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Analytical models of suture formation in salt canopies for safer well planning

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ABSTRACT

The development of suture zones between salt sheets issued from nested feeder stocks is visualized here as the salt sheets grow and coalesce into a canopy. The analytical models are based on complex potentials, which provide exact solutions for multiple source flows as they compete for space when spreading into a viscous continuum (a salt canopy). Vertical cross-sections and base-of-salt maps, both rendered from seismic images, have previously revealed the existence of suture zones inside major salt sheets. A better understanding of the sutures is required to safely drill hydrocarbon reservoirs located below such salt bodies. The suture zones are potential drilling hazards due to anomalous pressure behavior of entrapped sediments. A large range of suture shapes and overriding structures are seen in seismic sections of salt canopies; an even larger range of suture shapes is modeled here by systematically varying the key parameters responsible for their formation. A better understanding of the structural evolution of sutures improves their early detection and reduces the risk of drilling hazards.

1. Introduction

Detailed understanding of the coalescence of salt issued from several feeder stocks is required to interpret a large range of suture types and overriding structures seen in seismic sections of salt canopies. The Sigsbee salt canopy, one of the largest gravity-spreading structures on Earth, is today mostly buried by a sedimentary overburden ranging in thickness from less than 100 m to many kilometers (Fig. 1). The canopy is formed by the coalescence of salt sheets supplied by more than 100 salt feeder stocks (Diegel et al., 1995; Hudec and Jackson, 2006, 2009; Peel et al., 1995). The buried canopy continues its advance in SSE direction toward the continental slope, and its siliciclastic roof overthrusts the adjacent seafloor in the principal direction of the canopy creep (Hudec and Jackson, 2009). Although details of salt sutures become increasingly better visible in high-resolution seismic data (e.g., Laake and Fiduk, 2013), drillers and seismic interpreters benefit from models that explain the formation and variety in shapes of salt sutures. With the focus of hydrocarbon exploration and production shifting to deep pre-salt targets (Fig. 1 inset), the number of wells drilled in salt canopies is likely to increase.

Major advances in the understanding of salt canopy formation and suture terminology have been comprehensively reviewed and expanded in a recent study by Dooley et al. (2012). The junctions between coalesced salt sheets form various types of sutures (Fig. 2). One type of suture forms by internal folding and disruption of the original contact surface between the salt sheet and its overlying sediment veneer; these are termed autosutures. Larger and more prominent sutures form when different salt sheets coalesce: the junctions between different coalesced salt sheets are called allosutures (Fig. 2).

The identification and avoidance of allosutures is of growing importance when planning wells through allochthonous salt in costly deepwater wells (e.g., Gulf of Mexico and Brazilian presalt basins). Allosutures in salt canopies require special attention when drilling for hydrocarbons below the salt. They commonly include trapped sediments (Liro et al., 2004), which can be a hazard for drilling (Dooley et al., 2012; Kukla et al., 2012; Weijermars et al., 2013). Sedimentary stringers entrapped in the salt may contain either overpressured or underpressured pore fluids (Israel et al., 2008; Schoenherr et al., 2007), depending on the depth at which the stringers were originally trapped and their subsequent rise or fall within the salt body. Stringers enveloped by the salt will not adjust to pore-fluid pressure if disconnected from the surrounding porous rocks; rock salt has negligible porosity and is impermeable (except under unusual conditions, such as very shallow burial or high fluid pressures; Urai and Spiers, 2007). Consequently, sedimentary stringers trapped at salt canopy sutures inside salt bodies may trigger kicks (when overpressured) or cause lost circulation (when underpressured, creating so-called "thief zones"); both of these risks make drilling through a salt canopy potentially hazardous (Weijermars et al., 2013). Thus a major goal when planning wells through allochthonous salt in the deepwater Gulf of Mexico is to identify and avoid allosutures. This task is complicated because allosutures

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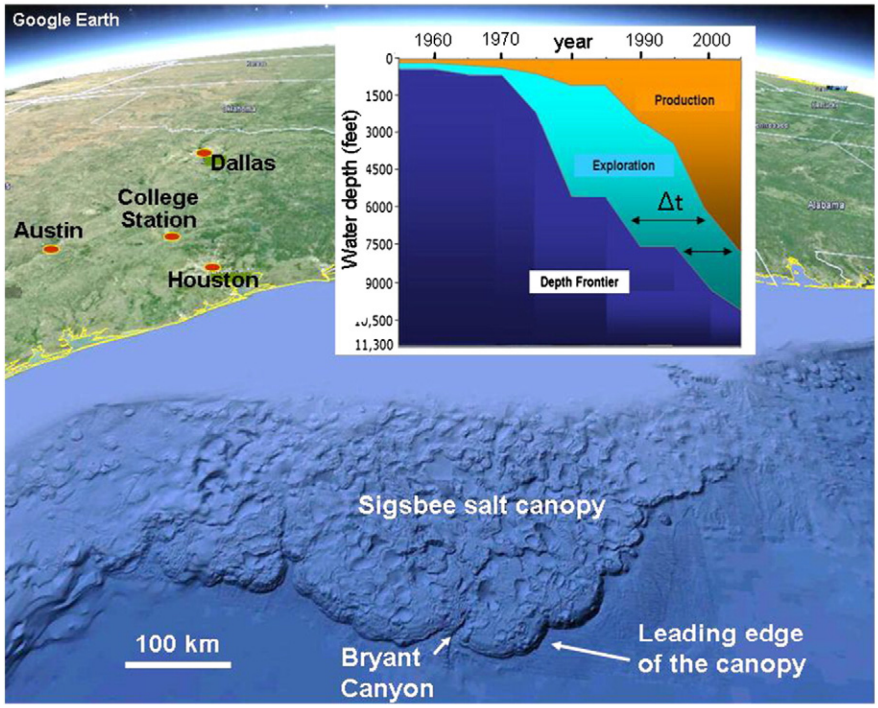

Fig. 1. Shaded relief of the Central Gulf of Mexico seafloor bathymetry. Hummocky terrain is underlain by the allochtonous Sigsbee salt canopy which expands toward the leading edge down the continental shelf Courtesy: Google Earth. Scale is only approximate (due to perspective view dimensional distortions occur toward the horizon). Inset graph shows petroleum exploration progressively moves outward from the shallow shelf area to deeper water, followed by production wells after a certain time lag (Δt).
Source of inset: Couvillion (2012).

can be complexly deformed in colliding salt sheets that flow at different rates and in different directions (Fig. 2).

Further studies that improve our understanding of suture formation can help anticipate the structural complexity when drilling in the salt canopy. Such models are especially useful when drilling plans are developed for less well imaged regions. This study visualizes the interaction of salt stocks and salt sheets using analytical models based on complex potentials. Such models are capable of modeling multiple source flows scaled with variable source strength, with and without a regional creep superimposed on the source flows issued by the salt stocks. The sutures modeled here provide templates for recognizing corresponding structures in salt sheets that coalesced to form a canopy during their advance down the continental slope.

2. Analytical model description

The formation of allosuture patterns seen in natural salt sheets can be modeled analytically. We assume that the shapes of allosutures are principally determined by the relative position of their feeder stocks, their respective flux magnitude, any superposed far-field flow (due to the regional slope), and the relative onset times of flux from the individual salt feeders. These principal input parameters and initial conditions

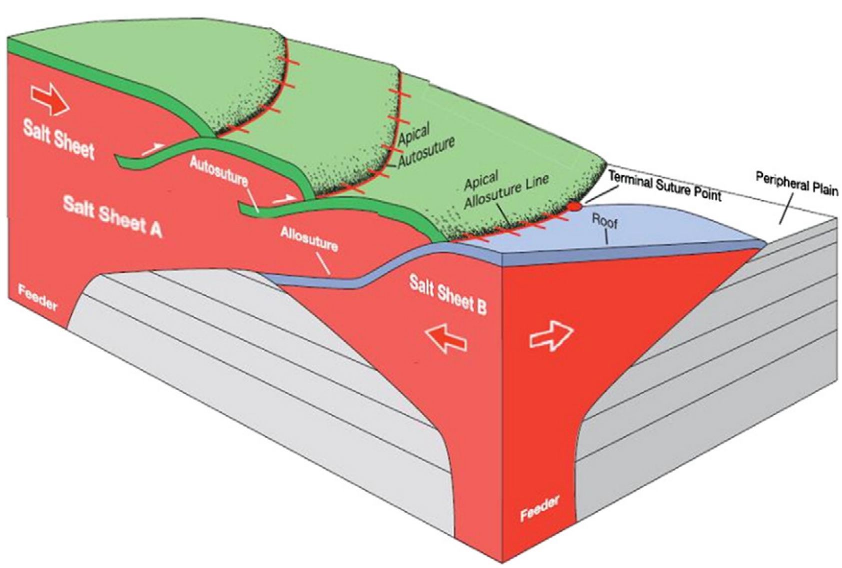

Fig. 2. Block diagram showing the characteristics of allosutures and autosutures. Allosutures form at the junction of two coalescing salt sheets, each with their own feeders. Autosutures form between two lobes or flow cells of the same salt sheet moving at different speeds or in different directions (after Dooley et al., 2012).