An Emplacement Model for Allochthonous Salt Sheets with Implications Toward Subsalt Exploration

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ABSTRACT

A model for allochthonous salt sheet emplacement is presented to explain observed overthrusting of thick sediment columns above these sheets. This model, termed the basal salt shear model, entails an initial salt sheet emplacement stage with salt extruding or intruding near the sea floor. Subsequent sediment loading upon the sheet drives salt withdrawal and suprasalt sediment deformation. Salt withdrawal occurs via pure shear within the salt sheet. As sediments thicken over the salt sheet, overpressures develop in a subsalt transition zone. These anomalously high pore fluid pressures facilitate simple shearing beneath the sheets by reducing the effective normal stress, thereby allowing lateral movement of the sheets and their overlying sediments with minimal force.

Evidence supporting the basal salt shear model includes: (1) lithologically distinct transition zones beneath salt sheets, (2) overpressures in these transition zones, (3) stratigraphic sections above salt repeated below salt, (4) compressional features in front of salt sheets, (5) thick sediment escarpments near salt sheet toes, and (6) low velocity zones near salt sheet bases.

Characteristics of the basal salt shear model significantly impact subsalt hydrocarbon exploration. The overpressured shear zone may be a path for hydrocarbon migration, a seal, or a reservoir, depending upon its local characteristics. One may be able to estimate the hydrocarbon column height of a nearby reservoir in contact with the shear zone based on the detection of hydrocarbons in the shear zone. Also, hydrocarbon reservoirs trapped against shear zones may have larger hydrocarbon columns and different updip limits than expected. Furthermore, this model implies that subsalt reservoir sands may be younger and originate from a more basinward depositional environment than otherwise expected. Finally, geophysicists should consider anomalous velocities near the base of salt sheets when depth migrating seismic data.

INTRODUCTION

The relatively low density and viscosity of salt suggest that it behaves like an igneous body, flowing upward and laterally along a path of least resistance. One model for salt emplacement contends salt sheets intrude into the uncompacted sediment near the sea floor as a horizontal body (e.g., Nelson and Fairchild, 1989; Seni and Jackson, 1989; Sumner et al., 1991). Horizontal salt intrusion usually occurs at depths less than 300 m (1000 ft) beneath the sea floor (Nelson and Fairchild, 1989).

The horizontal intrusion model does not generate lateral displacement of suprasalt sediments relative to subsalt sediments. Subsalt drilling, however, has revealed stratigraphic sections above salt sheets repeated beneath the sheets (McGuinness and Hossack, 1993). This implies overthrusting. Overthrusting can be explained by the salt glacier model (McGuinness and Hossack, 1993; Fletcher et al., 1995; Hudec et al., 1995), which suggests that the salt flows onto or near the sea floor, carrying a thin (less than 250 m) accumulation of near-surface sediments.

The salt glacier model employs shearing within the salt sheet to produce overthrusting. However, seismic evidence shows overthrust detachment planes that connect with salt sheet bases (Brooks, 1994). The basal salt shear model explains overthrusting and also the detachment planes observed at the base of salt. The basal salt shear model (Fig. 1) proposes that salt sheets originate as either a horizontal intrusion near the sea floor or as an extrusion directly onto the sea floor. Differential sedimentation yields salt withdrawal and growth faulting in the suprasalt section (e.g., Sumner et al., 1991; Bradshaw and Watkins, 1994; Zhang and Watkins, 1994). As sedimentation thickens the overlying sediment, anomalously high pore fluid pressures develop in the sediments immediately beneath the salt sheet. Before the salt withdraws entirely, these pore fluid pressures can reduce the effective normal stress dramatically. This reduction facilitates lateral movement of the salt sheet and suprasalt sediments with minimal tectonic forces. As the thrust fault zone cuts up section in a stairstep manner, it produces repeated section.

MECHANICS OF BASAL SALT SHEARING

Clastic deposition upon a salt sheet forms a thick column of overlying sediments. This column creates a large downward force, which translates into a high coefficient of friction along potential subsalt thrust planes. Overcoming this friction ordinarily requires considerable horizontal forces. Horizontal forces from updip loading, however, usually do not amass because the salt readily remobilizes via pure shear within the salt (Sumner et al., 1991; Bradshaw and Watkins, 1994). Simple shearing in subsalt sediments, therefore, requires an additional mechanism.

Hubbert and Rubey (1959) suggest anomalously high pore fluid pressures facilitate overthrusting by reducing the effective normal stress. This reduction essentially lifts the overlying rock, allowing lateral motion along the thrust plane with incremental shearing force. As the pore pressure increases, the lateral force required to produce horizontal motion decreases.

Their work is based on the Mohr-Coulomb law, which states that shearing along a plane within a rock will occur when the critical shear stress

$$t_{crit} = t_0 + (s - p)\tan f$$

is reached. In this equation t_0 is the shear strength of the material when s is zero, s is the stress normal to the slip plane, p is the pore fluid pressure, and f is the angle of internal friction.

As pore fluid pressure (p) within the rock increases, the quantity (s - p) decreases significantly. As this quantity tends toward zero, the coefficient of friction along the potential fault plane (related to tan f) becomes insignificant. The critical stress required for shear failure (t_{crit}) of the rock approaches the shear strength of the material (t_0).

Any previously existing plane of weakness, such as a bedding plane or fault plane, reduces the shear strength of the material (t_0 becomes zero in the case of an existing fault plane). If anomalously high pore fluid pressure exists in conjunction with a previously existing plane of weakness, shear translation can result with minimal force applied. We shall provide observations that indicate overpressures exist below salt sheets. Further, O'Brien and Lerche (1994) predict that sediments surrounding horizontal salt sheets will typically meet Mohr's criterion for failure during salt sheet emplacement. This condition creates zones of weakness beneath and ahead of salt sheets. These zones of weakness, in conjunction with overpressures, provide the essential criteria for shear displacement with minimal lateral force.

Due to the low shear strength of salt, shearing occurs within the salt body during its initial emplacement. Shearing continues within the salt sheet as long as the shear strength of salt is lower than the shear strength of the surrounding sediments. We believe shearing occurs within the salt sheet until anomalously high pore pressures develop below the sheet. When overpressures reduce t_{crit} to a level below the yield strength of salt, shearing shifts to the subsalt transition zone.

Kupfer (1976) suggested geopressured water within the salt may facilitate internal salt movement due to dehydration of gypsum into anhydrite. During overthrusting, therefore, the zone of shearing may encompass both the basal salt and the sediments immediately beneath the salt sheet. Kupfer (1976) observed similar shear zones associated with salt diapirs that permeated 150 m (500 ft) into the salt and approximately 300 m (1000 ft) into the sediments.

OBSERVATIONS

There are several observations that support the basal salt shear model for the emplacement of salt sheets. These include (1) detection of "transition zones" immediately beneath salt sheets, (2) overpressured sediments discovered beneath salt sheets, (3) stratigraphic sections above salt repeated below salt, (4) evidence of compression at the toe of salt sheets, (5) thick sediment accumulations over salt sheets as they move, and (6) evidence of sediments intermixed with the basal salt.

(1) Evidence of a thrust fault zone at the base salt-sediment interface includes the detection of an anomalous transition zone in the sediments immediately beneath some salt sheets. House and Pritchett (1995) describe this as a lithologically distinct zone. The shearing and mixing of sediments along the thrust fault may cause this transition zone. Kupfer (1976) similarly interpreted anomalous shale zones surrounding salt diapirs as a type of fault gouge.

Transition zones are analogous to previously described gumbo zones (House and Pritchett, 1995), unconsolidated rubble zones (LeBlanc, 1994), and possibly shale sheaths (Kupfer, 1976). These terms, however, all imply specific lithologic characteristics that may not be descriptive of all such zones. LeBlanc (1994) used the term "transition zone" to characterize the area near salt edges and Gretener (1979) used the term "transition zone" to describe regions where pressure grades from normal to overpressured. We use the term "transition zone" to refer to the anomalous, overpressured region immediately beneath salt sheets. The typical composition of this zone is shale, but it may be a heterogeneous mixture of several lithologies.

(2) The presence of overpressured sediments immediately beneath salt sheets also supports the basal salt shear model. O'Brien et al. (1993) and O'Brien and Lerche (1994) found three out of four wells studied were extremely overpressured and the fourth was highly overpressured beneath salt. They explain this phenomenon as the result of a permeability barrier formed by the salt sheet. House and Pritchett (1995) also describe abnormally high pressures, isolated to the transition zone immediately beneath salt, which approach formation fracture pressures. This

overpressure of pore fluids beneath the salt facilitates shearing within the transition zone.

(3) McGuinness and Hossack (1993) reveal stratigraphic section above salt sheets repeated beneath them in two Gulf of Mexico wells. Operator reports show the OCS-G-7719 #1 (South Marsh Island 200) well drilled to upper Pliocene sediments above salt, but found a middle Pleistocene section immediately beneath the salt. Similarly, the OCS-G-7690 #1 and #1ST (Vermilion 356) wells drilled to upper Miocene sediments above salt and penetrated upper Pliocene sediments beneath the salt. These examples suggest overthrusting of the suprasalt sediments.

(4) With the overthrusting of a thick section, compression of sediments ahead of and above the allochthonous salt sheet would occur. Listric normal faulting dominates Gulf of Mexico structural styles, but one can observe thrust faults that protrude from the bases of salt sheet toes (Fig. 2). Huber (1989) documented the Ewing Bank Thrust, which is located just ahead of a salt sheet. The OCS-G-5809 #1 and #1ST (Ewing Bank 988) wells are direct evidence of this thrusting because they cut the Ewing Bank Thrust Fault and encounter repeated section beneath it (Fig. 3). Seni and Jackson (1989) proposed thrust faults of this nature may later reactivate as counter-regional growth faults. The present-day absence of compressional features, therefore, does not necessarily imply overthrusting has not occurred.

(5) The basal salt shear model requires thick sediment accumulations over salt sheets to generate transition zone overpressures. Figure 4 illustrates an overthrust section, which is several thousand feet thick, near the Sigsbee Escarpment. The minibasin overlying the salt sheet in this example suggests overthrusting occurred after significant suprasalt sedimentation.

(6) We propose that overthrusting of the salt sheet and its overlying sediments creates a fault zone near the base salt-sediment interface. Zones of low velocity within the basal salt section of the OCS-G-12635 #2 (Garden Banks 165) well (Fig. 5) may indicate zones of subsalt sediments intermingled with the basal salt. This interlayering of sediments within the salt may represent the upper portion of a thrust fault zone. This phenomenon is similar to the sedimentary gouge observed in shear zones within salt diapirs (Kupfer, 1976).

IMPLICATIONS FOR SUBSALT HYDROCARBON EXPLORATION

Subsalt exploration for hydrocarbons is still in its infancy. The basal salt shear model has several implications that could influence exploration for and development of subsalt hydrocarbon accumulations.

For example, the overpressured transition zone has multifarious functions. It can be a path for hydrocarbon migration, a seal, or a reservoir, depending upon its local characteristics. First, these overpressured transition zones can provide a permeability pathway for hydrocarbon migration (House and Pritchett, 1995). Hydrocarbons can migrate upward along the salt feeder and through the transition zone. Hydrocarbons can also migrate upward through subsalt sands and leak into the transition zone where the sand and transition zone contact one another.

Second, the transition zone can provide a trapping mechanism much like a pressure-sealing fault. Hydrocarbons migrating laterally through the high-pressured transition zone can be injected into low-pressured underlying sands and trapped due to the pressure differential. Similarly, the transition zone can trap hydrocarbons migrating upward through subsalt sands because the transition zone overpressures prohibit fluid invasion.

Third, subsalt transition zones could prove to be reservoirs themselves (LeBlanc, 1994).

Extensive leakage of hydrocarbons from below, or lateral migration of fluids through the zones, could saturate them. Transition zones are probably not of reservoir quality, however, since observed log characteristics show them to be shale prone.

Another implication of the basal salt shear model is that subsalt well data may reveal unpenetrated hydrocarbon reservoirs. If hydrocarbons trapped against the transition zone exceed its seal capacity, surplus hydrocarbons leak into the transition zone. If one establishes (e.g., from additional well data) that no hydrocarbons migrated through the transition zone, yet hydrocarbons are detected in this zone, one can conclude there is a reservoir filled to capacity in contact with the transition zone. Furthermore, one can predict the hydrocarbon column height of this untested reservoir by estimating the change in pressure across the seal and the difference between the reservoir's water and hydrocarbon pressure gradients (column height = change in pressure/change in gradient).

Hydrocarbons trapped against subsalt transition zones can have larger hydrocarbon columns and different updip limits than expected. Large pressure differences between transition zones and underlying reservoirs increase the sealing capacity of transition zone traps. Increased sealing capacity can yield larger hydrocarbon columns. In addition, the updip reservoir limit depends on the transition zone thickness and the reservoir dip. Thick transition zones and/or shallow-dipping reservoirs yield trap locations significantly displaced from where they would be if reservoirs extended nearer to the base of salt.

The basal salt shear model also implies that subsalt stratigraphy may be significantly different than anticipated. Overthrusting transports the overlying section basinward, laterally separating sediments that were once conformable. The subsalt section may, therefore, be younger than expected and originate from a more basinward depositional environment than the section immediately above salt.

Finally, the presence of overpressured thrust fault zones creates low velocity zones beneath salt sheets. If thrust fault zones extend into the basal salt, a layered transition from salt to sediment velocities also occurs. Velocity models used for depth migration should incorporate this information.

CONCLUSIONS

Later stages of allochthonous salt sheet emplacement may involve overthrusting of the salt and overlying sediments with most or all of the shearing occurring within a subsalt transition zone. Anomalously high pore fluid pressures in the sediments immediately beneath the salt sheets facilitate this overthrusting. Numerous observations support the basal salt shear model. These observations include distinct lithologic zones beneath salt sheets, extremely overpressured formations immediately below salt, geologic sections above salt repeated beneath salt, compressional features at the toes of salt sheets, thick sediment accumulations in place over salt sheets as they move, and low velocity zones near salt sheet bases.

The basal salt shear model provides insight toward the exploration and development of subsalt reservoirs. This model suggests the overpressured transition zone can be a region of subsalt shearing. This zone may act as a migration pathway, a trapping mechanism, or a reservoir. Traces of hydrocarbons found in this zone may indicate a nearby reservoir whose hydrocarbon column can be estimated. The basal salt shear model also suggests that optimal exploration and development well locations may be different from those previously anticipated.

Furthermore, the subsalt section may be younger than expected and originate from a more basinward depositional environment than the section immediately above salt. Finally, velocities near the base of salt sheets may be somewhat more erratic than previously expected. This erratic behavior influences velocity models for depth migration.

Limited data are available to provide clues regarding subsalt reservoirs because of the paucity of existing subsalt wells. The basal salt shear model provides valuable information for optimizing new wells. Future subsalt drilling will determine the validity of this model and the extent of overthrusting in the Gulf of Mexico.

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FIGURE CAPTIONS

Figure 1. During stage 1 of the basal salt shear model, the salt sheet is emplaced as a salt extrusion directly onto the sea floor or as an intrusion near the sea floor. During stage 2, sediment loading upon the sheet drives salt withdrawal and suprasalt sediment deformation. Salt withdrawal occurs via pure shear within the salt sheet. During stage 3, sediments thicken over the salt sheet and overpressures develop in a subsalt "transition zone." Anomalously high pore fluid pressures drive simple shearing beneath the salt sheet. Suprasalt sediments are overthrust with the salt.

Figure 2. The reverse fault seen here protrudes from the base of a salt sheet in the southern Ship Shoal and Ewing Bank areas, Gulf of Mexico. This evidence supports overthrusting along a subsalt shear zone after significant burial of the salt sheet. (Seismic line reproduced courtesy of Diamond Geophysical Service Corporation.)

Figure 3. Repeated section interpreted in the OCS-G-5809 (Ewing Bank 988) #1 and #1ST wells. This results from the Ewing Bank Thrust Fault, which cuts both wells.

Figure 4. Thick suprasalt overburdens are required to induce overpressures in the transition zone. This overthrust section, near the Sigsbee Escarpment in the Walker Ridge area, Gulf of Mexico, is approximately 3500 feet thick at its leading edge.

Figure 5. Low velocity zones (LVZ) near the base salt in the OCS-G-12635 (Garden Banks 165) #2 well. These may represent subsalt sediments intermixed with salt along a shear zone. Log curves shown are spectroscopy gamma ray (GR), deep induction enhanced borehole corrected resistivity (IDEB), and sonic (DTLN).