Salty Matters

John Warren -Sunday April 29, 2016

Red Sea Metals: What is the role of salt in metal enrichment?

Introduction

Work over the past four decades has shown many sediment-hosted stratiform copper deposits are closely allied with evaporite occurrences or indicators of former evaporites, as are some SedEx (Sedimentary Exhalative) and MVT (Mississippi Valley Type) deposits (Warren, 2016). Some ore deposits, especially those that have evolved beyond greenschist facies, can retain the actual salts responsible for the association, primarily anhydrite relics, in proximity to the ore. Such deposits include the Zambian and Redstone copper belts, Creta, Boleo, Corocoro, Dzhezkazgan, Kupferschiefer (Lubin and Mansfeld regions), Largentière and the Mt Isa copper association. All these accumulations of base metals are associated with the formation of a burial-diagenetic hypersaline redox/mixing front, where either copper or Pb-Zn sulphides tended to accumulate. Mechanisms that concentrate and precipitate base metal ores in this evaporite, typically halokinetic, milieu are the topic of upcoming blogs. Then there are deposits that are the result from hot brine fluids, tied to dissolving evaporites and igneous activity, mixing and cooling with seawater, so precipitating a variety of hydrothermal salts, sometimes in including economic levels of copper, lead and zinc (Warren, 2016)

In this article, I focus on one such hypersaline-brine deposit, the cupriferous hydrothermal laminites of the Atlantis II Deep in the Red Sea and look at the role of evaporites in the enrichment of metals in this deposit. It is a modern example of a metalliferous laminite forming in a brine lake sump on the deep seafloor where the brine lake and the stabilisation of the precipitation interface is a result of the dissolution of adjacent halokinetic salt masses. Most economic geologists classify the metalliferous Red Sea deeps as SedEx deposits, but the low levels of lead and high levels of copper, along with its stratigraphic position atop seafloor basalts, place it outside the usual Pb-Zn dominant system that typifies ancient SedEx deposits. Some economic geologists use the Red Sea deeps as analogues for volcanic massive sulphides, and some argue it even illustrates aspects of some stratiform Cu accumulations. Many such economic geology studies have the propensity to ignore the elephant in the room; that is the Red Sea deeps are the result of brine focusing by a large Tertiary-age halokinetically-plumbed seafloor brine association. This helps explain the large volume of metals compared to Cyprus-style and mid-ocean ridge volcanic massive sulphides (Warren 2016, Chapters 15 and16).

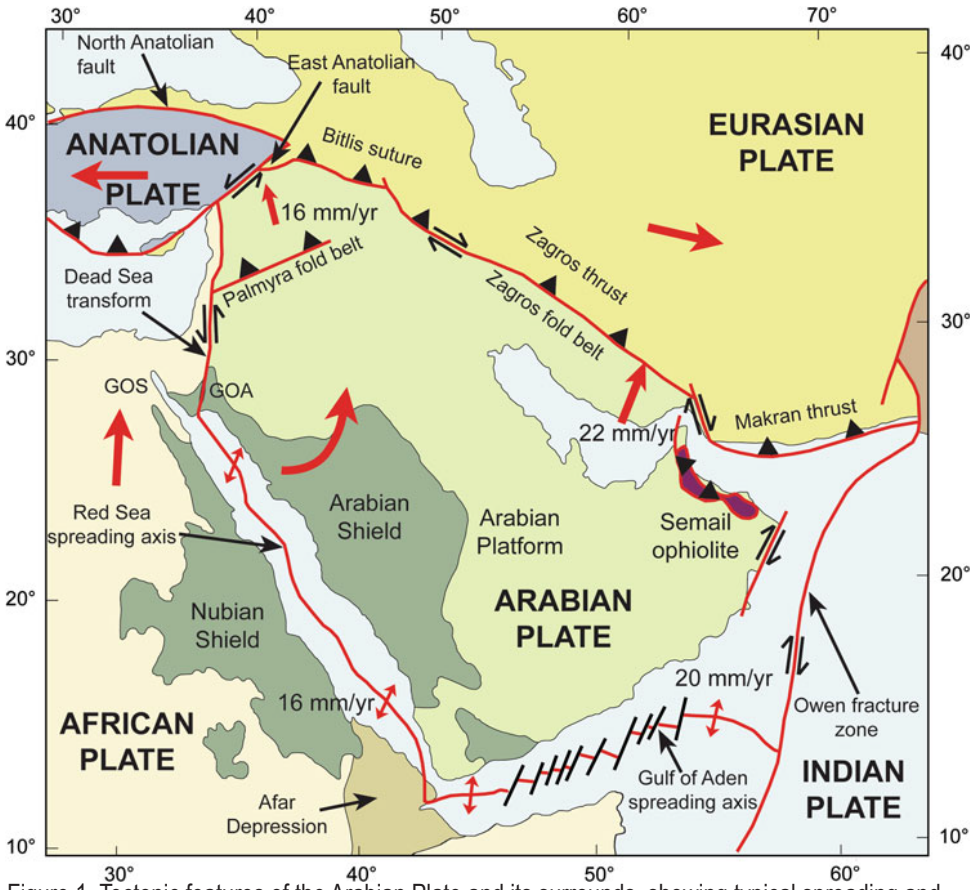

Figure 1. Tectonic features of the Arabian Plate and its surrounds, showing typical spreading and subduction rates (after Stern and Johnson, 2010; Rasul and Stewart, 2015).

In my mind what is most important about the brine lakes on the deep seafloor of the Red Sea is the fact that they exist with such large lateral extents only because of dissolution of the hosting halokinetic slope and rise salt mass. Seismic surveys conducted in the past decade in the Red Sea show extensive salt flows (submarine salt glaciers) along the whole of the Red Sea Rift (at least from 19–23°N; Augustin et al., 2014; Feldens and Mitchell, 2015)). In places, these salt sheets flow into and completely blanket the axial region of the rift. Where not covered by namakiers, the seafloor comprises volcanic terrain characteristic of a mid-ocean spreading axis. In the salt-covered areas, evidence from bathymetry, volume-balance of the salt flows, and geophysical data all seems to support the conclusion that the sub-salt basement is mostly basaltic in nature and represents oceanic crust (Augustin et al., 2014).

The Rift

The Red Sea, located between Egypt and Saudi Arabia, represents a young active rift system that from north to south transitions from continental to oceanic rift (Rasul and Stewart, 2015). It is one of the youngest marine zones on Earth, propelled by an area of relatively slow seafloor spreading (≈1.6 cm/year). Together with the Gulf of Aqaba-Dead Sea transform fault, it forms the western boundary of the Arabian plate, which is moving in a north-easterly direction (Figure 1; Stern and Johnson, 2010). The plate is bounded by the Bitlis Suture and the Zagros fold belt and subduction zone to the north and north-east, and the Gulf of Aden spreading center and Owen Fracture Zone to the south and southeast. The Red Sea first formed about 25 Ma ago in response to crustal extension related to the interface movements of the African Plate, the Sinai Plate, and the Arabian Plate (Schardt, 2016). The present site of Red Sea rifting is controlled, or largely overprinting, on pre-existing structures in the crust, such as the Central African Fault Zone. In the area between 15° and 20° along the rift axis, active seafloor spreading is prominent and is characterized by the formation of oceanic crust with Mid-Ocean Ridge Basalt (MORB) composition for the last 3 Ma (Rasul and Stewart, 2015). In contrast, the northern portion of the Red Sea sits in a magmatic continental rift in which a mid-ocean ridge spreading centre is just beginning to form. That is, the split in the crust that is the Red Sea is unzipping from south to north (Figure 1).

The Salt

The rift basement is covered a thick sequence of middle Miocene evaporites that precipitated in the earlier hydrographically isolated stage of rifting (Badenian – Middle Miocene). The maximum thickness of rift-fill sediments, including halokinetic salt, is around 8,000 m in the Morgan basin in the southern Red Sea (Farhoud, 2009; Ehrhardt et al., 2005). Girdler and Southren (1987) conclude that Miocene evaporites first accumulated on Red Sea transitional crust but must have later flowed downdip to now cover parts of the axial zone (basaltic) of the Plio-Pleistocene oceanic crust. At latitudes of 20° to 23° N, transform fracture zones provide focused passage-ways for salt flow. They also

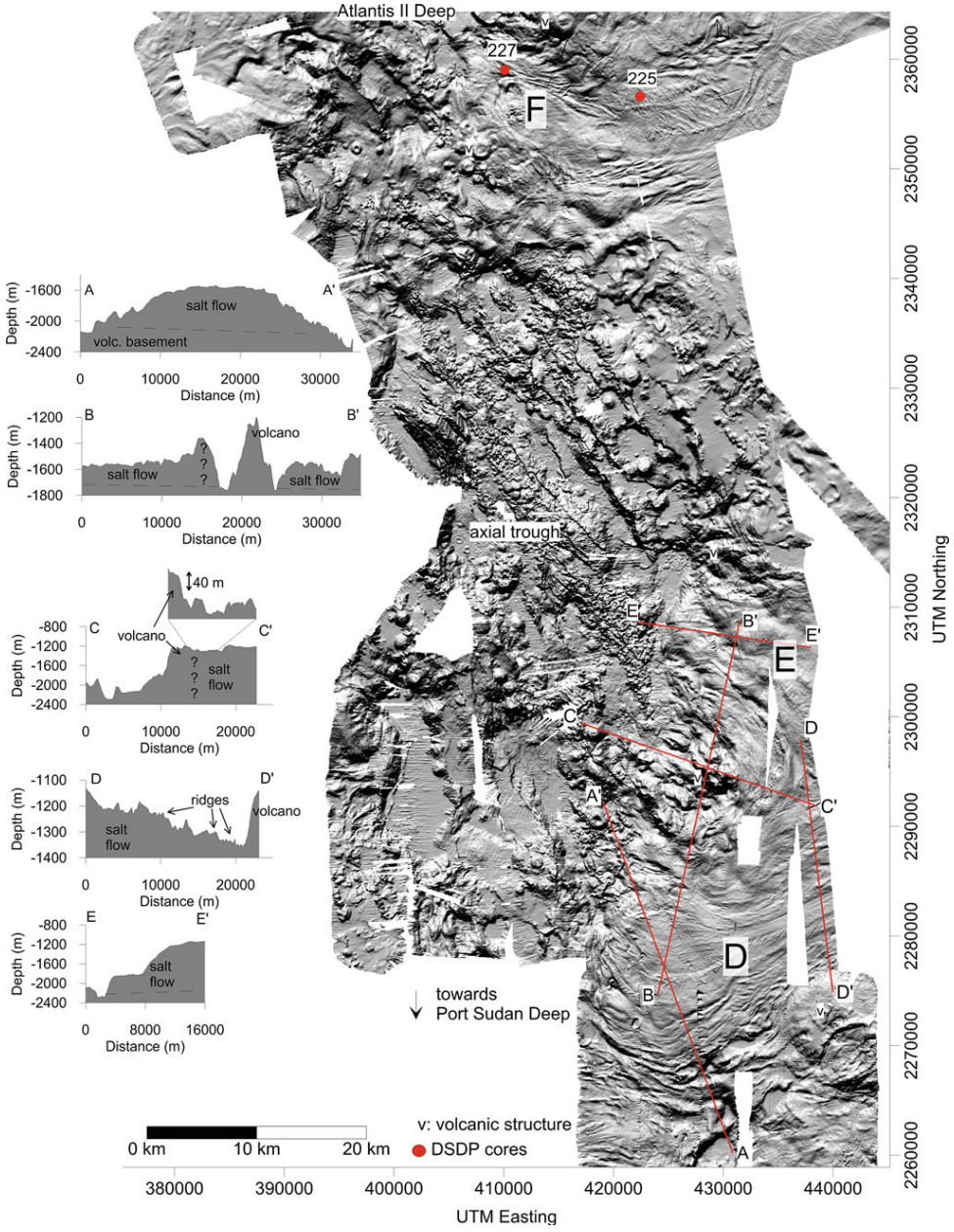

Figure 2. Shaded relief image of multibeam data south of Atlantis II Deep showing three flowlike salt -cored features D, E, and F in the Central Red Sea (after Feldens and Mitchell, 2015).

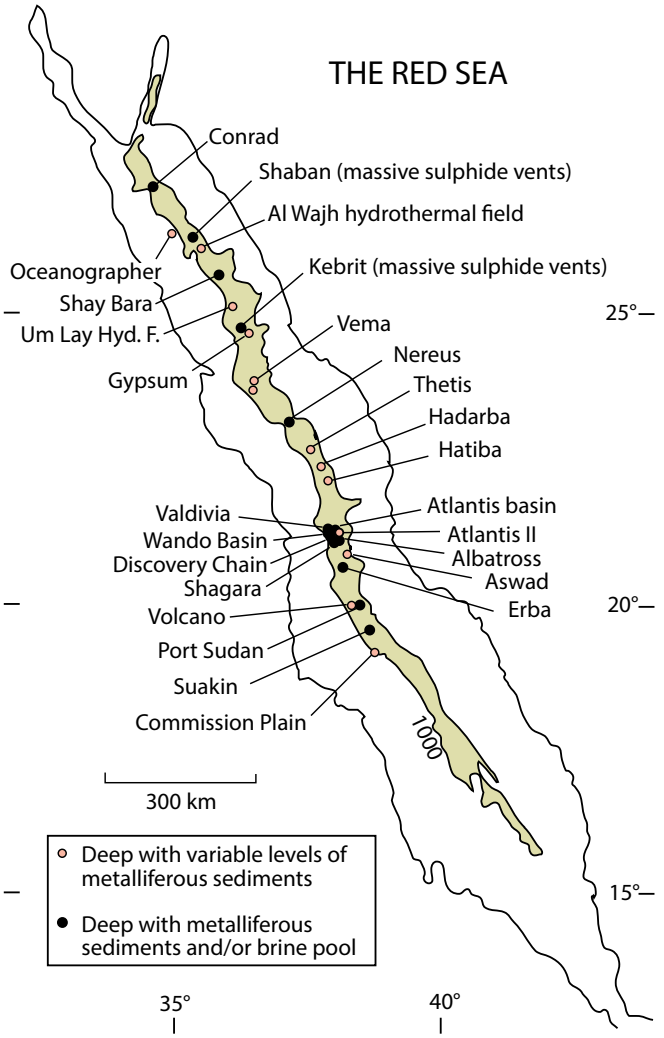

Figure 3. Locality map of deeps along the Red Sea showing different characteristics, metalliferous versus brine (in part after Blum & Puchelt, 1991).

enable the involvement of dissolving salt in axial hydrothermal circulation, so producing pools of dense hot brines and the topographic isolation of spreading segments into evaporite-enclosed deeps (Feldens and Mitchell, 2015). So today, flow-like features cored by Miocene evaporites are situated along the axis of the Red Sea atop younger magnetic seafloor spreading anomalies. However, not all brine seeps occur in or near the deep axis of the Red Sea on the downdip edge of flowing Miocene salt, some occur in much shallower suprasalt positions nearer the coastal margins of the Red Sea, in waters just down dip of actively-growing well-lit coral reefs (Batang et al., 2012).

Six salt flows, most showing rounded fronts in plan-view, with heights of several hundred meters and widths between 3 and 10 km, are seen in high-resolution bathymetry and DSDP core material around Thetis Deep and Atlantis II Deep, and between Atlantis II Deep and Port Sudan Deep (Figure 2; Feldens and Mitchell, 2015; Mitchell et al., 2010). Relief on the underlying volcanic basement surface likely controls the positions of individual salt flow lobes. On the flow surfaces, along-slope and downslope ridge and trough morphologies have developed parallel to the local seafloor gradient, presumably due to the extension of the hemiplegic sediment cover or strike-slip movement within the evaporites.

Some sites with irregular seafloor topography are observed close to the flow fronts, interpreted to be the result of dissolution of Miocene evaporites, which contributes to the formation of brine lakes in several of the endorheic deeps (Feldens and Mitchell, 2015). Based on the vertical relief of the flow lobes, deformation is still taking place in the upper part of the evaporite sequence. Considering the salt flow that creates the Atlantis II Deep in more detail, strain rates due to dislocation creep and pressure solution creep are estimated to be 10–14 sec-1 and 10–10 sec-1, respectively, using given assumptions of grain size and deforming layer thickness (Feldens and Mitchell, 2015). The latter strain rate is comparable to strain rates observed for onshore salt flows in Iran and signifies flow speeds of several mm/year for some offshore salt flows. Thus, salt flow movements can potentially keep up with Arabia–Nubia tectonic half-spreading rates across large parts of the Red Sea (Figure 1)

The Deeps

Beneath waters more than a kilometre deep, along the deep rift axis, there are 26 brine pools and deeps, some of which are underlain by metalliferous sediments (Figure 3; Blanc and Anschutz 1995, Blum and Puchelt, 1991). Because of varying size, age, and formation history between the various deeps, Ehrhardt and Hübscher (2015) discriminate between central and northern Red Sea deeps. The larger central Red Sea deeps are located in the axial trough and are separated by inter-trough zones. They are floored by young basaltic crust and exhibit magnetic anomalies not older than 1.7 Ma. The northern Red Sea deeps are smaller and form only isolated deeps within the axial depression. Some of them are accompanied by volcanic activity. Many of the central Red Sea deeps contain bottom-water brines and metalliferous sediments, pointing to hydrothermal circulation of seawater (Schmidt et al., 2015). The largest and most prominent deep is the Atlantis II Deep, located in the central part of the Red Sea in the vicinity of other large deeps such as the Chain Deep and Discovery Deep. Other prominent deeps are the Tethys and Nereus Deeps further north, but still in the central part of the Red Sea.

Historically, the various deeps along the Red Sea rift axis are deemed to be initial seafloor spreading cells that will accrete sometime in the future into a continuous spreading axis. Northern Red Sea deeps are isolated structures often associated with single volcanic edifices in comparison to the further-developed and larger central Red Sea deeps where small spreading ridges are locally active (Ehrhardt and Hübscher, 2015). But not all deeps are related to initial seafloor spreading cells, and there are two types of ocean deeps: (a) volcanic and tectonically impacted deeps that opened by a lateral tear of the Miocene evaporites (salt) and Plio-Quaternary overburden; (b) non-volcanic deeps built by subsidence of Plio-Quaternary sediments due to evaporite subrosion (dissolution) processes. Type b) deeps develop as evaporite collapse structures (Figure 4: Ehrhardt and Hübscher, 2015). In contrast, the type (a) volcanic deeps can be correlated with their positions in NW–SE-oriented segments of the Red Sea, which are daylighted volcanic segments. The N–S segments,

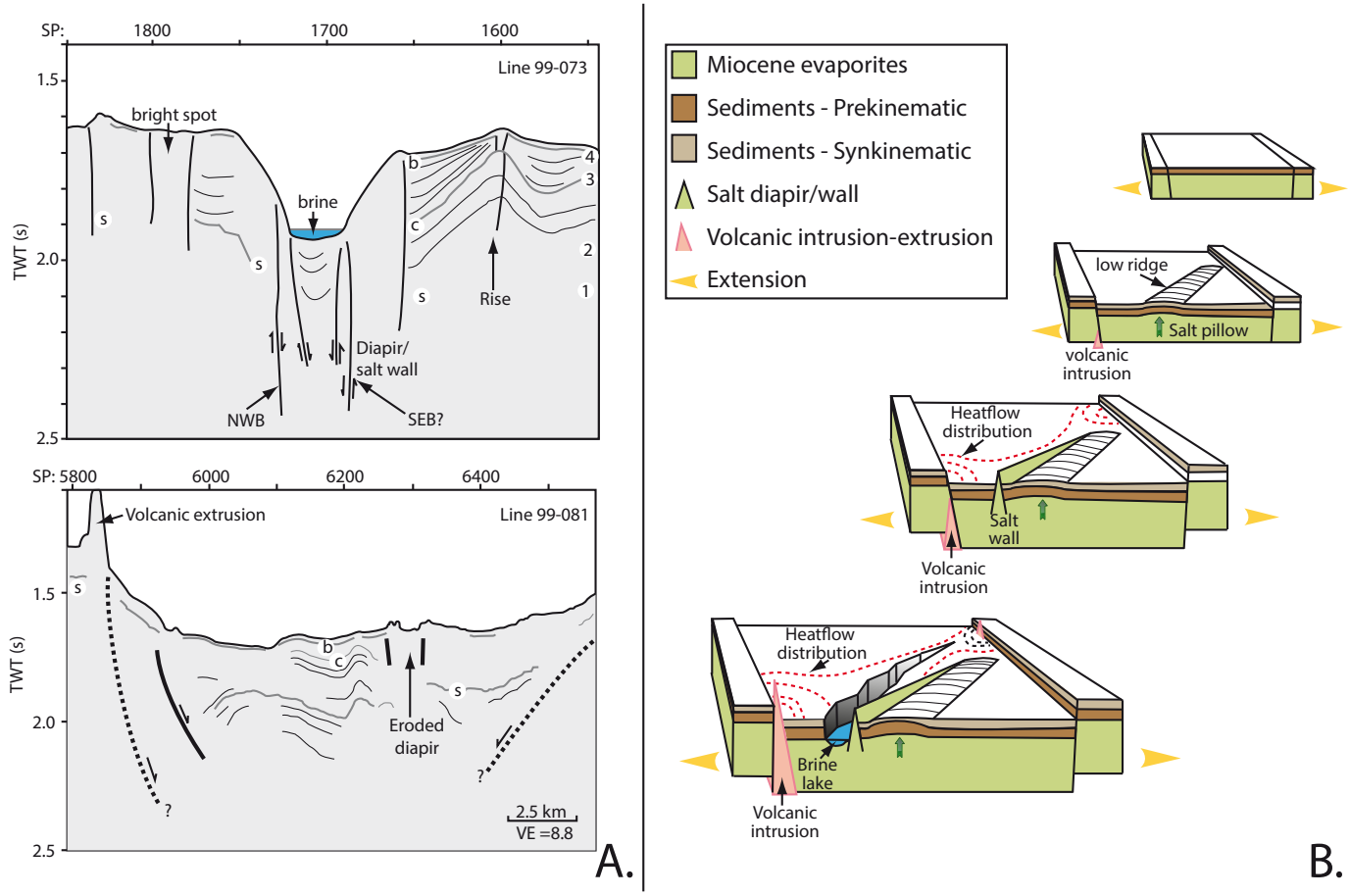

Figure 4. Conrad Deep at the northern end of the axial rift in the Red Sea. A) Representative seismic showing the association of extension, diapirism and volcanism as the brine deep forms. Some salt structures are active, some are collapsing. Collapsed structures probably contribute to formation of brines and brine pools. B) Evolution of the features in the Conrad Deep as it experiences ongoing extension (after Ehrhardt et al., 2005).

between these volcanically active NW–SE segments, is called a "non-volcanic segment" as no volcanic activity is known, in agreement with the magnetic data that shows no major anomalies. Accordingly, the deeps in the "nonvolcanic segments" are evaporite collapse-related structures creating discontinuities and brine breakout zones in and atop the salt sheets without the need for a seafloor spreading cell.

Such evaporite collapse-type ocean deeps are not limited to the non-volcanic segments, as subrosion processes driven by upwells in hydrothermal circulation are possible at any part of the axial depression, especially along fault damage zones. The combined interpretation of bathymetry and seismic reflection profiles gives further insight into the nature of lateral salt gliding in the Red Sea. Salt rises are typically present where the salt flows above basement faults. The internal reflection characteristic of the salt changes laterally from reflection-free to stratified, which suggests significant salt deformation during the salt deposition. Acoustically-transparent halite accumulated locally and evolving rim synclines were filled by stratified evaporite-related facies. (Figure 5)Both types of deeps, as defined by Ehrhardt and Hübscher (2015), are surrounded by thick halokinetic masses of Miocene salt with brine chemistry in the bottom brine layer that signposts ongoing halite subrosion and dissolution. Red Sea deeps were discovered in the 1960s at a time when lateral translation of salt (gliding and spreading) and the formation of density stratification that define deepsea hypersaline anoxic lakes (DHALS) were not known (Warren, 2016). Today, with our knowledge of seeps and hypersaline seafloor depressions in halokinetic terranes on the slope and rise in the Gulf of Mexico and accretionary ridges in the parts of the Mediterranean Sea, we now know that the brine-filled deeps on the floor of the Red Sea are just another example of DHALs. What is most interesting in the chemical make-up Red Sea DHALS are the elevated levels of iron, copper and lead that occur in some deeps, especially the deepest and one of the most hypersaline set of linked depressions known as the Atlantis II deep (Figure 6).

Brine Chemistry in Red Sea DHALS

Most Red Sea deeps contain waters with somewhat elevated salinities, compared to normal seawater (Table 1). Bulk chemistry of major ions in bottom brines from the various Red Sea DHALS are covariant and are derived by dissolution of the adjacent and underlying Miocene halite (Figure 7; replotted from Schmidt et al., 2015).

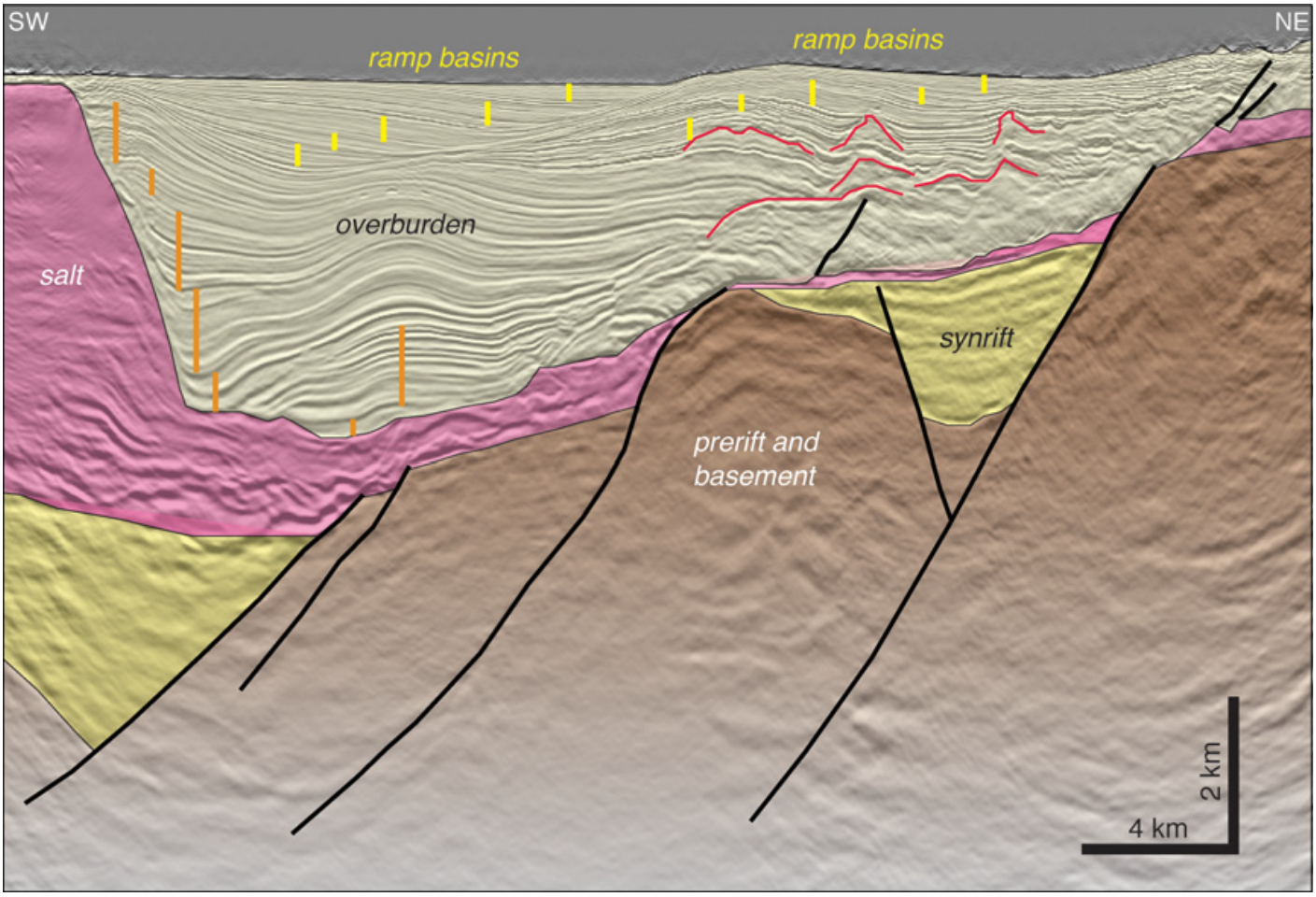

Figure 5. 3-D depth-migrated seismic profile from the Saudi Arabian half of the northern Red Sea. Red lines in overburden show tops of carbonate buildups. Vertical lines indicate depocenter axes: orange pattern shows a half-turtle adjacent to a diapir; yellow lines show two sets of landward-shifting depocenters (ramp basins) in the same stratigraphy that record basinward translation over ramps in the salt décollement formed by the two major basement faults. Vertical exaggeration 2 : 1; data courtesy of Saudi Aramco. (after Rowan, 2014)

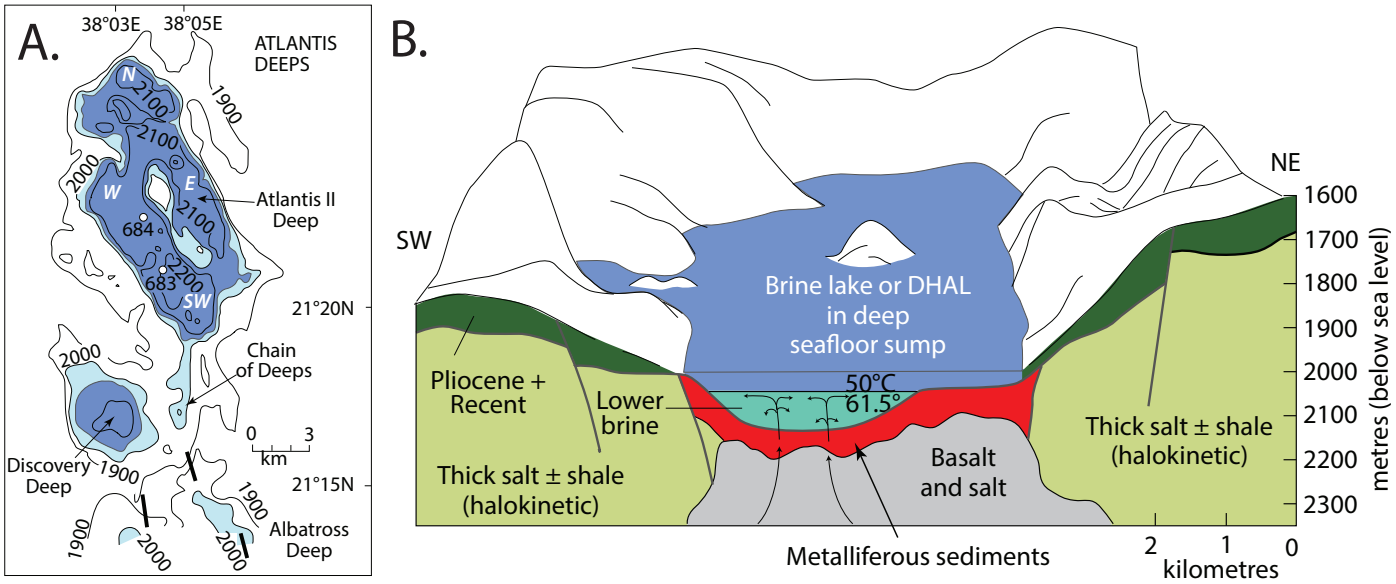

Figure 6. Atlantis II Deep region, Red Sea. A) Bathymetry of the Atlantis II deep and adjacent seafloor depressions, contours in metres (after Anschutz and Blanc, 1995). B) Schematic showing relationship of Atlantis brine lake (DHAL) to adjacent dissolving masses of halokinetic Miocene salt (after Anschutz & Blanc 1995).

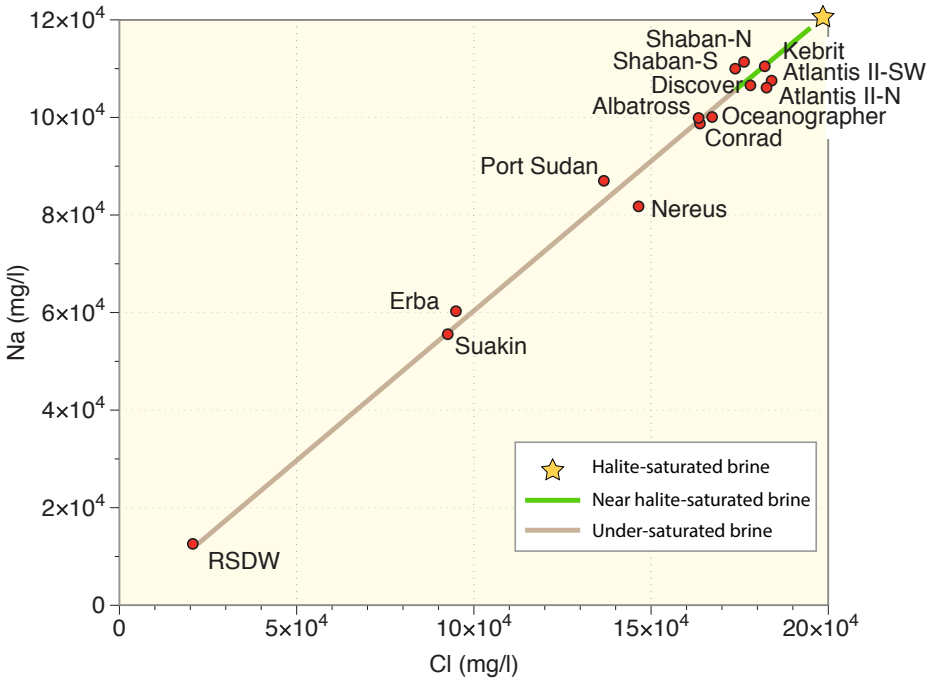

Figure 7. Na and Cl concentrations of Red Sea brine plot along a mixing line between Red Sea deep seawater (RSDW) and nearly saturated waters in the more saline deep brines (replotted from Table 1 in Schmidt et al., 2015).

Mineralization in Red Sea DHALS

Economically, the most important brine pool is the Atlantis II Deep; other smaller deeps, with variable development of metalliferous muds and brine sumps, include; Commission Plain, Hatiba, Thetis, Nereus, Vema, Gypsum, Kebrit and Shaban Deeps (Figure 3; Chapter 15, Warren 2016). Laminites of the Atlantis II Deep are highly metalliferous, while the Kebrit and Shaban deeps are of metalliferous interest in that fragments of massive sulphide from hydrothermal chimney sulphides were recovered in bottom grab samples (Blum and Puchelt, 1991). All Red Sea DHALS are located in sumps along the spreading axis, in the region of the median valley. Most of these axial troughs and deeps are also located where transverse faults, inferred from bathymetric data, seismic, or from continuation of continental fracture lines, cross the median rift valley in regions that are also characterised by halokinetic Miocene salt. Not all Red Sea deeps are DHALS and not all Red Sea DHALS overlie metalliferous laminites.

The variably metalliferous seafloor deeps or deepsea hypersaline anoxic lakes (DHALs) in the deep water axial rift of the Red Sea define the metalliferous end of a spectrum of worldwide DHALs formed in response to sub-seafloor dissolution of shallowly-buried halokinetic salt masses. What makes the Red sea deeps unique is that they can host substantial amounts of metal sulphides, and, as Pierre et al. (2010) show, a Red Sea deep without the seafloor brine lake, is not significantly mineralised.

In my opinion, it is the intersection of the DHAL setting with an active to incipient midocean ridge (ultimate metal source), and a lack of sedimentation in the DHAL, other than hydrothermal precipitates (including widespread hydrothermal anhydrite), that explains the size and extent of the Atlantis II deposit. Its salt-dissolution-related brine hydrology, with a lack of detrital input, changes the typical mid-ocean massive-sulphide ridge deposit (with volumes usually around 300,000 and up to 3 million tonnes; Hannington et al., 2011) into a more stable brine-stratified bottom hydrology, which can fix metals over longer time and stability frames, so that the known sulphide accumulation in the Atlantis II Deep today has a metal reserve that exceeds 90 million tonnes.

The Red Sea DHAL evaporite-metal-volcanic association underlines why vanished evaporites are significant in the formation of giant and supergiant base metal deposits. Most thick subsurface evaporites in any tectonically-active metalliferous basin tend to flow and ultimately dissolve. Through their ongoing flow, dissolution and alteration, chloride- and sulphate-rich evaporites can create stable brine-interface conditions suitable for metal enrichment and entrapment. This takes place in subsurface settings ranging from the burial diagenetic through to the metamorphic and into igneous realms. An overview of a selection of the large-scale ore deposits associated with hypersaline brines tied to dissolving/altered and "vanished" salt masses, plotted on a topographic and salt basin base, shows that the majority of evaporite-associated ore deposits lie outside areas occupied by actual evaporite salts (Figure 8; see Warren Chapters 15 and 16 for detail). Rather, they tend to be located at or near the edges of a salt basin or in areas where most or all of the actual salts have long gone (typically via subsurface dissolution or metamorphic transformation). This widespread metal-evaporite association, and the enhancement in deposit size it creates, is not necessarily recognised as significant by geologists not familiar with the importance of "the salt that was." So evaporites, which across the Phanerozoic constitute less than 2% of the world's sediments, are intimately tied to (Warren, 2016):

All supergiant sediment-hosted copper deposits (halokinetic brine focus)

More than 50% of world's giant SedEx deposits (halokinetic brine focus)

More than 80% of the giant MVT deposits (sulphate-fixer & brine)

The world's largest Phanerozoic Ni deposit

Many of the larger IOCG deposits (meta-evaporite, brine and hydrothermal)

Figure 8. A selection of metalliferous ore deposit provinces where formation is tied to the presence of hypersaline brines and/or evaporites (see Warren 2016 for further explanation of these and many other saline-tied deposits). Also, positions of the world's larger halite-dominated basins are plotted as orange-coloured areas, anhydrite-dominated as green (base metal plots and types extracted from SaltWorks® 1.6 database).

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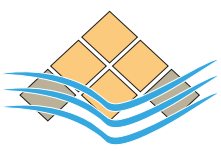

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