Geodynamic evolution of domes on the mid-Norwegian continental margin

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Abstract

The mid-Norwegian passive margin is characterized by a pattern of basinward stepping rifting. In the outer, Cretaceous and Early Tertiary part of the margin, a number of dome-shaped structures are present. Regionally, compressional domes are mapped in extensive parts of the Cretaceous-Tertiary depocentres of the NW European margins between mid-Norway and the northern Rockall Trough. In mid-Norway at least two dome types exist, and their development was spread over much of the Tertiary Era. Major phases include 1) latest Cretaceous-Early Tertiary syn-rift extensional doming, 2) mid-Tertiary post-break up compressional doming, 3) Neogene modification of dome flanks by differential loading from a large prograding glacio-marine sequence.

The first phase we attribute to the combination of regional extension and pronounced magmatic underplating of the margin. In the broadest sense of the term, this relates to the appearance of the Iceland “hotspot”. The second phase was associated with a major change in North Atlantic-Arctic plate configuration, which in turn coincided with apparent changes in activity of the Iceland hotspot. The third phase was largely an effect of differential sedimentary loading of thick and rapidly deposited glacio-marine prograding wedges, which indirectly relates to large scale Neogene epeirogenic uplifts on the Norwegian mainland.

Introduction

The mid-Norwegian passive margin (Fig. 1), bordering the NE Atlantic, broke up in Early Eocene time (Chron 24, c. 54 Ma) after approximately 300 Ma of episodic rifting (e.g. Doré et al, 1999). Opening of the North Atlantic occurred progressively northward from the area of initial separation between Iberia and Newfoundland in Aptian time and reached into the Labrador Sea and Baffin Bay by latest Cretaceous or Early Paleocene time (Fig 2). Early linkage of the North Atlantic and Arctic was possibly achieved via the Wegner transform between Baffin Bay and the Arctic Eurasia Basin in Early Paleocene time. Remarkably, despite this apparent successful linkage, the NE Atlantic opened soon thereafter (in Early Eocene) and rapidly became the dominant arm of North Atlantic plate separation. The Iceland hotspot has been captured in the NE Atlantic spreading system since break-up.

The Cretaceous North Atlantic passive margins were non-volcanic, while the Early Tertiary NE Atlantic margins were volcanic. The key factor influencing the onset of the pronounced NE Atlantic magmatism is traditionally thought to be decompressional melting of abnormally hot asthenosphere, associated with the Iceland hotspot (e.g. White & McKenzie, 1989); Iceland has generally been considered to be the surface manifestation of a mantle plume rooted at the core mantle boundary. A fundamental question regarding the North Atlantic-Arctic linkage is whether the Iceland hotspot governed break-up of the NE Atlantic or whether it formed as a consequence of plate tectonic factors during break-up. This in turn relates to one of the hottest ongoing debates in geoscience, between advocates of Morgan’s (1971) mantle plumes concept and that of top-down plate tectonic advocates (e.g. Anderson, 2001; Foulger, 2002). The outcome of the debate is likely to have significant influence on the models we apply to volcanic passive margins. Regardless of this debate, the Early Tertiary magmatic influence on the mid-Norwegian margin cannot be overlooked.

A significant North Atlantic-Arctic plate reorganization occurred in earliest Oligocene time (Chron 13, c. 35 Ma), when drift of Eurasia relative North America changed from a southeasterly to a more easterly direction. A sequence of linked events date back to this event, such as the build-up of the Iceland Plateau and the development of the prominent V-shaped ridges along the spreading axes south and north of Iceland (e.g. Jones et al, 2002). Traditionally the V-shaped ridges have been attributed to an increase in the flux of the Iceland plume (e.g. Vogt, 1971).

Pre-break up extensional domes

The oldest domes on the mid-Norwegian passive margin are extensional features that formed during the final phase of rifting, in Maastrictian to Paleocene times. The northern and southern Gjallar Ridge Highs (Figs. 1 & 3) in the outer Vøring Basin are broad extensional culminations enveloped by a dome-shaped syn-rift unconformity surface. These extensional terrains may be classified as incipient core complexes (Lundin & Doré, 1997). Directly below the shallow dome expression, at the base of the crust, is a strong, well-defined dome-shaped reflector. The two dome-shaped surfaces are superimposed in space and are genetically related.

Based on seismic refraction studies (OBS) the deep reflector represents the top of underplating (e.g. Wheeler et al., 2002). Above this deep dome it is possible to distinguish diapiric bodies in the lower crust. Development of the Gjallar Ridge Highs clearly has a significant tectonomagmatic component, and may conceivably be regarded as examples of reactive diapirism (cf. Vendeville & Jackson, 1992) at a crustal scale. Analogous to reactive salt diapirism, the domes probably represent mobilized plastic lower crust and underplated melt in response to extension of the brittle upper crust and sedimentary succession. A rotated fault block prospect has been drilled in the northern Gjallar Ridge and turned out to be dry.

The palaeo-Vema Dome (Fig 4) is another dome we include in this family of tectonomagmatic extensional domes in the outer Vøring Basin. The palaeo-Vema Dome experienced a more pronounced diapiric style of doming than did the Gjallar Ridge Highs. This dome rose in Maastrictian-Paleocene time, became deeply truncated by erosion in Late Paleocene time, and collapsed in Early Eocene time. Rise and fall of the palaeo-Vema Dome is separate from a post-break up phase of compressional doming that formed the structure that is named the Vema Dome.

Post- break up compressional doming

The second family of domes is of post-break up age, and formed in mid-Tertiary time. These domes are generally characterized by simple geometries, such as four-way anticlinal closure, and are regarded to be compressional features (e.g. Doré & Lundin, 1996). A series of domes lie en echelon along the Jan Mayen Lineament, a presumed NW-trending crustal weakness (Blystad et al, 1995). The dome closest to the Norwegian mainland, named Ormen Lange, is a major Paleocene gas discovery (c. 12 TCF). The next dome outboard of Ormen Lange (Fig. 5), named Havsule, was found to be dry due to lack of reservoir.

A possible cause of these domes is left-lateral reactivation of the Jan Mayen Lineament during the major North Atlantic-Arctic plate reorganization in earliest Oligocene time (Chron 13, c. 35 Ma). In addition, we have previously suggested that plume-influenced seafloor spreading phenomena (ridge push and mantle drag) may have been the driving force for the mid-Tertiary compression (Lundin & Doré, 2002). The validity of this hypothesis is strongly linked to the origin and nature of the Iceland hotspot, a subject that is, as indicated earlier, under debate.

The current Vema Dome is a compressional feature that overprints the older Vema Dome. It appears that the older dome acted as a buttress to the younger dome. The current dome folds the extensional terrain of the palaeo-Vema Dome. A fault block prospect within the current dome has been drilled but proved to be dry. One major problem with this prospect is the deep truncation and erosional breaching of the palaeo-dome, which can be expected to have caused loss of a conceivable hydrocarbon accumulation.

The Naglfar Dome lies largely within Hel Graben, a latest Cretaceous to Late Paleocene collapsed part of the margin. The Naglfar Dome is buttressed between the Vøring Marginal High and the Nyk High. This dome has recently been drilled and discovered non-commercial amounts of gas in an extensional fault block within the dome.

The Helland Hansen Arch, is a major mid-Tertiary compressional dome, measuring c. 200 km in length and up to 60 km in width. The western side of the arch is partly formed by compressional inversion of the Rås Basin against its western boundary fault system, the Fles Fault Complex. A well has been drilled in the southern Helland Hansen Arch but was dry due to lack of reservoir.

The eastern flank of the Helland Hansen Arch has been significantly overprinted by sedimentary loading of a thick westward prograding Late Pliocene – Pleistocene glacio-marine succession. Structural backstripping of the Plio-Pleostocene load indicates that the arch initially was a weakly expressed dome, or monoclinal flexure. This Plio-Pleistocene succession relates to glacial erosion of the Norwegian mainland during the Neogene northern hemisphere climatic deterioration. However, it appears that regional scale Neogene uplifts of the mainland acted as nucleation sites for the ice cap build-up. These uplifts belong to a series of widely spaced Neogene uplifts in the margins surrounding the NE Atlantic (e.g. Japsen & Chalmers, 2000). The size and magnitude of these epeirogenic uplifted regions is much larger than that of the mid-Tertiary domes on the margins. While the mid-Tertiary domes may have formed by intra-plate deformation, this is not a likely mechanism for those regions uplifted in Neogene. The geodynamic origin of the Neogene domes remains unresolved, but an attractive hypothesis relates them to mantle diapirism (Rohrman & van der Beek, 1996).

Exploration implications

Understanding the timing and geodynamic processes behind the domes is highly relevant to exploration. In deep water gravity-driven depositional systems, which have characterized the mid-Norwegian margin during the Cretaceous and Tertiary, the timing of dome growth may directly influence reservoir presence. Presence or absence of such reservoirs in dome traps depends on the timing of doming versus reservoir deposition. Naturally, for a dome trap to work, the doming must not postdate hydrocarbon charge. Uplift and erosional or structural breaching that postdate charge will lead to loss of hydrocarbons through leakage. Late stage structural modification by sediment loading can potentially alter spill points and induce remigration. As for other types of prospects, understanding the timing of the various key elements in a given dome prospect is critical. If magmatic processes are involved in dome generation, it is important to appreciate the effects of heat flow on local organic maturation and on diagenesis.

Conclusions

- Latest Cretaceous-Early Tertiary syn-rift extensional domes on the mid-Norwegian margin were intimately related to tectonomagmatic processes associated with the final phase of NE Atlantic rifting. In particular there appears to be a relationship between upper crustal brittle extension and underplating, heating and flow of lower crust. This in turn relates to the vigorous Early Tertiary magmatism in the NE Atlantic, which traditionally is considered to be an effect of the Iceland hotspot.

- Mid-Tertiary post-break up compressional domes appear to relate to a North Atlantic-Arctic plate reorganization. This event coincides with the onset of an apparent increase in activity on the Iceland hotspot, which may have induced compression in the margins.

- The post-break-up domes were modified in Neogene time by differential sedimentary loading during build-out of thick glacio-marine prograding sequences. Ice caps responsible for the glacial erosion probably nucleated on broad epeirogenic domes situated on the Norwegian mainland. The origin of these domes, which are widely spaced around the NE Atlantic margins has been proposed to relate to mantle diapirism.

- Whether or not the Iceland hotspot is a classic plume (Morgan, 1971) or a response to plate tectonic developments remains unclear. Resolving this issue will influence the fundamental understanding of the interaction between the lithosphere and asthenosphere. The geodynamic processes behind the various mentioned domes are all possible to relate to a plume. However, many aspects of Iceland do not correspond to a classic plume, so this process understanding may have to be revisited.

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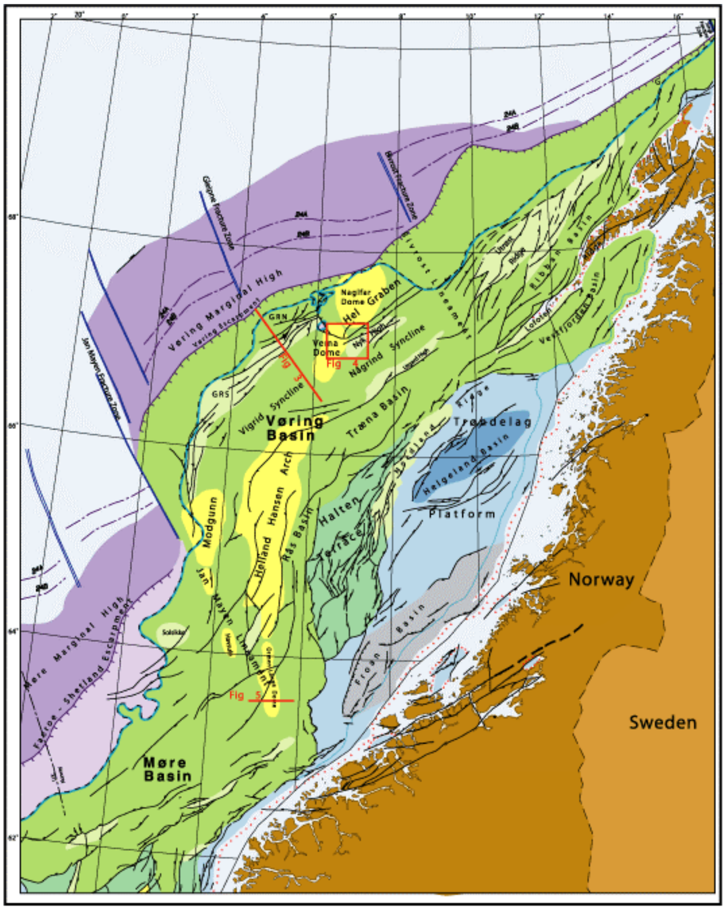

Fig.1 Simplified tectonic and structural nomenclature map of the mid-Norwegian margin. Modified from Blystad et al. (1995). Compressional domes are shown in yellow. Extensional domes: GRN= Gjallar Ridge North; GRS= Gjallar Ridge South, and possibly Solsikke. Figures 3, 4, and 5 are marked in red.

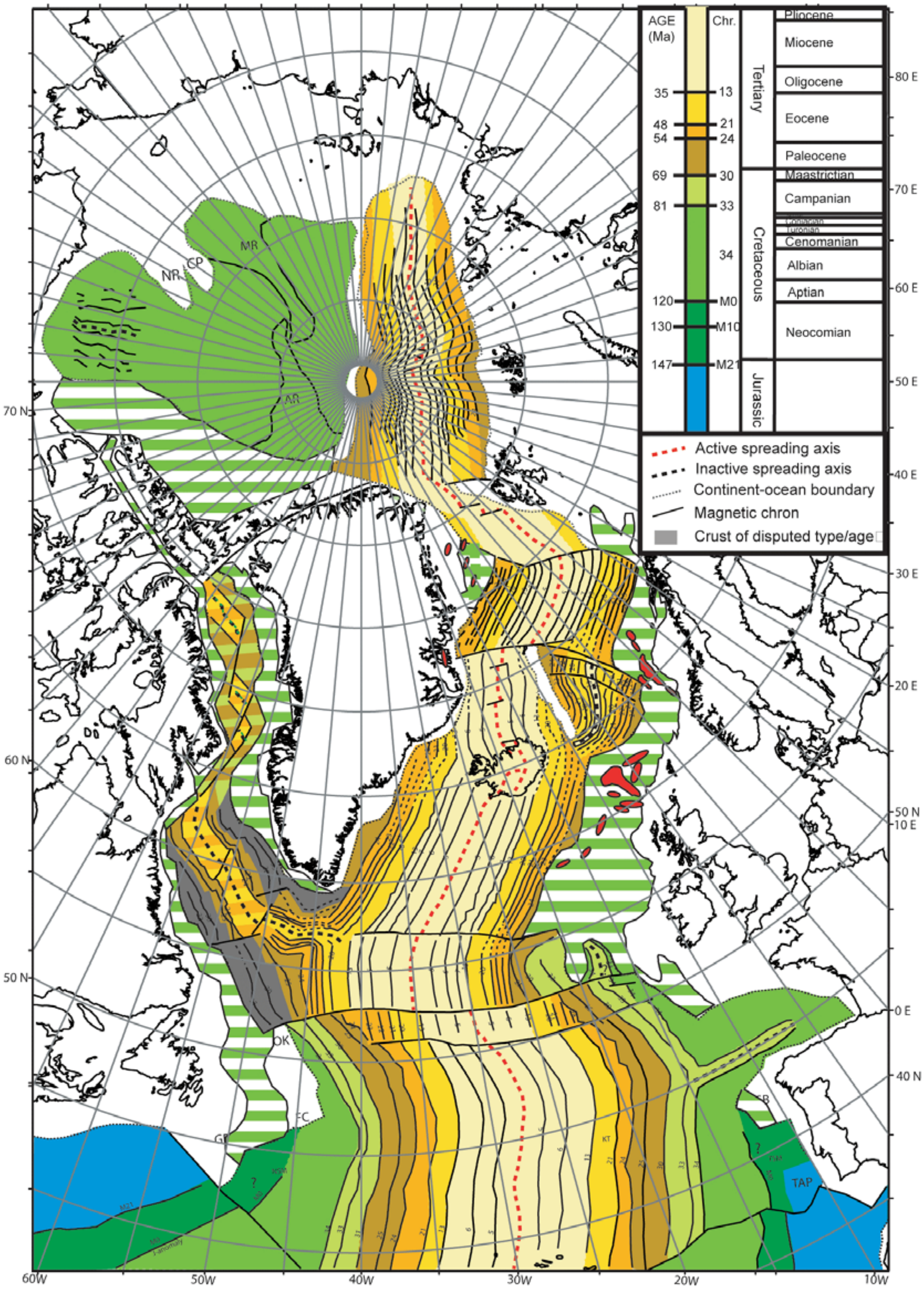

Fig. 2 Simplified seafloor map of North Atlantic and Arctic. The green-white striped areas represent Cretaceous-Tertiary rifts along the margins. Red blobs are mid-Tertiary compressional domes. Those on the NE Greenland margin are schematically located.

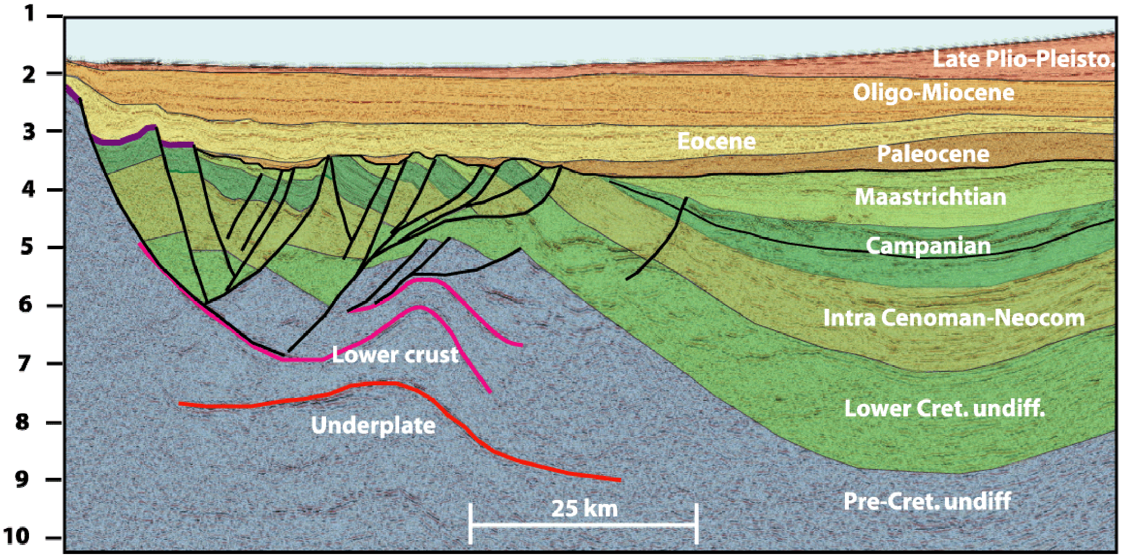

Fig. 3. Seismic profile across the Northern Gjallar Ridge and Vigrid Syncline. For location see Fig. 1.

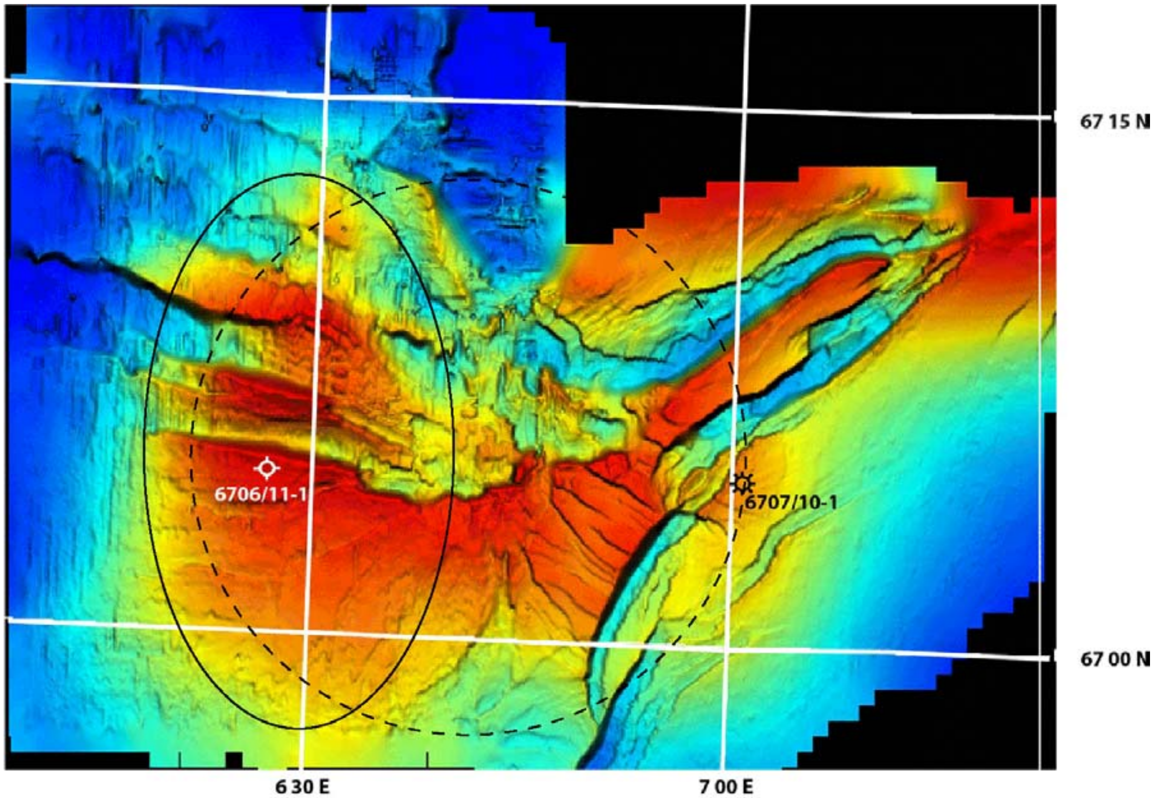

Fig. 4. Shaded relief structural map of the Campanian reservoir level in the Vema Dome. The current Vema Dome (solid outline) overprints the older and collapsed palaeo-Vema Dome (dashed outline). The palaeo-dome may have extended further NE than shown here. 6706/11-1 tested the Vema Dome and was dry, while 6707/10-1 tested the Nyk High and discovered c. 1 TCF gas. For location see Fig. 1.

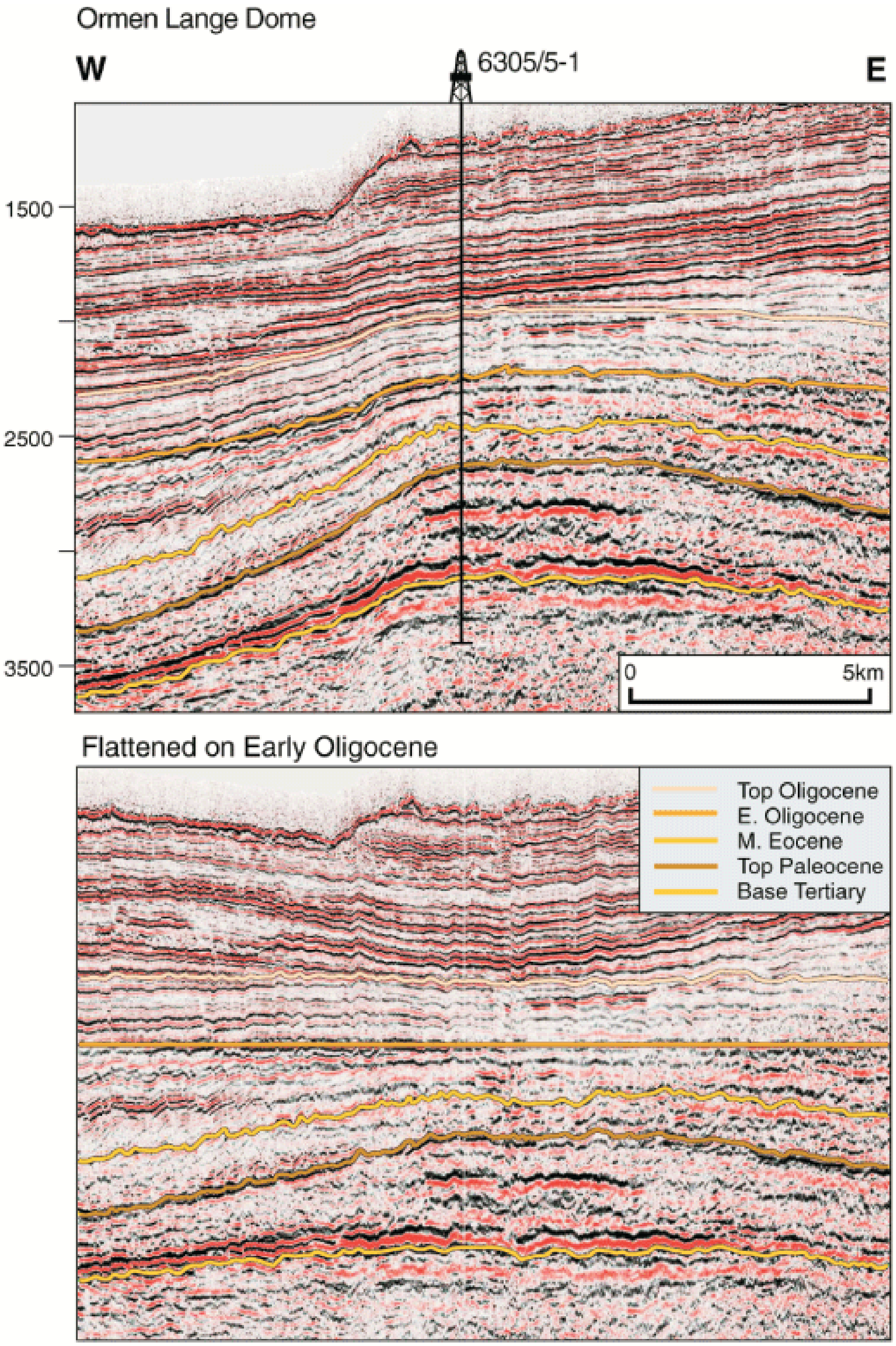

Fig. 5. Seismic section across the Ormen Lange Dome. This dome experienced two phases of mid-Tertiary compression. a) Middle Eocene – Early Oligocene, b) Early Miocene. The bright anomalies relate to a c. 12 TCF gas accumulation. For location see Fig. 1.