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Comment on: "Insights on the tectonic styles of the Red Sea rift using gravity and magnetic data" by Saada et al. (2021)

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Abstract:

Global grids of geophysical data or properties of the Earth are increasingly being used, perhaps because they are easy to access and make calculations on. Where original data are proprietary, researchers can sometimes obtain a form of those data within these grids, albeit at commonly lower resolution. Examples include gravity fields (Balmino et al., 2011; Sandwell et al., 2014), thicknesses of sediment overlying basement (Whittaker et al., 2013; Straume et al., 2019), Earth's topography (Smith and Sandwell, 1997; Becker et al., 2009; Ryan et al., 2009; Weatherall et al., 2015), crustal thickness (Laske et al., 2013), seafloor spreading history (Müller et al., 1997) and magnetic fields (Maus et al., 2009). However, depending on the type of study, when working with such data, we need to know the distribution of the original measurements that were used to compile those grids, hence which grid nodes contain interpolated values and which nodes are close to measurement sites. Ideally, we should be aware of the noise characteristics and resolution of such data also. The term "grid resolution" is commonly used in the literature but is misleading, as it refers to the spacing of nodes in the grid, not the resolution of the contributing data. Resolution can also be affected by processing steps used to create the grid. The article of Saada et al. (2021) describes important calculations and useful observations, though some parts of the study illustrate issues that can be encountered in analysing global grids. Given the increasing use of global grids, we provide this comment to help engender discussion.

Saada et al. (2021) computed radially-averaged power spectra of EMAG2 grid values within squares of 150 X 150 km. The gradients of those spectra in the spatial frequency range 0.03–0.2 radians/km were then used to derive Curie point depths using the method of Blakely (1988). Knowing Earth's surface temperature and the Curie temperature, these depths were converted to temperature gradients, from which heat flow values were estimated using a single conductivity (2.93 W/m°C). Some aspects of their map reproduced in Figure 1a are reasonable. For example, values are generally greater within the sea, where heatflow should be higher generally if associated with rifting (Cochran, 1983). The heatflow values in Figure 1b comprise measurements from heatflow probes mainly. Those heatflow values vary strongly because heatflow is obtained by measuring temperature gradient, usually with a short probe, and sediment thermal conductivity, which are both susceptible to uncertainties, and because heat flow varies strongly around the Red Sea axis (Martinez and Cochran, 1989; Makris et al., 1991). Hence, the values in Figure 1b are noisy. Nevertheless, there is a high density of measurements along the three profiles marked in Figure 1b traversing the northernmost Red Sea (data collected on *RV Conrad* (Martinez and Cochran, 1989)). The peak values at the centres of those three profiles are comparable to those of Figure 1a.

However, we generally expect high crustal temperatures at shallow depths all along the basin axis, which is not shown in Figure 1a. For example, deeps (closed-contour depressions) containing hot brines are found north of 19°N (Pautot et al., 1984; Schmidt et al., 2015). Those brine-filled deeps are more closely spaced than the heatflow highs in Figure 1a. Bathymetry data collected with multibeam sonars reveal a rugged morphology with cones and ridges within the deeps and, south of 19°N, along the axis (Mitchell et al., 2010; Ligi et al., 2012; Augustin et al., 2014; Augustin et al., 2016). Volcanic rocks have been recovered by dredging in these areas (e.g., Altherr et al., 1988; Haase et al., 2000). The high Bouguer anomalies along the centre of the Red Sea (Izzeldin, 1987) are a sign that the mantle is shallower there, brought up in response to seafloor spreading, which has been documented with magnetic anomalies (Vine, 1966; Chu and Gordon, 1998). Heat flow is low along the axis at 22°-23°N in Figure 1a, despite coinciding with volcanic geomorphology observed in the multibeam data. Northeast of Port Sudan (Figure 1a), heatflow in a line of measurements rises to above 300 mW/m^2 at the axis (Makris et al., 1991), in contrast with the lower values in Figure 1a. Why aren't the heatflow values more continuously elevated along the Red Sea axis in Figure 1a?

Some shipboard magnetic measurements provide traverses across the rift axis, in particular those of *RRS Shackleton* (Figure 1c). Individual magnetic anomaly profiles (Figure 2) across the high heat flow area at Atlantis II Deep do not obviously reveal any difference in frequency content compared with profiles to north and south of that region where heat flow values are smaller in Figure 1a. To investigate further, we accessed the most recent version of the EMAG2 database online (Meyer et al., 2017) (https://www.ncei.noaa.gov/products/earth-magnetic-model-anomaly-grid-2), but it is not accompanied by much information on individual data contributions. The codes in the online database suggest that regional grids of unknown characteristics contributed to these Red Sea areas. In introducing EMAG2, Maus et al. (2009) wrote: "To further improve the representation of magnetic anomalies over the oceans, we avoided precompiled oceanic anomaly grids and reverted to the original track line data where available." Issachar et al. (2022) independently assessed the quality of shipboard magnetic data in the Red Sea by comparing data at crossing tracks and levelling. The measurement locations from the cruise data that they selected as higher quality are shown in Figure 1c. In Figure 1d, we show an estimate of the density of those measurements. The full wavelengths corresponding to the 0.03–0.2 radians/km frequency range analysed by Saada et al. (2021) are indicated by the horizontal bars in Figure 1c (47.1 and 314 km). The areas of apparently more reasonable (high) heat flow coincide with dense shipboard magnetic data (northern area of the *RV Conrad* survey, the Atlantis II Deep area and parts of the *RV Valdivia* survey). In between those areas, coverage was much sparser, with spacings between the *RRS Shackleton* lines comparable with the 47.1 km wavelength. We suspect therefore that a radially averaged power spectrum would be strongly influenced by effectively only interpolated values, suppressing power at the higher frequencies. This would make the Curie Point Depth appear deeper than it is and thus artificially lower any derived heatflow values. In some areas of higher data density, sedimentary sources of magnetic anomalies may instead raise power around 47.1 km wavelengths (Stewart and Johnson, 2007). Besides their depths, the shapes and sizes of magnetic sources affect the power spectra (Spector and Grant, 1970). In the Red Sea, we can expect sources of various shapes and sizes varying in importance across the region; sedimentary bodies are likely to form horizontal sheets, magnetization acquired in the cooling lower crust and upper mantle of rift or spreading centres probably forms inclined sheets of alternating remanent magnetization polarity (Dyment and Arkani-Hamed, 1995) and there are localised bodies also (Cochran, 2005).

Saada et al. (2021) used a global Bouguer gravity anomaly grid WGM 2012, as have some others working on the Red Sea (Sang et al., 2023). However, the grid was produced using a 2.67 Mg/m^3 crustal density to remove all topographic effects (Balmino et al., 2011). This density is too high within the Red Sea, where evaporites and other sediments form the seabed. Seismic data typically show areas either sides of the deeps as dominated by these sediments (Izzeldin, 1987; Mitchell et al., 2010; Ehrhardt and Hübscher, 2015). A more appropriate density is ~2.20 Mg/m^3 (Izzeldin, 1987), i.e., nearly 0.5 Mg/m^3 smaller. From the Bouguer slab formula (Telford et al., 1976), a 1000 m variation in depth would lead to ~21 mGal error. If Bouguer anomalies were more correctly calculated for the Red Sea, the 2D forward modelling scheme outlined by Saada et al. (2021) would likely have led to mantle rocks in some of their profiles deeper than shown by more than a kilometre. Furthermore, in our opinion, the forward models in their Figures 18 and 19 contain more detail than can be justified. Constraints on such structures need to be provided, e.g., with positions of seismic reflections shown and the methods used to convert them from seismic travel time into depth explained. In addition, gravity modelling of strongly different density structures can predict similar gravity anomalies (Stewart and Johnson, 1994), so constraints on density, such as velocities from seismic refraction surveys and velocity-density relationships, are needed to reduce modelling ambiguities. Saada et al. (2021) showed a map of basement depth from source parameter imaging (their figure 11), but it does not reproduce the variation from deep-seismic imaging, which reveals basement forming a ridge down the central Red Sea axis (Izzeldin, 1982; Izzeldin, 1987; Shi et al., 2018). Checks against alternative estimates of features, such as basement here, can help in identifying problems with methods based on potential fields.

The global grids are extremely useful and, despite our criticisms, the Saada et al. (2021) results illustrate this. It is interesting that their heatflow estimates for the northern Red Sea approach those that have been measured (Martinez and Cochran, 1989). Although the irregularity of the magnetic field in that area suggests localised volcanic sources (Cochran, 2005), this apparently has not affected the results. In future, the variation along the Red Sea might be better studied along individual segments of the ship-board data (Figure 1c) or using more nearly continuous aeromagnetic datasets (Stewart and Johnson, 2007; Rasul et al., 2015). Furthermore, the global grids might be more useful to researchers if they were to incorporate more information to help the reader evaluate the quality of the grids in local areas.

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Figure captions:

Figure 1. Maps of the Red Sea in Universal Transverse Mercator zone 36.
(a) Heatflow derived by Saada et al. (2021) from power spectral analysis of the EMAG2 magnetic anomaly grid.
(b) Heatflow measurements from the International Heatflow Commission (https://ihfc-iugg.org/products/global-heat-flow-database).
(c) Research vessel tracks obtained from the National Centers for Environmental Information (https://www.ncei.noaa.gov/) for cruises in which magnetic anomaly measurements were found to be reliable (Issachar et al., 2022).
(d) Density of the magnetic measurements in (c). To reduce the effect of varied sampling along tracks between cruises, the measurements were first averaged in squares of 0.05°X0.05°. The map shows the numbers of those averages within cells of 0.25°X0.25°.

Figure 2. Magnetic measurements along 10 *RRS Shackleton* tracks. Profiles from bottom to top correspond with profiles A-J of Mitchell and Park (2014). Values on left are the computed average latitude of each data profile.

Altherr, R., Henjes-Kunst, F., Puchelt, H. and Baumann, A., 1988. Volcanic activity in the Red Sea axial trough - evidence for a large mantle diapir? Tectonophys., 150: 121-133.
Augustin, N., Devey, C.W., van der Zwan, F.M., Feldens, P., Tominaga, M., Bantan, R. and Kwasnitschka, T., 2014. The transition from rifting to spreading in the Red Sea. Earth Planet. Sci. Lett., 395: 217-230.
Augustin, N., van der Zwan, F.M., Devey, C.W., Ligi, M., Kwasnitschka, T., Feldens, P., Bantan, R. and Basaham, A.S., 2016. Geomorphology of the central Red Sea Rift: Determining spreading processes. Geomorph., 274: 162-179.
Balmino, G., Vales, N., Bonvalot, S. and Briais, A., 2011. Spherical harmonic modelling to ultra-high degree of Bouguer and isostatic anomalies. J. Geodesy, 86: 499-520.
Becker, J.J., Sandwell, D.T., Smith, W.H.F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S.-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G. and Weatherall, P., 2009. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30 PLUS. Marine Geodesy, 32: 355-371.
Blakely, R.J., 1988. Curie temperature isotherm analysis and tectonic implications of aeromagnetic data from Nevada. J. Geophys. Res., 93: 11,817-811,832.
Chu, D. and Gordon, R.G., 1998. Current plate motions across the Red Sea. Geophys. J. Int., 135: 313-328.
Cochran, J.R., 1983. A model for the development of the Red Sea. Am. Assoc. Petrol. Geol. Bull., 67: 41-69.
Cochran, J.R., 2005. Northern Red Sea: Nucleation of an oceanic spreading center within a continental rift. Geochemistry, Geophysics, Geosystems, 6: Paper Q03006, doi:03010.01029/02004GC000826.

Dyment, J. and Arkani-Hamed, J., 1995. Spreading-rate-dependent magnetization of the oceanic lithosphere inferred from the anomalous skewness of marine magnetic anomalies. Geophys J. Int., 121: 789-804.

Ehrhardt, A. and Hübscher, C., 2015. The northern Red Sea in transition from rifting to drifting - lessons learned from ocean deeps. In: N.M.A. Rasul and I.C.F. Stewart (Editors), The Red Sea: The formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences, Berlin Heidelberg., pp. 99-121.

Haase, K.M., Mühe, R. and Stoffers, P., 2000. Magmatism during extension of the lithosphere: geochemical constraints from lavas of the Shaban Deep, northern Red Sea. Chemical Geology, 166: 225-239.

Issachar, R., Ebbing, J. and Dilixiati, Y., 2022. New magnetic anomaly map for the Red Sea reveals transtensional structures associated with rotational rifting. Scientific Reports, 12: art. 5757.

Izzeldin, A.Y., 1982. On the structure and evolution of the Red Sea. PhD Thesis, Université Louis Pasteur: 163p.

Izzeldin, A.Y., 1987. Seismic, gravity and magnetic surveys in the central part of the Red Sea: their interpretation and implications for the structure and evolution of the Red Sea. Tectonophysics, 143: 269-306.

Laske, G., Masters, G., Ma, Z. and Pasyanos, M., 2013. Update on CRUST1. 0—A 1-degree global model of Earth's crust. Geophysical Research Abstracts, European Geoscience Union, 15: abs. 2658.

Ligi, M., Bonatti, E., Bortoluzzi, G., Cipriani, A., Cocchi, L., Caratori Tontini, F., Carminati, E., Ottolini, L. and Schettino, A., 2012. Birth of an ocean in the Red Sea: Initial pangs. Geochem. Geophys. Geosys., 13: Paper Q08009, doi:08010.01029/02012GC004155.

Makris, J., Tsironidis, J. and Richter, H., 1991. Heatflow density distribution in the Red Sea. Tectonophys., 198: 383-393.

Martinez, F. and Cochran, J.R., 1989. Geothermal Measurements in the northern Red Sea: Implications for lithospheric thermal structure and mode of extension during continental rifting. J. Geophys. Res., 94: 12,239-212,266.

Maus, S., Barckhausen, U., Berkenbosch, H., Bournas, N., Brozena, J., Childers, V., Dostaler, F., Fairhead, J.D., Finn, C., von Frese, R.R.B., Gaina, C., Golynsky, S., Kucks, R., Lühr, H., Milligan, P., Mogren, S., Müller, R.D., Olesen, O., Pilkington, M., Saltus, R., Schreckenberger, B., Thébault, E. and Caratori Tontini, F., 2009. EMAG2: A 2–arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. Gechemistry, Geophysics, Geosystems, 10: art. Q08005.

Meyer, B., Saltus, R. and Chulliat, A., 2017. EMAG2v3: Earth Magnetic Anomaly Grid (2-arc-minute resolution). Version 3. NOAA National Centers for Environmental Information. Accessed 11 September 2023.

Mitchell, N.C., Ligi, M., Farrante, V., Bonatti, E. and Rutter, E., 2010. Submarine salt flows in the central Red Sea. Geol. Soc. Am. Bull., 122: 701-713.

Mitchell, N.C. and Park, Y., 2014. Nature of crust in the central Red Sea. Tectonophys., 628: 123-139.

Müller, R.D., Roest, W.R., Roger, J.-Y., Gahagan, L.M. and Sclater, J.G., 1997. Digital isochrons of the world's ocean floor. J. Geophys. Res., 102: 3211-3214.

Pautot, G., Guennoc, P., Coutelle, A. and Lyberis, N., 1984. Discovery of a large brine deep in the northern Red Sea. Nature, 310: 133-136.

Rasul, N.M.A., Stewart, I.C.F. and Nawab, Z.A., 2015. Introduction to the Red Sea: Its origin, structure, and environment. In: N.M.A. Rasul and I.C.F. Stewart (Editors), The Red Sea: The formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences., Berlin Heidelberg, pp. 1-28.

Ryan, W.B.F., Carbotte, S.M., Coplan, J.O., O'Hara, S., Melkonian, A., Arko, R., Wiessel, R.A., Ferrini, V., Goodwillie, A., Nitsche, F., Bonczkowski, J. and Zemsky, R., 2009. Global multi-resolution topography synthesis. Geochem. Geophys. Geosys., 10: Art. Q03014.

Saada, S.A., Mickus, K., Eldosouky, A.M. and Ibrahim, A., 2021. Insights on the tectonic styles of the Red Sea rift using gravity and magnetic data. Mar. Pet. Geol., 133: art. 105253.

Sandwell, D., Müller, R.D., Smith, W.H.F., Garcia, E. and Francis, R., 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science, 346: 65-67.

Sang, Y.-D., Adam, B.M.T., Li, C.-F., Huang, L., Wen, Y.-L., Zhang, J.-L. and Liu, Y.-T., 2023. Punctiform breakup and initial oceanization in the Central Red Sea Rift. J. Mar. Sci. Eng., 11: art. 808.

Schmidt, M., Al-Farawati, R. and Botz, R., 2015. Geochemical classification of brine-filled Red Sea deeps. In: N.M.A. Rasul and I.C.F. Stewart (Editors), The Red Sea: The formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences. Springer Earth System Sciences, Berlin Heidelberg, pp. 219-233.

Shi, W., Mitchell, N.C., Kalnins, L. and Izzeldin, A.Y., 2018. Oceanic-like axial crustal high in the central Red Sea. Tectonophys., 747-748: 327-342.

Smith, W.H.F. and Sandwell, D.T., 1997. Global sea floor topography from satellite altimetry and ship soundings. Science, 277: 1956-1962.

Spector, A. and Grant, F.S., 1970. Statistical models for interpreting aeromagnetic data. Geophysics, 35: 293-302.

Stewart, I.C.F. and Johnson, P.R., 1994. Satellite gravity and Red Sea tectonics, Saudi Arabian Deputy Ministry for Mineral Resources, Saudi Arabia, Open-File Report USGS-OF-94-10 (IR-877), 22 p.

Stewart, I.C.F. and Johnson, P.R., 2007. Spectral analysis of aeromagnetic data over the Precambrian shield and Phanerozoic cover rocks, Kingdom of Saudi Arabia, Saudi Arabian Deputy Ministry for Mineral Resources, Saudi Arabia, Saudi Geological Survey Technical Report SGS-TR-2007-2, 33 p.

Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., et al., 2019. GlobSed: Updated total sediment thickness in the world's oceans. Geochemistry, Geophysics, Geosystems, 20: 1756-1772.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1976. Applied Geophysics. Cambridge University Press, New York, 860 pp.

Vine, F.J., 1966. Spreading of the ocean floor - new evidence. Science, 154: 1405-1415.

Weatherall, P., Marks, K.M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J.E., Rovere, M., Chayes, D., Ferrini, V. and Wigley, R., 2015. A new digital bathymetric model of the world’s oceans. Earth and Space Science, 2: 331-345, doi: 310.1002/ 2015EA000107.

Wessel, P., and Smith, W.H.F., 1991, Free software helps map and display data, EOS, Transactions, American Geophysical Union, 72, 441.

Whittaker, J.M., Goncharov, A., Williams, S.E., Müller, R.D. and Leitchenkov, G., 2013. Global sediment thickness data set updated for the Australian-Antarctic Southern Ocean. Geochem. Geophys. Geosys., 14: doi:10.1002/ggge.20181.