Volcanic chimneys atop granitic basement of the Frøya High

(Norwegian Sea)

A possible source for natural hydrogen ?

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Introduction

- With respect to the most suitable geological province for Hydrogen exploration, the Norwegian Sea area yields several characteristics that makes it quite interesting:
  - Thinned-crust basins with possible serpentinization of ultramafic rocks along the deeper parts of the Vøring Basin.
  - A wide complex of magmatic intrusion (Latest Paleocene sills and dykes) within the thick Cretaceous stratigraphic succession of the Vøring Basin.
  - Shallow granitic basement highs and subsequent volcanic intrusion (**Fig. 1**).
- Hundreds of kilometers away from the North Atlantic Margin, where the Jan Mayen fracture zone hits the Norwegian coastline, an overall gravity high anomaly, defined as the Frøya High is located just north of the Jan Mayen fracture zone (**Fig. 2**). Studies (Trice, *et al.*, 2019) from seismic data and exploration wells reveal that the gravity high anomaly relates to shallow basements rocks, with a very thin to absent Triassic-Jurassic sedimentary cover (**Fig. 3**). The area is quite shallow (top basement at less than 2s TWT) and characterized by absence of hydrocarbon source rock in the west and with immature source rock (Spekk Fm.) towards the east. Exploration wells indicate that the basement is granitic and biotite-rich. Cores from other wells on the Frøya High area also report granitic basement containing hematites, a ferric mineral known to be the result of biotite oxidation, liberating hydrogen as a byproduct.
- Intrusive sills within Paleocene sediments, but also a group of extrusive Eocene volcanoes, are clearly visible on the south-eastern side of the Frøya High (**Fig. 4, 5 & 6**). The Eocene age of the volcanoes corresponds to other extrusive volcanic events of the greater Vøring region, towards the end of the North Atlantic breakup. Some of these structures are fully buried in the sedimentary cover, while others remain as relief on the seabed due to extensive erosion from the Mid-Miocene to Pleistocene.

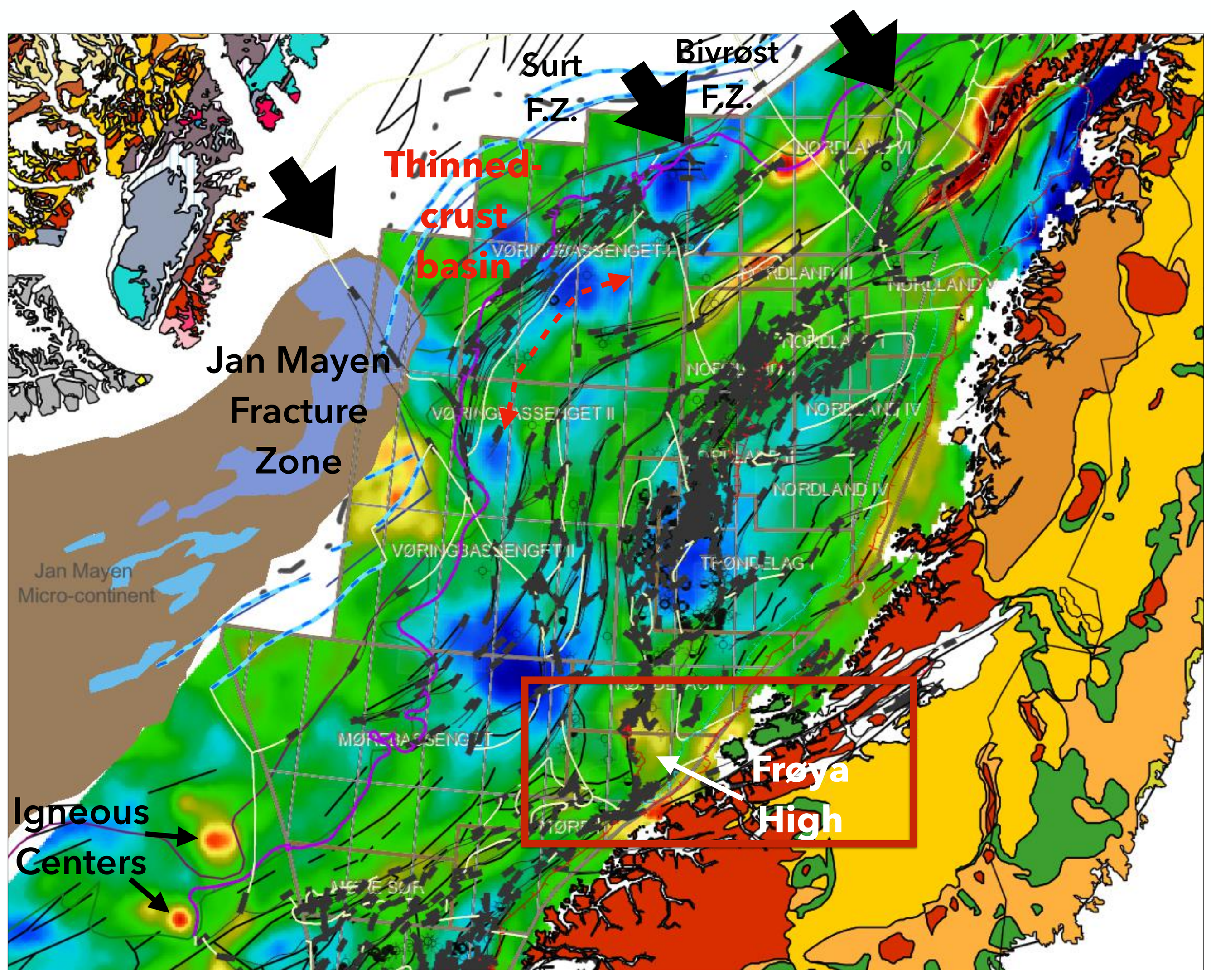

Fig. 1: Free-air gravity map of the Norwegian Sea and main structural elements

- Several positive gravity anomalies (red) are lined up along the Klakk and Vingleia Fault Complex that delineate the western edge of the Frøya High and Froan Basin respectively. They are mostly associated with a postive magnetic signature, indicating basement origin, rich in ferrous material.
- Two major positive gravity anomalies characterize the Frøya High suggesting its complex origin: Northern anomaly **(N1)**, relatively symmetric, Southern anomaly **(N2)** elongated, NE-SW trending, striking across the Jurassic margin

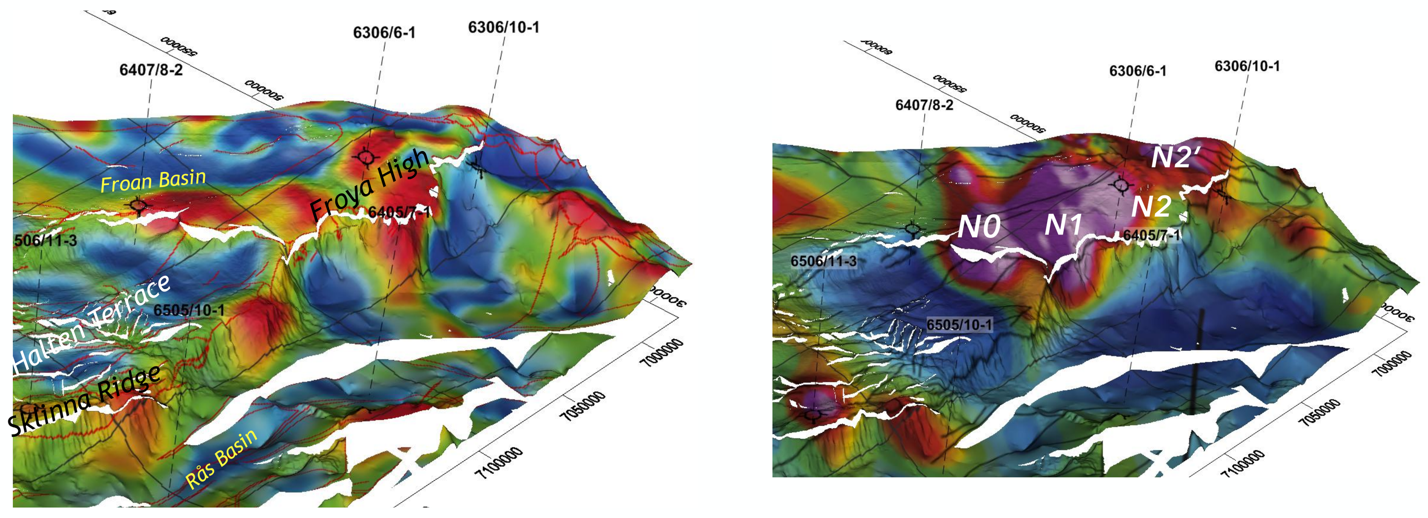

Fig. 2: Bouguer Gravimetry and Magnetic Anomaly draped at top BCU structure map.

Basement High

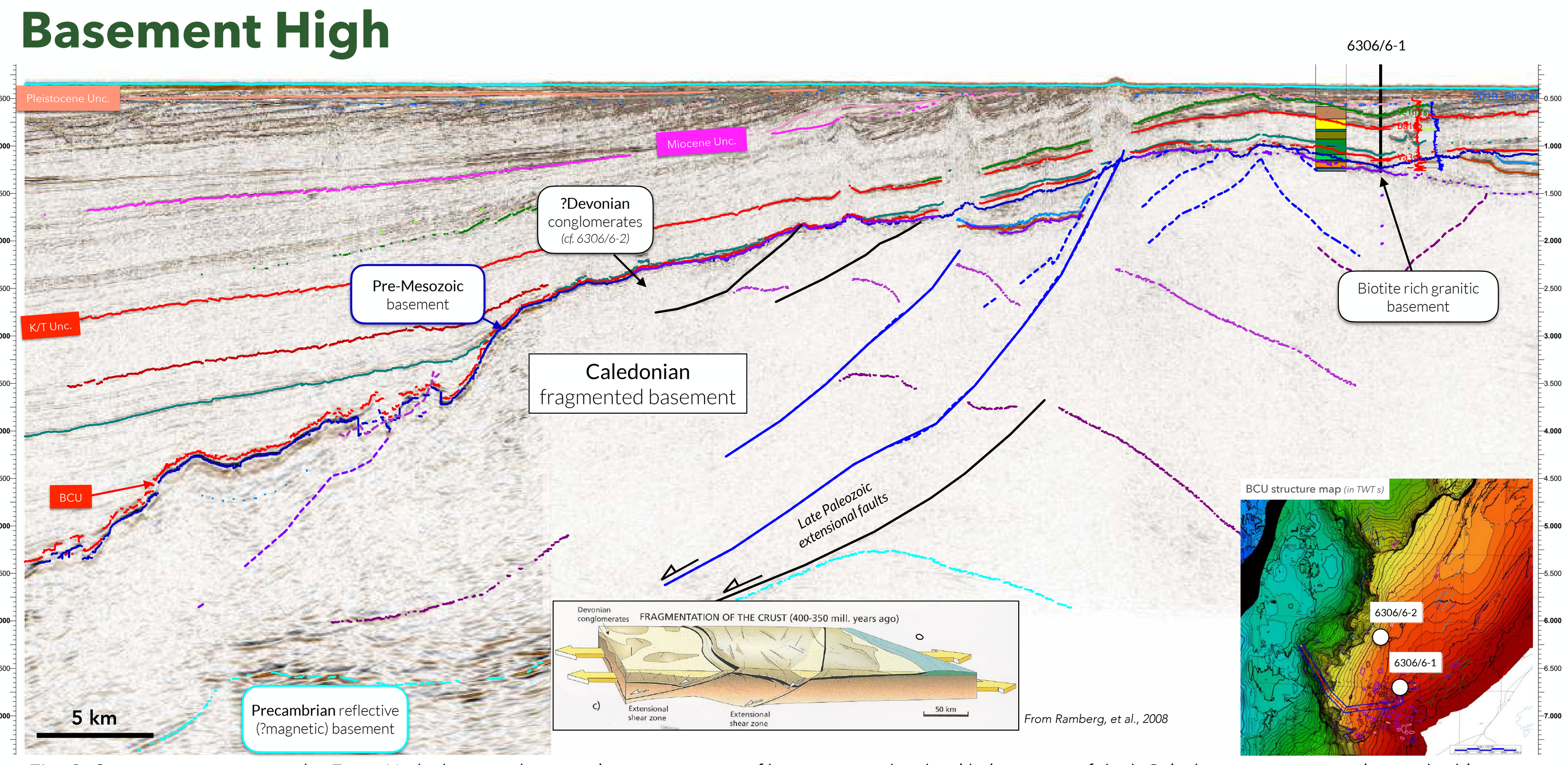

Fig. 3: Seismic section across the Frøya High showing the complex organization of basement rocks, that likely consist of thick Caledonian nappes overlying a highly reflective unit that can be assimilated to the Precambrian magnetic rocks out-cropping along the Norwegian coastline.

Relationship between Basement faults & volcanic activity

(Intrusive & extrusive)

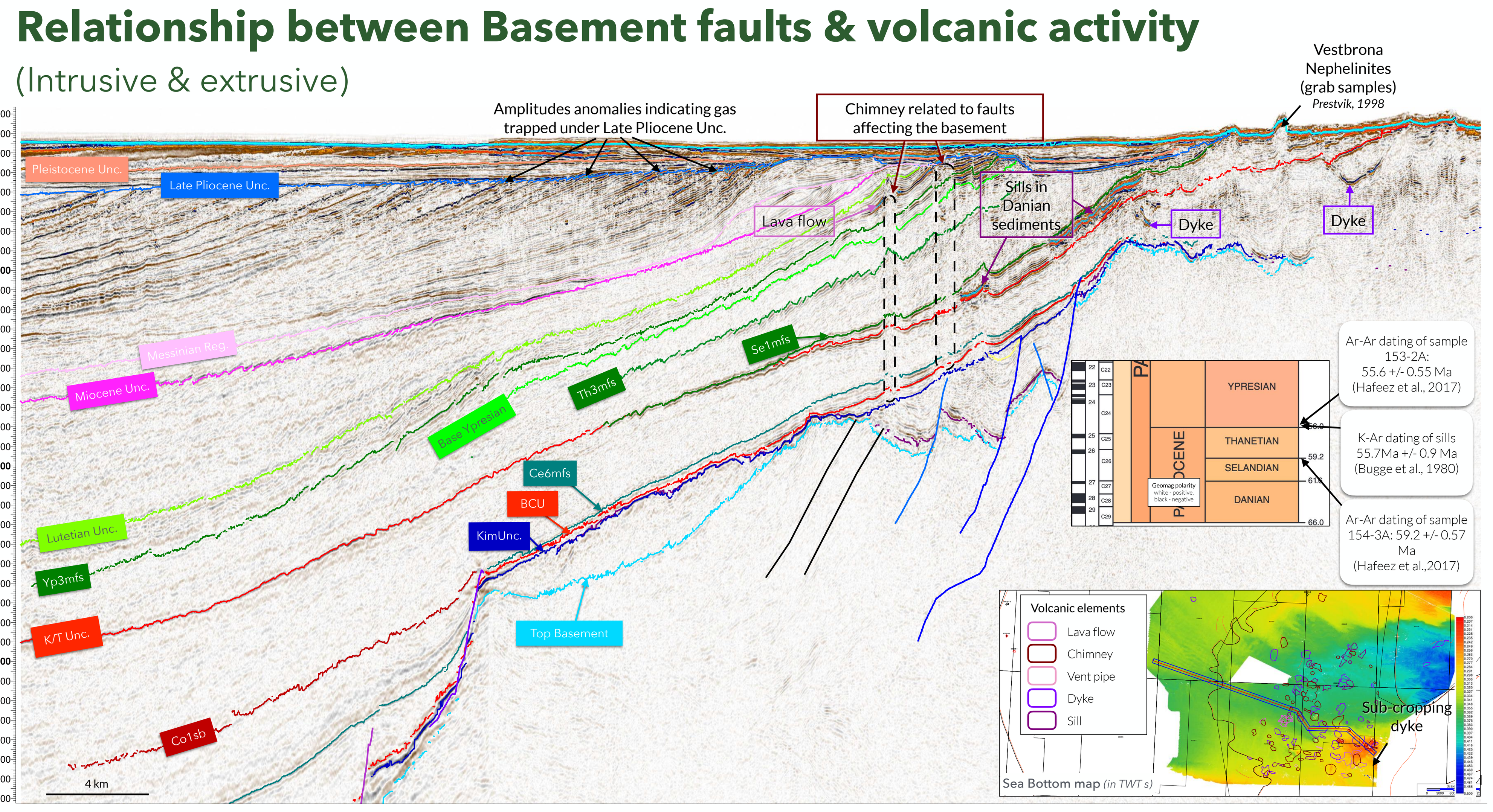

Fig. 4: Paleocene dykes, Eocene Volcanoes and gas chimneys at the top of the Frøya High, sourced from deeply rooted intra-basement faults.

Eocene Volcano

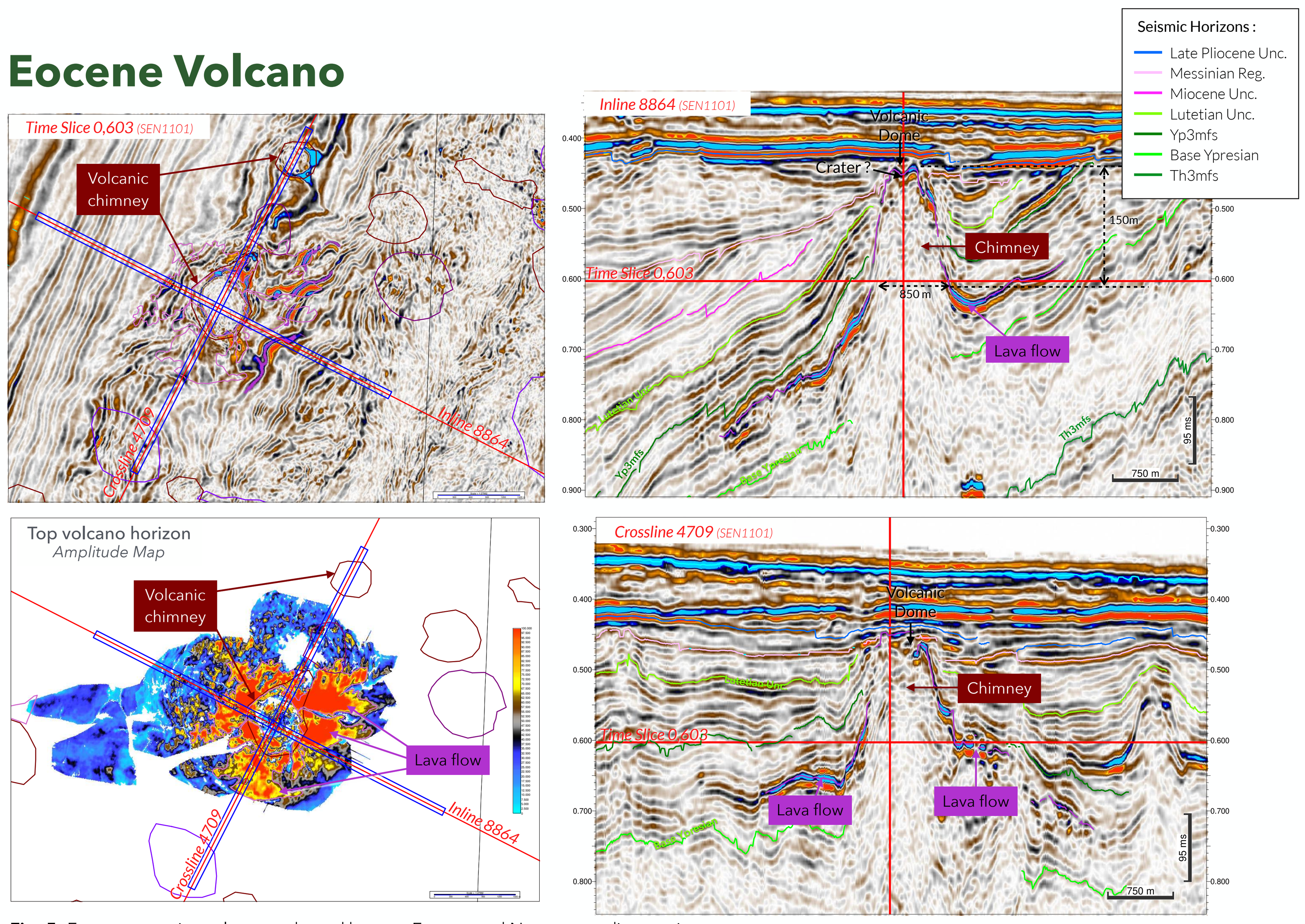

Fig. 5: Eocene extrusive volcanoes draped by post Eocene and Neogene sedimentation.

Hypotheses

- There is very little evidence of felsic or mafic intrusive rocks containing hydrogen (Smith, *et al.*, 2005). However, alkaline intrusions (carbonatite and nephelinite complexes comprising olivine-rich rocks from mantle depths), appear to have an association with gases including hydrogen:

$$\underbrace{3Na_3Fe_4^{2+}Fe^{3+}Si_8O_{22}(OH)_2}_{\text{Arfvedsonite}} + 2H_2O \longrightarrow \underbrace{9NaFe^{3+}Si_2O_6}_{\text{Aegirine}} + \underbrace{2Fe_3O_4}_{\text{Magnetite}} + \underbrace{6SiO_2}_{\text{Quartz}} + 5H_2$$

(Salvi & Williams-Jones, 1997)

- The Vestbrona nephelinite source at the top of the Frøya High was probably generated from partial fusion within the mantle, during the latest stages of the North Atlantic breakup (**Fig. 7**).
- The juxtaposition of these mafic intrusions at the top of granitic basement containing hematites, a ferric mineral known to be the result of biotite oxidation, may have provided favourable conditions for the creation of a H_2 flux.

Spatial distribution of intrusive & extrusive events with respect to Grav-Mag data

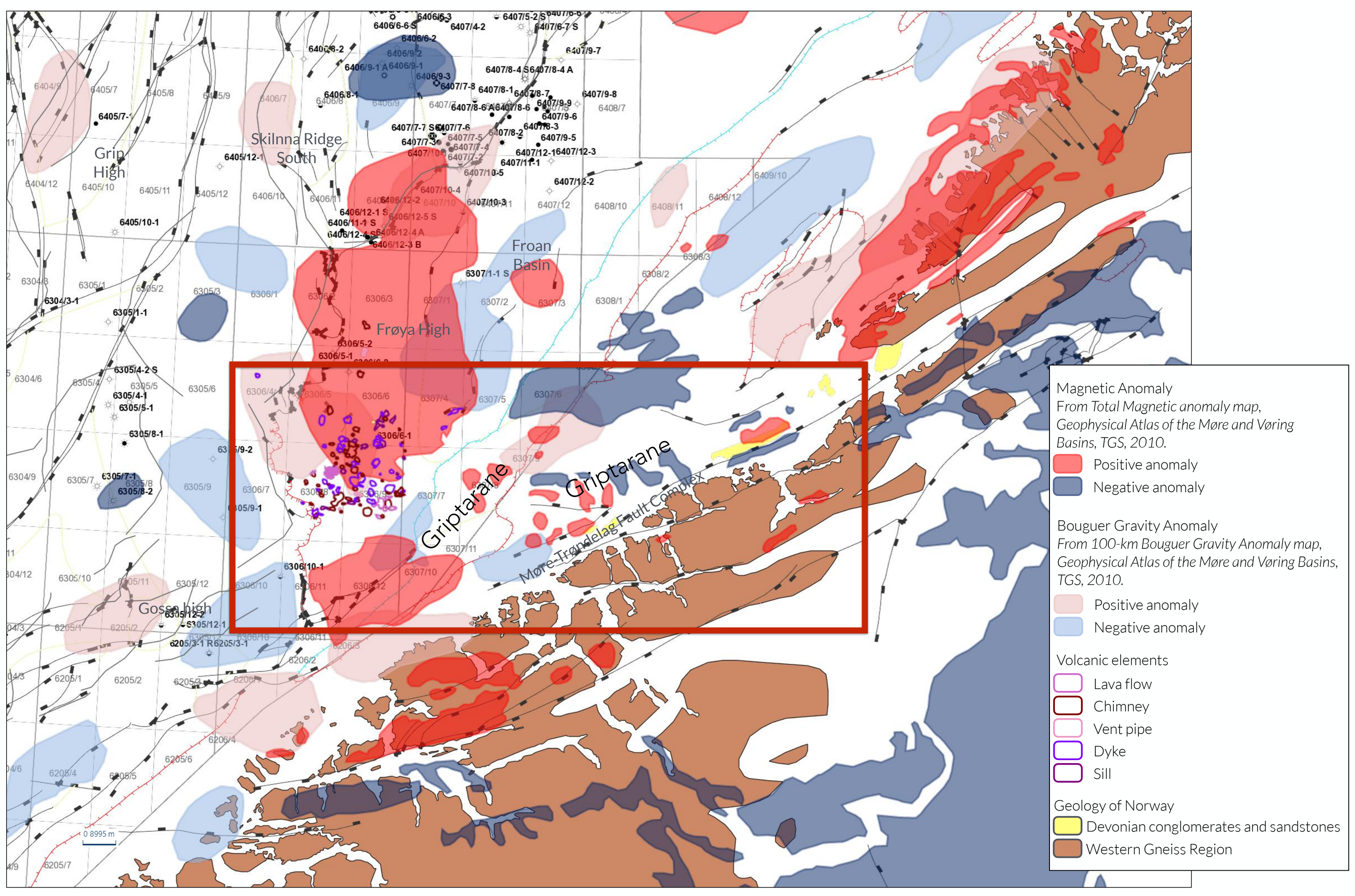

Fig. 6: Spatial distribution of intrusive and extrusive events on the southern margin of the Frøya High magnetic anomaly. They appear to be in the continuity of the Griptarane area along the Møre Trøndelag Fault Complex, where similar patchy distribution of magnetic anomalies can be observed.

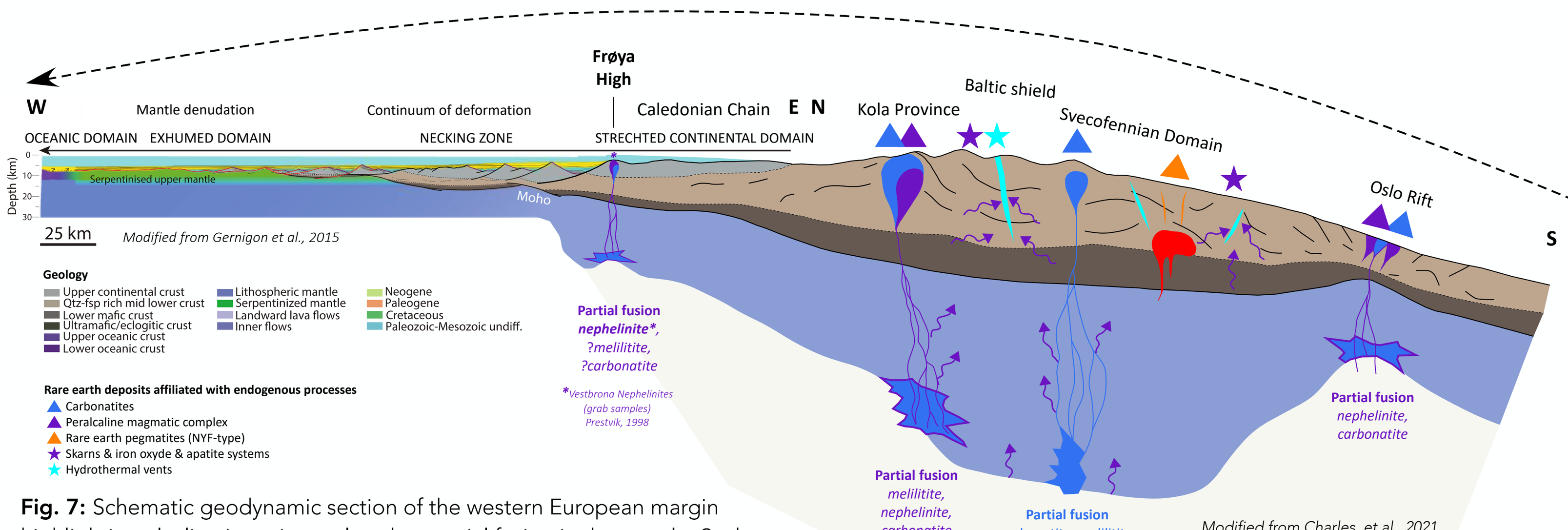

Fig. 7: Schematic geodynamic section of the western European margin highlighting alcaline intrusions related to partial fusion in the mantle. Such alkaline igneous rocks are associated with aulacogens, failed arm rift systems, and (here) the Jan Mayen Fracture Zone (modified from Gernigon, *et al.*, 2015 & Charles, *et al.*, 2021).

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