Comment on ‘A Miocene age for the Molo Formation, Norwegian Sea shelf off Vestfjorden, based on marine palynology’

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Introduction

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First, I thank Grøsfjeld et al., (2019) for a well-organised paper that provides new insight on the age of the Molo Formation penetrated in exploration well 6610/3–1 off Vestfjorden/Lofoten, Norway. The stratigraphic position of the Molo Formation is well established above the Mid Miocene Unconformity (MMU) and below the Quaternary Naust Formation (Rise et al., 2005). Historically, recognition of in situ vs. resedimented forms has been a challenge and therefore the age assignments vary from Oligocene to Pliocene (Rokoengen et al., 1995; Henriksen & Weimer, 1996; Eidvin et al., 2007; 2014; Eidvin & Riis, 2013; Grøsfjeld et al., 2019). The aim of this comment is to discuss if some of the marine palynomorphs that Grøsfjeld et al. (2019) interpreted as in situ are instead resedimented as this may re-date the Molo Formation to the Early Pliocene (Fig. 1) Grøsfjeld et al. (2019) clearly state that the assemblages are strongly dominated by reworked taxa, Paleogene taxa being particularly abundant. They discussed two age hypotheses for the Molo Formation, a Mid–Late-Tortonian, which they preferred, and a Messinian. They also gave a maximum age of Middle Miocene (Serravallian) and a minimum age of Lower Pliocene (Zanclean). My age suggestion corresponds with their minimum age and is slightly younger than their second hypothesis. The small shift in age is significant and of regional importance because it shifts the Molo Formation from a syn- to post- Mid Miocene compressional phase (Løseth & Henriksen, 2005). Hence, the Molo Formation will be younger than the syn-tectonic Kai Formation which was deposited during the global Mid to Late Miocene event (Potter & Szatmari, 2009).

Background

The Molo Formation is a 600 km-long coastal delta with up to 400 m-high clinoforms, located at the inner mid-Norwegian Margin (Rokoengen et al., 1995; Henriksen & Weimar, 1996; Bullimore et al., 2005; Eidvin et al., 2007; Løseth et al., 2017). The original northern, southern and eastern parts are missing through erosion by the Quaternary Upper Regional Unconformity (URU). Westwards, the prograding clinoforms of the Molo Formation downlap the MMU and, before reaching the eastern edge of the syn-tectonic

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Kai Formation, quickly thin to below seismic resolution. Løseth et al. (2017) subdivided the Molo Formation into a lower Molo Formation transgressive unit and termed the main regressive part, which previous authors have term the Molo Formation, the upper Molo Formation. The MMU is an erosional unconformity along the entire eastern basin margin that dips smoothly westwards. The position of the pre-MMU coastlines are unresolved east of the present truncation (Løseth et al., 2017).

In situ or resedimented

Grøsfjeld et al. (2019) identified the marine palynomorphs *Operculodinium piaseckii* and *Minisphaeridium latirictum*, which have their Lowest Occurrence (LO) in either Oligocene or Lower Miocene and Highest Occurrence (HO) in Late Miocene (Tortonian), to constrain their preferred age hypothesis for the Molo Formation (Fig 1). The large time range of these marine palynomorphs implies that they could have lived during the Oligocene to Early Miocene and have been resedimented. Alternatively, they could have lived during Late Miocene (Tortonian) and be in situ as suggested by Grøsfjeld et al. (2019). My hypothesis is that any marine palynomorphs in the Molo Formation with LO in Early Miocene or older should be considered as resedimented.

Arguments for re-interpretation of the age of the Molo Formation

It is well established that Eocene and Oligocene marine forms are resedimented (Grøsfjeld et al., 2019). When they deposited, the coast was far to the east, in the clastic source area of the Molo Formation. Below, I provide two arguments to further extend the period the coast remained at this position to address the resedimented vs. in situ palynomorph discussion.

(1) What was the reason for uplift and exposure of the former marine shelf sediments that became the clastic source area for the Molo Formation?

The Miocene compressional phase formed large inversion domes and reactivated basement-involved normal faults in a reverse mode, some lying geographically close to well 6610/3–1 (Løseth & Henriksen, 2005). The huge compressive stresses also uplifted Norway and the British Isles and their flanking shelves were also raised and exposed, with subsiding basins forming in between (Riis, 1992; Riis & Fjeldskaar, 1992; Løseth & Henriksen, 2005; Hillis et al., 2008; Japsen et al., 2014; Løseth et al., 2017; 2020). The Kai Formation is syn-tectonic with respect to the compressional phase and infills synclines between the domes in the deeper part of the Norwegian margin. The onset of the compression is set to the Mid Miocene by the syn-tectonic Kai Formation (Eidvin et al., 2000; 2007). The landward termination of the Kai Formation is mapped farthest to the west of all Cenozoic formations (Løseth & Henriksen, 2005). The erosive MMU is east of the wedge-out termination. Here, Løseth et al., (2017) mapped erosional valley shapes on 3D seismic data on the MMU. The uplift of the inner mid Norwegian margin can therefore be linked to the onset of the compressional phase. This implies that marine conditions could have prevailed in the clastic source area to the Molo Formation up to the Mid Miocene. Therefore, any fossils with LO of Early Miocene or older can be re-sedimented.

(2) What are the youngest resedimented forms immediately above the MMU?

Ideally, resedimented fossils should have an inverse age, with the youngest forms in the oldest sediments above the MMU. Indeed, the lower Molo Formation (Løseth et al., 2017) is dated by Eidvin et al. (2007) as Early Miocene in Well 6407/9-5 in the southern part of the Molo Formation. Note that Eidvin et al. (2007) termed this interval the Upper Brygge Formation while Løseth et al. (2017) showed on good quality 3D seismic images that (a) the erosive MMU is below these sediments and (b) the

Figure 1. Assumed *in situ* marine polymorphs from parts of the Molo Formation (Grøsfjeld et al., 2019). The marine palynomorphs *Batiacasphaera micropapillata* complex, *Reticulatosphaera actinocoronata*, *Operculodinium piaseckii* and *Minisphaeridium latirictum* (red overlay), that have their lowest occurrence in either Oligocene or Early Miocene, are considered resedimented and should be removed from the *in situ* forms. An Early Pliocene age (Zanclean. 5.5–3.5 Ma) is suggested for the remaining marine polymorphs in the Molo Formation in well 6610/3–1.

geomorphological patterns within this unit are indicative of coastal deposition processes. Therefore, I suggest that the Early Miocene age is based on resedimented forms. Grøsfjeld et al. (2019) reported that Eidvin et al. (2007) did find Late Miocene to Early Pliocene *Barssidinium graminosum* in these sediments in well 6507/9-5 but interpreted them as cavings. The overlying upper Molo Formation has numerous Oligocene and Eocene fossils; and hence the inverse stratigraphy.

Both approaches suggest that any fossils with Lowest Occurrence (LO) of early Mid Miocene age or older can be resedimented. The marine palynomorphs *Operculodinium piaseckii* and *Minisphaeridium latirictum* that have Lowest Occurrence (LO) in either Oligocene or Early Miocene in Fig. 8 in Grøsfjeld et al. (2019) may therefore be resedimented. My understanding is that the remaining marine palynomorphs in the Molo Formation best fit an Early Pliocene age (Zanclean. 5.5–3.5 Ma) (Fig. 1).

Implication of a Pliocene age for the Molo Formation

I use 3D seismic data to investigate the geological record spanning the Molo and Lower Naust formations in parts of the inner mid-Norwegian margin around Well 6610/3–1 (Figs. 2 & 3). Fig. 3 illustrates amplitude values along a detailed constructed surface that intersects the prograding clinoforms. The position of one clinoform-intersection appears as a continuous reflection-line, showing the location of that clinoform at this time. Fig. 3 illustrates the stratigraphic evolution and progradation of the Molo and early Naust formations, like growth rings in trees. Well 6610/3–1 only penetrated a small part of the Molo Formation (red overlay) and the westernmost clinoforms in the Molo Formation are located 19 km west of Well 6610/3–1. The Molo to Naust transition is reflected in a change in the surface expression of the foresets intersected from linear in the Molo Formation to sinuous / arcuate in the Naust Formation Fig. 3. A series of dip-orientated incisions and associated erosional products are interpreted at the outer edge of the Molo Formation (white overlay in Figs. 2 & 3). I interpret the incisions in the westernmost part of the Molo Formation to have occurred over a relatively short period because the steeply dipping delta front is, except from the small incisions, well preserved. The Naust Formation belongs to the lowermost Naust Formation (N-1) of Montelli et al. (2017).

I do not know the exact time that it took for the regressive coastal Molo delta to migrate 19 km westwards from Well 6610/3–1, but the progradation may have lasted into the upper Pliocene. The transition from the Molo Formation to the Naust Formation may therefore have occurred near the Pliocene–Quaternary transition (2.6 Ma), time equivalent to when Jansen & Sjøholm (1991) recorded increasing volumes of iceberg-rafted debris delivered to the surrounding seas as ice sheets built up

Figure 2. Seismic profile across the Molo and eastern Naust formations on the inner mid-Norwegian margin. The seismic profile is a random line from 3D seismic data that intersects the position of well 6610/3–1. Coloured overlays of Molo (yellow), incision to the top of the Molo Formation and associated sediments (white) and Naust Formation (green) are shown. Note that only small parts of the prograding clinoforms in the Molo Formation were penetrated by well 6610/3–1 (red overlay). Location in Figure 3. The red dotted line indicates the position of the stratal slice described in Figure 3. MMU – Mid Miocene Unconformity.

Figure 3. Amplitude map showing the Molo and Naust formations infill of the inner mid-Norwegian Margin. The amplitudes are extracted from a surface that cuts prograding clinoforms (dashed red line in Figure 2). Yellow overlay is the Molo Formation, the red overlay is the part of the Molo Formation that was drilled by well 6610/3-1; the white overlay marks incised canyons at the western edge of the Molo Formation, and the green overlay is the Naust Formation.

over the adjacent mid-latitude land masses. The Molo to Naust transition may therefore represent the dramatic climate shift that led the Northeast Atlantic into an Ice Age at around 2.6 Myr ago at the beginning of the Quaternary Period, similar to the climate evolution found in the North Sea by Løseth et al. (2020).

With a Pliocene age for the Molo Formation, my preferred late Cenozoic geological model for the mid-Norwegian margin is illustrated in Fig. 4.

Figure 4. Schematic geological evolution of the inner mid-Norwegian margin from Early Miocene to present.

Conclusions

- The marine palynomorphs *Operculodinium piaseckii* and *Minisphaeridium latirictum* in well 6610/3–1, that have LO in either Oligocene or Early Miocene, are interpreted as resedimented and should not be used to constrain the age of the Molo Formation.
- Based on the age of the remaining marine palynomorphs (Fig.1), the Molo Formation in Well 6610/3–1 (Grøsfjeld et al., 2019) is most likely of Early Pliocene age (Zanclean. 5.5–3.5 Ma).
- The Molo Formation was deposited after the termination of the Miocene compressional phase and is younger than the Kai Formation.
- The Molo Formation coastal delta migrated 19 km farther westwards after the sediments dated in well 6610/3–1 were deposited. I suggest that the Molo Formation is of Pliocene age.
- The transition from the Molo to the Naust Formation occurred at the beginning of the Quaternary Period during a dramatic climate shift that led the Northeast Atlantic into an Ice Age at around 2.6 Myr ago.

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