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Running title:
LONG-TERM DEVELOPMENT OF POLYGONAL FAULT SYSTEMS

Polygonal fault systems on the mid-Norwegian margin: A long-term source for fluid flow

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Abstract: 2D and 3D seismic data from the mid-Norwegian margin show that polygonal fault systems are wide-spread within the fine-grained, Miocene sediments of the Kai Formation that overlie the Mesozoic/Early Cenozoic rift basins. Outcropping polygonal faults show that de-watering and development of polygonal faults commenced shortly after burial. On the other hand, the polygonal fault system's stratigraphic setting, upward decreasing fault throw, and the association with fluid flow features that are attributed to de-watering of the polygonal fault systems shows that polygonal faulting and fluid expulsion is an ongoing process since Miocene times.

The advent of 3D seismic data acquisition and interpretation led to the discovery of a new, non-tectonic class of faults called polygonal fault systems (Cartwright, 1994). Such fault systems occur frequently in the fine-grained fill of sedimentary basins (Cartwright & Dewhurst, 1998). Cartwright & Lonergan, 1996 have suggested that the formation of polygonal fault systems is related to sediment contraction and fluid expulsion, as they are layer-bound and not related to adjacent basement. The processes leading to contraction and water expulsion are still debated (cf. Cartwright *et al*., this volume). Possible processes involved in their development include syneresis of colloidal sediments (Dewhurst *et al*., 1999) and Rayleigh-Taylor instabilities due to density inversions (Watterson *et al*., 2000). Understanding of such fault systems is important as they interact with adjacent reservoirs (Cartwright, 1994), and because they might control fluid flow on a regional scale (Henriet *et al*., 1991).

Growth-related sedimentary successions at the top of the polygonal fault systems revealed that their development commences during early burial of the host sediments

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(Cartwright & Lonergan, 1996, Lonergan *et al*., 1998). However, until now there was little information how long the involved processes remain active. Here, we present evidence from 3D and 2D seismic data for long-term fluid flow from the polygonal fault systems of the mid-Norwegian Vøring Basin. It suggests that fluid expulsion related to polygonal fault development in this area is an ongoing processes since the Early Miocene.

Polygonal fault systems on the mid-Norwegian margin

The mid-Norwegian continental margin has formed as a result of several rifting episodes leading to Late Paleocene/Early Eocene continental break-up and development of the Norwegian-Greenland Sea (Skogseid *et al*., 2000). Subsequently, the margin experienced an episode of moderate compression during the Oligocene and Miocene, which led to the development of dome structures (Brekke & Riis, 1987, Skogseid & Eldholm, 1989, Doré & Lundin, 1996, Vågnes *et al*., 1998). From the Pliocene to the Pleistocene the margin was glaciated yielding a thick wedge of clastic sediments on the shelf (Vorren *et al*., 1998). Here, we focus on the area north of the Storegga Slide, a large submarine slope failure that occurred at 8200 yrs b.p. (Haflidason *et al*., 2001). The sedimentary successions in this area include the Brygge Formation of the Eocene / Oligocene Hordaland Group, the Miocene/ earliest Pliocene Kai Formation, which is generally characterized by fine-grained hemipelagic oozes, and the Plio-/Pleistocene glacially derived hemipelagic contourites and debris flows of the Naust Formation (Blystad *et al*., 1995, Rokoengen *et al*., 1995).

Hjelstuen *et al*. (1997) mapped the extent of small-offset faults on the mid-Norwegian margin (Fig. 1) showing that they are wide spread in the upper Oligocene and Miocene successions of the Vøring Margin. 3D seismic data show the polygonal shape of these faults in plan view (Fig. 2). This shape implies a lack of dominant strike directions. The faults commonly occur in at least two tiers in the uppermost Brygge and in the Kai Formations.

Their vertical extent is variable, i.e. the upper and lower terminations of adjacent faults do not necessarily occur at the same stratigraphic level (Fig. 3a). The fault frequency is much higher in the lower part than in the upper part of the tiers. Major faults cut through the whole tier, whereas many smaller faults exist in the lower part and terminate either at deeper stratigraphic levels or at major faults (e.g. Fig. 2). The fault frequency is lower where the host formation thins out towards the Tertiary dome structures.

On 2D seismic lines the average spacing between individual faults is smaller than the maximum polygon diameter determined from the 3D seismic data measured at the top of the tiers (Fig. 3b). This supports the interpretation that most of the faults in the 2D seismic data are indeed part of polygonal fault systems.

Generally, the fault throw is highest close to the lower termination (Fig. 3c) with an average between 20 – 40 ms, but may occasionally reach much higher values. The height of the faults varies depending on the thickness of the hosting Kai Formation, i.e. where the formation is thicker the faults have a greater vertical extent and vice versa.

In the northwestern part of the study area where the Kai Formation is not overlain by the Naust Formation the faults reach close to the sea floor (Fig. 4a). In the eastern part of the study area, i.e. above the Ormen Lange Dome, they are buried by up to 1000 m of sediments.

The sediments of the Naust Formation are generally not faulted. However, they frequently show gentle deformation where polygonal faults exist in the underlying formations.

Fluid Flow

The study area is characterized by a number of fluid flow indicators in the geological and geophysical data. The most prominent evidence stems from laterally narrow, i.e. 20-200 m wide, circular zones of up-bending, low-amplitude reflectors (Fig. 5). In the following we call these zones pipes, because they are similar to those reported from the Niger Delta and onshore Rhodes by Løseth *et al*. (2001). Løseth *et al*. (2001) interpreted them to be the result of episodic fluid expulsion. The pipes on the mid-Norwegian margin originate at different depth, most often at the base of an inferred gas hydrate layer (Mienert *et al*., 1998, Posewang & Mienert., 1999), and in some instances at the upper termination of polygonal faults in the top of the Kai Formation, which coincides with a layer of high reflectivity (Fig. 3a). They never occur within or below the polygonal fault systems. The upper termination of the pipes is at different stratigraphic levels within the Naust Formation or at the sea bed (Fig. 4). The pipes are up to 600 ms two-way-travel time or approximately 550 m high (Fig. 3a). There are some pipes with down-bending reflectors, which we interpret as a result of velocity pull-down possibly indicating active fluid expulsion (circle in Fig. 3a). The upper terminations of pipes with down-bending reflectors are at different stratigraphic levels, but we do not observe any of these pipes reaching the seabed. Pronounced step-wise seismic amplitude changes and step-wise changes in the amount of reflector pull-up in the pipes (e.g. Fig. 4c at 1.3 s) are consistent with episodic rather than continuous activity.

A second line of evidence for substantial fluid flow can be derived from side-scan sonar data showing pockmarks above some of the pipes (Fig. 5). Pockmarks are frequently caused by fluid flow (Hovland & Judd, 1988).

Finally, pronounced seismic amplitude anomalies at the base of the gas hydrate stability zone also indicate a dynamic fluid flow system (Fig. 3a). These amplitude anomalies are interpreted to be the result of free gas that is trapped underneath hydrate sediments (Mienert *et al*., 1998, Posewang & Mienert, 1999). Mienert & Posewang (1999) showed seismic evidence for fluid expulsion from the gas hydrate system. The seismic fluid flow indicators are most common near the northern sidewall of the Storegga Slide, and relatively sparse in the rest of the study area.

Discussion

Fluid origin

The processes leading to polygonal fault system development are not well understood, but all genetic models for polygonal fault systems involve fluid expulsion from the host rock. The volume of expelled fluids might be as much as 60 % (Verschuren, 1992). It is therefore reasonable to anticipate that the polygonal fault systems provide a major source for the fluid flow observed in the study area. We also recognize that some fluids might ascend from greater depth. However, from the absence of fluid flow indicators underneath or within the polygonal fault systems we infer that the volumes of such fluids must be small compared to the fluids expelled from polygonal fault systems. Sampling of the ascending fluids in one of the still active pockmarks and their geo-chemical analysis may constrain the fluid origin in more detail, but this has not been attempted so far.

Fluid channeling

Polygonal fault systems are wide-spread in the study area (Fig. 1 and 2). However, fluid flow indicators are not similarly abundant. Most often they occur in areas with gas hydrates or glacial debris flows in the overburden. We interpret this observation as an indication for diffuse flow of fluids out of the polygonal fault system that is not observable in the seismic data unless the fluids get trapped either by hydrated sediments or by less permeable debris flows. In these instances pockets with high pore pressure will develop that will expel fluids episodically when the pore pressure exceeds the strength of the trap and causes pipes and amplitude anomalies observed in the seismic data.

In the area with observed fluid-escape features the polygonal faults terminate into a layer, which shows increased reflectivity in seismic sections (Fig. 3a), probably indicating the accumulation of gas-enriched fluids within the sediments. Even though the main flow from here might be diffusive, the fact that some pipes start at the upper termination of polygonal faults (Fig. 3a) suggests that the polygonal faults or their vicinity are preferential pathways for fluid migration.

Timing

Outcropping polygonal faults at the sea floor in the western part of the study area (Fig. 1 and 4) show that polygonal faults start to develop immediately after burial in accordance to the observations of growth structures observed by Cartwright, (1994) and Cartwright & Lonergan (1996). Assuming that de-watering of the polygonal fault system causes the observed fluid flow we can take the seismic fluid flow indicators as a proxy for the timing of the process that leads to the development of polygonal fault systems. Fig. 4 shows pipes that have their upper termination at different stratigraphic levels. These stratigraphic levels denote the earliest possible dates for the pipes, and possibly time of activity assuming that they have not been re-used. The fact, that some pipes continue all the way to the sea floor causing pockmarks implies that fluid flow and therefore de-watering of the polygonal fault system must have been active until recently.

The monotonous downward increase of fault throw is a second line of evidence pointing to an extended de-watering history. If the sediments would expel the entire amount of pore water immediately after burial, the throw along individual faults should be constant with depth. Lithological variations, e.g. variations in water content, should give random variations in throw. Only a process that is active over the entire burial history of the polygonal fault system would result in a monotonous downward increase of fault throw. The frequently observed reduced throw in the lowermost part of the faults is not well understood. It possibly indicates that initiation of the process depends on a threshold thickness of the previously deposited sediments, before it picks up.

We do not observe clustering of the upper terminations of the pipes at any particular stratigraphic level. This does not allow deducing temporal variations of fluid flow. However, the fact that the fault throw is decreasing upwards indicates that most of the faulting happens during burial and we infer that fluid flow due to de-watering was most vigorous at an early stage of polygonal faulting and that it decreased subsequently. The moderate deformation of the overlying Naust Formation, i.e. no clear faults but rather sacking structures, supports the interpretation that most faulting already occurred before deposition of this unit.

The area in which polygonal fault systems occur on the mid-Norwegian margin is extensive (Fig. 1) and pipes related to fluid flow are found in many places within this region. This leads us to conclude that long-term fluid flow related to polygonal faults is a general pattern. Nevertheless, there are some areas such as the northern sidewall of the Storegga Slide, in which pipes are more abundant than elsewhere. This suggests that de-watering and polygonal faulting is variable in time and space – most likely as a result of external forces such as the Storegga Slide or thickness variations of the faulted sediment units. In fact, the Kai Formation is thickest in the northern part of the Storegga Slide area (Britsurvey, 1999).

Finally, the downward increase in fault frequency and the ensuing downward decrease in fault block size point towards long-term and still ongoing sediment contraction and fluid expulsion. Small-size fault blocks in the lowermost parts of the polygonal fault system combine into larger fault blocks higher up in the sections. We interpret this as a change of faulting scale. Faults apparently start to grow in the lower part and advance upwards until they terminate either at the upper boundary or into another fault and thus they focus strain along fewer faults. This is consistent with a long-term activity of the faults.

Conclusions

3D seismic data from the Ormen Lange Dome demonstrate the existence of polygonal fault systems on the mid-Norwegian margin. Extrapolating the results of 3D-seismic imaging by using 2-D seismic data and the mapping results of Hjelstuen *et al*. (1997) we find that substantial parts of the outer Vøring and Møre margins are underlain by polygonal fault systems. Stratigraphically, the fault systems are located in the fine-grained, hemi-pelagic sediments of the Kai Formation which were deposited during the Miocene.

Under the assumptions that seismic fluid flow indicators can be taken as a proxy for active fluid flow the duration of polygonal fault system development can be quantified. The variable stratigraphic position of the top terminations of the fluid flow indicators implies that the processes that cause fluid expulsion and perhaps development of the polygonal fault systems have been active on the mid-Norwegian margin ever since Miocene times.

Fluid flow from the polygonal fault systems and its spatial relationship to the occurrence of natural gas hydrates poses the question whether both are related, and whether the polygonal fault systems might be a source of fluids that are involved in the development of gas hydrates. Coincidence of some polygonal faults and the northern Storegga Slide side-wall might indicate that the polygonal fault systems play a role for continental slope stability. These questions have to be investigated in more detail in the future.

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Figure Captions

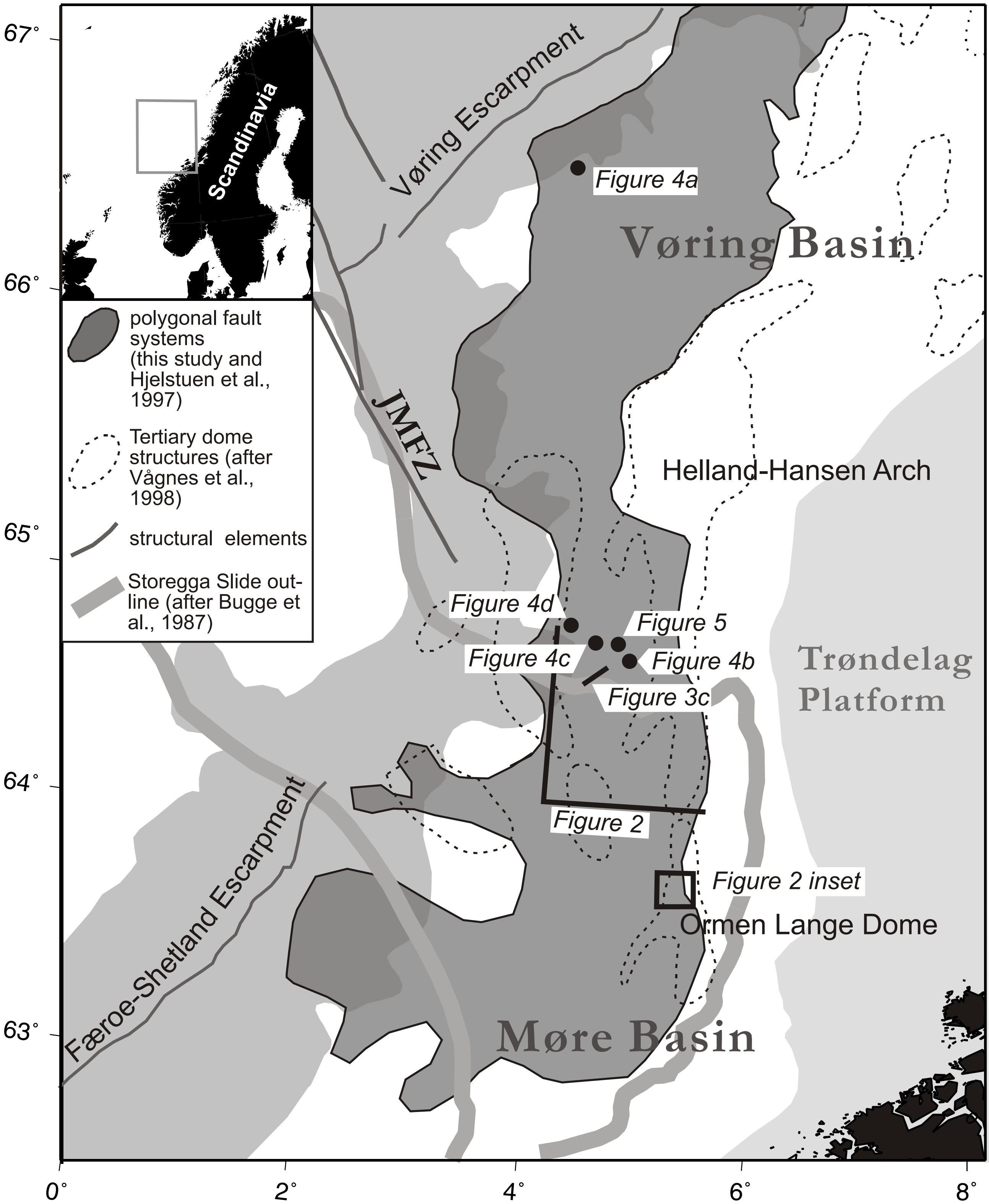
Fig. 1: Polygonal faults on the mid-Norwegian margin are primarily located within the Cretaceous/Early Tertiary rift basin between the break-up related volcanic rocks to the west (light gray, after Berndt et al., 2001) and the Trøndelag platform in the East (light gray, after Blystad et al., 1995). Black lines and circles indicate seismic examples shown in Figs. 2-5. JMFZ, Jan Mayen Fracture Zone.

Fig. 2: Regional seismic section showing polygonal fault systems (cf. Fig. 1 for location). The inset shows the dip attribute map of a horizon slice from the Ormen Lange 3D block located to the south of the seismic section. The inset is projected onto the seismic line with the dashed line indicating approximate depth.

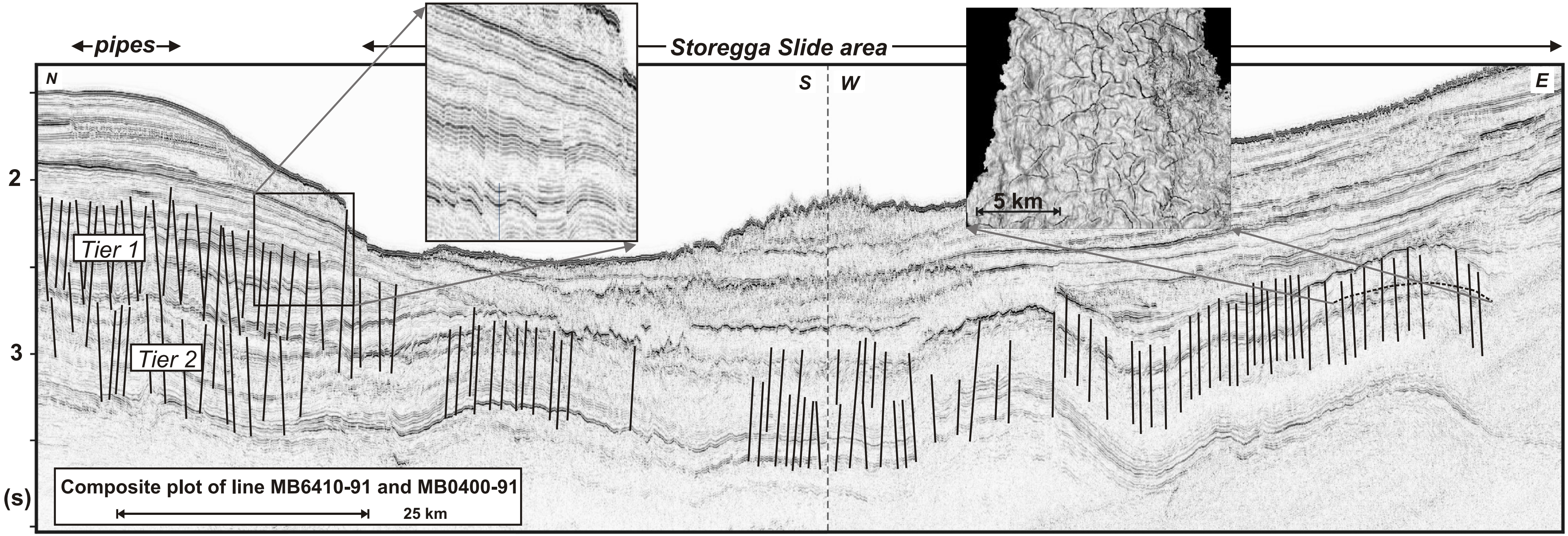
Fig. 3: a) High-resolution seismic profile JMF97 (courtesy Fugro Geoteam AS) showing pipes originating at the upper termination of polygonal faults (arrows). It also shows an example for a possibly still active pipe with down-bending reflectors (circle). Bottom simulating reflector (BSR) indicates the base of the gas hydrate stability zone. b) Distance between faults in 2D seismic lines and width of polygons in 3D seismic data; Norm. count, number of polygons with a given diameter divided by number of polygons evaluated in total. c) Fault throw for 30 to 50 faults on individual 2D seismic lines (names indicated). The throw along polygonal faults generally increases downward. In some areas, however, the throw near the lower fault termination decreases, e.g. line NH9753-402.

Fig. 4: Seismic evidence for prolonged polygonal fault system development. a) Polygonal faults offset the sea floor. c-d) Fluid expulsion related pipes that terminate at different stratigraphic levels, Naust A-E, Pleistocene (0.015 my.-18 m.y.); Naust F-H, Pliocene (1.8-3.6 m.y.); Kai A-C, Miocene (23.8 m.y.). Seismic panels located on Fig. 1.

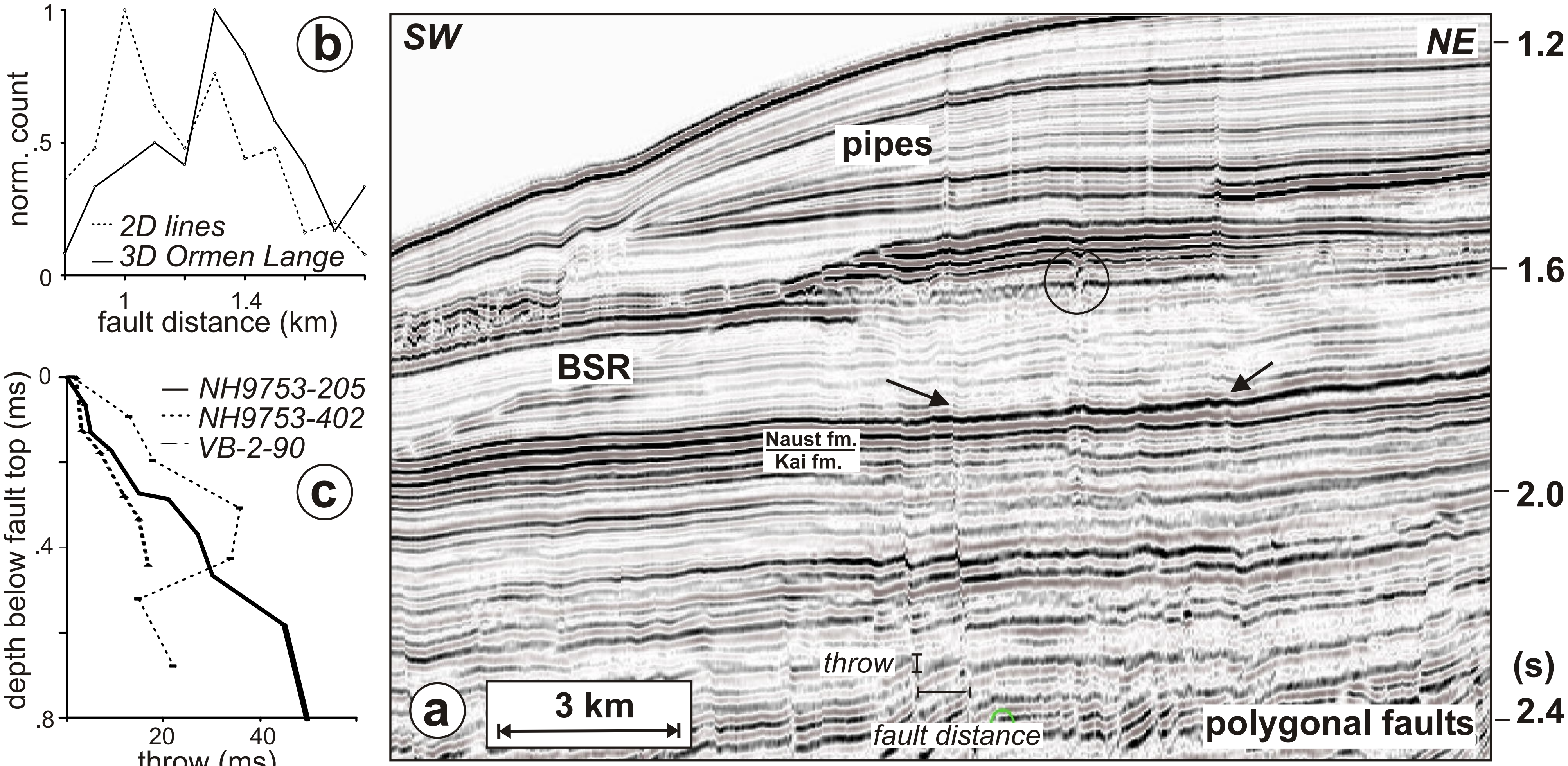
Fig. 5: Composite plot of side-scan sonar sea floor backscattering image (top) and high-resolution single channel seismic profile (bottom) showing that some of the pipes terminate in circular pockmarks. Dark colors in the side-scan sonar data indicate high backscatter.



Berndt et al., figure 1



Berndt et al., figure 2



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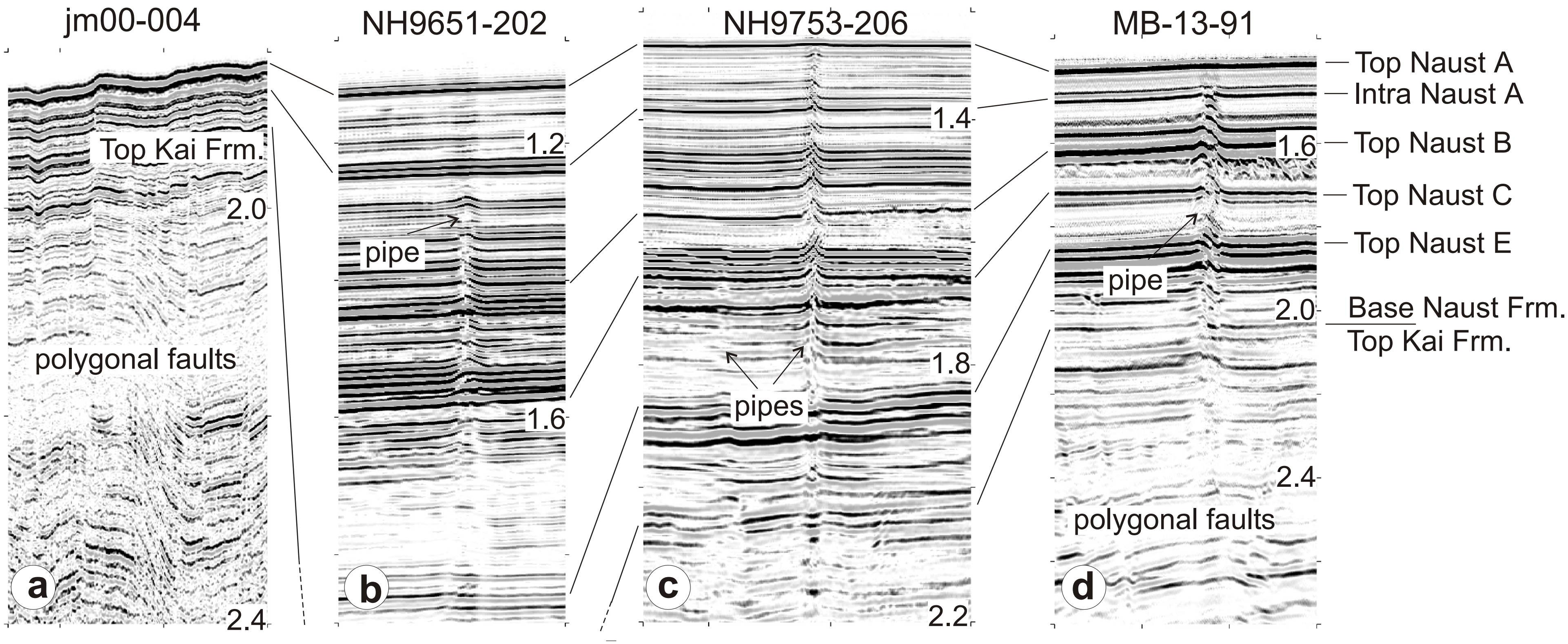
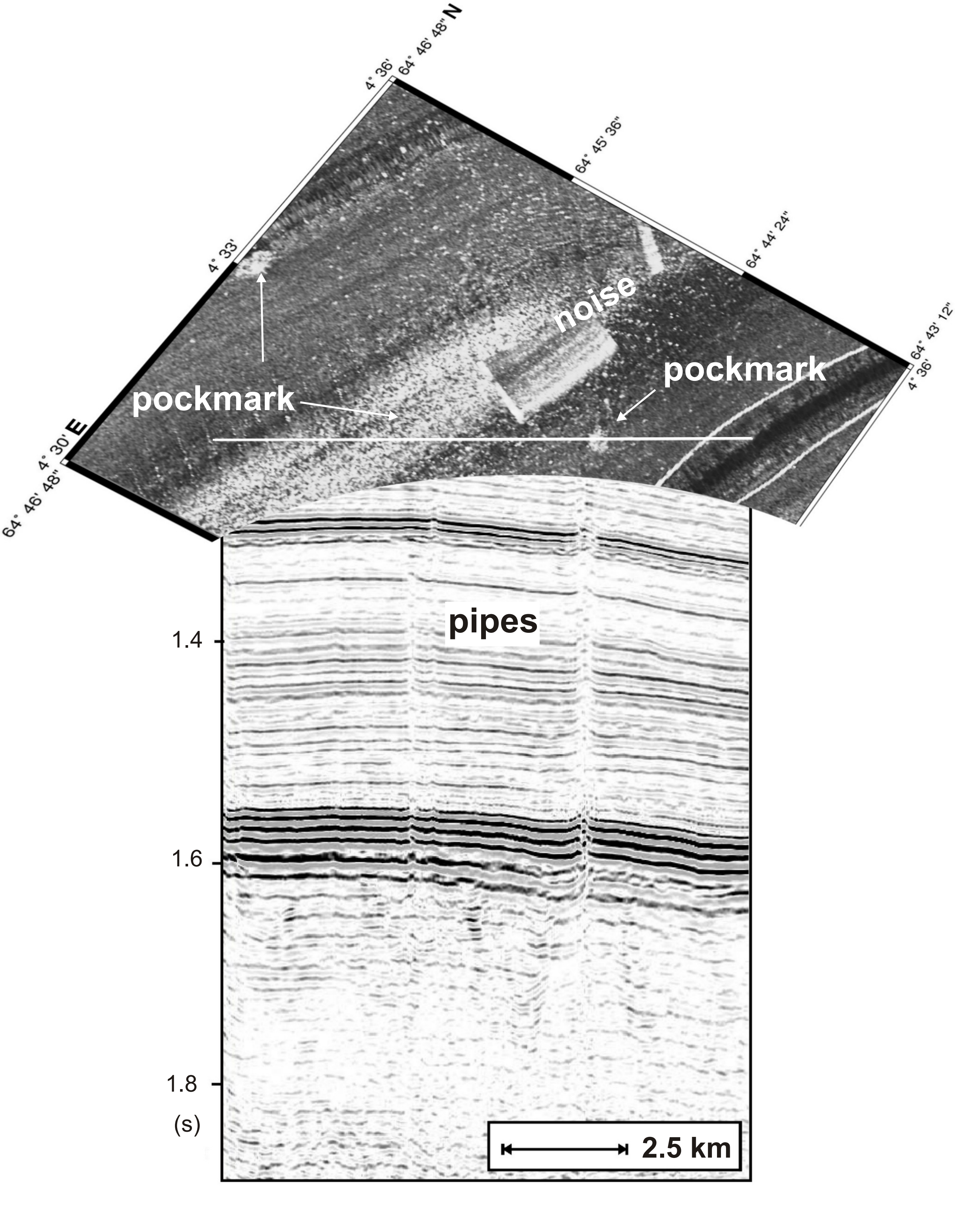


Berndt et al., figure 4



Berndt et al., figure 5