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Mobilizing salt: Magma-salt interactions

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ABSTRACT

Salt sequences form an integral part of many sedimentary basins worldwide. Many of these basins have experienced igneous activity either syn- or post-deposition of the salt sequences. Despite this, little work has so far been undertaken to understand magma-salt interactions within the subsurface, and how aspects such as salt halokinesis may be influenced by igneous activity. Within this paper, we detail the first direct description of relationships and textures that are developed during intrusive igneous-salt interaction. We show that salt composition appears to play a dominant role in controlling where igneous intrusions invade laterally through salt sequences in a sedimentary basin. In particular, we illustrate that hydrous salts, such as carnallite, act as preferential horizons for lateral magma intrusion. This lithological control appears primarily related to the heating and subsequent dehydration reaction of carnallite, which causes the carnallite to behave as viscous fluidal horizons, resulting in the non-brittle emplacement of magma, and spectacular peperitic salt-magma mingling textures. We suggest that heating and transformation of carnallite and other hydrous salts into viscous fluidal horizons during igneous intrusion within a regional salt sequence may act as a possible trigger for contemporaneous halokinesis, by creating fluid-like viscous detachment layers. Over longer time scales, however, a solidified rigid boxwork of dikes and sills may create zones of increased mechanical strength that will locally inhibit further salt flow.

INTRODUCTION

Salt sequences typify many sedimentary basins worldwide, and play a significant role in their petroleum systems by acting as seals and creating traps (Warren, 2006). A number of these basinal salts have been impacted by intrusive and extrusive igneous events, either syn- or post-depositionally (Loehr, 1979; Knipping, 1989; Carniel et al., 2010; Wall et al., 2010; Playà and Gimeno, 2006). While the diagenetic and tectonic interaction of dissolving and flowing salt with other sediments in these basins has been intensively studied (e.g., Underhill, 2004; Cartwright et al., 2012; Jackson and Lewis, 2012), there is currently very little published work on the impact of igneous systems on subsurface salt sequences, despite evaporites and volcanism forming important components in many rifted margins. In particular we do not know (1) how igneous activity in a basin interacts with salt sequences, (2) the emplacement mechanism by which magma intrudes into salt sequences, and (3) if lithological variation in salt sequences imparts any control on sites of emplacement into a salt mass. Additionally, we have little predictive knowledge to assess what parts of a salt sequence may be impacted by igneous activity.

Hence the aim of this paper is to explore the interaction of salt with mafic igneous intrusions via a case study in the Herfa-Neurode mine in central Germany (part of the Werra salt complex) (Fig. 1). Within the mine, Miocene (15–20 Ma) mafic magma intruded the Permian (255 Ma) salt mass, driving spectacular intermingling and melting textures within the hydrous salts of the halite-dominant Zechstein salt sequence. In particular, we note that horizons rich in different salt types, such as halite (NaCl) or carnallite ($KMgCl_3 \cdot 6H_2O$), play a key role in controlling both where the magma intrudes laterally within the salt sequence and the emplacement mechanism of the magma (brittle versus non-brittle). Although examples analyzed in this study are restricted to the mine scale, igneous emplacement mechanics, by their nature, will operate on a scale-invariant basis (e.g., McCaffrey and Petford, 1997; Schofield et al., 2012). We therefore suggest similar, but as yet unrecognized, evaporite-dependent interactions may occur at the basin scale in regions where significant igneous activity is developed in close proximity to mineralogically diverse and significant evaporite sequences (e.g., Brazil, Angola, Afar, Siberia, and the North Sea).

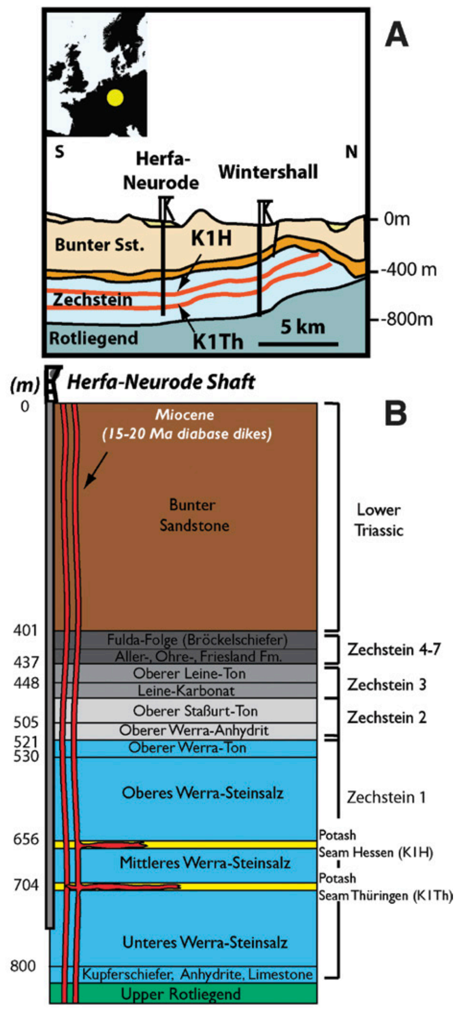

Figure 1. A: Location of Herfa-Neurode mine (Germany) and sketched cross section (modified from Warren, 2006) across mine complex. K1H—Kaliflöz Hessen; K1Th—Kaliflöz Thüringen; Sst.—sandstone. B: Stratigraphic column through mine and levels of the two potash seams where sill intrusions occur (modified from Schade, 2008).

GEOLOGICAL OBSERVATIONS

The study took place in the Herfa-Neurode mine located in the Werra-Fulda Basin in the Hessian district of central Germany (Fig. 1). The sequences studied consist of the carnallite-rich Kaliflöz Hessen (K1H) and Kaliflöz Thüringen (K1Th) intervals, located 650–710 m below the present-day surface and which form part of the Zechstein 1 (Z1) bedded Werra salt succession (Warren, 2006). K1H and K1Th range in thickness from 2 m to 10 m, and are generally subhorizontal. The deposits were laid down in the epicontinental marine restricted Southern Permian Basin, which records at least six evaporation cycles (Z1–Z6) and extends over a distance of 1700 km from northern England to the Baltic States (van Wees et al., 2000).

Our observations focus on dike intersections with the two mined potash salt horizons (K1H and K1Th). A range of intrusion styles, facies, and textures can be directly observed within the mine (Figs. 2, 3, and 4), with dikes and sills

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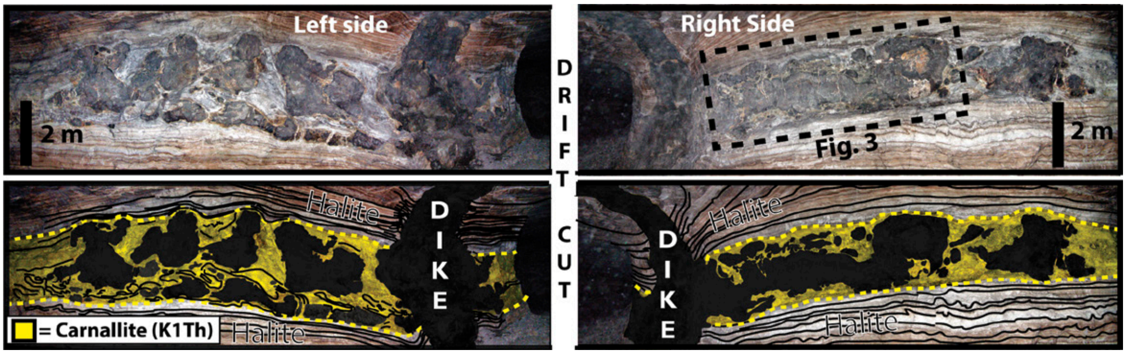

Figure 2. Drift cut through dike and sill. Note planar contacts of upper part of dike in contact with layered halite. Highly bulbous, pillow-like nature of sill can be seen where it has intruded ~2.5-m-thick sequence rich in carnallite. K1Th—Kaliflöz Thüringen.

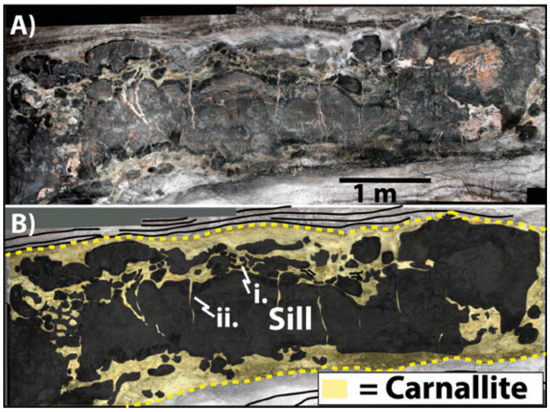

Figure 3. A: Enlargement of Figure 2. B: Interpretation of A. Note fluidal peperitic texture developed at sill margins between salt and diabase (see Movie DR1 in the Data Repository [see footnote 1]). i—texture indicative of non-brittle fluidal interface having been in existence between intruding magma and carnallite sequence at time of intrusion (i.e., both were acting as viscous fluids); brittle cooling fractures can also be seen, having opened subvertically within irregular sill body. ii—fractures filled with salt, indicating that carnallite sequence was still behaving as viscous fluid during cooling of diabase sill.

ranging from tens of centimeters to 4–5 m in thickness. For ease of comparison, intrusive structures will be broadly divided into brittle and non-brittle styles, although it is clear that intrusion margins can display aspects of both styles in close proximity.

Non-Brittle Emplacement

Generally, subvertical diabase dikes cutting the halite-dominated sequences within the mine typically possess planar sides, implying that they are emplaced in a brittle fashion (Rubin, 1995). However, where dikes cut through carnallite-rich layers, they locally display irregular bulbous contacts and sill-like geometries (Fig. 4A).

The relationship between evaporite mineralogy and dike-sill morphology is illustrated in Figure 2, where a subvertical dike displays a bulbous protrusion that feeds a subhorizontal, ~2-m-thick sill that intrudes into a carnallite-rich layer. Internally, the sill does not display planar contacts; rather, it has an irregular chaotic form, made up of bulbous pods or pillows of diabase with extensive amoeboid, globular, and elongate globule peperitic texture (after Skilling et al., 2002) (i in Fig. 3B; Fig. 4B). Peperite is an indicative texture developed when non-brittle emplacement and fluid-like interactions between intruding magma and the host rock have occurred (Schofield et al., 2012). Therefore the bulbous non-planar nature of the sill intrusions and the associated peperitic internal textures imply that the magma was intruding in a non-brittle fashion into the carnallite horizon. For this to occur, the carnallite must have also been acting in a non-brittle fluid-like fashion during sill intrusion.

Brittle Emplacement

In addition to the dominant non-brittle, peperite-like structures displayed in the sills, a series of cross-cutting brittle fracture fills are observed within the diabase blocks (ii in Fig. 3B). Importantly, these fractures are infilled with re-crystallized sylvite and carnallite, suggesting that the salt was still in a viscous state during fracture formation, thus allowing it to enter the cooling diabase fractures as they formed.

Fractures within the sill bodies fall into two main types. On a larger scale (tens of centimeters to meters), fractures occur that either partially or completely cut through the sill. Margins of these fractures do not always show sharp contacts, and can display a hackled appearance on the fracture walls (Figs. 4C–4E). On a smaller (centimeter) scale, fractures, commonly occurring at contacts, on occasion display heavily fractured and brecciated edges (Fig. 4F).

DISCUSSION AND CONCLUSIONS

Magma Cooling and Fractures

The nature and timing of all of the fractures seen within the sills appear to be largely controlled by the cooling (and contractional) regime of the intruding magma. Although the magma intruded in the sills in a largely non-brittle manner, during cooling, at the point at which the magma started to contract and form fractures, the surrounding salt was still hot enough to

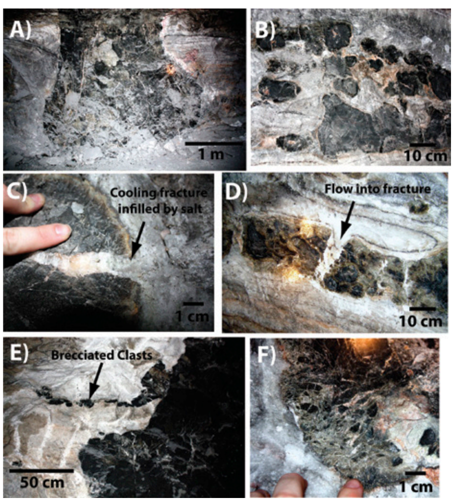

Figure 4. A: Dike showing bulbous margins at contact with carnallite sequence. Creation of bulbous contact appears to be first stage in lateral emplacement of magma into carnallite horizons. See text for details of processes involved. B: Peperitic texture developed between carnallite and diabase sill. C: Injection of salt slurry into cooling joints (see ii in Fig. 3B). D: Evidence of salt flow and creep during cooling of magma, leading to boudinage and expansion of cooling joint, and flow of salt into expanded fracture. E: Brecciated "train" of diabase clasts emanating from non-brittle sill contact, due to creep of salt after diabase has cooled and become brittle. F: Development of complicated salt-magma cooling texture at bulbous diabase contact.

remain as a viscous fluid and undergo creep. This appears to have led to boudinage-type processes, with sill fractures being expanded and pulled open as the magma in the sills solidified (Fig. 4D). The progression of the magma cooling and moving into a brittle regime can also be seen in Figure 4E, which shows a progression from the non-brittle contact of a sill intrusion to a brecciated angular "train" of clasts that display rotation. These appear to have formed when the cooling magma was in a semi-brittle state and was sheared in an elongate fashion by creep in the adjacent carnallite and sylvite (Fig. 4E).

TABLE 1. DECOMPOSITION (LOSS OF STRUCTURAL WATER) AND MELTING POINT TEMPERATURES FOR SELECTED EVAPORITE SALTS

Salt	Formula	Decomposition/melt point (°C)	Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
Epsomite	$MgSO_4 \cdot 7H_2O$	>40–80 °C, loss of water	0.6
Gypsum	$CaSO_4 \cdot 2H_2O$	100–150 °C, loss of water	2.5
Bischofite	$MgCl_2 \cdot 6H_2O$	>120 °C, loss of water	2
Carnallite	$KMgCl_3 \cdot 6H_2O$	140–170 °C, loss of water	0.8
Kieserite	$MgSO_4 \cdot H_2O$	150–200 °C, loss of water	2
Sylvite	KCl	750–790 °C, anhydrous melt	6.7
Halite	NaCl	804 °C, anhydrous melt	6.1
Anhydrite	$CaSO_4$	1460 °C, anhydrous melt	5.7

Note: Decomposition range of hydrous salts depends on pressure and permeability constraints, while thermal conductivities vary according to temperature and pressure (Warren, 2006).

Magma Emplacement and Control of Salt Composition

The composition of salt appears to control where sill intrusions develop within an evaporite sequence. In comparison to halite, carnallite layers in particular appear to act as preferential horizons for sill intrusion. However, when compared to non-intruded carnallite sections, the amount of the magma added to the carnallite horizon represents an addition of ~155% to the horizon. Although some minor doming and host-rock deformation in the carnallite and halite layers above the sill intrusion occurs, this is localized and can only account for ~52% of intruded material (see the GSA Data Repository[1]). The addition of igneous material therefore appears to have been accommodated mostly within the carnallite, by either fluid release (see below) or out-of-section flow of the carnallite. The emplacement mechanism of magma intruding into the carnallite horizon is dominated by non-brittle viscous fluid-fluid interaction (i.e., both the magma and salt were simultaneously acting as viscous fluids during magma intrusion; e.g., Schofield et al., 2012).

Carnallite is mechanically weak and can behave in a ductile fashion (Urai et al., 2008). However, more importantly, carnallite ($KMgCl_3 \cdot 6H_2O$) has a hydrated lattice structure and becomes a viscous fluid when temperatures exceed 140–170 °C as its structural water together with $MgCl_2$ are released (Table 1), resulting in carnallite converting to sylvite plus $MgCl_2$ solution (Warren, 2006). In contrast, the halite above and below the carnallite horizon is anhydrous, with a melting point of ~800 °C. Therefore, it seems likely that the markedly different temperatures at which carnallite and halite begin to act as viscous fluids dictated the mechanism of emplacement (i.e., non-brittle), and in turn thus controlled where the magma preferentially intruded.

In other salt-bearing basins worldwide that have been influenced by igneous activity syn– to post–salt deposition (see the Data Repository), it therefore seems likely that intrusions will preferentially exploit and therefore become concentrated in horizons where carnallite or other common hydrous salt sequences (e.g., gypsum, bischofite) occur. As other hydrous salts (including gypsum) also lose their structural water between 100 °C and 150 °C (see Table 1), it is likely therefore that they will also behave in a non-brittle fashion during magma emplacement.

Wider Implications: Afar

Our work highlights the myriad of emplacement mechanisms that can operate during magma intrusion; in particular, it highlights the notion that magma intruding into a sedimentary basin should not be viewed as having always done so via brittle processes, particularly when dealing with lateral magma emplacement, due to the important role host-rock lithology can play in influencing magma emplacement mechanisms (Schofield et al., 2012).

For example, much recent work has investigated present-day subsurface magma emplacement in the Danakil Depression, Afar, based on seismic and InSAR measurements (Wright et al., 2006, 2012). The assumption is that magma emplacement causes brittle failure (seismically visible fault responses) in and around intruding bodies of magma, and the ground surface above the magma body becomes domed. However, the Danakil Depression and the surrounding region of the Afar contain thick sequences of Pleistocene–Miocene salt, with at least 970 m of evaporite having accumulated beneath the salt pan of Northern Danakil. This sequence also includes laterally continuous horizons of carnallite (ranging from 3 m to 25 m in thickness) in association with the hydrous salt bischofite (~100 m in thickness), occurring at depths ranging from 200 m to 900 m below the surface, as confirmed by borehole data (Hutchinson and Engels, 1970; Allana Potash Corporation, 2011). The Northern Danakil also contains the northern zone of the Erta Ale volcanic range, which is both seismically and volcanically active (Wright et al., 2012), and throughout the past 8–10 m.y., periodic basaltic dike intrusions have sporadically punctured the evaporite deposits (Darrah et al., 2013). Interestingly, as illustration of the close relationship between salt sequences, which are known to contain carnallite and other hydrous salts and the Erta Ale volcanism, the western flank of the Holocene-aged Gada 'Ale volcano, which represents the most prominent northern volcano in the Erta Ale chain, is uplifted by ~100 m by a 2-km-wide salt dome (Barberi and Varet, 1970).

If the same igneous emplacement processes as described within this paper occurred or are occurring currently within the subsurface in the Afar, then it is conceivable that where the magmatic-volcanic feeding system has cut through the hydrous salt sequences of carnallite and bischofite, intrusion may be focused laterally into salt sequences away from the feeding dikes. In such a circumstance, emplacement may not be recorded seismically (cf. Wright et al., 2012), due to non-brittle intrusion of magma into the salt mass. This raises the possibility that, in the Afar, seismology-based evidence may have overemphasized the vertical movement of magma in dikes, and that substantial, unrecorded lateral movement of magma may be occurring or has occurred through non-brittle accommodation in subsurface salt sequences. This is supported by bedded halite and carnallite sequences underlying the entire Danakil, although they are currently obscured by dike-fed lava flows and alluvium (Warren et al., 2006). In the German mine complex, the dikes post-dated the deposition of the salt by 235 m.y., but the carnallite sequences still influenced the zones of sill intrusion. Therefore in the Afar, where the age gap between the carnallite deposition and volcanism is small, it seems logical to suggest that the same emplacement mechanisms will operate within the subsurface today.

Furthermore, as shown in the mine examples, the majority of volume accommodation of the intruding magma appears to occur within the carnallite horizon, and by localized host-rock

[1]GSA Data Repository item 2014208, Table DR1 (carnallite-bearing successions and associated volcanism worldwide). Figure DR1 (photo showing localized nature of the doming and host rock deformation that has accommodated sill emplacement), and Movie DR1 (series of photos of a sill intrusion into the Carnallite), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

deformation. This implies that if intrusion is occurring into hydrous salt sequences in the Afar, then relatively little uplift of overlying units would occur. In such circumstances, InSAR measurements may not record lateral emplacement into the salt sequences.

Implications for Halokinesis within Sedimentary Basins

It is clear that magma has the ability to heat adjacent salt and cause it to begin to flow. Underhill (2009) suggested that halokinesis within the southern North Sea basins may have been triggered by the intrusion and subsequent heating of a series of Paleogene dikes, but did not give any details of a potential mechanism. Although the examples we have presented within this paper are small in scale, it is important to note that igneous emplacement mechanics operate on a generally scale-invariant basis (McCaffrey and Petford, 1997; Schofield et al., 2012). Therefore relationships described within this paper, given enough magma supply, could operate over a range of scales, with magma intruding laterally over a large distance. Certainly within the mine, there is documented evidence for 100 m of lateral sill emplacement sourced from 1- to 2-m-thick dikes (Dietz, 1928). Therefore in other basins that have experienced substantial amounts of syn- to post-intrusive activity with respect to salt deposition (e.g., Brazil, Angola, Afar, Siberia; see the Data Repository), it seems likely that the potential exists to drive significant disruption and flow within the salt sequences, largely focused into intervals with abundant hydrous salts. Given enough magma supply, this disruption of salt, on a short term, may in some cases be enough to trigger salt halokinesis (*sensu stricto*: Underhill, 2009).

However, conversely, we also tentatively suggest that, over a longer term, the intrusion of magma into hydrous salts may actually act to impede subsequent halokinesis in the vicinity of intrusions. Although halite is typically the dominant chloride lithology within salt sequences, carnallite horizons are typically among the weakest units within salt sequences and, along with other hydrous salts, form mechanically weak layers in a salt sequence. These are thought to be important in creating heterogeneous deformation during the process of halokinesis (Strozyk et al., 2012; Jackson et al., 2014). The intrusion of magma, and creation of fluid-like behavior in hydrous salts, will quickly cease once the dike-sill network and salt have cooled and solidified. Once solidified, the presence of a substantial sill network within horizons of weak hydrous salt will tend to increase their mechanical strength and therefore may "lock up" zones of previously weak hydrous salts—that is, forming a rigid framework of intrusions, decreasing grain-boundary deformation of the salt, and thus degrading a disseminated zone's ability to act as a mechanically weak region, and therefore locally inhibiting post-intrusion salt flow.

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