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Review Article

The Moho: Boundary above upper mantle peridotites or lower crustal eclogites? A global review and new interpretations for passive margins

Rolf Mjelde [a,*], Alexey Goncharov [b], R. Dietmar Müller [c]

[a] Department of Earth Science, University of Bergen, Allégt. 41, 5007 Bergen, Norway
[b] Geoscience Australia, GPO Box 378, Canberra, ACT, 2601, Australia
[c] The University of Sydney, School of Geosciences, Building F05, NSW 2006, Australia

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A B S T R A C T

We have performed a global study of 2D crustal scale wide-angle profiles across passive margins, with regard to local elevations in the Moho which could possibly be interpreted as indicative of lower crustal eclogites. A total of 16 candidates have been found, mainly in the North Atlantic and around Australia. These cases make up c. 6% only of the total profile length studied, confirming the interpretation of the Moho generally representing the top of the mantle. The interpreted candidates for lower crustal eclogites indicate that there may be a link between eclogite bodies and continental suture zones in the Barents Sea, off mid-Norway, in the Newfoundland Appalachians and in the Yilgarn Craton, western Australia. It is also possible that there is a genetic link between the formation of Caledonian eclogites and the Jan Mayen Fracture Zone, which is the only major fracture zone in the North Atlantic. Several of the inferred lower crustal eclogite bodies are located close to lines of major changes in strain, such as coastlines and shelf edges, indicating that lower crustal eclogite bodies may be important in guiding the evolution of basin architecture. Interpreting the Moho beneath the Bedout High on the northwest shelf of Australia as the top of a body of lower crustal eclogites, may imply that the northern termination of the Lambert Shelf represents a paleo suture zone and that the western termination of the Broome Platform acted as a major transfer zone. The significant increase in crustal thickness implied by the eclogite model has important implications for estimates of stretching history, subsidence and hydrocarbon maturation modelling.

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1. Introduction

The Mohorovičić discontinuity, usually referred to as the Moho, was first observed in 1909 by Andrija Mohorovičić as a marked increase in the velocity of waves generated by earthquakes (Mohorovičić, 1910).

* Corresponding author. Tel.: +47 55582879.
E-mail addresses: Rolf.Mjelde@geo.uib.no (R. Mjelde), Alexey.Goncharov@ga.gov (A. Goncharov), d.muller@usyd.edu.au (R.D. Müller).

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Based on later results from earthquake seismology and controlled-sourced seismology (the seismic wide-angle technique) it is generally accepted that the Moho is present beneath both continental and oceanic crust. It is identified as a first order discontinuity where the seismic P-wave velocity increases from typically 6.5–7.0 km/s to above 8.0 km/s in continental lithosphere, and from about 6.8–7.3 km/s to above 7.6 km/s in oceanic lithosphere (e.g. White et al., 1992). The Moho is generally interpreted as the boundary between crustal felsic–mafic rocks and upper mantle ultra-mafic peridotites (Christensen and Mooney, 1995). This interpretation, which provides the crustal thickness directly, represents an important constraint for a wide range of geodynamic models. We recognize that the crust–mantle transition in many areas may be seismically complex within a 1–2 km wide transition-zone (the 'Moho transition'; e.g. Collins, 1991; Korenaga and Kelemen, 1997), but it falls beyond the scope of this paper to discuss that topic.

Some studies have suggested that the Moho does not necessary correspond to the crust–mantle boundary (Griffin and O'Reilly, 1987; Mengel and Kern, 1992). Based on results from a large amount of 2D wide-angle seismic data acquired along the mid-Norwegian passive margin, NE Atlantic, the simplistic view of the Moho being the crust–mantle boundary (or transition) has been challenged in that area as well. It has been proposed that the Moho in parts of the area may represent the top of lower crustal eclogites related to the Caledonian Orogeny (e.g. Olafsson et al., 1992). If correct, this interpretation implies significant underestimation of the local crustal thickness, potentially misleading sub-sequent geodynamical modelling. In the present paper we review these interpretations, and based on the characteristic observations from the Norwegian margin, we perform a global assessment of 2D crustal-scale profiles. The aim with the study is to obtain an estimate of the relative abundance of lower crustal eclogites, and to discuss the range of geodynamical implications this interpretation might provide. The study focuses on passive continental margins, also including the craton area immediately landward of the margin.

2. Crustal eclogites

Eclogites are formed when predominantly mafic crustal rocks are subducted during continent-continent collisions. The Caledonian Orogeny is well expressed onshore Norway, and eclogitized rocks are exposed in various zones in the Western Gneiss Region, western Norway (Fig. 1; Andersen et al., 1991; Austrheim, 1987). The eclogitization took place at a temperature of about 700 °C and a pressure between 18 and 21 kbar (Jamtveit et al., 1990). The extension of the Caledonides commenced in Early Devonian, during the waning stages of thrusting (e.g. Fossen, 2000; Milnes et al., 1997). Various mechanisms for exhuming the eclogites have been proposed, including entrapment within thrust zones and gravitational, lithospheric delamination (e.g. Andersen et al., 1991). Whatever mechanism, it is widely accepted that eclogites may be found at all crustal levels after cessation of extension.

A pure lower crustal eclogite will have a density around 3.5 g/cm^3, whereas partly eclogitized lower crust may express densities similar to that of mafic underplated material (about 3.0 g/cm^3, e.g. Griffin and O'Reilly, 1987). Combined wide-angle and gravity models have shown that lower crustal bodies with densities in the order of 3.5 g/cm^3 may remain gravitationally stable as an integrated part of the crust for more than 100 myr (e.g. Raum et al., 2006).

Mafic lower crustal rocks may enter the eclogite stability field during cooling (Griffin and O'Reilly, 1987), but as the temperature decreases and fluids are sparse, kinematic arguments indicate that this phase change is unlikely to be efficient (Austrheim and Griffin, 1985).

3. Results: candidates for lower crustal eclogites

In this section we will first review published cases of Moho being interpreted as the top of lower crustal eclogites. We will then discuss the criteria used by the various authors for these cases, and finally, we will choose the most reliable criteria to be used in the search for lower crustal eclogite candidates along other passive margins investigated by use of high-quality wide-angle seismic.

3.1. Published cases from the NE Atlantic: a review

Talwani and Eldholm (1972) were the first researchers who interpreted positive gravity anomalies off the Norwegian coast as intra-basement high-density bodies emplaced during the Caledonian Orogeny. Close to one of these anomalies in the Møre Basin, Olafsson et al. (1992) interpreted a shallowing in the Moho as Caledonian high-density rocks (Fig. 2). The shallow Moho was identified from Expanded Spread Profiles, and they inferred an up to 7 km thick lower crustal body with velocity of 8.5 km/s, significantly higher than the surrounding 7.8–8.2 km/s velocity. Olafsson et al. (1992) argued that interpreting the

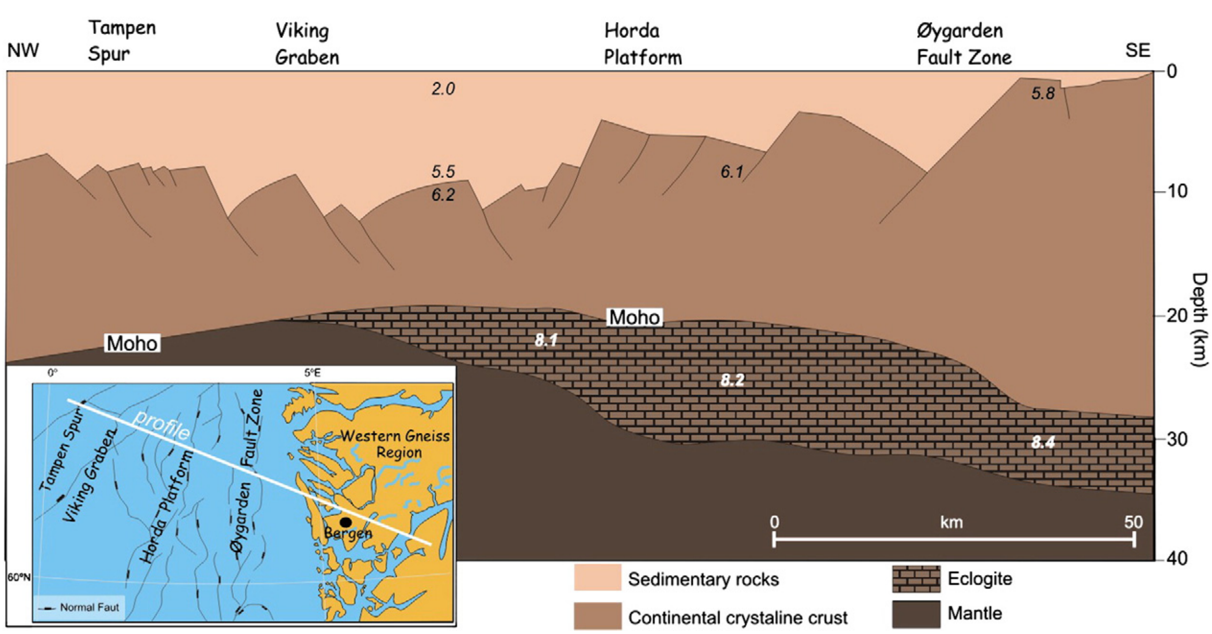

Fig. 1. Expanded spread profile model off western Norway. Modified from Christiansson et al. (2000).

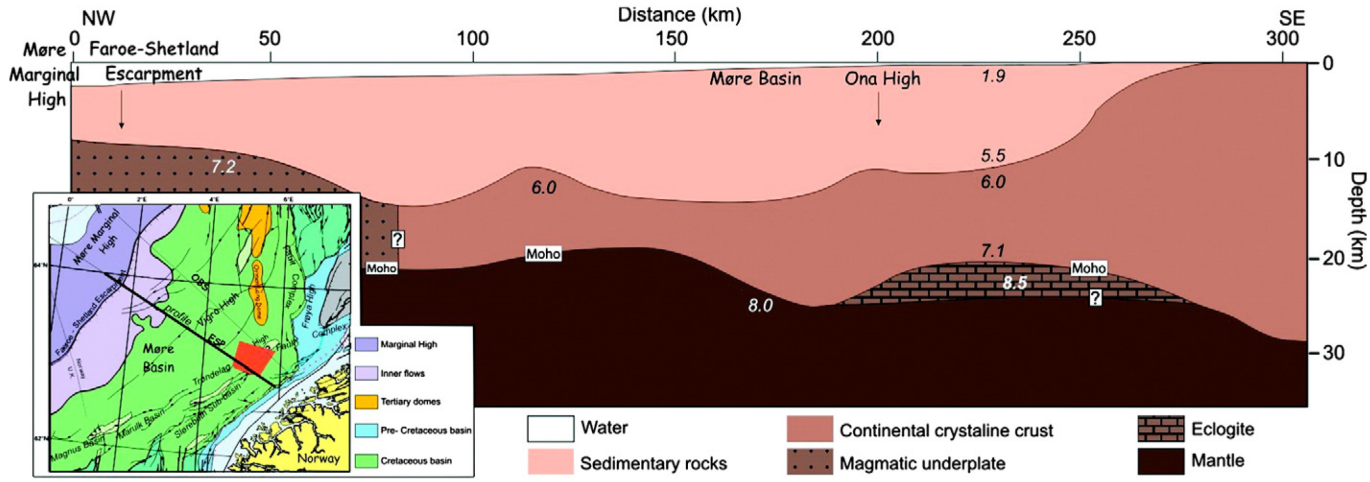

Fig. 2. Expanded spread profile model across the Møre Basin, mid-Norwegian Margin. Modified from Olafsson et al. (1992). Part of the lower crustal high-velocity layer (7.2 km/s) may extend further southeast-wards along the profile (Mjelde et al., 2009a, 2009b).

Moho above the body as the crust–mantle boundary would lead to unrealistically strong crustal thinning towards the coastline.

This localised shallowing of the Moho in the Møre Basin has been confirmed from the modelling of Ocean Bottom Seismic (OBS) data (Fig. 3; Mjelde et al., 2008). These authors note that the trend of the body is significantly different from that of the lower crustal 7.2–7.5 km/s body located further northwestwards and generally associated with intrusions related to the last phase of rifting and break-up (e.g. Mjelde et al., 2008).

Lower crustal eclogites have also been inferred in the North Sea, immediately westward of the exposed eclogites within the Western Gneiss Region (Fig. 1; Christiansson et al., 2000). Beneath the Horda Platform, high-quality multichannel seismic (MCS) data provide images of two Moho candidates, of which the uppermost coincides with a 8.2 km/s refractor identified from expanded spread profiles. Results from tectonostratigraphic modelling and isostatic considerations, based on a dense grid of MCS data and drillholes, are not compatible with the shallow Moho candidate being the crust–mantle boundary (Odinsen et al., 2000), and Christiansson et al. (2000) thus interpret the shallow Moho as the top of a lower crustal eclogite body. Lower crustal eclogites related to the Caledonian collision zone have also been inferred in the southern North Sea (Abramovitz et al., 1998).

A strong shallowing of the Moho has also been observed in three OBS-models across the Rån Ridge, located in the southwestern corner of the Vøring Basin (Fig. 4). The P-wave velocity and density within this body is estimated to be ca. 8.35 km/s and ca. 3.5 g/cm^3, respectively, which is significantly higher than the corresponding measurements in the upper mantle nearby (Raum et al., 2006). These authors argue that it is unlikely that the body can be explained by lower crustal ductile extension accompanied by mantle unroofing, since imprints of such a process is not found within the shallower crustal structures. Furthermore, the V_p/V_s-ratios in the 8+ km/s body are estimated to 1.80–1.85, which is significantly higher than the value generally found in ultramafic rocks, about 1.7 (Holbrook et al., 1992). It is thus concluded that the body most likely consists of lower crustal eclogites formed during the Caledonian orogeny.

Further north in the Vøring Basin, OBS-data have indicated local shallowing of the Moho beneath the Utgard Ridge (Fig. 5; Mjelde et al., 1998). Tectonic modelling has shown that if the shallow Moho is interpreted as the crust–mantle boundary, an unrealistic spike in the stretching factor appears (Wangen et al., 2011). The spike disappeared when it was assumed that the crust–mantle boundary is located approximately 6 km deeper beneath the ridge. Wangen et al. (2011) thus interpreted the Moho there as the top of lower crustal eclogites. The interpreted eclogite body is in this case localised where the magmatic underplate terminates eastwards. The underplate is preferably interpreted as 30–50% Early Cenozoic mafic intrusions, but it cannot be excluded that it represents older, Caledonian high-

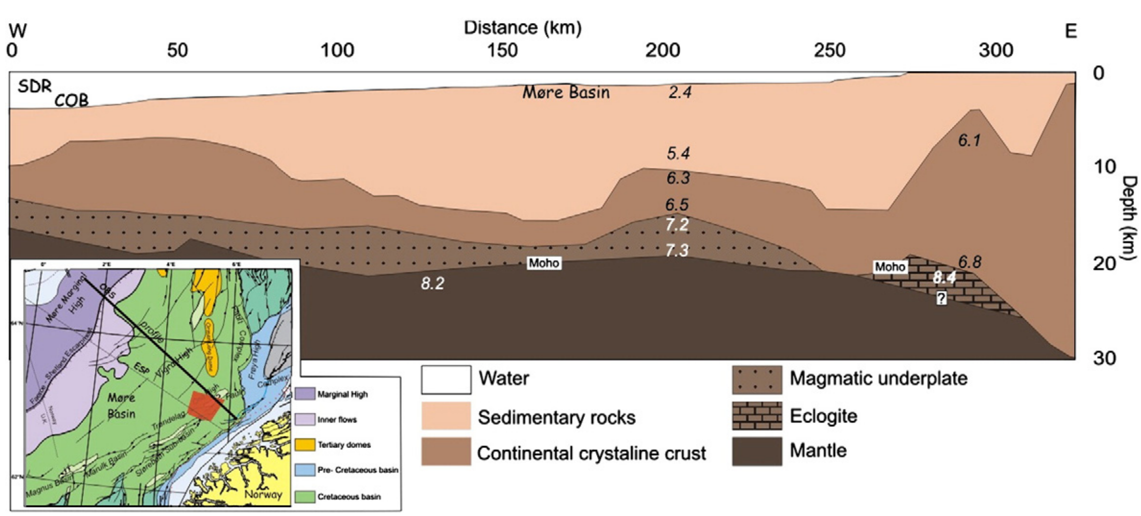

Fig. 3. OBS model across the Møre Basin, mid-Norwegian Margin. Modified from Mjelde et al. (2008).

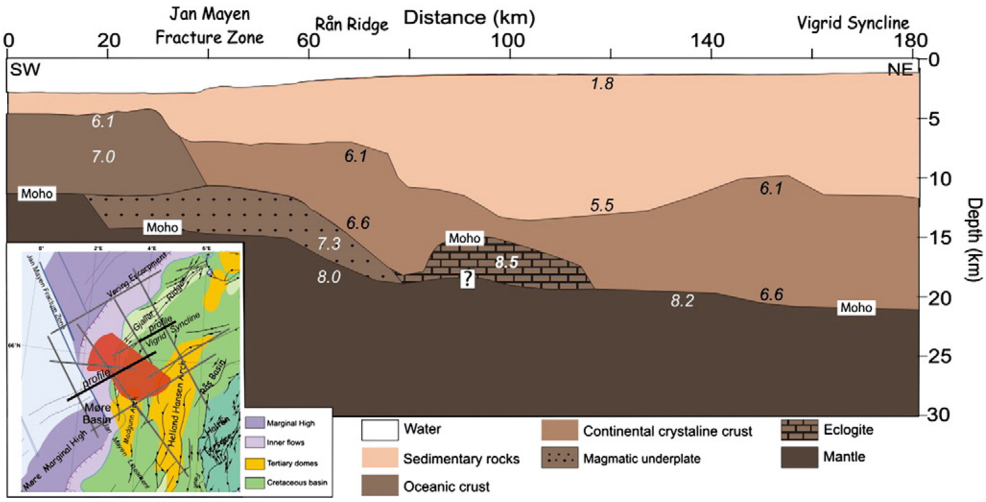

Fig. 4. OBS model across the southern Vøring Basin, mid-Norwegian Margin. Modified from Raum et al. (2006).

grade rocks (e.g. Mjelde et al., 2009b). In either case, the eclogite interpretation implies comparable crustal thickness beneath the Nyk and Utgard highs.

In the Barents Sea, the main Caledonian suture between Barentsia and Baltica has been inferred from OBS-data (Fig. 6; Breivik et al., 2002). The Moho beneath the suture is associated with anomalously high seismic velocities (8.5 km/s) and densities (3.45 g/cm^3), and a small crustal root (3–5 km). Breivik et al. (2002) associated this anomaly with the presence of eclogites, and it is likely that the crust–mantle boundary here is deeper than the Moho.

Further westwards in the Barents Sea, Breivik et al. (2003) inferred the main Caledonian suture between Laurentsia and Barentsia (Fig. 7). The modelled OBS data indicate that the Moho beneath the suture is associated with anomalously high seismic velocities (8.4 km/s) and a small crustal root (2–3 km). The feature, which is not resolvable in the gravity field, is by Breivik et al. (2003) associated with eclogites. It is thus possible that the crust–mantle boundary also in this area is located deeper than the Moho.

3.2. Evaluation of eclogite criteria

From the section above we can conclude that the investigations partly aimed at distinguishing eclogites from peridotites have identified five criteria; 1) eclogites may have higher V_p, 2) higher V_s, 3) higher V_p/V_s, 4) eclogites may be associated with double Moho reflections, and 5) eclogites may correspond to areas with tectonically unrealistic shallowing of the Moho.

We consider the two examples in the Barents Sea as special cases, as they should be regarded as moderately extended mountain ranges (Breivik et al., 2002, 2003). In these cases the main suture (reverse fault), although subject to extensional reactivation, can be clearly interpreted from the multichannel seismic data. The link between the main fault and the high P-wave velocities and densities makes the eclogite interpretation straightforward.

The other examples represent a passive margin where much larger post-collisional extension has removed all imprints of the main suture fault itself. Of the five cases where eclogites have been inferred, only two provide evidence for elevated V_p, and only one discusses the elevated density, V_p/V_s-ratio or double Moho criteria. The main reason for this lack of clear eclogite imprint on physical properties is probably that the lower crustal bodies represent a mixture of eclogite and rocks of crustal affinity, making the bodies indistinguishable from upper mantle periodities. It should also be mentioned that the physical properties of peridotite varies significantly with composition and peridotite many express strong anisotropy (Kobussen et al., 2006; Weiss et al., 1999). The appearance of a double Moho should only be expected in special cases,

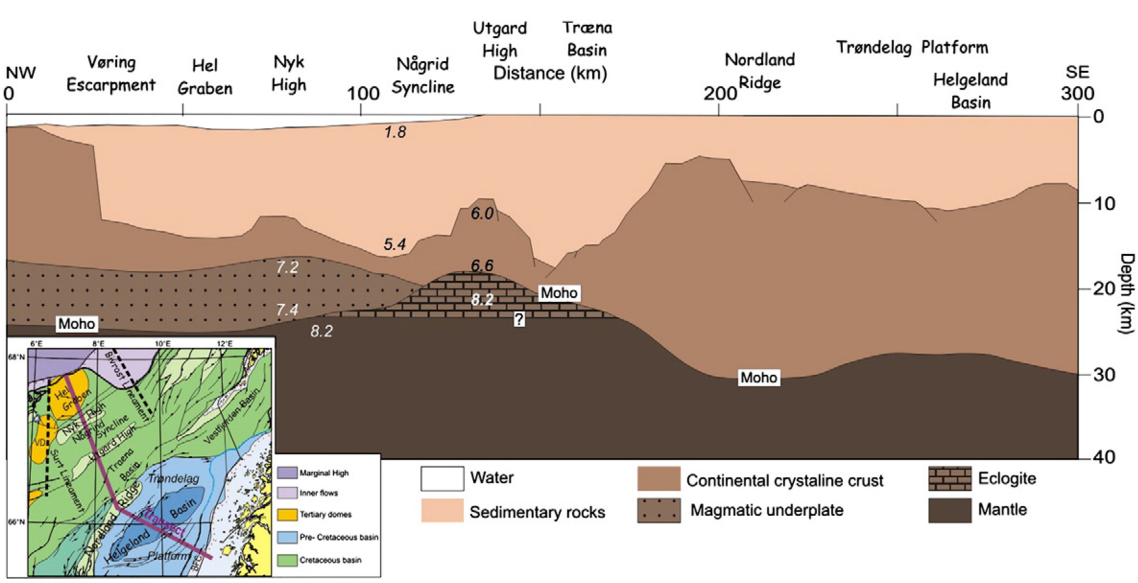

Fig. 5. Tectonic model based on OBS data across the northern Basin, mid-Norwegian Margin. Modified from Wangen et al. (2011).

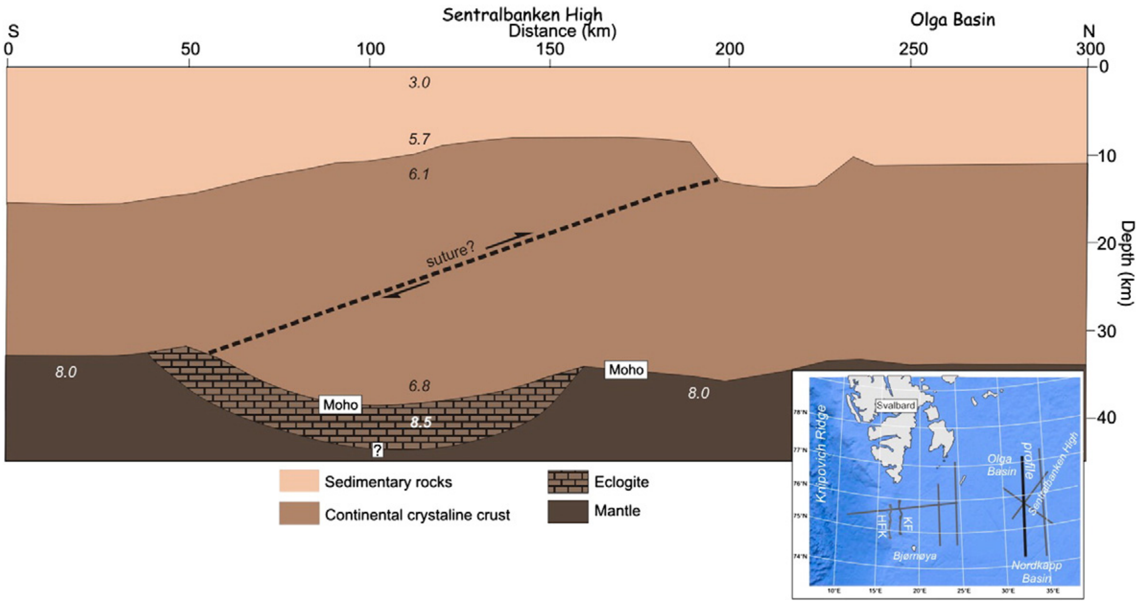

Fig. 6. OBS model across the main Caledonian suture between Barentsia and Baltica, Barents Sea. Modified from (Breivik et al., 2002).

since the impedance contrast between eclogites and peridotites (the lower boundary) generally would be modest. All these criteria are thus poor for distinguishing between eclogites and peridotites.

The shallow Moho criterion is the only one invoked for all five examples. It is thus the only criterion that could be considered as robust, and we will in the following identify candidates for lower crustal eclogites in areas with apparently anomalously large extension, expressed as areas associated with Moho uplift that appear geologically unrealistic, if the Moho is interpreted as the base of the crust. These areas could be associated with a local domelike uplift, or a larger area of shallow Moho suggesting significant isostatic imbalance. Although poor, the other eclogite criteria discussed above will also be used in the search.

3.3. New interpretations from the N. Atlantic area

Modelling of OBS data helped Mjelde et al. (1993) to reveal a significant shallowing of the Moho beneath the Lofoten Ridge (Fig. 8). The shallowing was interpreted as lateral flow of ductile lower crust and subsequent mantle uplift, related to a lithospheric extensional fault dipping downwards to the west. The structure is very similar to that of the Utgard High (Fig. 5), and it is possible that the Moho beneath the Lofoten Ridge marks the top of lower crustal eclogites, not the mantle.

Voss and Jokat (2009) discussed a composite crustal/upper mantle profile located across the East Greenland margin just north of the Jan Mayen Fracture Zone (Fig. 9). The profile was derived from modelling of OBS data offshore and combined gravity modelling and studies of receiver functions onshore. Immediately landwards of the Western Fault Zone their model shows a distinct 5 km shallowing of the Moho, which cannot be directly related to crustal thinning in the layers above. The area is located just off the main coastline, and the feature expresses the same characteristics as the lower crustal body offshore the Møre coast interpreted as eclogites (Figs. 2, 3). We thus suggest that the local, shallow Moho modelled off East Greenland may represent lower crustal eclogites.

A Moho shallowing in the order of 15 km has been modelled from OBS data beneath the Newfoundland Appalachians (Fig. 10; Funck et al., 2001). The shallowing may be partly related to Iapetan rifting in late Neoproterozoic (about 600 Ma), but the Moho uplift is located approximately 50 km southeastward of the main rift. Since the Moho uplift cannot be explained by a simple rift model, we propose that it can possibly be related to a body of lower crustal eclogites.

Along the coastline of northwestern Spitsbergen Ritzmann and Jokat (2003) observed an approximately 4 km Moho uplift from seismic recordings with landstations (Fig. 11). The uplift is not associated with indications of thinning in the layers above. Ritzmann and Jokat (2003)

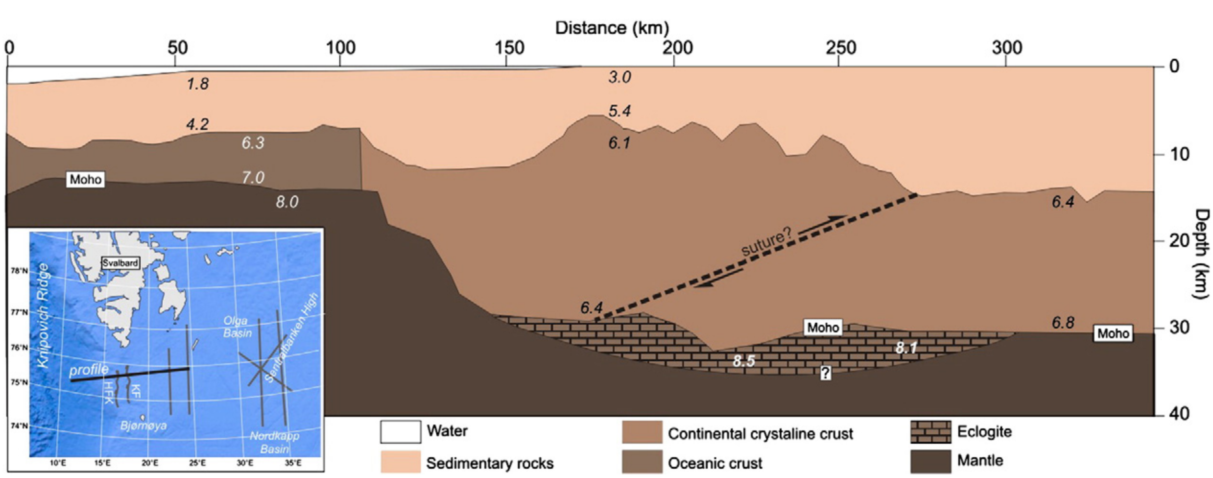

Fig. 7. OBS model across the main Caledonian suture between Laurentsia and Barentsia, Barents Sea. Modified from (Breivik et al., 2003).

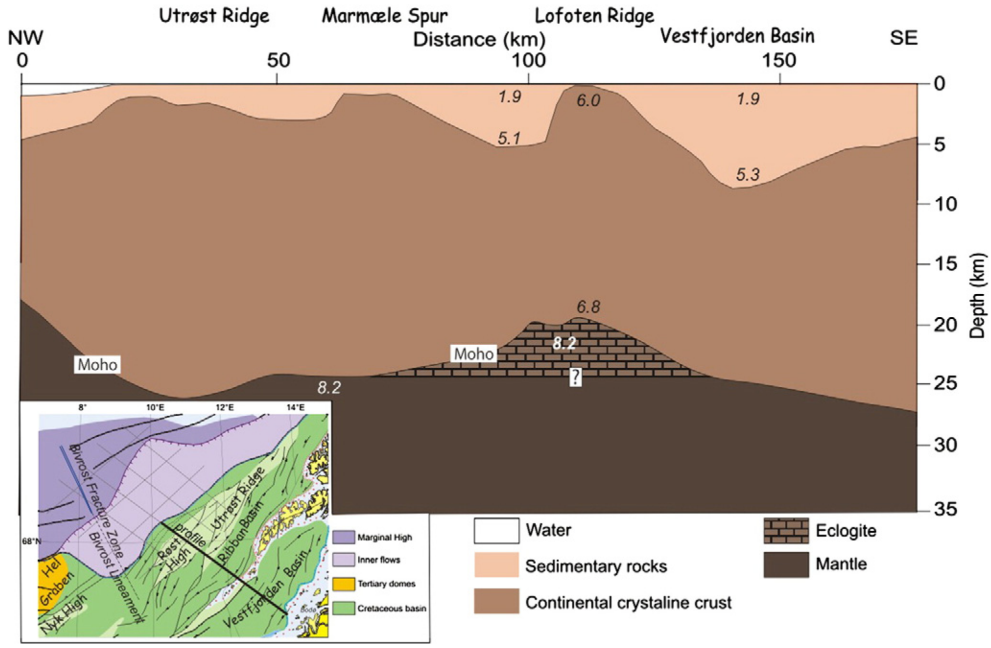

Fig. 8. OBS model across the Lofoten shelf, mid-Norwegian Margin. Modified from Mjelde et al. (1993).

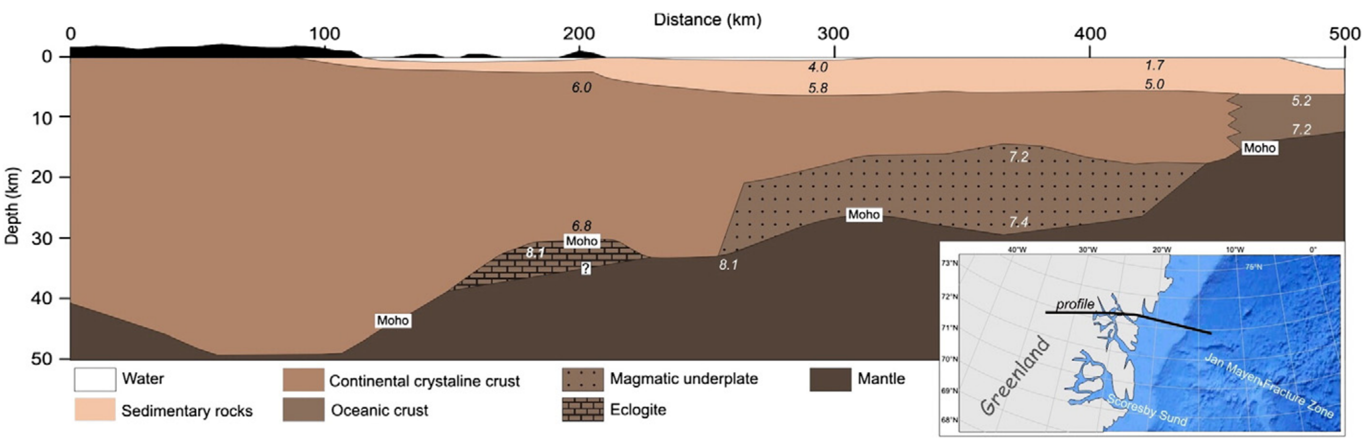

Fig. 9. A composite crustal/upper mantle profile located across the East Greenland margin just north of the Jan Mayen Fracture Zone, derived from OBS and gravity data, as well as studies of receiver functions. Modified from Voss and Jokat (2009).

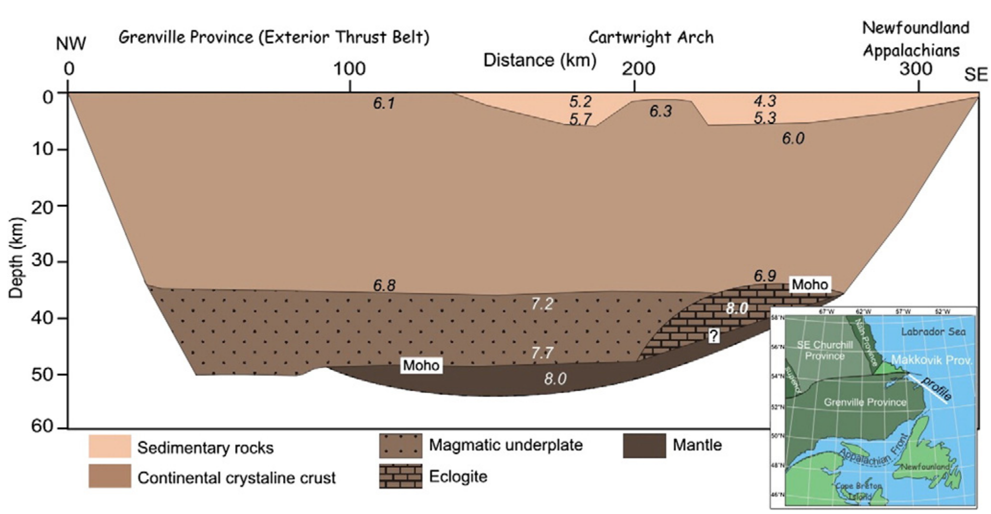

Fig. 10. OBS model across the Newfoundland Appalachians. Modified from Funck et al. (2001).

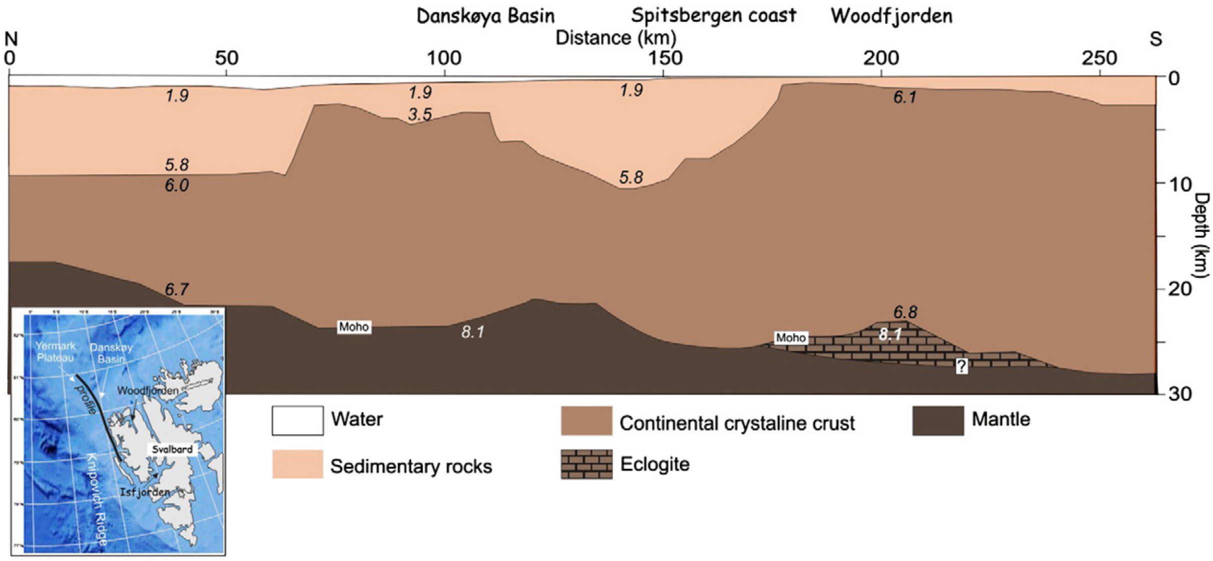

Fig. 11. Wide-angle model along the coastline of northwestern Spitsbergen, N. Atlantic. Modified from Ritzmann and Jokat (2003).

interpreted the lower crustal velocities in their model as indicative of mafic granulites, and we suggest that the Moho uplift may be interpreted as the top of a lower crustal eclogite body. The body is located within Laurentia, as the Caledonian front most likely is associated with the Billefjorden FZ further eastwards (Breivik et al., 2005).

3.4. New interpretations from Australia

Within the Archaean rocks of the Yilgarn Craton in western Australia, Dentith et al. (2000) modelled an approximately 8 km local uplift in the Moho from wide-angle seismic data (Fig. 12). The Moho shallowing corresponds to an eastward dipping zone in the crust, roughly marking the boundary between high-grade metamorphic rocks in the west, and lower-grade granitoid-greenstone terrains further east. Dentith et al. (2000) suggested that the dipping high-velocity zone is either due to the presence of mafic to ultramafic intrusions, or that it represents a fault-bounded mega-sliver with oceanic affinities. With reference to the Caledonian eclogites discussed above, we propose that the lower crustal high-velocity terrain in the Yilgarn Craton may be interpreted as eclogites.

Tassel and Goncharov (2006) presented a combined wide-angle and gravity model for the crust and upper mantle from the southern Yilgarn Craton, across the Proterozoic Albany-Fraser Orogen and into the offshore Bremer sub-basin (Fig. 13). The modelling indicated a crustal root of up to about 30 km, representing roughly a doubling of the crustal thickness, beneath the southern margin of the Yilgarn Craton. It is intriguing that the impressive crustal root appears to have very limited effects on the present-day topography. The amplitude of the crustal root is significantly reduced if parts of the surrounding sub-Moho layer are interpreted as lower crustal eclogites. This interpretation provides a crustal section closer to isostatic balance. The eclogites north of the crustal root would correspond to those interpreted from the Dentith et al. (2000) profile (Fig. 12).

The crustal-scale features between the Precambrian Australian craton and the Timor Basin have been found from the modelling of OBS and gravity data (Fig. 14; Petkovic et al., 2000). The model documents crustal thinning from the Yampi shelf, across the Londonderry High and Vulcan sub-Basin to the Ashmore Platform, associated with the formation of an up to 15 km thick sedimentary basin. If the Moho is interpreted as the top of the mantle beneath the Yampi shelf, it reveals a surprisingly thin crust here; about 30 km, being only 1–2 km thicker than the crust beneath the Vulcan sub-Basin. Along this profile, Petkovic et al. (2000) modelled wide-angle reflections originating from 38 to 45 km depth. If this interface is interpreted as the crust–mantle

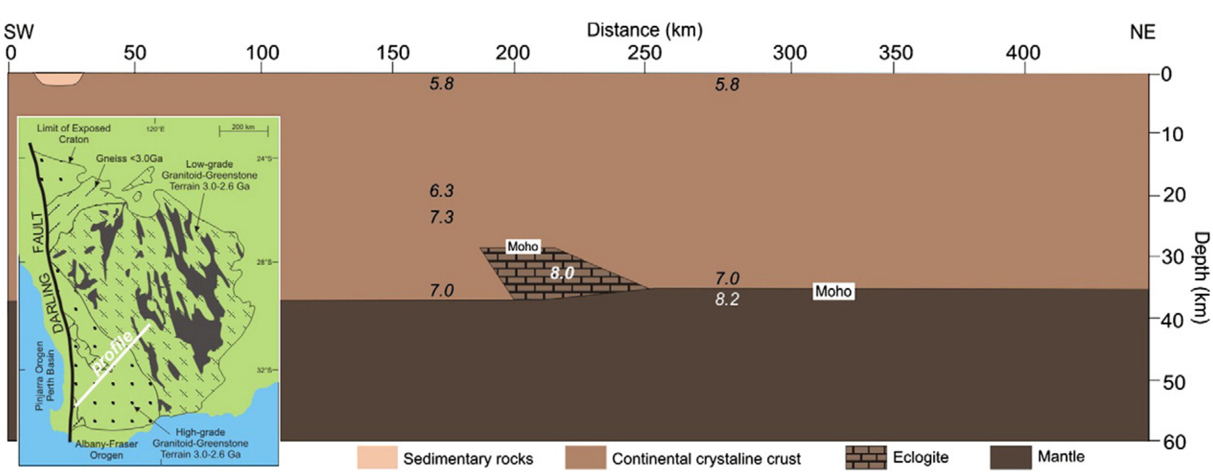

Fig. 12. Wide-angle model across the Archaean rocks of the Yilgarn Craton, W. Australia. Modified from Dentith et al. (2000).

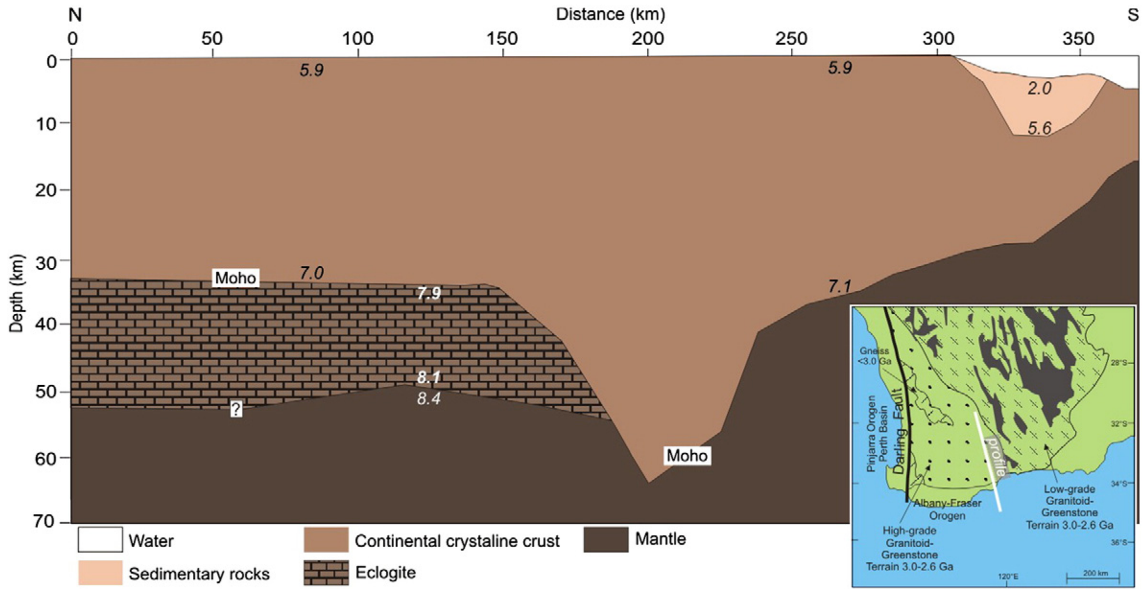

Fig. 13. A combined wide-angle and gravity model for the crust and upper mantle from the southern Yilgarn Craton, across the Proterozoic Albany-Fraser Orogen and into the offshore Bremer sub-basin. Modified from Tassel and Goncharov (2006).

boundary under the Yampi shelf, the Moho may be related to the top of a lower crustal eclogite body. This interpretation is supported by the higher P-wave velocities and densities modelled at the Moho here; 8.1 km/s and 3.35 g/cm^3 versus 8.0 km/s and 3.33 g/cm^3 off the shelf. This interpretation implies that the deepest interface must originate from within the upper mantle along the central and northwestern part of the profile.

The roughly circular Bedout High in the Roebuck Basin within the NW shelf of Australia has been interpreted as an end-Permian impact structure (Becker et al., 2004), and as a structure that has been rifted off the Broome Platform by two orthogonal, consecutive Paleozoic episodes of rifting (Fig. 15; Müller et al., 2005). The Bedout High consists of two separate highs separated by a Paleozoic fault, and is associated with a Moho uplift of 7–8 km, which may be interpreted as indicative of the presence of lower crustal eclogites.

From combined OBS and potential field data, Direen et al. (2008) obtained crustal models along two profiles across the continent-ocean-transition at the outer Exmouth Plateau to the Gascoyne Abyssal Plain, NW Australia (Fig. 16). Between oceanic crust and thinned continental crust, their study indicated an approximately 200 km wide zone consisting of a mixture of highly thinned continental crust and magmatic rocks, referred to as the Volcanic Margin Transition. Immediately landward of the Volcanic Margin Transition–Continental Boundary, their models indicates the presence of Moho uplifts in the order of 5 km, which may be interpreted as lower crustal eclogites.

3.5. New interpretations from other passive margins

Hirsch et al. (2009) presented a crustal scale model across the western South African passive volcanic margin, based on OBS and gravity data. Beneath the shelf edge, their model indicates 5–10 km uplift of the Moho (Fig. 17). The feature, which is located about 100 km landwards of the lower crustal high-velocity layer associated with magmatism, expresses similar characteristics as the lower crustal eclogite body inferred off Møre (Fig. 3).

Modelling of OBS data across the Ghana Transform Margin reveals an approximately 5 km shallowing of the Moho beneath the

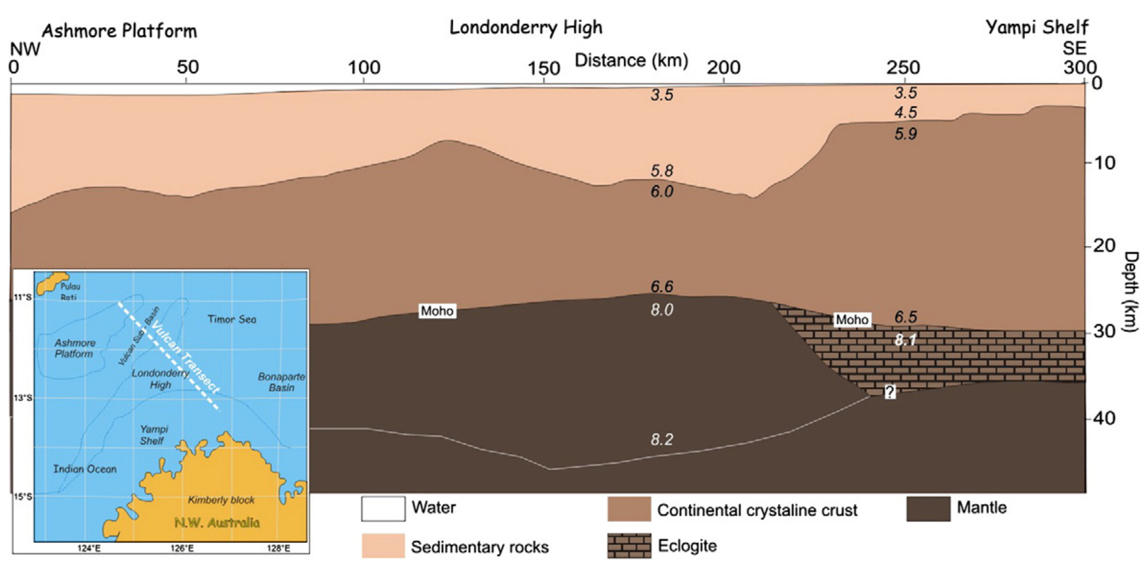

Fig. 14. A combined OBS and gravity model between the Precambrian Australian craton and the Timor Basin. Modified from Petkovic et al. (2000).

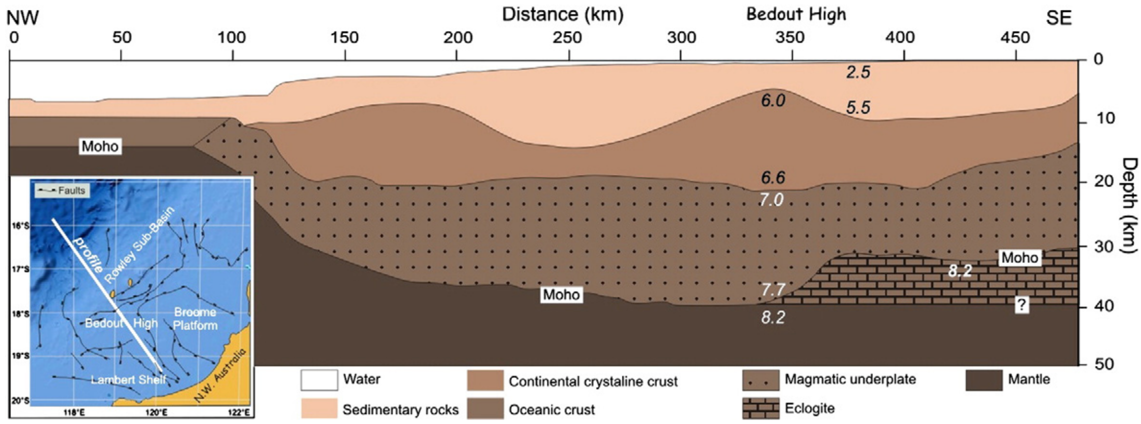

Fig. 15. OBS model across the Bedout High, NW Australian shelf. It is likely that the magmatic underplate terminates near the SE border of the Bedout High. Modified from Müller et al. (2005).

Continent-Ocean-Transition (Fig. 18; Edwards et al., 1997). We propose that the feature could be indicative of the presence of lower crustal eclogites.

We have reviewed published data from other margins with regard to local Moho uplifts which could be interpreted in terms of lower crustal eclogites. Our study has included about 33,000 km 2D crustal scale profiles across passive margins located in the Atlantic, Indian Ocean, South China Sea and Antarctica. The 17 candidates we have described above (Fig. 19), where the Moho is interpreted as the top of lower crustal eclogites, represent about 1900 km or approximately 6% of the total profile length studied. See Table 1 for a complete list of references.

4. Discussion

The new candidates for lower crustal eclogites presented above all fulfil the shallow Moho criterion, and two fulfil the double Moho criterion (Yilgarn Craton and Yampi shelf). None of the candidates fulfil the V_p, density or V_p/V_s criteria. Since the interpretation for the most part is based upon one criterion, it is important to underline that interpreting the Moho as the top of a local eclogite body is not the only viable interpretation for the structures. All of these features can be explained by other models involving e.g. lateral ductile lower crustal flow, simple-shear extension, components of strike–slip deformation, complex strain distribution and variations in lithospheric strength. However, we argue that the eclogite hypothesis is plausible, and that this interpretation is supported by the fact that the eclogite candidates seem to indicate a pattern, which will be elaborated below. If the hypothesis is correct, failure to recognize the presence of eclogites will induce significant shortcomings in geodynamical interpretations and models of rifted margin evolution.

4.1. Eclogites indicative of suture zones

The best documented cases where eclogites have been related to suture zones are found in the Barents Sea (Breivik et al., 2002, 2003, 2005; Figs. 6, 7). Interpreting the lower crustal/upper mantle models in terms of eclogites in this area was critical in revealing the possible suture zones between Laurentsia/Barentsia and Barentsia/Baltica, respectively (Fig. 20).

The main Caledonian suture along the mid-Norwegian Margin has been assumed to be located somewhere beneath the Trøndelag Platform (Fig. 21; Torsvik and Cocks, 2005). Following the link between possible lower crustal eclogites and suture zones, we propose that the Moho uplift beneath the Utgard High may be related to the Caledonian suture off mid-Norway (Fig. 21). This would imply that the suture is linked to the Fles Fault Complex. The Moho uplift beneath the Lofoten Ridge may be interpreted as the northward continuation of the suture.

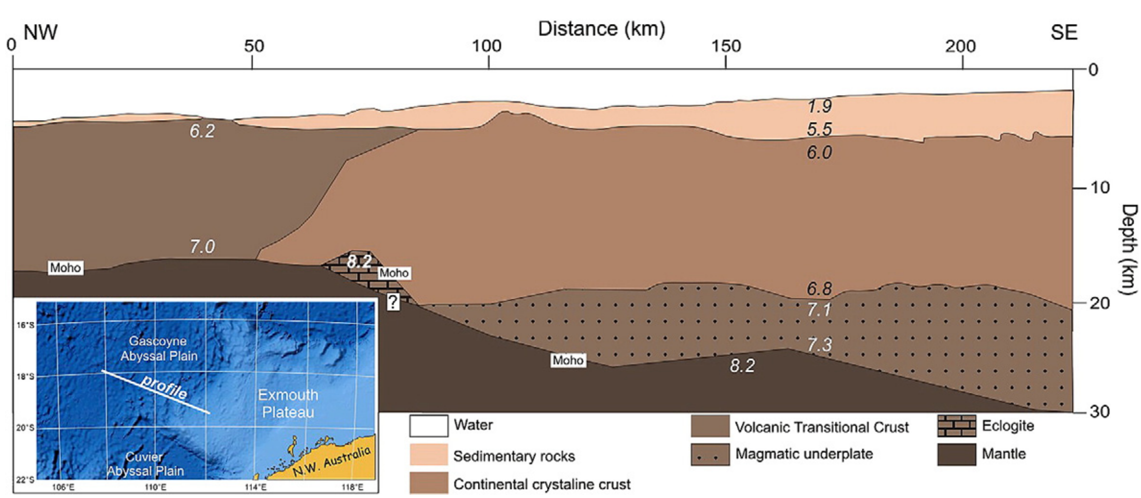

Fig. 16. A combined OBS and potential field model across the continent-ocean-transition at the outer Exmouth Plateau to the Gascoyne Abyssal Plain, NW Australia. Modified from Direen et al. (2008).

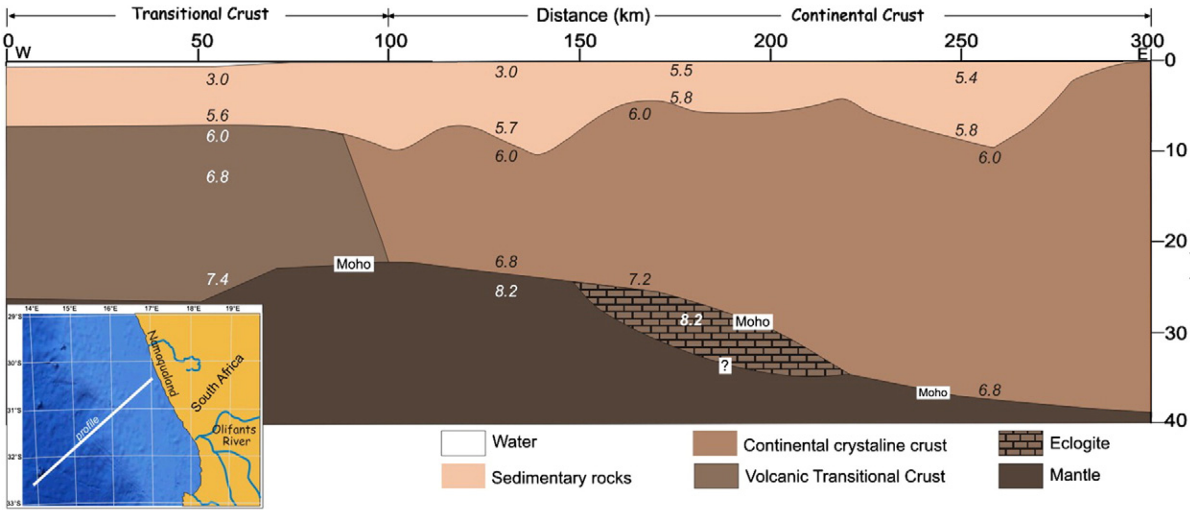

Fig. 17. A combined OBS and gravity model across the western South African passive volcanic margin. Modified from Hirsch et al. (2009).

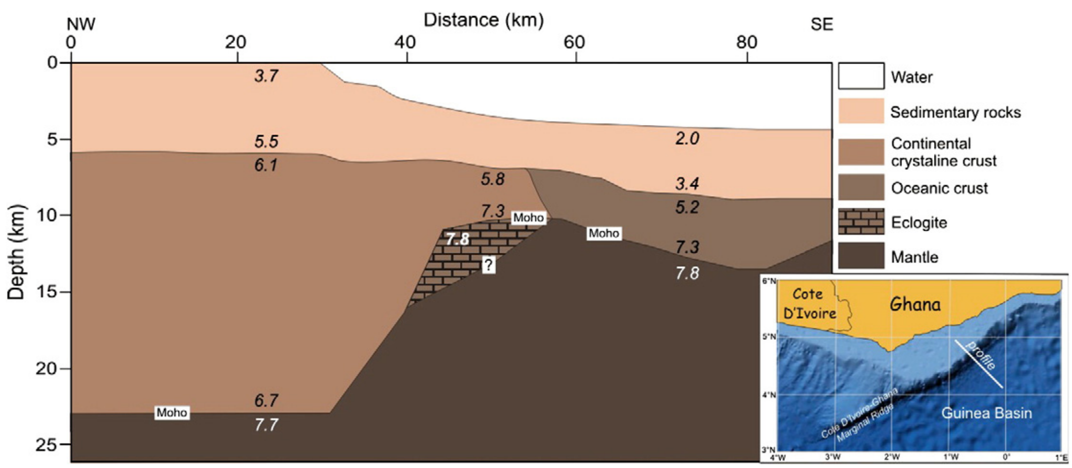

Fig. 18. OBS model across the Ghana Transform Margin, W. Africa. Modified from Edwards et al. (1997).

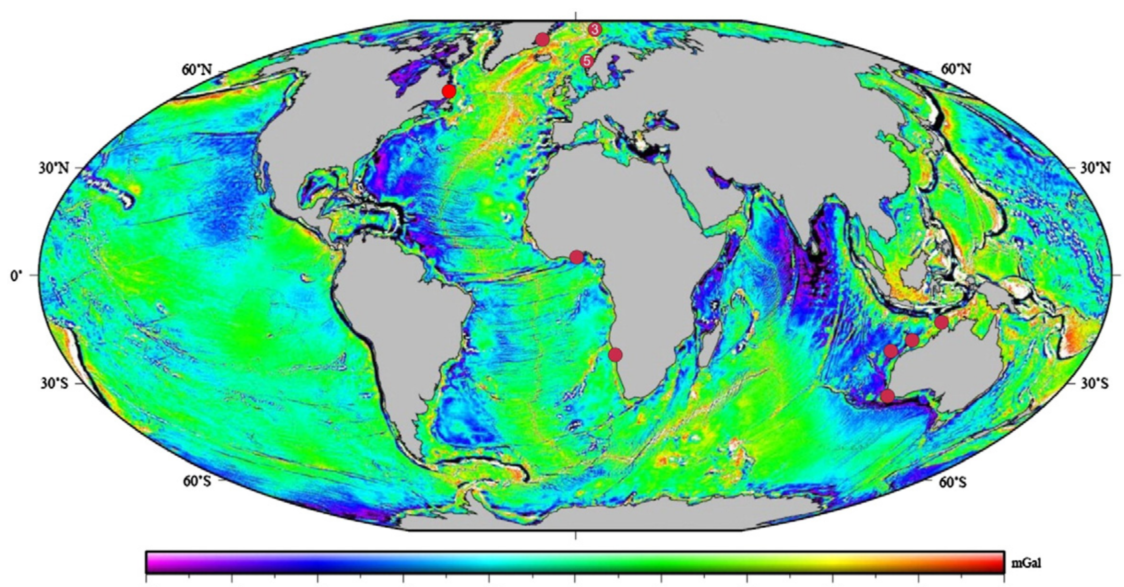

Fig. 19. Ocean gravity map with rough location of all 16 candidates for lower crustal eclogites discussed in this paper (red dots). Numbers refer to the total number of candidates for each area (when larger than one).

Table 1
List of all scientific papers studied with regard to lower crustal eclogites.

Eclogite candidates identified
N. Atlantic
Breivik et al. (2002, 2003)
Christiansson et al. (2000)
Funck et al. (2001)
Olafsson et al. (1992)
Mjelde et al. (1993, 1998, 2008)
Raum et al. (2006)
Ritzmann and Jokat (2003)
Voss and Jokat (2009)
Wangen et al. (2011)
S. Atlantic
Hirsch et al. (2009)
Edwards et al. (1997)
Australia
Dentith et al. (2000)
Direen et al. (2008)
Müller et al. (2005)
Petkovic et al. (2000)
Tassel and Goncharov (2006)
Eclogite candidates not identified
N. Atlantic
Afilhado et al. (2008)
Bird et al. (2005)
Bullock and Minshull (2005)
Chian et al. (1995)
Dean et al. (2000)
Faleide et al. (1991)
González et al. (1999)
González-Fernández et al. (2001)
Holbrook et al. (2001)
Hopper et al. (2003)
Kodaira et al. (1998)
Korenaga et al. (2000)
Lau et al. (2006)
Mickus et al. (2009)
Morgan and Barton (1990)
Mjelde et al. (1992, 1997, 2001, 2009)
Rovere et al. (2004)
Morgan and Barton (1990)
Reid (1994)
Ritzmann et al. (2004)
Raum et al. (2005)
Thinon et al. (2003)
Weigel et al. (1995)
White et al. (2008)
Whitmarsh et al. (1996)
Wyer and Watts (2006)
Mediterranean
Mauffret et al. (2001)
S. Atlantic
Aslanian et al. (2009)
Barker (1999)
Bauer et al. (2000)
Christeson et al. (2008)
Contrucci et al. (2004)
Gladczenko et al. (1998)
Greenroyd et al. (2007)
Houtz et al. (1977)
Moulin et al. (2005)
Parsiegla et al. (2009)
Peirce et al. (1996)
Rodger et al. (2006)
Schnabel et al. (2008)
Watts et al. (2009)
Wilson et al. (2003)
Australia
Finlayson and Mathur (1984)
Finlayson and Collins (1993)
Drummond et al. (1998)

Table 1 (*continued*)

Eclogite candidates not identified
Australia
Fomin et al. (2000)
Goncharov (2001, 2004)
MacCready et al. (2006)
Indian Ocean
Behera et al. (2004)
Collier et al. (2009)
South China Sea
Klingelhoefer et al. (2009)
Wang et al. (2006)

This interpretation implies that the suture is offset by about 40 km across the Bivrost Lineament, which is generally interpreted as a Caledonian transfer zone (e.g. Doré et al., 1997).

Based on their model from the Newfoundland Appalachians, Funck et al. (2001) suggested that the northern continuation of the Appalachian deformation front is located close to the eastern limit of the Cartwright Arch (Fig. 10). Following the same arguments as for the lower crustal bodies off Norway, we suggest that part of the Newfoundland Moho uplift may correspond to eclogites formed during the Appalachian Orogeny. The same interpretation may be applied for the inferred lower crustal crustal high-velocity terrain in the Yilgarn Craton, i.e. it may be interpreted as eclogites related to an Archean suture zone.

4.2. Eclogites related to Fracture Zones

The well studied Moho uplift beneath the Rån Ridge, southern Vøring Basin, is located just north of the Eastern Jan Mayen Fracture Zone (FZ), where the Continent-Ocean-Boundary is offset about 200 km (Vøring Transform Margin, Fig. 21). At the conjugate margin, the Moho uplift in the model of Voss and Jokat (2009) is located just north of the Western Jan Mayen FZ (Figs. 9, 19). Interpreting these two Moho uplifts as lower crustal eclogites suggests a genetic link between the formation of the eclogites and the Jan Mayen FZ, which is the only major FZ in the North Atlantic. It is possible that the precursor of the FZ acted as a major transfer zone during the formation of the Caledonides, facilitating emplacement of lower crustal eclogites, but it is also possible that the Caledonian eclogites acted as strain barriers forcing the post-orogenic rifting and break-up axis to adjust. A similar interpretation is possible for the Moho uplift at the Ghana Transform Margin (Fig. 18; Edwards et al., 1997).

4.3. Eclogites beneath shelf edge

Several of the inferred lower crustal eclogite bodies are located close to lines of major changes in strain, such as coastlines and shelf edges. This applies to the bodies in the North Sea (Christiansson et al., 2000), Møre Basin (Mjelde et al., 2008; Olafsson et al., 1992), Yampi shelf (Petkovic et al., 2000) and off South Africa (Hirsch et al., 2009). We propose that the eclogite bodies may act as strain barriers, as they have different densities and rheological properties compared to the surrounding rocks.

Within this framework, it is possible to propose that the eclogite body we infer near the Spitsbergen coastline (Ritzmann and Jokat, 2003) may have acted as a critical parameter in the localization of the Greenland-Spitsbergen sheared margin itself. Furthermore, it is possible that the eclogite body we interpret at the outer Exmouth Plateau (Direen et al., 2008) may have played an important role in localising the Volcanic Margin Transition–Continental Boundary.

Interpreting the Moho beneath the Bedout High as the top of a body of lower crustal eclogites favours the multi-phase extensional hypothesis outlined by Müller et al. (2005). This may suggest that the northern

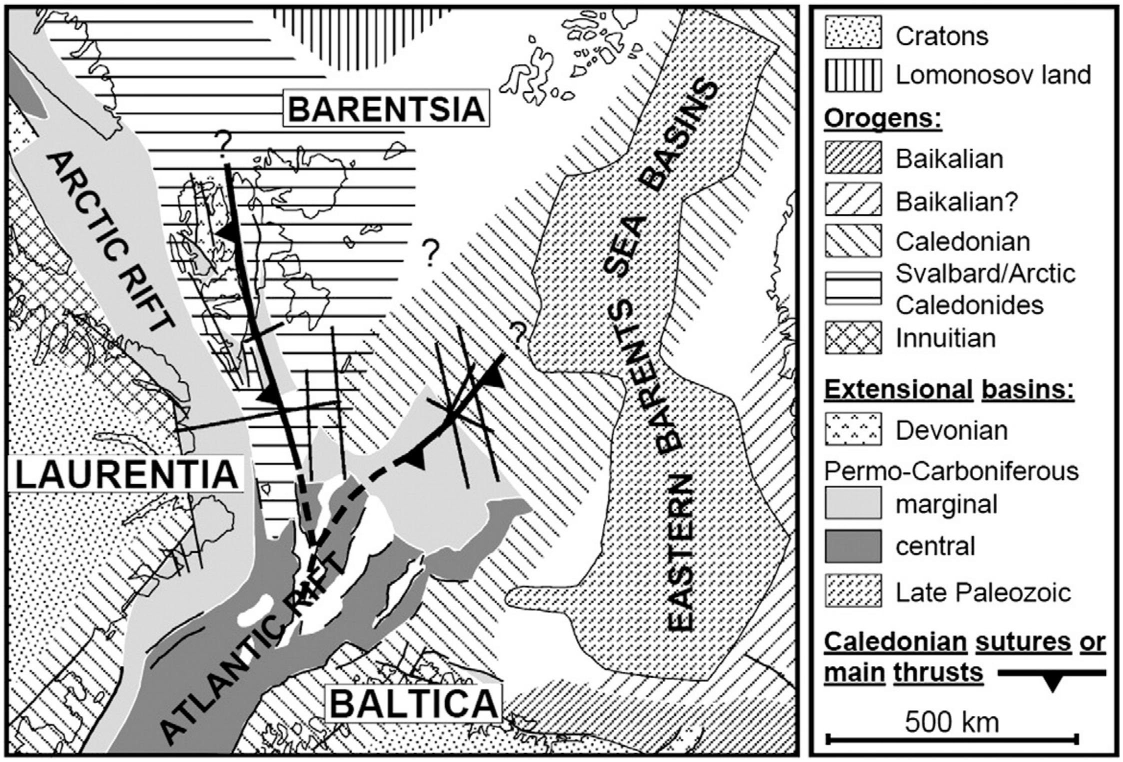

Fig. 20. Location of modeled OBS profiles (from Breivik et al., 2002, 2003, 2005) and the proposed Caledonian sutures (from Breivik et al., 2005), compared to a Caledonide model modified from Gudlaugsson et al. (1998).

termination of the Lambert Shelf represents a paleo suture zone and the western termination of the Broome Platform may have acted as a major transfer zone.

It should finally be noted that the Moho map for Australia (Collins et al., 2003) does not generally correlate with main crustal terrains as defined on the basis of geological and geophysical character and tectonic age (Myers et al., 1996). This observation may support the interpretation of the Moho not always coinciding with the crust–mantle-boundary.

4.4. Further applications and research

Lithospheric delamination models, where parts of the upper mantle lithosphere and lower crust sink into the deeper mantle, are frequently invoked in order to explain various geological observations. A recent example concerns the New Caledonia Trough, where Sutherland et al. (2010) explain the apparent lack of crustal extensional features in the trough by invoking a detachment fault, delaminating the lower crust. While we recognize that this model is viable, an alternative model invoking eclogites might also be possible. Upper mantle eclogites would have sufficiently high densities to sink during the initiation of subduction, and eclogitic remnants in the lower crust might explain the present gravity high along the New Caledonia Trough.

Another example concerns the Musgrave Province in central Australia, where potential field modelling has indicated prominent crust–mantle boundary uplift beneath a high density crustal terrain (Aitken et al., 2009). This interpretation implies anomalously high strength of the lithosphere. These strength estimates will be significantly modified if the shallow crust–mantle boundary alternatively is interpreted as the top of a body of lower crustal eclogites.

We recognise that the hypothesis discussed here is speculative and that further work is needed in order to test it. The best candidate for more studies might be the body in the North Sea (Fig. 1). A detailed OBS study with about 5 km OBS spacing extended with land-stations across the Western Gneiss Region where eclogites are present at the surface, might provide the direct link and resolution in V_p and V_p/V_s that is needed. The double Moho is here clearly seen in MCS data, and receiver function studies might provide useful information on the lowest Moho candidate and possibly deeper lithospheric interfaces. The stratigraphy is well known in the area from a large concentration of MCS data and drillholes, and refined tectonic modelling ought to give new insights on the depth to the base of the crust.

5. Conclusions

We have studied about 33,000 km 2D crustal scale wide-angle profiles across passive margins located in the Atlantic, Indian Ocean, South China Sea and Antarctica, with regard to local uplifts of the Moho that possibly could be indicative of lower crustal eclogites, not upper mantle peridotites. We have identified a total of 16 candidates, which make up approximately 6% of the total profile length studied. This relatively low percentage confirms that the common interpretation of the Moho being the top of the mantle, is generally viable.

However, the candidates for lower crustal eclogites identified indicate a common pattern, and failure to recognize the presence of eclogites in these cases may induce significant shortcomings in geodynamical interpretations. For instance, there may be a link between lower crustal eclogites and continental suture zones in the Barents Sea, off mid-Norway, in the Newfoundland Appalachians and in the Yilgarn Craton, western Australia.

Furthermore, there appears to be a genetic link between the formation of the eclogites and the Jan Mayen Fracture Zone, which is the only major fracture zone in the North Atlantic. It is possible that the precursor of the fracture zone acted as a major transfer zone during the formation of the Caledonides, facilitating emplacement of lower crustal eclogites, but it is also possible that the inferred Caledonian eclogites acted as strain barriers forcing the rifting and break-up axis to adjust. A similar geodynamical interpretation is possible for the Moho uplift at the Ghana Transform Margin.

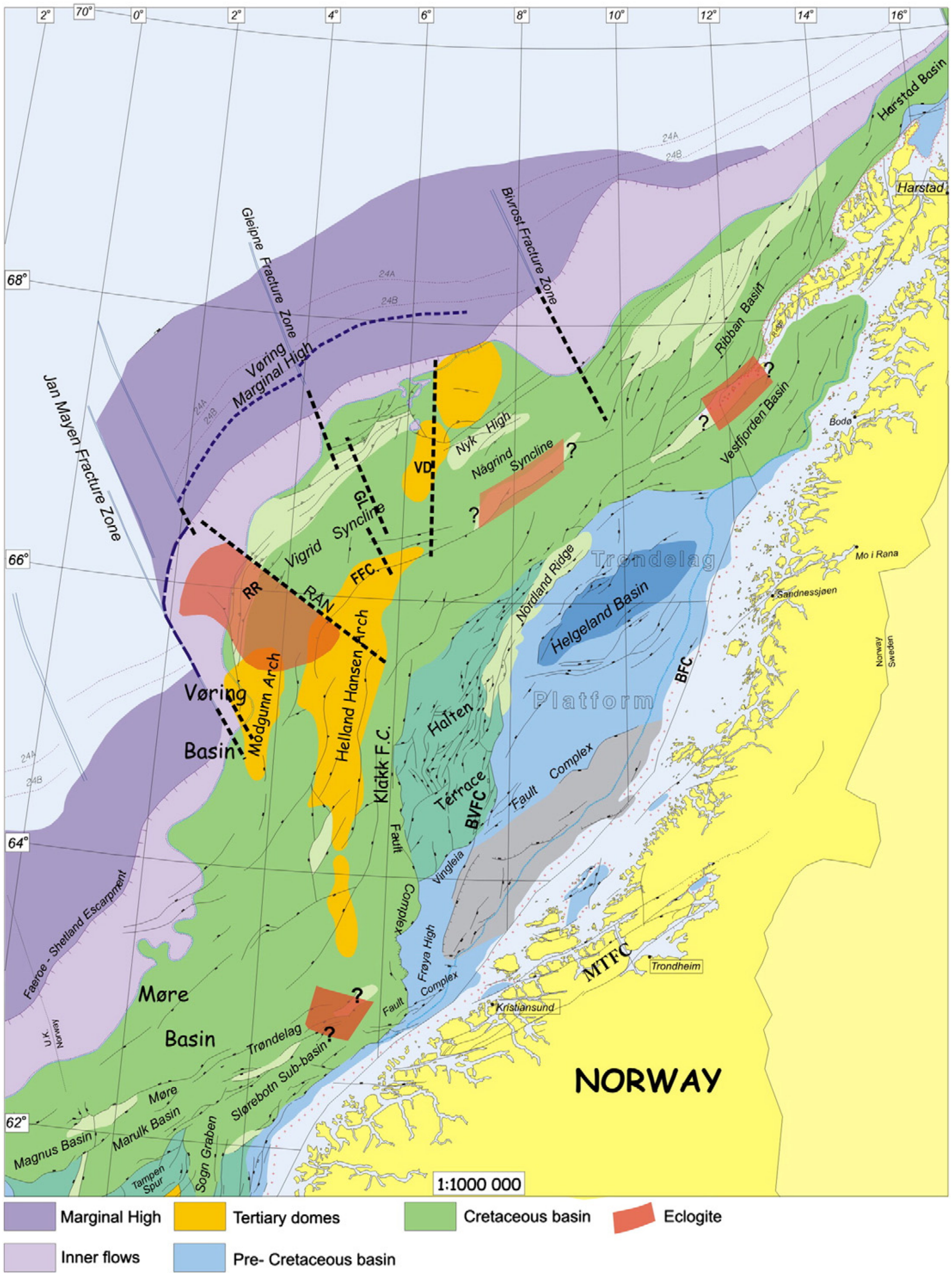

Fig. 21. Location of all candidates for lower crustal eclogites along the mid-Norwegian margin discussed in this paper.

Several of the inferred lower crustal eclogite bodies are located close to lines of major changes in strain, such as coastlines and shelf edges. This applies to the bodies in the North Sea, mid-Norwegian Margin, Yampi shelf (NW Australia) and off South Africa. We propose that the eclogite bodies may act as strain barriers, as they have different densities and rheological properties than the surrounding rock.

Interpreting the Moho beneath the Bedout High, NW Australia as the top of a body of lower crustal eclogites may suggest that the northern termination of the Lambert Shelf represents a paleo suture zone and the western termination of the Broome Platform may have acted as a major transfer zone.

The majority of the proposed candidates for lower crustal eclogites are found in the North Atlantic and around Australia. We propose that this bias is mainly a function of data coverage, not geological differences. The fact that no candidates are found along non-volcanic margins may be attributed to the much larger degree of extension there, removing observable imprints of the eclogite forming orogeny.

Acknowledgments

The idea for this study emerged from the large amount of models derived from Ocean Bottom Seismic (OBS) data acquired in the North Atlantic. We thank engineers from the University of Bergen and engineers and scientists from Hokkaido University and IFM-GEOMAR for the invaluable participation in planning and executing these surveys. We acknowledge The Norwegian Petroleum Directorate, Statoil, Norsk Hydro, Total, and the Norwegian Research Council for funding these projects. The present paper can to a large extent be attributed to the fruitful environment for scientific discussions the first author experienced during a research stay at the School of Geosciences, University of Sydney. We thank Prof. J.I. Faleide and Dr. Asbjørn Breivik, University of Oslo, for the strong support, Beata Mjelde for drawing figures and two anonymous reviewers for their very constructive comments.

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