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The evolution of the Massif Central rift : spatio-temporal distribution of the volcanism

LAURENT MICHON¹ and OLIVIER MERLE¹

Key words. – Massif Central, Cenozoic, Rifting, DEM, Volcanism, Tectonic

Abstract. – The Massif Central area is the largest magmatic province of the West-European Rift system. The spatio-temporal distribution of Tertiary-Quaternary volcanism in the Massif Central, France, shows that three magmatic phases can be defined, each of them characterized by different volumes and different locations. The first event, termed the *pre-rift magmatic event*, is very scarce and restricted to the north of the Massif Central. It is suggested that this could result from lithospheric bending of the European lithosphere ahead of the incipient Alpine chain during the Paleocene. The second event, termed the *rift-related magmatic event*, is located in the north of the Massif Central only and is spatially connected with zones of high crustal thinning (i.e. the Limagne graben). It immediately follows Oligocene graben formation and associated sedimentation, and is represented by more than 200 scattered monogenic edifices. This second event can be attributed to partial melting as a consequence of lithospheric thinning that affected the north of the Massif Central during the rifting event. The lack of volcanism in the south during the same period of time is probably related to the very slight lithospheric thinning during the Oligocene. The third event, termed the *major magmatic event*, started first in the south in the upper Miocene at about 15 Ma, well after the end of the sedimentation. It is unrelated to any extensional event. This major magmatic event reached the north of the Massif Central at about 3.5 Ma, following a pause in volcanism of about 6 Ma after the rift-related magmatic event. These two episodes of the major magmatic event are spatially and temporally associated with the two main periods of uplift, suggesting a common origin for volcanism and uplift processes. The major magmatic event can be attributed to late thermal erosion of the base of the lithosphere above a mantle diapir, as suggested by seismic tomography data. This general magmatic evolution drawn from data at the Massif Central scale may apply to the Eger graben as well, as the three magmatic events described in this study (pre-rift magmatic event, rifting event and post-Miocene volcanic event) are also reported in the literature. This suggests that a single cause should explain the formation of the entire western European rift surrounding the Alpine mountain belt.

Evolution du rift du Massif central : distribution spatio-temporelle du volcanisme

Mots clés. – Massif Central, Cénozoïque, Rifting, MNT, Volcanisme, Tectonique.

Résumé. – Le rift Ouest-européen correspond à un épisode d'extension lithosphérique qui s'est produit de l'Eocène supérieur jusqu'au Miocène inférieur. La direction d'extension est globalement perpendiculaire au front de la chaîne alpine et s'exprime, d'est en ouest, par la formation du graben de l'Eger, du graben du Rhin et des fossés d'effondrement du Massif central. Le Massif central est la plus importante province magmatique liée à cet épisode de rifting. Le volcanisme de cette province peut être séparé en trois épisodes successifs. 1. *Épisode de magmatisme pré-rift*. Cet épisode correspond à 15 localités répertoriées presque exclusivement dans le nord du Massif central et datées du Paléocène à la fin de l'Eocène. 2. *Épisode de magmatisme syn-rift*. La sédimentation oligocène s'est effectuée à un niveau proche de celui de la mer et pratiquement sans manifestation volcanique. À l'échelle du rift (i.e. de la Bresse à la Limagne), l'extension symétrique de l'Eocène supérieur à l'Oligocène moyen est devenue asymétrique à partir de l'Oligocène supérieur. L'épisode de magmatisme a débuté à l'Oligocène supérieur et s'est principalement développé au Miocène inférieur, pendant une quinzaine de millions d'années. Il est spatialement lié aux zones d'amincissement crustal maximal (fossé de la Limagne) et est absent de la partie sud du Massif central où les récentes données géophysiques montrent que l'amincissement crustal est négligeable. 3. *Épisode de magmatisme majeur*. Cet épisode a démarré au sud du Massif central près de 15 Ma d'années après la fin de la sédimentation oligocène. C'est l'épisode majeur avec le développement des grandes provinces magmatiques du Cantal, du Velay ou de l'Aubrac. Une reprise plus tardive du volcanisme se produit dans la partie nord du Massif central, près de 6 Ma après la fin de l'épisode précédent dit syn-rift. Dans son ensemble, cet épisode majeur est caractérisé par deux pics d'activité : de 9 à 6,5 Ma uniquement au sud du Massif central, puis de 3,5 à 0,5 Ma tant au nord qu'au sud du Massif central.

L'analyse du MNT permet de montrer que le nord du Massif central présente un champ de structures dominé par des failles nord-sud. Il s'agit de failles d'âge varisque réactivées en faille normale pendant l'extension et la création des fossés d'effondrement. L'étude des profils d'équilibre des rivières au passage de certaines failles ainsi que l'âge des coulées de lave actuellement en position de reliefs inversés montrent que le soulèvement dans cette partie nord a débuté

té il y a environ 3 Ma et se poursuit actuellement. Au sud, le MNT révèle un champ de failles dominant orienté N135°E, souligné en particulier par des alignements volcaniques tels l'Aubrac, le Velay ou le Deves. Cette direction majeure a été acquise pendant le soulèvement de la partie sud qui a débuté il y a environ 10 Ma, bien avant le soulèvement plus récent de la partie nord. Ce soulèvement s'est ralenti entre 5,5 Ma et 3-3,5 Ma pour redevenir très actif depuis cette période jusqu'à l'actuel, comme dans la partie nord.

L'épisode magmatique pré-rift, extrêmement limité en volume, est attribué à une flexure de la lithosphère européenne au moment des premières compressions alpines pendant le Paléocène. Cette flexure de la lithosphère est encore apparente à l'échelle de la France grâce aux données de géophysique ou de géomorphologie dans le Massif central et le Morvan. L'épisode magmatique syn-rift, restreint au nord du Massif central, est clairement associé aux zones d'amin-cissement crustal maximal résultant principalement de l'extension asymétrique E-W oligocène supérieur à miocène inférieur. Cet amincissement lithosphérique permet d'expliquer, par décompression du manteau, le faible taux de fusion partielle nécessaire pour rendre compte du volcanisme, localisé au nord, de l'Oligocène supérieur au Miocène inférieur. L'orientation N-S dominante observée sur le MNT est un héritage de cette période d'extension E-W où les failles sub-méridiennes d'âge varisque ont été réactivées. L'épisode magmatique majeur est caractérisé par deux pics d'activité qui sont synchrones des deux périodes de soulèvement maximal : au sud vers 10-5,5 Ma, puis au nord et au sud à partir de 3-3,5 Ma. Au sud, la radiographie de la croûte et de la limite lithosphère-asthénosphère obtenue par sismique classique et tomographie sismique montre que le manteau lithosphérique a subi un très fort amincissement tandis que l'épaisseur de la croûte est quasi-normale. L'anomalie thermique définit sous la lithosphère dans cette partie sud témoinne alors d'une érosion thermique de la base de la lithosphère, responsable du soulèvement isostatique et du premier pic d'activité magmatique. Un second épisode d'érosion thermique à la base de la lithosphère, plus diffus mais réparti du nord au sud, expliquerait la seconde période de soulèvement isostatique ainsi que le second pic d'activité magmatique enregistrés au nord et au sud à partir de 3,5 Ma.

INTRODUCTION

The West-European plate was affected by a rifting episode from the upper Eocene to the early Miocene (Priabonian to Burdigalian) [Ziegler, 1992; Bois, 1993]. Extension is roughly perpendicular to the Alpine front and generated a graben system, which includes, from east to west, three main segments : the Eger graben of the Czech Republic, the Rhinegraben of Germany and the French Massif Central grabens. These three segments are characterised by the occurrence of a typical intraplate alkaline volcanism either within the grabens or along their margins [Wilson and Downes, 1991].

The Massif Central area is the largest magmatic province of the West-European Rift system. The origin of the magmatism is still a matter of debate [Wilson and Downes, 1991]. The presence of a hot spot below the Massif Central has long been advocated [Brousse, 1974]. Different hypotheses such as the upwelling of numerous associated mantle diapirs [Nicolas *et al.*, 1987] or a large aborted mantle plume located at depth and common to the entire western part of the European plate [Hoernle *et al.*, 1995; Granet *et al.*, 1995] have been proposed. It has also been suggested that the magmatism could result from a mantle destabilization induced by the Alpine collision [Sobolev *et al.*, 1997].

In these previous studies, the link between extension and magmatism was not clearly established. The aim of this paper is to provide an interpretation of the spatio-temporal distribution of the volcanism by integrating recent geological, geophysical and geochemical data from the Massif Central. This makes it possible to unravel the different kinematic history between the northern and the southern part of the Massif Central during the Tertiary.

DISTRIBUTION OF THE VOLCANISM

The Massif Central Cenozoic volcanism is spread out from the Drevin in the north to the Escandorgue area in the south

(fig. 1 and 2). Volcanism started 65 Ma ago in the Paleocene and the most recent eruptions can be dated from the Holocene [Bellon *et al.*, 1974; Brousse, 1974; Vincent *et al.*, 1977; Maury and Varet, 1980; Mergoïl et Boivin, 1993; Nehlig *et al.*, 1999]. The classification into different magmatic provinces has been attempted [Goër de Herve and Mergoïl, 1971; Brousse, 1974 ; Maury and Varet, 1980 ; Mergoïl and Boivin, 1993]. These studies clearly show that each magmatic province is characterised by some well defined periods of activity and that two main volcanic phases can be distinguished during the Cenozoic : the pre-rift and the post-rift volcanic phases.

This distinction in two periods can be significantly improved and refined by compiling the different ages of the volcanic provinces, which are geographically listed from north to south (fig. 1). Such a classification allows the distinction of three main volcanic phases.

Pre-rift magmatic event

From the early Paleocene up to the end of the Eocene, a scarce and scattered volcanism, consisting of less than 15 necks and volcanoes, occurred in the northern part of the Massif Central. Only one magmatic manifestation is reported from the southern part (fig 2a). In the Charollais area, 7 volcanoes have been recognised dated from 64.5 to 36.7 Ma with K/Ar method [Bellon *et al.*, 1974]. Near Menat, several outcrops of basalt around a maar have been dated from the Paleocene at around 60 Ma with the K/Ar method [Vincent *et al.*, 1977], a result consistent with paleontological data [Kedves, 1967; Russel, 1967]. In the Forez, the pre-rift magmatic activity is restricted to a single volcano, which erupted 62 Ma ago [Lenoir *et al.*, 2000]. Here, the lava has a melilitite composition and corresponds to the most under-saturated magma type recorded in the Massif Central [Hernandez, 1976]. Along the borders of the Limagne graben, near Vichy and Servant, two volcanoes (45.8 and 44 Ma) display inverted reliefs (Mont Pérourx and the Champonier dyke) [Brousse and Lefevre, 1990]. The only pre-rift volcanic manifestation described in the south-

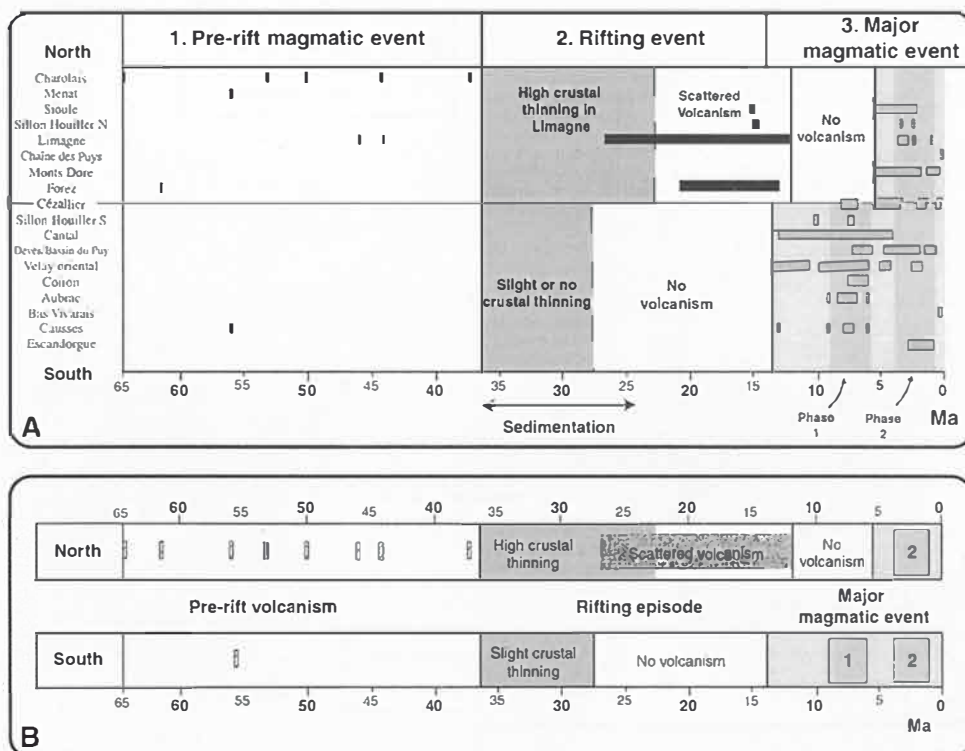


FIG. 1. – A) Spatio-temporal distribution of the volcanism in the Massif Central area: the rifting event include both the sedimentation/extensional period and the scattered volcanism recorded in the north. Note the lack of volcanism after the sedimentation period in the south. For explanation see the text. Established from radiometric data [Bellon *et al.*, 1974; Vincent *et al.*, 1977; Baubron *et al.*, 1978; Cantagrel and Boivin, 1978; Bellon and Hernandez, 1979; Maury and Varet, 1980; Baubron and Demange, 1982; Cantagrel and Baubron, 1983; Gastaud *et al.*, 1983; Chantepeie, 1990; Goër *et al.*, 1991b; Mergoill and Boivin, 1993; Rochette *et al.*, 1993; Cheguer, 1996; Nehlig *et al.*, 1999]. B) Synthetic representation of volcanism in the Massif Central. Boxes 1 and 2 represent the two peaks of activity during the major magmatic event.

FIG. 1. – A) Répartition spatio-temporelle du volcanisme: l'épisode de rifting inclut les périodes d'extension et de sédimentation, et la phase de volcanisme dispersé dans la partie nord. Noter l'absence de volcanisme après la période de sédimentation dans la moitié sud. [D'après les travaux de Bellon *et al.*, 1974; Vincent *et al.*, 1977; Baubron *et al.*, 1978; Cantagrel and Boivin, 1978; Bellon and Hernandez, 1979; Maury and Varet, 1980; Baubron and Demange, 1982; Cantagrel and Baubron, 1983; Gastaud *et al.*, 1983; Chantepeie, 1990; Goër *et al.*, 1991a; Mergoill and Boivin, 1993; Rochette *et al.*, 1993; Cheguer, 1996; Nehlig *et al.*, 1999]. B) Représentation synthétique du volcanisme du Massif central. Les caissons 1 et 2 représentent les deux pics d'activité durant la phase majeure de volcanisme.

ern part of the Massif Central is a basanitic neck in the Tassières hamlet near Séverac le Château (57 Ma) [Baubron *et al.*, 1978].

The above ages were obtained in the 1970s and the 1980s by the K/Ar method. New datings using the $^{40}\text{Ar}/^{39}\text{Ar}$ method, carried out in the Massif Central, clearly shows that previously published ages based on the K/Ar method must be interpreted with care. For example, the Marcoux melilitite, which has been previously dated at 49.8 Ma with the K/Ar method [Bellon and Hernandez, 1979], has given an age of about 62 Ma using the $^{40}\text{Ar}/^{39}\text{Ar}$ method [Lenoir *et al.*, 2000]. However, these data confirm the time span of the pre-rift magmatism from Paleocene to Upper Eocene. The lavas of the pre-rift volcanism are highly under-saturated (alkali basalt to melilitite), which strongly suggests small degrees of partial melting (< 5%) of a CO_2 - and H_2O -rich mantle source [Edgar, 1987; Wilson *et al.*, 1995].

Rifting magmatic event

From the upper Eocene to the end of the lower Miocene, the Massif Central was affected by east-west extension, which led to the formation of numerous grabens [Bergerat, 1985;

Blès *et al.*, 1989; Lacombe *et al.*, 1993; Merle *et al.*, 1998]. In the northern part of the Massif Central, the three most important grabens are N-S oriented. From east to west, they are the Bresse graben, the Roanne-Montbrison graben and the Limagne graben [fig. 1 in Merle *et al.*, 1998]. As shown from an experimental study, the geometry of the system can be explained as resulting from symmetric extension during the upper Eocene and middle Oligocene [Merle *et al.*, 1998; Michon and Merle, 2000]. In the upper Oligocene and to a lesser extent in the lower Miocene, subsidence remained very active as indicated by the sedimentation rate in the western Limagne graben while there was a lull in Roanne-Montbrison and Bresse grabens [Merle *et al.*, 1998; Hugueney *et al.*, 1999]. In the south, the main sedimentary basins are Le Puy, Saint Flour and Aurillac basins but these are much less developed than in the northern part. The distinction between well defined N-S grabens in the north and small and non-oriented basins in the south is reinforced by recent geophysical data [Zeyen *et al.*, 1997].

The Moho depth, together with thick sequences of Oligocene syn-rift sediments (up to 3000 m in the Limagne graben) [Morange *et al.*, 1971], clearly reveal high crustal

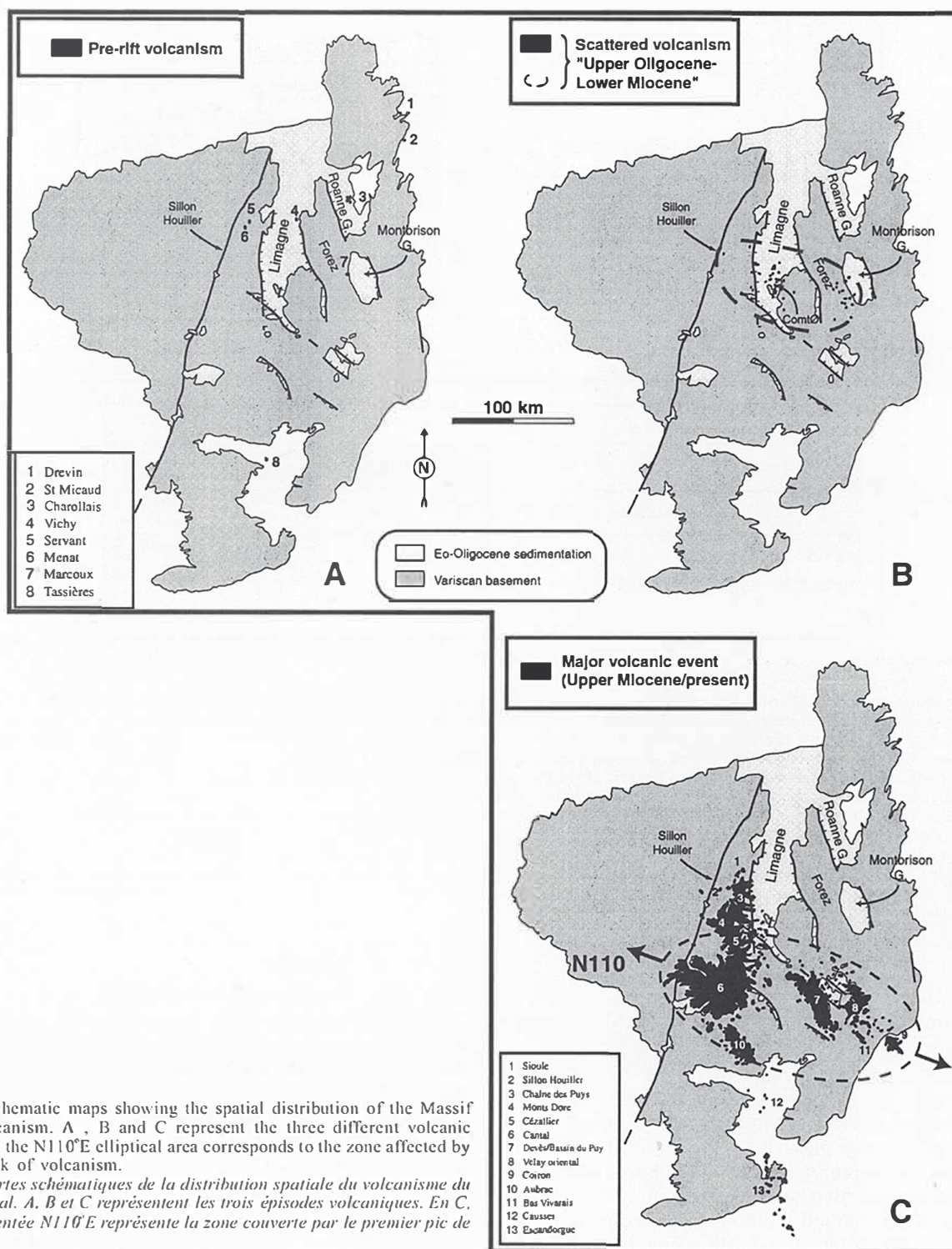


FIG. 2. – Schematic maps showing the spatial distribution of the Massif Central volcanism. A, B and C represent the three different volcanic events. In C, the N110°E elliptical area corresponds to the zone affected by the first peak of volcanism.

FIG. 2. – Cartes schématiques de la distribution spatiale du volcanisme du Massif central. A, B et C représentent les trois épisodes volcaniques. En C, l'ellipse orientée N110°E représente la zone couverte par le premier pic de volcanisme.

thinning in the northern part of the Massif Central [fig 11 in Zeyen *et al.*, 1997]. The Moho is at 26 km depth in the west [Zeyen *et al.*, 1997] and 29.5 km in the east [Bergerat *et al.*, 1990], indicating a thinning of the crust to 23.3 km and 28 km below the Limagne and Bresse grabens, respectively. This yields 25% crustal thinning beneath the Limagne graben and 10% below the Bresse [Merle *et al.*, 1998]. According to the sedimentation history, most of the 25%

crustal thinning in the Limagne graben can be considered to have occurred in the upper Oligocene and to a lesser extent in the lower Miocene.

In the southern part of the Massif Central, the Moho is flat-lying at a depth of about 28 km. The average topographic elevation of the Variscan basement is about 1000 m. This suggests slight crustal thinning during the

ripping event. This is correlated with the low thickness of the Eo-Oligocene sediments, which never exceeds a few hundred meters.

These data reveal a strikingly different tectonic evolution between a northern part of the Massif Central where significant crustal thinning has occurred and the southern part where the rifting was limited. Despite the occurrence of a few volcanic minerals in some upper Rupelian sediments [Devineau, 1996], the rifting event is mainly characterised by the lack of volcanic activity during sedimentation both in the north and the south of the Massif Central.

The "rift-related magmatic event" started in the late Oligocene at a time when sedimentation was on the decline. It lasted about 15 Ma up to the end of the lower Miocene. Peperitic deposits interbedded in the upper Oligocene sediments [Hourrière *et al.*, 1998] prove that this scattered magmatic event is coeval with the asymmetric phase of rifting. The volcanism is located in the northern part of the Massif Central only and is totally unknown in the southern part (fig. 1). Moreover, it is restricted to the western area of the northern part, which indicates that it is spatially connected with the area of high crustal thinning, that is the Limagne graben.

More than 200 monogenic scattered volcanoes erupted during this period mainly within the Limagne graben (*s.l.*) or the Forez areas (fig. 2b). Two volcanic manifestations only have been reported far away from the graben areas near the Variscan Sillon Houiller fault (fig 2b). The magmatism is mainly characterised by alkaline basaltic to nephelinitic lavas (85% of the total volume) and the only magmas exhibiting a differentiation trend are located in the Comté area, in the heart of the Limagne graben [Tricot, 1975] (fig. 2b). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating from this area indi-

cate volcanic activity between 20 and 22 Ma with a climax at about 21 Ma [Cheguer, 1996].

Major magmatic event

The beginning of the major magmatic event is not coeval in the southern and northern parts of the Massif Central. It started in the south, in areas that lack any volcanism before that period, except the Paleocene Tassières neck (fig 1 and 2a). Eruptions took place from the upper Miocene, at least 15 Ma after the end of the sedimentation. In the north, the major magmatic event started after a gap of about 6 Ma in the upper Miocene. The volume of erupted magma during this period is much larger than during any previous magmatic events, and is estimated from 1000 to 1500 km³.

As revealed by the estimation of volumes erupted during this period, the major magmatic event was characterised by two peaks of activity (fig. 1b). The first peak can be dated from 9 to 6 Ma and is associated with the building of the largest magmatic provinces of the Massif Central (Cantal, Aubrac, Velay, Causses and Coirons), following a N120°E/N140°E average trend (Cantal (85% of the trachy-andesitic stratovolcano ages between 9-6 Ma), Aubrac (8,7-6 Ma), South Velay (83% of the ages between 9-6 Ma), Causses (9.2-5.8 Ma) and Coirons (7.9-6.2 Ma)) [Baubron and Demange, 1982; Mergoil and Boivin, 1993; Féraud and Campredon, 1983; Fréour, 1998] (fig 2c). This huge volume of volcanic activity is restricted to a N110°E oriented elliptical area in the south (fig. 2c) where the Oligocene crustal thinning was negligible (<< 5 %). There is a very good correlation between the location and orientation of these large magmatic provinces in the field and the mantle thermal anomaly beneath as deduced by seismic

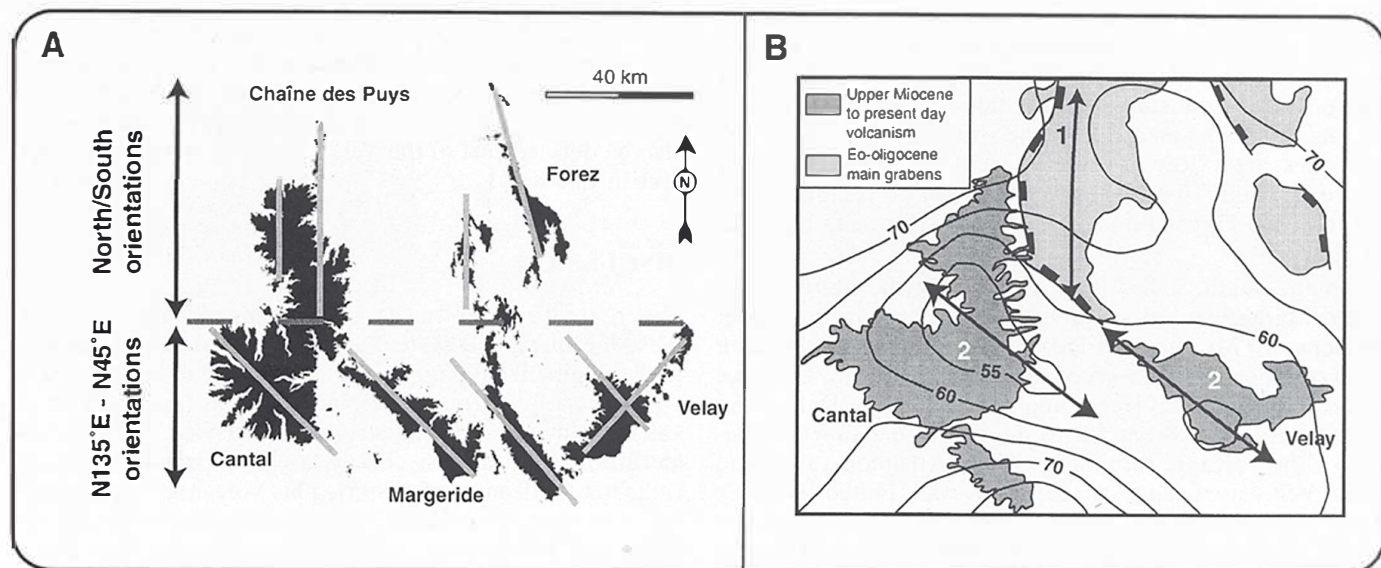


FIG. 3. – A) Structural setting of the northern and the southern parts of the Massif Central. In black, elevation higher than 1000 m. Prominent orientations are N135°E in the south and N-S in the north. B) Schematic map presenting the orientation of the Eo-Oligocene crustal thinning in the north (1) and the thermal anomaly orientation in the south (2). Lithosphere asthenosphere boundary (LAB) topography given in kilometres [from Sobolev *et al.*, 1997].

FIG. 3. – A) Cadre structural des parties nord et sud du Massif Central. En noir sont représentées les altitudes supérieures à 1000 m. Les orientations dominantes de la moitié sud sont N135°E et la partie nord est marquée par des directions N-S. B) Carte schématique présentant l'orientation de l'amin-cissement crustal éo-oligocène dans le nord (1) et l'orientation de l'anomalie thermique dans le sud (2). Limite lithosphère-asthénosphère (LAB) en kilo-mètres [d'après Sobolev *et al.*, 1997].

tomographic studies [Granet *et al.*, 1995; Sobolev *et al.*, 1997] (fig. 3).

In contrast to the first peak, the second peak of volcanism occurred both in the north and the south of the Massif Central. From 3.5 Ma to 0.5 Ma, it led both to the building of new provinces such as Escandorgue, Monts Dore and Devès, and the reactivation of old magmatic provinces (Limagne, Causses, Velay and Sioule). The spatial distribution of this second peak is more elongated in the north-south direction (from the Chaîne des Puys to the Escandorgue) than the first peak but has a quite similar east-west width. The main volcanic provinces formed during this period are the Monts Dore and Sancy stratovolcanoes and the Devès basaltic shield. The other provinces are characterised by limited monogenic activity (Escandorgue, Velay) during which relatively small volumes of lava were erupted. Following this second peak, the last eruptions in the Massif Central occurred from the upper Pleistocene to the present-day in the Chaîne des Puys, the Céallier and in the Ardèche area (Bas Vivarais) [Goer *et al.*, 1991a; Rochette *et al.*, 1993].

Erupted magmas are sub-alkaline (basalt to rhyolite) or alkaline (basanite to phonolite) intraplate lavas. The geochemical and Sr-Nd-Pb isotopic compositions of the most primitive mafic magmas from the Cantal stratovolcano can be modelled by mixing partial melts of: (i) an asthenospheric component with isotopic composition between depleted mantle and high μ (HIMU) endmembers for which there is no need to invoke the existence of a deep mantle plume and (ii) a lithospheric component derived from the old Variscan lithosphere [Wilson and Downes, 1991].

TIMING OF UPLIFT

Marine to laguno-lacustrine Eo-Oligocene sediments can be seen at elevations of several hundred metres (up to 1000 m), which clearly indicates post-Oligocene uplift of the whole area. In the studied zone, this uplift post-dates that of the southern margin of the Massif Central in the Cévennes area [Rey, 1973]. It occurred from the Upper Miocene (about 10 Ma) with a maximum of regional doming from the Upper Pliocene (3.5 Ma) [Derruau, 1971; Le Griel, 1988].

In the south, it has been shown that the uplift in the Velay, Margeride and southern Forez started in the Upper Miocene, 10 Ma ago, and led to the formation of the main trend of topography observed nowadays [Etienne, 1970; Le Griel, 1988; Goër de Herve and Etienne, 1991; Defive and Cantagrel, 1998]. From 5.5 to 3-3.5 Ma, the superimposition of the volcanic formations in the Allagnon valley and in the Velay area suggests that uplift was limited [Goër de Herve and Etienne, 1991; Augendre, 1997]. Following this period, doming became again very active and led to important inverted relief of volcanic formations (e.g. the Céallier eastern border, the Allagnon and Allier valley and the Escandorgue).

In the north, some very clear fault traces and the study of river entrenchment, together with the cross-cutting relationships with well-dated Cenozoic volcanic formations, demonstrates that the main uplift of the northern part of the Massif Central postdates 3-3.5 Ma. Firstly, departures from equilibrium profiles, as in the Forez area (fig. 4), at the

crossing of fault traces along streams running in the same lithology cannot be ascribed to the Oligocene sedimentation period but demonstrates very recent differential uplift. Secondly, from the Lower Miocene to the Upper Pliocene, this uplift was slight or even inactive as lava flows from that period of time are now found superposed, which indicates that they flowed out within the same paleo-valleys. The occurrence of several Pliocene volcanic formations several hundred metres above the present day watercourses clearly shows a strong excavation of the rivers since 3-3.5 Ma.

PRESENT-DAY STRUCTURAL TRENDS

Using a Digital Elevation Model (DEM with a 50 m resolution step), it can be shown that the northern Massif Central displays a N-S oriented fault pattern whereas the southern part displays a N135°E oriented fault pattern (fig. 3a). Both directions result from older Variscan tectonics, as shown by structural studies in other areas of the Massif Central that lack any imprint of the rifting episode [Feybesse, 1981].

Although the prominent directions of the major faults in the north are commonly N-S or near N-S, some oblique orientations are reported either in the Limagne graben or within the Hercynian basement area on the edge of the graben. In the Combrailles area (NW of Clermont-Ferrand), uplift is indicated by a downthrow of more than one hundred metres of Variscan basement through reactivation of well defined Variscan faults such as the Sillon Houiller or through the reactivation of some previously undescribed oblique networks such as the Morge faulted zone (N55°E) (fig 5). The Morge faulted zone is one of the most seismic areas of the Massif Central [Dorel *et al.*, 1995] possibly resulting from residual or continuing activity of the uplift process.

In the south, the DEM analysis reveals a prominent N135°E oriented fault pattern underlined by several volcanic alignments (Aubrac, Devès and Velay), the elliptic shape of the Cantal stratovolcano and the trend of the Margeride horst (fig. 3a). A single N045°E direction can also be defined east of the Velay, a common Variscan direction in this area.

DISCUSSION

The pre-rift volcanism is present throughout the entire West-European Rift system and is arranged roughly parallel to the Alpine front (fig. 6). It is scarce and characterised by a few tens of outcrops of primary magmas ranging from alkali basalt to very undersaturated lavas such as the melilitites of Marcoux, Essey-la-Côte, Grand Valtin and Bohemia [Wilson *et al.*, 1995]. This volcanism started during the late Cretaceous and mainly occurred in the Paleocene and Eocene. At the European scale, this period (i.e. around the Cretaceous-Tertiary transition) corresponds to the early Alpine compression and to the peak of the high-pressure metamorphism in the Sesia zone [see Merle and Michon, 2001].

The buckling of the lithosphere as a response to compression was recently studied by numerical modelling [Cloetingh *et al.*, 1999]. For a 300 Ma lithosphere, that is the inferred age of the European Variscan lithosphere, results show that the buckling can be preserved during several

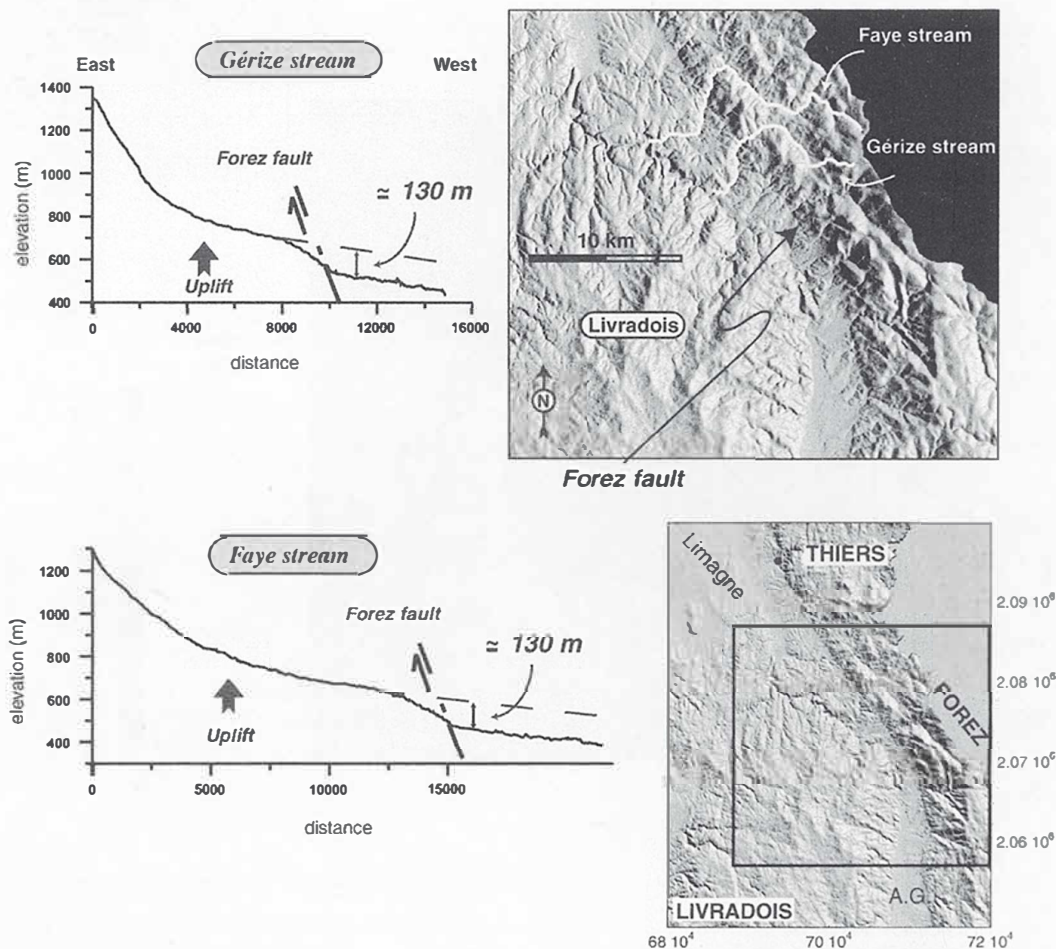


FIG. 4. – Topographic profiles of two streams running across the Forez fault. Departures from the equilibrium profiles of the streams when crossing the fault indicate recent vertical movements, as already suggested by the very clear fault trace of the fault on the DEM. A.G.: Ambert graben.
 FIG. 4. – Profils topographiques de deux ruisseaux recoupant la faille du Forez. Les ruptures de pentes des profils aux passages de la faille du Forez indiquent des mouvements verticaux récents. Cette tectonique est également suggérée par le tracé très net de la faille du Forez sur le MNT. A.G. : Fossé d'Ambert.

tens of million years. They are also in good agreement with geological studies at the scale of the Massif Central. Gravity data show the existence of crustal ridges which have been attributed to lithospheric buckling at about 60 Ma as a result of early Alpine compression [Lefort and Argawal, 1996]. Southeast of the Paris Basin, the doming is concentric around the Alpine belt and reveals a curved uplifted zone, which goes from the north of the Massif Central to the south of the Rhine graben [Lefort and Argawal, 1996, Fig 10]. We believe significant that this concentric ridge around the Alpine belt corresponds to the location of the pre-rift volcanism. As an attempt to interpret this pre-rift volcanism, whose spatial distribution is not related to the main Limagne and Rhine grabens but with a large-scale crustal undulation, we propose that it may result from a low to very low degrees of mantle melting induced by lithospheric doming and adiabatic decompression during the early Alpine compressive event. The activity of the pre-rift volcanism up to the Eocene could be explained by the preservation of the lithospheric buckling. This hypothe-

sis is reinforced by geomorphological studies which show a general uplift of the Massif Central and Morvan area at the same period [Le Griel, 1988; Wyns, 1999].

The rifting volcanic event, which is contemporaneous with the upper Oligocene-lower Miocene rift sedimentation, occurred in the west of the northern part of the Massif Central. This magmatic phase is clearly related in space and time to the asymmetric rifting episode, which induced significant crustal thinning in the west, mostly below the Limagne graben [Merle *et al.*, 1998]. Assuming that high crustal thinning results from the stretching of the whole lithosphere, the scattered volcanic activity recorded from the upper Oligocene to lower Miocene may be induced by low degrees of mantle melting ($< 10\%$) due to mantle decompression during extension. This interpretation is reinforced by the lack of volcanism in the southern part where very slight crustal thinning occurred during the Oligocene. The scattered volcanic event is then interpreted as a consequence of the rifting episode in the northern part of the

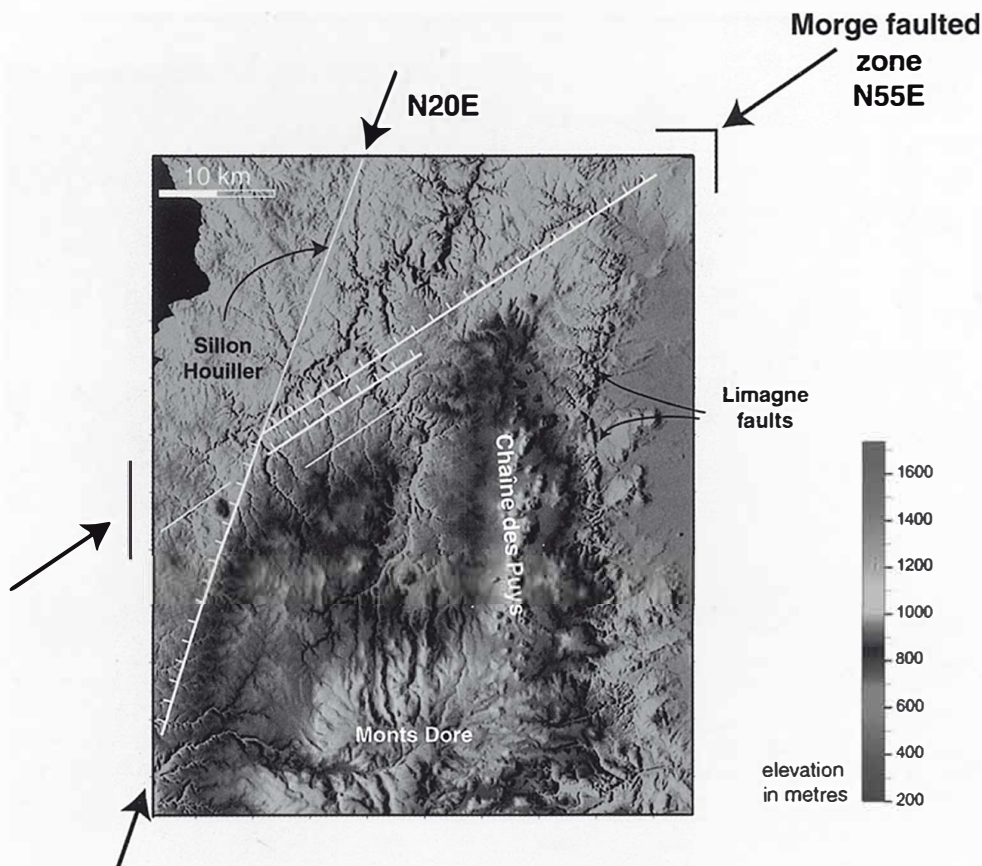


FIG. 5. – Digital Elevation Model (DEM) of the Combrailles area. The Sillon houiller and the Morge faults bound a horst on which the Monts Dore and Chaîne des Puys volcanic provinces were built up.

FIG. 5. – Modèle numérique de terrain (MNT) de la région des Combrailles. Le Sillon houiller et la faille de la Morge bordent un horst sur lequel se sont construites les provinces volcaniques des monts Dore et de la chaîne des Puys.

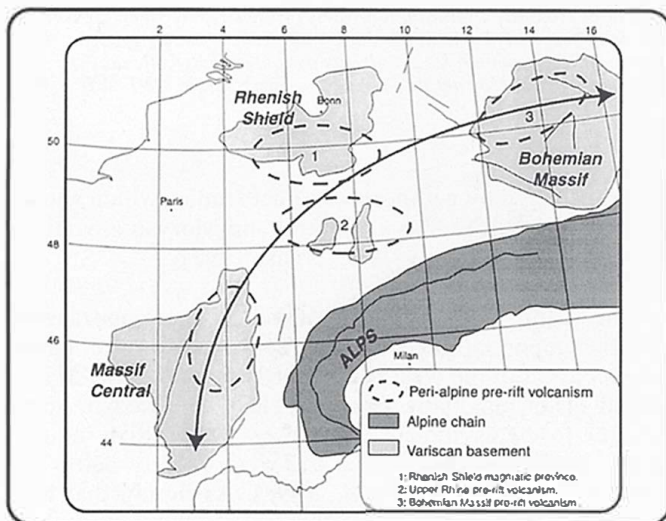


FIG. 6. – Distribution of the pre-rift volcanism in western Europe showing a concentric trend around the Alpine belt.

FIG. 6. – Distribution du volcanisme pré-rift en Europe de l'Ouest montrant l'arrangement concentrique autour de la chaîne alpine.

Massif Central. In this area, the main structures which formed during this rifting event are N-S oriented, mostly perpendicular to the extension direction [Bergerat, 1985], and the present structure is probably inherited from that period.

After a lack of volcanism both in the northern and southern parts, voluminous magmatic activity started at 14 Ma and 5.5 Ma ago in the southern and northern parts, respectively. This major volcanic event is characterised by a more or less continuous activity up to the present-day and can be divided into two volcanic peaks. These two peaks are spatially and temporally associated with the two main periods of uplift, suggesting a common origin for volcanism and uplift processes.

In the south, it is probably significant to consider the parallelism between the trend of major faults, the long axis of the two principal magmatic provinces (Cantal and Devès-Velay) and the thermal anomaly orientation (fig 3). The elongated thermal anomaly just below the Cantal and Devès-Velay volcanic provinces suggests that the major volcanic event was induced by this significant asthenospheric upwelling south of the main rifting area. In contrast with lithospheric mantle thinning deduced from the seismic tomography, slight crustal thinning in the same area indicates that upwelling of the lithosphere/ asthenosphere boundary does not result from Eo-Oligocene extension but is probably due to a late process of thermo-mechanical ero-

sion along the lithosphere base. Such a thermal erosion at the lithosphere base would have caused (i) the major magmatic event and (ii) the uplift of the volcanic area as a result of isostatic adjustment.

The occurrence of two peaks of magmatism and uplift could be attributed to two episodes of thermal erosion at the base of the lithosphere spaced by about 5 Ma. The first episode, from 9 Ma to 6 Ma, was restricted to the southern part of the Massif Central whereas the second one, from 3.5 to 0.5 Ma, was less pronounced, but more widespread: from the Chaîne des Puys in the north to the Escandorgue in the south.

This general magmatic evolution drawn from data at the Massif Central scale may apply to the Eger graben as well, as the three magmatic events described in this study (pre-rift magmatic event, rifting event and post-Miocene volcanic event) are also reported in the literature [Bellon and Kopecky, 1977; Dudek and Elias, 1984] (fig 7). This suggests that a single cause should explain the formation of the entire western European rift surrounding the Alpine mountain belt.

CONCLUSIONS

This study on the spatio-temporal distribution of volcanism in the Massif Central makes it possible to propose three successive magmatic events during the Tertiary evolution of the Massif Central.

1. Pre-rift magmatic event. – This volcanic phase is extremely small, but common to the entire West-European Rift system [Bellon and Kopecky, 1977; Vincent *et al.*, 1977; Lippolt, 1983; Brousse and Lefèvre, 1990]. The parallelism between the pre-rift volcanic belt and the Alpine

front could be explained by a flexure of the lithosphere during early Alpine late Cretaceous-Paleocene compression.

2. Rifting magmatic event. – From the Priabonian up to the end of the early Miocene, three main N-S grabens were initiated in the northern part of the Massif Central. In the upper Oligocene, extension remained active in the west only, leading to a significant crustal thinning below the western Limagne graben (up to 25%). This lithospheric stretching induced a scattered late Oligocene-lower Miocene volcanic phase located from the Roanne-Montbrison graben in the east to the Sillon Houiller in the west. In the south, a very slight crustal thinning occurred during the Oligocene rifting period. It is considered that this thinning was not large enough to trigger volcanism, as it occurred in the north during the lower Miocene.

3. Major magmatic event. – This volcanic episode, which started 14 Ma ago in the south and 5.5 Ma ago in the North, is characterised by two peaks of volcanism (9-6 and 3.5-0.5 Ma). Timing and structural features of the major magmatic event indicate that it is unrelated to Eo-Oligocene extensional processes. The first peak of this major magmatic event, which occurred in the south of the Massif Central only, is coeval with an episode of uplift and is attributed to a thermal erosion along the base of the lithosphere. The second peak, which is also coeval with an episode of uplift, would be induced by a similar process, but below a larger area, from north to south, than for the first peak.

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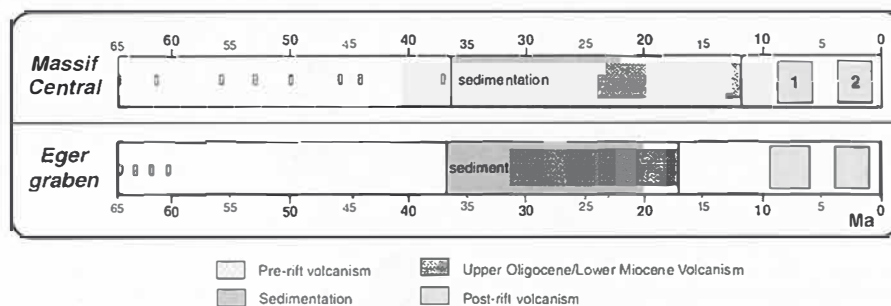


FIG. 7. – Comparative Tertiary evolution of the Massif Central and of the Eger graben. In the Massif Central, data from the northern and southern part are gathered in the same diagram and the major magmatic event is schematically represented by the two peaks of activity (1 and 2). Note the strong similarities between these two segments of the West-European rift, separated by several hundred kilometres. The similarity indicates an evolution linked to common regional factors.

FIG. 7. – Comparaison de l'évolution tertiaire du Massif central et du graben de l'Eger. Dans le Massif central, les données des parties sud et nord sont rassemblées en un tableau unique et la phase majeure de volcanisme est représentée par les deux pics de magmatisme (1 et 2). Noter les fortes similitudes d'évolution entre ces deux segments du rift Ouest-européen, séparés par plusieurs centaines de kilomètres.

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