Seismic Delineation of Igneous Sheet Complexes on the Exmouth Plateau (NW Australia): Origin, Emplacement Mechanism and Implications for Petroleum Generation*

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Abstract

The Exmouth Plateau (Figure 1) off the northwest coast of Australia is a sedimentary basin formed as a response to several extension episodes. The earliest of these is a poorly defined late Permian event, to accommodate deposition of the Triassic Locker shale and subsequent thick Mungaroo Formation deltaics consisting of sand-rich fluvial and/or tidal channels cutting through a matrix of fine-grained silt, shale and coal rich deposits (Figure 2). The Mungaroo is Rhaetian to Norian (Late Triassic) in age and reaches a thickness of as much as 10 km. Renewed extension took place at the end of the Triassic and Middle Jurassic resulting in block faulting of the Triassic Mungaroo Formation and deeper section (Figure 2) (Driscoll and Karner, 1998; Frey et al., 1998), followed by limited deposition during the Jurassic. During the Callovian, a major unconformity developed, signaling the end of major extension and onset of a thermal sag phase on the Exmouth Plateau, with sedimentation continuing in mini-basins derived from eroding tilted fault blocks.

Different theories exist for the timing of breakup, whereas earlier models preferred an Early Cretaceous breakup (Hopper et al., 1992; Frey et al., 1998), more recent models suggest a possible Late Jurassic breakup (Heine and Muller, 2005) based on magnetic lineations and plate reconstructions. Prior to the magmatic event, the region experienced anomalously low subsidence followed by an increase of subsidence and deposition of the deltaic Barrow group during the Valanginian (Driscoll and Karner, 1998). Breakup was largely contemporaneous with magmatic sills and dikes intruding the Mungaroo and younger formations between the Late Jurassic and Early Cretaceous (Symonds et al., 1998) and extrusion of seaward dipping reflector series (SDR's) and flood basalts from the Gascoyne margin rift axis (Rey et al., 2008) (Figure 2). Evidence from Yardie East-1 well (Figure 1) on the Exmouth Peninsula classifies the sills as dolerites, whereas the flood basalts have not been sampled directly and are interpreted from seismic characteristics (Rey et al., 2007). Mutter et al. (1989) identified a High Velocity Body (HVB) on ESP (Enhanced Spread Profile) refraction seismic, interpreted as underplated magmatic material at the base of the crust (Hopper et al., 1992), presumed to be of similar age as sill/dike intrusion. At the end of the Valanginian the area was affected by another major unconformity that is more pronounced towards the shelf in the east, generating significant erosion in the south and east. Finally, the area experienced post-rift sedimentation and subsidence throughout the Cretaceous and Tertiary, affected by a major Campanian inversion event followed by Neogene compression as a result of plate reorganization (Longley et al., 2002).

Seismic Interpretation

Various 2- and 3-dimensional (2D and 3D) seismic reflection datasets were used in this study. However the primary dataset was the 2D NWS07 seismic survey acquired by PGS in 2007 using a shot interval of 37.5 m, a streamer length of 8 km and a nominal fold of 106. Total record length is 12 seconds. Depth conversion for 2D line NWS07-10A in Figure 2 was performed by using smoothed seismic stacking velocities. The main 3D survey used (Figure 1) was the Keystone survey shot in 2008 by Western Geco using 8 streamers with a streamer length of 5 km, a shot interval of 18.75 m, a nominal fold of 66 and a record length of 6 seconds. The Keystone survey was complimented by various bordering open file 3D seismic datasets and merged into one seismic volume. Igneous sills are easily recognized on seismic data due to their sub-horizontal nature and high acoustic impedance, resulting in bright amplitudes on seismic sections (Figure 2). Moreover, they tend to be of limited extend and often crosscut sedimentary rocks at a low angle. Dikes on the other hand, are poorly imaged on seismic data owing to their sub-vertical nature. They are visible when their thickness exceeds the horizontal seismic resolution (18.75 m). Figure 3 shows a sill turning into a dike, with a straight blade-like dike trace visible on a time slice. Thinner dikes can sometimes be inferred from the abrupt termination of sills and sub-vertical zones of poor imaging. Vertical seismic resolution decreases deeper in the section and this has important implications for the resolution thickness of the sills.

Assuming an interval velocity of 5 km/s for the intrusives and using a resolution thickness equal to / (with = interval velocity and = dominant frequency), the shallow (less than 5 km depth) sills have a resolution thickness of 35 m, while deeper down, at around 10 km depth, resolution thickness increases to >100 m. Although sills are very prominent in the center of the seismic section (Figure 2), there is a relative absence of sills toward the northwest and southeast (Figure 1). A possible explanation is that fractionated melt densities at the HVB were too high to generate shallower melt emplacement here, suggesting more MgO rich pricritic compositions with higher densities (>2.7 g/) (Cox, 1980; Karlstrom and Richards, 2011) in the west of the Exmouth Plateau. Deeper sills display undulating and irregular shapes and form interconnected networks (Figure 2, Figure 4) in a tree-like upward branching pattern (Polteau et al., 2009). Shallower sills are more isolated and show classic saucer-shape features.

Sills frequently crosscut fault-planes without being offset, indicating that sill intrusions postdate Early-Middle Jurassic extensional block-faulting (Figure 2). Dating of the fluid escape features associated with sill intrusion (Davies et al., 2002) by correlating the top and base horizon at the conical shaped fluid escape structure located above a sill edge (Figure 5) to nearby wells, yield an age of 152 Ma consistent with previous estimates (Symonds et al., 1998). This defines the paleoseabed during magmatism as indicated on Figure 2, located just above the main Callovian unconformity. The deeper section in Figure 2, below 12 km depth, is a reflection-free zone with a few isolated relatively flat sills. Further down, at 15-20 km the top HVB is imaged in the NW covering approximately 16. (Figure 1). Top HVB displays bright horizontal reflections suggesting that the HVB consists of sills, with the impedance contrast possibly indicating higher velocity/density ultramafic cumulates interfingering with lower velocity/density gabbro (Cox, 1980). Thickness of the HVB unit is estimated between 10 km near the Cape Range Fault zone (CRFZ), to 3.5 km in the Central Exmouth Plateau (Figure 1) derived from seismic refraction and gravity data (Lorenzo et al., 1991; Mutter et al., 1988; Frey et al., 1998). Refraction velocities of 7-7.4 km/s suggest that the HVB is a mafic or ultramafic magma chamber (White and McKenzie, 1989; Coffin and Eldholm, 1994; Ridley and Richards., 2010). Imaging of the HVB is poor in the center of the section (Figure 2), attributed to imaging deterioration caused by the stacked sill complex in the shallower section, but offset 2D seismic and gravity modeling indicate that the HVB is present here (Frey et al., 1998).

Maturation

The influence of sills and dikes on source rocks is limited as a result of relatively thin thermal aureoles of the intrusions, as well as the dispersed nature of the coaly source rocks. Since most intrusions are located fairly deep in the basin (> 5-6 km) they are currently in the overmature window, based on burial alone. However this might have been different in the Cretaceous, just after intrusions were generated at Late Jurassic/Early Cretaceous breakup time. Nonetheless, thermal influence is considered to be minor owing to the thickness of the intrusions (several tens of meters) and their limited extent. This is further evidenced by the presence of several TCF-size gas fields in the region apparently unaffected by intrusions at depth. Nevertheless, intrusions could prove to be important by influencing hydrocarbon migration paths. The influence of the deeper HVB is generating a hardly susceptible heat anomaly at around breakup time that is now long decayed.

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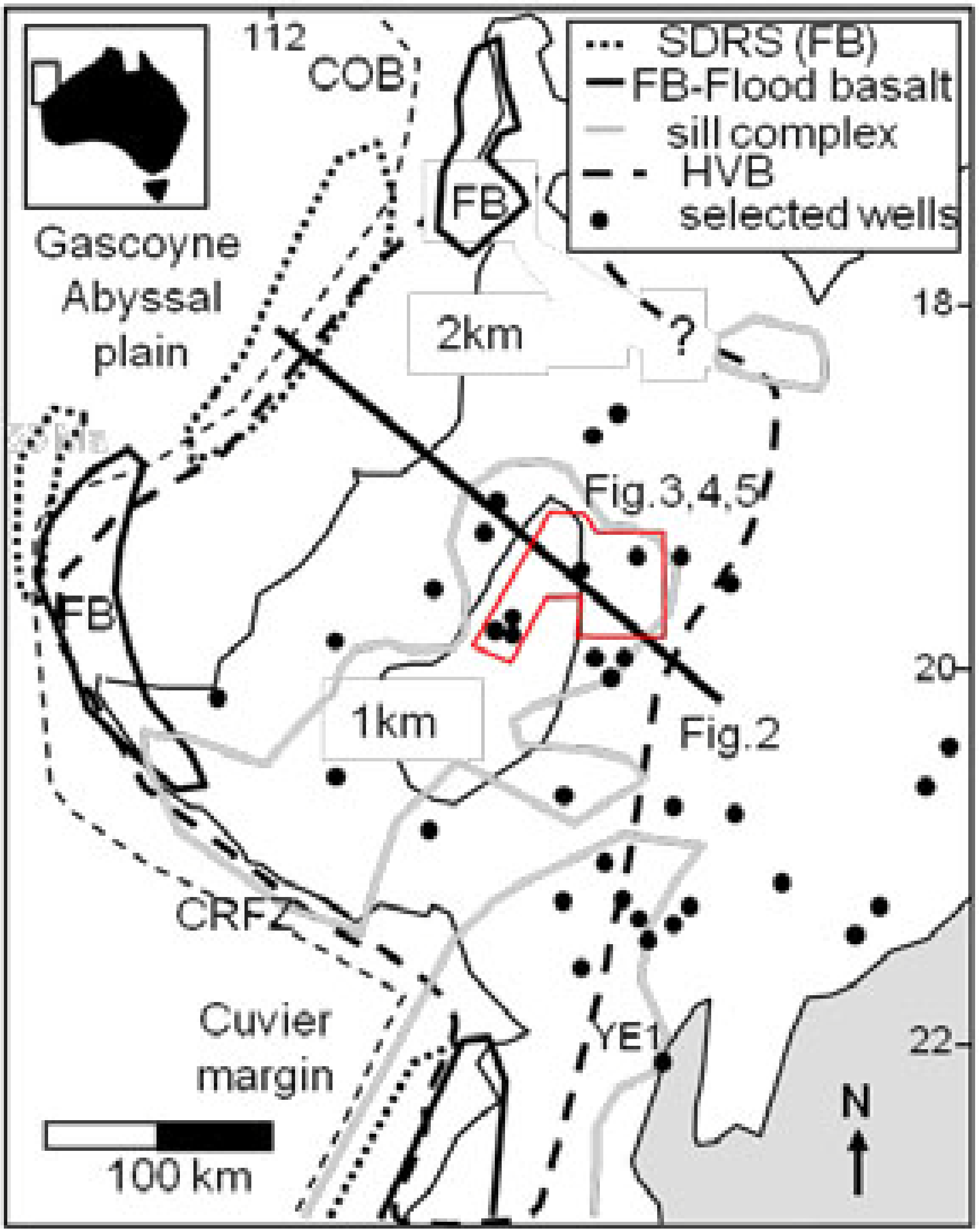

Figure 1: Map of Exmouth Plateau, modified from Rey et al. (2008). SDR: Seaward Dipping Reflector Series; Top HVB: High Velocity Body; COB: Continent Ocean Boundary; YE1: Yardie East 1 well. Bathymetry is denoted in km.

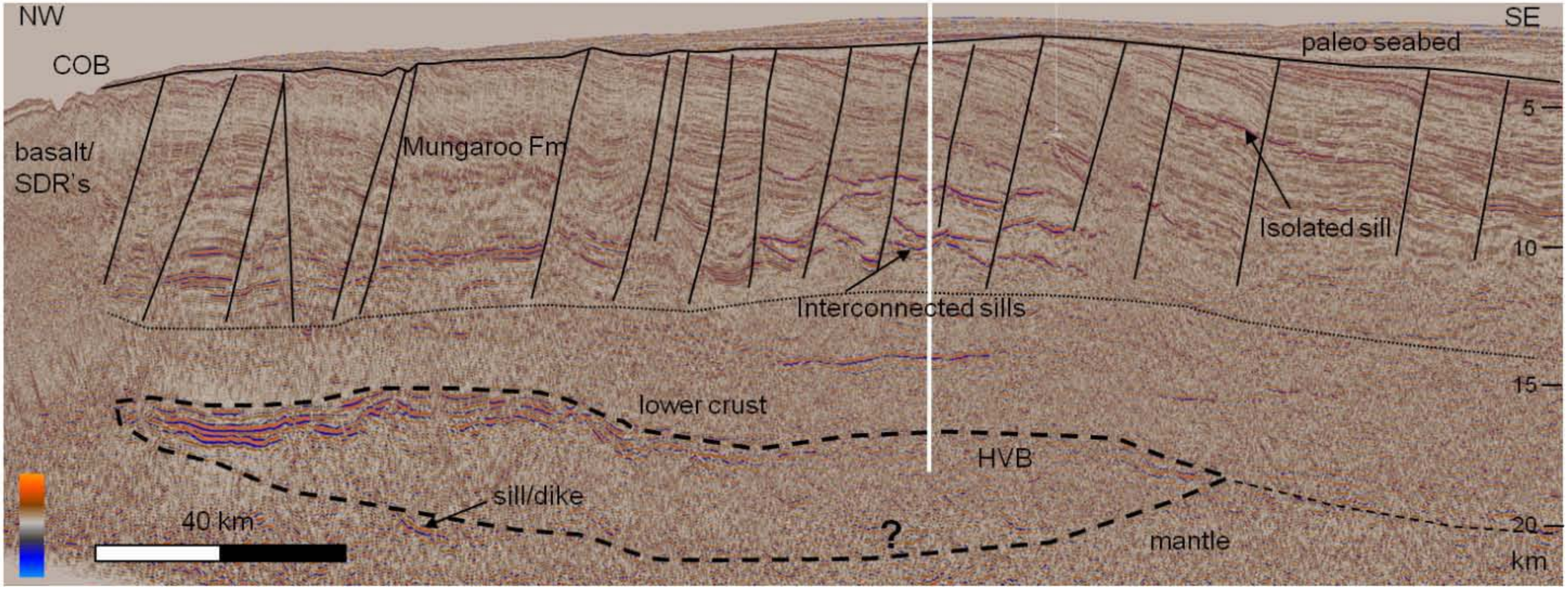

Figure 2: Seismic depth section (for location see Figure 1). Stippled line is approximate brittle-ductile transition derived from extrapolated well paleo-thermal indicators (vitrinite reflectance). Faults and paleo-seabed at time of intrusion are shown in black lines. Thick dashed outline: HVB. B. Seismic two-way-time cube, subcrop of 3D dataset, showing detail of tree-like interconnected sills.

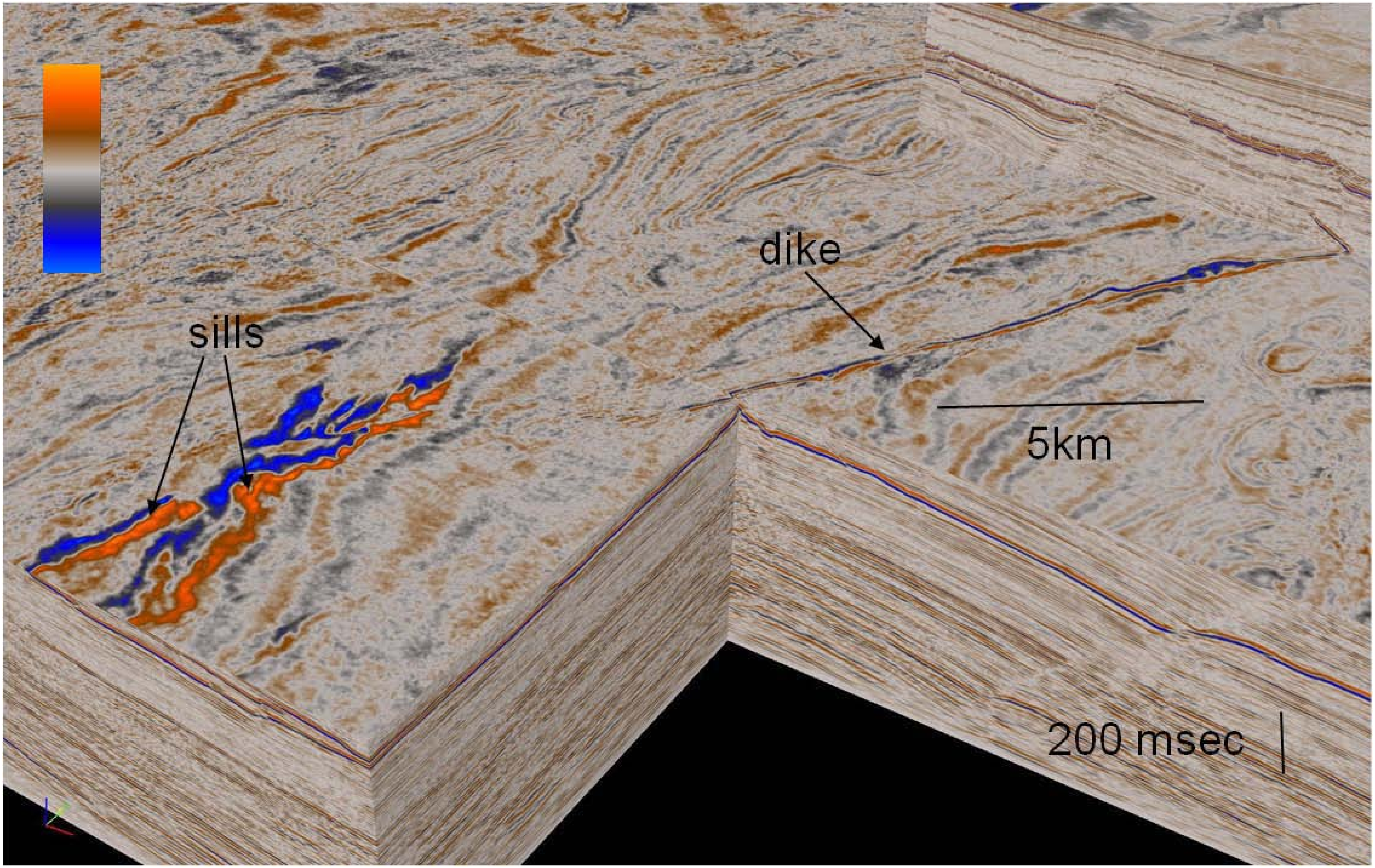

Figure 3: Sills and dike trace on a time slice, both originating from sills.

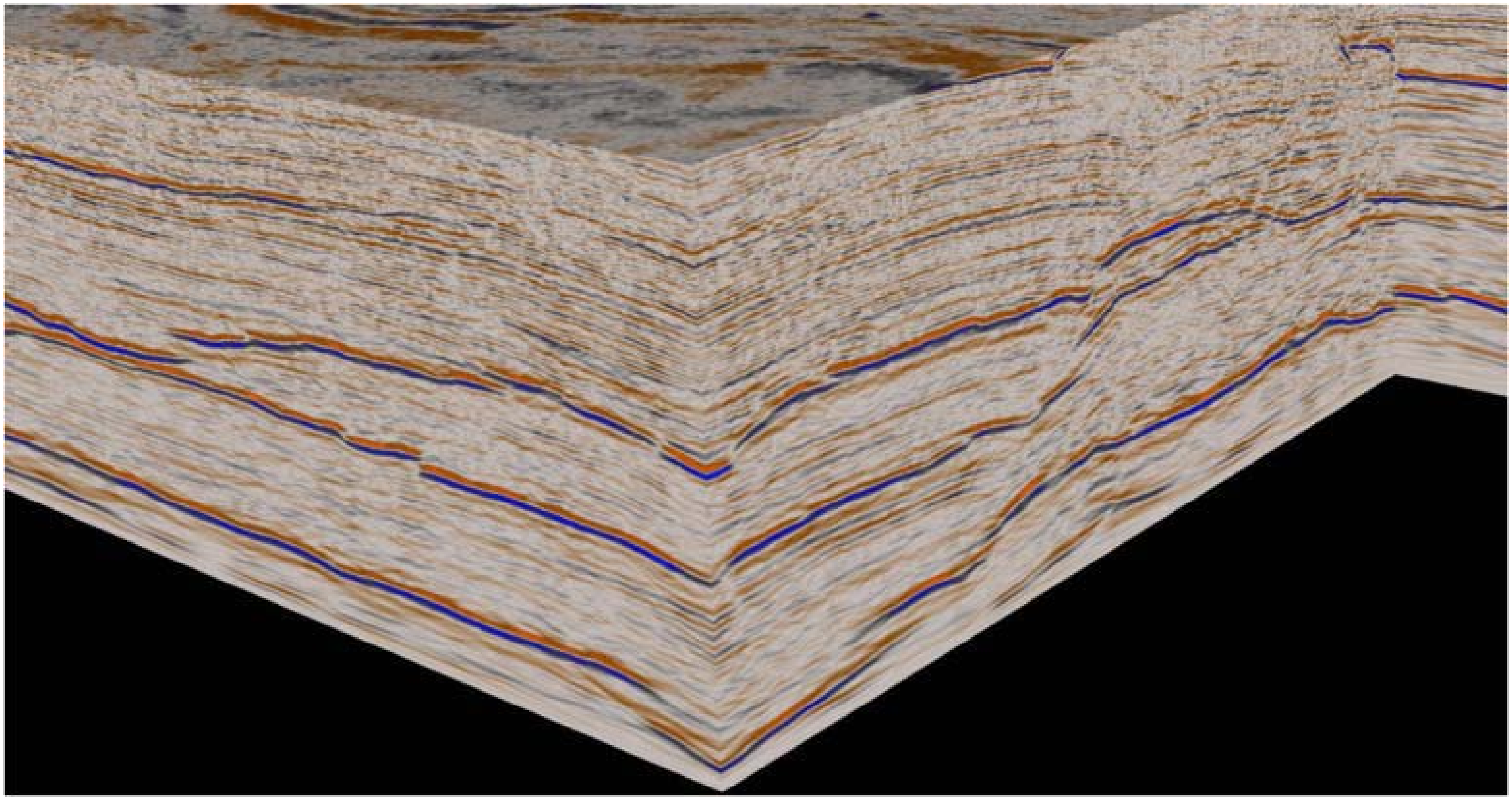

Figure 4: Sill sheets feeding each other forming an interconnected sill complex.

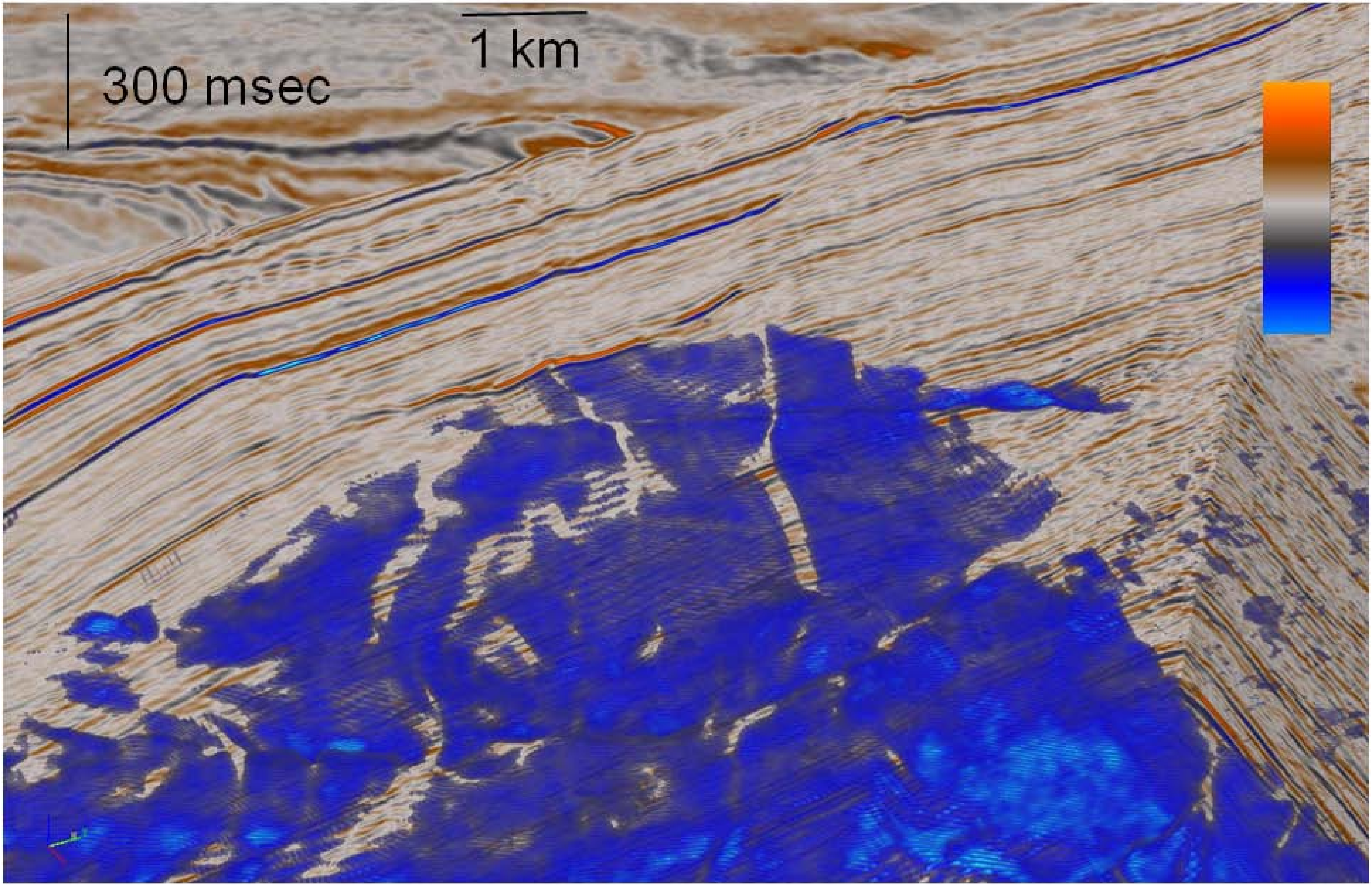

Figure 5: Base of a sill (blue) showing a fluid escape structure or vent at the end of the sill, note velocity pull-up.