features for thick-skinned extension.

A strike-slip fault is a fault in which the displacement vector is parallel to the fault's strike, and thus to the Earth's surface (Biddle & Christie-Blick, 1985). They are usually steeper than other faults and, in many cases, linear features. Curvatures and subsidiary structures also occur along strike-slip faults. These include restraining and releasing bends, pull-apart basins, and Riedel shears (Sylvester, 1988). The latter occur as synthetic or antithetic shears, characterized by the same or opposite sense of motion, as well as being at a low or high angle to the main shear zone.

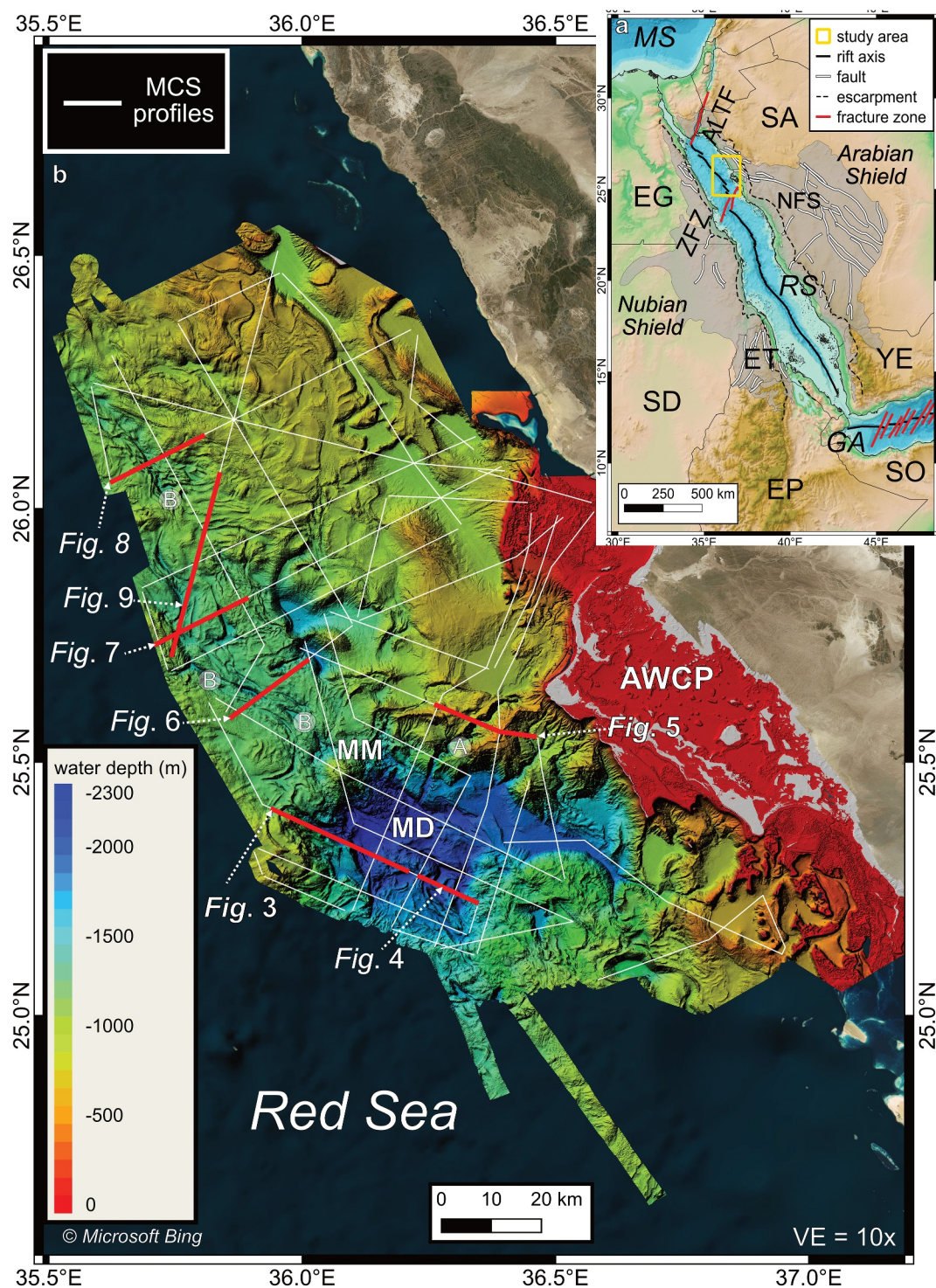
Strike-slip motion within rift systems parallel or at small angles to the rift axis is reported for continental rifts; however, not at active mid-ocean ridges, transversal shear dominates along oceanic transform faults and fracture zones. Examples of rift-parallel strike-slips are found in the East-African rift valley. For the Malawi rift, Ring et al. (1992) demonstrated that rifting commenced with the formation of half-grabens bounded normal faults and later extension was additionally accommodated by strike-slip faulting. The strike-slip regime led to basement uplift within the rift in regions of local transpression, but it also created alluvial basins caused by local trans-tension. For the Afar Triangle, Abbate et al. (1995) determined a main sinistral displacement of the rifted lithospheric plates. Here, rift-parallel shear added to the divergent plate movement led to an anticlockwise shift of the plates around the Afar junction. 3-D numerical lithospheric-scale experiments by Brune (2014) showed that oblique rifting led to rift axis-parallel strike-slip as well as synthetic and antithetic Riedel shears formation.

In this study, a new set of multi-channel reflection seismic (MCS) and multibeam data acquired in 2023 during RV Meteor cruise M193 (Lüdmann et al., 2023) was used to reconstruct the tectonic regime offshore of the Al Wajh carbonate platform (AWCP), situated at the Saudi Arabian NRS margin, and to explore the opening mechanism of the NRS basin (Figure 1). The cruise M193 was carried out in a crucial tectonically diagnostic area, where the middle and northern rift sectors meet and are displaced to the right by approximately 100 km along the Zabargad Fracture Zone (ZfZ, Figure 1a) (e.g., Augustin et al., 2021; Ligi et al., 2018; Marshak et al., 1992). This new data set of relatively closely spaced MCS lines and high-resolution bathymetry sheds light on the structure of rift section junctions and the continuation of the NRS rift sector. The results were correlated with published vertical gravity gradient (VGG) data (Sandwell et al., 2014), magnetic data from different cruises (Issa-char, 2021), available historical earthquake data ( $M > 4.0$ ; <https://www.usgs.gov/programs/earthquake-hazards>), and ocean bottom seismometer data (Shiddiqi et al., 2025a) to obtain a holistic image.

### 1.1. Geological Background

The Red Sea is a young rift basin situated between the African and Arabian plates (Figure 1a), which has undergone a transition from the syn-rift to the post-rift phase since the onset of the Pliocene (Delaunay et al., 2023; Hughes & Johnson, 2005; Tubbs et al., 2014). The Red Sea basin is bordered by mountain ranges that rise to elevations exceeding 2,000 m. The basin extends approximately 2,000 km in length and reaches a maximum width of 355 km. Its average depth is about 490 m, while the deepest point reaches around 2,860 m (Augustin et al., 2014; Yao et al., 2014). The opening of the Red Sea began around 25–23 Ma along an NNW–SSE striking axis, separating the Nubian and Arabian shields and resulting in crustal thinning and subsidence that promoted the formation of an initial graben structure connected to the Mediterranean Basin (e.g., Bosworth & McClay, 2001;





**Figure 1.** (a) Geographical map showing the Red Sea and its border countries. Tectonic features modified from Bosworth et al. (2005), Fritz et al. (2013) and Augustin et al. (2021). ALTF, Aqaba-Levant Transform Fault; EG, Egypt; EP, Ethiopia; ET, Eritrea; GA, Gulf of Aden; MS, Mediterranean Sea; NFS, Najd Fault System; RS, Red Sea; SA, Saudi Arabia; SD, Sudan; SO, Somalia; YE, Yemen; ZTZ, Zabargad Transform Zone. (b) Map of the study area (yellow frame in a) showing the multibeam bathymetry (30 m resolution) underlain by hillshade layer with 10 times vertical exaggeration. Red lines indicate the location of example profiles. AWCP, Al Wajh Carbonate Platform; MCS, multi-channel seismic; MD, Mabahiss Deep; MM, Mabahiss Mons.

Cochran, 1983; Pisapia et al., 2024). After the establishment of the left-lateral Aqaba–Levant transform around 12–14 Ma (Figure 1a), the direction of extension of the Red Sea changed from being orthogonal to the rift axis into oblique extension in a NNE direction, parallel to the transform (Bosworth et al., 2005; Lyberis, 1988). The major tectonic feature of the ZFZ connects the northern and central rift axes of the Red Sea (Figure 1a). Most rifting models locate the origin of the ZFZ at Zabargad Island, an uplifted block of sub-Red Sea lithosphere, overlain by a Lower Cretaceous sandstone-limestone unit, an evaporite unit and uplifted Pleistocene reefs (Bonatti et al., 1981; Bosworth et al., 1996). However, the northward continuation of the ZFZ remains controversial. Recently, Augustin et al. (2021) proposed an NNE–SSW trend based on strong negative VGG data, which terminated the ZFZ near the southern tip of the AWCP (Figure 1a).

Based on GPS data, the current extension rates of the Red Sea are at  $17 \pm 1 \text{ mm yr}^{-1}$  and  $7 \pm 1 \text{ mm yr}^{-1}$  for the southern and northern parts, respectively (ArRajehi et al., 2010). In the southern Red Sea, seafloor spreading has started 5 Ma ago, resulting in the development of a continuous axial valley, as evidenced by ocean floor basalt samples and linear magmatic anomalies (Bonatti, 1985; Cochran, 1983; Röser, 1975). In contrast, in the central and NRS, oceanic volcanics have only been proven to occur in partially connected basins (Bonatti, 1985; Cochran, 2005; Ligi et al., 2012). In the NRS, these so-called deeps are more widely spaced than in the central part. The deeps have been suggested to indicate discrete axial spreading centers embedded in thinned continental crust (e.g., Cochran, 1983, 2005; Saada et al., 2021).

According to the stratigraphic table published by Hughes and Johnson (2005) for the northeastern Red Sea, the sequences imaged in our seismic data comprise the acoustic basement of the reflection seismic system consisting of the massive halite of the Mansiyah Formation and magmatic rocks of unassignable age (Table 1a). Older syn-rift deposits, such as the Maqna Group or the underlying Burqan Formation, cannot be detected because the acoustic signal is hampered by the salt and magmatic rocks. In addition to halite, the Middle Mansiyah Formation contains layers of gypsum and anhydrite. On top of the Mansiyah Formation follows the late Middle to Upper Miocene Ghawwas Formation, which comprises a thick sequence ( $>1,200 \text{ m}$ ) of interbedded fine-to coarse-grained siliciclastics and thin beds of anhydrite, also known as layered evaporites. The youngest stratigraphic unit on top is the Lower Pliocene to recent Lisan Formation. This consists of calcareous open marine clastic sediments and thick reefal limestone successions fringing the basin margins. Its thickness is difficult to determine; drill wells show values ranging from 448 to 1,372 m (Hughes & Johnson, 2005). A major unconformity, the S-reflector, separates the Lisan Formation from the underlying Ghawwas Formation (e.g., Ehrhardt & Hübscher, 2015; Izzeldin, 1987; Mitchell et al., 2010; Ross & Schlee, 1973).

## 1.2. Study Area

The study area stretches from the margins of the AWCP that are dominated by carbonate deposits to the abyssal depths of the Mabahiss Deep that reach 2200 mwd. Also, it covers the delta deposits of the large drainage basin of the Wadi Al-Ham that enters the Red Sea just north of the AWCP. The M193 cruise explored the waters to the West of the AWCP.

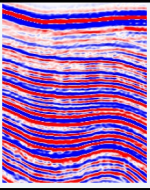
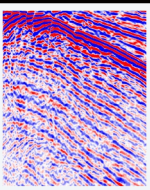
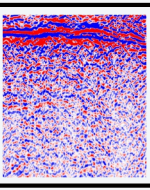
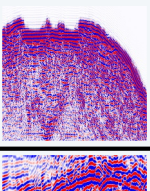
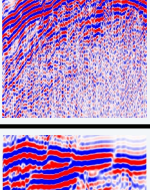
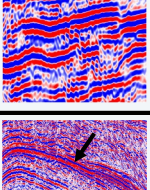
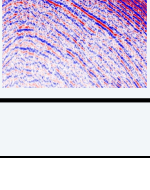
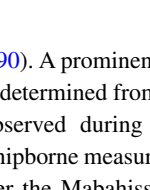
The AWCP is a Pliocene to present carbonate buildup, established on top of the post-rift strata (Figure 1b). It is one of the largest land-attached carbonate platforms at the Saudi-Arabian margin and almost completely rimmed by a coral reef belt (Petrovic et al., 2022; Rowlands et al., 2012). Such carbonate platforms are known to have been established on subsurface rift structures such as landward tilted half grabens onshore and nearshore northern Saudi Arabia that are overlain by a thick succession of syn- and post-rift strata (Baby et al., 2024; Polis et al., 2005; Rowan, 2014).

A major onshore tectonic structure, the Neoproterozoic Najd Fault System, can be traced toward the present shoreline in the NRS (Figure 1a). It is a NW–SE-striking sub-parallel wrench fault system, which crosses the Arabian shield and extends into northeast Nubia. It was formed in the course of shield amalgamation in the Proterozoic (Al-Husseini, 2000; Hamimi & Fowler, 2021; Kozdroj et al., 2012). A branch of it, the Ajjaj Shear Zone, is located in our study area north of the AWCP (Figure 2). It was indicated by sinistral shear along a ca. 160 km long fault zone (Hamimi & Fowler, 2021). North of the AWCP it bends from NW–SE to W–E direction. Mitchell et al. (2025) suggested based on geophysical data that the Ajjaj Shear Zone may extent into the NRS.

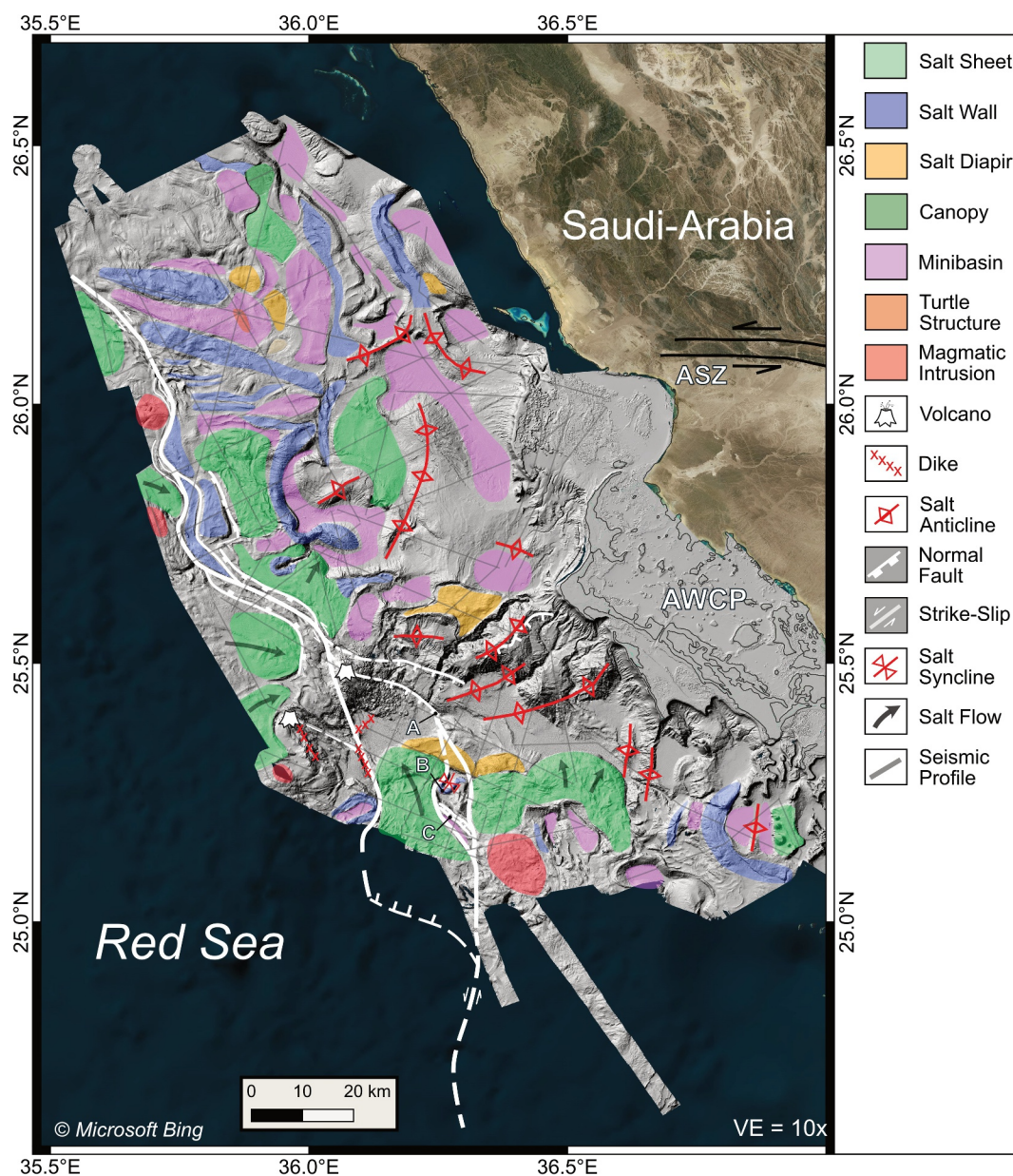
The Mabahiss Deep (Figure 1b) represents a major structural feature in the study area, a rhombic-shaped basin that has been interpreted to represent an isolated oceanic rift with associated submarine volcanism (Guenoc



**Table 1**  
*Seismic Stratigraphy and Seismic Facies*

| a           |                                       |                    | b                                                                                   |                                                                                                                                   | Seismic interpretation                                 |
|-------------|---------------------------------------|--------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| Series      | Seismic units and sequence boundaries |                    | Seismic facies                                                                      |                                                                                                                                   |                                                        |
| Pleistocene | Lisan Group                           |                    |    | parallel continuous reflections of high- to medium-amplitude                                                                      | hemipelagic sediments of the Lisan Group               |
|             |                                       |                    |    | parallel continuous reflections of medium- to low-amplitude                                                                       | layered evaporites and shales of the Ghawwas Formation |
| Miocene     | Late                                  | S-reflector        |    | high-amplitude reflections<br>Internal: acoustically turbid to transparent, in places reflections of variable amplitude           | massive halite of the Mansiyah Formation               |
|             |                                       |                    |   | rough surface reflections of high-amplitude. Internal: acoustically turbid, in places strong reflections                          | submarine volcano                                      |
|             | Middle                                | Ghawwas Formation  |  | rough surface reflections of high-amplitude. Internal: acoustically turbid, in places subparallel reflections of medium-amplitude | magmatic intrusion                                     |
|             |                                       |                    |  | subparallel continuous reflections of high-amplitude                                                                              | lava flows or sills                                    |
|             | Early                                 | Mansiyah Formation |  | parallel continuous single or double reflector of high- to medium-amplitude                                                       | S-reflector                                            |
|             |                                       |                    |  | parallel continuous single or double reflector of high- to medium-amplitude                                                       | S-reflector                                            |

et al., 1988, 1990). A prominent submarine volcano, the Mabahiss Mons at its northern rim exhibits MORB basalt characteristics determined from surface samples (van der Zwan et al., 2015). Pillow lavas covering the volcano's flank were observed during an M193 ROV dive, documenting the volcano's recent activity (Lüdmann et al., 2023). Shipborne measurements by Pautot et al. (1986) showed linear magnetic anomalies oriented roughly NW to SE over the Mabahiss Deep. Guennoc et al. (1990) attributed these anomalies to ultra-slow seafloor spreading (ca. 0.5 cm/year).



**Figure 2.** Mapped faults, magmatic and salt-related structures. All displayed salt-related structures are covered by suprasalt strata. Basemap: shaded relief with 10 times vertical exaggeration. AWCP, Al Wajh Carbonate Platform; ASZ, Ajjaj Shear Zone.

## 2. Methods and Data

### 2.1. MCS Data

The reflection seismic survey was conducted using a 144-channel digital streamer system from Hydrosience Technologies Inc., featuring an active length of 600 m and hydrophone group intervals of 4.167 m. Data were digitized at a sampling interval of 1 ms, with a record length of 4 s. The streamer depth was maintained at 3–5 m below the sea surface using four navigational control units (“birds”). Navigation was provided by the shipboard Seapath GPS. Seismic energy was generated by a two-airgun cluster towed at a water depth of 2.5 m, 35 m astern of the vessel. The array comprised a standard GI gun (total volume of 105 in<sup>3</sup>) and a mini-GI gun (total volume of 45 in<sup>3</sup>), both manufactured by Sercel. The guns were fired in GI-mode every 25.0 m at a pressure of 160 bar.

Data processing was performed using Halliburton-Landmark ProMAX 2D software, including band-pass filtering (20–200 Hz), spherical spreading correction, 2D surface-related multiple estimation and subtraction to suppress multiples. To correct for reflection-point smear caused by dipping reflectors in stacked data, pre-stack normal dip moveout correction was applied. The data were subsequently stacked with a bin size of 12.5 m. A post-stack time migration was conducted to accurately position dipping reflections and to collapse diffraction events. For interpretation, the seismic data were integrated with multibeam bathymetric data within the Petrel software suite (Schlumberger). A mis-tie analysis was performed utilizing the multibeam bathymetry as the reference surface. For the example profiles presented here, we applied a final bandpass frequency filter (20–60 Hz) to enhance imaging of seismic reflections beneath the salt layer.

A sequence-stratigraphic approach was used to interpret the seismic data in order to identify depositional units bounded by unconformities or their correlative conformities and to establish their relative chronological order. This approach is based on mapping reflection terminations (toplap and baselap) and seismic facies, including internal reflection patterns (e.g., parallel, dipping, or chaotic) as well as reflection amplitude and continuity (Mitchum et al., 1977; Wilgus et al., 1988). To tie the mapped seismic units to stratigraphic and lithological units, we integrated multiple sources, including the lithostratigraphy of the Red Sea region reported by Hughes and Johnson (2005), results from DSDP Leg 23B (Whitmarsh et al., 1974), and published multichannel seismic surveys (e.g., Ali, Decarlis, et al., 2023; Ali, Koyi, et al., 2023; Baby et al., 2024; Ehrhardt & Hübscher, 2015; Mitchell et al., 2021).

## 2.2. Multibeam Data

Multibeam data comprising the shown topographic surface were collected during two research cruises in 2019 with the King Abdullah University of Science and Technology (KAUST) vessel R/V THUWAL (Petrovic, Lüdmann, et al., 2023; Petrovic, Panara, & Vahrenkamp, 2023; Petrovic, Reijmer, et al., 2023) and during the M193 research cruise in 2023 with the R/V Meteor. Both data sets were acquired using a hull-mounted Kongsberg EM710 system, and in the case of the M193 cruise, additionally with an EM122 system. The multibeam echosounder data sets were initially processed onboard using QPS Qimera software for cleaning the bathymetric data. Final processing in the lab included artifact removal using the swath editor, slice editor, and 3D editor.

For the M193 data, tide correction was performed using a station in Al Wajh (26.250°N, 36.433°E) from the GEOSA (Saudi General Authority for Survey and Geospatial Information) online database. Sound velocity profiles (SVPs) were obtained through 12 CTD casts and one eXpendable Sound Velocity (XVS) probe, and loaded into the Kongsberg Seafloor Information System (SIS) software to correct ray tracing during the survey. Due to the extreme physical and chemical characteristics of the water column in the Red Sea, the SIS algorithm for SVP interpolation sometimes produced artifacts along the water column in the SVPs. To improve the interpolation of sound speed at the maximum depths in the study area, SVPs were processed using the Sound Speed Manager (Masetti et al., 2020), which incorporates a larger database of SVPs already collected in the Red Sea by KAUST. The calculated resolution of the bathymetric grid is 30 m. All presented maps are projected in WGS84.

## 2.3. Gravity Data

For correlating the mapped tectonic structures, we used ocean surface curvature or vertical gravity gradient (VGG) data derived from the global marine gravity field model SIO V32.1 provided by the Scripps Institution of Oceanography. This model offers a high spatial resolution of approximately 1–2 km and incorporates updated satellite altimetry together with shipborne gravity measurements (Sandwell et al., 2014). Bouguer anomaly data are not publicly available in the NRS, and their use would additionally require reliable assumptions about terrain density, which is difficult to obtain due to the massive salt layers. Another reason for selecting VGG data is their sensitivity to shallow, high-frequency geological structures, such as faults, magmatic intrusions, sedimentary basins, and salt-related contacts. Therefore, VGG data represent the most suitable option for correlation with our medium-penetration MCS data.



### 3. Results

#### 3.1. Seafloor Topography

The study area reveals a highly structured relief, consisting of ridges, basins and hills. The main topographic feature is the Mabahiss Deep to the southwest of the AWCP (Figure 1b). It is rhombic in shape and bordered by steep slopes. The basin floor is located at a water depth of 2,200 m. At its northwestern rim, two volcanoes are situated: Mabahiss Mons, which exhibits a pit crater, and an unnamed cone-shaped volcano without a central crater, located 14 km southwestward. The northern rim of the basin is marked by a prominent canyon striking north-south that has incised deeply (>500 m) into the surrounding strata of the slope (Petrovic, Panara, & Vahrenkamp, 2023). It starts in a subbasin north of the AWCP and terminates in the Mabahiss Deep, where it transitions into a submarine fan (Figure 1b, A).

A second prominent feature is a meandering graben system with intra-graben highs that begins at the northwestern corner of the Mabahiss Deep and continues in a north-northwesterly direction (Figure 1b, B). In places, the difference in relief between the central graben and its shoulders exceeds 550 m, and the width of the system varies between 2 and >10 km. It narrows in the north-northwest, where it runs more or less straight.

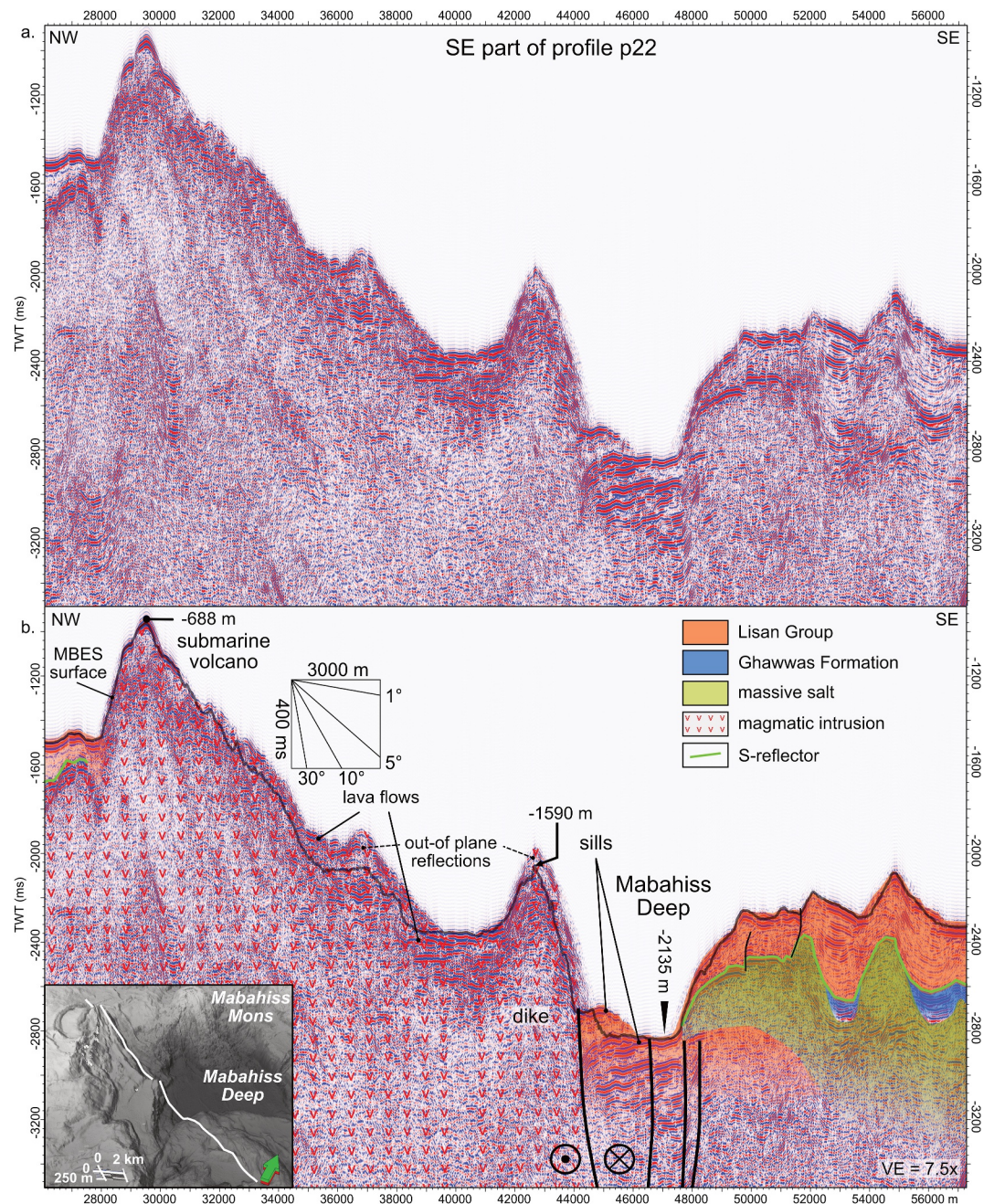
#### 3.2. Seismic Stratigraphy

From the MCS data, the main structures were interpreted, such as subsalt and suprasalt faults, seismic units and salt structures. Based on the prominent S-reflector, we encompassed the post-salt strata of the Lisan Group, the layered evaporites of the Ghawwas Formation and the massive halite of the Mansiyah Formation (Table 1a). In addition to sedimentary rocks, magmatic rocks were identified in the seismic data.

In particular, in the minibasins, the Lisan Group (Table 1b) is characterized by parallel and continuous reflections of high-to medium-amplitude. Similarly, the Ghawwas Formation exhibits parallel and continuous reflections, albeit of medium-to low amplitude. The Lisan Group covers the entire study area except for some magmatic edifices such as the Mabahiss Mons. Massive halite is delineated internally by a turbid seismic facies with low-amplitude reflections or even reflection-free parts. Locally, internal parts may exhibit subparallel reflections. Magmatic rocks are generally indicated acoustically by high-amplitude reflections. Magmatic bodies exhibit these reflections on their tops, which are characterized by a rough relief. These bodies are acoustically transparent internally, with strong amplitudes in places. Lava flows and sills are depicted by subparallel, high-amplitude reflections. The S-reflector is a continuous, single, or double reflector, with high-to medium-amplitude. Often pronounced as an angular unconformity on top of the halite and layered evaporites, it can be traced throughout the study area except at Mabahiss Deep, where magmatic rocks outcrop.

#### 3.3. Tectonic Structures

Deep-seated faults, discernible through the thick salt layer, are primarily confined to the Mabahiss Deep and a narrow, meandering graben zone with intra-graben highs, extending from the Mabahiss Mons in a north-northwest (NNW) direction (Figure 2). Seismic profiles crossing the Mabahiss Deep reveal steep boundary faults delineating the basin flanks. For example, line p22 at the southern extremity of the deep (Figure 3) displays steep basin faults that converge at depth. Here, the basin fill, composed of hemipelagic sediments interbedded with sills, is offset by one of these faults. Southward of this location, the faults continue along a graben roughly 700 m wide, as evidenced by the bathymetric data (Figures 1b and 2). In the northward direction, these faults converge and extend along the western margin of the Mabahiss Deep as a single fault. This fault is suggested to continue below the Mabahiss Mons and proceeds within a subsequent graben-like feature to the NNW of the volcano (Figure 1b, B). The volcano also marks the origin of two major normal faults striking WNW–ESE, which delineate the northern flank of the Mabahiss Deep. At their eastern end (Figure 2, A), the lower normal fault is joined by a deep-seated fault bordering the basin's eastern side, which extends in an SSE direction and runs parallel to the basin's western boundary fault (Figure 2). Along its trajectory, this fault bifurcates and one of the branches bends in the SW–NE direction, forming a compression zone approximately 7.5 km wide between the two master faults (Figure 2, B). South of the bend, both fault branches rejoin and extend south-southeastward. Seismic line p22 intersects this bending zone, revealing faulted and folded suprasalt strata associated with the boundary faults (Figure 4). Within this zone, folded strata form ridges and small basins, aligned parallel to the bend, trending SW. These ridges underlie zones of rising salt, which result in the development of a small salt



**Figure 3.** Part of MCS profile p22. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section from southeast to northwest traverses the flank of a submarine volcano, an exposed dike, the southern tip of the Mabahiss Deep and a giant salt sheet overlain by younger sediments which advances over the basin floor (Figure 2). Insert map locates profile on oblique of seabed topography (white line). Indicated are deep-seated faults bounding the basin and offsetting the sills. It is striking that the faults converge downwards. MBES = multibeam echo sounder.

syncline (Figure 2, B). This syncline, tilted and plunging NE, was formed by salt ascending along the slip surfaces of the deep-seated faults, creating a salt horn (Figure 4). In contrast to a fallen diapir formed in an extensional regime, the salt horn observed here formed on the hanging wall of the fault, migrating upward along the slip face. Further from the bending zone, where the master faults realign SSE, ridges and small basins trend NW–SE, exhibiting a slight obliquity relative to the faults (Figure 2, C). The structures terminate where the master faults rejoin.



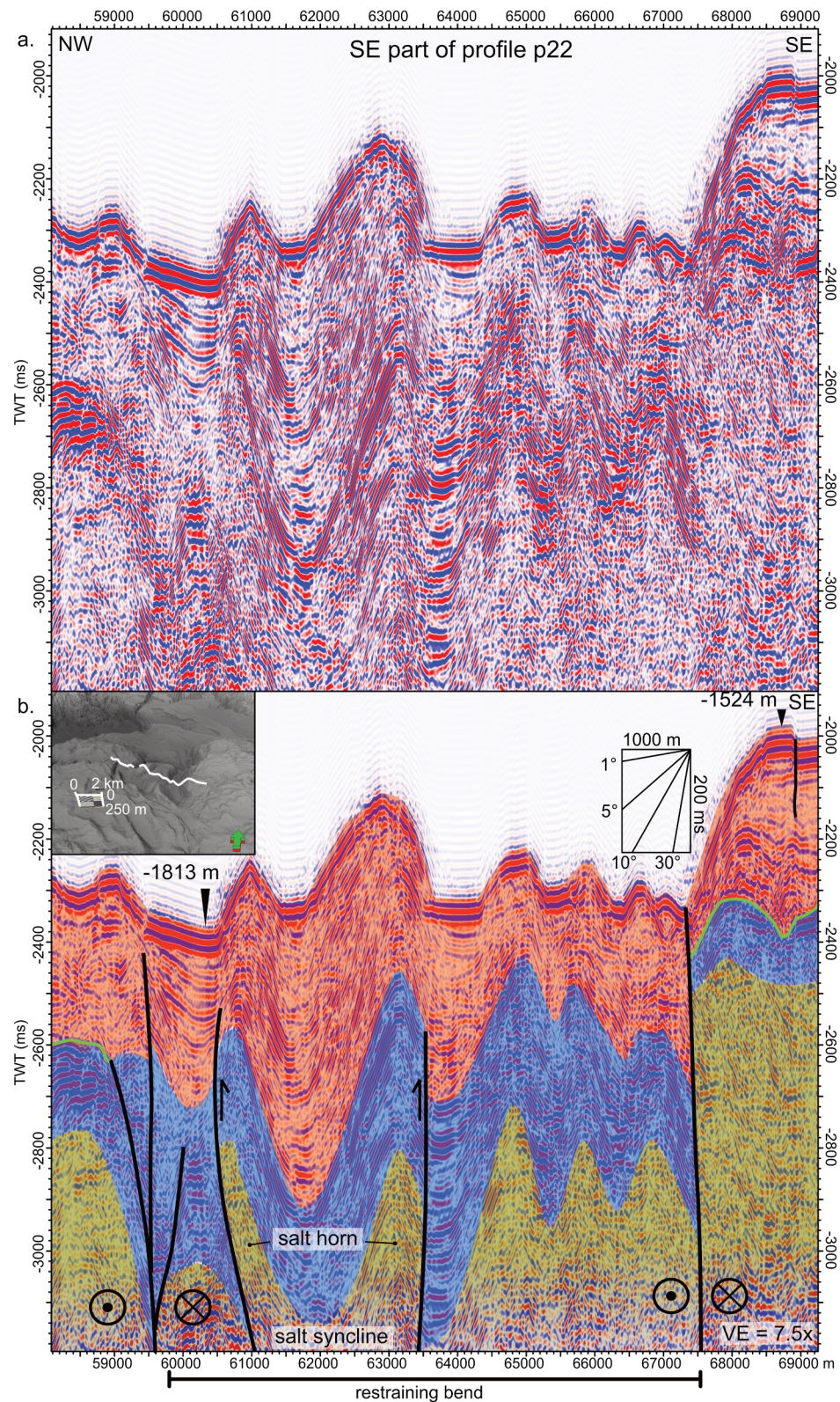


Figure 4.



Concerning canyon A of Figure 1b, profile p19 crosses its upper portion, revealing its floor reaching approximately 300 m below its shoulders (Figure 5). Both flanks of the canyon are characterized by salt anticlines that fold and fault the overlying strata. A detachment runs layer-parallel between the stratal packages A and B and outcrops at the canyon floor. The strata (B) on the eastern flank terminate with an onlap against this detachment (yellow arrows in Figure 5).

The main basin fault on the western side of the Mabahiss Deep extends in a north-northwesterly direction along a meandering path. Seismic profile p02, which intersects this fault near Mabahiss Mons, shows a narrow central graben approximately 200 m wide and 450 m deep, bounded by steep basement faults (Figure 6). Three additional deep-seated faults, parallel to these, converge in the down-dip direction. This fault system constitutes a large graben, roughly 5.5 km in width, featuring an uplifted block at its center. Profile p13 further north, crossing the same fault system at the bend, presents a similar structure but with a broader fault zone exceeding 10.5 km in width (Figure 7, 2500–13500 m). The boundary faults are deep-seated normal faults that converge downward, with the blocks in between being underlain by salt walls. Multiple processes—including salt flow, faulting, and subaerial erosion—have contributed to the current morphology (Figure 7). Faulting in this region was likely initiated after the formation of the S-reflector around 5 million years ago. Presently, a thin sediment cover overlays the area. In the northwestern part of the study area, the fault system continues in a north-northwest direction, narrowing to around 3 km in width (Figure 8).

### 3.4. Salt Structures

The majority of the study area is underlain by the mobile, massive halite of the Mansiyah Fm., which is manifested in various salt structures (e.g., diapirs, salt walls, salt sheets, etc., Figure 2). Seismic data do not reveal any halite outcropping at the seafloor; even near-surface salt is consistently covered by a veneer of younger sediments. Numerous minibasins with thick sedimentary infills are situated between these salt structures. Their orientation exhibits greater complexity than the salt structures described by Ali, Koyi, et al. (2023) from offshore Egypt, which predominantly align with the Red Sea rift axis along the NW-SE to NNW-SSE direction (approximately N150°E, Cochran, 2005).

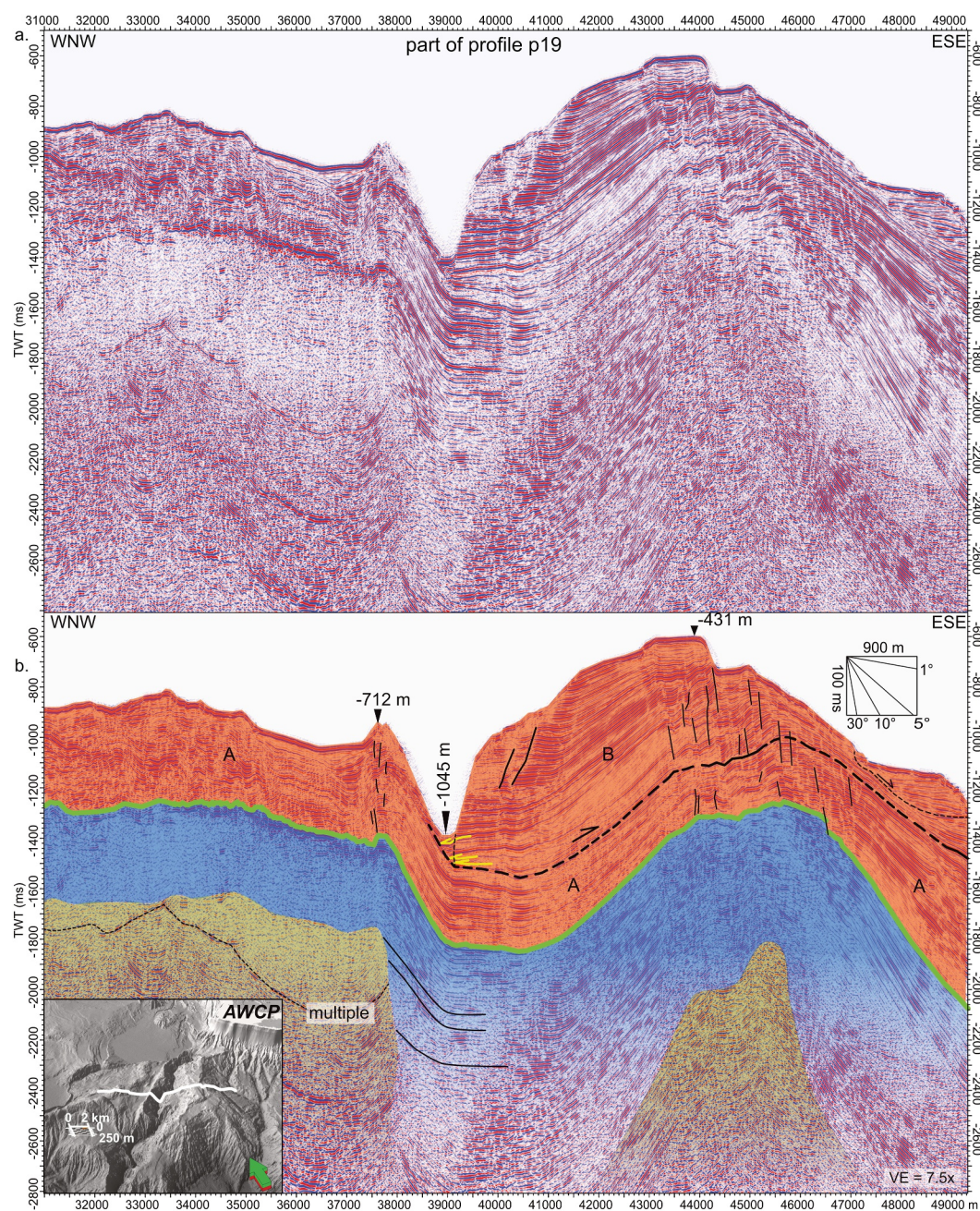
Offshore the AWCP, salt anticlines trend perpendicular to the platform rim, in a WSW-ENE to SSW-NNE orientation (Figure 2). Near the shoreline northwest of the AWCP, salt walls and minibasins are nearly aligned NNW-SSE. Notably, an area to the east of the curved fault system displays salt structures, oriented W-E to WNW-ESE. Seismic profile p14 crossing these structures reveals that several trapezoid-shaped salt walls have uplifted the overburden documented by the growth strata below the S-reflector (Figure 9). The salt walls display two distinct generations of flaps separated by an angular unconformity, probably indicating a break in the salt wall rise. The overlying strata exhibit faulting and erosion at their upper contact. Salt flow initiation predates approximately 5 Ma, as evidenced by the erosion of the salt wall crests marked by the S-reflector, observed in profiles p13 and p14 (Figures 7 and 9).

Large salt sheets are mapped in several locations, predominantly near the identified fault systems and magmatic intrusions (Figure 2). Many of these sheets demonstrate landward flow directions, traceable through the overburden to the seabed. This flow induces transverse folding of the overlying strata. An illustrative example is a salt sheet at the southern margin of the Mabahiss Deep, advancing downslope and northwestward over basin sediments (Figure 3). Its roof is overlain by a thick sediment layer, and the overburden is disrupted by small ascending salt walls as well as normal faults running parallel to the front of the salt sheet.

### 3.5. Magmatic Structures

In the vicinity of the unnamed volcano south of Mabahiss Mons, magmatic dikes are exposed at the seafloor, trending in the NNW direction (Figures 2 and 3). Furthermore, seismic facies interpretation reveals additional

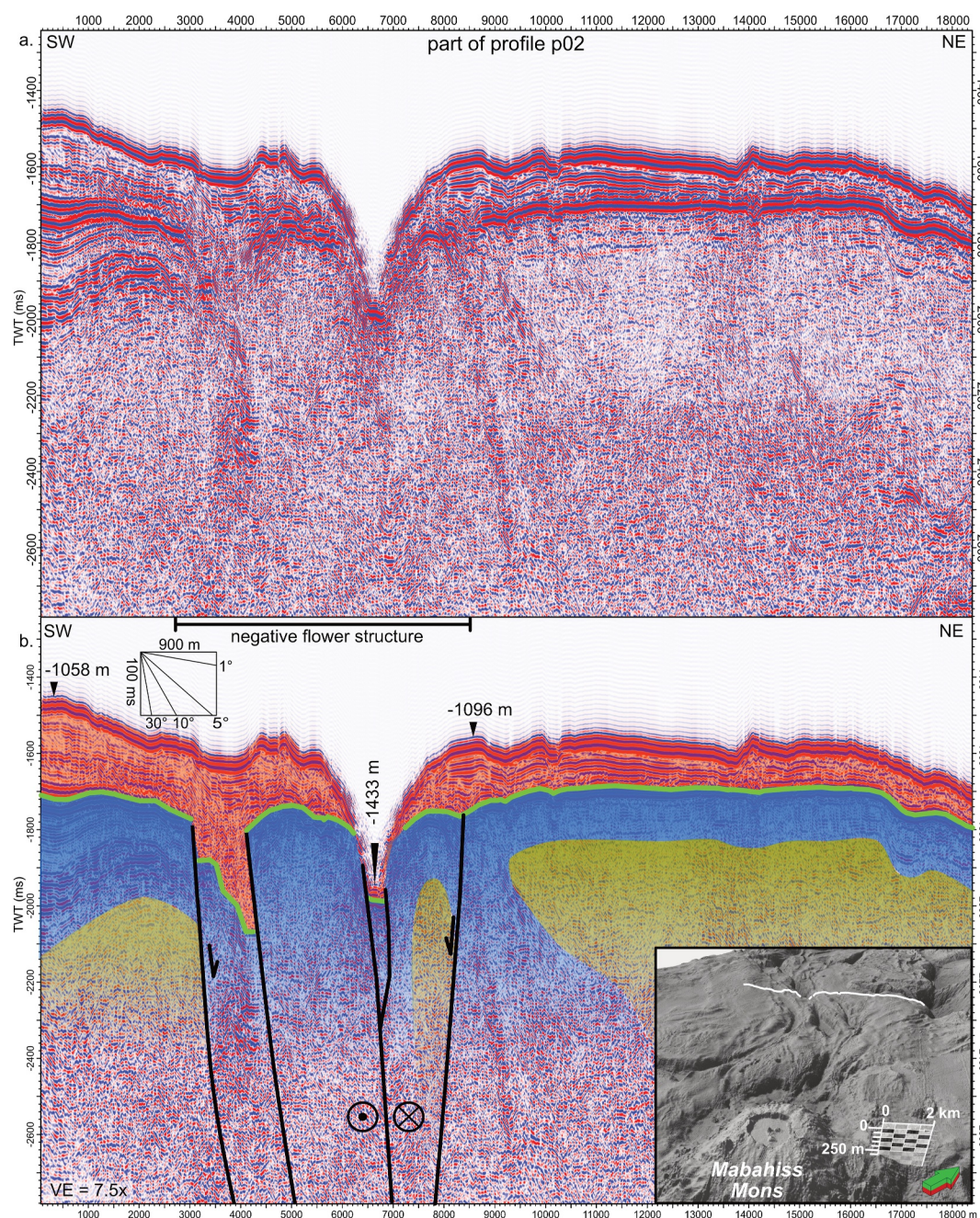
**Figure 4.** Part of MCS profile p22. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section from southeast to northwest traverses several ridges and minibasins as part of a restraining fault bend (Figure 2, B). The deep-seated faults in the bending zone offset the seismic units vertically. The varying thickness of the units between the faults suggests a translation perpendicular to the section, which proves the strike-slip nature of the faults. Salt is mobilized along the faults forming a salt horn and is forced to move into the anticlines by differential loading. Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.



**Figure 5.** Part of MCS profile p19. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section which traverses the deep slope canyon that connects an upper slope minibasin with the Mabahi Deep (Figure 2). The development of the canyon is interpreted here as not related to steep basement faults but is instead the result of the extension of the subsurface strata between two salt anticlines. The eastern canyon side moved eastward along a layer-parallel detachment fault (black dashed line), thereby the hanging wall strata (B) slightly rotated and tilted west-northwestward, onlapping the detachment (yellow arrows). West of the Canyon, the strata above the fault (B) were most likely removed during the anticline uplift. Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.

magmatic features, such as lava flows or sills intercalated within sedimentary sequences in the Mabahi Deep, along the flanks of the volcanoes, and beneath a sedimentary cover adjacent to the mapped fault system (Figure 2). Seismic line p13 intersects the edge of such a magmatic intrusion overlain by a substantial sedimentary sequence (Figures 7, 0–3,000 m and Table 1b).





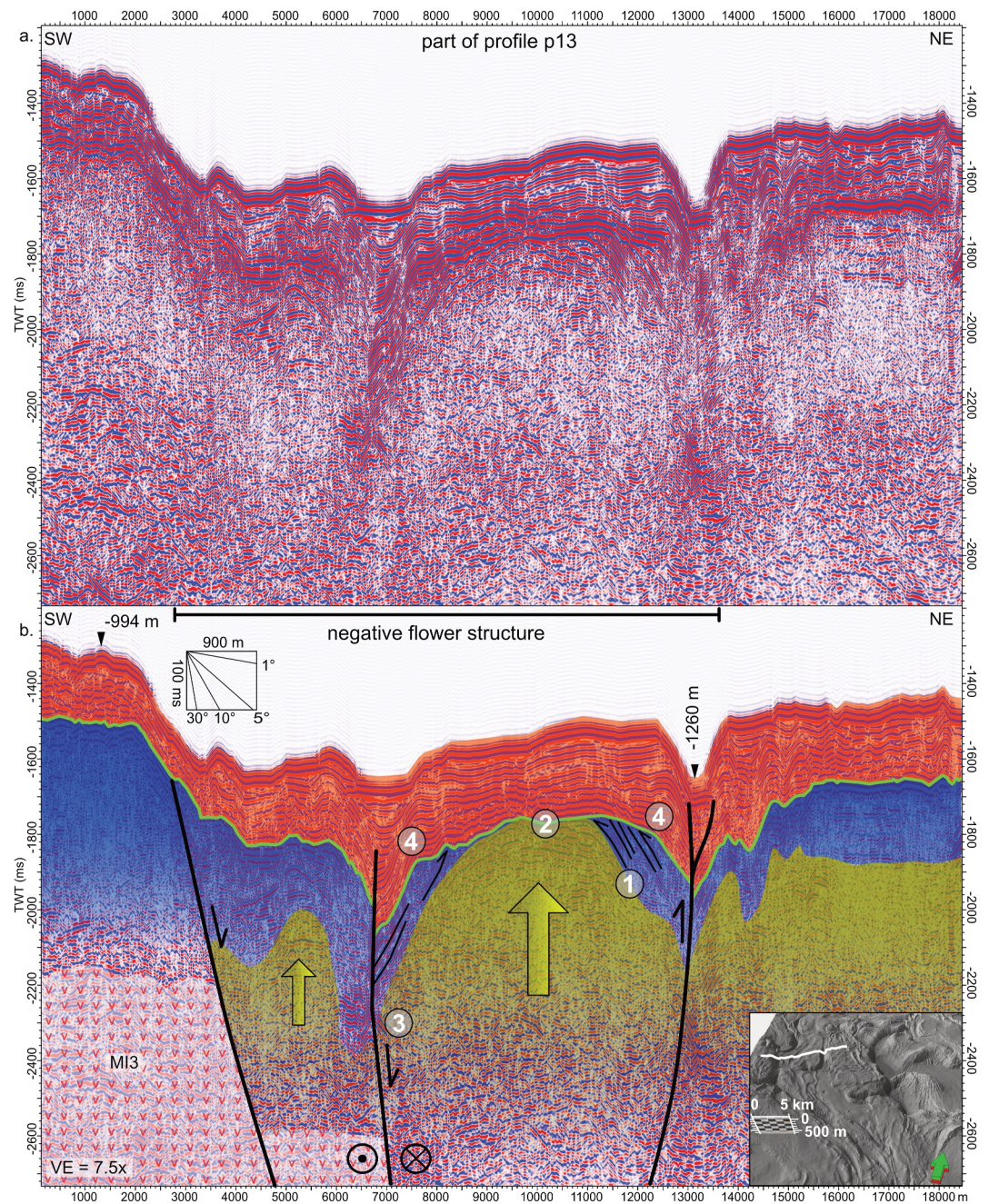
**Figure 6.** Part of the MCS profile p02. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section which traverses the bending north-northwestward trending graben system (Figure 2). The graben is defined by deep-seated faults that converge downward. The offset of the S-reflector indicates that fault movement initiated at least after 5 million years ago and appears to still be active, as evidenced by the small depression above the downthrown block in the SW. Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.

## 4. Discussion

### 4.1. Tectonic Regime and Implications on Red Sea Opening

There are two principal systems of faults in the study area. The first is a sinuous fault system striking NNW–SSE, along the presumed trend of the Red Sea rift axis (Figure 1b, B). It forms a fault-bounded graben system with intra-graben highs and is directly connected to the fault-bounded Mabahiss Deep, which defines the second major

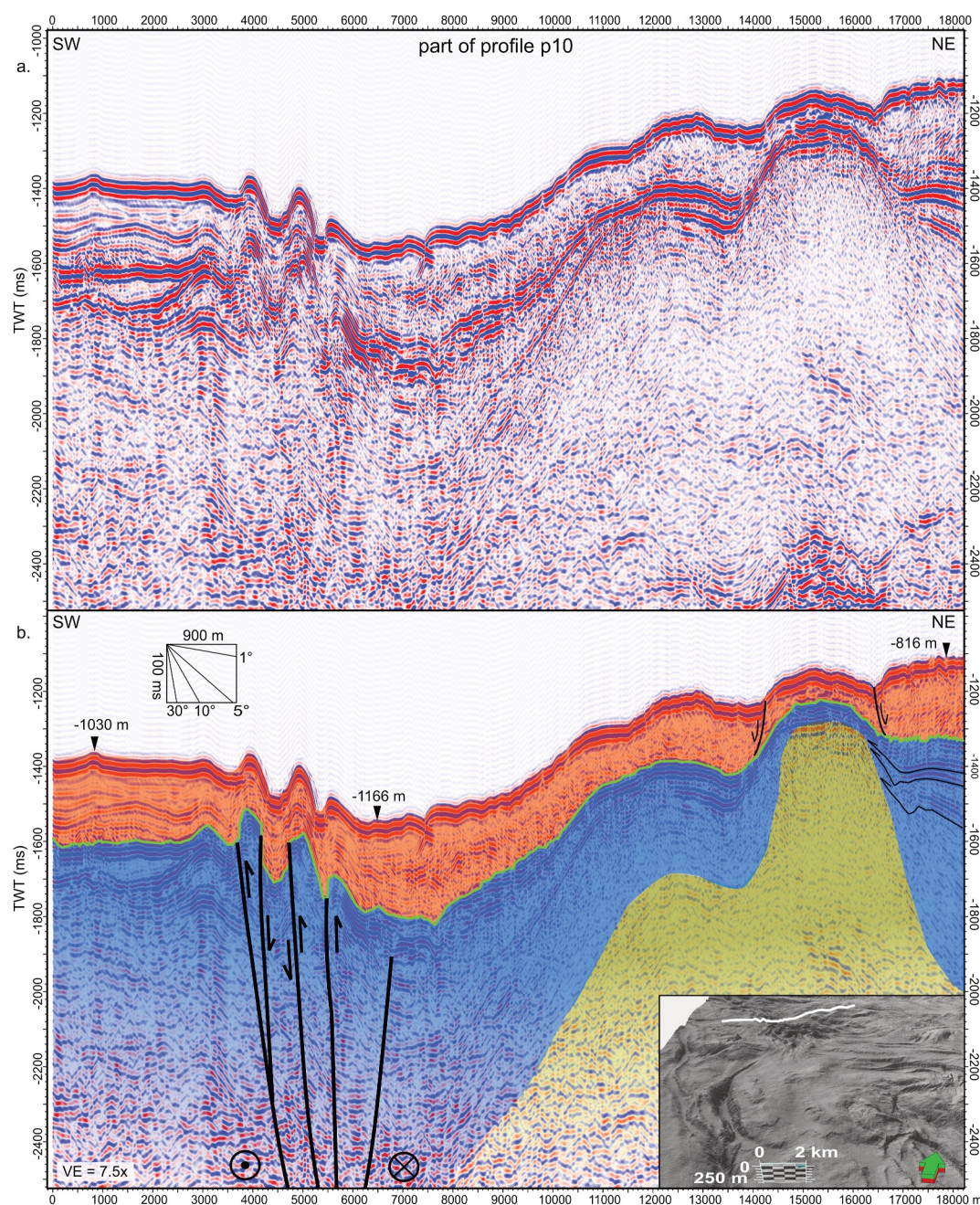




**Figure 7.** Part of MCS profile p13. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section which traverses the bending north-northwestward trending graben system further to the NNW (Figure 2). Here, the graben is broader and, as shown on profile p02 (Figure 6), is defined by deep-seated faults that converge downward. The central block records the timing of various events. Before the subaerial erosion (S-reflector) about 5 Ma ago, salt was mobilized, actively rising, and forming a salt wall, which tilted its overburden strata (1). Afterward, the salt wall crest and flaps were truncated by erosion (2). Subsequently, faulting occurred, offsetting the S-reflector (3), as also seen in profile p02 (Figure 6). Finally, salt continued to rise, uplifting and tilting the strata above the S-reflector (4). Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.

fault system (Figure 10). The rift axis is offset either side of the ZFZ (Figure 1a), so that it lies closer to the coastline on its northern side. There, the axis lies approximately 115 km from the western NRS coastline and 80 km from the eastern NRS coastline. However, the distance of the axis to the rift shoulders on the conjugate margins remains nearly identical (Figure 1a). Several historical earthquakes with magnitudes >4 and focal depths

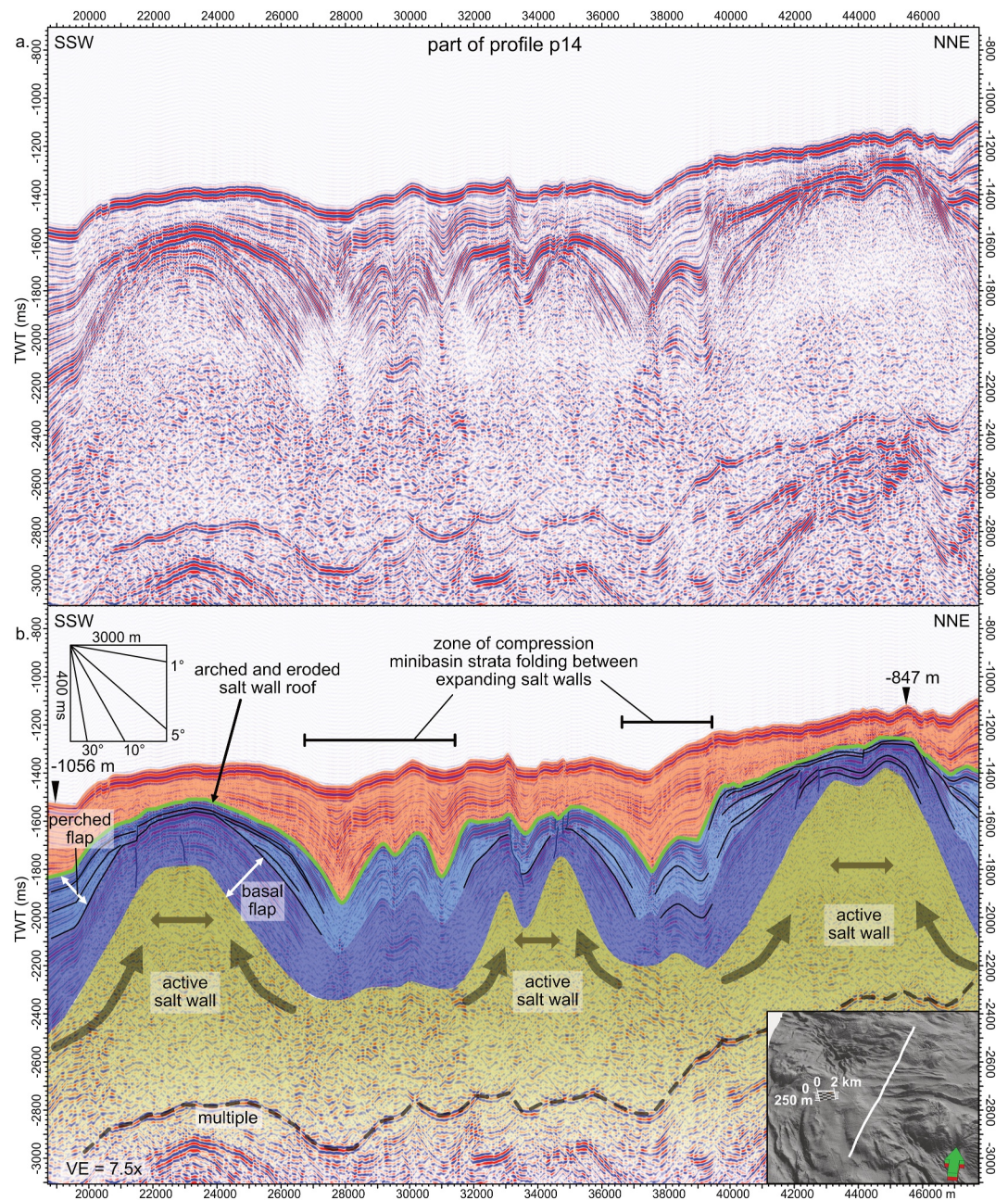




**Figure 8.** Part of MCS profile p10. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section which traverses the bending north-northwestward trending graben system in the north-northwesternmost part of the study area (Figure 2). In this section, the fault zone is narrower, but it similarly consists of deep-seated faults that converge downward, as shown for the other parts of the bending graben system. Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.

of around 10 km have been recorded along the mapped faults (Figure 10), confirming both the deep-seated roots of these structures and their ongoing tectonic activity. Notably, these focal depths are consistent with the modeled thickness of hyperextended continental crust ( $<10$  km) at the northern Red Sea rift axis, as reported by Gaulier, Le Pichon, et al. (1988), Gaulier, Villemin, and Colletta (1988), Le Magoarou et al. (2021), and Ali, Decarlis, et al. (2023).

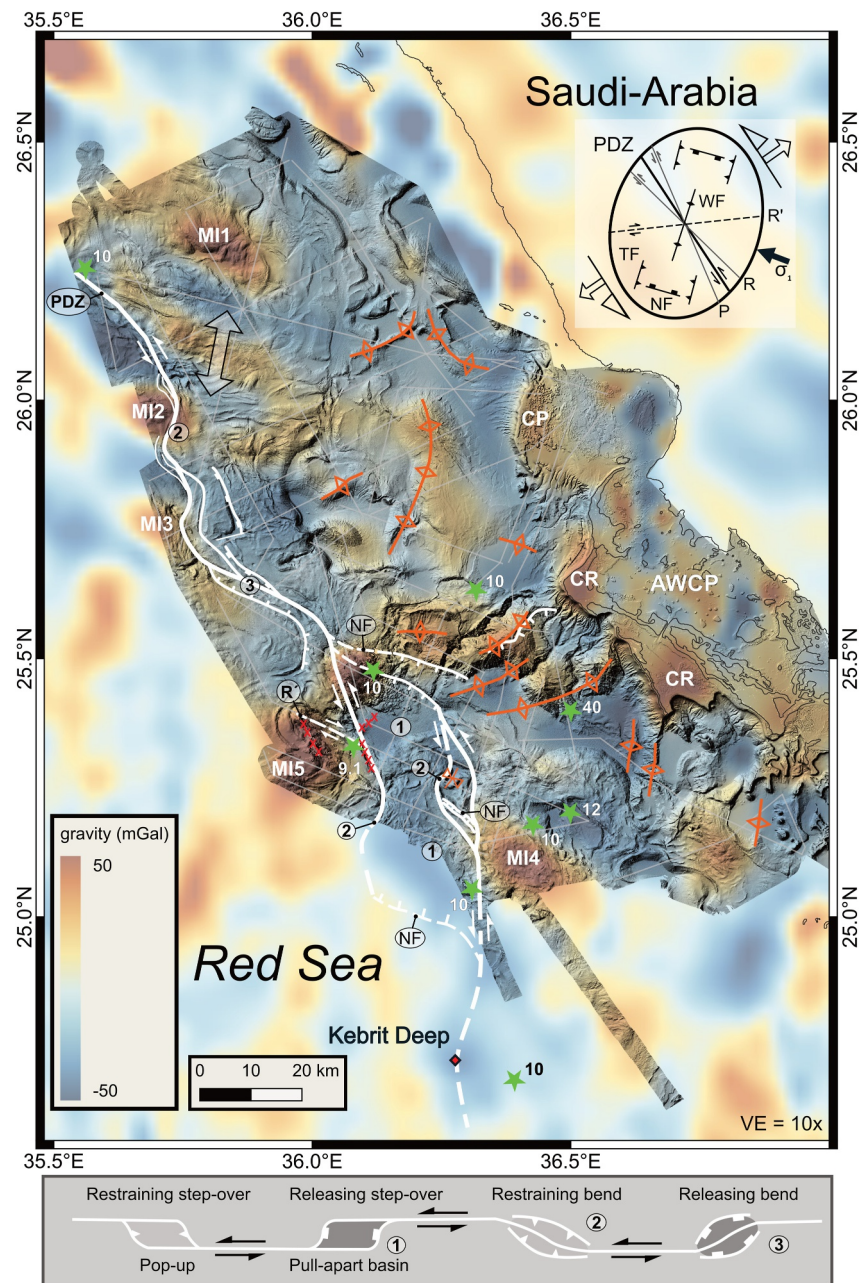




**Figure 9.** Part of the MCS profile p14. (a) Uninterpreted version (location see Figure 1b). (b) Interpreted cross-section which traverses a zone of elongated topographic features striking oblique to the bending graben system (Figure 2). The surface relief is controlled by several active salt walls that developed under an extensional regime. Areas between the expanding salt walls subsided due to salt withdrawal and were simultaneously subjected to lateral pressure, which led to folding of the subsurface strata. Insert shows seafloor topography and location of the example profile (white line). For legend, see Figure 3.

The morphology of the mapped sinuous fault system in some respects appears analogous to the East African Rift System (EARS), which comprises a series of overlapping and interacting half-grabens (Rosendahl, 1987). These half-grabens are typically manifested as curved, half-moon-shaped structures with alternating dips, resulting in a sinuous valley geometry. Applying the EARS analogue to our study area would suggest the presence of alternating listric faults dipping either WSW or ENE, perpendicular to the rift axis. Consequently, basement blocks would be expected to exhibit landward tilting along these listric faults. However, the analogy does not hold as seismic data from the study area do not reveal any major listric faults within the mapped fault system, as





**Figure 10.** Vertical gravity gradient and mapped tectonic structures. Vertical gravity gradient (Sandwell et al., 2014) draped over shaded relief with 10 times vertical exaggeration. AWCP, Al Wajh Carbonate Platform; CR, Carbonate reef; MI, magmatic intrusion. Schematic strain ellipse for extension normal to NNE-SSW strike-slip and associated secondary structures: NF, normal fault; PDZ, principal displacement zone; P, secondary synthetic shear; R, Riedel shear; R', conjugate Riedel shear; TF, thrust fault; WF, wrench fault;  $\sigma_1$ , max. principal stress less than  $45^\circ$  to master fault after Biddle and Christie-Blick (1985). Green stars = historical earthquake locations with  $M > 4$ . Numbers indicate focal depths in km (<https://www.usgs.gov/programs/earthquake-hazards>). For symbol legend, see Figure 2.

characteristic of conventional simple or pure shear rift models. Instead, the data show relatively steep faults that conjugate at depth—a fault pattern characteristic of flower structures, wherein faults splay upward from a common root zone or principal displacement zone (PDZ) (Cunningham & Mann, 2007; Tchalenko and Ambraseys, 1970).

Hence, we interpret the NNW–SSE-trending fault system as a strike-slip zone that accommodates both releasing and restraining bends (Figure 10). The principal sense of slip is sinistral, in agreement with the left-lateral motion observed along the northern Arabian plate boundary in the Gulf of Aqaba (ArRajehi et al., 2010; Hofstetter, 2003). In addition, an NNE-oriented extensional component (ArRajehi et al., 2010) results in a trans-tensional, oblique opening of the NRS rift. Seismic profiles p02, p13, and p22 reveal downthrown blocks bounded by upward-diverging faults, which are indicative of negative flower structures (Figures 6–8). A distinguishing feature of a strike-slip zone—unlike extensional graben systems dominated by synthetic normal or growth faults—is the simultaneous occurrence of both normal and reverse faults, in many cases converging (Mann, 2007). Notably, owing to the dominant extensional component along the fault system, positive flower structures at restraining bends have only been observed in a single location along the eastern boundary fault of the Mabahiss Deep (Figure 4; see later discussion). In some locations, depressions generated by these faults are subsequently modified by salt tectonics, as demonstrated by line p13, where initially downthrown blocks were later uplifted and tilted as a result of salt diapirism (Figure 7).

Additional evidence for transtensional strike-slip activity is provided by the zone of east–west-oriented salt structures adjacent to the northern segment of the proposed shear zone (Figures 9 and 10). In this region, halokinesis is triggered by extension oblique ( $<45^\circ$ ) to the shear zone, as illustrated by the strain ellipse in Figure 10. As a result, subsidiary structures such as salt walls and minibasins have formed (Figure 2). Initial extension and faulting of the suprasalt strata likely initiated reactive diapirism, which subsequently developed into active diapirism, as demonstrated in MCS line p14 (Figure 9). The strata between these salt walls are subject to subsidence and folding, related to salt withdrawal and lateral stress caused by salt wall extension, respectively. Extension within this zone is overcompensated by lateral salt wall expansion, which leads to folding of sediment infills in minibasins. This implies that the rate of salt wall inflation exceeds the rate of tectonic expansion associated with the strike-slip zone. In an overall compressional regime, salt walls would typically be constricted to form hourglass-shaped structures or penetrate their roof strata (Hudec & Jackson, 2007). The observation that the roof strata of these salt walls are truncated indicates that salt diapirism commenced prior to subaerial exposure at 5 Ma, analogous to the timing of salt rise in the PDZ (Figure 7). Currently, active salt flow is evidenced by seafloor topography, which mirrors the uplift of the salt wall roofs.

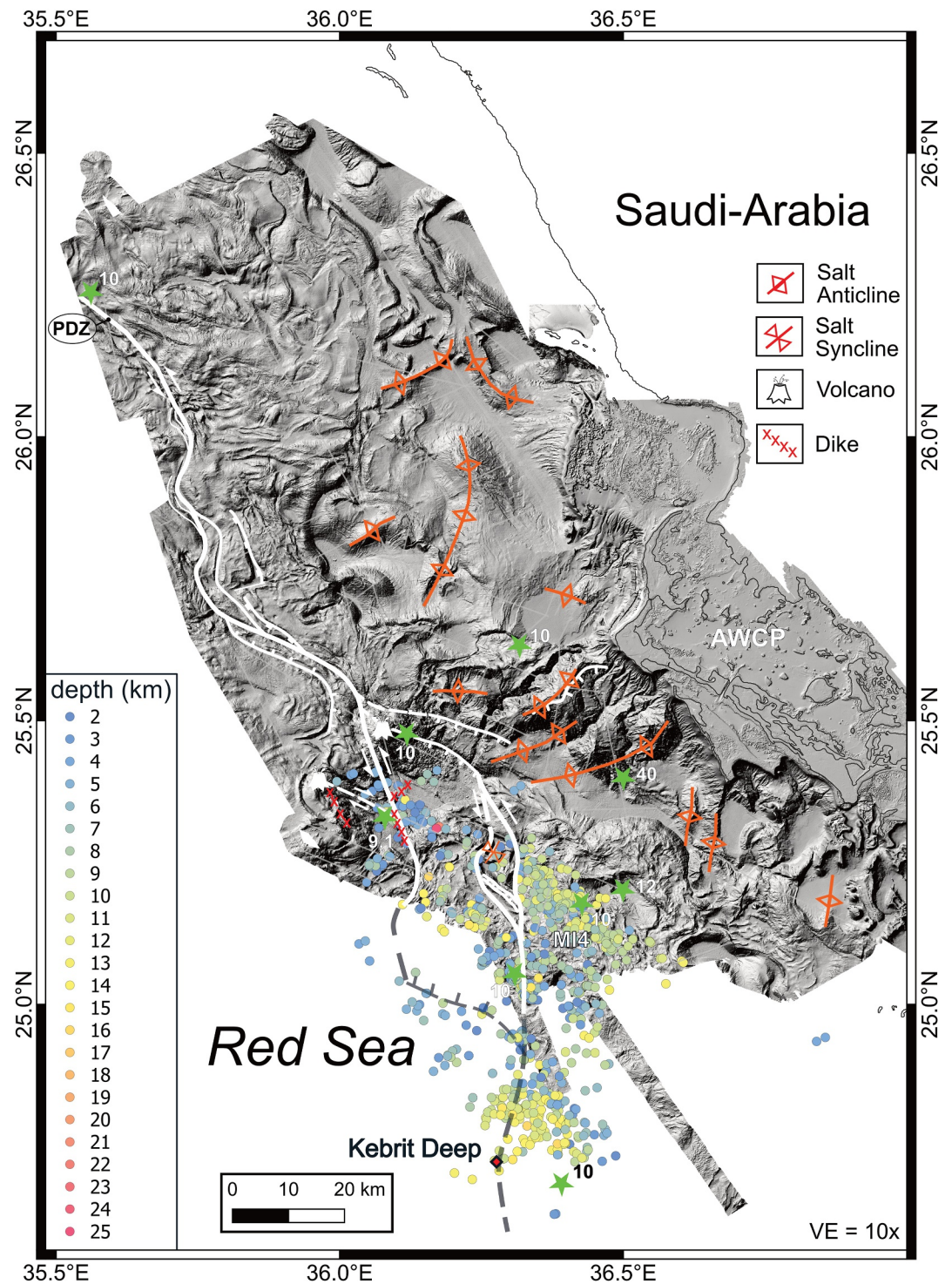
The second fault system that bounds the Mabahiss Deep is characterized as a large pull-apart basin. This basin is rhomboidal in shape and measures approximately 50 km in length and 16 km in width. Its sedimentary infill reaches  $>2$  km, indicated by a gravity low of about  $-40\text{E}$  (Figure 10). At its eastern and western margins, the basin is delineated by deep-seated, overstepping strike-slip faults, as well as oblique normal faults in both the northern and southern margins (Figures 2 and 10). These features are diagnostic of strike-slip fault oversteps (Aydin & Nur, 1982; Mann, 2007). The southern extent of the pull-apart basin is inferred from local gravity anomalies, which indicate an area of low gravity (Figure 10). Earthquakes located at its southern limit are a further indication of active movement (Figures 10 and 11). The eastern boundary fault displays a pronounced right bend, where the master fault splays and compression becomes significant (Figures 4 and 10). The location of NW–SE trending normal faults and the occurrence of a spreading axis segment proposed by Shiddiqi et al. (2025b) for the Mabahiss Deep are not observed in our data.

The second fault system is likely a part of the ZFZ, with the Mabahiss Deep pull-apart basin located at its northern terminus. The ZFZ displaces rift segments to the right; however, the shear across the fault is left-lateral, consistent with the kinematic principles documented for both transform and transfer faults (e.g., Wolfson-Schwehr & Boettcher, 2019).

## 4.2. Salt Structures Pattern

Mobilized salt is the primary factor shaping the distinctive hilly topography of the present-day seafloor in the study area (Figure 2). The spatial distribution and morphology of the various subsurface salt structures provide important insights into the prevailing tectonic regime. Although the arrangement of these salt structures is complex, three distinct domains are identified. The first domain encompasses the AWCP and its adjacent slopes. The AWCP developed atop Pliocene siliciclastic sediments, which are likely underlain by landward-dipping half-grabens and mobilized salt (Baby et al., 2024). Under the load exerted by overlying sediment and carbonate buildups, the underlying salt likely migrated basinward following the pressure gradient (Smith & Santamarina, 2022), accumulating along the slopes and forming large salt anticlines (Figure 2). Salt flow is also thought to





**Figure 11.** Present seismicity in the study area was reported by Shiddiqi et al. (2025a). Green stars = historical earthquake locations with  $M > 4$ . Numbers indicate focal depths in km (<https://www.usgs.gov/programs/earthquake-hazards>). AWCP, Al Wajh Carbonate Platform. MI, magmatic intrusion; NF, normal fault; PDZ, principal displacement zone.

have contributed to the destabilization of the southern platform margin, where platform parts fractured and subsequently rafted atop the mobile salt layer (Petrovic, Lüdmann, et al., 2023). The second domain is located offshore, north of the AWCP. In this zone, elongated salt structures such as salt walls and associated minibasins

trend nearly NNW–SSE, that is, parallel to the suggested rift axis. These features are interpreted to be related to basement-involved extension; above seaward dipping rift faults as described for this region (see Geological Background). The third domain, located around the PDZ, is likewise dominated by thick-skinned tectonics. Here, salt structures are primarily controlled by the prevailing stress field associated with the transtensional fault zone, involving the basement and entire sedimentary column.

Overall, most of the salt structures in the study area display diagnostic features indicative of extensional tectonics (Figure 2). Basement-detached contractional salt tectonic features—such as buckling, thrusting, and diapir squeezing—do not occur in the study area. Extension is primarily accommodated by the lateral widening of salt walls and the subsidence of minibasins resulting from salt withdrawal beneath these structures. Subsidiary faulting of the suprasalt strata occurs above salt walls or salt anticlines (Figures 5 and 9). Extensional features commonly observed along the Egyptian margin, such as ramp-syncline basins and rollovers (Ali, Koyi, et al., 2023), are absent here.

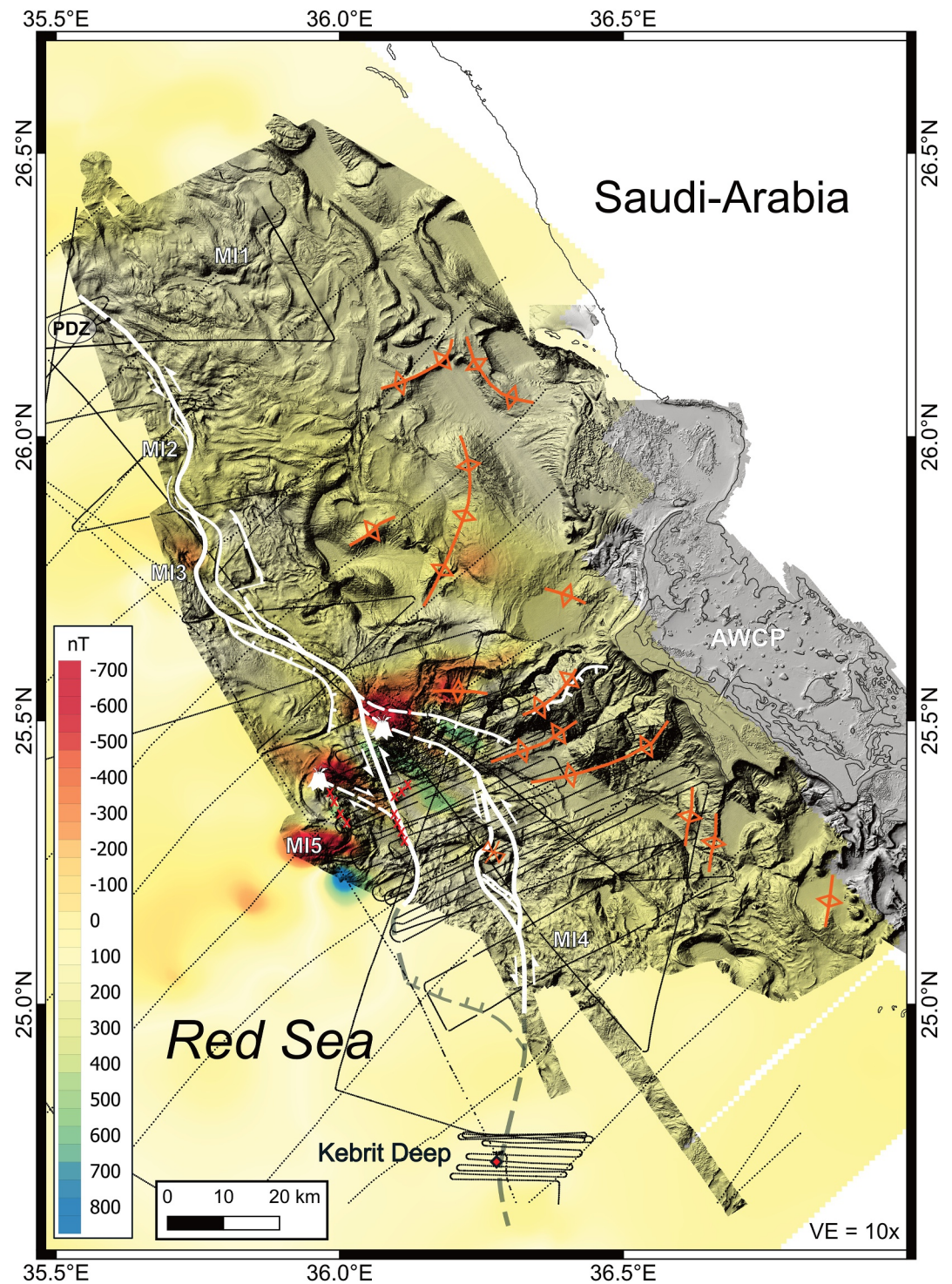
Similar structures to the meandering tectonic depression have been interpreted as evaporite suture zones in the central Red Sea, formed by the perpendicular convergence of salt flows (Augustin et al., 2016; Feldens & Mitchell, 2015; Mitchell et al., 2010). However, no clear indications of converging salt flows could be observed on either side of the mapped bending strike-slip zone. Conversely, the salt flow directions derived from the MBES and MCS data (gray arrows in Figure 2) along profile P02 (Figure 6) point away from the bending zone and further northwards, the salt structures are oriented obliquely to the depression, which rules out convergent flow. Even more strikingly, the distinct vertical displacement of the S-reflector within the depression (Figures 6 and 7) emphasizes that this is a tectonic structure controlled by faults. While salt is capable of creeping at ambient temperatures, local heating can significantly enhance its ability to flow (Jackson & Hudec, 2017; Underhill, 2009). For example, Underhill (2009) suggested that halokinetic flow in the North Sea was triggered by local dike emplacement beneath the Zechstein salt layer, where heat reduces the viscosity of salt, thereby promoting its mobilization. Consistent with that view, our data reveal a close spatial association between large, advancing salt sheets and the mapped magmatic intrusions (Figure 2). It is likely that, in the vicinity of these intrusions, substantial volumes of salt have been mobilized and extruded to the surface, where they laterally spread and became overlain by a veneer of younger sediments.

### 4.3. Magmatic Features

Several magmatic features are present in the study area, including volcanoes, dikes, sills, lava flows, and large magmatic intrusions. Volcanoes and major magmatic intrusions, as interpreted from seismic data, correlate well with pronounced positive VGG anomalies of approximately 50E (Figure 10). Furthermore, both volcanoes and the magmatic intrusion identified here correlate with distinct magnetic anomalies (Issachar, 2021; Figure 12, MI3 and MI5). Most of these magmatic features are spatially associated with the mapped fault system. A prominent example is Mabahiss Mons, located at the intersection between the western boundary strike-slip fault of the pull-apart basin and the normal faults that terminate the basin to the north (Figures 1b and 10). Such a tectonic setting creates regions of crustal weakness that facilitate magma ascent to the seafloor. Another volcano is situated on a proposed antithetic R' shear fault—a fault type characteristic of shear zones, developing at high angles to the master fault (Sylvester, 1988). It likely follows the steep southern margin of a depression that begins at the summit of the volcano and extends to the western boundary of the Mabahiss Deep (Figures 1b and 10). Further evidence is provided by the occurrence of large earthquakes (magnitude >4) with focal depths of 10 km, two of which are located on faults directly associated with these volcanic edifices (Figure 10, green stars). Volcanism tends to occur at rift segment boundaries, such as the observed volcanoes. Corti (2008) reports this relationship between rift segmentation and volcanism for the East African rift system.

Another magmatic feature closely related to the fault system is a dike parallel to the western boundary fault of the pull-apart basin. This dike is imaged on seismic line p22 and appears as a small ridge on the seafloor (Figure 3). In contrast, large magmatic intrusions MI2–MI5, located adjacent to the PDZ (Figure 10), are not directly linked to the major fault system. They are interpreted to represent isolated magmatic centers rather than persistent spreading ridges, such as those observed in the southern Red Sea. MCS line p13 crosses the margin of one such magmatic intrusion (between 0 and 4000 m and below 2180 ms), which likely consists of a succession of lava flows and pyroclastic deposits (Figures 7 and 10, MI3). The intrusion of MI4 is not confirmed by a corresponding





**Figure 12.** Magnetic anomalies derived from re-processing of shipborne data (track lines indicated) merged and conformed to a recent satellite model LCS-1 (Issachar, 2021). MI, magmatic intrusion (see also Figure 10).

magnetic anomaly, which may be attributed to the limited number of survey track lines that approach but do not cross the body (Figure 12). Instead, MI4 is delineated by a dense seismicity cluster and a high vertical gravity gradient (VGG; Figures 10 and 11).

#### 4.4. Rift Nature

The new data presented here provide significant insights into the characteristics of the rift system in the northern Red Sea. They indicate that the system is in the preliminary stage of seafloor spreading. The observed left-lateral strike-slip along the NRS rift axis suggests oblique continental rifting, as ridge-transverse seafloor spreading combined with ridge-parallel strike-slip motion would be mechanically implausible. This interpretation is supported by three-dimensional numerical experiments of Brune (2014) on a lithospheric scale to simulate oblique rifting. He determined rift-axis-parallel shear, which predates continental breakup and subsequent seafloor spreading. The NRS is probably in the same stage of breakup as proposed by Ligi et al. (2018), accompanied by submarine volcanism and magmatic intrusions (MI1-4, Figure 10), as well as underplating of the stretched continental crust by gabbroic melts.

Further observations may contradict the presence of oceanic crust below the NRS. Although our MCS data have limited penetration, they show no evidence of oceanic crust. Other studies in the South China Sea have shown that oceanic crust underlying more than 1.5 km of sediment is clearly imaged using similar high-resolution MCS systems (Lüdmann et al., 2001). In contrast to the South China Sea, the salt in the NRS considerably attenuates the seismic signal. Nevertheless, if there was oceanic crust present, the boundary between dense oceanic basement and the overlying sediments, marked by a distinct impedance contrast, should be detectable. Another consideration is that, if seafloor spreading has occurred, a breakup unconformity should be present, marking the transition from active rifting to early seafloor spreading. Such an unconformity is not reported for the NRS and not seen in our MCS data. Furthermore, if the W–E oriented salt structures north of the shear zone (Figures 9 and 10) are associated with displacement along underlying basement faults, they could be linked to the onshore Ajaj Shear Zone (Figure 2). The inferred transtensional regime may have reactivated these W–E oriented shear faults, converting them into normal faults. This implies that the onshore structures extend toward the present rift axis, together with the continental crust.

#### 5. Conclusions

Our study reveals the presence of a major transtensional strike-slip system coinciding with the axial rift zone of the NRS in the Saudi Arabian sector. The meandering, deeply rooted faults create both releasing and restraining bends, with extension prevailing over strike-slip—evidenced by the abundance of negative flower structures. Displacement of the S-reflector within the strike-slip fault zone, as well as the exposure of faults at the seafloor, suggests that transtension in this area initiated after the formation of the Upper Miocene unconformity, approximately 5 million years ago (Bosworth et al., 2005), and persists to the present. This time frame coincides with an intensification of slip along the Dead Sea/Aqaba strike-slip fault system, which led to the opening of multiple pull-apart basins in the fault zone (Tubbs et al., 2014).

At the Mabahiss Mons, the master strike-slip fault bends and continues in the southward direction. At the same time, the fault creates a stepover that leads to the formation of a major pull-apart basin, known as the Mabahiss Deep, which opens in a north–south direction. Further south, the master strike-slip fault continues, as evidenced by the general trend of the isobaths in this region and from the fact that the Kebrit Deep lies in line with it (see Figures 10 and 11). Here, Ehrhardt and Huebscher (2015) determined distinct N–S directed strike-slip movement. The Mabahiss Deep and the southward extending strike-slip fault is likely a part of the ZFZ, which offsets the rift segments to the right; however, the shear across the fault is sinistral. It is likely that the rotation of the Red Sea opening direction around 12–14 Ma, from axis-normal to oblique, resulted in the replacement of early distal rift-parallel structures by a new transtensional pattern closer to the rift axis, with salt structures oriented obliquely.

#### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

#### Availability Statement

Multibeam data from the R/V Meteor cruise is available via Lüdmann et al. (2025a, 2025b) on the PANGAEA database (Felden et al., 2023). The compiled bathymetric surface can be accessed via Lüdmann et al. (2026) as a



digital elevation model and the processed MCS examples lines via Lüdman and Westphal (2026) as CDP-sorted files in SEG Y format.

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