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Eclogites and their geodynamic interpretation: a history

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Abstract

Haüy coined the term eclogite, meaning "chosen rock", in 1822, but de Saussure had already observed rocks of this type in the Alps four decades earlier. Throughout the 19th century, the origin of eclogite remained an enigma, in spite of great progress in our knowledge of this rock. The first chemical analyses, carried out around 1870, showed that its bulk composition was the same as gabbro. Therefore, eclogite was thought to be either an igneous rock of gabbroic composition or a metamorphosed gabbro. This second hypothesis became preferred when progressive transitions were observed between gabbros and eclogites. In 1903, simply by comparing the molar volumes of gabbroic and eclogite parageneses, Becke inferred that eclogite was the high-pressure equivalent of gabbro. In 1920, eclogite was involved in the conception of the metamorphic facies by Eskola. However, a few researchers denied the existence of an eclogite facies, and claimed that high stress instead of high lithostatic pressure could generate eclogites. In the 1960s, consideration of the water pressure parameter also favoured the belief that eclogite was simply the anhydrous equivalent of amphibolite. Finally, eclogite was definitely considered as a high-pressure metamorphic rock following the development of experimental petrology and the application of thermodynamics. In recent years, the discovery of ultrahigh-pressure coesite-bearing rocks in the crust has drastically changed geologists' ideas concerning the limits of eclogite-facies crustal metamorphism. Eclogites have been involved in several geodynamic theories. Around 1900, kimberlite studies favoured the idea that eclogite might be abundant in the interior of the Earth. In 1912, Fermor predicted the existence of a dense eclogite-bearing zone in the mantle. This "eclogite layer" hypothesis was still envisaged as late as 1970. The alternative "peridotite" hypothesis became preferred when experimental investigations demonstrated that the gabbro-to-eclogite transition could not coincide with a sharp Mohorovičić discontinuity. Before plate tectonics, high-pressure belts were interpreted as remnants of ophiolite-bearing "geosynclines", metamorphosed by loading during thrust faulting. After the acceptance of plate tectonics, around 1970, the same high-pressure Alpine-type belts came to be considered as former oceanic crust, transformed into eclogite within subduction zones, and subsequently incorporated into mountain belts. Surprisingly, formation of eclogite in "subsidence" zones (i.e. subduction zones) had already been envisaged as early as 1931 by Holmes, the inventor of a convection-current theory. In the 1980s, many authors tried to apply the model of Alpine-

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type high-pressure belts to eclogites enclosed within the gneisses of ancient orogens, but the question remains obscure nowadays. These eclogites have been involved in the "in situ versus foreign" controversy and in the unresolved enigma of ultrahigh-pressure metamorphism. The latter came under scrutiny in 1984 after the discovery of coesite and diamond in some eclogite-facies rocks. It has been a matter of considerable interest during the last two decades. Currently, the debate is focused on the geodynamic mechanisms responsible for the exhumation of these rocks, a question that will probably remain unresolved for part of the coming century.

1. Introduction

When Haüy created the name "eclogite", meaning *select* or *chosen rock*, in 1822, he was impressed by the beauty of the rock and by the peculiarity of its mineral association. He certainly did not realise that this rock would prove to be a "chosen" rock in more than one sense. Indeed, over the last two centuries, eclogite has contributed to the birth of several major concepts in metamorphism. These include the "volume law" and the role of pressure, the existence of metamorphic rocks derived from igneous rocks, and the widely used concept of mineral facies. Moreover, eclogite has been involved in many geodynamic hypotheses. The occurrence of a hypothetical "eclogite layer" beneath the Earth's crust has been under discussion up to late in the twentieth century. After plate tectonics had arisen in the 1960s, most eclogites came to be considered as resulting from subduction of oceanic crust. Finally, in the two last decades, eclogite and eclogite-facies rocks were also involved in the intriguing problem of ultrahigh-pressure metamorphism, after the discovery of coesite-bearing crustal rocks.

In this paper, we attempt to survey two centuries of interrelation between metamorphic petrology and geodynamics by reviewing the history of eclogite, which once more naturally emerges as the "chosen rock" for such a task. The paper is divided into two main parts. We first report the advances in our knowledge of the rock (discovery, metamorphic origin, high-pressure conditions of formation: Section 2). Then, we present the various geodynamic theories and problems centred on eclogite ("eclogite layer", subduction of oceanic crust, exhumation of ultrahigh-pressure rocks: Section 3).

2. History of a chosen rock

2.1. Discovery and definition

René-Just Haüy (1822) (Fig. 1) coined the term "eclogite" from the Greek word εκλογή, meaning *choice*. In the second edition of his *Traité de minéralogie*, he wrote that

> "diallage [i.e. clinopyroxene] is considered the main mineral [of this rock], and constitutes with garnet a binary association to which can be unevenly added kyanite, quartz, epidote and lamellar amphibole. I gave to this rock the name eclogite, which means choice, or selection because its components, which do not usually coexist together in primitive rocks, as do the feldspar, mica and amphibole, seem to have chosen themselves to constitute a peculiar association. This rock occurs in Carinthia, Sau-Alpe and Styria [Austrian Empire]"

Fig. 1. The abbot René-Just Haüy (1743–1822), mineralogist, member of the French *Académie des Sciences* and one of the inventors of the metric system. In 1822, he created the name eclogite, meaning "chosen rock" (© Bibliothèque nationale de France).

(see note 1a in the Appendix for the French original text). Haüy's collection, which is still preserved at the *Muséum National d'Histoire Naturelle* in Paris, contains 7 samples from "*Pays de Bayreuth*" (Bavaria, Germany) that are labelled *éclogite* (see note 1b in the Appendix).

Thereafter, many petrologists have claimed that Haüy was the first to have discovered eclogites, but this assumption is unfair since others had observed eclogites before he created the name. Indeed, during the Neolithic, humans already appreciated eclogite for its high density and hardness, and used it to make tools, particularly in Europe (e.g. Lohmann, 1884; Franchi, 1904; D'Amico et al., 1995; Hovorka et al., 2000). From a scientific point of view, we owe the first description of an eclogite to Horace-Bénédict de Saussure (1779–1796: Fig. 2). In his *Voyages dans les Alpes*, he mentioned a "*beautiful rock that is not described yet*" and that he had found as pebbles in the Rhone valley near Geneva. The rock was dense, hard, and made of garnet crystals in a green matrix of "jade" (pyroxene ?) and "schorl" (prismatic amphibole ?). In 1767 and 1774, he observed similar rocks cropping out at Le Brévent near Chamonix (Savoy) and Montjovet (Aosta Valley: see note 2 in the Appendix). The first occurrence is certainly connected with the well-known Lac Cornu eclogite, only 2 km away. The beauty of the rock of Montjovet particularly impressed him: "*Cette pierre paroît au soleil de la plus grande beauté*." De Saussure's collection, which still exists in Geneva (see Lanterno, 1976), contains a score of eclogite, eclogite micaschist, and glaucophanite specimens that were sampled in various parts of the Alps (see note 2 in the Appendix). Déodat Gratet de Dolomieu also mentioned the occurrence of rocks made of green "schorl" and garnet in "primitive

Fig. 2. Horace-Bénédict de Saussure (1740–1799) by Jean-Pierre Saint-Ours, 1796. Although only the third man to climb Mont-Blanc, Saussure was the first to describe, under various names, eclogites, eclogite micaschists and glaucophanites from the Alps (see note 2 in the Appendix; © Bibliothèque nationale de France).

mountains'', and he discussed at length the reason why these two minerals crystallise together (Dolomieu, 1794). Finally, the great German geologist Abraham Gottlob Werner knew of some eclogites in the Austrian Alps and southern Germany, notably the famous occurrence of Silberbach. He described them as composed of garnet, ''omphazit'' and, occasionally, ''cyanit'' (Werner, 1817).

The name *eclogite* has proved useful, since it was soon used by European authors to describe rocks from southern Germany and Austria (Leonhard, 1823), the Western Alps (Necker, 1828; Fournet, 1841; Favre, 1867), Vendée in western France (Rivière, 1835, 1844), Saxony in Germany (Naumann, 1838; Müller, 1846), Bohemia (Hochstetter, 1855; Patton, 1887), Venezuela (Wall, 1860), Norway (Hiortdahl and Irgens, 1862; Reusch, 1877, 1883), Galicia in Spain (Macpherson, 1881), Silesia (Traube, 1889) and Scotland (Teall, 1891). However, a lot of confusion existed in many of these early studies, which—it should be remembered—were performed without the microscope. While garnet was recognised without difficulty, the pyroxene matrix was referred to either as ''diallage'', ''omphazit'', ''körniger Strahlstein'', ''schorl'' or ''smaragdite''. Smaragdite, a name created by

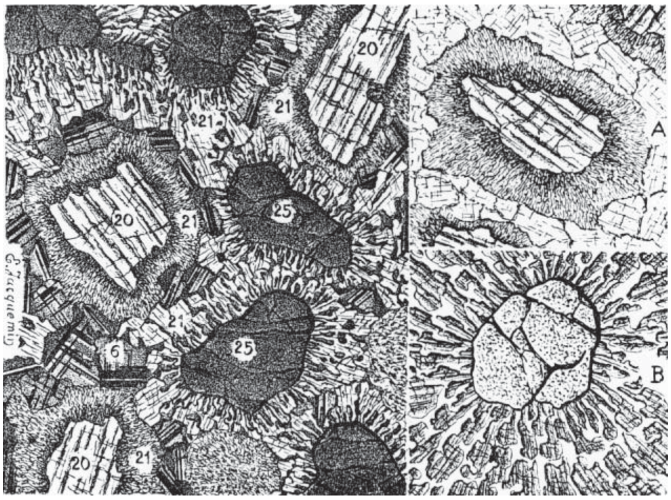

Fig. 3. Retrogression structures in eclogite according to Alfred Lacroix (1891). Garnet crystals (25) are corroded by a "kelyphite" made of amphibole + plagioclase (see enlargement B); omphacite (20) is also partly replaced by a clinopyroxene + oligoclase symplectite (21) (see enlargement A); eclogite from Kerscao, Plounevez-Lochrist, Pays de Léon, France.

Fig. 4. Secondo Franchi (1859–1932), engineer of the *Reale Ufficio geologico d'Italia*. He studied the "*micascisti eclogitici*" of the Alps and, in 1902, observed the reaction jadeite + quartz→albite (see Stella, 1933; photograph from Novarese, 1938; © Servizio geologico d'Italia).

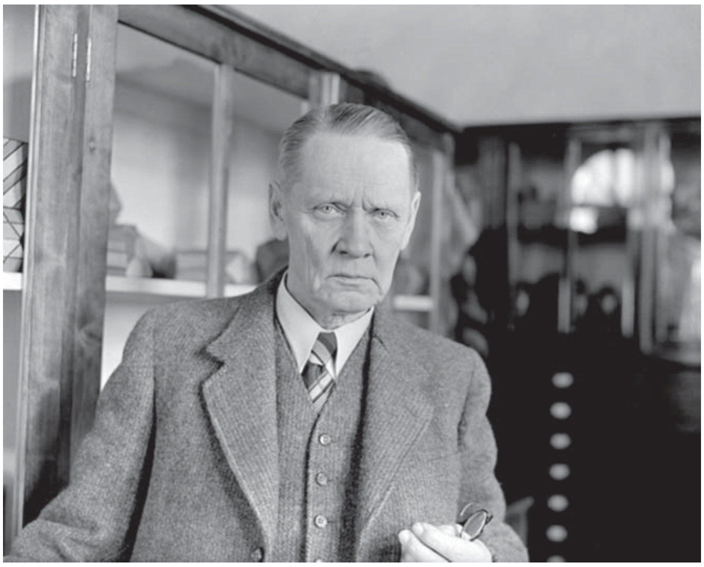

Fig. 5. The Finnish petrologist Pentti Eskola (1883–1964). While studying the eclogites of Norway in Oslo (1920, 1921), he developed the concept of mineral facies which, among others, comprises an eclogite facies (© Geological Survey of Finland).

de Saussure (1779–1796), was a greenish but poorly defined silicate. Omphacite, also a green mineral, had been named by Werner (in Hoffmann and Breithaupt, 1815, vol. 2, part 2, p. 302) after the Greek ομφαξ meaning "green grapes", with reference to its colour. Haüy (1822) regarded Werner's omphacite as a green variety of his "diallage" (i.e. clinopyroxene). Because clinopyroxene in eclogite generally displays a beautiful emerald green colour, the name omphacite was finally adopted, while the use of the word "smaragdite" became restricted to green amphiboles that are also common in eclogites (see Drasche, 1871).

2.2. Early petrological investigations

The polarising microscope, which had been in use since the middle of the 19th century (see Hamilton, 1992), led to a great progress in the petrographical knowledge of eclogite. Thus, in the years 1880–1920, several important monographs were published on eclogites from Bavaria and Austria (Riess, 1878; Lohmann, 1884; Ippen, 1892; Düll, 1902; Hezner, 1903; Kieslinger, 1928), France (Lacroix, 1891; Joukowsky, 1902; Brière, 1920), California (Holway, 1904), and Norway (Eskola, 1921). These works include precise mineralogical and petrographical descriptions of the eclogite parageneses, together with details on two important structures that commonly occur in eclogite, namely kelyphite coronae around garnet crystals and symplectites developing from omphacite (Fig. 3).

The name "kelyphite" was coined by Schrauf in 1882 from the Greek word κέλυφος, meaning shell, to describe coronae between garnet and olivine in peridotites (Schrauf, 1882; see Godard and Martin, 2000). It also became used to describe amphibole-bearing coronae around garnet in eclogite, the nature of which is, however, much different (Fig. 3b). Holland (1896), Sederholm (1916) and, principally, Hezner (1903) carried out detailed studies of this metamorphic reaction. The first elegant interpretation of these coronae was proposed by Fermor (1912) who considered them as resulting from the breakdown of garnet during decompression (see note 3 in the Appendix).

Omphacite replacement by symplectites, the second common structure (Fig. 3a), was also observed by several authors (e.g. Becke, 1882; Patton, 1887; Teall, 1891; Lacroix, 1891; Franchi, 1902a; Hezner, 1903; Grubenmann, 1904–1907; Weinschenk, 1904) and described in detail by Brière (1920) and Eskola (1921). These authors painstakingly identified the clinopyroxene + plagioclase and amphibole + plagioclase associations among the cryptocrystalline products that replace the omphacite. This process of omphacite replacement was apparently first understood by the Italian petrologist Franchi (1902a) and afterwards by Eskola (1921). It was interpreted as resulting from the exsolution of the jadeite molecule from omphacite, which results in albite production: 1 omphacite [Jadeite$_x$ Augite$_{1-x}$] + x quartz $\rightarrow$ x albite + (1$-x$) augite. To arrive at this conclusion, we had to wait for improvements in our knowledge of the jadeitic clinopyroxenes.

The discovery of the relationship between jadeite and eclogite is in itself a long story. Jade was known since Neolithic times and has long been used for manufacturing hatchets and jewels (see Bishop, 1906). The Indians of Central America called it "chalchihuilt", and the Chinese also knew this stone as "Yü", which they collected in Yü Shan (the "mountains of jade"). It was first described in Europe by Nicolás Monardes, in 1565, as "*la piedra dela yjada*" (the colic[-curing] stone), because of its (doubtful) curative powers. This name was strangely translated as "*pierre de jade*" by French lapidaries, and thus became our "jade". Early mineralogists such as Haussmann (1813), Hoffmann and Breithaupt (1815), Haüy (1822) and, principally, Alexis Damour (1863, 1865, 1881) differentiated two main species of jade, one made of a calcic amphibole ("nephrite") and the other of a new Na–Al-bearing silicate that Damour called "jadéite". At first, Damour (1863, 1865) believed that his jadeite was a kind of "wernerite" (i.e. scapolite), because of its chemical formula. However, Krenner (1883), Arzuni (1883), Cohen (1884) and Clarke and Merrill (1888) clearly established, from the physical and optical properties of the mineral, that it was actually a sodic and aluminous clinopyroxene. The connection between eclogite and jadeite was first suspected by Damour, who showed in 1881 that the "green substance" (i.e. omphacite) of an eclogite from Fay-de-Bretagne, in Western France, was close to jadeite in composition. Finally, several authors established that omphacite in eclogite was a solid solution of augite and jadeite, with minor aegyrine content (e.g. Zambonini, 1901; Bishop, 1906; Washington, 1922; Perrier, 1924; Sahlstein, 1935). Franchi (1900) (Fig. 4) also showed that the jadeite-bearing rocks of the Alps are ordinarily associated with eclogites. The same author (Franchi, 1902a) was apparently the first to describe the well-known reaction jadeite + quartz$\rightarrow$albite. He also interpreted the replacement of omphacite by symplectites in eclogite as resulting from jadeite exsolution (see above). Eskola (1921) further developed this interpretation.

2.3. Metamorphic versus magmatic origin

While our knowledge of eclogite progressed, the problem of its origin remained an enigma. The debate turned on one main question: Is eclogite a metamorphic or a magmatic rock?

Around 1820, Ami Boué developed the new concept of metamorphism, as a consequence of Hutton's magmatic theory (e.g. Boué, 1820, 1824). Although Boué had already used the French word *métamorphose*, it is to Lyell (1830–1833) that we owe the term "metamorphism" (from μετα [trans] and μορφή [form]). During almost all of the 19th century, the concept was restricted to the effect of temperature and the action of fluids, and regarded as applicable to sedimentary rocks (see: Daubrée, 1859; Delesse, 1857–1961; Hunt, 1884; Williams, 1890; Zittel, 1899). Temperature and fluids were considered as the driving forces for mineralogical transformations, "pressure" (in fact, stress) being responsible only for schistosity development.

As for the eclogites, a few authors began to consider them as metamorphic rocks (e.g. Lipold, 1855; Lüdecke, 1876; Riess, 1878; Zirkel, 1894; Düll, 1902; Hezner, 1903; Becke, 1903; Grubenmann, 1904–1907; Brière, 1920). Their main argument was that eclogites are foliated just as any other metamorphic rock. They have thus undergone dynamometamorphism together with their surrounding gneiss whose metamorphic origin was undoubted. Other authors, however, believed that they were magmatic rocks (e.g. Hiortdahl and Irgens, 1862; Brøgger, 1880; Kolderup, 1903; Eskola, 1921; Dal Vesco, 1953). This gave rise to a long controversy that apparently degenerated into a chauvinistic quarrel between Austrians and Germans who favoured the metamorphic origin, on the one hand, and Scandinavians who preferred the magmatic hypothesis, on the other (see Perrier, 1924). It was also partly due to a misunderstanding since some of the purported magmatic eclogites were actually garnet-pyroxenite layers within peridotites. Such rocks are not considered as true eclogites nowadays (e.g. Ravier, 1964; Smulikowski, 1964a).

Meanwhile, the first chemical analyses of eclogite and its constituent minerals (e.g. Mauthner, 1872; Gerichten, 1874; Dathe, 1876; Riess, 1878; Schuster, 1878) clearly revealed that eclogite has the bulk composition of a gabbroic rock, although its mineral composition was far removed from that of a gabbro. This conclusion did not solve the problem of the origin, as it was compatible with both hypotheses: eclogite either could be a magmatic rock of a gabbroic composition or derived from gabbro by metamorphism. This last idea, however, was rather innovative since the concept of regional metamorphism had so far been applied only to sedimentary rocks.

The study of glaucophane-bearing rocks, with which eclogites are commonly associated (Section 3.2), helped to elucidate the question. Progressive transitions were observed from unmetamorphosed gabbros or basalts, to glaucophane-bearing metabasites, and finally glaucophane eclogites (e.g. Bonney, 1879; Koto, 1887; Lepsius, 1893; Franchi, 1895; Holway, 1904; Smith, 1906; Zambonini, 1906; Lacroix, 1941). This was a major argument in favour of the metamorphic origin of eclogites and their associated glaucophanites. More recently, several authors (e.g. Bearth, 1959, 1970; Coleman and Lee, 1963) have described glaucophanites with preserved pillow-lava and breccia structures.

Nevertheless, the metamorphic origin was not easily acknowledged and remained disputed for a long time. Brière (1920), for instance, argued in her thesis that the French eclogites had resulted from metamorphism of gabbroic rocks, not only because eclogite compositions were the same as gabbros but also because they followed variations typical of a gabbroic series. In 1981, I had the chance to meet Yvonne Brière, when she was 92. She told me that the members of her thesis examining board, at La Sorbonne University in Paris, had severely criticised her hypothesis of a metamorphic origin. She was thus very pleased to learn, 61 years later, that her opinion was now widely accepted.

Surprisingly enough, among the supporters of the magmatic origin was the great Finnish petrologist Pentti Eskola (Fig. 5) who considered the eclogites of Norway as having crystallised at high pressure from an "eclogite magma" (Eskola, 1921). He attributed foliation to "stress during consolidation". Even the secondary kelyphite (see Section 2.2) was attributed by him to a late magmatic (re)crystallisation stage. Thus, the greatest contributor to the concept of metamorphic facies believed that eclogite was a magmatic rock, although he had apparently changed his mind by 1939 (i.e. Eskola, 1939). A few other petrologists believed in a metamorphic origin but preferred calcareous sediments as the protoliths instead of gabbro (e.g. Ghosh, 1941; Smulikowski, 1964b; Vogel and Garlick, 1970). This strange idea was apparently due to confusion with metamorphic calc-silicate rocks made up of grossular-rich garnet and jadeite-free clinopyroxene, which vaguely resemble eclogite.

Finally, a consensus gradually emerged. Eclogite was thought to result from the metamorphism of gabbroic or basaltic rocks, for three main reasons: (a) Progress in geochemistry showed that eclogites have all the features of gabbros (major and trace elements, REE, isotopes) and show variations typical of gabbroic differentiation; (b) The structures of the former gabbro or basalt protoliths were still recognizable in cases where eclogite-facies metamorphism was static (e.g. Chenevoy, 1958; Miller, 1970; Vraná et al., 1975); (c) The gabbro-to-eclogite transformation was confirmed experimentally (Ringwood and Green, 1966; Green and Ringwood, 1967a, 1972). Nevertheless, several authors nowadays accept that some mantle eclogites (griquaite, grospydite) could have been formed from magma at high-pressure conditions.

2.4. The concept of high-pressure eclogite-facies metamorphism

When the connection between eclogite and gabbro came to be considered around 1900, the following question arose: How can we account for such a great difference in mineralogy between gabbro and eclogite, while their chemical compositions are so similar?

As it turned out, pressure was an elegant answer to this question. The well-known Clausius-Clapeyron equation, which expresses the pressure-volume control of reactions, clearly predicts that an increase of pressure should lead to the formation of minerals of higher density. The first application of this basic idea to rocks, often referred to as "the volume law", was apparently due to Lepsius (1893). The Austro-Hungarian petrologist Friedrich Becke, the inventor of the famous "Becke line" method in microscopy, was the first who applied the volume law to eclogites (Becke, 1903). Simply by comparing the molar volumes of gabbroic and eclogite parageneses (Table 1), he concluded that eclogite was the high-pressure equivalent of gabbro. This constitutes, in my opinion, one of the most ingenious ideas of the whole history of petrology. The conclusion was soon adopted by several researchers (e.g. Grubenmann, 1904–1907; Fermor, 1912, 1913 [see note 3 in the Appendix]; Boeke, 1915; Eskola, 1920, 1921), many of whom, however, did not refer to Becke's work. It eventually received an experimental confirmation 63 years later.

In the same period, the notion of mineral facies was being developed. Barrow (1893) introduced the concept of progressive regional metamorphism and used critical index minerals to define metamorphic zones. Van Hise (1898) proposed four "depth zones", whereas Grubenmann (1904–1907) distinguished three consecutive zones with increasing depth (i.e. epi-, meso- and catazones), eclogite belonging to the deepest zone. The introduction of pressure as a new independent intensive variable in addition to temperature led to an improvement of the concept by Eskola (1915, 1920, 1921, 1929, 1939) and Becke (1921), with the participation of Goldschmidt. According to Eskola, rocks belonging to a given facies originated under similar temperature (T) and pressure (P) conditions. At these particular P–T conditions, their mineral composition is dependent only on the bulk chemical composition, while a given composition results in the same set of minerals, whatever the mode of crystallisation, metamorphic, magmatic or even hydrothermal. Indeed, as suggested by the "volume law", eclogite and glaucophanite were considered as having formed under high-P/high-T and high-P/low-T conditions, respectively. They were naturally chosen as

Table 1
Table based on the work of the Viennese petrologist Friedrich Becke (1903), applying the "volume law" to eclogites. Becke compared eclogite and gabbroic parageneses of the same composition. From their differences in molar volume, he inferred that eclogite was the high-pressure equivalent of gabbro. Molar volumes are expressed in cm^3 mol^{-1}; R = (Ca, Mg, Fe). Note that the glaucophane formula given by Becke is not correct

Gabbro (Olivin, Augit, Basischer Plagioklas)			Eklogit (Omphacit, Granat, Quarz)	
Augit		=	Granat	
Ca Mg Si_2 O_6	68		R_3 Al_2 Si_3 O_{12}	121
Mg Al_2 Si O_6	68			
	136			
Augit + Anorthit		=	Granat + Quarz	
Ca Mg Si_2 O_6	68		R_3 Al_2 Si_3 O_{12}	123
Ca Al_2 Si_2 O_8	101.1		Si O_2	22.8
	169.1			145.8
Olivin + Anorthit		=	Granat	
Mg_2 Si O_4	43.9		R_3 Al_2 Si_3 O_{12}	121
Ca Al_2 Si_2 O_8	101.1			
	145.0			
Albit des Plagioklases		=	Na-Al-Silikat des Omphacit [Jd] + Quarz	
Na Al Si_3 O_8	100.3		Na Al Si_2 O_6	64.6
			Si O_2	22.8
				87.6
Nephelin + Albit		=	Glaukophan	
Na Al Si_3 O_8	100.3		Na_2 Al_2 Si_4 O_{12}	137
Na Al Si O_4	59			
	156.3			
		=	Jadeit	
			2 (Na Al Si_2 O_6)	122.8

type rocks for the "eclogite facies" (Eskola, 1920, 1921, 1929; Becke, 1921) and "blueschist facies" (Eskola, 1929, 1939). We should clearly understand that, in Eskola's mind, rocks of a given facies could be either magmatic or metamorphic. Although he accepted that metamorphic eclogites might exist, he favoured a magmatic origin for eclogite (see Section 2.3). Over the next decades, however, it became evident that magmatic rocks could not crystallise over a large range of T. There are no magmatic rocks in the low-T "greenschist facies", for example. Therefore, the concept of mineral facies (Eskola, 1920, 1921) evolved into that of metamorphic facies (Eskola, 1929, 1939).

If it has any basis in reality, Eskola's eclogite facies should not only comprise basic rocks but also ultrabasic and pelitic rocks as well. Garnet peridotites have been regularly recognised as the ultrabasic member of the eclogite facies (e.g. Eskola, 1921; O'Hara, 1967; Medaris and Carswell, 1990). On the other hand, pelitic eclogite-facies rocks are extremely rare. Stella (1894) provides us with the first example of such a rock. He discovered micaschists in the Western Alps that showed analogies with eclogite, which he called "*micascisti eclogitici*" (see Compagnoni et al., 1977). These eclogite micaschists, made of white micas, garnet, quartz, jadeite-rich clinopyroxene and rutile, were further studied by Franchi (1900, 1902a). They remained without an equivalent for a long time, and eclogite-facies pelitic rocks, whether described as "eclogite micaschists", "mucronites" or Mg-rich talc-bearing "whiteschists", are still exceptional nowadays (see Mottana et al., 1990, pp. 35–46; e.g. Sobolev and Shatsky, 1990; Tagiri and Bakirov, 1990; Wallis et al., 1997). In most cases, the gneisses enclosing eclogites apparently show no evidence of eclogite-facies metamorphism. Later, this observation led to a controversy about the mechanism of eclogite emplacement within gneisses (in situ versus foreign origin: see Section 3.3).

The almost total failure to recognise eclogite-facies parageneses of pelitic composition encouraged some researchers to reject the existence of an eclogite facies (e.g. Wieseneder, 1935; Backlund, 1936; Korzhinskii, 1940; Buddington, 1943; Sørensen, 1953; Roever, 1955; Chenevoy, 1958) and to raise objections against the high-pressure theory (see: Ebert, 1936; Nikitin, 1942; Smulikowski, 1964b). Most of these authors claimed that high stress rather than high lithostatic pressure could generate dense mineral assemblages. In this manner, eclogites might have formed at moderate depths in the crust during intense dynamometamorphism. Similar hypotheses, invoking stress or "tectonic overpressure", were repeatedly put forward until recently, although considered heretical by the majority (see Smith, 1995, pp. 336–341). Even more surprising hypotheses were also envisaged involving contact metamorphism, hydrothermal activity or metasomatism (e.g. Hentschel, 1937; Taliaferro, 1943; Switzer, 1945; Smulikowski, 1960).

In the 1960s, a new concept arose, namely water pressure (P_{H_2O}), which led some researchers to minimize the role of pressure in eclogite metamorphism. Early experimental work (Yoder and Tilley, 1962) suggested that eclogite stability depended mainly on P_{H_2O}. Eclogite, an almost anhydrous rock, was thought to represent the dry metamorphism of gabbroic or basaltic protoliths under low or moderate pressures. Amphibolite, on the other hand, would have resulted from wet metamorphism under the same *P–T* conditions (e.g. Yoder, 1955; Fry and Fyfe, 1969, 1971; Bryhni et al., 1970; Ghent and Coleman, 1973; De Wit and Strong, 1975). This hypothesis was abandoned when experimental studies (e.g. Ringwood and Green, 1966; Green and Ringwood, 1967a, 1972) demonstrated that eclogite parageneses are restricted to high pressures. Other studies (e.g. Essene et al., 1970; Holland, 1979) also revealed that eclogite stability is not restricted to low water pressures, although the eclogite-amphibolite transition is naturally sensitive to P_{H_2O} (see Carswell, 1990a).

Meanwhile, progress in crystallography had revealed the true essence of an eclogite. The behaviour of some cations in crystals, particularly Al, accounted well for the high density of eclogite parageneses (Wickman, 1943; Fairbairn, 1943; Thompson, 1947; White, 1964; Smith, 1982). Because of their relatively large size, Al cations are not stable at high P in tetrahedral sites, which are compressed as pressure increases. Therefore, high pressure, and to a lesser extent low temperature, favours Al in sixfold-coordination (i.e. Al^{VI}), which is the case of eclogite minerals, whereas low pressure favours minerals with Al in tetrahedral sites (i.e. Al^{IV}). The well-known univariant reaction 1 albite$\rightarrow$1 jadeite + 1 quartz, for instance, can be simply written as 1 $Al^{IV}\rightarrow$1 Al^{VI}. At much higher pressure, Si is in turn expelled from the tetrahedral sites, forming minerals such as majoritic garnets (e.g. Ringwood, 1970; Ringwood and Major, 1971) and stishovite (e.g. Stishov and Popova, 1961; Stishov, 1962).

After confirmation by experimental work, eclogite was definitely considered a high-pressure metamorphic rock of deep origin. The invention and development of the solid-media apparatus (e.g. Yoder, 1950; Boyd and England, 1960a) and the diamond-anvil cell (Coes, 1953; Weir et al., 1959) led to great progress in high-*P*-*T* experimental petrology, the main stages of which were high-*P* synthesis of diamond (Bundy et al., 1955), study of the quartz-coesite transition (Coes, 1953; Boyd and England, 1960b), determination of the stability fields for Al_2SiO_5 polymorphs (Khitarov et al., 1963; Bell, 1963; Althaus, 1967), investigation of the gabbro–eclogite transition (Ringwood and Green, 1966; Green and Ringwood, 1967a, 1972: (Fig. 6), and the study of the albite = jadeite + quarz univariant reaction (see: Yoder, 1950; Newton and Smith, 1967; Holland, 1980). Since the 1970s, use of equilibrium thermodynamics has allowed the application of these new and abundant experimental data to natural eclogite parageneses (see Carswell and Harley, 1990). The stability of the omphacite solid solution (e.g. Kushiro, 1969; Holland, 1983, 1990) and the use of geothermometers based on (Fe, Mg)-exchange between garnet and clinopyroxene (e.g. Råheim and Green, 1975), among others, led to the determination of *P*–*T* paths for many eclogites worldwide. The estimates of *P*–*T* conditions for the eclogite parageneses were generally $P > 1.4$ GPa at $T = 500–800$ °C. Estimated pressures have greatly increased in comparison to early estimates that hardly ever attained 1 GPa. Finally, in recent years, the discovery of coesite-bearing crustal rocks (Chopin, 1984, 1987; Smith, 1984; see Section 3.4) has raised the upper pressure limit of the eclogite facies to more than 4 GPa.

During the two last decades, there has also been a tremendous advance in other fields of eclogite studies: geochronology (see Gebauer, 1990), petrofabric analysis and plastic deformation mechanisms (see Godard and Van Roermund, 1995), the role of kinetics (see Rubie, 1990) and behaviour and recycling of fluids during subduction (e.g. Ahrens and Schubert, 1975; Philippot, 1993; Philippot and Rumble, 2000). Since 1982, an International Eclogite Conference takes place every 4 years. Several books have been published (e.g. Smith, 1988a; Carswell, 1990b; Coleman and Wang, 1995), as well as hundreds of monographs and articles (Fig. 7), indicating that there is more interest in eclogite than ever before.

3. Geodynamic interpretations

While our knowledge of eclogite improved, several hypotheses, sometimes confused and embroiled in controversies, have been put forward to interpret eclogite and eclogite-facies rocks in terms of geodynamics. We present here some of these hypotheses and controversies. The reader should be aware, however, that the most recent of them, still under debate, are too close for a proper historical perspective.

During the two last centuries, the survey of eclogite occurrences, first in Europe and then worldwide, has revealed that there are "eclogites and eclogites". Several eclogite classifications were proposed (e.g. Eskola, 1921, 1939; Smulikowski, 1964a; Coleman et al., 1965; Banno, 1970), in which eclogites were discriminated on the basis of their mode of occurrence, mineral and bulk compositions, and geodynamic setting. The classifications of Smulikowski (1964a) and Coleman et al. (1965) are somewhat similar and have proved to be useful. They are still occasionally used. The three eclogite groups proposed by these authors are very different in terms of geodynamics, giving rise to specific hypotheses and, therefore, we present them separately.

(a) Eclogites from the mantle (i.e. group I of Smulikowski and group A of Coleman et al.). These eclogites are associated with ultrabasic rocks, either in peridotite bodies or as xenoliths in kimberlite pipes. They were involved in the "eclogite layer" controversy presented in Section 3.1. Moreover, their origin (mantle melt or subducted oceanic crust) is still debated.

(b) Ophiolitic eclogites (i.e. group II of Smulikowski and group C of Coleman et al.).

They are associated with glaucophanites and, with them, form high-pressure belts in orogens. Since the outset of plate tectonics, they have been considered as remnants of paleo-subduction zones (Section 3.2).

(c) Eclogites within gneiss (i.e. group III of Smulikowski and group B of Coleman et al.).

These eclogites were involved in the "in situ versus foreign" controversy (Section 3.3) and in the still unresolved enigma of ultrahigh-pressure metamorphism (Section 3.4).

3.1. Mantle eclogites and the so-called "eclogite layer"

The historical background of the study of mantle eclogites is closely connected to that of kimberlites. Since a historical review of kimberlites, however, is beyond the scope of this paper, we only recall here the principal stages of this history (see also: Boutan, 1886; Lewis, 1897; Julien, 1909; Wagner, 1914; Williams, 1932; Bardet, 1973–1977; Meyer, 1979). Diamonds have been mined in South Africa since 1867, either in placers or in "blue grounds", to which Lewis gave the name "kimberlite" (Lewis, 1897, p. 50). Cohen (1872), Moulle (1885) and Lewis (1887) interpreted these "blue grounds" as volcanic pipes. Similar kimberlite pipes were also discovered in the USA (see Bonney in Lewis, 1897; e.g. McGetchin and Silver, 1972), Rhodesia (Mennell, 1910), Australia (e.g. Card, 1902), Tanganyika (e.g. Williams, 1932) and Siberia (e.g. Moor, 1941; Leontev and Kadensky, 1957). Cohen (1879) recognized eclogite together with peridotite among the nodules of the diamond-bearing breccia of Jagersfontein, in South Africa. Because of his discovery of diamond in eclogite nodules from a kimberlite, Bonney (1899, 1899–1900, 1900) identified eclogite as being the parental rock of diamond. Meanwhile, the origin of eclogite nodules was debated. Some petrographers saw in them segregations from the kimberlite magma, whereas others interpreted them as fragments derived from some formation of eclogite existing at a great depth (see: Bonney, 1899–1900, 1907; Wagner, 1914). This latter hypothesis was supported by the new idea that eclogite and diamond were the high-pressure equivalents of, respectively, gabbro (see Section 2.4) and graphite (Moissan, 1893, 1894; Bakhuis-Roozeboom, 1901; see Bundy et al., 1955).

Kimberlite studies favoured the idea that eclogite could be abundant in the interior of the Earth. In 1912, L. L. Fermor, geologist of the Geological Survey of India (see: Krishnan, 1954; West, 1989), used the volume law to predict the existence of a dense eclogite-bearing "infra-plutonic zone" (i.e. the mantle) lying beneath a "plutonic zone" (i.e. the crust) and extending downwards "as far as the presumed metallic core of the earth" (Fermor, 1912, 1913; see note 3 in the Appendix). He proposed that a sharp transition in rock densities due to the gabbro-to-eclogite transition might occur between the plutonic and infra-plutonic zones. In his opinion, such a transition might well agree with the principle of isostasy, and could be the source of basaltic magmas (Fermor, 1914). Fermor's hypothesis was at the origin of the "eclogite layer" theory, which, at first sight, was confirmed by the existence of eclogite xenoliths in kimberlite pipes and by the well-known

"Moho" discontinuity, discovered by the Croatian seismologist Andrija Mohorovičić in 1910 (Mohorovičić, 1910; see Grau, 1977). Eskola accepted and developed the theory together with his friend Goldschmidt in Oslo (Eskola, 1921, 1936; Goldschmidt, 1922; see Buddington, 1943). On the basis of seismological data, Goldschmidt (1922) postulated an eclogite layer with a density of 3.4–4.0 located between 120 and 1200 km beneath the surface. In 1921, Eskola went to the Geophysical Laboratory in Washington to test the theory by synthesizing minerals at high pressures. The experiments failed, however, but the eclogite theory aroused lively discussion, and became supported by researchers such as Holmes (1926) and Wagner (see: Marmo, 1965). Other petrologists, for the most part Backlund (1936) and Korzhinskii (1940), disapproved of the concept, considering eclogite as being merely a rare crustal rock rather than derived from the mantle (see Section 2.4).

The existence of an eclogite layer in the upper mantle was still envisaged as late as 1971 (e.g. Birch, 1952; Lovering, 1958; Kennedy, 1959; Carr, 1966; Ito and Kennedy, 1970; Sobolev and Sobolev, 1971; Tarkov et al., 1971), although rejected by several authors who preferred the "peridotite" hypothesis (e.g. Verhoogen, 1954; Kuno, 1959; Harris and Rowell, 1960; Ringwood, 1962; Sheynmann, 1963; Harris et al., 1967; see: Wyllie, 1965, 1970; Stegena, 1966; Kuno, 1967; Bott, 1971). The first group of authors regarded the Mohorovičić discontinuity as a phase transition (i.e. basalt or gabbro to eclogite), whereas the latter supported the existence of a chemical discontinuity (i.e. basaltic or sialic crust to peridotite). The eclogite-layer hypothesis was apparently supported by seismological data and considerations on isostasy, which predicted physical properties for the upper mantle (density = 3.3 g/cm^3; V_P = 8.1 km/s) that seemed compatible with eclogite. The supporters of the eclogite layer assumed that the Earth's temperature increases with depth a little more slowly under the oceans than under the continents, explaining the varying depths to the Mohorovičić discontinuity—i.e. to the gabbro–eclogite transition—under the oceans and continents (e.g. Kennedy, 1959).

The hypothesis was abandoned after the first experimental investigations on the gabbro-to-eclogite transition, which were performed mainly by Green and Ringwood (Kushiro and Yoder, 1964; Ringwood and Green, 1964, 1966; Green, 1967; Green and Ringwood, 1967a, 1972; see Green, 1998). These studies demonstrated that (a) the transition was not sharp (Fig. 6), unlike the Mohorovičić discontinuity, and (b) was too deep to coincide with the discontinuity under the oceans. The alternative hypothesis was a fertile peridotitic upper mantle with the capacity to yield basalt by partial melting and whose model composition was termed "pyrolite" (e.g. Ringwood, 1962; Green and Ringwood, 1963, 1967b; see Green, 1998). The peridotite hypothesis was definitely accepted when, around 1971, peridotite massifs in thrust ophiolites were identified as being fragments of the upper mantle (e.g. Davies, 1971; Bezzi and Piccardo, 1971; see Section 3.2).

Indeed, eclogite xenoliths from kimberlites do exist and demonstrate the presence of eclogite in the mantle, though as a minor constituent. The origin of these mantle eclogites has been a matter of debate during the three last decades. While some authors proposed an origin as mantle cumulates or melts, others postulated models for an origin as subducted oceanic crust (see e.g. Schulze and Helmstaedt, 1988; Dawson and Carswell, 1990, pp. 344–348). This question is still debated nowadays. Possibly, eclogites of both origins exist.

3.2. Ophiolitic eclogites: a record of subduction

Around 1970, the discussion on eclogite left the so-called eclogite layer to focus on subduction zones where, according to the new theory of plate tectonics, oceanic lithosphere was subducted. In a

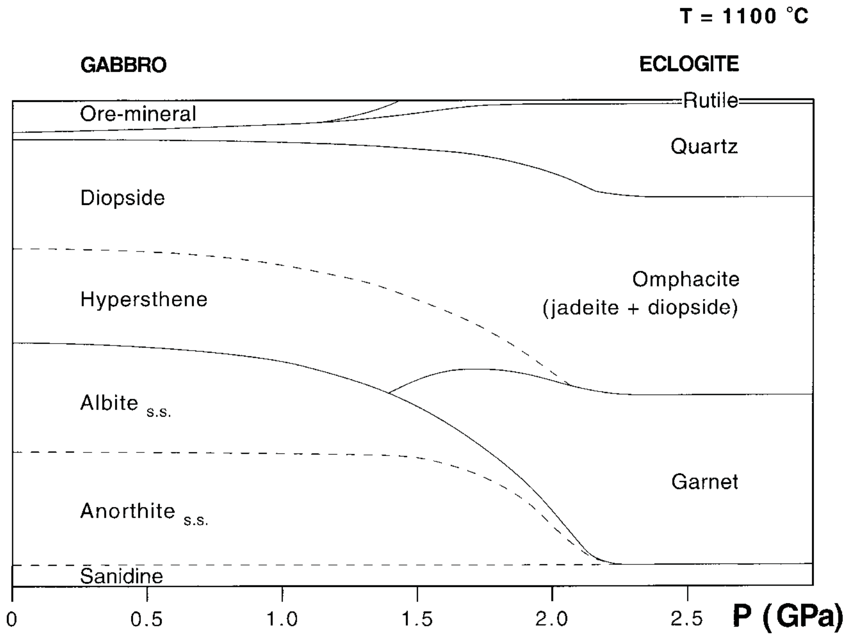

Fig. 6. "Diagrammatic representation of the change of mineralogy with change of pressure at 1100 °C in the quartz tholeiite composition" (from Green and Ringwood, 1967a). The gabbro-to-eclogite transition was investigated experimentally by Green and Ringwood in 1966–1967. The results showed that the transition is progressive and occurs at high-pressure conditions (see text).

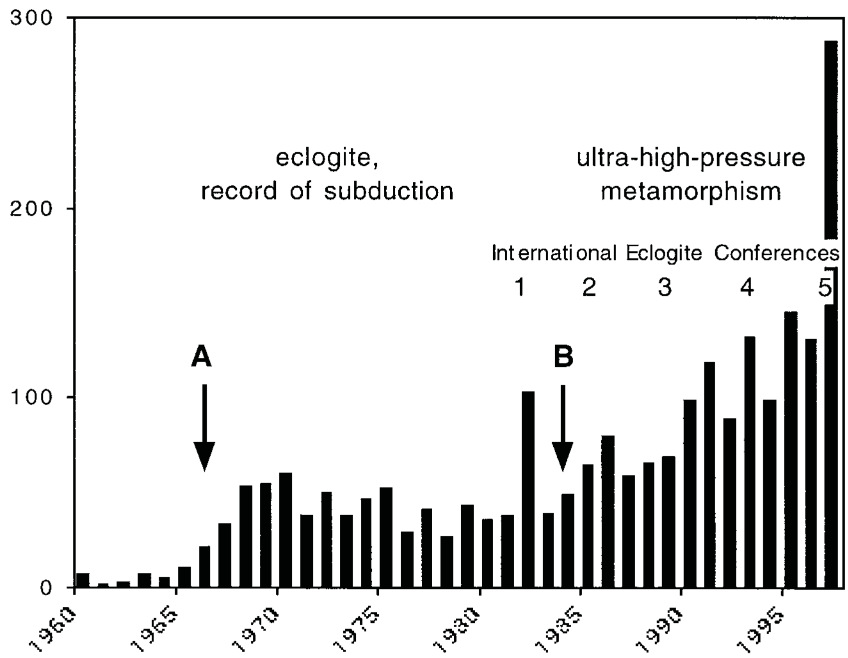

Fig. 7. Frequency histogram of references on eclogite in the geological literature. Vertical axis: yearly frequency of the word "eclogite" (or any related words) in the title of geological references. Source: Georef database (© SilverPlatter). A: beginning of plate tectonics; B: first discovery of coesite-bearing crustal rocks.

very few years, there was a complete renewal of hypotheses on Alpine-type glaucophane-bearing high-pressure belts, which came to be considered as relics of partly subducted oceanic crust.

It is again to de Saussure (1779–1796) that we owe the first description of glaucophanites. On the 20 August 1792, he visited the famous glaucophanite occurrence of Saint-Marcel (Aosta Valley, Italian Alps). He described the rock as composed of "*schorl bleuâtre*" (bluish schorl) and garnet (see note 2 in the Appendix). Much later, blueschists were also described in Greece by Hausmann (1845), who created the name glaucophane (from γλαυκός [bluish] and φαινω [to appear]). Strüver (1875), on the other hand, chose the name "gastaldite" for a similar blue amphibole of the Alps and this last name was used by Italian geologists until around 1900. Glaucophane-bearing rocks have been described in Greece (Hausmann, 1845; Lüdecke, 1876; Lepsius, 1893), in New-Caledonia (Jannettaz, 1867; Lacroix, 1941), the Alps (Strüver, 1875; Bonney, 1879, 1886; Cossa, 1880; Termier, 1891; Franchi, 1895, 1902b; Piolti, 1902; Zambonini, 1906; Dal Piaz, 1928), on the Île de Groix in France (Barrois, 1883; Lasaulx, 1883, 1884), Japan (Koto, 1887; Suzuki, 1924), Indonesia (Retgers, 1891), California (Palache, 1894; Ransome, 1894; Smith, 1906; Borg, 1956), and Venezuela (Dengo, 1950; Schürmann, 1950). Peculiar dense minerals such as lawsonite were considered typical of blueschists (e.g. Ransome, 1895; Franchi, 1897). Commonly, these glaucophanites were associated with ultramafites and glaucophane-bearing eclogites (e.g. Cossa, 1880; Piolti, 1902; Franchi, 1902b; Holway, 1904; Weinschenk, 1904; Smith, 1906; Dal Piaz, 1928). Furthermore, transitions to unmetamorphosed gabbro or basalt were observed (e.g. Bonney, 1879; Koto, 1887; Lepsius, 1893; Franchi, 1895; Holway, 1904; Smith, 1906; Zambonini, 1906; Lacroix, 1941; Bearth, 1959, 1970; Coleman and Lee, 1963). Consequently, blueschist terrains clearly appeared as metamorphosed "ophiolites".

The modern concept of ophiolite results from a long and confused evolution. Alexandre Brongniart created the name in 1827 to describe serpentinites. It was derived from the Greek 0φις meaning snake, with reference to serpentine pseudomorphs after olivine, a structure that resembles the skin of a snake. It was first applied as an alternative for serpentinite, a name which is itself derived from the Latin "serpens" (snake) for the same reason. Steinmann (1927) elevated ophiolite from a rock term to a rock association of serpentinised peridotites, gabbros and dolerites (see: Coleman, 1977b; Green, 1971). This "Steinmann trinity" became considered as typical of Alpine-type orogens and was thought to form by the intrusion and eruption of igneous rocks on the floor of a "geosyncline" (e.g. Brunn, 1960, 1961; see Wyllie, 1970). The latter concept of geosyncline had been created by Hall (1859), theorised by Dana (1873) and further developed by Haug (1900) (see: Knopf, 1948; Aubouin, 1965; Schneer, 1997). It foreshadowed the ocean of modern plate tectonics. A geosyncline was a deep marine basin where sediments were deposited and then involved in an orogen. As a weak zone in the crust, it was regarded as the preferred site for tectogenesis and the development of a subsequent orogenic belt.

Schürmann (1951–1956) showed that blueschists and eclogites were localized in high-pressure belts, which he interpreted as remnants of ophiolite-bearing geosynclines that had disappeared during tectogenesis. The high-pressure metamorphism of these ophiolites was generally attributed to load metamorphism caused by tectonic burial during thrust faulting (e.g. Blake et al., 1969; Niggli, 1970; Frey et al., 1974). Miyashiro (1961) showed the existence, in the circum-Pacific region, of low-pressure belts arranged parallel to the ophiolite-bearing high-pressure belts. He envisaged that such paired metamorphic belts might correspond respectively to the margin and the centre of a geosyncline.

Although the geosyncline theory prefigured in some way modern plate tectonics, the advent of the latter radically modified the interpretation of ophiolite and blueschist terrains. Gass (1968) proposed that ophiolites were fragments of the ocean floor. Soon afterwards, Moores and Vine (1971) regarded them as representing an ancient oceanic crust. Thus, "geosynclines" became "ocean basins". Furthermore, the sea-floor spreading theory, conceived in the 1960s by, among others, Dietz (1961), Hess (1962, 1965), Vine and Matthews (1963), Hurley (1968) and Le Pichon (1968), had the subduction of oceanic crust as a necessary corollary (Wilson, 1965). The term "subduction", from *sub-* [under] and *ducere* [to pull], was introduced as early as 1951 by André Amstutz to designate the abrupt descent of a segment of lithosphere. After the "Penrose Conference" of December 1969, it came to be used as a plate tectonic concept (White et al., 1970; see: Dickinson, 1970; Lanterno, 1982). The subduction of oceanic lithosphere was also in agreement with the seismic zones that Wadati (1935) and Benioff (1954, 1955) had already defined.

Subduction of an oceanic crust to depths should logically produce eclogite. Very surprisingly, Arthur Holmes, a professor of geology at the University of Durham (England), had already imagined a close hypothesis as early as 1931. In an article entitled "Radioactivity and Earth movements", Holmes (1931) invoked convection currents in the substratum of the continents to explain continental drift (Fig. 8; see note 4 in the Appendix). Because of the radioactivity, the temperature should be higher beneath the continents than under the ocean. Therefore, currents would rise under continents, spread horizontally, and move downward under oceans in "subsidence" zones where eclogite would form, resulting from "directional pressure" (see note 4). Being heavy, the eclogite is carried down and thus contributes to the convection. On the other hand, Holmes did not understand the rifting process [see Fig. 8(c)]. This hypothesis of eclogite formation was ignored at the time. The supporters of Alfred Wegener's theory did not understand the implications of Holmes's convection currents on the continental drift theory (see Gohau, 1991).

Indeed, the idea that oceanic crust can be transformed into eclogite in subduction zones emerged during the years 1970–1975 and, naturally, high-pressure belts came to be considered as metamorphosed oceanic lithosphere (e.g. Coleman, 1971, 1977a,b; Ernst, 1971, 1975a,b; Fry and Fyfe, 1971; Maresh, 1972; Miyashiro, 1972, 1973; Nagle, 1974; Platt, 1975; Råheim and Green, 1975; Erdmer and Helmstaedt, 1983). The paired metamorphic belts of Miyashiro (1961) were reinterpreted in the light of the new subduction zone model (e.g. Oxburgh and Turcotte, 1970) as resulting from the contrasted thermal gradients between the cold subducting oceanic slab and the edge of the island arc (e.g. Miyashiro, 1967, 1972, 1973; Ernst et al., 1970). The high-temperature retrogression of many high-pressure belts—i.e. a clockwise P–T path—was explained by a return to a more normal geothermal gradient once subduction had stopped (e.g. Ernst et al., 1970). Furthermore, Green and Ringwood (1968) demonstrated that partial melting of eclogite could give rise to the calc-alkaline magma series occurring in island arcs above subduction zones. The last piece of the puzzle to fall into place was the emplacement mechanisms for high-pressure terrains during tectogenesis, i.e. continental collision (e.g. Laubscher, 1969) or obduction (e.g. Coleman, 1971, 1977a,b). Within 10 years, plate tectonics had radically modified our understanding of high-pressure belts.

3.3. Eclogites enclosed within gneisses: "in-situ versus foreign" controversy

Because the model of oceanic crust subduction proved successful and fruitful in the case of Alpine-type blueschist terrains, many authors, including myself, tried to apply the model to eclogites enclosed within gneisses in ancient orogens. Subduction, continental collision and obduction were the master keywords in the literature on eclogites during the 1980s (see: Kienast,

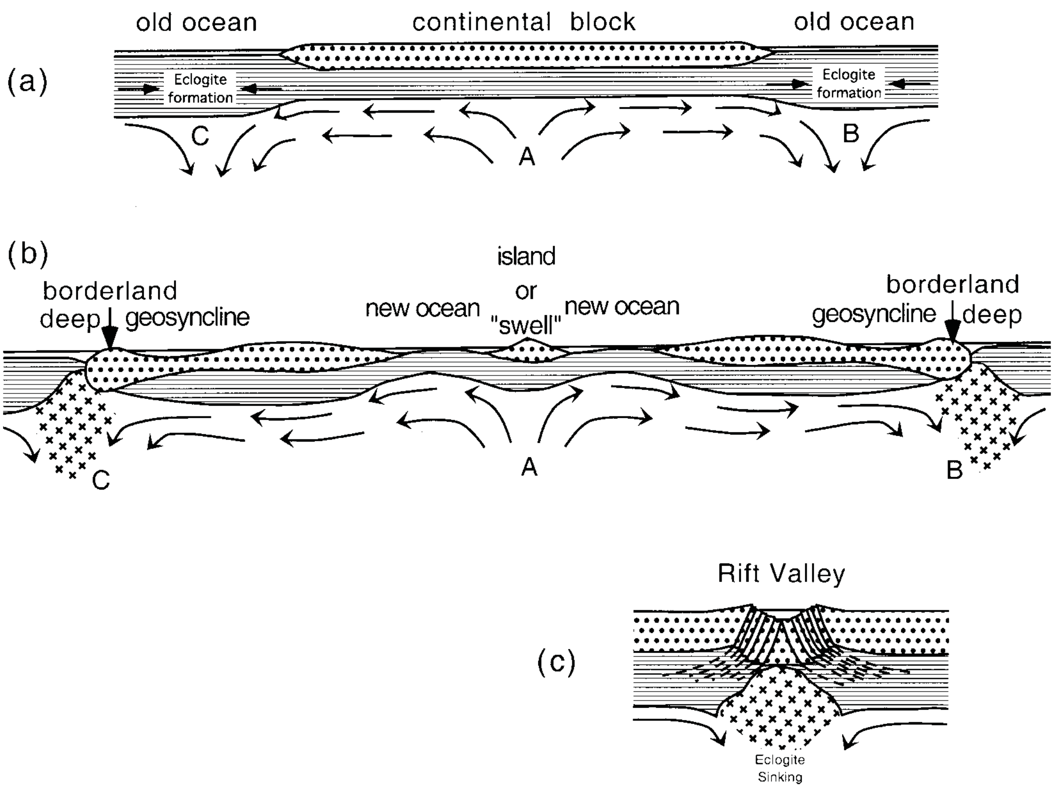

Fig. 8. Holmes's hypothesis for eclogite formation (Holmes, 1931). This hypothesis foreshadows the modern concept of subduction zone. (a): "Sub-continental circulation. Upper or sial layer, dotted. Intermediate layer (amphibolite, gabbro, etc.) line-shaded. Substratum, unshaded." (b): "Distension of the continent on each side of A leaving an island or ≪swell≫ in the ≪dead≫ area above A. Above B and C eclogite formation results from the crystallisation of the material of the intermediate layer, and oceanic deeps are produced. The front part of the sial is thickened and a borderland results. Behing this, one effect of the heat transport from A to B or from A to C is the development in each case of a geosyncline." Crosses in c and b represent sinking blocks of eclogite. (c): "Illustrating the formation of a rift valley by subsidence of the sial over the belt of eclogite formation.".

1983; Godard, 1988; O'Brien et al., 1990; Schmädicke, 1994). Even small and isolated eclogite boudins were often thought to derive from an ocean. This hypothesis was supported since the 1970s by geochemical studies indicating that some of these eclogites have geochemical features of Mid Ocean Ridge Basalts (e.g. Montigny and Allègre, 1974). Moreover, many eclogites revealed an early *P–T* history apparently different from their surrounding gneiss, and this could be interpreted as resulting from the accretion of an eclogitised oceanic crust during continental collision.

As a matter of fact, the major problem concerning these eclogites was their relationship with the surrounding gneisses, which frequently do not show any evidence of eclogite-facies metamorphism. Several solutions have been proposed to explain this inconsistency: rejection of the high-pressure conditions of formation for the eclogites (see Section 2.4); formation of the eclogites at mantle-depths and subsequent emplacement in their surrounding gneiss during a plastic deformational event; formation of the eclogites in situ in their present host gneisses, followed by a late obliteration of the eclogite-facies parageneses in the surrounding gneiss. The debate evolved into a controversy, which mainly concerned the eclogites of Norway ("in situ versus foreign origin": see Smith, 1988b, pp. 8–11; Schmädicke, 1994). Although not completely solved, the problem is less topical nowadays.

A careful examination of the gneiss has shown that eclogite-facies relics do exist in some of these rocks. There is now a tendency to consider that eclogite-facies parageneses are much more easily preserved in eclogite than in gneiss, where the combined effects of fluids, plasticity and kinetics lead to recrystallisation during retrogression (e.g. Rubie, 1990; Schmädicke, 1994).

The origin of eclogites enclosed within gneisses of ancient orogens is still obscure. Several hypotheses are generally envisaged: subduction of oceanic crust subsequently incorporated into orogenic belts during continental collision, high-pressure metamorphism of a sialic crust or, even, tectonic emplacement of mantle eclogites into the crust, together with peridotites. Furthermore, the problem has been further confused by the recent question of ultrahigh-pressure metamorphism.

3.4. *Ultrahigh-pressure metamorphism: still enigmatic*

Chopin (1984) described coesite inclusions and quartz pseudomorphs after coesite in garnet crystals of a pyrope quartzite from Dora–Maira (Italian Western Alps; Fig. 9). The ultrahigh-pressure polymorph of silica now known as coesite was first synthetized by Coes (1953). It was then discovered in kimberlite eclogites (Smyth and Hatton, 1977), but its presence in such diamond-bearing mantle rocks, though interesting, was not surprising. Discoveries of coesite in crustal rocks, on the other hand, drastically changed petrologists' ideas about the limits of crustal metamorphism. The scale of metamorphic pressure, all suddenly, reached 5 GPa.

The discovery of coesite by Chopin (1984) was nevertheless preceded by similar but more disputable discoveries. Chesnokov and Popov (1965) had already identified coesite pseudomorphs in eclogites from the south Ural Mountains. Knauer and Matthes (1970) also observed aggregates of radiating graphite in the Wessenstein eclogite (Bavaria). From their description, we can assert that these inclusions were probably pseudomorphs after diamond. Finally, Lappin and Smith (1981) proposed pressures as high as 3 GPa for eclogites of the Selje district in Norway. Unfortunately, these early discoveries remained ignored, perhaps because two of them were not published in English, but also because scientists were probably not ready to hear about ultrahigh-pressure metamorphism.

After Chopin (1984, 1987), other petrologists reported coesite or pseudomorphs after coesite in eclogites and eclogite-facies rocks. Sobolev and Shatsky (1986), Schreyer (1988), Coleman and Wang (1995), Chopin and Sobolev (1995) have given detailed historical accounts of these discoveries. Therefore, we only mention them here briefly. Coesite or quartz pseudomorphs after coesite have been reported from the Alps (Chopin, 1984, 1987; Reinecke, 1991), Norway (Smith, 1984), Dabieshan and "Su-Lu" in eastern China (Yang and Smith, 1989; Okay et al., 1989; Wang et al., 1989, 1993; Enami and Zang, 1990; Hirajima et al., 1990; Brunel et al., 1991; Okay, 1993; etc., see Wang et al., 1995), Kazakhstan (Tagiri and Bakirov, 1990), Urals (Chesnokov and Popov, 1965; Lennykh et al., 1995), Saxony and Sudetes in Europe (Schmädicke, 1991; Bakun-Czubarow, 1991), and Mali (Caby, 1994). New high-pressure minerals were discovered (ellenbergerite, Mg-carpholite...). More surprisingly, microdiamond inclusions or graphite pseudomorphs after diamond have also been discovered in Morocco (Beni Bousera peridotite massif: Pearson et al., 1989), Russia (gneiss of the Kokchetav massif: Sobolev and Shatsky, 1987, 1990), eastern China (Dabieshan eclogite: Xu et al., 1991; Zhang et al., 1991), Norway (gneiss on Fjörtoft island: Dobrzhinetskaya et al., 1993, 1995; see Smith, 1995) and Saxony (gneiss in the Erzgebirge: Nasdala and Massonne, 2000). Haggerty and Sautter (1990) presented petrological evidence for an ultradeep (>300 km) origin of some ultramafic xenoliths from kimberlites, corresponding to depths as low

Fig. 9. The first coesite inclusion discovered in a crustal rock by Christian Chopin in 1984 (© Ch. Chopin). Coesite inclusions are surrounded by a quartz corona that developed during retrogression. The increase of volume due to the coesite→quartz transition produced radiating fractures in the host garnet. This observation, together with similar subsequent discoveries, was at the origin of the concept of ultrahigh-pressure metamorphism. 0.9 cm on the photo = 0.1 mm (i.e. width of the photo = 1.185 mm).

as the mantle transition zone. Surprisingly, several authors (e.g. Yang et al., 1993; Dobrzhinetskaya et al., 1996; Van Roermund et al., 2000) also presented similar evidence for garnet peridotites enclosed in gneisses, but this is still a matter of debate (see arguments for and against in Green et al., 2000, and Trommsdorff et al., 2000, respectively).

Ultrahigh-pressure metamorphism has been a matter of considerable interest and debate during the last two decades. Currently, the problem is not so much the recognition of the reality of ultrahigh-pressure metamorphism as the geodynamic mechanisms that could explain how such deep rocks have been incorporated into the sialic crust and exhumed to the surface. The explanations advocated in the literature range from overpressure (see Smith, 1995, pp. 336–341) to exhumation favoured by erosion or tectonic thinning after continental collision (see Platt, 1993; Hacker and Peacock, 1995). Subduction down to depths of 250 km and subsequent exhumation of continental material have been confirmed by numerical models (e.g. Shemenda et al., 1996; Ranalli et al., 2000). However, the problem is far from being solved and will certainly remain an enigma for some time to come.

4. Conclusion

Eclogite is an example of a rock that has proved to have a kind of destiny in the history of the geological sciences. As we have seen, it has been at the origin of major concepts and developments in endogenous petrology (Section 2), and has been involved in many geodynamic hypotheses (Section 3). The fundamental reason for this particularity may be linked to the hybrid nature of this rock, which is crustal by its composition and origin, but already belongs to the mantle because of the deep structural level where it is formed. Whatever the reasons, eclogite studies over two centuries have produced numerous questions, hypotheses, theories and controversies, which all together have been exceptionally fruitful. They represent a nice example of the relevance and efficiency of the inductive method in science, which is based on the accurate observation of facts.

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Appendix

Note 1: Creation of the name "eclogite" by René-Just Haüy (1822). Eclogite samples in Haüy's collection

Note 1a: Haüy (1822), vol. 2, p. 456: "Dans la première [de trois roches primitives], la diallage est considérée comme faisant fonction de base, et forme avec le grenat une combinaison binaire à laquelle sont censés s'unir accidentellement le disthène, le quarz, l'épidote et l'amphibole laminaire. J'ai donné à cette roche le nom d'*éclogite*, qui signifie *choix*, *élection* parce que ses composans, n'étant pas de ceux qui existent communément plusieurs ensemble dans les roches primitives, comme le feldspath, le mica, l'amphibole, semblent s'être choisis pour faire bande à part. Cette roche se trouve en Carinthie, dans le Sau-Alpe, et en Styrie."

Haüy (1822), vol. 4, pp. 548–549: "Eclogite (*). Diallage verte et grenat. Composans accidentels: disthène, quarz, epidote blanc vitreux, amphibole laminaire, fer sulfuré magnétique. [...] (*) d'εκλογή, *choix*, parce que les composans de cette roche n'étant pas de ceux qui existent plusieurs ensemble dans les roches primitives, tels le feldspath, le mica, etc., semblent s'être choisis pour faire bande à part."

Note 1b: Haüy's collection of rocks still exists at the *Galerie de Minéralogie*, *Muséum National d'Histoire Naturelle*, in Paris. It contains 7 samples that are labelled *éclogite* (505, 506, 509–513). All originate from "*Pays de Bayreuth*" (Bavaria). 505 and 506 are from "Hoff"; 510 originates from Gefrees, near Münchberg. All are definitely eclogites except 513, which contains too much feldspar to deserve the name eclogite. The collection catalogue mentions a few other eclogite samples that are now missing: 507, 508 (from Carinthia), 514, 517.

Note 2: Eclogite, eclogite micaschist and glaucophanite samples in Saussure's collection (18th century)

De Saussure's collection can be seen at the *Muséum d'Histoire Naturelle de Genève*, in Switzerland (see Lanterno, 1976). Each of the samples are arranged in a box, with a reference to the section in *Voyages dans les Alpes* (Saussure, 1779–1796), where the rock is described. Unfortunately, some disarrangement has occurred since 1779, and these references are not always correct. We list below those samples that we have identified as being eclogite, eclogite micaschist or glaucophanite (# refers to the sample number in the collection, and § to the section in *Voyages dans les Alpes*). Note that de Saussure called "schorl" any kind of dark or greenish mineral with prismatic habits, such as amphibole, pyroxene and tourmaline.

#41392, 41393 (§194 [doubtful; possibly §145]): pebbles composed of a beautiful eclogite, Rhone valley near Geneva ("*roche grenatique prise dans les environs de Genève*").
#41526, 41527, 41530 (§647, §649): amphibolitised eclogite with kelyphite coronae, Le Brévent, Haute-Savoie, France ("*Je trouvai cependant sur la cime* [du Brévent] *une roche composée de schorl noir en aiguilles, de quartz & de grenats* [dont la] *forme étoit exactement rhomboïdale*").
#41790 (§965): retrogressed and foliated eclogite, with an "eclogite micaschist" layer, Montjovet, Aosta Valley, Italy ("[along the road near Mont-Jovet,] *alternatives continuelles de stéatites, de roches de corne, de schorl, de grenats & d'une roche mélangée de quartz, de mica & de pierre calcaire*").
#41791, 41793 (§965, §966): beautiful layered and light-coloured eclogite, Montjovet, Aosta Valley, Italy ("[along the road near Mont-Jovet,] *on rencontre des rochers composés d'un mélange de schorl verd foncé en aiguilles brillantes & de grenats rouges en masse ou confusément crystallisé*").
#41795 (§966): retrogressed eclogite, Montjovet, Aosta Valley, Italy ("*roche schisteuse grenatifère*").
#42560 (§2282): amphibole-rich light-coloured rutile-bearing eclogite, Mont-Cervin, Valais, Switzerland ("*amphibolite à grenats*").
#42571-42573 (§2293): glaucophanite [# 42572: typical garnet glaucophanite], from Saint-Marcel, Aosta Valley, Italy ("*schorl bleuâtre*").

Note 3: The hypothetical eclogite-bearing "infra-plutonic zone", as a consequence of the volume law, by L. L. Fermor (1912)

"[...] I was led to consider various other garnetiferous rocks, such as eclogite, and to arrive at the conclusion that the deeper one goes in the earth's crust the more abundant must the garnets become, on account both of the increasing pressure and of the increasing temperature, the high temperature inducing the molecular mobility necessary to permit the constituents of pyroxene, olivine, and anorthite, to rearrange themselves as the denser molecule garnet. The conclusion drawn was that below a certain depth all the ferromagnesian minerals, such as pyroxene, amphibole, olivine, and biotite, with anorthite, have rearranged themselves as far as possible into garnets, for thereby the maximum reduction in volume and absorption of heat is effected.

At present, petrologists regard the plutonic rocks, such as granite and gabbro, as the most deep-seated known rocks. But, under the effects of enormous pressures, the granites should become garnetiferous and the gabbros be converted into eclogites, and the conclusion seems inevitably to follow that beneath the rocks now known as plutonic there must be a zone of garnetiferous rocks extending downwards in a plastic-solid form as far as the presumed metallic core of the earth. For this zone, unless a better term suggests itself, I propose the name *infra-plutonic*.

The characteristic minerals of the infra-plutonic zone will be those that occupy the least volume. The commonest mineral in the basic rocks will be *garnet*, and the nature of the associated minerals will depend upon the excess constituents left over after the maximum possible number of garnets has been formed. They will be various varieties of pyroxene or olivine, with occasional anorthite feldspar. One other mineral may be specified as characteristic of the basic infra-plutonic rocks, namely *diamond*, which may be regarded as the molecularly dense form of the graphite occurring in rocks nearer the surface.

Normally, the infra-plutonic rocks will not reach the earth's surface, as their upward passage must in most cases be accompanied by a reduction of pressure whilst the temperature is still high, enabling the garnets to break down, with increase of volume, into less dense minerals such as pyroxene and olivine. Under certain circumstances, however, particularly if a slow reduction in pressure is accompanied by a more rapid reduction of temperature, due to the lowering of the isogeotherms in a given part of the earth's crust, we may expect the eclogites finally to arrive at the surface; although even then there may often be a partial breaking up of the garnet with the production of the well-known *kelyphite* rims or *reaction borders* of some garnetiferous peridotites.

It is interesting to note that the original matrix of diamond proves in almost every case to be some form of peridotite or eclogite. For instance, the blue ground of the diamond-bearing pipes of Kimberley is a brecciated mass of altered peridotite and eclogite with scattered diamonds, and these pipes have evidently been filled from great depths below the earth's crust. It is possible that they have tapped the infra-plutonic zone."

Note 4: Formation and sinking of eclogites in "subsidence" zones [i.e. subduction zones], by A. Holmes (1931, pp. 580–583)

See Fig. 8.

We must [...] consider what will happen at the continental margins, or generally, where two [convection] currents meet and turn downwards. The crust above the zone of contact will be thrown into powerful compression and the amphibolite layer will tend to be thickened by accumulation of material flowing in from two directions. The observed effects of dynamic metamorphism at high temperature and differential pressure on such material lead us to expect that recrystallisation into the high-pressure facies, *eclogite*, will here take place on a large scale. The change of density from 2.9 or 3.0 to 3.4 or more, combined with the simultaneous operation of isostasy would lead to marked subsidence. Sinking of blocks of eclogite would also be facilitated by stoping promoted by the tongues of basaltic magma that would inevitably be present. Such foundering would effectually speed up the downward current for two reasons: the greater density of the sinking blocks, and the cooling of the substratum material in their vicinity.[. . .] We may notice that [eclogite formation] provides a mechanism for 'engineering' continental drift, and at the same time for discharging some of the excess heat generated in the substratum. Each part of the continental block would be enabled to move forward, partly by the fracturing and foundering of the belt of ocean floor weighed down with eclogite immediately in front, and partly by over-riding the ocean floor along thrust planes lubricated by magmatic injections from below. The hypothesis of eclogite formation is supported by the fact that it provides a reasonable explanation of oceanic deeps. It is consistent with their depths, as judged from the requirements of isostasy, and with their occurrence in front of the active orogenic arcs bordering the Pacific on the Asiatic and Austral-asiatic side. That oceanic deeps are under compression is the opinion of Meinesz. He sees in downward flexure under stress a reason for the local defects of gravity revealed over deeps by his gravity surveys of the oceans. Evidence of the foundering of blocks [of eclogite] is from the nature of the case not easy to find, but it may be forthcoming from the occurrence of deep earthquakes (arising from 100 km or more) off the coast of Japan, and by the signs of volcanic activity that have been detected in the floor of the Tuscarara Deep. The upper or sialic layer of the continental margin will also be thickened by the differential flowage of its levels towards the obstructing ocean floor. Here thickening of the crust and mountain building will occur, and the mountain roots, unable to sink, will begin to fuse and give rise to igneous activity of the Circum-Pacific type with basalt-andesite-rhyolite volcanoes [. . .]. The time taken for a block of eclogite to fuse completely is probably of the order of 50 million years. Thus, sinking blocks should have nearly reached the bottom of the substratum before becoming entirely fluid, and streaks in the ascending currents should therefore be fed with magma much more nearly basaltic in composition than the general body of the substratum. The ascending currents will approach the surface in the region behind the advancing continent, and thus the new ocean floor is likely to receive the whole of the basaltic material available. With ascending currents of such relatively light material, and descending currents made relatively dense by the presence in them of eclogite blocks, the whole circulation will be speeded up while continental drift is in progress [. . .]."

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