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REVIEW ARTICLE

The great eclogite debate of the Western Gneiss Region, Norwegian Caledonides: The in situ crustal *v*. exotic mantle origin controversy

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Abstract

An entertaining debate arose in the latter half of the 20th century among scientists working on the spectacular eclogite facies rocks that occur within metamorphic rocks of the Western Gneiss Region (WGR) of the Norwegian Caledonides. It resulted in part from Eskola's influential publication "On the Eclogites of Norway" who concluded, incorrectly, that mafic eclogites within gneisses (external eclogites) and garnetiferous ultramafic rocks within peridotite lenses had a common origin. The debate featured two end-member positions. One was that all these garnet-bearing assemblages, regardless of association, had an exotic origin, where they recrystallized at extremely high pressures and temperatures (*P–T*) in the mantle and then were tectonically inserted upward into the crust. The other was the in situ origin where this recrystallization occurred within the enclosing gneisses during regional metamorphism. Garnet peridotites and pyroxenites have compositions identical to ultramafic xenoliths in kimberlites and define *P–T* conditions that are appropriate to the upper mantle. Therefore, peridotite lenses were generally (and correctly) interpreted to be mantle fragments. However, some extended this exotic origin to external eclogites, particularly coarse-grained orthopyroxene- (and coesite-) bearing eclogites, which also formed at extremely high *P–T*. They noted an apparent pressure and temperature disequilibrium between anhydrous eclogites and the surrounding amphibolite facies gneisses. It was generally accepted that eclogites could form only in "dry" environments ($P_{H_2O} << P_{total}$). Thus, eclogites had to form within the anhydrous mantle rather than the host hydrous crust. Finally, there was doubt as to whether the necessary *P–T* conditions could be generated in continental crust, even when tectonically thickened. The arguments for an in situ origin were based largely on external eclogites. Thin sections showed garnet cores with amphibolite facies inclusions and rims with eclogite facies minerals suggesting prograde metamorphism. Similarly, core to rim changes in mineral chemical composition were consistent with increasing *P–T*. Coesite and microdiamond were found in both eclogites and host gneisses. Finally, thermobarometry showed burial depths increased from SE to NW across the WGR. Breakthroughs occurred when old assumptions were discarded. Eclogite recrystallization actually can occur in the presence of water. Eclogites and garnet peridotite and pyroxenites had completely different histories.

They give different ages, formed under different P–T conditions, and have different geochemical fingerprints. The debate was finally resolved when it became generally accepted that continental crust could subduct into the mantle. Thus, it could subduct to eclogite facies depths where, simultaneously, peridotites could be inserted from the overlying mantle wedge. Both sides of the debate were correct! However, eclogites recrystallized “in situ” only because the enclosing crust was deep in the mantle and garnet peridotites did invade continental crust as solids, but only because the crust was below a mantle wedge. The “Great Debate” was fierce at times, but it led to the modern understanding that continental subduction is a vital part of mountain building.

KEYWORDS
continental subduction, eclogite, garnet peridotite

1 | INTRODUCTION

There is a poem (published in Gardner, 1995) by the 19th century American poet John Godfrey Saxe, based on an ancient Hindu parable, about unsighted people touching different parts of an elephant and coming to completely different conclusions about what they were touching (Figure 1). An analogous situation occurred during the second half of the 20th century as Earth scientists began an intense study of the eclogites and garnetiferous ultramafic rocks within the Western Gneiss Region (WGR, Figure 2), a metamorphic terrane that occurs at the base of the Norwegian Caledonides. These rocks became famous when Pentti Eskola wrote his highly influential manuscript “On the Eclogites of Norway” in 1921. His intention was to expand on his earlier classic work “The Mineral Facies of Rocks” (1920) by describing, classifying, and inferring the origin of these spectacular-looking, high-P rocks.

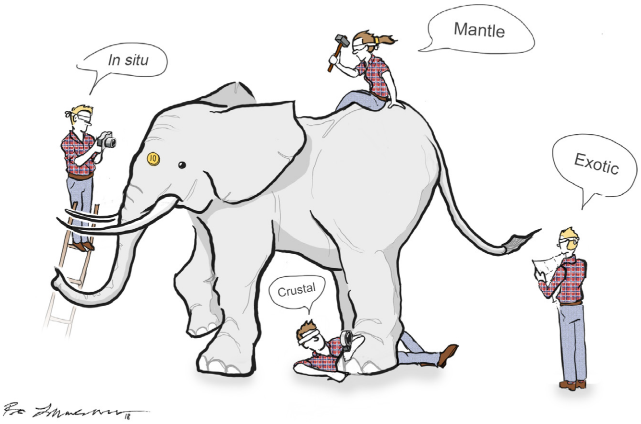

FIGURE 1 Cartoon based on John Godfrey Saxe’s poem about blind men (in this case blindfolded geologists) and an elephant. Touching different parts of the elephant led to different, and incorrect, conclusions of its identity. Cartoon drawn by Bo Johansson Möller

Eclogites are metamorphic mafic rocks that occur as boudins, lenses, and a few larger masses (some >1 km^2) within the largely amphibolite facies metamorphic rocks of the WGR. They are widely distributed (Figure 2). They are called “external” or “crustal” eclogites to distinguish them from rocks of similar composition that occur as lenses within peridotites (“internal eclogites”). Both types of eclogite should, in turn, be distinguished from garnet-bearing ultramafic rocks (garnet peridottes and garnet pyroxenites) that occur within large garnet-free dunite and harzburgite bodies. These ultramafic lenses, some of which cover several km^2, are also widely distributed in the gneisses of the WGR, but only a few of them contain garnet-bearing assemblages (Figure 2). Failure to make distinctions between these different rock types confused the issue of how they formed. Most investigators accepted Eskola’s general conclusion that all formed at very high pressure. The question was where? There were two end-member positions. One was the “exotic mantle origin” where both the eclogites and the garnetiferous ultramafic rocks crystallized or recrystallized deep in the mantle and then were tectonically inserted into their present position in the metamorphic crustal rocks of the WGR. The other was the “in situ” or “crustal” origin where at least the eclogites recrystallized within the gneisses and metasedimentary rocks of the continental crust during regional metamorphism. Both sides made reasonable arguments, but were influenced by their specialties. So structural geologists emphasized different lines of evidence than mineralogists, while geochemists and petrologists found other observations more compelling, and even they did not necessarily agree with each other. In other words, we were observing different parts of the elephant and could not come to a coherent understanding of that elephant until we made new

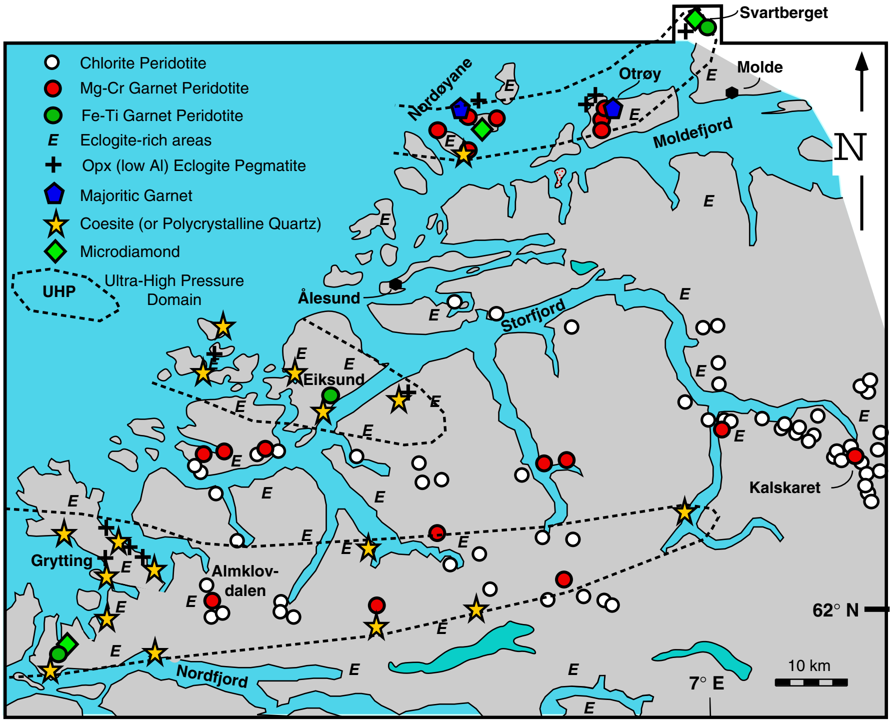

FIGURE 2 Simplified map of the Western Gneiss Region showing the approximate locations of the heterogeneous eclogite facies assemblages that characterize the region and the names of some important localities. Three ultrahigh pressure domains are outlined by a dotted pattern (Hacker et al., 2010). Eclogites within these domains include the coarse-grained orthopyroxene-bearing eclogites of the "Gryting type," which gave contested (but correct) ultrahigh pressures of recrystallization. Modified from Brueckner (1998) and Vrijmoed et al. (2006)

discoveries, discarded some of our old assumptions and conceded that those on the other side of the debate might have some valid points.

Two of Eskola's conclusions complicated the debate. First, he equated what we now would call external eclogites (non-foliated = "Duen type"; foliated = "Lyngenes type") with what we would now call garnet peridotites and garnet pyroxenites (="Rødhaugen type"). He actually described eight types of eclogite with the eighth ("Eclogite-pegmatite of the Gryting type") creating additional confusion, as discussed further below. Second, he concluded that all eight rock types, and the gneisses that enclose them, as well as associated anorthosites, had a common igneous origin as magmatic differentiates that crystallized at extremely high pressures ("On the Genetic Connection between the Eclogites, Dunites and Labradorite-rocks"). "All these rocks no doubt have been derived by a process of differentiation from one and the same magma, but the details or causes of this process we may at present leave undiscussed." Dunite and anorthosite layers do occur in layered intrusions of the Skaergaard type (i.e. Bushveld Stillwater, Muskox, others), which clearly formed through magmatic differentiation through the classic Bowen Reaction Series (Bowen, 1928). It is therefore not surprising that Eskola postulated a related origin (Bowen wrote his classic book after Eskola's publications, but layered intrusions were already known to exist). Eskola's conclusion of a common igneous origin is now known to be incorrect, but was widely accepted at the time.

Eskola did consider other cases; for example where "…a solid gneiss mass ('of granite') was pressed down deep enough to meet gabbroid magma which, after having enclosed fragments from the gneiss, solidified as a true eclogite." Another case he considered was where, "…owing to the gravitational control… there may have been chances for the inclusions to be caught up from beneath as well as to sink down ('into the crystallizing and differentiating gneiss magma') from above." Elements of present day models can be found in these statements. A pressed down "solid mass of granite" could be interpreted as subducted continental crust. Inclusions that "sink down" could refer to peridotites sinking from a mantle wedge into underlying granitic crust.

This is where matter stood for several decades. It was not until 30 years later that the igneous origin assumption was challenged by Gjelsvik (1952) who mapped the WGR during World War II (and simultaneously fought against the occupying Germans). He found eclogite facies corona assemblages around igneous minerals in WGR dolerites and concluded that eclogites were metamorphic, not igneous, rocks.

2 | THE DEBATE

Eskola in 1921 lacked the numerous investigative tools we have today. Since then geothermobarometers, geochronometers, kinematic analyses, electron microprobes, mass spectrometers, and many other tools and techniques became available. However, the early application of these new methods seemed to further inflame the "in situ" *v.* "exotic" debate, which sometimes became quite contentious and resulted in duelling papers published in major journals like *Geology*, *The Journal of Petrology and Nature* (e.g. Lappin, M.A., Discussion; Krogh, E.J., Reply, 1977).

2.1 | The exotic mantle origin

The "exotic mantle origin" position was heavily influenced by the garnetiferous assemblages (i.e. the aforementioned "Rødhaugen type") found within some WGR peridotites, most notably those at Almklovdalen, and Kalskaret (Figure 2). As noted, Eskola equated these ultramafic assemblages with the mafic assemblages (i.e. the external eclogites) that occur within the gneisses. A very influential paper by O'Hara and Mercy (1963) emphasized that the composition and mineralogy of the Kallskaret garnet pyroxenite near Tafjord were very close to those of ultramafic nodules in kimberlites. Kimberlites are of obvious mantle origin; therefore, the Kallskaret body also had a mantle origin. Successive publications came to a similar "mantle origin" conclusions based on thin section petrography, mineral and whole-rock chemistry, and the early application of geothermobarometers. The most reliable techniques used the partitioning of Mg and Fe between garnet and clinopyroxene to determine temperature. Pressure was determined by measuring Al concentrations in orthopyroxene. These techniques resulted in very high temperature and pressures estimates, as is appropriate if they were derived from the upper mantle (e.g. 715–847°C, 18–29 kbar, Carswell, 1986; ~820°C, ~28.1 kbar, Medaris, 1980a, 1980b).

Despite this consensus, there seemed to be an intractable problem. The peridotites do not occur within kimberlites or similar igneous intrusives, but rather as bodies, sometimes km-scale masses, directly within crustal, largely granitic, metamorphic rocks. So how did they move up from the dense mantle (~3.2 g/cm^3) into the less dense continental crust (~2.7–2.8 g/cm^3) to get to their present position? A sketched cross-section diagram of the Kalskaret peridotite (O'Hara & Mercy, 1963) shows the banding in the gneisses folded upward near the peridotite contacts, looking as if the peridotite had forced itself upwards as it rose through the crust. "Field relations in the Kalskaret area (text-figures 5 and 6) suggest, however, that some of the peridotites were emplaced by more or less vertical movements in narrow zones after the formation of the recumbent folds." (O'Hara & Mercy, 1963, p. 258). O'Hara and Mercy (1963) went on to suggest that external eclogites were also introduced as a "solid intrusion." The intrusion process may have been similar to the "watermelon seed" mechanism: dense mantle rocks forced upwards by tectonic pressures ("squeezing") at depth although in reality no publication at the time on WGR peridotites and eclogites used this term as a possible explanation.

Adding to this confusion was a Harvard Ph.D. dissertation (1963) by Harrison "Jack" Schmitt, the future astronaut, who mapped a very large peridotite–eclogite body (0.4–1.0 km^3) near Eiksunddal (Figure 2). The complex is compositionally layered, very similar to Skaergaard and other layered intrusions, but the rocks are now in the eclogite facies. These layers include thick zones (up to 10 m) of garnet peridotite. Did these peridotite layers indicate intrusion from the mantle into the crust? Schmitt concluded that the Eiksunddal body did not intrude as a solid body as proposed by O'Hara and Mercy (1963), but rather as a magma that evolved into a highly differentiated pluton and subsequently was metamorphosed in situ into eclogite facies assemblages during the Caledonian Orogeny. Schmitt never published his dissertation but subsequent studies (i.e. Carswell, Harvey, & Al-Samman, 1983; Jamtveit, 1987) confirmed his conclusions. Ultimately, Carswell et al. (1983) concluded that there are two actually two compositionally different types of garnet "peridotite" in the WGR: the type rich in Fe and Ti, represented by the Eiksunddal complex and the recently described Svartberget garnet–peridotite–websterite body (Vrijmoed, Van Roermund, & Davies, 2006); and the type rich in Mg and Cr, represented by the Almklovdalen and Kalskaret bodies. The Fe-Ti type underwent the same metamorphic evolution as the external eclogites although their evolution was complicated by the fact that some have undergone extensive metasomatism (see below). In any case, the arguments listed above for an "exotic" mantle origin should be restricted to Mg-Cr–rich peridotites.

It is no surprise that Mg-Cr–rich garnet peridotites originated from the mantle. However, coarse-grained, orthopyroxene-bearing eclogites within gneisses (the "Gryting type" type of Eskola mentioned above) also seemed to give surprisingly high pressures (30–40 kbar, Lappin & Smith, 1978). These ultrahigh pressure (UHP) estimates led to the conclusion that these orthopyroxene-bearing assemblages, and therefore by extension the other external eclogites within gneisses, formed under conditions that could not be met in the continental crust, even where crustal thickness is doubled or even tripled. Therefore, it was argued, they must have formed in the mantle and were inserted into the crust tectonically along with the garnet peridotites (Lappin & Smith, 1978).

Another argument for a mantle origin for external eclogites was the apparent disequilibrium between their eclogite facies assemblages and those of the gneisses that enclose them. The gneisses usually contain mineral assemblages characteristic of the amphibolite facies (and locally the granulite facies). They give *P*–*T* estimates of 10–15 kbar and 600–700°C, conditions that can be met in thickened continental crust, but are not high enough to account for the >30 kbar, >1200°C estimates for Gryting-type eclogites. These high-*P* estimates were further re-enforced when the high-P polymorph of SiO_2, coesite, was discovered not only in Gryting-type eclogites (Smith, 1984), but in other external eclogites as well. Coesite requires pressures of 25–30 kbar (80–100 km depth) at temperatures between 600 and 800°C and so, it was argued, must have formed at mantle depths. Importantly, coesite was described initially as within eclogites only, not in the host gneisses and so seemed to confirm the apparent disequilibrium between eclogites and the host country rocks.

Other arguments for a mantle origin were less persuasive. Layering in the gneisses is locally discordant to eclogites (Bryhni, Green, Heier, & Fyfe, 1970), which tend to occur as boudins, and also as more angular blocks. These discordant relationships could attest to some sort of solid introduction into the gneisses, but, as noted by Bryhni et al. (1970), they could also reflect different behaviour between ductile gneisses and rigid eclogites.

2.2 | The “in situ” origin

The arguments for an in situ origin were equally compelling, but only when applied to external eclogites. As noted above, Gjelsvik (1952) had observed that coarse-grained gabbros with clear igneous textures contained eclogite facies corona assemblages around primary igneous minerals. Subsequent studies by Mørk (1985) confirmed Gjelsvik’s observation and provided more details on the partial transition of igneous protoliths to eclogites. Other studies (e.g. Krogh, 1982) showed that many eclogites contain garnet with lower pressure (amphibolite facies) mineral inclusions in the cores (e.g. amphibole and plagioclase) and eclogite facies minerals in or next to their rims (e.g. omphacite and rutile). Electron microprobe scans across mineral grains showed similar evidence of increasing pressures and temperatures during metamorphism, usually an increase in Mg and decrease in Fe from core to rim in garnet (Bryhni & Griffin, 1971). Pressures and temperatures estimated from grain rims generally gave lower values (23–30 kbar, 550–740°C) than those calculated from garnet peridotites and the Gryting-type eclogites (see Cuthbert, Carswell, Krogh-Ravna, & Wain, 2000; for review). This led some to argue (e.g. Carswell, Krogh, & Griffin, 1985) that the much higher pressures estimated for eclogites of the Gryting type were flawed. In fact they were not flawed, the pressure estimates were essentially correct (temperatures, however, were too high). Gryting-type eclogites (including the Svartberget eclogite) occur within three antiforms (Figure 2), which expose UHP (i.e. coesite- and/or microdiamond-bearing) eclogites in their cores, and lower pressure eclogites along their limbs (Hacker et al., 2010). The apparent discrepancy between high and ultrahigh pressure (HP/UHP) estimates for different eclogites turns out to have a structural explanation.

A major breakthrough occurred when eclogite geothermobarometry on a regional scale showed increasing temperature and pressure from SE to NW across the WGR indicating increasing burial to the NW (Krogh, 1977). This trend is somewhat obscured by the three east-trending antiforms with UHP assemblages in the cores (Figure 2), but overall is confirmed by recent studies (Hacker et al., 2010). This observation led to the suggestion that the WGR had been subducted deep into the earth with the NW corner subducted to the deepest level. Krogh believed subduction occurred during the Precambrian, reflecting a commonly held assumption in the 1960s and 1970s that the eclogites formed during a Precambrian recrystallization event (see below).

Sporadic occurrences of omphacite and other evidence of HP/UHP metamorphism in felsic gneisses were discovered and used to further support arguments that the eclogites and enclosing gneisses recrystallized under the same eclogite facies conditions (Cuthbert & Carswell, 1982; Krogh, 1980, 1982; Mysen & Heier, 1972). These occurrences were consistent with similar discoveries in high-P terranes within the Alps (Compagnoni, 1977) and Scotland (Sanders, 1979). Ultimately, coesite (Wain, 1997) and microdiamond (Dobrzhinetskaya et al., 1995) were found within gneisses enclosing the eclogites, thus finally dispelling the purported disequilibrium between eclogite and host gneiss.

Another breakthrough came when published Sm–Nd garnet–clinopyroxene ages indicated that eclogite facies recrystallization occurred during the Scandian orogeny (*c.* 430–400 Ma, Griffin & Brueckner, 1980; Mørk & Mearns, 1986), the same event that recrystallized the enclosing country rocks. This result was met with initial scepticism since eclogite formation was widely regarded as a Precambrian event. However, subsequent dating by other decay schemes (U–Pb zircon, rutile and monazite ages, and Lu–Hf mineral ages) confirmed this Scandian origin (see review in Kylander-Clark, Hacker, Johnson, Beard, & Mahlen, 2009). A picture emerged where the WGR was subducted deep into the Earth during a collision between Baltica and Laurentia which produced the necessary pressures and temperatures to generate eclogite facies assemblages.

3 | INTERNATIONAL ECLOGITE CONFERENCES

A major contribution to the understanding of eclogites, garnet peridotites, and related rocks was the organization of International Eclogite Conferences. The first was organized by David Smith and held in Clermont-Ferrand, France in September, 1982 (https://www.e–periodica.ch/digbib/view?pid=smp–001:1981:61::402#179). These conferences met every four years initially, separated by Eclogite Field Symposia. Now the conferences and symposia are merged and meet every two years. They are usually preceded and followed by field trips to HP/UHP terranes near the meeting site. In between are three or four days where an international cast of scientists present talks on a variety of topics, mostly centred on HP/UHP metamorphism and related subjects. Most meetings resulted in a special publication featuring subjects presented at each meeting. The cross-fertilization provided by this mechanism proved invaluable for starting the process that ultimately resolved the in situ *v.* exotic origin debate in the WGR, which was raging when the first meeting occurred and which led to some uncomfortable confrontations during the meeting. Notwithstanding these moments, advances in understanding HP/UHP processes in one terrane could be applied to other terranes. For example, the first conference had a field trip to the Sesia Lanzo zone in the Alps where it was shown that high-*P* minerals occur in both eclogites and in the surrounding crustal rocks (Compagnoni, 1977).

4 | RESOLUTION

The in situ origin for external eclogites appears compelling today, but it failed to explain the presence of mantle-derived garnet peridotites in the WGR. As studies of these peridotites continued, it became clear that they had an entirely different history than the eclogites in the gneisses. Geochronological investigations indicated that the garnetiferous assemblages within these peridotites formed during the Proterozoic, well before the Scandian orogeny (Mearns, 1986). *P–T* investigations showed that the garnet peridotites and garnet pyroxenites originally recrystallized at mantle pressures, but subsequently underwent an evolution towards lower pressures and temperatures (Carswell, 1986; Medaris, 1980a), which contrasted with the evolution towards higher pressures and temperatures shown by the eclogites. Ultimately Medaris (1980b) proposed a convergent evolution during the Scandian orogeny with external eclogites showing a prograde evolution and garnet peridotites and pyroxenites showing a retrograde evolution towards a common pressure and temperature.

The subduction of continental crust into the mantle can explain this convergence and is favoured by most (but not all) investigators today (Figure 3). According to the model, the Scandian orogeny occurred when the western margin of Baltica subducted beneath Laurentia to the great depths required for mafic igneous rocks to recrystallize into (external) eclogite through prograde metamorphism, even to the UHP conditions required to form Gryting and Svartberget type eclogites. Subduction to these depths also resulted in a wedge of Proterozoic or older lithospheric mantle above the subducted Baltic crust (Andersen, Jamtveit, Dewey, & Swensson, 1991). This geometry allowed fragments of that mantle wedge to entrain downward (or laterally) into subducted Baltica (Brueckner, 1998) thus resolving the issue of how the peridotites were inserted into continental crust. Lateral or downward emplacement of dense mantle into less dense crust is buoyantly permissible. Ultimately, Baltica reversed itself and exhumed towards the surface, carrying its cargo of eclogites and garnetiferoius peridotites

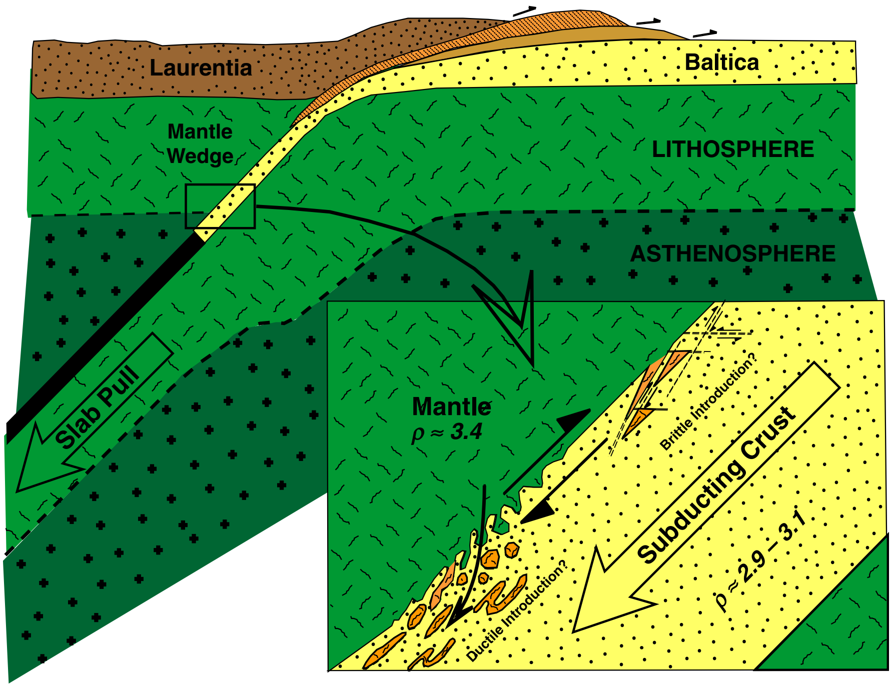

FIGURE 3 Schematic diagram showing the Baltic continental margin subducted beneath Laurentia illustrating how this mechanism generates the necessary *P–T* conditions for eclogite facies metamorphism while simultaneously resulting in a mantle wedge that is a plausible source for introducing garnet peridotites and pyroxenites into the subducted continental crust. Modified from Brueckner (1998)

towards the core of the Norwegian Caledonides (Hacker et al., 2010). The garnet peridotites presumably developed their retrograde core to rim patterns after they were inserted into the crust and carried upward.

5 | OBSTACLES

A major stumbling block to understanding eclogite paragenesis was the assumption in the 1960s and 1970s that eclogites could only form in "dry" environments where $P_{\text{total}} >> P_{H_2O}$. This assumption made it difficult to believe that eclogites could recrystallize within a relatively hydrous continental crust. A very influential paper on the genesis of basalts by Yoder and Tilley (1962) supported this assumption where it stated "Eclogite itself is not stable in the presence of water and gives place to amphibolite or pyroxene hornblendite." Indeed, most eclogites have amphibolitized margins that contrast with the largely anhydrous eclogite facies minerals in the eclogite core. These margins and the enclosing amphibolite facies gneisses clearly recrystallized in the presence of water. At the time, finding a mechanism for generating an anhydrous core in an overall water-rich environment was daunting, so it was easier for some to assume the eclogites were derived from a presumably anhydrous mantle and then inserted into the crust. However, the anhydrous mantle model failed to explain measured ^{87}Sr/^{86}Sr isotope ratios of clinopyroxene separated from some types of "external" eclogites, particularly from Eskola's "pegmatitic" Gryting type, which gave high (crustal) values (0.707 and 0.715, Brueckner, 1977). These high values contrasted with extremely low, but typical mantle values, for clinopyroxene separated from peridotites and pyroxenites (0.702–0.703, Brueckner, 1977). The striking coarse-grained nature of the Gryting-type eclogites also suggested recrystallization in the presence of a fluid.

The required presence of fluids for eclogite recrystallization was finally demonstrated when Håkon Austrheim (1987) described a thin shear zone full of eclogite facies minerals enclosed in the anhydrous (granulite facies) rocks of the Lindås Nappe, an allochthon adjacent to the WGR. The shear zone contains eclogite facies assemblages including hydrous phases such as phengite. The message was clear; "dry" granulite facies rocks placed under HP/UHP conditions did not recrystallize into eclogite facies mineralogies, while the rocks of the shear zone did. The introduction of water along the shear was required to nucleate the formation of eclogite facies minerals (shearing probably played a role as well). This solved the Sr dilemma noted above. Subsequent work on Gryting-type eclogites throughout the WGR has shown that water-soluble components (K, Ca, P, Si, even C) were introduced from the gneisses into the eclogites along with water (Vrijmoed et al., 2006). These fluids were presumably generated through the dehydration reactions of hydrous minerals within the surrounding gneisses, particularly phengite (Griffin, 1987). The introduction of these C-rich fluids at very high pressures into the eclogites and peridotites of the NW corner of the WGR resulted in the formation of microdiamond during Scandian subduction (Brueckner, Carswell, & Griffin, 2002; Scambelluri, Pettke, & van Roermund, 2008; Van Roermund, Carswell, Drury, & Heijboer, 2002).

Another key impediment was the lack of trustworthy radiometric ages from the eclogites in the 1960s and 1970s. The host gneisses of the WGR gave Rb–Sr whole-rock ages that were Precambrian, but minerals within the gneisses gave Caledonian (Scandian) Rb–Sr and K–Ar ages (*c.* 405 Ma, e.g. Brueckner, 1972). Did the Caledonian mineral ages simply reflect a weak thermal overprint on rocks that were intensively deformed during the Proterozoic? Was "Caledonization" weak or intense? Unfoliated granitoids that cross-cut what appeared to be the regional schistosity gave Proterozoic Rb–Sr whole-rock ages (Brueckner, 1972) suggesting Caledonization was weak and, by implication, that the eclogites formed during the Precambrian. However, more recent work has demonstrated that Scandian deformation and recrystallization, i.e. "Caledonization," was extremely heterogeneous in the WGR (Labrousse, Jolivet, Agard, Hébert, & Andersen, 2002). Eclogites are largely confined to thick Scandian shear zones, which separate thick lithotectonic units with weak or non-existent Caledonian fabrics (Young, 2017). These lithotectonic units retain Proterozoic metamorphic facies, structures and fabrics, including the unfoliated granites that gave the misleading Proterozoic ages.

In addition, determining the age of eclogite rcrystallization directly from eclogites proved difficult during the early days of the debate. Eclogite minerals, with the notable exception of phengite (which was not initially recognized as a high-*P* mineral), are K-poor and early attempts at dating these minerals by K–Ar tended to result in pre-Caledonian ages, almost certainly the result of inherited excess Ar (Lux, 1985; McDougall & Green, 1964). Furthermore, K- (and Rb-) bearing minerals that did generate *c.* 405 Ma K–Ar and Rb–Sr ages, such as amphibole and biotite, were clearly secondary, so the assumption that eclogite recrystallization was a Precambrian event continued to be held by many geologists. Largely overlooked was a Scandian U–Pb age determined from zircon separated from an eclogite published by Krogh, Mysen, and Davis (1974). Unfortunately, the age was published in a Carnegie Institute yearbook that was not widely distributed among geologists. It was not until 1980 when Sm–Nd mineral isochrons from external eclogites gave relatively consistent Scandian ages (Griffin & Brueckner, 1980) that opinion gradually shifted from a Precambrian to a Caledonian origin for eclogite formation.

Eskola's assumption of a common origin for external eclogites and garnet peridotites and pyroxenites continued to delay a resolution of the in situ *v*. exotic origin of external eclogites. This issue came to a head when abstracts were presented at the annual American Geophysical Union meeting in Toronto in 1980. One abstract (Brueckner & Griffin, 1980) presented the Caledonian ages from external eclogites mentioned above. Another abstract (Jacobsen & Wasserburg, 1980) presented a Proterozoic age determined from a garnet pyroxenite. This apparent contradiction resulted in the cancellation of the oral presentation of the Proterozoic age. But all ages were correct! As already noted, ultramafic garnetiferous assemblages had a completely different history than the external eclogites. Sm–Nd and Lu–Hf results from garnet peridotites/pyroxenites invariably give Proterozoic ages (reviewed in Brueckner et al., 2010) except in the northwest corner of the WGR where, locally, third-generation garnet gives Scandian ages (Spengler, Brueckner, van Roermund, Drury, & Mason, 2009). The Proterozoic ages confirmed what many suspected based on the contrasting peak *P–T* calculations, contrasting core to rim variations in Mg and Fe, and contrasting isotopic values discussed above. Ultimately it became clear that garnet peridotites and pyroxenites and eclogites underwent completely different early histories, which converged during the Scandian orogeny, but it took time for this revelation to fully sink in.

Perhaps the most significant hindrance to the deep subduction model was the assumption that only oceanic lithosphere could be subducted into the mantle, not "buoyant" continental crust. This was a keystone assumption of early Plate Tectonic theory and is still maintained by some textbooks today. A major goal of Earth scientists should be to rid the literature of this assumption. Because of it, early collision models for the Caledonides published as recently as the 1980s show or suggest (correctly) underthrusting of one continental margin beneath another (Cuthbert, Harvey, & Carswell, 1983; Jamtveit, 1987; Krogh, 1977). But they do not show the margins penetrating into the mantle. Subduction models showing mantle wedges above subducted continental crust were, however, published to explain Alpine orogenies (Butler, 1986; Platt, 1986; Wheeler, 1991) and in 1995, Chemenda published a highly persuasive subduction and eduction analogue experiment using waxes and other materials that convinced many of us to consider the idea that continental crust could subduct into and exit from the mantle. In the end, no single discovery led to acceptance of continental subduction. Instead, it gained general (but not universal) acceptance because of its geometric simplicity and plausibility. The pull exerted by subducting oceanic lithosphere should result in at least some subduction of the attached continental lithosphere, particularly where the continental crust on top of this lithosphere is thin and forms a small percentage of its total thickness and mass. It is an elegant mechanism that explains both HP/UHP metamorphism of continental crust and the introduction of mantle fragments into it (Figure 3).

Ultimately, Andersen et al. (1991) published a collision model for the Scandian orogeny showing Baltica deeply subducted into the mantle beneath Greenland with a Laurentian mantle wedge above it. We now accept that continental crust can subduct to depths of at least 150 km, and probably more (Liou, Ernst, Zhang, Tsujimori, & Jahn, 2009). However, unlike oceanic crust, it is too buoyant to remain in the mantle and so some (many? all?) return towards the surface to form HP/UHP terranes in mountain systems. Other subducted continental fragments may stall in the mantle, heat up and return as melts to underplate continents or to form late orogenic or post-orogenic granites (Brueckner, 2009; Hacker, Kelemen, & Behn, 2011).

6 | CONCLUSION

Accepting ideas that previously were rejected (i.e. accepting UHP estimates, the presence of fluids, the probability of continental subduction, etc.) took off our blindfolds and let us view the WGR eclogites and peridotites holistically rather than along specialized perspectives, which ultimately led to a reasonable consensus. We finally could visualize the general outlines of the elephant. This consensus accepts that the Mg–Cr garnet peridotites of the WGR were indeed derived from the mantle, demonstrating an "exotic mantle" origin while the external eclogites recrystallized in the crust, supporting the "in situ" model. Ironically, however, eclogite recrystallization occurred in the crust as a result of that crust being deep within the upper mantle. Equally ironic is that garnet peridotites did indeed invade continental crust from the mantle, but not by rising upward, but rather by moving laterally or downward into the underlying crust and then being carried passively upward as the crust re-emerged from the mantle. A recent twist is that diamond formed within some peridotites, but not as is normal when the peridotites were part of an ancient mantle, but later, within the subducting Baltic crust, which contaminated the peridotites with carbon-bearing fluids as the peridotites were carried passively deeper into the diamond stability field (Scambelluri et al., 2008; Spengler et al., 2009; Van Roermund et al., 2002). Thus, this late generation (Scandian) diamond formed under unusual and transient conditions, in an environment of mantle within crust within mantle.

The study of the WGR and its cargo of eclogites and garnet peridotites is far from over. Many of its puzzling features and contradictions remain, but they will gradually be resolved as our blindfolds fall away and more of this enigmatic terrane is revealed.

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This manuscript is a review of the eclogite controversy based on personal recollections, conversations with friends on both sides of the debate, and a review of the literature. It is not intended to be a comprehensive review of the geology of the Western Gneiss Region and its eclogites and peridotites. I thank M. Britt Mørk, S. Cuthbert and C. Möller for correcting my mistakes, filling gaps in my memory and providing me with important references and ideas. Most citations are from the 1960s through the 1990s when the debate was raging. More recent citations are intended to fill the gaps or to provide summaries.

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REFERENCES

Andersen, T. B., Jamtveit, B., Dewey, J. F., & Swensson, E. (1991). Subduction and eduction of continental crust: Major mechanisms during continent–continent collision and orogenic extensional collapse, a model based on the southern Norwegian Caledonides. *Terra Nova*, *3*, 303–310. https://doi.org/10.1111/j.1365-3121.1991.tb00148.x

Austrheim, H. (1987). Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth and Planetary Science Letters*, *81*, 221–232. https://doi.org/10.1016/0012-821X(87)90158-0

Bowen, N. L. (1928). Evolution of the igneous rocks. Princeton: Princeton University Press, 332 pp..

Brueckner, H. K. (1972). Interpretation of Rb–Sr ages from the Precambrian and Paleozoic rocks of southern Norway. *American Journal of Science*, *272*, 334–358. https://doi.org/10.2475/ajs.272.4.334

Brueckner, H. K. (1977). A crustal origin for eclogites and a mantle origin for garnet peridotites: Strontium isotope evidence from clinopyroxenes. *Contributions to Mineralogy and Petrology*, *60*, 1–15. https://doi.org/10.1007/BF00372847

Brueckner, H. K. (1998). Sinking intrusion model for the emplacement of garnet-bearing peridotites into continent collision orogens. *Geology*, *26*(7), 631–634. https://doi.org/10.1130/0091-7613(1998)026<0631:SIMFTE>2.3.CO;2

Brueckner, H. K. (2009). Subduction of continental crust, the origin of post-orogenic granitoids (and anorthosites?) and the evolution of Fennoscandia. *Journal of the Geological Society*, *166*, 753–762. https://doi.org/10.1144/0016-76492008-028

Brueckner, H. K., Carswell, D. A., & Griffin, W. L. (2002). Paleozoic diamonds within a Precambrian peridotite lens in UHP gneisses of the Norwegian Caledonides. *Earth and Planetary Science Letters*, *203*(3/4), 805–816. https://doi.org/10.1016/S0012-821X(02)00919-6

Brueckner, H. K., Carswell, D. A., Griffin, W. L., Medaris, L. G., Van Roermund, H. L. M., & Cuthbert, S. J. (2010). The mantle and crustal evolution of two garnet peridotite suites from the Western Gneiss Region, Norwegian Caledonides: An isotopic investigation. *Lithos*, *117*, 1–19. https://doi.org/10.1016/j.lithos.2010.01.011

Brueckner, H. K., & Griffin, W. L. (1980). Caledonian Sm–Nd ages of Norwegian eclogites. *EOS Transactions of the American Geophysical Union*, *61*, 38.

Bryhni, I., Green, D. H., Heier, K. S., & Fyfe, W. S. (1970). On the occurrence of eclogite in Western Norway. *Contributions to Mineralogy and Petrology*, *26*, 12–19. https://doi.org/10.1007/BF00373337

Bryhni, I., & Griffin, W. L. (1971). Zoning in eclogite garnets from Nordfjord, West Norway. *Contributions to Mineralogy and Petrology*, *32*, 112–125. https://doi.org/10.1007/BF00383054

Butler, R. W. H. (1986). Thrust tectonics, deep structure and crustal subduction in the Alps and Himalayas. *Journal of the Geological Society, London*, *143*, 857–873. https://doi.org/10.1144/gsjgs.143.6.0857

Carswell, D. A. (1986). The metamorphic evolution of Mg–Cr type Norwegian garnet peridotites. *Lithos*, *19*, 279–297. https://doi.org/10.1016/0024-4937(86)90028-9

Carswell, D. A., Harvey, M. A., & Al-Samman, A. (1983). The petrogenesis of contrasting Fe–Ti and Mg–Cr garnet peridotite types in the high grade gneiss complex of western Norway. *Bulletin de Mineralogie*, *106*, 727–750.

Carswell, D. A., Krogh, E. J., & Griffin, W. L. (1985). Norwegian orthopyroxene eclogites: Calculated equilibration conditions and petrogenetic implications. In D. G. Gee, & B. A. Sturt (Eds.), The Caledonide Orogen–Scandinavia and related areas (pp. 823–842). Chichester: Wiley.

Compagnoni, R. (1977). The Sesia-Lanzo Zone: High pressure-low temperature metamorphism in the Austroalpine Continental Margin. *Rendiconti della Societa Italiana di Mineralogia e Petrologia*, *33*, 335–374.

Cuthbert, S. J., & Carswell, D. A. (1982). Petrology and tectonic setting of eclogites and related rocks from the Dalsfjord area, Sunnfjord, west Norway. *Terra Cognita*, *2*, 315–316.

Cuthbert, S. J., Carswell, D. A., Krogh-Ravna, E. J., & Wain, A. (2000). Eclogites and eclogites in the Western Gneiss Region, Norwegian Caledonides. *Lithos*, *52*, 165–195. https://doi.org/10.1016/S0024-4937(99)00090-0

Cuthbert, S. J., Harvey, M. A., & Carswell, D. A. (1983). A tectonic model for the metamorphic evolution of the Basal Gneiss Complex, western south Norway. *Journal of Metamorphic Geology*, *1*, 63–90. https://doi.org/10.1111/j.1525-1314.1983.tb00265.x

Dobrzhinetskaya, L. F., Eide, E. A., Larsen, R. B., Sturt, B. A., Trønnes, R. G., Taylor, W. R., … Posukhova, T. V. (1995). Microdiamonds in high–grade metamorphic rocks of the Western Gneiss region, Norway. *Geology*, *23*, 597–600. https://doi.org/10.1130/0091-7613(1995)023<0597:MIHGMR>2.3.CO;2

Eskola, P. (1920). The mineral facies of rocks. *Norsk Geologisk Tidsskrift*, *30*(6), 1–52.

Eskola, P. (1921). On the eclogites of Norway. *Videnskapsselskapets Skrifter. I. Mathematisk–naturvidenskabelig Klasse*, *8*, 1–121.

Gardner, M. (1995). Famous poems from bygone days. Mineola, NY: Courier Dover Publications, 124 pp. ISBN 978-0-486-28623-5.

Gjelsvik, T. (1952). Metamorphosed dolerites in the gneiss area of Sunnmøre. *Norsk Geologisk Tidsskrift*, *30*, 33–134.

Griffin, W. L. (1987). 'On the eclogites of Norway'-65 years later. *Mineralogical Magazine*, *51*, 333–343. https://doi.org/10.1180/minmag.1987.051.361.01

Griffin, W. L., & Brueckner, H. K. (1980). Caledonian Sm–Nd ages and a crustal origin for Norwegian eclogites. *Nature*, *285*, 319–321. https://doi.org/10.1038/285319a0

Hacker, B. R., Andersen, T. B., Johnston, S., Kylander-Clark, A. R. C., Peterman, E. M., Walsh, E. O., … Young, D. (2010). High–temperature deformation during continental–margin subduction and exhumation: The ultrahigh–pressure Western Gneiss Region of Norway. *Tectonophysics*, *480*(1–4), 149–171. https://doi.org/10.1016/j.tecto.2009.08.012

Hacker, B. R., Kelemen, P. B., & Behn, M. D. (2011). Differentiation of the continental crust by relamination. *Earth and Planetary Science Letters*, *307*, 501–516. https://doi.org/10.1016/j.epsl.2011.05.024

Jacobsen, S. B., & Wasserburg, G. J. (1980). Nd and Sr isotopes of the Norwegian garnet peridotites and eclogites. *EOS Transactions of the American Geophysical Union*, *61*, 389.

Jamtveit, B. (1987). Metamorphic evolution of the Eiksunddal eclogite complex, and some tectonic implications. Sunmøre, western Norway. *Contributions to Mineralogy and Petrology*, *95*, 82–99. https://doi.org/10.1007/BF00518032

Krogh, E. J. (1977). Evidence of Precambrian continent–continent collision in Western Norway. *Nature*, *267*, 17–19. https://doi.org/10.1038/267017a0

Krogh, E. J. (1980). Compatible *P–T* conditions for eclogites and surrounding gneisses in the Kristiansund Area, Western Norway. *Contributions to Mineralogy and Petrology*, *75*, 387–393.

Krogh, E. J. (1982). Metamorphic evolution of Norwegian country rock eclogites, as deduced from mineral inclusions and compositional zoning in garnets. *Lithos*, *15*, 305–321. https://doi.org/10.1016/0024-4937(82)90021-4

Krogh, T. E., Mysen, B. O., & Davis, G. L. (1974). A Paleozoic age for the primary minerals of a Norwegian eclogite. *Carnegie Institute Washington Yearbook*, *73*, 575–576.

Kylander-Clark, A. R. C, Hacker, B. R., Johnson, C. M., Beard, B. L., & Mahlen, N. I. (2009). Slow subduction of a thick ultrahigh–pressure terrane. *Tectonics*, *28*, TC2003. https://doi.org/10.1029/2007tc002251

Labrousse, L., Jolivet, L., Agard, P., Hébert, R., & Andersen, T. B. (2002). Crustal–scale boudinage and migmatization of gneiss during their exhumation in the UHP province of Western Norway. *Terra Nova*, *14*, 263–270. https://doi.org/10.1046/j.1365-3121.2002.00422.x

Lappin, M. A.Discussion; Krogh, E. J., Reply (1977). Crustal and *in situ* origin of Norwegian eclogites. *Nature*, *269*, 730. https://doi.org/10.1038/269730a0

Lappin, M. A., & Smith, D. C. (1978). Mantle–equilibrated orthopyroxene eclogite pods from the Basal Gneisses in the Selje District, Western Norway. *Journal of Petrology*, *19*(3), 530–584. https://doi.org/10.1093/petrology/19.3.530

Liou, J. G., Ernst, W. G., Zhang, R. Y., Tsujimori, T., & Jahn, B. T. (2009). Ultrahigh–pressure minerals and metamorphic terranes – The view from China. *Journal of Asian Earth Sciences*, *35*, 199–231. https://doi.org/10.1016/j.jseaes.2008.10.012

Lux, D. R. (1985). K–Ar ages from the Basal Gneiss Region, Stadlandet area, Western Norway. *Norsk Geologisk Tidsskrift*, *65*, 277–286.

McDougall, I., & Green, D. H. (1964). Excess radiogenic argon and isotopic ages on minerals from Norwegian eclogites. *Norsk Geologisk Tidsskrift*, *44*, 183–196.

Mearns, E. W. (1986). Sm-Nd ages for Norwegian garnet peridotite. *Lithos*, *19*, 269–278. https://doi.org/10.1016/0024-4937(86)90027-7

Medaris, L. G. (1980a). Petrogenesis of the Lien peridotite and associated eclogites, Almklovdalen, Western Norway. *Lithos*, *13*, 339–353. https://doi.org/10.1016/0024-4937(80)90053-5

Medaris, L. G. (1980b). Convergent metamorphism of eclogite and garnet–bearing ultramafic rocks at Lien, West Norway. *Nature*, *283*, 470–472. https://doi.org/10.1038/283470a0

Mørk, M. B. E. (1985). A gabbro to eclogite transition on Flemsøy, Sunnmøre, west Norway. *Chemical Geology*, *50*, 283–310. https://doi.org/10.1016/0009-2541(85)90125-1

Mørk, M. B. E., & Mearns, E. W. (1986). Sm–Nd isotopic systematics of a gabbro–eclogite transition. *Lithos*, *19*, 255–267. https://doi.org/10.1016/0024-4937(86)90026-5

Mysen, B. O., & Heier, K. S. (1972). Petrogenesis of eclogites in high-grade metamorphic gneisses exemplified by the Hareidland eclogite, west Norway. *Contributions to Mineralogy and Petrology*, *36*, 73–94. https://doi.org/10.1007/BF00372836

O'Hara, M. J., & Mercy, E. L. P. (1963). Petrology and petrogenesis of some garnetiferous peridotites. *Transactions of the Royal Society Edinburgh*, *6*(12), 251–314. https://doi.org/10.1017/S0080456800038424

Platt, J. P. (1986). Dynamics of orogenic wedges and the uplift of high–pressure metamorphic rocks. *Geological Society of America Bulletin*, *97*, 1037–1053. https://doi.org/10.1130/0016-7606(1986)97<1037:DOOWAT>2.0.CO;2

Sanders, I. S. (1979). Observations on eclogite- and granulite-facies rocks in the basement of the Caledonides. In A. L. Harris, C. H. Holland & B. E. Leake (Eds.), Caledonides of the British Isles-reviewed. *Special Publication of the Geological Society of London*, *8*, 97–100.

Scambelluri, M., Pettke, T., & van Roermund, H. L. M. (2008). Majoritic garnets monitor deep subduction fluid flow and mantle dynamics. *Geology*, *36*, 59–62. https://doi.org/10.1130/G24056A.1

Schmidt, H. H. (1963). Petrology and structure of the Eiksunddal eclogite complex. Hareidlandet, Sunnmare, Norway. Unpublished Ph.D. thesis. Harvard University, USA.

Smith, D. C. (1984). Coesite in clinopyroxene in the Caledonides and its implication for geodynamics. *Nature*, *310*, 641–644. https://doi.org/10.1038/310641a0

Spengler, D., Brueckner, H. K., van Roermund, H. L. M., Drury, M. R., & Mason, P. R. D. (2009). Long-lived cold burial of Baltica to 200 km depth. *Earth and Planetary Science Letters*, *281*, 27–35. https://doi.org/10.1016/j.epsl.2009.02.001

Van Roermund, H. L. M., Carswell, D. A., Drury, M. R., & Heijboer, T. C. (2002). Micro–diamonds in a megacrystic garnet-websterite pod from Bardane on the island of Fjørtoft, western Norway: Evidence for diamond–formation. *Geology*, *30*, 959–962. https://doi.org/10.1130/0091-7613(2002)030<0959:MIAMGW>2.0.CO;2

Vrijmoed, J. C., Van Roermund, H. L. M., & Davies, G. R. (2006). Evidence for diamond–grade ultra-high pressure metamorphism and fluid interaction in the Svartberget Fe-Ti garnet peridotite-websterite body, Western Gneiss Region, Norway. *Mineralogy and Petrology*, *88*, 381–405. https://doi.org/10.1007/s00710-006-0160-6

Wain, A. L. (1997). New evidence for coesite in eclogite and gneisses: Defining an ultrahigh pressure province in the Western Gneiss Region of Norway. *Geology*, *25*, 927–930. https://doi.org/10.1130/0091-7613(1997)025<0927:NEFCIE>2.3.CO;2

Wheeler, J. (1991). Structural evolution of a subducted continental sliver; the northern Dora Maira massif, Italian Alps. *Journal of the Geological Society, London*, *148*, 1101–1113. https://doi.org/10.1144/gsjgs.148.6.1101

Yoder, H. S., & Tilley, C. E. (1962). Origin of basalt magmas: An experimental study of natural and synthetic rock systems. *Journal of Petrology*, *3*, 342–529. https://doi.org/10.1093/petrology/3.3.342

Young, D. J. (2017). Structure of the (ultra)high–pressure Western Gneiss Region, Norway: Imbrication during Caledonian continental margin subduction. *Bulletin of the Geological Society of America*. https://doi.org/10.1130/b31764.1; 5 figures; Data Repository item 2017308.

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