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## **Seismic Interpretation and Characterization of Igneous Rocks in Jan Mayen Microcontinent, Norwegian-Greenland Sea\***

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### **Abstract**

The aim of this work is to interpret evidence of magmatic activity from seismic reflection data and to see how it influences the geodynamic evolution of Jan Mayen Microcontinent (JMMC).

Igneous rocks in the JMMC are positive high amplitude reflections, which are acoustically hard and are either concordant or discordant to sedimentary bedding. The two major seismic facies interpreted from 2D seismic reflection data are a) irregular, bedding discordant, intrusive rock, i.e., dykes, saucer-shaped, bowl-shaped, transgressive intrusions and b) horizontal, layered, and bedding parallel positive reflections e.g., pillow basalts and tabular sills. The JMMC is delimited by these igneous rocks into a western margin rich in extrusive rocks and an eastern region characterized by intrusive igneous rocks.

Volcanic sills in the study area are often associated with post-depositional deformation of the Paleogene rocks. Individual sills show complex fragmentation and are found close to faults. Based on their interaction with volcanic sills, faults in the study area include deep-seated and hard-linked, intermediate and shallow faults. The important piece of information from this work is that magmatic intrusions influenced configuration of faults and are major control on structural segmentation in the study area. Volcanic rocks in the JMMC were emplaced in Early Eocene during the opening of the southern Greenland Sea and in Oligocene times due to re-configuration of plate orientation and motion.

## Introduction

Improvement in seismic imaging techniques and volcanostratigraphy has enlightened scientific curiosity of what magmatic processes and deposits are (Planke et al., 2000). Magmatism during continental breakup can affect the geodynamic development, structures, and maturation of source rocks along continental margins as they are often transient and voluminous (Holford et al., 2012; Jones et al., 2007). Classic examples of magmatic deposits are found along the Northeastern Atlantic margins in Greenland, the Vøring margins, the Møre Basin, the Faroe Islands, the Rockall trough, and in the NW British Isles (Gernigon et al., 2004; Hansen et al., 2011).

However, an important aspect of magmatism on continental margin that remain poorly understood and documented is the implication such processes have on fault segmentation and reconfiguration. The aims of this study are to (a) find evidence for volcanic deposits along the Jan Mayen Microcontinent, JMMC, (b) characterize the deposits, and (c) understand the implication they have on fault development especially segmentation and reactivation. The study area is in the central part of the North Atlantic Ocean, between the Kolbeinsey Ridge and the Aegir Ridge ([Figure 1](#)). The Beerenberg volcano is north of the JMMC and at its southwestern part is a N-S narrow ridge called the Jan Mayen Ridge, JMR ([Figure 1a](#)). Péron-Pinvidic and Manatschal (2010) classified the Jan Mayen as a microcontinent based on its size and separation from other continental crust by an oceanic crust.

## Geologic Setting

Much of the geologic development of the JMMC before Eocene are similar to those of its conjugate margins of Norway and Greenland. The geologic history of these two margins before Eocene times are strongly influenced by the Caledonian orogeny of c. 400 Ma and the collision between Laurasia and Western Siberia at c. 240 Ma (Doré, 1991; Johansen et al., 1994). In the mid-Permian, significant extension and normal faulting occurred in East Greenland while extension of the Norwegian margin started in Late Permian to Early Triassic (Faleide et al., 2008). Late Triassic to Early Jurassic was generally tectonically quiescent in most of the basinal areas. In the Late Jurassic to Early Cretaceous, the African and American plates had rifted in the southern and central parts of the Atlantic Ocean. Rifting created extensive Cretaceous age basins on East Greenland and Norwegian margins, which is the main NE-SW structural trend seen on the margins today (Faleide et al., 2008).

A final stage of rifting throughout the Late Cretaceous to Early Eocene separated the continental plate into two separate parts, Greenland and the Eurasian plate. The breakup which occurred in the Early Eocene at about 54-55 Ma was accompanied by 3-6 million years of volcanism along the Norwegian margin and initiation of an oceanic crust (Gernigon et al. 2012, Faleide et al, 2008, Mjelde et al., 2008). The oceanic crust first formed at the Aegir Ridge, off the mid-Norwegian margin and the Mohn's Ridge. Consequently, a second event of irregular spreading commenced in Oligocene time when the Kolbeinsey Ridge evolved after which the eastern and western sides of the JMMC recorded intense volcanic activity.

## Data and Methods

The primary data used for this work are seismic reflection vintages acquired from 1979 (JM-1979) until 2012 (JM-2012). For this reason, acquisition and processing parameters are variable from one survey to the other. The recent vintages (JM 2011, JM 2012, and JM 2012-OBS)

have recording length of 9216 ms and vertical sampling rate of 2 ms giving maximum theoretical frequency of 250 Hz (Nyquist frequency). On the other hand, the older vintages (JM 1979 and JM-1988) have vertical sampling rate of 4 ms (Nyquist frequency of 125 Hz). The seismic data are not depth-converted. They are in reverse Society of Exploration Geophysicists (SEG) polarity convention. An increase in acoustic impedance with depth is a trough or blue reflector. Vertical seismic resolutions for the dataset using an average velocity of 2200 m/s and dominant frequency of 50 Hz are 11 m. The available borehole in the study area are shallow and they include DSDP well 346, 347, and 349 ([Figure 1c](#)).

Seismic interpretation include the mapping of regional horizons and several hard kicks indicative of igneous rocks in the subsurface. The hard kicks are seismic high amplitude anomalies characterised by localized brightening of positive amplitude values with similar polarity as the seabed (*cf.* Alves et al., 2015). Igneous intrusions are positive high-amplitude anomalies with complex geometries, often showing local transgression i.e., movement of the anomaly up or down in the stratigraphy and abrupt terminations of their edges (*cf.* Planke et al., 2000; Poulteau et al., 2008). The extrusive igneous rocks are characterized using seismic volcanostratigraphy technique defined by Planke et al., 2000. Furthermore, for faults intruded by the volcanic sills, throw (t) vs. depth (z) plots was computed. The throw is the difference between hangingwall and footwall cut-offs (*cf.* Omosanya et al., 2015). This exercise is necessary to understand the role of magmatic intrusion at influencing fault reactivation and vertical segmentation.

## Results

On seismic sections, igneous rocks in the study area are positive high-amplitude anomalies with similar polarity as the seabed reflection. Their high amplitude is due to the high difference in acoustic impedance between them and their sedimentary counterparts (Smallwood and Maresh, 2002; Alves et al., 2015). The igneous rocks on seismic sections are (a) continuous, layered, bedding-parallel and structureless reflectors ([Figure 2](#)) and (b) as structured, vertical to sub-vertical tabular and convex-up anomalies ([Figure 3](#)). The first kind of rocks are dominant on the western part of the JMMC where they occur at intermediate depth of 2.5 to 3.5 s TWTT ([Figure 2](#)). These rock types are extrusive igneous rocks or layered basalts. The second type of igneous rocks are intrusive sills and dykes, which are common on the eastern part of the JMMC. They include tabular sills, transgressive sills, dykes, saucer or bowl-shaped, and eye-shaped sills ([Figure 3a](#) to [Figure 3e](#)). Sills in the study area intrudes both the Eocene and Oligocene sediments ([Figures 2](#) and [Figure 3](#)).

The saucer-shaped sill have an inner sill, an inclined sheet, an outer sill, and accommodation folds or forced folding at their upper part ([Figure 3a](#)). Force folding is evidence for post-depositional deformation of the overlying strata. Transgressive sills are several saucer-shaped sills that move-up stratigraphic intervals and link at sill-sill junctions ([Figure 3b](#)). Eye-shaped sills forms when a lower saucer-shaped sill merges with an upper convex-down sill at a subtle sill-sill junction ([Figure 3e](#)). Dykes are vertical structures ([Figure 3c](#)). Additional volcanic structures found in the study area may include stocks, batholiths, and laccoliths.

Furthermore, several vertical discontinuities are interpreted on both sides of the JMMC. These discontinuities are faults with variable geometry and relationship with sills and basalts. Faults in the study area are located next to sills, detaches on sills and are located above sills ([Figure 4](#)). The faults include deep-seated and hard-linked faults ([Figure 3c](#) and [Figure 3e](#)), intermediate faults ([Figure 2a](#), [Figure 4d](#), and [Figure 4e](#)) and shallow faults ([Figures 2a](#) and [Figure 4a](#)). The fault planes are generally planar, sometimes with complex intersection geometry such as

conjugate faults ([Figure 4c](#) and [Figure 4e](#)). Individual sills show complex vertical fragmentation because of faulting. Where sills intrude fault planes, fault reactivation are suspected (e.g., [Figure 4a](#) and [Figure 4e](#)).

### Conclusions

- Igneous rocks in the study area include extrusive basaltic rocks and intrusive dykes and sills.
- The extrusive rocks are common on the western part of the JMMC while their intrusive counterparts are dominant on the eastern section.
- The intrusive rocks includes tabular, transgressive, saucer, and eye-shaped sills and dykes.
- In the study area, sills are common with faulting. Sill intrusion influences vertical segmentation and reactivation of faults in the study area.
- A major constraint to the interpretation of the sills on the western part of JMMC is the presence of migration smiles or processing artefacts that mimic the geometry of the overlying saucer-shaped sills.

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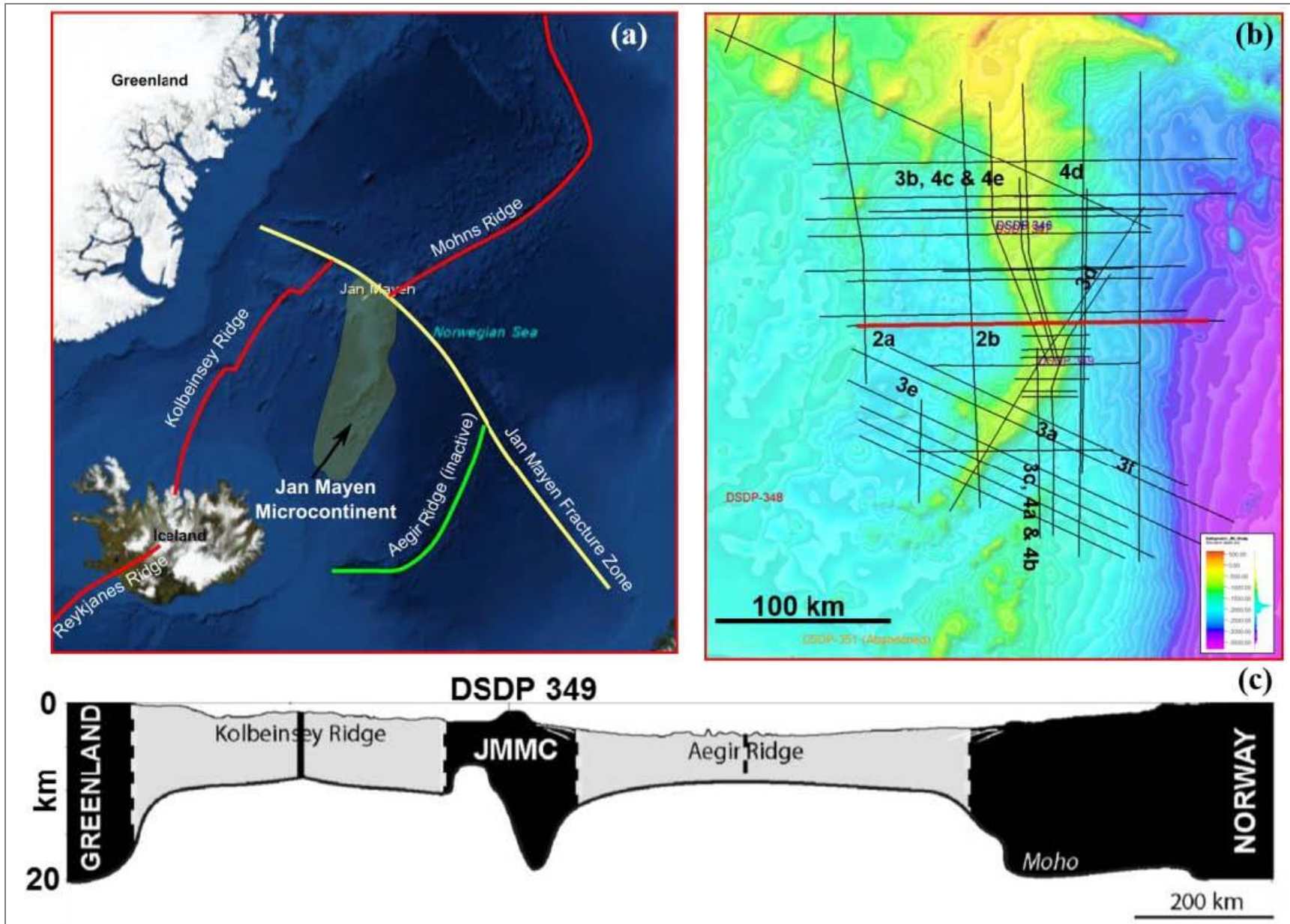


Figure 1. (a) Location of the Jan Mayen Microcontinent Continent (JMMC) and its other associated structural elements. (b) Bathymetry map across the JMMC and location of seismic lines used in this study. (c) Schematic crustal transect across the Greenland Sea - Norwegian. The JMMC is located between the Kolbeinsey and Aegir Ridge (Modified after Gaina et al., 2002). Numbers on [Figure 1b](#) shows the location of the seismic lines in [Figure 2](#), [Figure 3](#), and [Figure 4](#).

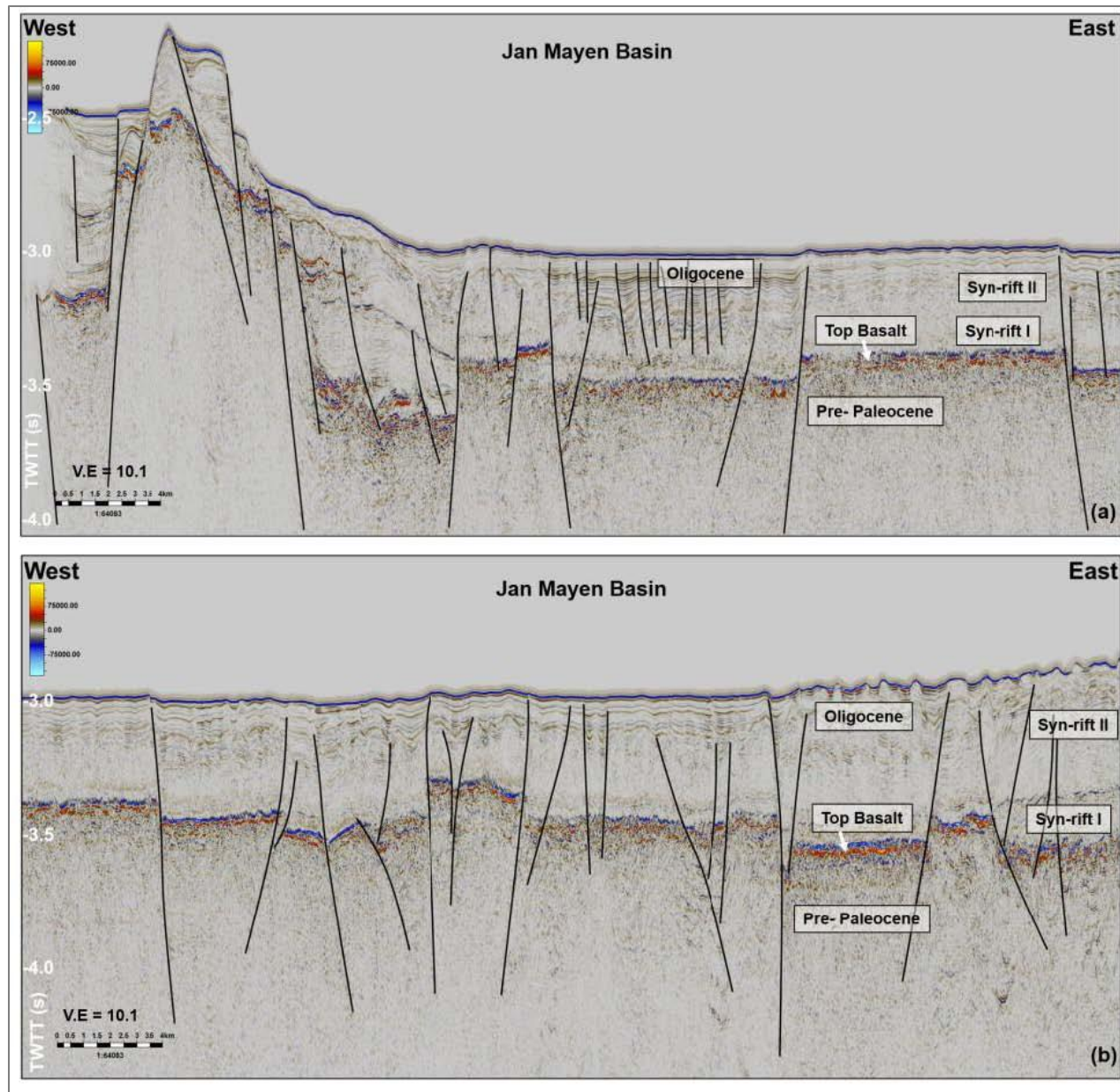


Figure 2. Seismic lines across the western part of the JMMC showing the different kinds of vertical discontinuities interpreted with the post-Paleocene sediments. Faults in the study area include deep-seated/hard linked faults, intermediate and shallow faults. See [Figure 1](#) for location of seismic sections.



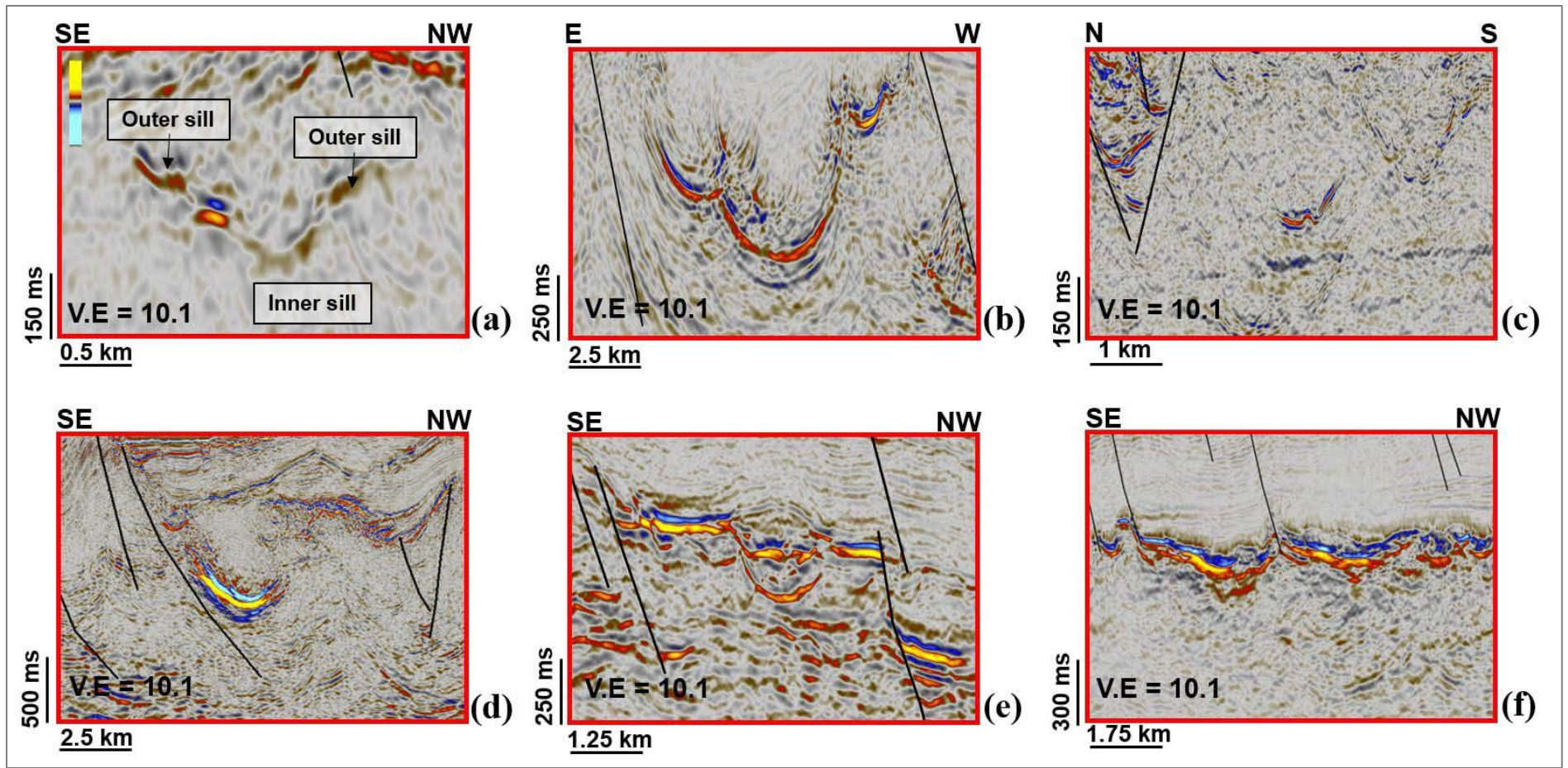


Figure 3. Examples of igneous rocks from the study area (a) saucer-shaped sill, (b) transgressive sill, (c) dyke, (d) bowl-shaped sill, (e) eye-shaped sill, and (f) flood basalt. The igneous rocks include extrusive and intrusive types. On seismic sections, they are hard kicks with similar polarity as the seabed reflection. See [Figure 1](#) for location of seismic sections.



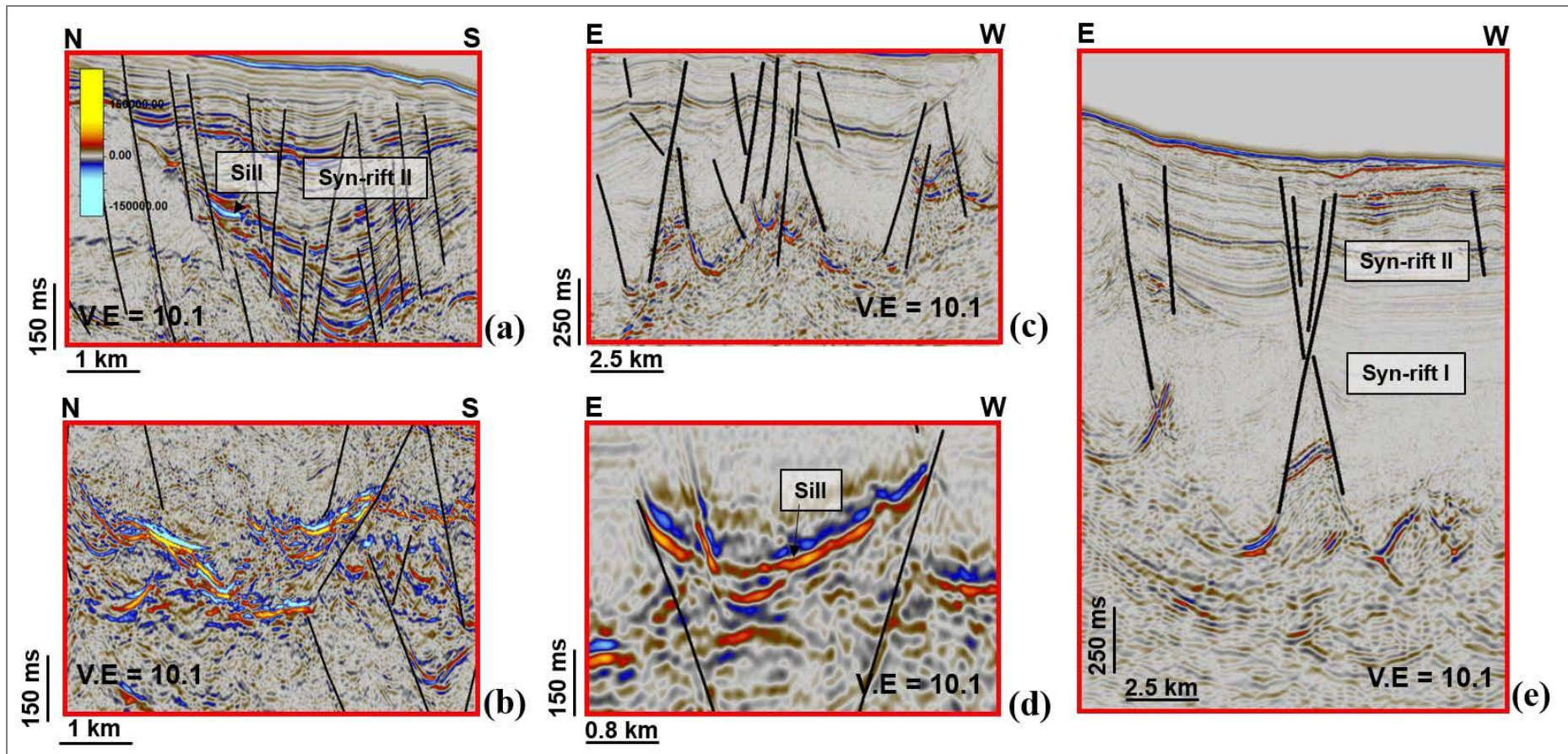


Figure 4. Sill-fault interactions in the study area (a) a sill intruded into an array of normal faults. The host sediments were deposited during the second episode of rifting (b) faults tipping out onto transgressive sills (c) conjugate fault sets soling out on volcanic sills (d) post-emplacment deformation of a sill by conjugate faults (e) deep-seated conjugate faults associated with transgressive sills. See [Figure 1](#) for location of seismic sections.