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# Viscous flow during salt welding

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ABSTRACT

Salt can be partially removed by viscous flow from between wall rocks to form a *salt weld*. Welds in autochthonous and allochthonous salt can form significant structures in evaporite basins, where petroleum and mineral discovery can hinge on whether salt welds act as seals or windows for migrating hydrocarbons or brines containing dissolved metals. Despite the importance of welds, little is known about salt evacuation during welding. We investigate viscous flow during welding using analytical and numerical models, based on exact solutions to the Navier–Stokes equations for idealized geometries and boundary conditions. We explore two questions: how does salt thin during evacuation, and what are the limits of viscous flow during salt welding? Hydraulic-gradient and displacement boundary conditions are shown to drive salt evacuation, which is rate-limited by drag along the boundaries of a salt layer. Where salt flow is restricted, for example beneath a broad, prograding sediment wedge, up to ~50 m salt can remain in an incomplete weld. Where salt flow is unrestricted, for example beneath a subsiding minibasin, viscous flow can remove all but a vanishingly thin (<<1 m) salt layer. In both cases, any remaining salt must be dissolved to leave a weld containing no remnant salt. Evacuation rate increases with increasing differential stress and decreasing flow length and dynamic viscosity of the salt. Translation of wall rock parallel to bedding may result in a fault weld but may also inhibit evacuation if the displacement counteracts flow driven by a hydraulic gradient. Evacuation of multilayered evaporites is controlled by the distribution of layer thickness and viscosity. Multilayered evaporites can be compositionally modified during evacuation.



## 1. Introduction

Salt, used here to describe any rock composed primarily of halite, creeps as a viscous or power-law fluid over geologic time. Salt flows under a wide range of geologic conditions (Hudec and Jackson, 2007; Weijermars et al., 1993). Tens to hundreds of kilometers of extension or shortening can detach on salt layers (e.g., Brun and Fort, 2004; Duval et al., 1992; Fort et al., 2004; Harrison, 1995; Laubscher, 1961; Mohriak et al., 1995; Rowan et al., 2004). Over time, an initially tabular salt deposit may evolve into an enormous variety of diapirs, canopies and other salt structures. As salt flows into these structures, the source layer can thin to form a *salt weld*.

A salt weld was originally defined as a discordant surface resulting from the complete evacuation of salt (Jackson and Cramez, 1989). Jackson and Talbot (1991) expanded this definition to include zones of nearly complete salt evacuation. Though salt welds were first formally defined by these authors, the idea of vanished salt was already known (e.g., Trusheim, 1960), and welds themselves were known by other names, such as "evacuation surface" or "cicatrice salifère" (literally, salt scar) (Burollet, 1975). Among many geologic examples, Schuster (1995) characterized shallowly detached salt welds in onshore and offshore Louisiana, and Rowan et al. (1999) classified salt welds in the northern Gulf of Mexico based on their geometry and regional context. Numerical simulations of salt flow (e.g., Cohen and Hardy, 1996; Ings and Shimeld, 2006; Massimi et al., 2007; Schultz-Ela and Jackson, 1996) have successfully modeled salt-sediment interaction, but focused on structure and stratigraphy in the overburden and not on the associated welds. Subsurface welds are imaged by seismic data, but the temporal resolution of many reflection seismic surveys is too coarse (greater than ~30–50 m of halite for peak frequencies of ~10–30 Hz) to display the internal structure of welds. Furthermore, seismic data and well information related to welds are sparse and commonly proprietary. Outcrops are useful for studying the mesoscale structure of welds and are locally well exposed, as in the La Popa Basin, northern Mexico (Giles and Lawton, 1999; Rowan et al., 2012), but may be of mediocre quality due to near-surface dissolution (e.g., Dyson and Rowan, 2004; Harrison and Jackson, 2008; Willis et al., 2001).

Field exposures indicate that salt welds can be internally complex structures (Rowan et al., 2012) traceable for 10 km or more across evaporite basins (Fig. 1). A large proportion of a source layer may be removed because of lateral salt expulsion during regional extension, loading by overburden, and downdip flow. Salt welds vary from subhorizontal primary welds formed by lateral salt expulsion (e.g., Burollet, 1975; Duval et al., 1992; Ge et al., 1997; Hall, 2002; Jackson

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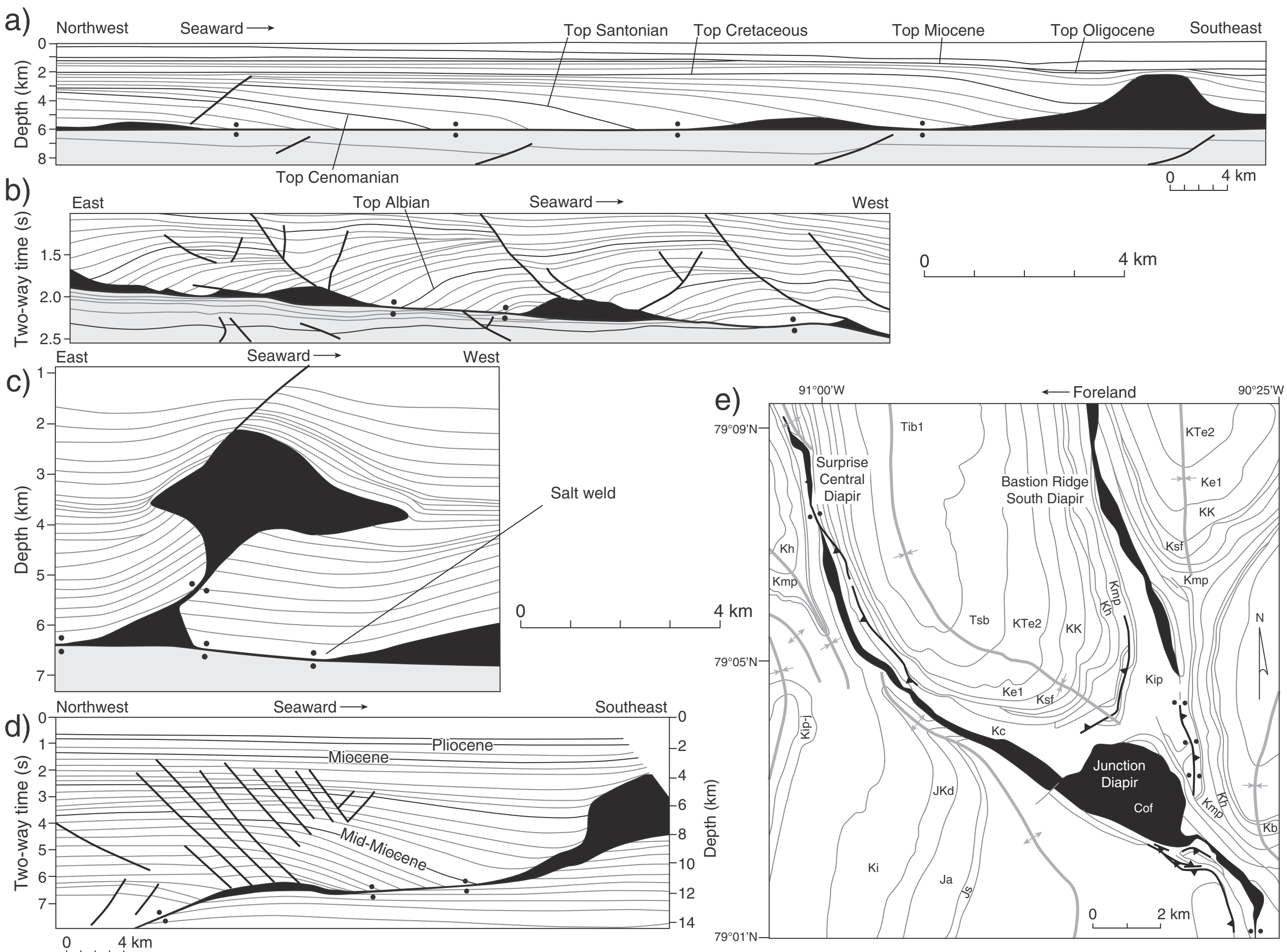


**Fig. 1.** Examples of salt welds. Cross sections at two different scales reflect the widely variable sizes of salt welds. Time-domain cross sections were converted to depth using an appropriate uniform seismic velocity for each example. The cross sections are not vertically exaggerated. (a) Primary weld produced by seaward expulsion of Aptian salt, Santos Basin, Cabo Frio, deepwater Brazil (after Mohriak et al., 1995). (b) Primary weld associated with raft tectonics (extreme extension) over Aptian salt, Lower Congo Basin, Cabinda shelf (after Chimney and Kluth, 2002). (c) Secondary weld produced by lateral shortening of a diapir of Aptian salt at the updip end of an ultra-deepwater thrust belt, Lower Congo Basin (after Jackson et al., 2008). (d) Tertiary weld produced by Jurassic salt expulsion in a stepped counterregional allochthonous sheet, deepwater Louisiana, Gulf of Mexico (after Schuster, 1995). (e) Tertiary welds produced by orogenic shortening of Carboniferous diapiric walls rising from a mid-Cretaceous salt canopy, Sverdrup Basin, Axel Heiberg Island, Nunavut, Arctic Canada (after Harrison and Jackson, 2008).

and Cramez, 1989; Mohriak et al., 1995) to steep secondary welds formed during shortening of salt diapirs (e.g., Brun and Fort, 2004; Dooley et al., 2009; Giles and Lawton, 1999; Gottschalk et al., 2004; Rowan et al., 1999; Sherkati et al., 2006; Vendeville and Nilsen, 1995). Allochthonous salt sheets and canopies can be evacuated to form tertiary welds, which can be stacked high in the stratigraphic succession (e.g., Diegel et al., 1995; Rowan et al., 1999; Schuster, 1995). As salt evacuates to form a weld, these movements are recorded in the variable thickness, dispersal patterns, and facies distributions of overlying sediments (e.g., Hudec et al., 2009; Rowan and Weimer, 1998). Furthermore, salt welding can affect the growth of adjacent salt structures as they are cut off from the source layer (e.g., Burollet, 1975; Ge et al., 1997; Hudec et al., 2009; Vendeville and Jackson, 1992b). Salt layers are particularly efficient as a décollement for thin-skinned deformation because of their weakness (Davis and Engelder, 1985). However, continued evacuation may increasingly deform surrounding rocks, as thinned salt forms a less effective detachment than thick salt (Cotton and Koyi, 2000; Vendeville et al., 1993).

Predicting which welds leak or seal hydrocarbons is essential in exploration of many hydrocarbon-bearing basins affected by salt tectonics. Hydrocarbons sourced in subsalt source rocks can migrate through salt windows – permeable areas of thin or vanished salt – and be trapped in suprasalt reservoirs (Guardado et al., 2000; McBride et al., 1998; Rowan, 2004). Countless discoveries in the Gulf of Mexico, Campos Basin, and offshore Angola rely on cross-weld hydrocarbon migration. Alternatively, a subsalt reservoir may require an adjacent salt weld to seal. For example, recent exploration targets below allochthonous salt in the Gulf of Mexico (e.g., Kaskida, Keathley Canyon Block 292/291) and below autochthonous salt in the Campos and Santos Basins of offshore Brazil (e.g., Wahoo discovery, Block BM-C-30) rely in part on welds to seal. Seal continuity and integrity depend greatly on remnant salt thickness, so understanding how salt thins during welding is crucial to exploration success.

Two main processes create salt welds: viscous flow and dissolution. Viscous flow shears halite to form flow folds and buckles or dismembers competent beds within the evaporite layer. The result is high strains within the weld. Dissolution near the surface by meteoric water can remove soluble evaporite minerals, leaving insoluble residues, and (in welds shallower than ~1 km) voids or collapse structures. Dissolution during salt welding is controlled by the permeability of the host rocks and by the flux, hydrodynamics, and composition of subsurface waters (Anderson, 1981; Anderson and Kirkland, 1980; Ge and Jackson, 1998; Lohmann, 1972). Salt can dissolve from the top, base, and sides, or from porous interbeds (Cartwright et al., 2001). Understanding salt dissolution near the