Subsurface seismic record of salt glaciers in an extensional intracontinental setting (Late Triassic of northwestern Germany)

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ABSTRACT

In the Northwest German Basin of Central Europe, Late Triassic interaction of normal faulting and salt diapirism during regional extension in subsalt basement locally initiated lateral flow of surface-piercing salt in namakiers (salt glaciers). Using seismic sections and variance attribute maps derived from high-resolution three-dimensional seismic data, we show that when a syndepositional fault cuts a near-emergent diapir crest, the caprock carapace was breached, opening a pathway for salt extrusion. The fault escarpment and the adjacent fault-induced depression allowed focused gravity-driven downward flow of salt across the land surface (a namakier) and its subsequent preservation and encasement in continental (arid redbed) sediments. Geodynamically there is an apparent distinction between the compressional setting of modern namakiers in the arid deserts of Iran and the fault-intersected extensional setting of stacked Keuper namakiers. Stacked namakiers preserved in thicknesses that are seismically resolvable are interpreted to indicate hyperarid conditions in Keuper time. The climate was typical of the highly continental Late Triassic Pangaean supercontinent as it rifted and sagged to form the incipient Atlantic Ocean.

Keywords: salt glacier, diapirs, Northwest German Basin, continental redbeds, extension.

INTRODUCTION

Extrusions of diapiric salt onto continental and marine basins have been described by a number of authors (see GSA Data Repository Table DR1[1]). Active salt glaciers (namakiers) are spectacularly exposed on the flanks salt mountains as high as 300 m in the Zagros fold belt of onshore Iran in a system dominated by tectonic shortening. Today, outside of the Dead Sea depression, there are no terrestrial namakiers in regions of extensional tectonics (see the footnote of Table DR1). Even in the Dead Sea depression, the tectonic setting is not regional extension; rather, it is a local-scale rapidly subsiding transtensional pull-apart basin situated on a regional transform fault (Al-Zoubi and Ten Brink, 2001). In this paper, using cross sections and variance attribute analysis from three-dimensional (3D) seismic data, we present the first (to our knowledge) documentation of a subsurface example of a tiered set of namakiers in an extensional terrestrial (redbed) setting. It is the preserved remnant of a number of ancient salt glaciers extruded onto a Late Triassic redbed landscape within the subsiding Triassic Northwest German Basin.

The structural regime in the Late Triassic of the intracontinental Northwest German Basin of Central and northern Europe reflects incipient North Atlantic rifting and extension that locally formed graben structures (Ziegler, 1990). Rifting in the study area triggered salt movement and near-surface responses, including reactive, active, and passive diapirism (Mohr et al., 2005). The depositional surface in Late Triassic (Keuper) time was made up of a series of salt-filled low-relief playas and pans surrounded by desert redbeds, salt-filled domes, and occasional namakiers.

GEOLOGICAL EVOLUTION OF THE EAST FRISIA AREA

The investigated salt structure is one of a number of similar structures in the east Frisia area of northwestern Germany, located near the Germany-Netherlands border (Fig. 1A). The salt structures are arranged in a series of elongated NNW-trending diapirs, spaced at intervals of ~10 km (Fig. 1B).

Late Paleozoic sedimentation in the east Frisia area (Fig. 1C) deposited upper Rotliegend sediments in a series of playa mudflat–sandflat settings in an extensional regime. Approximately 800 m of bedded sulfate and halite were deposited in this area during the hydrographic isolation and drawdown of the Late Permian Zechstein evaporite basin (Jaritz, 1973; Warren, 2006). Triassic sedimentation changed from continental clastics during the Early Triassic Buntsandstein to shallow-marine sequences of carbonates and evaporites in the Middle Triassic Muschelkalk, to continental clastics with intercalated saline-pan evaporites during Keuper time.

Several phases of Triassic rifting influenced the area and triggered its multiphase salt tectonics (Figs. 1D, 1E). Kinematic restoration modeling shows that decoupled extension in the late Early (middle Buntsandstein) and Middle Triassic (middle Muschelkalk) initiated salt diapirism and lateral salt flow with growth of a pillow-like salt structure (Mohr et al., 2005). Subsequent formation of a basement graben in the early Late Triassic triggered

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[1]GSA Data Repository item 2007240, Table DR1, summary table of selected worldwide salt extrusion occurrences, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

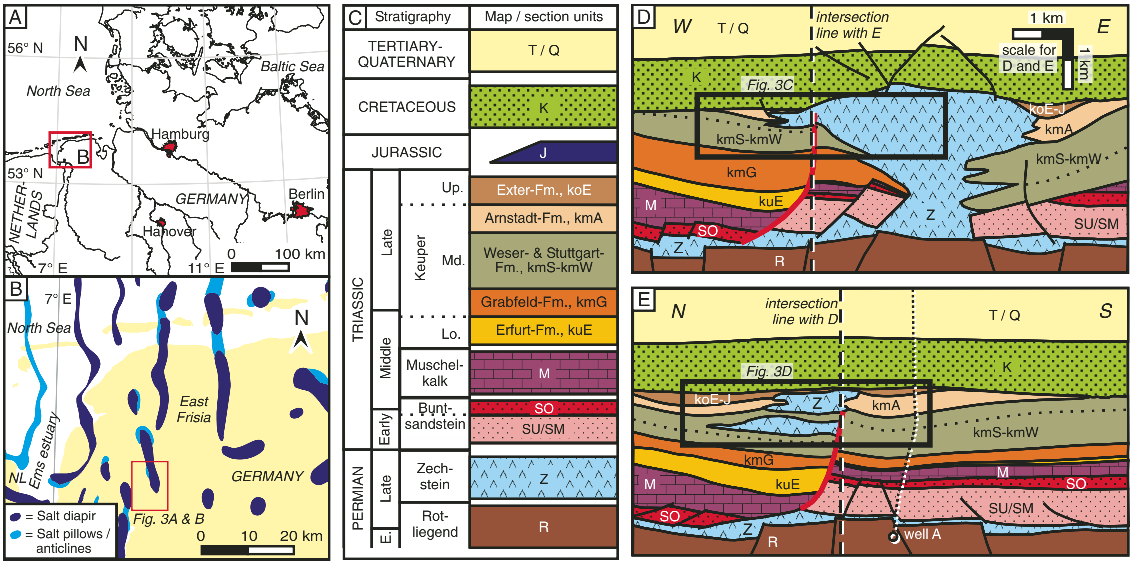

Figure 1. A: Location of study area (inset B) in east Frisia, northwestern Germany, near Germany-Netherlands border. B: Distribution and spacing of salt diapirs and salt pillows and/or anticlines in investigated area. C: Simplified stratigraphy of study area. D: Geological interpretation of seismic W-E section through the salt diapir and the peripheral sink. Rectangle indicates location of enlarged seismic sections (see Figs. 3C, 3D). E: Interpretation of N-S seismic section perpendicular to D showing important extensional fault and linked salt structures in its northern part. Vertical dotted line indicates intersection of the two profiles.

reactive diapirism and the collapse of the salt pillow followed by passive diapirism, during which salt remained at or near the surface, feeding peripheral salt glaciers. The extrusion process stopped in the latest Late Triassic and Jurassic as the falling diapir crest was covered by marine sediments (Mohr et al., 2005).

A major unconformity at the base of the Cretaceous (Figs. 1D, 1E) marks a subsequent episode of regional uplift and tilting in the Middle Jurassic–Early Cretaceous, accompanied by erosion and salt dissolution. Late Cretaceous–early Tertiary compressional tectonics renewed vertical salt movement under substantial sedimentary cover (Mohr et al., 2005).

NAMAKIERS: ANALOGS SUPPLY THE INTERPRETIVE FRAMEWORK

The geometry, evolution, structural framework, and depositional environment of the Triassic salt glacier show similarities to modern continental Iranian namakiers (extrusive salt glaciers) on the flanks of salt-cored mountains in an overthrust and wrench-faulted setting and to extension-driven Neoproterozoic "Christmas tree" diapirs that now crop out as salt ablation (allochthon) breccia and rauhwacke in the Flinders Ranges of South Australia (Dyson, 2004).

Namakiers, or salt glaciers, are surface halokinetic features that can range in size from hundreds of meters to tens of kilometers across and in shape from local rugose wing-like expansions of a diapir stem, to mushroom-shaped lateral extensions of diapirs, to extensive sheets that coalesce into stratiform salt canopies, tiers, or layers. Namakiers creep downslope under very low shear stress after dramatic weakening of the salt by the processes of recrystallization and grain refinement, and associated changes in deformation mechanisms, from dislocation creep to solution-precipitation creep (Urai et al., 1986; Schléder and Urai, 2007).

Salt extrusion to the surface can occur once or many times in the history of a sedimentary basin and can be driven by extension, sediment loading, or compression. The loci of most intense salt flow can thus migrate across a basin over time. The study area (Fig. 1A) represents one of the cases where salt extrusions can be tied to a local extensional faulting regime combined with erosional thinning at or near the crest of a growing salt-filled structure. Neoproterozoic salt constitutes the salt source in the namakiers of the Dashti and Hormazgan provinces in the Zagros fold belt of Iran (Fig. 2), while Miocene salt creates active namakiers in a redbed landscape near Qom, central Iran. Flow rates are much faster during periods of rainfall, and the morphology of the namakiers is a function of the rates of extrusion, lateral flow, and solution by rainwater (Kent, 1958; Talbot and Alavi, 1996). Many flows are sourced on anticlinal flanks rather than anticline crests (Table DR1).

In extensional salt provinces, salt allochthons and namakiers may form during the active to passive diapir phases, where erosion and normal faulting thin the overburden at the diapir's culmination. Gravity shedding and faulting of thinned overburden then allow caprock fragments and salt to flow onto the land surface.

Outer edges of namakiers expand and contract via an interplay between rates of salt supply, external sediment supply (loading), and salt dissolution (Wenkert, 1979). While a salt tongue is at the surface it is continually subject to damming behind outcrop ridges, dissolution,

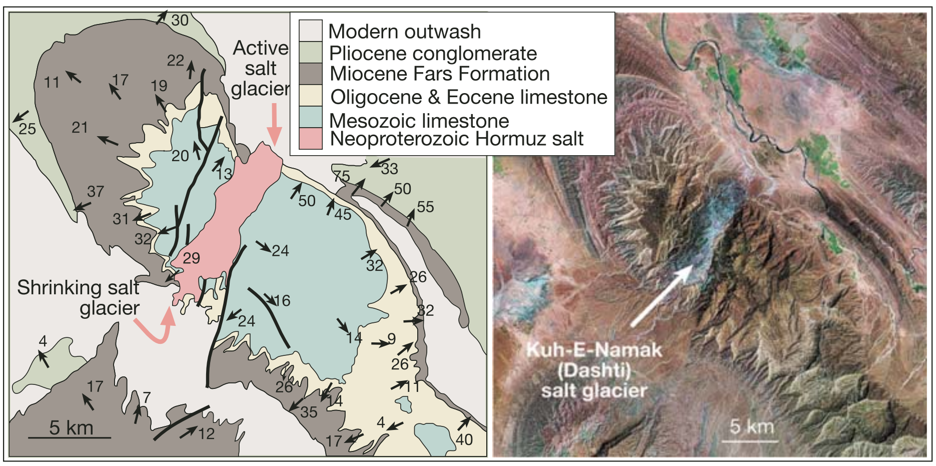

Figure 2. Surface geology (left) and Landsat image (right) of Kuk-e-Namak (Dashti), Iran, 28°16′N, 51°42′E. Faults intersecting the anticlinal dome facilitated salt breakout and formation of surface salt glacier, or namakier. Black arrows indicate bedding dip and azimuth in anticlinal beds (geology after Kent, 1958; Landsat image courtesy of National Aeronautics and Space Administration).

and reworking, and it can supply highly saline groundwater to salt pans in playa and pans atop adjacent rim synclines (zones of salt deflation). Such groundwater-driven reworking of halite from the crests of growing salt structures into peripheral halite pans is seen in the distribution of several evaporite generations in the Ravar basin of eastern Iran (Stocklin, 1961, *in* Jackson et al., 1990) and in the distribution of potash ores in ancient pans about the periphery of Cretaceous salt structures near Khon Kaen, northeastern Thailand (Warren, 2006). Correlations of wireline logs of saline-pan halite beds intersected in wells A–C in the study area suggest a similar dissolution-precipitation interplay in Northwest German Basin withdrawal sinks.

The process of diapir and/or namakier dissolution and contemporaneous precipitation to form stacked saline pan beds, as well as surface outflow of namakier salt, resulted in the preservation of recycled Permian salt in younger stratigraphic levels (i.e., Triassic). This supports Trusheim's (1971) model of salt cyclicity in continental basins and is consistent with the notion that layered Triassic salt originated entirely (in the case of Keuper salt) or at least partially (in the case of Early Triassic Buntsandstein and Muschelkalk salt) from the near surface and surface reworking of the main Permian salt source.

LATE TRIASSIC SALT GLACIERS

In the study area, seismic variance analysis was carried out on a high-resolution 3D seismic data set. This clearly images (buried) salt extrusions ~50 m below the basal Cretaceous unconformity, at ~2 km depth. The variance map shows the morphology of the buried salt glacier to be a fan-like salt apron that covers older sedimentary layers (Fig. 3A). The tongue of the buried extrusion has a jagged outline and an irregular rugged surface with a divergent lineation from east to west. This contrasts with the smooth surfaces of the adjacent clastic sedimentary strata. The extrusion is on the western flank of a NNE-trending salt diapir, which has high variance contrast.

For detailed interpretation of the variance map (Fig. 3A) and for stratigraphic calibration, we used additional information from the 3D seismic data volume and wireline data from four nearby exploration wells (Fig. 3B). Borehole A is 500 m southwest of the diapir (see Figs. 1E, 3B, and 3D), which has a notable bulge in its westernmost part. West of the bulge a surrounding rim syncline is not developed, whereas elsewhere it is typically filled with upper Keuper to Jurassic sediments. The salt glacier, now probably the residue of a former larger salt extrusion, widens into the direction of flow to the southwest. It covers an area of 2.4 km^2, is 2.7 km long, and is 0.5–2.2 km wide. The southern end of the structure trends southeast and is enclosed by a small graben structure. The topographic low of the graben most likely formed the preferred flow path for the namakier. There is also a NE-SW–trending low north of the salt extrusion. This depression, formed by a normal fault (Figs. 1D, 1E), is mostly covered by the namakier.

A seismic cross section (Fig. 3C) of the mapped namakier (labeled as salt glaciers I–IV in Fig. 3) displays a 50–100-m-thick unit of lenticular shape defined by strong seismic reflectors. The strong seismic reflectivity of the glaciers can either be caused by a thin salt layer or represent a residual clay and anhydrite layer related to a dissolution carapace. The lenticular cross section of the salt glacier is clearly traceable through the entire 3D seismic volume and can be distinguished from the flanking sedimentary layers.

Three previous salt extrusions of middle Keuper age are identified in seismic data from the Weser and Arnstadt Formations, and indicate classic "Christmas-tree" morphologies (Figs. 1D, 1E, 3C, and 3D). The seismic profiles show salt wings connected to the western diapir and characterized by irregular low-contrast reflectors that are similar in character to those of the salt mass of the diapir, and thus clearly distinguishable from the adjacent sedimentary layering. For example, the lowermost salt glacier (IV) (Fig. 3D) forms a wedge of ~500-m-thick allochthonous salt between sedimentary strata. This oldest extrusion is only visible in the N-S section (Fig. 3D) because it spreads to the north, in contrast to salt glaciers II and III, which extend to the northwest, and the youngest salt glacier (I; Fig. 3C), which shows a southwestward flow direction.

A major normal fault cuts the sedimentary layers in the eastern part of the seismic sections (Figs. 3C, 3D). On the variance map (Fig. 3A) the fault is indicated by a horizontal offset of the sedimentary strata on both sides of the salt glacier. As can be seen in Figures 1D and 1E (red line), the listric extensional fault with a NW dip was active throughout the Mesozoic. The fault cuts the salt diapir only during late-middle Keuper to late Keuper time (kmW-ko; Fig. 1C).

DISCUSSION

The investigated area is in a marginal position of the Permian and Triassic basins in Central Europe and is close to major faults (Ziegler,

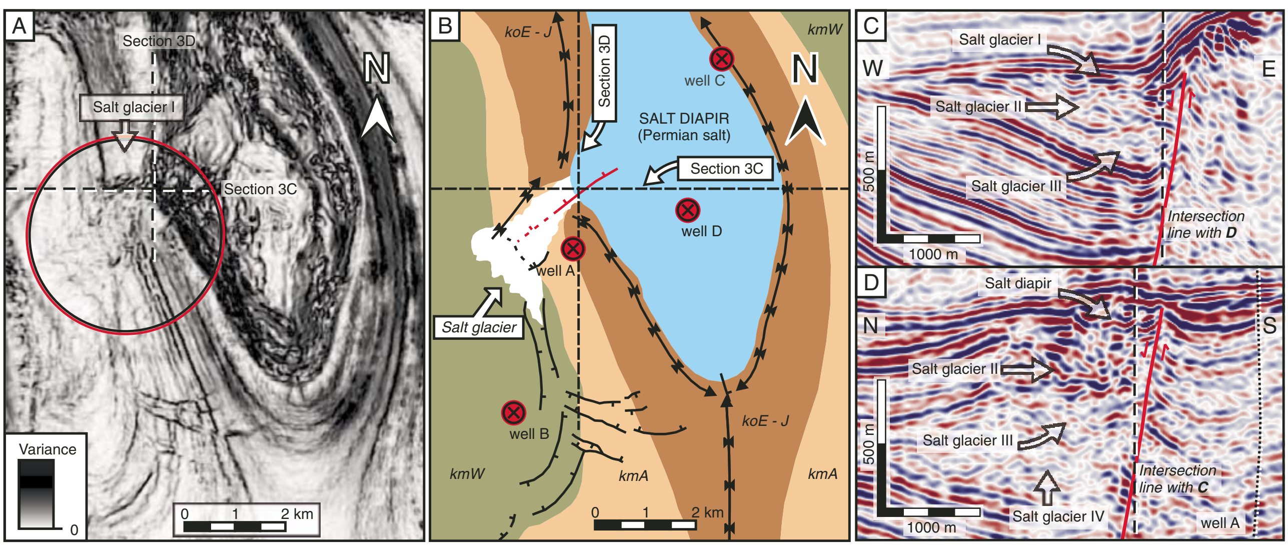

Figure 3. A: Variance map 50 m below unconformity at base of the Cretaceous displays uppermost salt extrusion as fan-like structure inside the circle. B: Geological interpretation of A showing geometry of Late Triassic salt glacier, position of the two cross sections of Figure 1, and location of the wells. C, D: Enlarged seismic sections (2.5 ×) showing salt glacier generations and salt diapir, and accompanying sedimentary layers (location in A; see Figs. 1D, 1E). Vertical dotted lines mark intersection of the two seismic profiles. Trace of well A is shown by dotted line in southern part of section D.

1990). Supra-salt extensional faulting in the Late Triassic overburden adjacent to the diapir fits the regional tectonic setting of the Triassic of the Northwest German Basin (Frisch and Kockel, 1999; Kockel, 2002). Several pulses of basin extension triggered and controlled the main phase of salt diapirism and allochthon growth (Mohr et al., 2005). Regional structure in the study area is characterized by normal faults with adjacent syndepositional depressions that were variably active throughout the Triassic and indicates a loading response via ongoing detached supra-salt faulting. Accommodation space for sediment fill was maintained by the ongoing interplay between regional extension, salt flow, and depositional loading in depressions adjacent to the growing diapir.

At times when a syndepositional fault intersected and cut a near-emergent diapir crest, the caprock was breached and a pathway opened for salt extrusion coupled to renewed diapirism. The fault escarpment and the fault-induced depression allowed gravity-driven downward flow of salt across the land surface (a namakier) and its subsequent preservation atop continental (arid redbed) sediments that were accumulating in fault-defined collapse depressions adjacent to the growing salt diapir. Somewhat similar fault intersections of overburden atop salt-filled bulges also control the onset of the namakier stage and active diapirism on or near the crests of compressional growth anticlines in southeastern Iran (Fig. 2; Warren, 2006).

Although both are redbed settings and namakiers occupy local fault-defined depressions in the landscape, there is an obvious tectonic distinction at the regional scale between modern namakiers in Iran and the fault-intersected extensional setting of the Keuper namakiers: the former is characterized by tectonic shortening, the latter by extension. With the possible exception of the Pleistocene in the Dead Sea depression, active terrestrial namakiers occur in compressional terrestrial (not marine) settings, as in the Iranian, Atlas, and Andean compressional belts (Table DR1). There are no large diapir-fed namakiers at the surface in any modern terrestrial setting characterized by broad regional extension (rifting). This is not to say that namakiers cannot form during extension in a terrestrial continental setting, only that they do not do so today under contemporary tectonics and climate. Namakiers occur in older extensional terrestrial settings; remnants of Miocene salt at the Pleistocene continental land surface are seen in seismic data from the Dead Sea diapirs (Al-Zoubi and Ten Brink, 2001) and Miocene diapiric salt relicts are at the Miocene land surface along the Yemeni Red Sea coast (e.g., Davison et al., 1996). Today, salt allochthons in extensional settings are largely restricted to submarine continental slope and rise settings in passive continental margins. Gravity gliding into the basin at the submarine continental margin, with upslope extension and downslope compression, controls the formation of diapirs and their allochthon wings and tiers. Contemporary salt crests and canopies are typically beneath ~50–100 m of poorly consolidated deep-marine mud and silt, as in the Gulf of Mexico and the Santos Basin of Brazil (Warren, 2006).

That the Late Triassic climate of the Northwest German Basin allowed terrestrial namakiers to be preserved and stacked with thicknesses that are seismically resolvable argues that hyperaridity dominated in these isolated extensional depressions across substantial time frames. Otherwise rainfall and groundwater flushing would have prevented the preservation and stacking of namakier levels, as it possibly does in Iran and the Dead Sea depression today. The distinction supports the notion that hyperarid conditions were typical in the interior of the Pangaean supercontinent, even as it was rifting to become the incipient Atlantic Ocean.

No borehole has cored any of the Triassic namakiers documented in this study. The Late Triassic section is considered noneconomic and is only intersected during the drilling of boreholes designed to test for much deeper sub-Zechstein hydrocarbon traps. We suggest that much of the Triassic section in the Northwest German Basin retains evidence of multiple former namakier levels that were subject to pervasive synformational leaching and are too thin or possess too little acoustic contrast to be resolved seismically. Karstification and dissolution of a namakier, even as it is flowing, always creates a carapace breccia and a circum-namakier dissolution breccia (allochthon breccias of Warren, 2006). Somewhat more humid climatic episodes in the Triassic would have caused all namakiers to shrink from their maximum extent, even after they were buried. Based on analogy to allochthon outcrops and breccia chains preserved in the "Christmas Tree" diapirs of the Flinders Ranges, we consider it highly likely that there are numerous levels of former namakier (subseismic resolution) in the circum-diapir Triassic of the Northwest German Basin. In many such levels the namakier halite was completely dissolved, and all that remains is a thin stratiform layer composed of an allochthon breccia comprising anhydrite residuals, clays, and salt-transported sedimentary blocks.

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