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The Variscan French Massif Central—a new addition to the ultra-high pressure metamorphic 'club': exhumation processes and geodynamic consequences

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Abstract

This paper presents the first documentation of coesite-bearing eclogites in the eastern French Massif Central (Monts du Lyonnais unit) and discusses the exhumation processes for these very high-pressure rocks. A combination of mineralogical and geochronological datasets allows us to quantify a depth-time path and related exhumation rates. High-pressure metamorphism is constrained to 400–420 Ma (minimum 28 kbar or ca. 90 km). By 360–380 Ma, the rocks were exhumed to 30 km depth. These kinetic results conform to the geological constraints extracted from the tectonic and sedimentary record of the eastern French Massif Central.

These multidisciplinary approaches provide new information on Paleozoic orogeny and allow us to discuss the relative roles of subduction and collision in exhumation of very high-pressure rocks. We suggest that a significant amount of exhumation of these rocks occurred during subduction, prior to continental collision; continental collision itself was responsible only for the final stages of exhumation under a transpressive regime. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: coesite; French Massif Central; exhumation processes; Variscan belt

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1. Introduction

Since its first report, as a 'shock' phenomenon from Meteor Crater, Arizona (Chao et al., 1960), coesite has garnered much attention as an ultrahigh-pressure (UHP) metamorphic mineral from eclogites in mountain belts of different ages and in apparently varied tectonic settings (e.g. Chopin, 1984; Smith, 1984; Okay et al., 1989; Wang et al., 1989; Enami and Zang, 1990; Wang and Liou, 1991; Chopin et al., 1991; Reinecke, 1991; Schertl et al., 1991; Schmädicke, 1991; Xu et al., 1992; Li et al., 1993; Okay, 1993; Zhang and Liou, 1994; Eide, 1995; Wain, 1997). The common point of interest underlying these studies has been the need to subduct crustal material to depths >100 km to produce coesite and related UHP minerals (microdiamonds for example, see Dobrzhinetskaya et al., 1995), as well as the need to exhume these rocks under conditions that maintain the minerals under earth surface conditions (see reviews in Carlswell, 1990; Coleman and Wang, 1995; Spalla et al., 1996). Therefore, these minerals and the understanding of their genesis and preservation have been deemed crucial for understanding lithosphere dynamics.

From the Paleozoic eclogites of Europe, coesite-bearing assemblages have been reported in the Norwegian Caledonides (Smith, 1984), in the Polish

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Sudetes (Bröcker and Klemd, 1996) and in the Saxonian Erzgebirge (Schmädicke et al., 1992) but were previously unknown in the axial zone of the Variscan belt (i.e. Moldanubian zone), even if very high- pressure metamorphic conditions were locally recognized (Kotkova et al., 1998; Vrana, 1998). The purpose of this study is thus (1) to present the first report of coesite within Paleozoic eclogites from the French Massif Central; (2) to discuss the depth-time path analysis of these rocks; and (3) to interpret their exhumation in light of the geological evolution of the eastern French Massif Central. The addition of yet another eclogite-bearing collisional belt to the UHP realm suggests that the conditions for their genesis are not necessarily 'unusual'; this should perhaps lead in the future to a common adjustment in the general dynamics and physical-chemical properties we utilize as inputs for models of the evolution of mountain belts.

2. Geological setting

2.1. The French Massif Central in the Variscan belt

The Variscan orogenic belt in western Europe marks the continental collision zone between Laurasia to the north and Gondwana in the south (Dewey and Burke, 1973; Bard et al., 1980; Matte, 1986, 1991; Franke, 1989). The French Massif Central, with probable Gondwana origin, lies in the western part of the Variscan Belt and experienced orogenic events from Late Silurian-Early Devonian (average age for high-pressure metamorphism, Pin and Peucat, 1986; Ledru et al., 1989) up to Late Carboniferous times. The latter period was dominated by a major extension due to a gravity collapse of the belt (Ménard and Molnar, 1988; Burg et al., 1990; Malavieille et al., 1990; Van Den Driessche and Brun, 1991; Faure, 1995). Crustal thickening is well documented from Middle-Late Devonian up to Early Carboniferous time via the stacking of two main gneissic units or 'internal nappes' (Burg and Matte, 1978; Burg et al., 1984; Ledru et al., 1989 1994a; Fig. 1) comprising an upper, originally deep-seated metamorphic unit, with the so-called leptyno-amphibolite group at its base (Santallier et al., 1988), resting upon a medium-grade, frequently anatectic, gneissic series. The gneissic series contains primarily continental metasediments of late Proterozoic to early Paleozoic ages intruded by some early Ordovician magmatic rocks. The internal nappes overlie the southern Paleozoic complex, a para-autochthon, composed mainly of micaschists with local orthogneisses (Ledru et al., 1994b).

The high-pressure metamorphic rocks of the French Massif Central are mainly located in the upper gneissic unit within the leptyno-amphibolite group (Santallier et al., 1988; 1994). The latter is an association of metagreywackes, micaschists, metabasalts, metadolerites, metagabbros, "leptynites", metarhyolites, metagranites and peridotites. Eclogites are associated with acid and mafic high-pressure granulites (Forestier et al., 1973; Nicollet and Leyreloup, 1978; Pin and Vielzeuf, 1983) and also with spinel and/or garnet lherzolites (Lasnier, 1968a,b, 1977; Gardien et al., 1988, 1990). The protoliths of the Massif Central eclogites correspond to mafic magmas of oceanic affinities that originated in oceanic, arc or back-arc domains (Cabanis et al., 1983; Briand et al., 1988; Dubuisson et al., 1988; Bodinier et al., 1988; Downes et al., 1989; Paquette et al., 1995). Calculated pressures for eclogite facies metamorphism range between 13 and 20 kbar for temperatures in between 650 and 750°C (see reviews in Mercier et al., 1991; Matte, 1998).

2.2. The eastern French Massif Central.

A geological cross-section (Figs. 1 and 2) distinguishes the main units of the northeastern French Massif Central from north to south: the Morvan and Beaujolais units, the Devonian Brevenne ophiolitic unit, the Monts du Lyonnais unit, the Stephanian intracontinental basin of St. Etienne, and the Velay migmatitic complex.

The Morvan and Beaujolais units primarily comprise Carboniferous subalkaline granitoids (Ploquin et al., 1994), intrusive within small remnants of an eclogite-bearing gneiss unit, and Visean volcano-sedimentary deposits (Feist et al., 1994). In the Beaujolais area, a Devonian ophiolite, associated with the Brevenne unit (see also below), forms an elongated and NE-trending zone unconformably overlain by Visean sediments (Sider et al., 1986; Ploquin et al., 1994).

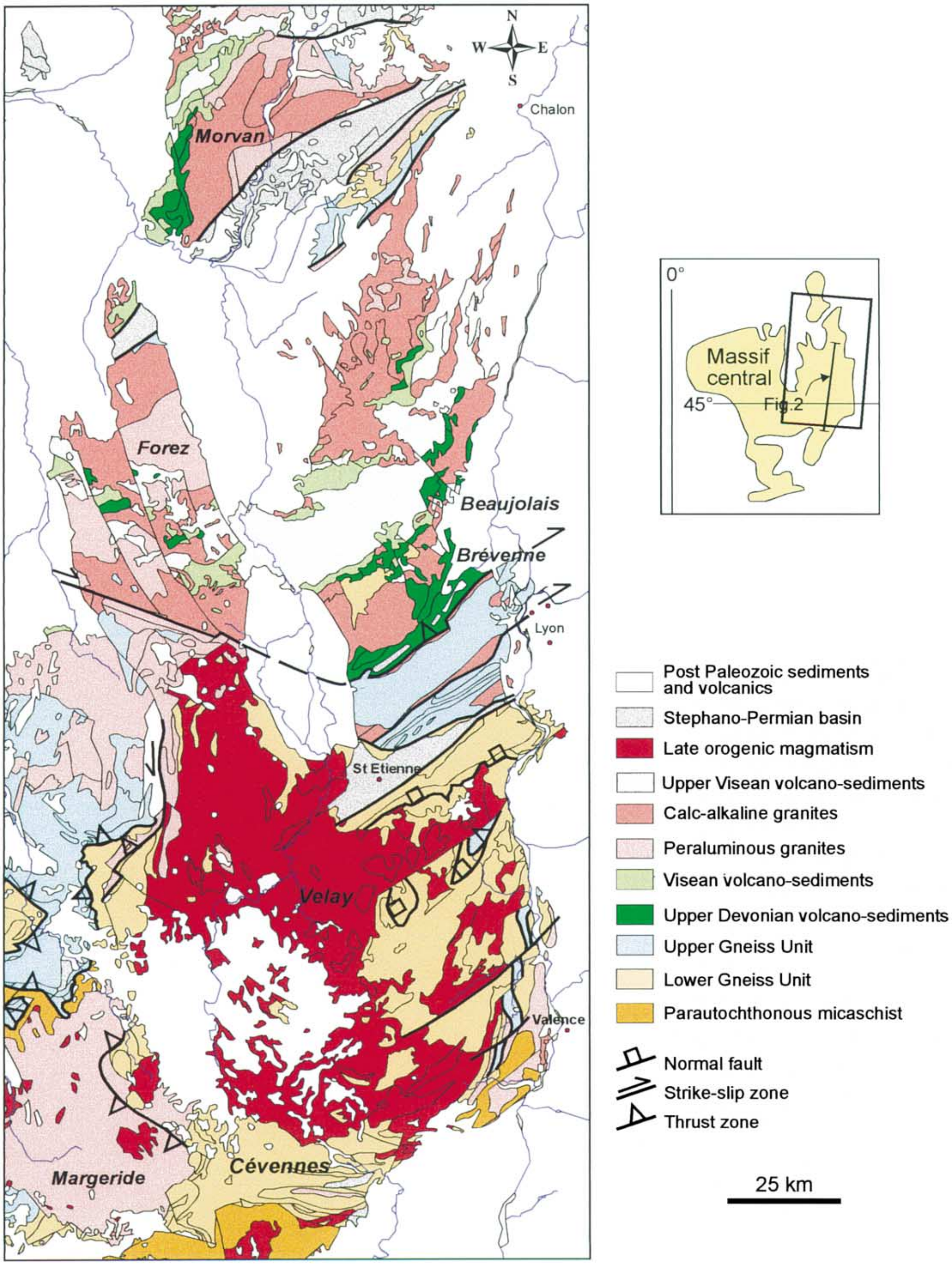


Fig. 1. Geological map of the Northeastern French Massif Central (modified after the 1/1.000.000 Geological Map of France).

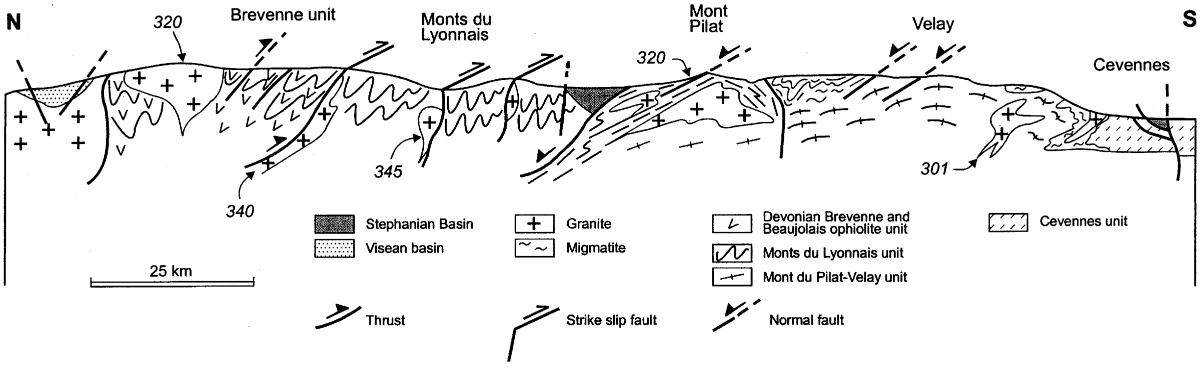


Fig. 2. North–South cross section of the northeastern French Massif Central showing the main tectonic units and their structural relationships. The ages of some granites are indicated as a general chronological reference (see text for discussion).

The Devonian Brevenne ophiolitic unit consists of an association of metabasalts and metarhyolites intruded by trondhjemitic bodies (Peterlongo, 1970; Piboule et al., 1982, 1983). The ophiolitic unit was generated in a submarine environment, an interpretation supported by systematic intercalations of reef limestones with acid lavas (Pin et al., 1982; Delfour et al., 1989). These intercalations are cut and overlain by intrusive gabbros and dolerites and by submarine basaltic lavas that, in turn, are overlain by siltstones with pyroclastic intercalations (Milési and Lescuyer, 1989; Feybesse et al., 1996). The Brevenne metavolcanics have been affected by two deformation events progressively developed under greenschist facies conditions (Peterlongo, 1960; Fonteilles, 1968; Durand, 1981; Piboule et al., 1982; Feybesse et al., 1988). The ophiolitic unit is thrust over the Monts du Lyonnais unit along a dextral transpressional zone in which syntectonic granites were emplaced between 340 and 350 Ma (Gay et al., 1981; Feybesse et al., 1988; Costa et al., 1993). Monzonitic granites of Namurian-Westphalian age and a related contact metamorphic aureole postdate these Early Carboniferous events (Delfour et al., 1989).

The Monts du Lyonnais unit, part of the upper gneissic unit (Lardeaux, 1989; Ledru et al., 1989), comprises metasediments, orthogneisses with protoliths of Ordovician age, (Duthou et al., 1981; Dufour, 1982), leptynites (i.e. metarhyolites), amphibolites and minor marbles. This unit also contains lenticular relics of either crustal (mafic and acid granulites, eclogites, Lasnier, 1968a,b; Coffrant and Piboule, 1971; Dufour, 1985; Dufour et al., 1985; Lardeaux et al., 1989) or mantle origin (garnet and/or spinel bearing peridotites; Gardien et al., 1988, 1990). Eclogites are exposed, in close association with garnet-bearing peridotites, in the southernmost part of the Monts du Lyonnais unit. Eclogites and related garnet amphibolites also occur in a similar structural situation farther north (in the Morvan area, Godard, 1990) and southeast (in the Maclas-Tournon area, Gardien and Lardeaux, 1991). In the Monts du Lyonnais unit, three ductile strain patterns are recorded (Lardeaux and Dufour, 1987; Feybesse et al., 1996) and related to high- and medium- pressure metamorphic conditions: (1) relict high-pressure structures; (2) a NW–SE crustal shortening with a finite NNE–SSW stretching direction under amphibolite facies conditions; and (3) a deformation episode developed under a transpressional regime dated between 335 and 350 Ma (Gay et al., 1981; Costa, 1990; Costa et al., 1993) that corresponds to the main thrust-related deformation within the Brevenne ophiolite. A strong partitioning characterizes these tectonics (Fig. 2) and, in the southern part of the Monts du Lyonnais unit, the eclogites crop out exclusively in the strongly folded domains where they behave as rigid bodies in a deformed ductile matrix. We have never found any eclogitic body, even strongly retrogressed, within the shear zones.

The Stephanian intracontinental basin of St. Etienne formed in the hanging wall of the Mont Pilat extensional shear zone (Malavieille et al., 1990). The Mont Pilat unit, within the lower gneissic unit at the scale of the French Massif Central (Ledru et al., 1989), consists of aluminous micaschists, metapelites, orthogneisses and amphibolites (Chenevoy, 1964, 1970; Pitiot, 1984; Vitel, 1988; Gardien, 1990). This unit has a gently N-dipping foliation plane bearing a N–S stretching lineation. Numerous leucogranitic pods are oriented sub-parallel to this main foliation plane and have been dated at 322 ± 9 Ma (Caen-Vachette et al., 1984). Shear criteria are compatible with a top-to-the-north extension dated between 322 and 290 Ma (Malavieille et al., 1990; Costa, 1990; Gardien, 1990). This event was coeval with the development of low pressure-high temperature metamorphic conditions (3–5 kbar and 700–780°C, Gardien et al., 1997).

The Velay migmatitic complex the largest (120 × 100 km) granite-gneiss dome in France, comprises cordierite-bearing migmatites and monzonitic intrusives (Dupraz and Didier, 1988). The complex developed during a crustal-scale melting event that started under water-saturated conditions prior to 314 Ma and terminated under fluid-absent conditions around 300 Ma (Caen-Vachette et al., 1982, 1984; Mougeot, 1991) as a consequence of a regional high-temperature metamorphism (4–5 kbar and 800–850°C, Montel et al., 1986, 1992; Weber et al., 1986; Didier et al., 1987). In this context, cordierite-bearing granites are dated around 300 Ma (Caen-Vachette et al., 1982) and contain many metamorphic or magmatic enclaves (see Dupraz and Didier, 1988, for detailed discussion). The N–S structural asymmetry of the Velay dome is related to the interference of the horizontal expansion of the granitic dome during its emplacement and the regional scale asymmetric extension (Malavieille et al., 1990; Lagarde et al., 1993; Burg and Vanderhaegue, 1993).

3. Petrography of the Mont du Lyonnais eclogites

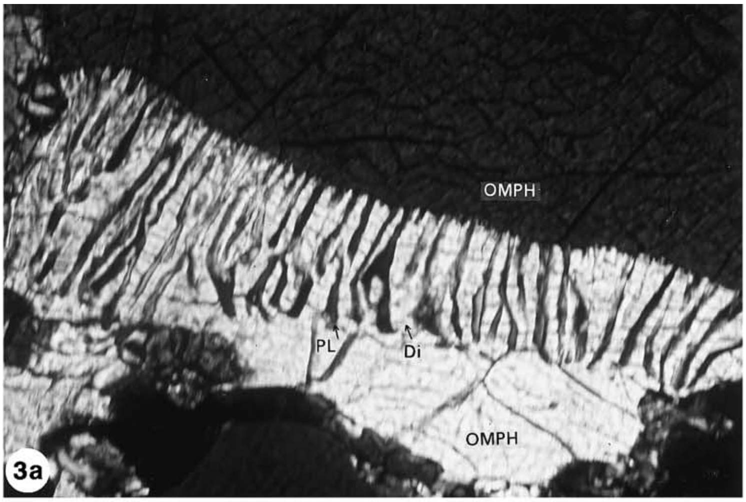
3.1. Field occurrence and sample descriptions:

The coesite-bearing eclogite occurs in the southern part of the Monts du Lyonnais unit, near St. Joseph in the Bozançon valley (1/50,000 geological map 'St Symphorien Sur Coise'; Feybesse et al., 1996) in association with 'common' eclogites and serpentinites. In the whole area, eclogites are preserved in low-strain lenses (meter-scale boudins) wrapped by amphibolites or amphibolite facies paragneisses. As a general rule, the eclogites from the Monts du Lyonnais unit are strongly retrogressed under granulite and amphibolite facies conditions and in 80% of the cases, the mafic boudins are composed of garnet-bearing amphibolites with relics of eclogitic minerals. Petrographically, three types of eclogite facies rocks can be distinguished: (1) fine-grained, dark-colored, kyanite-free eclogites, (2) fine- grained light-colored, often kyanite-bearing eclogites and (3) coarse-grained metagabbros (with coronitic textures) only partly re-equilibrated under eclogite facies conditions. As pointed out by various authors (Coffrant and Piboule, 1971; Coffrant, 1974; Blanc, 1981; Piboule and Briand, 1985), dark-colored eclogites are iron- and titanium-rich ($Fe0 + Fe_2O_3$ near 13% and TiO_2 >2%), aluminium-poor metabasalts (Al_2O_3 near 13–15%), while light- colored eclogites have higher aluminium contents (Al_2O_3 near 17–20%), and higher average magnesium values but lower titanium contents (TiO_2 <1,3%). Detailed geochemical investigations (Blanc, 1981; Piboule and Briand, 1985) have shown that these eclogites can be regarded as the variably fractionated members of a tholeiitic volcanic suite.

In the less retrogressed samples, the following mineral assemblages, representing the relicts of eclogite facies metamorphism, are recognized in the dark (1,2) and light (3,4) eclogites from the Monts du Lyonnais:

1. Garnet–omphacite–quartz–zoisite–rutile–apatite–sulfides,
2. Garnet–omphacite–quartz–zoisite–colorless amphibole–rutile–sulfides,
3. Garnet–omphacite–quartz or coesite–zoisite–kyanite–colorless amphibole–rutile,
4. Garnet–omphacite–quartz–zoisite–kyanite–phengite–rutile.

All these eclogites display, to varying degrees, evidence for secondary mineral reactions during decompression (Fig. 3a). The early stages of retrogression are characterized by the destabilization of omphacite into a coarse-grained symplectite of clinopyroxene (30% jadeite content) and plagioclase. This symplectite may also evolve into a late-stage globular microstructure (Fig. 3b), composed of constricted and fragmented plagioclase lamellae that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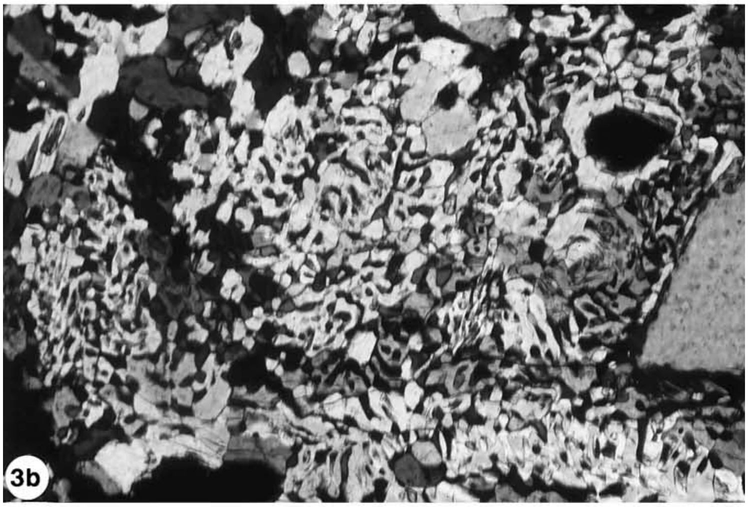
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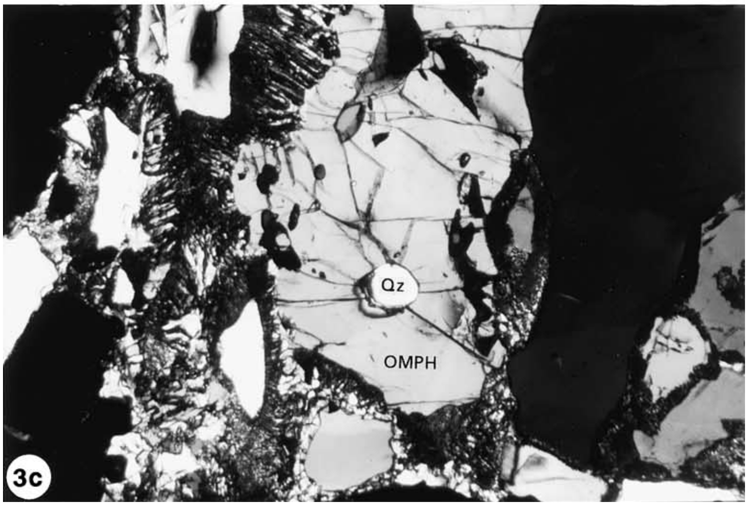
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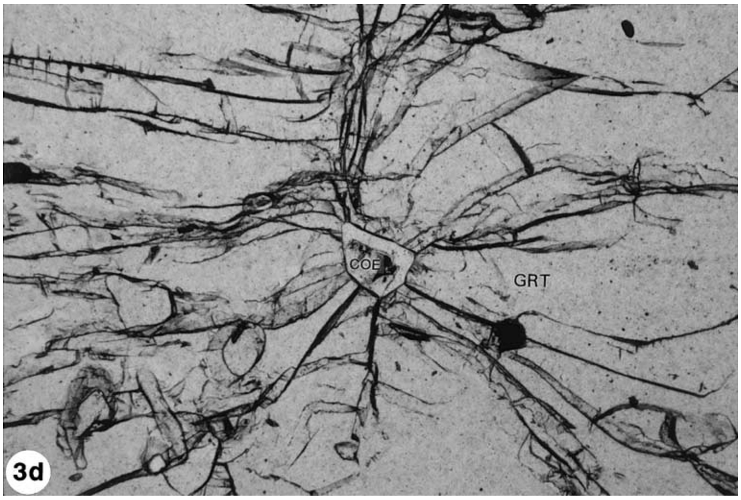


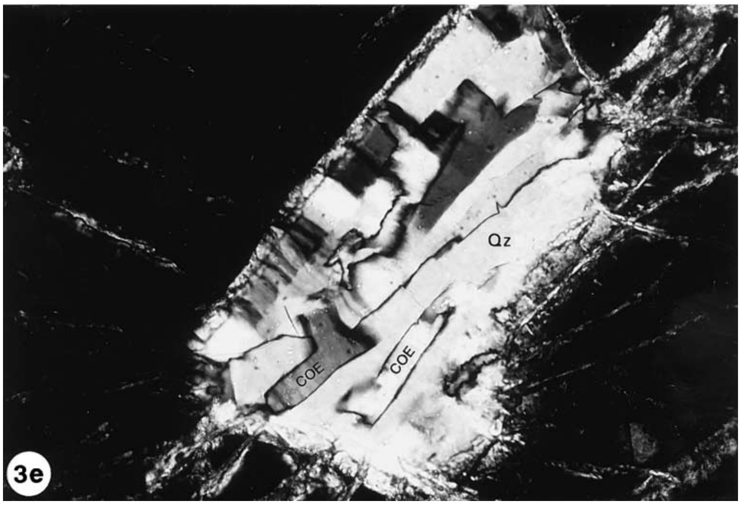


Fig. 3. (*continued*)

give rise to individualized globules of jadeite-poor clinopyroxene (5–10% jadeite content; Joanny et al., 1991). Later in this continuous retrogression process, clinoamphibole occurs instead of clinopyroxene. During retrogression, eclogitic garnets are rimmed and progessively replaced by coronas of plagioclase and clinoamphibole, while rutile is replaced by ilmenite and/or titanite. In a majority of samples, the most advanced stage of retrogression constitutes poikiloblastic green amphiboles in association with oligoclase and biotite neoblasts.

Fig. 3. Microphotographs showing the characteristic mineralogical features of the Monts du Lyonnais eclogites. (a) Retrogressed eclogite with clinopyroxene-plagioclase symplectite developed at the expense of omphacite. (b) Strongly retrogressed eclogite with globular-like symplectite. (c) Exceptionally fresh eclogite with well preserved omphacite and rutile grains. Quartz inclusion in omphacite is surrounded by radial cracks. (d) Inclusion of coesite, partly transformed in quartz, in garnet from a kyanite-bearing eclogite. Note the high-relief of coesite, with respect to quartz, and the radial cracks, in the garnet, around the inclusion.

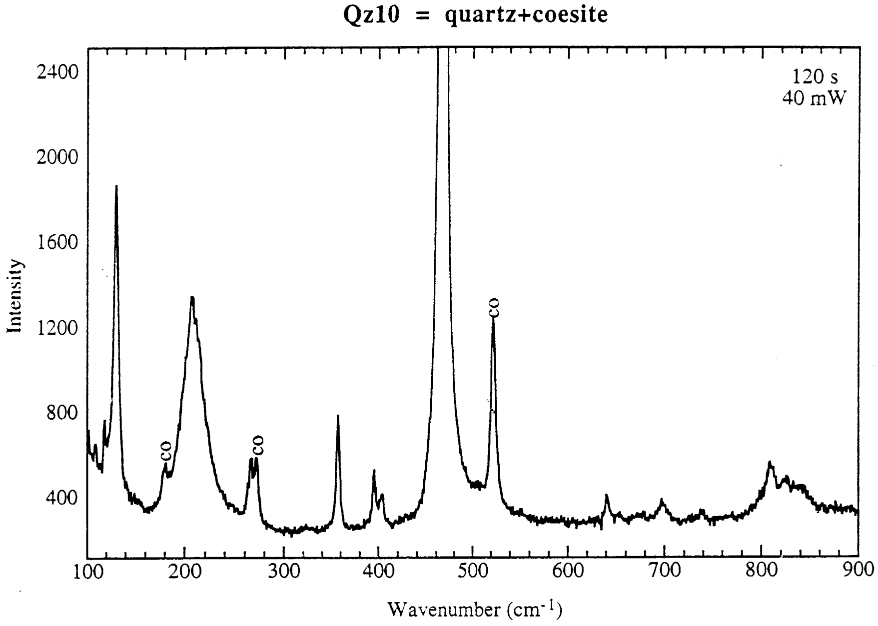


Fig. 4. Results of Raman spectrometry obtained on inclusion in garnet from the coesite- bearing eclogite. Typical Raman lines of quartz and coesite are indentified.

3.2. Occurrence of coesite and its pseudomorphs.

Coesite and quartz pseudomorphs after coesite were exclusively detected as inclusions in two garnet grains within one sample of kyanite-bearing eclogite (Fig. 3c). Silica polymorphs were distinguished optically, i.e. coesite was first positively identified relative to quartz by its higher refractive index (Fig. 3d) and was then confirmed with Raman spectroscopy by observation of the characteristics Raman lines 177, 271, 521 cm^{-1} (Fig. 4). Only two coesite grains are preserved as relics and, generally, coesite is completely transformed into polycrystalline radial quartz (palisade texture) or into polygonal quartz surrounded by radiating cracks. The extremely rare preservation of coesite in the Monts du Lyonnais eclogites results from the high-temperature conditions (near 750°C, see details in Dufour et al., 1985 and Mercier et al., 1991) reached during decompression as well as the consequence of fluid influx (hydration) during retrogression. Indeed, the kinetics of the coesite → quartz transformation are strongly temperature and fluid dependent (Gillet et al., 1984; Van der Molen and Van Roermund, 1986; Hacker and Peacock, 1995; Liou and Zang, 1996) and consequently, in the studied area, coesite has been almost entirely transformed into quartz.

4. Depth-time path analysis

A given P–T–t path reflects both the movement of a given sample in the crust and the thermotectonic evolution of the crust given that exhumation rates are different from uplift rates and that rocks behave as objects in a Lagrangian reference frame (see discussion in Duchêne et al., 1997, 1998). Therefore, understanding of exhumation velocities mandates a depth-time analysis. The latter is obtained by the appropriate mathematical combination of a P–T path with a T–t path by the formula $V_z = \mathrm{d}z/\mathrm{d}t = (1/\rho g)(\mathrm{d}P/\mathrm{d}t)(\mathrm{d}T/\mathrm{d}t)$, where V_z = vertical exhumation velocity, z = depth, t = time, ρ = density, g = gravitational constant, P = pressure, and T = temperature. We present below the P–T and T–t evolution of the Monts du Lyonnais eclogites used subsequently to calculate the vertical exhumation velocity.

Table 1
Representative analyses of garnet and clinopyroxenes from the Monts du lyonnais eclogites

Composition	Garnet	Clinopyroxene		
	In fresch coesite-bearing eclogite	In fresch coesite-bearing eclogite	In symplectite	In globularized symplectite from a strongly retrogressed eclogite
SiO_2	37.49	54.35	51.94	53.52
TiO_2	0.04	0.04	0.22	0.05
Al_2O_3	20.94	9.38	5.15	1.04
Fe_2O_3	2.08	0.16		0.28
FeO	23.74	5.99	6.52	4.62
MnO	1.40		0.14	0.04
MgO	4.57	8.68	11.01	15.45
CaO	8.81	15.73	21.03	23.24
Na_2O	0.04	5.73	1.90	0.45
K_2O	0.01	0.01	0.01	
Total	99.12	100.07	97.92	99.69
Si	2.964	1.966	1.952	1.988
Al^{IV}	0.036	0.034	0.048	0.012
Al^{VI}	1.915	0.366	0.181	0.033
Ti	0.003	0.001	0.006	0.001
Fe^{3+}	0.125	0.005		0.008
Fe^{2+}	1.569	0.181	0.205	0.144
Mn	0.094		0.004	0.001
Mg	0.537	0.468	0.617	0.855
Ca	0.747	0.610	0.848	0.925
Na	0.007	0.401	0.138	0.032
K	0.001	0.001	0.001	0.000

4.1. P–T evolution of the coesite bearing eclogite

The metamorphic peak conditions of the kyanite-coesite bearing eclogite can be constrained as follows:

The upper temperature limit is fixed by the stability field of the pyrope- coesite assemblage. Garnets in the studied sample contain predominantly almandine, pyrope and grossular components; therefore, the temperature of the ultrahigh pressure stage never exceeded 800°C (see discussion in Schertl et al., 1991).

Minimum temperatures between 700 and 750°C are indicated by the almost complete absence of zonation in the eclogitic garnets (see discussion in Spear, 1988). This assessment is supported by temperatures between 740 and 780°C, calculated using the Fe–Mg exchange of the garnet-clinopyroxene thermometers (Ellis and Green, 1979; Powell, 1985). This temperature range was obtained for most of the eclogites from the Monts du Lyonnais unit (see representative mineral analyses in Table 1 and discussions in Blanc, 1981; Dufour et al., 1985; Joanny et al., 1991).

Thus, for a nominal temperature of ca 750°C, a minimum pressure of 28 kbar is required for the occurrence of coesite (Fig. 5). This estimate is in agreement with the presence of kyanite instead of paragonite in equilibrium with garnet and omphacite (see Holland, 1979).

The retrograde *P–T* conditions for the Monts du Lyonnais eclogites have been constrained using the following observations:

Primary omphacite (42–47% jadeite) is replaced by a symplectite comprising a secondary clinopyroxene (30% jadeite) and plagioclase. Using the calibration of Joanny et al. (1991), based on the size of the inter-lamellae spacing and the related jadeite content of the clinopyroxene lamellae, a temperature of 730–780°C at around 15 kbar is proposed.

Contemporaneous with symplectite development, the eclogitic kyanite was replaced by secondary paragonite. According to the experimental data of Holland (1979), jadeite + kyanite association breaks down through the univariant reaction paragonite = jadeite + kyanite + H_2O. Using the internally consistent data set of Holland and Powell (1990) and assuming a water activity close to unity, the destabilization of a clinopyroxene with 45% jadeite content results in a pressure of ca. 17 kbar for a temperature of 750°C for the start of decompression (Fig. 5).

As retrogression proceeded, the symplectites evolved into globular microstructures containing clinopyroxene with only 5–10% jadeite content, while zoisite and kyanite developed rims of a corundum and plagioclase intergrowth; these features indicate a pressure drop below 10 to 8 kbar for a constant temperature of 750°C. At this stage, rutile was also replaced by titanite according to the allochemical reaction, rutile + quartz + Ca + Fe = titanite + /− ilmenite.

In many eclogites, amphibolite facies conditions are represented by amphibole + plagioclase coronas on garnet and, at a more thorough retrogression stage, eclogites are completely amphibolitized. This completely recrystallized metamorphic assemblage is composed of clinoamphibole (magnesio-hornblende) +

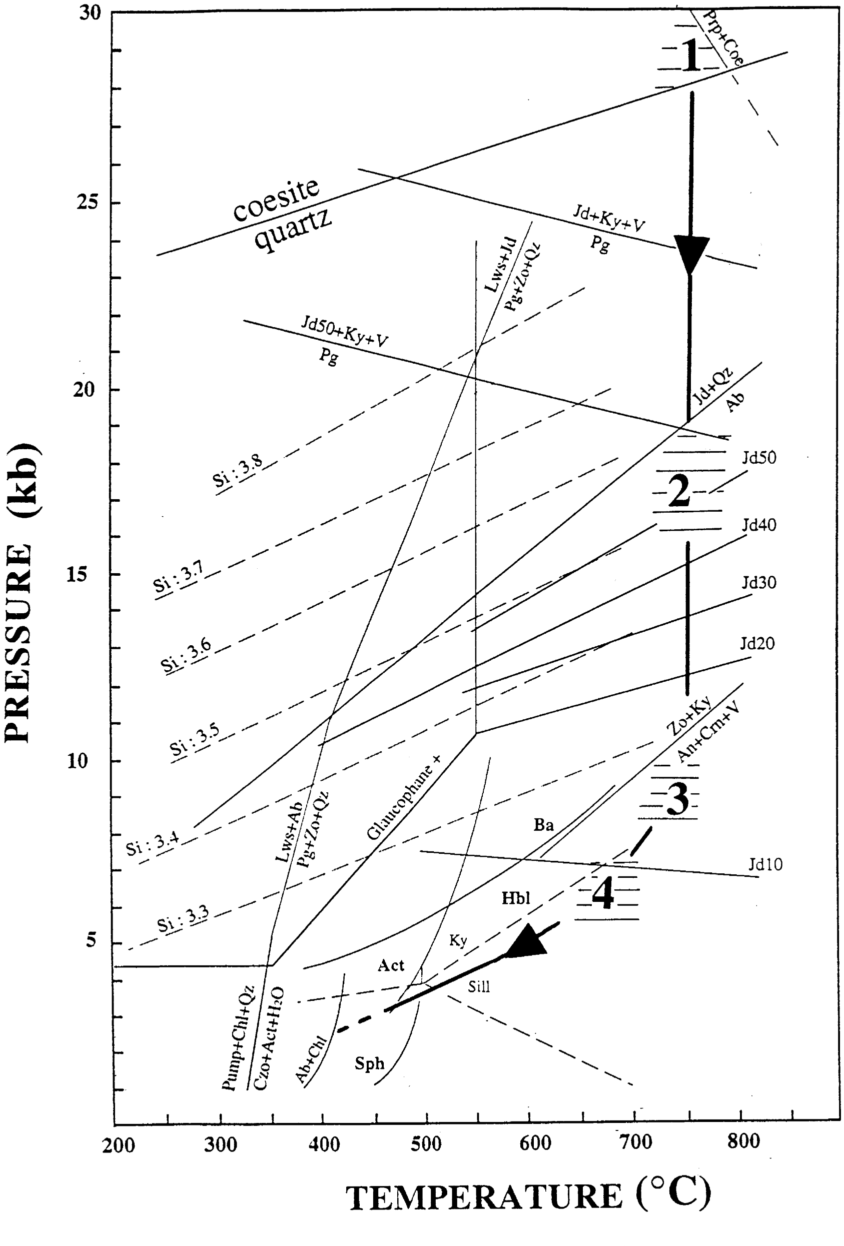


Fig. 5. *P–T* path of the Monts du Lyonnais coesite-bearing eclogite. Mineral abbreviations are from Kretz (1983). The reactions Jd + Ky = Pg and Jd50 + Ky = Pg are from Holland (1979).The reaction Jd + Qz = Ab is from Holland (1980). The reaction Lws + Jd (or Ab) = Pg + Zo + Qz is from Heinrich and Althaus (1988). Si content of phengite isopleths are from Massone and Schreyer (1987). The aluminium-silicate triple point is from Holdaway (1971). The coesite/quartz transition and the pyrope + coesite stability field are from Chopin (1984).The reaction Pump + Chl + Qz = Czo + Act + H_2O is from Nitsch (1971). The reaction Zo + Ky = An + Crn is after Boettcher (1970). Stability fields of barroisite, actinolite, and hornblende are after Ernst (1979). Glaucophane stability is after Maresch (1977). Upper limits of sphene and of actinolite + chlorite stability fields (i.e. greenschist to amphibolite facies transition) are after Moody et al. (1983).

plagioclase + garnet + ilmenite and/or titanite; previous studies estimated the metamorphic conditions for this stage to be 650–700°C and pressure of 7–9 kbar (Blanc, 1981; Dufour, 1985; Dufour et al., 1985). The P–T conditions for this stage, estimated from critical assemblages in the anatectic metapelites adjacent to the eclogite (e.g. quartz + plagioclase + K-feldspar + biotite + garnet + sillimanite + ilmenite), yield a similar temperature range of 650–720°C and water-vapor pressures in excess of 6–8 kbar (Lardeaux, 1989; Chenevoy and Ravier, 1989; Gardien et al., 1990).

Finally, in the more retrogressed eclogites, epidote and actinolite developed in association with chlorite, albite and titanite, indicating a late greenschist facies overprint.

The resulting P–T path of the Monts du Lyonnais eclogites is presented in Fig. 5 and is characterized by a nearly isothermal and high temperature (near 750°C) decompression from 28 to 10 kbar, followed by a decrease in both temperature and pressure conditions.

4.2. *T–t evolution of the coesite-bearing eclogite*

In the Monts du Lyonnais unit, as is the case in the entire French Massif Central, high-pressure metamorphism occurred between 420 and 400 Ma (Pin and Lancelot, 1982; Ducrot et al., 1983; Pin and Peucat, 1986; Paquette et al., 1995). Quantitative age constraints along the decompression path, critical to derivation of the exhumation history, have been documented by a combination of Rb/Sr and Ar/Ar data and concur with ages determined from other independent geologic means (fossils and relative age constraints, see below). The isotopic data quoted in this paper were taken either from the studied eclogites or from the neighboring rocks.

Rb/Sr whole-rock ages from five samples of anatectic metapelites, i.e. the country rocks surrounding the eclogites, yield an isochron date of 384 ± 16 Ma, interpreted as a crystallization age (Duthou et al., 1994). Despite potential discussion associated with the relatively large uncertainty on this age, we can utilize this age for the first portion of the decompression path and, combined with calculated pressure estimates for these rocks, can conservatively suggest that the Monts du Lyonnais unit was exhumed from depths of >100 km to at least 25 km by Middle Devonian time.

Ar/Ar data from amphiboles separated from a strongly retrogressed eclogite have yielded an age of 339 ± 4 Ma (Costa, 1990). Similarly, hornblendes from amphibolites representative of the regional amphibolite facies metamorphism record a plateau age of 345 ± 4 Ma (Costa et al., 1993). Both ages have been interpreted to represent cooling of these minerals through Ar closure of ca. 500°C (see Costa et al., 1993). In the Monts du Lyonnais orthogneisses, Ar/Ar data from muscovites yield plateau ages in the same range of 339–345 ± 4 Ma (Costa, 1990; Costa et al., 1993). These data suggest that the eclogites were situated at 12–18 km depths, appropriate for amphibolite facies retrogression, at 345–340 Ma. This is consistent with Ar/Ar analyses on biotites from syntectonic granites emplaced in strike-slip zones that post-date the development of the regional main foliation; the biotites yield plateau ages between 350 and 335 Ma (Costa et al., 1993). This bracket is supported by a Rb/Sr whole rock isochron of 339 ± 8 Ma obtained on syntectonic granites (Gay et al., 1981) and interpreted as crystallization age and therefore, of shear zone development. The temperature range proposed for the Ar/Ar biotite cooling ages (estimated at ca. 350–300°C) for these granites implies a time span of ca.10 Ma for emplacement of these bodies.

Post-tectonic granites produced contact metamorphism in the surrounding, folded greenschist facies metamorphic rocks of the Brevenne unit (Delfour et al., 1989, see Fig. 2). These late intrusions, in the northeast Massif Central, are Namuro-Westphalian and demonstrate that the uppermost part of the metamorphic pile in the northeast French Massif Central was situated in the brittle field between 320 and 310 Ma; emplacement depths at this time would have been around 4 or 5 km. K-feldspars and plagioclases from the Monts du Lyonnais orthogneisses have Ar/Ar plateau ages, respectively, of 320 ± 3 and 271 ± 3 Ma (Costa, 1990; Costa et al., 1993), in agreement with this paleodepth estimate.

4.3. *Exhumation rates of the coesite-bearing eclogite.*

The depth-time path of the Monts du Lyonnais eclogites is obtained by the combination of the previously presented P–T and T–t paths and we describe the salient features below (see also Fig. 6).

The first stages of exhumation were rapid with a duration of less than a few tens of million years. The

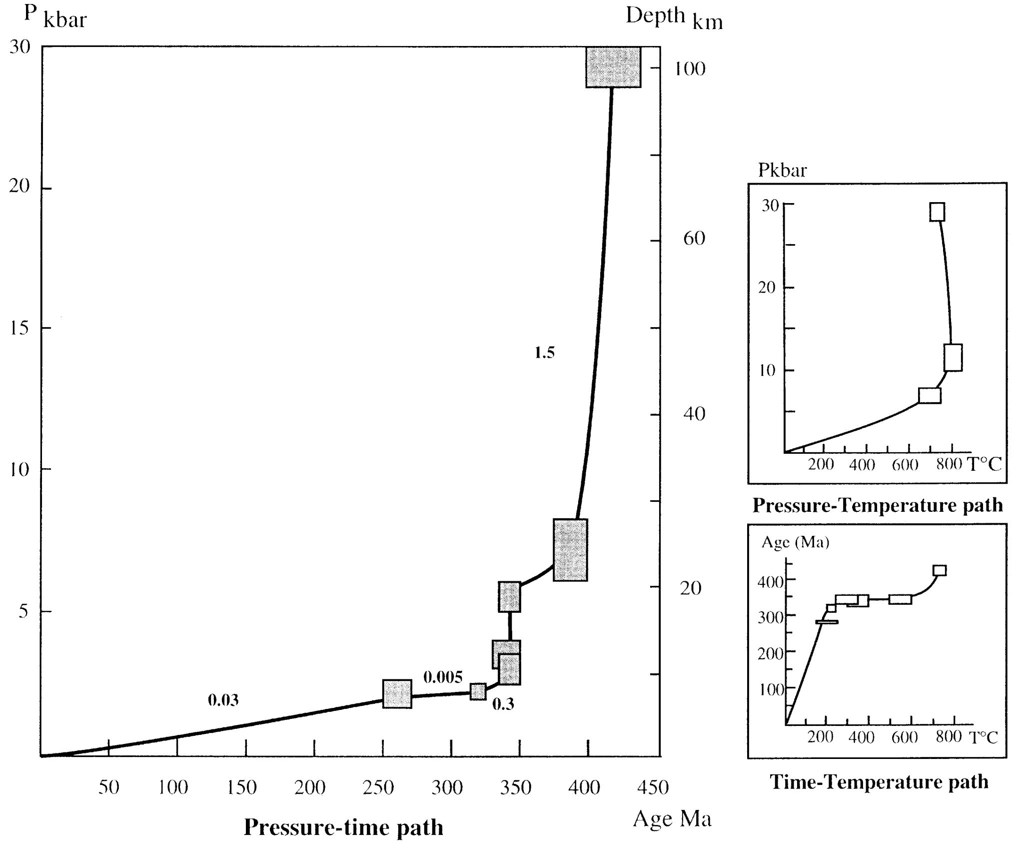


Fig. 6. Depth-time path of the coesite-bearing eclogite. Insets show the P–T path and the T–t path of this rock. Numbers are the calculated exhumation rates (see text for discussion).

high speed (>1.5 mm yr^{-1}) of the initial exhumation is confirmed by the thermal history of the studied eclogites; the eclogites retained their maximum temperatures (ca. 750°C) until depths of ca. 30 km were reached. The eclogites thus underwent 60 km of exhumation, to these relatively shallow crustal levels, before 350 Ma.

Exhumation rates decreased towards the surface, and the last 10–20 km toward the earth's surface was achieved at rates at least one order of magnitude slower (<0.3 mm yr^{-1}) than the initial exhumation rates.

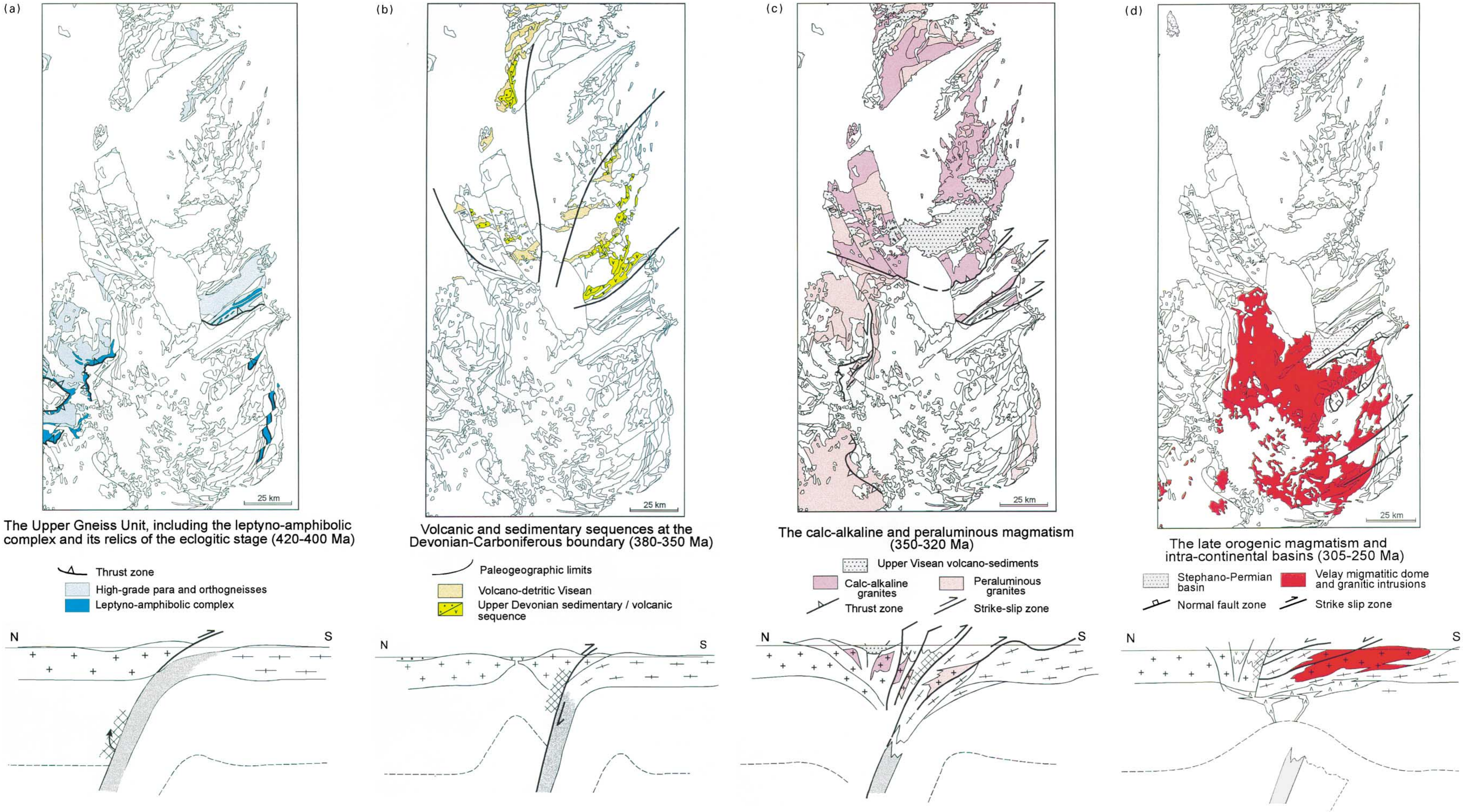
Such significant change in the exhumation rate of these bodies implies that the global exhumation of the studied eclogites is an additive result of mechanisms acting with different velocities.

5. Exhumation processes

5.1. Geological analysis.

In order to incorporate the previously established kinematic constraints into a coherent geological picture, we present and discuss a succession of geological maps through time in which, at each critical period, the depth of the eclogites is indicated (see Fig. 7).

(1) The 420–400 Ma period: At this time, subduction of oceanic crust was active and led to the development of high- to ultrahigh- pressure metamorphic conditions in the subducted slab. This phase corresponds to the closure of the Massif Central ocean (Matte, 1986; Franke, 1989; Faure et al., 1997).



(a) The Upper Gneiss Unit, including the leptyno-amphibolic complex and its relics of the eclogitic stage (420-400 Ma)

(b) Volcanic and sedimentary sequences at the Devonian-Carboniferous boundary (380-350 Ma)

(c) The calc-alkaline and peraluminous magmatism (350-320 Ma)

(d) The late orogenic magmatism and intra-continental basins (305-250 Ma)

Fig. 7. Geological maps of the northeastern French Massif Central through time (with four main time periods, see text for discussion) showing the progressive edification of the belt. The geodynamic 'cartoons' are only indicative and show the possible positions (i.e. depths) of the Monts du Lyonnais eclogites (sampled from the subducted oceanic crust and inserted in the mantle wedge and represented by the crossed zone in the cross sections) during the four critical periods of time.

(2) The 380–350 Ma period: At the surface, in the area north of the present-day Monts du Lyonnais unit, the mantle-derived bimodal suite of the Brevenne unit was emplaced during the 380–360 Ma period. The more recent geochemical investigations of these rocks (Sm-Nd isotopic system combined with trace elements systematics) suggest that the Brevenne unit originated in a subduction-related rift, i.e. in a Devonian back-arc basin emplaced on thinned continental crust (see detailed discussion in Pin and Paquette, 1997). This interpretation concurs with the geochemical data obtained on the Beaujolais ophiolite (Sider and Ohnensteter, 1986; Ohnenstetter and Sider, 1988; Ploquin et al., 1994). Furthermore, west and north of the present-day location of the Brevenne unit, coeval sedimentary facies are clearly compatible with the development of a subduction-like environment at such a period. In this region Delfour (1989); Feist et al.(1994, and references therein)have described:

- \- Bioclastic carbonates with crinoid packstones yielding corals and peloid and bioclastic wackestones alternating with laminated siltstones of Frasnian age (dated by conodonts, ostracods and foraminiferids).
- \- Laminated siltstones, shales with minor carbonate layers of Famenian age (based on trilobites and conodonts faunas) with volcanic intercalations (basalts, andesites and dacites) of calc-alkaline affinity.
- \- Dinantian volcano-sedimentary sequences with sandstones, siltstones, shales and limestones in association with dacitic ash flows, andesites, gabbros and trondhjemites.

As the Monts du Lyonnais eclogites, which derive from subducted oceanic crust, were exhumed to relatively shallow crustal levels (less than 25 km) before 360 Ma, and probably by 384 Ma (see preceding *T–t* section), we suggest that a significant part of the return to the surface of these eclogites occurred during continuous subduction of the Massif Central ocean. Indeed, this exhumation was partly coeval with the development of a back-arc basin, generating the Brevenne ophiolite. At the end of this period, eclogites were stocked between a 25 and 15 km depth, possibly close to the base of the magmatic arc. Such a position could explain the fact that these rocks underwent a strong thermal reequilibration under granulite or high- amphibolite facies conditions. For these reasons, the period between 360 and 350 Ma is considered as a transitional period between subduction-related displacement and transpressional tectonics related to arc-continent collision.

(3) The 350–320 Ma period: This period corresponds to the development of a transpressive regime giving rise to crustal-scale bulk shortening and promoting thrusting of the Brevenne unit upon the Monts du Lyonnais unit (Feybesse et al., 1988) along a dextral wrench-thrust zone (Fig. 7). Both Brevenne and Monts du Lyonnais units experienced strong strain partitioning (Lardeaux and Dufour, 1987; Feybesse et al., 1988) that resulted in the juxtaposition of two different strain domains: one domain is characterized by development of folds with subhorizontal axes and steep axial planes and by development of mainly S-tectonites with symmetric strain markers while the other domain is represented by ductile strike-slip zones (Fig. 7). In these zones of transcurrent deformation, syntectonic granites were emplaced and the lack of any associated contact metamorphism indicates that these granites were in thermal equilibrium with the surrounding country rocks (Gay et al., 1981; Lardeaux and Dufour, 1987). At the same time, but south of the Monts du Lyonnais unit, moderate crustal thickening resulted in the stacking of gneissic units in Haut-Allier and Vivarais areas (Fig. 7, see also Burg and Matte, 1978; Burg et al., 1984; Ledru et al., 1989). From a geodynamic viewpoint, such a structural pattern encompassing transpression and crustal stacking can be regarded as the result of an oblique arc-continent collision. During this period, eclogites are exhumed from ca. 20 km up to 5 km and were strictly located in the folded domains. We underline that, contemporaneously, but north of the Brevenne unit (i.e. the Morvan area), a large volume of calcalkaline granites was emplaced, while in different basins, calcalkaline and pyroclastic volcanic sequences were deposited together with shallow-marine platform sediments (Julien, 1881; Michel-Levy, 1908, 1926; Jung et al., 1939; Guffroy, 1959, 1960; Lys et al., 1961; Leistel and Bebien, 1982; Leistel and Gagny, 1984; Delfour, 1989). These rocks comprise the so-called Upper Visean ‘tufs anthraciferes’ and document that, during the 350–320 Ma period, the northernmost part of the Massif Central

was undergoing extension, possibly related to dextral transtension (like in southern Vosges or Black Forest) or to the development of a new subduction zone (closure of the Rheic ocean, Matte, 1986; Faure et al., 1997). Simultaneous arc-continent collision induced the shortening of the southern segment between the Brevenne and the Vivarais areas. The resulting moderate crustal thickening was responsible for the formation of peraluminous granites which are widespread in the Vivarais and Velay areas.

(4) The 320–290 period: Late orogenic extension at this time is well developed and documented south of the Monts du Lyonnais unit in the Pilat and Velay units (Fig. 7; Malavieille et al., 1990; Gardien, 1990; Faure, 1995). This tectonic regime controlled opening of the Stephanian intracontinental basins, in the hanging-wall of the main detachment zone, and the emplacement of the migmatic Velay dome at the foot-wall of the structure. At that time, the Monts du Lyonnais unit was a part of the hanging-wall, only affected by brittle extension. This brittle extension, combined with erosion, led to the final ascent (5 km) of the eclogites up to the surface.

5.2. Mechanisms of exhumation

As a consequence of the previous discussion, we suggest that the development of ultrahigh-pressure metamorphism as well as a significant amount of exhumation of coesite-bearing eclogites occurred during oceanic subduction. Because eclogites are closely associated with garnet (and/or spinel)-bearing ultramafic rocks and form tectonic lenses within high-grade paragneisses, a mechanism of mass transfer, during subduction, between the subducted crust and the overlying mantle wedge is needed. This sort of mass transfer is most easily envisioned via some kind of tectonic erosion process. Tectonic erosion, identified in actual subduction zones (Von Huene and Culotta, 1989; Lallemand et al., 1994), explains that trench sediments or slices of oceanic crust can be dragged down, transported and accreted in the mantle wedge. Another plausible model for tectonic erosion, the sinking intrusion model, has been recently proposed by Brueckner (1998) to explain the exchange of material across the Benioff plane: meter-to kilometer-scale lenses of mantle can sink in the subducted crust and eclogitized crustal slices can rise into the overlying mantle. Both of these modes of tectonic erosion can account for the separation of eclogitized metabasalts (or metagabbros) from the subducted oceanic lithosphere.

In the studied example, the most important part of the return of the eclogites toward the surface (i.e. from ca 100 to 25 km) was accomplished while subduction was still active. These circumstances for initial, rapid exhumation of the ultra-high pressure eclogites implicate mass transfer in the deformed ductile mantle wedge. A plausible mechanism is mass transfer by corner flow circulation (Cloos, 1982; Platt, 1986; Polino et al., 1990; Allemand and Lardeaux, 1997).

Following the ca. 60 km of very rapid exhumation associated with subduction-dominated conditions, vertical transport of ca.15–20 km occurred during oblique collision accommodated by deformation under a transpressive regime. This transpression-related exhumation is consistent with the thermo-mechanical modelling of Thompson et al. (1997).

The final 5 km of exhumation of the Monts du Lyonnais eclogites was the result of erosion and brittle extension during collapse of the previously shortened and thickened domain. Hence, in the studied area, extensional tectonics cannot be regarded as the main mechanism leading exhumation of high or ultrahigh-pressure rocks.

6. Consequences for variscan geodynamics

The discovery of ultrahigh -pressure metamorphic rocks in the French Massif Central precludes previous interpretations of the Variscan belt as the result of a simple stacking of one 30–40 km thick continent over another one of equivalent thickness (Burg and Matte, 1978; Burg et al., 1984; Matte, 1986; Mercier et al., 1991). Moreover, if we accept the idea that the Monts du Lyonnais eclogites were formed and partly exhumed while subduction was active (i.e. in the period 400–360 Ma), collision tectonics did not begin until nearly 350 Ma and some ‘classical’ concepts for Variscan orogeny need to be revisited. In this context we underline several open questions to serve as starting points for future studies in the Variscan belt:

What is the significance of high to medium-pressure granulites and related migmatites which are widespread in the upper gneissic unit of the French Massif Central? Until now, these high grade rocks, dated between 380 and 360 Ma, have been interpreted as the result of thermal reequilibration during crustal thickening (i.e. continental underthrusting). We suggest that this high temperature metamorphism occurred at the base of a magmatic arc (i.e. as part of the Brevenne back-arc basin setting) emplaced on thinned continental crust during subduction of the Massif Central ocean. In fact, high-grade metamorphism (granulite to amphibolite facies conditions) is well described within magmatic arcs developed upon subduction zones like the Chile Coastal Cordillera (Lucassen and Franz, 1996), in Alaska (De Bari and Coleman, 1989), or in the Kohistan island arc, Pakistan (Bard, 1983; Burg et al., 1998).

How do we define the so-called 'internal nappes' and the tectono-metamorphic zonation of the French Variscan belt ? This could be discussed on the example of the eastern French Massif Central. Until the present time, the Brevenne unit has been regarded as an uppermost allochthon, metamorphosed under greenschist facies conditions and emplaced upon the Monts du Lyonnais unit; the latter has been considered as a single crustal nappe metamorphosed under high -grade conditions (Feybesse et al., 1988; Ledru et al., 1989). In this classical scheme, the Monts du Lyonnais nappe corresponds to the upper gneissic unit resting upon the Pilat–Velay unit (i.e. the lower gneissic unit) as a consequence of continental underthrusting. In our alternative model, we regard the Brevenne–Velay cross section as the accretion of an arc, a subduction complex and a continental lower plate during an oblique arc-continent collision. The Beaujolais–Brevenne ophiolite and the related volcano-sedimentary sequence thus represent the uppermost part of the arc (Figs. 1 and 2). The migmatites and the granulitic rocks which form the northern part of the Monts du Lyonnais complex should, in this context, be interpreted as remnants of the metamorphosed crust on which the arc was emplaced and/or remnants of the base of the magmatic arc itself. The lenses of eclogites and peridotites embodied within metagreywackes and metapelites, which occur exclusively in the southernmost part of the Monts du Lyonnais area, could form the remnants of a subduction complex emplaced upon a north-dipping subduction zone. In this tectonic scheme, the Pilat–Velay metamorphic unit (Fig. 2) needs to be interpreted as the lower continental plate which progessively underthrusted the subduction complex. This geodynamic model is in agreement with the large scale anisotropy of the lithosphere mantle beneath the French Massif Central. Indeed, spatial variations of P-wave velocities and lateral variations of shear waves splitting support, out of the recent volcanic fields, an anisotropic model of the lithospheric mantle with high velocities oriented north–south (Granet et al., 1998; Plomerova et al., 1998). According to Plomerova et al. (1998), such a fast polarization pattern could be interpreted as the record, in the mantle, of the activity of a north–south oriented subduction zone.

What were the amount and processes of thickening of the continental crust during Variscan orogeny? In the last twenty years, the proposed tectonic models for high-pressure metamorphism development in the French Variscan belt have inferred significant crustal thickening by progressive stacking of continental slices. If we regard the eclogites and granulites as the products of subduction rather than the results of continental collision, and if we also accept the idea of an arc-continent collision beginning at around 350 Ma, only moderate crustal thickening would be required during the actual collision phase. This thickening could be achieved first, by arc accretion against a subduction complex and a continental plate and second, by shortening of the previously accreted system which led to thrust development, especially in the lower plate.

7. Conclusions

While the presence of yet another ultrahigh-pressure metamorphic occurrence in Europe is interesting, the more significant consequence is that ultrahigh-pressure rocks can probably be considered as a common feature in orogenic belts, envisaged even in strongly retrogressed areas like the Eastern French Massif Central. Combined structural, temporal and $P–T$ datasets support the premise that global exhumation of the Paleozoic coesite-bearing eclogites from the Monts du Lyonnais is an additive result of subduction and collision processes. However, the most significant amount of exhumation (nearly 60 km of vertical displacement) occurred, with high velocities of vertical displacement, during subduction in a back-arc environment prior to continental collision. Continental collision was responsible for the subsequent ascent of the eclogites to shallower crustal levels (ca. 15 km ascent), as a fraction of the exhumation was accommodated by deformation under a transpressive regime. Late orogenic extension, combined with erosion, was only responsible of the last 5 km ascent of the ultrahigh-pressure rocks to the earth's surface. We suggest that the French Variscan belt results from oblique arc-continent collision rather than simply continental underthrusting.

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