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1 Halokinetics and other features of GLORIA long-range
2 sidescan sonar data from the Red Sea

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16 multibeam sonar.

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20 Abstract

21 The Red Sea is an unusual example of a rift basin that transitioned from its
22 evaporitic stage to fully open-ocean conditions at the end of the Miocene (~5.3
23 Ma), much more recently than older Mesozoic margins around the Atlantic and
24 Gulf of Mexico. The patterns of halokinetic deformation occurring in the Red Sea

are potentially of interest for understanding more generally how evaporite deposits deform during this early stage. Relevant to this issue, a line of reconnaissance sidescan sonar data (GLORIA) collected along the Red Sea in 1979 is re-evaluated here. We first interpret the data with the aid of newly compiled bathymetry from multibeam sonars in the central and southern Red Sea. Features in the acoustic backscatter data are associated with ridges, valleys and rounded flow fronts produced by halokinetic deformation. Some areas of higher acoustic backscattering from the evaporites are suggested to relate to roughness produced by deformation of the evaporite surface. Within the volcanic (oceanic) axial valleys, areas of differing high and low backscattering suggest varied sediment cover and/or carbonate encrustations. With the benefit of the above experience, we then interpreted data from the northern Red Sea, where there are fewer multibeam data available. Rounded fronts of halokinetic deformation are present in the Zabargad Fracture Zone, a broad, shallow valley crossing the Red Sea obliquely. The presence of halokinetic deformation here is evidence that subsidence has occurred along the fracture zone. Elsewhere in the northern Red Sea, the GLORIA data reveal folds in the evaporite surface, suggesting local areas of convergence, like those implied by multibeam data from inter-trough zones further south. Some linear features are observed, many of which are likely to be ridges overlying salt walls. Interestingly, several such features are oriented along an accommodation zone that is oriented parallel to the plate spreading direction. Several rounded, corrugated features are interpreted as possible evaporite flow fronts. Overall, the impression from the data is of a strongly mobile seabed in the Red Sea because of halokinetic deformation, involving both vertical and horizontal movements. However, salt

walls appear more common than in the central and southern axial Red Sea, where horizontal movements instead tend to dominate.

Introduction

The Red Sea is an unusual example of rifted continent transitioning to ocean basin, with evaporites deposited up until the end of the Miocene deformed in a range of halokinetic structures as a result of the axial rifting and differential subsidence (Augustin et al., 2014; Augustin et al., 2016; Bicknell et al., 1986; Bonatti et al., 1984; Ehrhardt and Hübscher, 2015; Ehrhardt et al., 2005; Feldens and Mitchell, 2015; Girdler and Whitmarsh, 1974; Ligi et al., 2012; Ligi et al., 2011; Mitchell et al., 2010a; Mitchell et al., 2017; Rowan, 2014; Searle and Ross, 1975). Although the precise geometrical and temporal details have yet to be worked out, the Red Sea may suggest how the evaporites now forming thick but mobilised deposits around Atlantic and Gulf of Mexico basins deformed during the early stages of margin development in those areas (Bonatti et al., 1970; Pautot et al., 1966; Rona, 1982).

The Geological Long Range Inclined Asdic (GLORIA) was a low-frequency (6.5 kHz) sidescan sonar developed in the 1960s and 1970s for reconnaissance mapping of the seabed (Rusby et al., 1969; Rusby, 1970; Somers et al., 1978; Somers and Searle, 1984). During RRS *Discovery* cruise 103, the system was run along a zigzag track traversing the length of the Red Sea (Figure 1; Searle (1980)). Garfunkel et al. (1987) reported results of the survey covering the central and southern Red Sea, although they only showed GLORIA data with automatic gain control (AGC). AGC is high-pass filtering intended to highlight faults and other abrupt structures. We present the full dataset here without AGC

(though with time-varied gain compensating for spreading and attenuation losses), as variations in grey levels can help to reveal, for example, the extent of surface muddy sediment and rock outcrops. The GLORIA data are first compared with recently published bathymetry data collected with multibeam sonars (Augustin et al., 2014; Augustin et al., 2016; Mitchell et al., 2010a). The comparison shows how finer-scale features in the GLORIA images correspond with seabed structure. We then use that experience to guide interpretation of previously unpublished GLORIA data from the northern Red Sea, which reveal widespread halokinetic deformation, though with structures suggesting a different emphasis of vertical and horizontal movements.

Background to morphology and halokinetic deformation of the Red Sea

In the southern Red Sea south of $\sim 20^{\circ}\text{N}$, continuous magnetic anomalies and volcanic geomorphology suggest that an axial spreading centre is continuously exposed (Cochran, 1983; Augustin et al., 2014, 2016). In the free-air gravity field (lower-left inset to Figure 1), anomalies are subdued suggesting that the short-wavelength basement rugosity is also subdued. If the evaporites were deposited until the end of the Miocene with a continuous, horizontal surface throughout the Red Sea, the exposure of the spreading axis in the south is potentially explained simply by the higher elevation of the ridge axis near to the Afar mantle plume (Mitchell et al., 2017).

The central Red Sea ("Transitional region" in Figure 1) contains closed-contour depressions ("deeps") floored with volcanic geomorphological features in multibeam data. Those deeps are separated by elevated inter-trough zones (ITZs), which seismic reflection data suggest contain evaporites (Bonatti et al.,

1984). Magnetic anomalies outside the deeps are somewhat lineated but are subdued and their shapes in profile cannot be identified as seafloor spreading anomalies (Izzeldin, 1987), leading some authors to consider the deeps as new oceanic spreading centres and areas around them as highly extended continental crust (Bonatti et al., 1984; Ligi et al., 2011, 2012).

Improved resolution of the free-air gravity field obtained from satellite altimetry (Sandwell et al., 2014) has prompted another interpretation. The field shows many linear features crossing the central Red Sea in directions sub-parallel with the plate spreading direction ("FZs" in lower-left inset to Figure 1). These are similar morphologically in gravity data to short-offset fracture zones or other discontinuities of slow-spreading mid-ocean ridge spreading centres, suggesting that the central Red Sea is floored by oceanic crust (Mitchell and Park, 2014). If correct, magnetic anomalies may be attenuated as a consequence of greater depth of the crust associated with the loading by the evaporites, which reach several km in thickness away from the axis in seismic data (Izzeldin, 1987; Tramontini and Davis, 1969; Egloff et al., 1991). Other explanations include overlapping lava flows leaving distributed magnetization directions (Labrecque and Zitellini, 1985), hydrothermal alteration (Levi and Riddihough, 1986; Augustin et al., 2014) or lack of a well-defined extrusive layer (Dyment et al., 2013).

Mapping with multibeam sonars over the past decade has revealed an extensive pattern of glacier-like features, folds and faults that have been attributed to flowage of the Miocene evaporites in the central Red Sea (Mitchell et al., 2010; Augustin et al., 2014, 2016; Feldens and Mitchell, 2015). Figure 2 shows a 3D view of a segment of the data overlooking Erba Deep. Salt flows such

as those shown have rounded fronts in plan-view and profile, with longitudinal ridges and valleys much like ice glaciers (flow fronts can in detail have undulations or steps, which we show later produce curved repeated features in GLORIA images). The rift valley is floored with cones and irregular ridges typical of volcanic oceanic spreading centres. The ITZs are sites where flowage has been extensive, completely filling the axial valley (such as at the main flow in Figure 2), whereas the evaporites appear to be held back by obstructions in other areas, leaving the axial valley exposed. One obvious obstruction occurs immediately north of the largest flow in Figure 2, with lineaments in the evaporites wrapping around it as a result of the flowage.

Seismic basement in these areas generally dips away from the axis or is flat when corrected for seismic velocity (Egloff et al., 1991; Izzeldin, 1987; Tramontini and Davies, 1969). Some of the seismic data show a higher basement on either side of the axial valley (Izzeldin, 1987), much like the crestal mountains of a normal (un-sedimented) slow-spreading mid-ocean ridge. Local relief of the basement is also suggested by maps of Bouguer gravity anomalies (e.g., Mitchell et al., 2017). They show the above-mentioned fracture zone valleys lining up with the ITZs. As the evaporite surface and the seabed are also commonly depressed over the fracture zones, flowage appears to be preferentially exploiting gaps in the crestal mountains along the fracture zone valleys (Augustin et al., 2014; Mitchell et al., 2017). This inference suggests a link between basement structure and the pattern of flowage in the central Red Sea.

Less is known of the pattern of flowage in the northern Red Sea. The seabed generally dips towards the centre of the basin (Figure 1), suggesting that evaporites tend to flow towards the axis. As in the central Red Sea, the

evaporites can reach several km in thickness, although unlike the central Red Sea the underlying basement in places dip towards the rift axis (upper-left inset to Figure 1). Based on the various geophysical and geological data in the literature, almost the entire northern Red Sea is covered by evaporites so the features we observe below are mostly underlain by evaporites. Shallow seismic reflection data from the far northern Red Sea near Sinai have revealed salt walls overlying basement faults oriented NW-SE (Mart and Rabinowitz, 1986; Mart and Ross, 1987). Salt walls have similarly been found at Conrad and other deeps (Ehrhardt et al., 2005; Ehrhardt and Hübscher, 2015). Industry seismic reflection data suggest the existence of salt walls parallel to the Saudi Arabian coast (Richter et al., 1991) and similar structures exist on the opposing Egyptian side (Gordon et al., 2010). One segment of seismic reflection data from the Saudi Arabian margin (Rowan, 2014) shows a giant recumbent isoclinal fold in the evaporites produced by flowage towards the rift axis. However, the data publically available has been too limited to map out the directions of flowage and any relationships between that flowage and basement structure have been unclear.

Dataset and interpretation method

Data quality

According to the cruise report (Searle, 1980), the data were collected with the Mark II GLORIA system (Somers et al., 1978) with a 400 m tow cable during RRS *Discovery* cruise 103. The pulse repetition frequency was 40 s, so the maximum range achieved was 30 km, i.e., a maximum potential swath width of 60 km. Refraction effects mentioned below and strong attenuation in the Red Sea, where salinity can exceed 40 ppt., and shallow depths often led to around half the

maximum width in practice being imaged. The data recorded against acoustic travel time were converted by the shipboard engineers to slant range from the sonar vehicle using the known speed of sound in water and echo-sounder data. (As the data were not projected to ground range, features are geometrically distorted within the first few km of ship tracks.) A photographic film was then exposed with those results, with scan rate derived from navigation data to ensure common along and cross-track distance scales. The film was then developed and printed. We have digitally scanned the prints and assembled mosaics of the data along ship tracks as shown in Figures 3 to 7. Images were scaled and oriented so that the hourly tick marks shown down the centre of each swath matched the hourly marks along the ship tracks. (some images are offset from tracks to avoid overlaps).

The track for *Discovery* 103 obtained from the National Geophysical Data Center (NGDC; www.ngdc.noaa.gov) unfortunately contains some errors (Figure 1) that are not present in the track plot of the original cruise report (Searle, 1980). East of Mabahiss Deep, the provided track overlaps land. A sharp left jog of the track northwest of Vema Deep and a right jog east of Hatiba Deep are not associated with any indications of a sharp change of course in the GLORIA images (course changes would normally result in a loss of signal as the reception beam moved away from the transition beam during turns). As marked in Figure 1, no transit satellite fixes were recorded between 24° and 26°N, so navigation between these points was only by dead reckoning. We have positioned the GLORIA images ignoring the first jog mentioned, while the segment of imagery east of Mabahiss Mons seamount was positioned continuing the trend of the track running further north. Features in the data were also matched as closely as

possible to slopes in the multibeam bathymetry map of Guennoc et al. (1990) and with the linear feature marked "F" in Figure 6 constrained to lie seaward of land. The locations and geometries of features should be interpreted bearing in mind these potential navigational issues and the distribution of satellite fixes, although the data in the central and southern Red Sea appear mostly to correspond well with the newer multibeam data (Augustin et al., 2014; Augustin et al., 2016), which are shown in Figures 3 and 4.

Complicating the interpretation of the GLORIA images, ray-tracing calculations demonstrate that refraction of the signal in the water column can cause convergence of the signal towards the far range from the vehicle and limit the swath width (Mitchell and Somers, 1989; Searle et al., 1990). Although we have not carried out such calculations for the Red Sea survey, the GLORIA data show irregular bands of highly backscattered signal in the far range, running parallel to track (e.g., in the northerly swaths shown in Figures 4 and 5). In parts of the data from the northern Red Sea where this is a problem (Figure 7), segments of the far range parts of the data has been cut out to prevent them distracting readers. In another artefact, high backscatter from escarpments can appear more extended than the originating feature would suggest. For example, the two volcanic ridges in Thetis Deep (Figure 4) appear broader in the GLORIA data than in the multibeam data. This may be caused by one or more reflections from the sea surface extending the duration of high backscatter.

GLORIA data interpretation

Interpretation of sidescan sonar data can be difficult given the range of influences outlined below, but is effective if the interpreter bears these issues in

mind. Many complications are predictable and can be allowed for. High backscattering data are shown white and low backscattering black in these figures. When a half swath of data are viewed with the ship track higher up the page, the data appear as though a shaded relief map of the seabed, with a resolution of ~ 100 m across track. High backscattering is generally produced by a seabed that is rough at scales similar to the acoustic wavelength of the sonar (23 cm at 6.5 kHz here) and where there is a large acoustic impedance contrast at the seabed (Clay and Medwin, 1977). These conditions are often met by outcropping bedrock, in contrast with flat muddy sediments of smaller impedance contrast. The angle of incidence of the signal with the seabed also modulates the backscatter, so that the returned signal is greater at smaller angle of incidence (Mitchell and Somers, 1989). Backscatter modulated in this way can give an impression of seabed relief ("shape from shading"; Blondel and Murton, 1997). Also, given this incidence angle effect, the sonar tends preferentially to reveal surfaces such as fault scarps that are facing towards the sonar beam, conversely features parallel to the beam are not emphasized (though can be revealed if there is bedrock exposed along them). Because of the low frequency used with this sonar, the signal can penetrate a few metres into mud and the features may lie partly buried rather than at the seabed exactly (Mitchell, 1993). Whereas mid-grey tone in the imagery likely indicates an unconsolidated sedimentary seabed, black areas occurring behind bright areas can be caused by acoustic shadows cast by high-standing terrain (Mitchell, 1991), helping the interpreter identify areas of relief. Dredging of seabed areas in the Red Sea that have extremely low backscattering in multibeam acoustic data by one of us (NA) has recovered porous carbonate encrusted sediment, so such material (likely

deposited during the Last Glacial Maximum (Almogi-Labin et al., 1998; Milliman et al., 1969)) probably occurs in many of the areas of low GLORIA backscattering, overlain by a ~1 m drape of Holocene sediment (Mitchell et al., 2015).

We interpreted the data in the central and southern Red Sea first with the aid of the new multibeam sonar data. In the northern Red Sea, we have interpreted lineaments (both bright and dark) and backscatter boundaries mostly independently of multibeam data collected in the area since some navigational accuracy is questionable and the multibeam data are generally not available in digital form. Nevertheless, a number of published maps of multibeam data and knowledge gained from them along with seismic reflection data (Cochran et al., 1986; Coutelle et al., 1991; Ehrhardt and Hübscher, 2015; Ehrhardt et al., 2005; Guennoc et al., 1988; Guennoc et al., 1990; Mart and Ross, 1987; Martinez and Cochran, 1988) are available to confirm the nature of structures. We also created a bathymetry map for the area around Mabahiss Mons, a seamount in the northern Red Sea, by combining multibeam data of RV *Pelagia* from the Augustin et al. (2016) compilation with digital multibeam data of RV *Jean Charcot* from Guennoc et al. (1990). That map is shown in Figure 8. The features interpreted from the GLORIA data were then plotted over maps of the bathymetry (Figure 9) and free-air gravity anomalies (Figure 10), which allow the sonar features to be assessed in terms of factors likely to have affected evaporite movement (e.g., seabed gradient or basement topography, the latter reflected in the gravity field (Cochran and Karner, 2007; Mitchell and Park, 2014)). The lineaments were also plotted over a map of depth to the Miocene evaporite surface in Figure 11, which was derived from limited shallow-penetration seismic reflection data as described in Mitchell et al. (2017). Those

data were interpolated or extrapolated from ship tracks by 0.15° in latitude and longitude. Hence the map represents only general variations in the evaporite topography, whereas fine-scale variations due to the above-mentioned salt walls and diapirs are not visible.

Observations

Interpretation with multibeam data from the central and southern Red Sea

Interpreting the GLORIA data alongside multibeam data gives us knowledge of which features are likely to be imaged when we later interpret the northern Red Sea GLORIA data. However, the GLORIA data also extend our knowledge of structures beyond the areas covered by multibeam data in the central and southern Red Sea and provide additional seabed textural information.

Just north of 18°N in the far south of the area studied (Figure 3), the axial valley floor is marked by high backscatter ("HBVF"; please see key in figure for acronyms), though with apparently flat terraces in the multibeam data producing intermediate backscatter ("LBVF") presumably because of extensive sediment cover. Within the valley floor, cones identifiable in the multibeam data can also be observed in the GLORIA data ("v"), in places with collapse pits in their summits. In some areas, the fine structure of the faults corresponds well, for example, where marked by an asterisk ("*") in Figure 3 (in the multibeam data, these faults each have 200-400 m of relief). The GLORIA data extend the knowledge of faults beyond the multibeam data as previously outlined (Garfunkel et al., 1987).

Evaporite flow fronts appear in the multibeam data rounded in plan-view and in profile, with generally smooth sedimentary surfaces (Figure 2; Augustin et

al., 2014; Augustin et al., 2016; Feldens and Mitchell, 2015; Mitchell et al., 2010a). Flow fronts underlie the GLORIA vehicle track at the course change in the southeast of Figure 3 (so are not visible there in the GLORIA data from there exactly), but three flow fronts ~30 km across can be clearly observed in both the multibeam and GLORIA data to the NW of the turn. Flow fronts are commonly more highly backscattering than the sediment away from the deeps, probably because of small faults associated with extension in these areas or because less fine grained sediment deposits on the steeper slopes. Also, shortly after the course change, corrugated textures ("c") can be observed between the evaporite flows. In the swath of multibeam data crossing these structures, these areas contain small folds that are arcuate in plan-view (also marked "c"), where they have ~10-50 m of relief. Such structures have been interpreted as where parts of the flowing evaporites have become pinned or impeded by elevated underlying basement features such as seamounts (Mitchell et al., 2010a; Figure 2). The evaporite flow front on the east side of Suakin Deep has >1000 m of vertical relief in the multibeam data. In the GLORIA data, a number of lineaments on the flow front appear to correspond in the multibeam data with small undulations of the flow front topography of a few hundred metres. In contrast, an orthogonal downslope-oriented ridge and valley topography (slope failures?) is not visible in the GLORIA data due to the tendency to image features preferentially running parallel with the vehicle, not perpendicular.

Similar features are observable in the GLORIA data further north shown in Figure 4. However, whereas the evaporite surface away from the flow fronts is generally low backscattering, southeast of Atlantis II Deep there is an easterly oriented band of high backscattering from the surface of the evaporites ("HE").

We suspect that this backscattering was caused by faults and folds within the evaporite carapace, as observed around Thetis Deep (Mitchell et al., 2010a), and that they have produced facets facing the sonar and greater seabed roughness. The evaporite-filled depression within the inter-trough zone (ITZ) immediately north of Atlantis II Deep is also visible in the GLORIA swath collected running east to west (marked "c"). Folds are visible in the southerly side of this swath. They have reliefs of 50-150 m in the multibeam data and have been interpreted as the halokinetic convergence front (Augustin et al., 2014; Augustin et al., 2016).

The low backscattering within the north basin of Thetis Deep corresponds with areas where sediments have been sampled by coring (Mitchell et al., 2010b; Pierret et al., 2010). Generally, the undulations in the evaporite surface modulate the GLORIA data backscattering because of the incidence angle effect. The irregular rounded texture in the GLORIA data to the southeast of Erba Deep, for example, can be seen corresponding with surface undulations in the multibeam data. Similarly, the linear slopes running NW-SE northwest of the northern basin of Thetis Deep that have been suggested to represent flowage over rift valley wall faults (Mitchell et al., 2010a) appear as broad parallel bands in the GLORIA imagery (in the multibeam data, these slopes have reliefs of ~100-300 m over 5 km). The steep walls of Nereus Deep cast deep acoustic shadows so little internal structure is observed in the GLORIA image there.

Halokinetic and other features of the data in the northern Red Sea

The data from the northern Red Sea (Figures 5-7) contain many of the features described in the central and southern Red Sea (Figures 3-4), though largely without axial volcanic and tectonic features, as the seabed is almost fully covered

with evaporites and other sediments. Without the assistance of multibeam data, evaporite flow fronts and other features are more difficult to interpret from the data but we nevertheless propose likely examples.

Figure 5 reveals several areas of corrugated seabed, some of which are rounded in plan-view, much like the evaporite flow fronts in Figure 3. Flow directions of the interpreted evaporite flows next to Vema and Bannock deeps (eff1 and eff2) are difficult to ascertain from these images alone as both convex to northeast and concave to northeast corrugations occur (in Figures 9-11, we show preferred SW-directed flow as more compatible with the bathymetry gradients, though the bathymetry database is not based on continuous echosounder data). The Zabargad Fracture Zone comprises a broad though shallow trough running north-northeast of Zabargad Island. We feel more confident of the flow directions for eff3 to eff6 shown in Figure 5, in part because they would be compatible with gradients in the S reflection depths (Figure 11). Flows eff7 and eff8 were interpreted from the multibeam data in Figure 8. Flows eff9 to eff11 are more speculative.

Some sharp boundaries between high and moderate backscatter suggest changes of gradient from steep slope to sediment-filled basin (e.g., the boundary marked in Figure 6 "Base of slope" running irregularly parallel to track on both sides of the sonar). Some of these may be the bases of fronts of evaporite flowage. Some long (10-20 km) curvilinear features with smoothly varying backscatter are marked as "evaporite folds" in Figure 6 because they appear similar to the folds in the ITZ immediately north of Atlantis II Deep (Figure 4). They are oriented NNE, roughly parallel with the trend of the Red Sea axis. These features overlie a salt dome interpreted from industry seismic reflection

data (Richter et al., 1991). Features of similar appearance, though smaller (5-10 km) and oriented E-W are observable NE of Oceanographer Deep (Figure 7, immediately east of eff10).

In the northern Red Sea, lineaments with both sharp and gradual backscatter variations can be observed, suggesting a variety of faults and folds, of varied orientations. Other longer, broader and straighter bands of high backscattering are suggested to be larger faults. For example, one marked "F" in Figure 6 is oriented NNW and is shown controlling the coastline. In this case, a fine crenelation of the high backscatter zone suggests that this slope contains many small-scale gullies from mass-wasting. Another linear feature in the west of Figure 5 at 24°N ("F") is oriented N015°E. Although this part of the data was affected by the vessel positioning issues mentioned earlier, the vessel was most likely steered with a constant bearing (no deviations are shown in the cruise report (Searle, 1980)), so these directions are probably correct to within ~10°. As mentioned by Searle et al. (1980), the GLORIA data do not reveal much evidence for the Aqaba Fault (continuation of the Dead Sea Fault), although lineaments with the fault orientation are shown in Figure 7 where the fault has been located from seismic reflection data (Mart and Ross, 1987).

Discussion

Nature of flowage in the northern Red Sea

We concentrate discussion on the northern Red Sea, as the pattern of flowage is already well known in the central and southern Red Sea (Augustin et al., 2014, 2016). Whereas we anticipate the evaporites to form diapirs where they are loaded by thick terrigenous sediment near the coasts, as have been imaged with

seismic reflection methods (Richter et al., 1991; Gordon et al., 2010), away from those areas the nature of halokinesis is less clear. Rowan (2014) reported a high-quality section through 3D seismic data from near the Saudi Arabian coast, which shows a nappe produced by large-scale flowage seaward from the Arabian margin involving many kilometres of movement. On the other hand, Mart and Ross (1987) used an irregular grid of seismic reflection data to map out elongated diapirs of evaporites for ~100 km south of Sinai in the more central area, trending NNW over underlying largely inactive basement faults.

In the northern 200 km of the Red Sea, we observe some structures oriented NNW, parallel to the structures of Mart and Ross (1987), e.g., the lineaments immediately to NW and NE of Conrad Deep. Hence, some or most of these may be the seabed ridges overlying salt walls. Conrad Deep itself is oriented more NNE-SSW with salt walls imaged in seismic reflection data (Ehrhardt and Hübscher, 2015; Ehrhardt et al., 2005); a NNE-trending feature can be observed in the GLORIA data immediately SE of the deep marked in Figure 7 ("Conrad Deep fault?"). Some other linear features are more ambiguous in origin. For example, the lineament marked "F" next to Oceanographer Deep (Figure 7) could be a fault or the top of a salt wall. This feature is remarkably long (18 km) and lines up with the underlying accommodation zone in basement revealed by the gravity field (Figure 10). Other linear features can also be observed further northeast aligned with the accommodation zone. The maps of lineaments (Figures 9 and 10) show many other orientations of structures. The data also show rounded features that could be interpreted as flow fronts, such as eff10 in Figure 7, hence suggesting lateral movements.

If significant gravity-driven movement of the evaporites has occurred, it would be expected to have been oriented roughly perpendicular to the bathymetry contours in Figure 9 (i.e., to the NE on the African side and to the SW on the Arabian side). However, the gravity field (Figure 10) also reveals NW-trending anomalies that have been interpreted with the aid of seismic reflection and refraction data to be continental fault blocks (Cochran, 2005; Cochran and Karner, 2007). In the central Red Sea, the pattern of flowage appears modulated by the basement topography, with greater flowage over basement valleys where the evaporites are thicker and less impeded (Augustin et al., 2014; Augustin et al., 2016; Feldens and Mitchell, 2015; Mitchell et al., 2010a; Mitchell et al., 2017).

Whether basement topography modulates flowage also in the northern Red Sea is less clear. In that case, we might expect cross-sea features such as the accommodation zone marked in Figure 10 to be a zone of preferential movement. Perhaps the evaporite folds interpreted immediately east of eff10 could represent the convergence zone. However, we don't see obvious drag folds or Riedel-type shears that would help to identify differential movement. Nevertheless, some of our interpreted evaporite flow fronts suggest movement from areas of high free-air gravity (implying elevated basement) to low anomaly, such as eff7, eff9, eff10 and eff11, perhaps indicating some movements down gradients created by differential compaction of underlying sediments. In contrast with the central and southern Red Sea, the abundance of linear features and few rounded features suggests the importance of salt walls and hence vertical tectonics, rather than horizontal movements.

Mabahiss Mons seamount and Deep

The sonar swath ran immediately east of Mabahiss Mons seamount, the data in Figure 6 revealing an area of high backscattering most likely due to outcropping volcanic rock at least 10 km across. Comparing the apparent geomorphology in the GLORIA data with the multibeam bathymetry map of Guennoc (1990) the *Discovery* survey line ran over the boundary between Mabahiss West and East basins, which are both sediment-filled. One or more further sediment-filled basins run under the track to the SE. Curiously, narrow bands of low backscatter occur at the base of slope to the SE, which are either depressions filled with exceptionally low backscattering sediment. The seabed immediately to the NW of Mabahiss Mons also appears to comprise generally low backscattering sediment.

A higher resolution view is provided by the multibeam data in Figure 8. The structures here have been described by Metz (2013), who interpreted the lobate morphologies of the slopes, such as the southern slope of the West Basin, as due to evaporite flowage. He noted also that the patterns of lineaments on the sedimentary areas are similar to those of evaporite flows interpreted further south (Augustin et al., 2014; Augustin et al., 2016; Feldens and Mitchell, 2015; Mitchell et al., 2010a). Although the GLORIA data have lower resolution, many features can be associated with those of Figure 8, for example, a somewhat rounded backscatter E-W lineament immediately south of Mabahiss West Basin. The embayment of the NE slope of East Basin is observed in the GLORIA imagery, as well as the gullied slope of the steep escarpment marked F in Figure 6. Metz (2013) suggested that Mahahiss Mons probably blocks flowage into the Mabahiss West Basin from the north. The lack of halokinetic structures immediately NW of

Mahabiss Mons (south of "Evaporite Folds" marked on Figure 6) would be compatible with that idea.

Structures associated with the Zabargad Fracture Zone

A major tectonic structure running NNE immediately north of Zabargad Island is the Zabargad Fracture Zone (FZ), marked by an elongate free-air gravity low (Figure 10). The fracture zone is less clear in bathymetry maps, but a step or depression of ~100-200 m is commonly revealed in traversing ship tracks. This feature likely accommodates differential plate motion between the laterally offset extensional regions of Vema Deep and Gypsum Deep. The westerly major lineament marked "F" also is oriented NNE. However, this fault and another two minor faults within the fracture zone valley (Figure 5) lie counter-clockwise of the Arabia-Nubia motion direction of the last few million years according to Chu and Gordon (1998) (red lines in Figures 9 and 10), suggesting that motion across the fracture zone may be transtensional. The presence of rounded features with corrugations suggests flowage into the fracture zone valley (Figures 5). Such flowage implies that the floor of the fracture zone has subsided relative to adjacent basement blocks since the end of the Miocene termination of the evaporite phase, also compatible with transtensional deformation across the fracture zone.

Conclusions

The GLORIA images reveal lineaments (folds and faults) with a wide range of orientations in the northern Red Sea. Many linear features are likely to represent the surface expressions of salt walls. Interestingly some linear

features are oriented parallel with an accommodation zone revealed by the free-air gravity field. In the centre of that zone, the GLORIA data suggest a set of folds occurs, which may represent a zone of evaporite convergence. Elsewhere, the data show rounded corrugated features that may be flow fronts, many of which run from areas of free-air gravity highs to lows. Nevertheless, vertical tectonics (in the form of salt walls) appears to be emphasized over horizontal tectonics in the northern Red Sea, in contrast with the central Red Sea, where structures indicating horizontal movement dominate. The generally more subdued seabed gradients in the northern Red Sea, where the deeps are less well developed, may explain this difference. More generally, we predict that the style of early halokinetic deformation originally occurring at more mature margins such as around the Atlantic may crucially have depended on the original seabed and evaporite surface gradients, unfortunately parameters that are poorly known.

Rounded corrugated structures in the Zabargad Fracture Zone suggest flowage into the fracture zone depression. We suggest that this is caused by subsidence along the fracture zone and would be compatible with a change to transtensional deformation associated with a more recent change in plate motion. These and other structures revealed by the GLORIA images suggest excellent targets for surveys with more modern multibeam and sidescan sonars.

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703 Figure 1. Overview of the bathymetry and topography of the Red Sea basin with

704 the track (red) of RRS *Discovery* cruise 103. Tick marks are shown every hour of

705 survey time. Blue solid circles represent locations of transit satellite fixes. Red
 706 solid circles locate deeps compiled by Augustin et al. (2014) (only a selection of
 707 their names are shown). Topography and bathymetry data are from Becker et al.
 708 (2009). Inset (lower-left) shows a shaded-relief image of the satellite-derived
 709 marine gravity field (Sandwell et al., 2014, their version 18.0 shaded from
 710 N030°W). Further annotation: (ZI) Zabargad Island, (J) Jeddah, (PS) Port Sudan
 711 and (FZs) fracture zones. Second inset (upper left) is crustal cross-section near
 712 Conrad Deep interpreted by Martinez and Cochran (1989) from industry
 713 multichannel seismic reflection data.

714
 715 Figure 2. 3D view of multibeam data showing salt flows invading the axial rift
 716 valley, with Erba and Aswan deeps in the foreground (Augustin, 2014). Width of
 717 data in view is ~30 km. Depths in field of view vary from 800 m (white) to 2400
 718 m (blue).

Figure 3. GLORIA image panels shown alongside a shaded relief image of the multibeam bathymetry (Augustin et al., 2014; Augustin et al., 2016) (artificial sun from N060°E). GLORIA photographic prints have been scaled and oriented to the hourly marks along the *Discovery* trackline but are shown offset from the track to allow features to be compared with the multibeam data (black lines associate hour marks).

Figure 4. GLORIA image panels shown alongside a shaded relief map of the multibeam bathymetry, as Figure 3. Annotation ITZ: inter-trough zone (other annotation as Figure 3).

Figure 5. Gloria image panels oriented along *Discovery* track in the central Red Sea, with the topographic and bathymetry data of Becker et al. (2009) as background (colour scale as Figure 1). Arrows mark possible flowage directions.

Figure 6. GLORIA image passing over Mabahiss Deep, as Figure 5.

Figure 7. GLORIA images in the northern Red Sea, as Figure 5.

Figure 8. Bathymetry of Mabahiss Mons seamount and adjacent deeps.

Multibeam data include RV *Pelagia* data from the compilation of Augustin et al. (2016), supplemented with data from Guennoc et al. (1988; 1990). Where the sounding data from the two sets of surveys overlap, preference was given to the Augustin et al. (2016) data. The Guennoc et al. (1988; 1990) data were collected on RV *Jean Charcot* with a 16-beam multibeam sonar (narrower swaths in the figure). Artificial illumination is from N045°W. Fine line is the track of RRS *Discovery* cruise 103 lodged with the NGDC and bold line is the presumed true track.

Figure 9. Lineaments and other backscatter boundaries interpreted from the GLORIA overlain on the bathymetry (colours as Figure 1, though with intensities reduced). The 1000 m depth contour is shown. Red filled circles are the deeps, as Figure 1. Arrows indicate suggested evaporite flowage directions. Red bold lines show the Nubia-Arabia plate motion directions at 24° and 25.7°N from Chu and Gordon (1998) and finer red lines show their computed 95% confidence intervals.

Figure 10. As Figure 9, with the free-air gravity field as the background (Sandwell et al., 2014). Gravity anomalies are contoured every 10 mGal (0 mGal level annotated); cold colours (blue) represent low values and warm colours (red) represent high values). Heavy arrows are used to mark features.

Figure 11. As Figure 9, with depths to the S reflection (top of the Miocene evaporites) from Mitchell et al. (2017) as background.