Rocks explained 4

Eclogites

The beauty of an eclogite is something to behold: any petrologist marvels in the combination of red garnet and green omphacite that are the main mineral constituents of the rock. But besides their stunning appearance, there is much more to eclogites: fundamental concepts in metamorphic petrology and geodynamics were developed based on scientific investigations of eclogites. It is well established that they derive from precursor rocks of basaltic composition and form under high-pressure conditions at more than c. 45 km depth, but other aspects of their occurrences and geological significance remain debated. The relative scarcity of eclogites among crustal rocks renders them largely unknown to the layperson, so following the 200th anniversary of the term eclogite in 2022, there is an opportunity to take a closer look at this fascinating rock.

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The name eclogite was coined by the French mineralogist René Just Haüy (1743–1822), known as the 'Father of Crystallography' (Fig. 1). The term eclogite means 'chosen rock', a thoroughly deserved denomination, which Haüy based on the peculiar binary mineral assemblage of garnet and clinopyroxene, described in his *Traité de minéralogie*. Yet before Haüy, eclogites were described by various other geologists but with different names. Horace-Bénédict de Saussure observed the Lac Cornu eclogite in the French Western Alps and the German geologist Abraham Gottlob Werner described eclogites in the Austrian Alps and Bavaria.

But what is an eclogite? Eclogite is a metamorphic rock. Hence it is a rock that underwent changes in mineral content, mineral composition and structure compared with its precursor, or protolith. These changes occur in the solid state as the rock adjusts to physical conditions within Earth's crust that are different to those under which the rock originally formed and different to those at Earth's surface. The IUGS Subcommission on the Systematics of Metamorphic Rocks defines the rock eclogite as follows: '*plagioclase-free metamorphic rock composed of ≥75 percent vol. of omphacite and garnet, both of which are present as major constituents, the amount of neither of them being higher than 75 percent vol*'. This definition is primarily based on the hand specimen appearance (Fig. 2). Omphacite is a clinopyroxene, green in colour, which forms a solid solution between augite [$Ca(Mg,Fe)Si_2O_6$], jadeite [$NaAlSi_2O_6$] and aegirine [$NaFe^{3+}Si_2O_6$]. Other minerals, such as quartz, rutile, kyanite, phengite, amphibole and zoisite may be present, but they are not essential for the definition of eclogite (Figs 2, 3). Metamorphic rocks that contain both garnet and omphacite, but in smaller amounts than required for the definition of eclogite, are referred to as eclogitoids.

Studies of eclogites intensified at the end of the nineteenth century with the use of the petrographic microscope. Laura Hezner, a German geologist and the first woman to obtain a habilitation at the renowned *Eidgenössische Technische Hochschule* Zürich, studied eclogites from the Austrian Alps and noted that the mineralogical characteristics of eclogites compared with amphibolites (rocks primarily composed of hornblende and plagioclase) are due to differences in formation depth and pressure. The petrologist Friedrich Becke found that the mineral assemblages in eclogites have a lower molar volume than those in gabbros, concluding that eclogite is a high-pressure equivalent of gabbro as denser minerals should form at higher pressures. As the first geochemical analyses of eclogites became available and demonstrated a composition similar to gabbros, the origin of these rocks was debated at the beginning of the twentieth century: are eclogites magmatic or metamorphic in origin? In 1920, Yvonne Brière, a student of the French mineralogist Alfred Lacroix, established in her doctoral thesis on eclogites in Western France that the chemical trends observed in eclogites follow the tholeiitic differentiation trend observed in magmatic rocks, concluding that eclogites represent metamorphosed gabbros. Experimental confirmation that eclogites are high-pressure equivalents of gabbros was obtained in 1967 by the work of David Green and Alfred Ringwood in Australia. Field observations of pillow structures, which are typical for basalts erupted on the ocean floor at Earth's surface, preserved in eclogites from Switzerland and Corsica, provided further evidence for the eclogites' metamorphic origin.

If you are wondering why you rarely see eclogites, it may well be related to their relative scarcity. In the United Kingdom, for instance, there is only one eclogite occurrence, in Glenelg in north-western Scotland (Fig. 3). To be reached after a good four and a half hours drive from Glasgow, even geology field courses would rarely attempt to make a detour to visit this location. Eclogites are not commonly used as aggregates or building stones, and despite their beautiful colours they are also not often seen as decorative stones. One of the world's only buildings made of eclogite, a lookout built in 1925, can be found on the Weißenstein near Münchberg (Bavaria), Germany's most significant eclogite occurrence (Fig. 2).


Fig. 1. Statue of René Just Haüy, made by Isidore Hippolyte Brion, at the *Muséum national d'Histoire naturelle* (National Museum of Natural History) in Paris.

Eclogites and the eclogite facies

In any conversation with a metamorphic geologist the term 'metamorphic facies' will come up sooner or later, and it warrants a word of explanation before evaluating the role of eclogites any further. The concept of metamorphic facies, established by the Finnish geologist Pentti Eskola in the early twentieth century, is a fundamental concept in metamorphic petrology. A 'facies' refers to a certain mineral assemblage that depends on the specific metamorphic conditions, primarily defined through pressure and temperature (*P*–*T*). Eskola established the facies concept based on rocks of basaltic composition. As the metamorphic conditions change, different mineral assemblages will develop. This relationship between the bulk chemistry of the rock and its mineral content is systematic and a function of the metamorphic conditions. The metamorphic facies cover a wide range of crustal *P*–*T* conditions that are relevant for crustal metamorphism (Fig. 4).

At high pressure (>1.2 GPa, corresponding to c. 45 km depth) and medium to high temperatures (>450°C), the eclogite facies comprises the widest *P*–*T* region of any of the metamorphic facies (Fig. 4). Under these conditions, a rock of basaltic or gabbroic bulk chemistry will form garnet and omphacite, hence it will become an eclogite. The stability of these minerals in an eclogite defines the boundaries of the eclogite facies. Following a subduction geotherm that illustrates the temperature increase with depth of an oceanic plate descending beneath continental crust, the blue amphibole glaucophane and the white mica paragonite, which are stable together in the blueschist facies, will react to form garnet and omphacite at the transition toward the eclogite facies. Typical eclogite assemblages form at c. 1.4 GPa and corresponding temperatures of c. 500°C.

During collision tectonics, when two continental plates collide and form mountain ranges as the crust is compressed and thickened, rocks would follow a warmer geotherm, and the mineralogical change from the assemblage plagioclase + hornblende to omphacite + garnet will take place with increasing pressure. The reaction that defines the boundary between amphibole and granulite facies on the low-pressure side versus eclogite facies on the high-pressure side is albite = jadeite + quartz. This reaction delineates the boundary between plagioclase-present and plagioclase-absent regions in *P*–*T* space, and the jadeite produced will be incorporated into the omphacitic clinopyroxene in the eclogite mineral assemblage. Note, however, that not all protoliths will become 'eclogites' in the eclogite facies, as the facies are defined based on a basaltic or gabbroic bulk composition.

Eclogite-facies rocks, on the other hand, comprise any metamorphic rock that equilibrated under eclogite-facies *P*–*T* conditions. These can include rocks that contain some garnet and omphacite, but not in the amount seen in metamorphosed basalts or

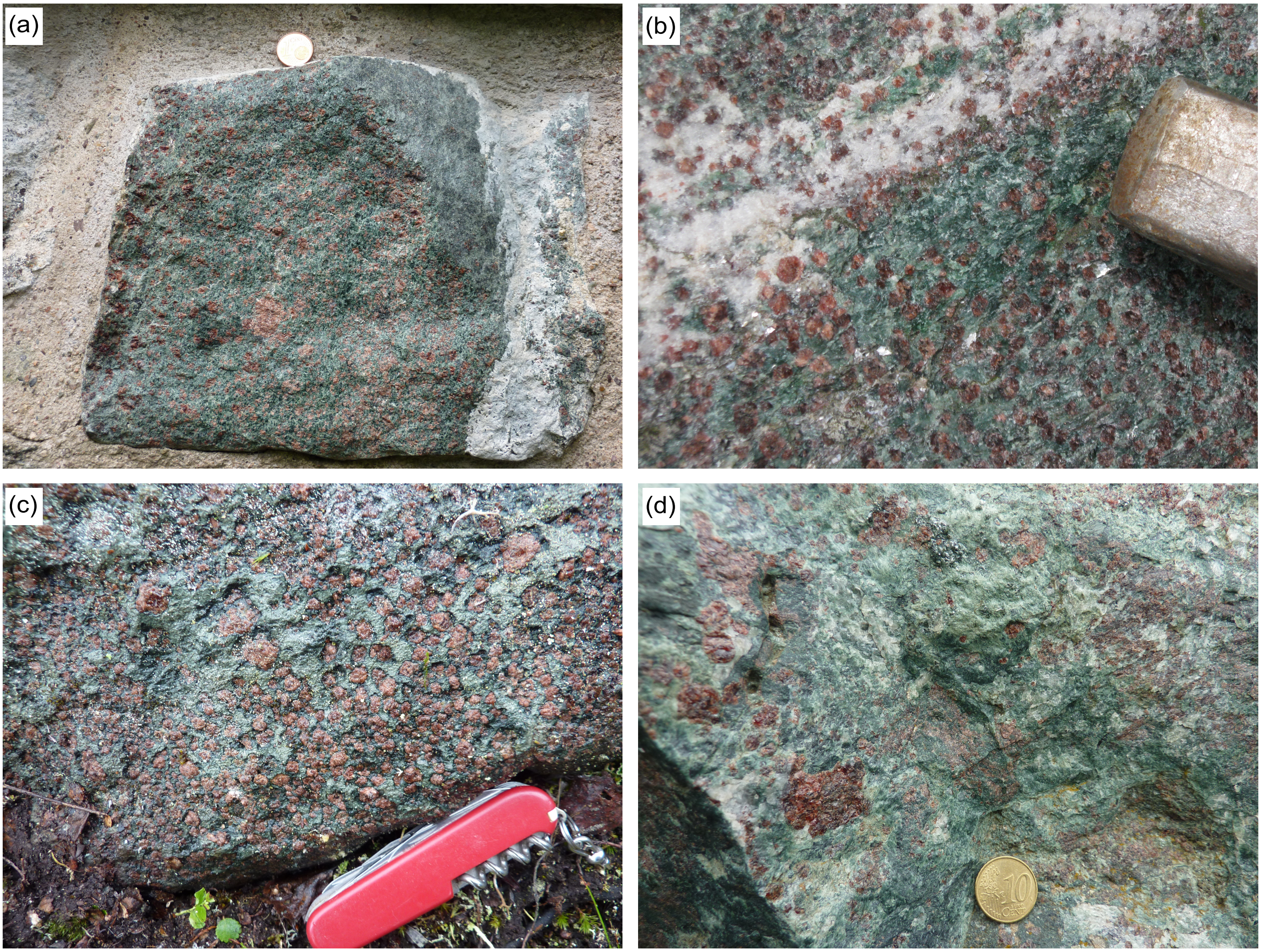

Fig. 2. Field occurrences of eclogite. (**a**) Block of eclogite from the Münchberg Gneiss Massif (Bavaria, Germany) in the lookout on the Weiβenstein, perhaps the only building in the world made of eclogite. (**b**) Eclogite from the Western Gneiss Region (Nordfjord, Norway) with bright green omphacite, red garnet and white bands composed of quartz and zoisite. Photo courtesy of Franziska Scheffler. (**c**) Eclogite from the Seve belt (Jämtland, Sweden) with retrograde amphibole forming around garnet crystals. (**d**) Eclogite from the Monviso metaophiolite, Western Alps (Italy).

gabbros. The eclogitic micaschists of the Sesia Zone (Italy), which have mudstones as protoliths, illustrate this point. Other lithologies form unique high-pressure mineral assemblages in the eclogite facies due to unusual bulk compositions. Whiteschists, with the characteristic mineral assemblage kyanite + talc, are unusually rich in Mg and Al and exclusively form under high-pressure. Other lithologies are unlikely to form minerals characteristic of high-pressure conditions during subduction, such as limestones and quartz-rich sandstones that will become eclogite-facies marble and quartzite, respectively. Collectively, eclogite-facies rocks are a rich source of knowledge with respect to high-pressure metamorphism, but the focus here shall be proper eclogites.

Eclogites and eclogites: different eclogite types in distinct geological settings

Already in 1931, the British geologist Arthur Holmes proposed that eclogites form in zones of ‘subsidence’. This concept, taking into account the high density of the eclogites, preconfigures our modern understanding of geodynamics following the plate tectonic revolution in the 1960s–1970s. Now, with contributions from experimental petrology and thermodynamic calculations, we know that eclogite is a high-pressure metamorphic rock and that basaltic oceanic crust forms eclogites during subduction. However, metamorphic rocks from subduction zones are not the only lithological association where eclogites can be found. In 1965, the American geologist Robert Coleman defined three distinct types of eclogites based on geologically similar occurrences (Fig. 5). Each of these types has its very own fascinating story, all of which are fundamental in shaping our view of the Earth today.

During subduction, oceanic crust, comprising basaltic lavas and gabbroic intrusive rocks, transforms into eclogites at depths > c. 45 km (Fig. 5). Following exhumation through subsequent tectonic processes, these eclogites typically occur as bands and lenses, often as

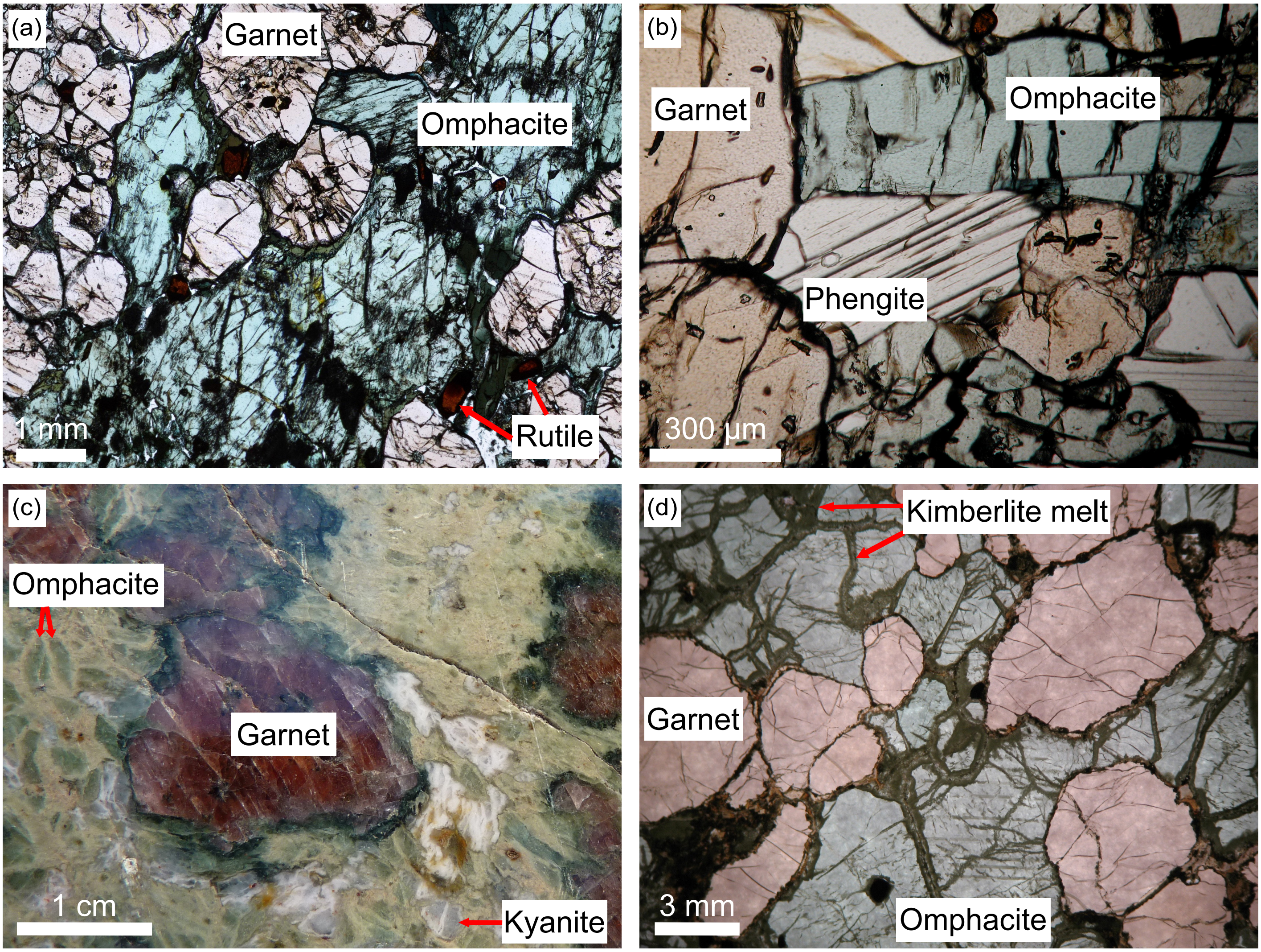

Fig. 3. Eclogites in polished sections and thin sections. (**a**) Eclogite from Glenelg (Scotland). Pink garnet and light green omphacite are the major minerals, brown rutile occurs as accessory mineral, and dark green amphibole replaces omphacite. (**b**) Eclogite from the Raspas Complex (Ecuador) with garnet, omphacite and phengite. The protolith is a mid-ocean ridge basalt. (**c**) La Compointrie eclogite (La Piltière, Saint-Philbert-de-Grand-Lieu, France), a Mg-rich eclogite with red garnet, bluish kyanite and emerald-green omphacite surrounded by a matte greenish matrix. Retrogression is indicated by pseudomorphs after kyanite (white spots) and amphibole-rich coronas around garnet. The protolith is a cumulate of a tholeiitic differentiation sequence (olivine leucogabbro). (**d**) Eclogite xenolith from the Koidu kimberlite cluster (Sierra Leone). During ascent of the xenolith in the kimberlite melt, decompression causes the minerals to crack, which facilitates melt infiltration and alteration that can be seen as the dark green material (Photo courtesy of Sonja Aulbach).

isolated blocks, associated with metamorphic rocks characteristic of subduction zone metamorphism, such as blueschists and serpentinites (Fig. 6). Examples of this first type of eclogite include occurrences in California (USA), Syros (Greece), New Caledonia, Guatemala, the Western Alps (Switzerland/Italy) and Corsica (France). Pseudotachylites, fine-grained rocks that form through frictional melting, which occur in these eclogites record deep earthquake processes in the subduction zone. The most significant change in physical properties during the transformation from gabbro/basalt to eclogite is the change in density from c. 3.0 g/cm^3 in gabbro to >3.3 g/cm^3 in eclogite. This densification of the subducted oceanic crust drives plate tectonic processes on Earth and is known as slab pull, the gravitational force on the cold and dense plate being subducted. Hence, the formation of eclogites is a fundamental premise for plate tectonic processes on Earth, which sets it apart from all other planetary bodies in our solar system.

A second type of eclogite forms in collisional orogenic belts from amphibolites or granulites. They occur as bands or lenses within gneissic terranes (Fig. 6), and examples include occurrences in the Western Gneiss region (Norway) and the Dabie orogen

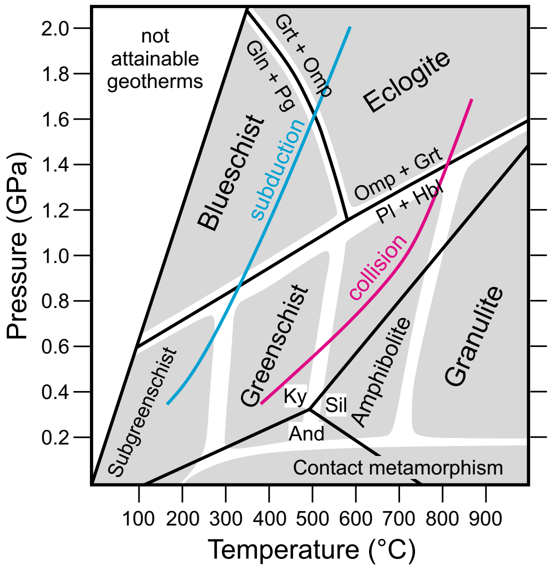

Fig. 4. Metamorphic facies diagram based on assemblages of metabasaltic rocks with representative geotherms for subduction and collision. The geotherms are curves that show the increase in temperature with depth within the Earth, and their position depends on the geotectonic setting. Key reactions that defined the boundaries of the eclogite facies are indicated (Grt = garnet, Omp = omphacite, Gln = glaucophane, Pg = paragonite, Pl = plagioclase, Hbl = hornblende). Phase transitions of the aluminosilicates (Al_2SiO_5) are given for comparison (Ky = kyanite, Sil = sillimanite, And = andalusite) (modified from Bucher and Grapes 2011).

(China). In these continent–continent collision settings, the continental crust thickens and as a result, mafic rocks in the deeper part of the crust transform into eclogites (Fig. 5). A feature that has puzzled geologists is the stark contrast between the high-pressure mineral assemblages preserved in eclogites compared with the felsic gneisses and migmatites (metamorphic rocks that have undergone partial melting), which typically show medium-pressure amphibolite-facies assemblages. There is now consensus regarding the origin of these eclogite pods in the felsic crust in favour of formation within the crust as opposed to tectonic emplacement. The lack of high-pressure mineral assemblages in the felsic rocks is influenced by bulk composition and reactivity of the rocks as well as residence time at depth and availability of fluid to facilitate the transformation. Findings of coesite (a high-pressure polymorph of quartz) and microdiamond, minerals that indicate ultrahigh-pressure conditions of >2.5 GPa, within gneisses surrounding the eclogites provided evidence from several terranes that the host gneisses indeed reached eclogite-facies conditions. Whether the bulk of felsic crust resisted transformation or transformed pervasively during exhumation so that no or few remnants of the peak mineralogy are preserved is still debated, but it seems clear that the low density of the felsic lithologies aided in the exhumation of the denser eclogites within them.

Whereas the first two eclogite groups are related to orogenic events, the third group has an entirely different mode of occurrence. Eclogites in this group, often termed ‘mantle eclogites’ occur as xenoliths (fragments of ‘foreign rock’ in the host magma) in kimberlites (mantle-derived ultramafic rocks that typically occur in vertical pipes) and basalts (Fig. 6). It was disputed for a long time whether these mantle eclogites crystallize directly from a magma in the mantle or whether they represent subducted basaltic material. Several lines of geochemical evidence point toward a derivation from recycled and metamorphosed basaltic ocean crust that formed at low pressures at or near Earth’s surface. This includes evidence for seafloor alteration in the protoliths based on fractionated stable isotope ratios that can only develop at low temperatures and evidence that the protoliths formed by melting at relatively shallow depths based on relatively flat rare earth element (REE) patterns that indicate a garnet-free mantle source. Moreover, relative enrichments of certain trace elements (e.g. Eu, Sr, Pb) that are preferentially hosted in plagioclase are observed. This is consistent with accumulation of plagioclase in the protolith, a feature typical of oceanic gabbros. As the consensus emerges that most mantle eclogites have an origin as

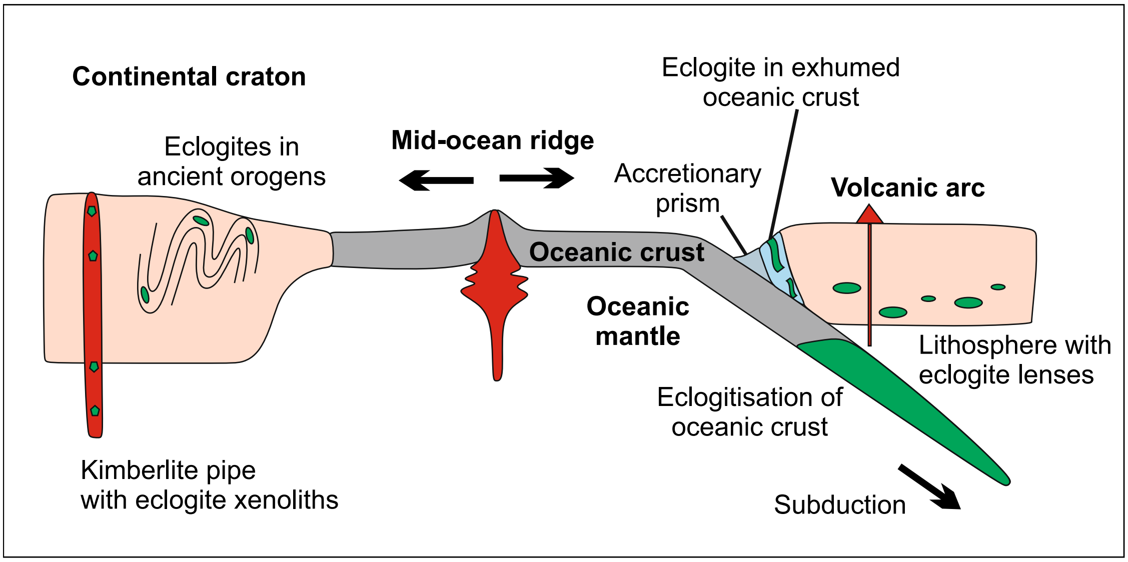

Fig. 5. Sketch illustrating the geodynamic settings of eclogite occurrences (not to scale). Inspired by a figure in Aulbach and Arndt (2019).

basaltic/gabbroic rocks at oceanic spreading ridges, that still leaves researchers with the considerable task to disentangle their complex history from magmatic differentiation during formation at the spreading ridge via seafloor alteration to subduction zone metamorphism with associated dehydration and melting, residence in the cratonic lithosphere and entrainment in the host kimberlite/basalt magma. Enthralling detective work on mantle eclogites has led to important constraints on their protoliths, which formed more than 2.6 billion years ago from a convecting mantle warmer by 100°C–150°C than the modern mantle and already geochemically affected by significant amounts of melt extraction.

Eclogites through time

Eclogites and eclogite-facies rocks represent high-pressure to ultrahigh-pressure (UHP) metamorphic conditions, characterized by a relatively low geothermal gradient and the deep subduction of crust (oceanic and continental). Eclogites have therefore been used to indicate modern-style plate tectonics with deep subduction and lateral motion of rigid plates. Since formation of the Earth 4.567 billion years ago, there is consensus that the geodynamic processes have changed through time from a warmer toward a colder regime in relation to the secular cooling of the planet. Metamorphic rocks representing low temperature – high pressure metamorphic conditions typical of the modern, cold subduction are widespread since the Neoproterozoic (1.0–0.54 Ga) and useful to trace geodynamic changes on Earth. Similarly, UHP rocks, characterized by coesite or diamond, occur predominantly in the Phanerozoic. The geological record from early Earth is more sketchy, and therefore it is debated when modern-style plate tectonics started and replaced stagnant-lid tectonics and flat subduction that are thought to have been dominant on early Earth.

Evaluating the secular change of metamorphic rocks associated with subduction and collisional orogenesis at convergent plate margins provides a framework to establish geodynamic changes. On balance, geological evidence and geodynamic modelling point toward the emergence of widespread subduction and plate tectonic processes by the late Archean to the early Proterozoic. This is consistent with the absence of eclogites before the late Mesoarchean (3.2–2.8 Ga). Mantle eclogites from Siberia and southern Africa record eclogitisation ages of 2.9 billion years. The oldest orogenic eclogites with geochemical characteristics of basaltic ocean crust show ages for eclogite-facies metamorphism clustering between 2.1 and 1.8 billion years. They include occurrences in the Congo Craton, the Belomorian Massif on the Fennoscandian Shield and the Trans-Hudson orogen of the Canadian Shield. For some of those, ages for the formation of the magmatic protoliths are similar to the oldest mantle eclogite ages. These constraints from the eclogites are consistent with a major change in the Earth's tectonic regime between 3.0 and 2.5 Ga and widespread cold and deep subduction since at least the Palaeoproterozoic (2.5–1.6 Ga).

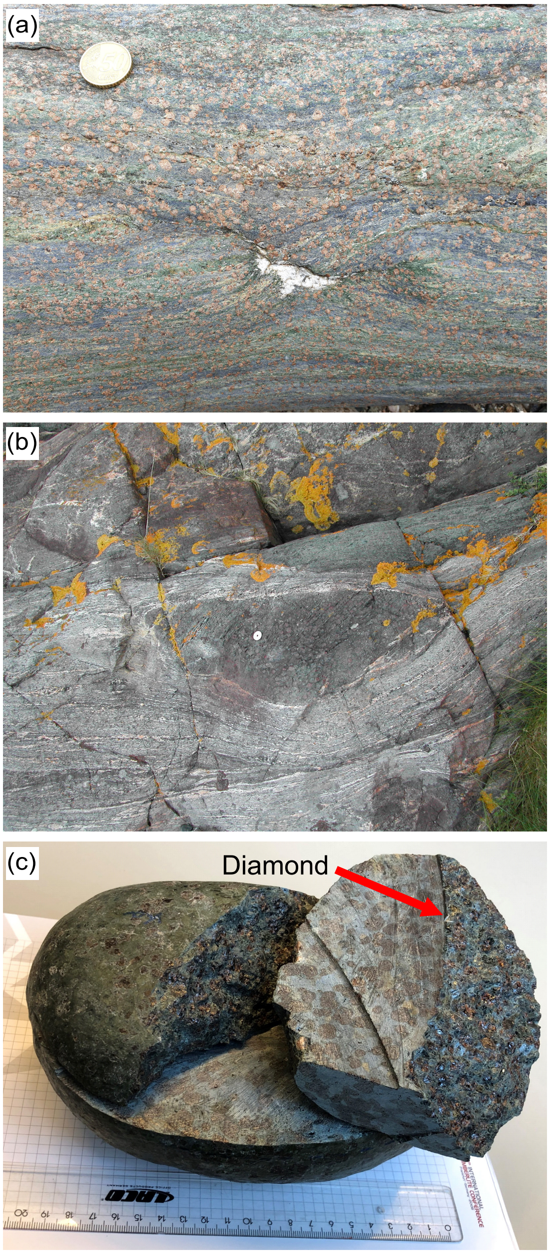

Fig. 6. Typical occurrences of the three different eclogite types. (**a**) Bands of eclogite interlayered with blueschist (Ile de Groix, Brittany, France). (**b**) Eclogite boudin in felsic gneiss (Otrøy, Western Gneiss Region, Norway). Photo courtesy of Dirk Spengler. (**c**) Exceptionally large eclogite xenolith with reddish garnet crystals in a matrix of greenish clinopyroxene (Koidu kimberlite complex, West African craton, Sierra Leone). This xenolith contains a c. 5 mm large diamond crystal (red arrow) (Photo courtesy of Sonja Aulbach).

How eclogites change our understanding of metamorphism

Eskola's concept of the metamorphic facies uses the assumption that pressure and temperature are the key parameters to determine the mineralogy of

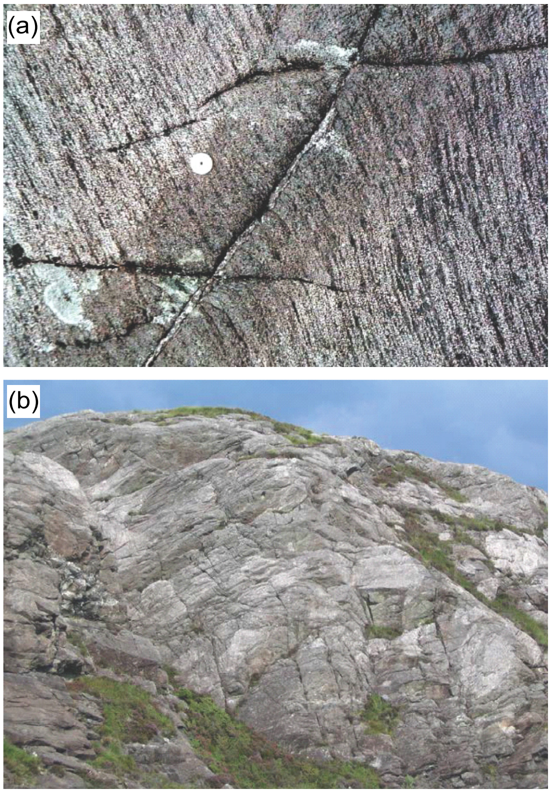

Fig. 7. Influence of fluid infiltration facilitating formation of eclogite (Bergen Arcs, Norway). (**a**) Fluid infiltration along a crack, causing eclogite formation in the host granulite. (**b**) Large scale shear zone with brecciation where dark areas have been eclogitised whereas light blocks represent remnants of the host granulite. Outcrop height c. 80 m (Photo courtesy of Uwe Altenberger).

a metamorphic rock of a specific composition. The rock-forming minerals reflect thermodynamic equilibrium during peak metamorphism and are preserved during exhumation. Although these assumptions have been very useful in studying metamorphic rocks, eclogites have played and continue to play a major role in challenging these assumptions.

The Bergen Arcs in western Norway, an area of thrust sheets that formed during the Caledonian orogeny around 430–410 million years ago, have been shown to constitute an extremely prolific area to study the transformation of Precambrian granulites into Caledonian eclogites. It is, in particular, the role of hydrous fluids and their effect on metamorphic reactions that has revolutionized metamorphic petrology. In his seminal study from 1987, the Norwegian geologist Håkon Austrheim noted that the formation of eclogites is not caused by changes in pressure–temperature conditions, but instead it is initiated by fluid infiltration along cracks. Field evidence clearly showed that the introduction of hydrous fluids is required to catalyse the reactions to form an eclogitic mineral assemblage and recrystallisation to eclogite (Fig. 7). Without fluid addition, metamorphic reactions are inhibited and the dry rocks retain their granulite-facies mineralogy. Here, fluids act as a catalyst. Their presence makes the metamorphic reactions many orders of magnitude faster and drives metamorphism. Importantly, the fluid-controlled eclogite formation affects the overall density of the deep crust and therefore its buoyancy and exhumation. Even when pressure and temperature conditions in the deep crust are within the eclogite facies, a granulite facies mineral assemblage may persist in dry crustal rocks for extended periods of geological time.

The pathways for the fluids in the deep crust are provided by earthquakes. As cracks open and minerals are pulverized, material transport is enhanced and the rock transformation from granulite into eclogite can proceed. The fluid infiltration not only has a catalysing effect on the eclogitisation process, but it also weakens the rock and can cause local pressure differences between reacted and unreacted rock. If the pressure is higher than the lithostatic pressure from the overlying rocks, overpressure is created. This overpressure, a significant deviation from the lithostatic pressure, is a phenomenon that has become a contentious issue in metamorphic petrology in recent years. The transition between granulite and eclogite in the Bergen Arcs provides outcrop and grain-scale evidence for variations in pressure, resulting in the juxtaposition of eclogite and granulite-facies rocks at the same depth and temperature conditions. In other words, the observed pressure perturbations contribute to the formation of eclogites at shallower depth than suggested from solely lithostatic pressure.

The findings that have been made by field-based studies of eclogites demonstrate their unique potential as a means to investigate geological processes at several tens of kilometres depth, regions that are otherwise inaccessible for geologists. The wealth of information that can be extracted from careful petrological studies using modern analytical equipment, supplemented by information derived from experiments, geophysical methods and modelling is astonishing, and there can be no doubt that much more is still to be discovered by future geoscientists.

Extraterrestrial eclogites

With subduction being a unique characteristic of Earth's plate tectonic regime, one would not expect that eclogites feature on other planetary bodies. Yet, eclogitic clasts with omphacite and garnet have been reported from meteorites. Pressure–temperature conditions determined for these clasts of ~3 GP and ~1000°C and the equilibration of elements between different minerals suggest that high-pressure conditions were sustained for some time (~100–1000 years), a scenario that cannot be reconciled with shock metamorphism. A plausible explanation for these eclogitic clasts involves two large collisions, first to place the clasts in the interior of a Moon-sized body and later to disrupt the body and transport the clasts into space. This is not a formation scenario comparable to terrestrial eclogites, but it has been speculated that eclogites may have been relevant to crustal recycling on Venus. In any case, it is intriguing to think that eclogites or eclogitoids may be out there in the far reaches of our solar system awaiting future discoveries.

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