

# REPEATED GROWTH AND CATASTROPHIC DESTRUCTION OF THE CANTAL STRATOVOLCANO (FRANCE)

Pierre NEHLIG<sup>1</sup>, Hervé LEYRIT<sup>2</sup>, Arnaud DARDON<sup>3</sup>, Gwenael FREOUR<sup>4</sup>,  
Alain de GOËR de HERVE<sup>3</sup>, David HUGUET<sup>1</sup>

---

<sup>1</sup> BRGM, BP 6009, F-45060 Orléans Cedex, France (corresponding author)

Tel. 33 2 38 64 32 50

Fax 33 2 38 64 33 34

E-mail [p.nehlig@brgm.fr](mailto:p.nehlig@brgm.fr)

<sup>2</sup> IGAL, 13, Bld de l'Hautil, F-95092 Cergy Pontoise Cedex, France

<sup>3</sup> Université Blaise Pascal, 5, Rue Kessler, F-63038 Clermont Ferrand Cedex, France

<sup>4</sup> Société Minière Sud Pacifique, Nouvelle Calédonie

**Abstract.** - A new conceptual model of the geological history of the Cantal stratovolcano (France) has resulted from integration of abundant unpublished data and new geological, geochemical, geophysical and geochronological data. Previously defined stratigraphic units and their volcanological significance have been reinterpreted. Covering almost 2500 km<sup>2</sup> for a present volume of almost 400 km<sup>3</sup>, the volcano is by far the largest of the western European stratovolcanoes and exhibits a great abundance of pyroclastic and epiclastic breccias.

The volcano erupted between 13 and 2 Ma on an uplifted Hercynian basement overlain by some Oligocene sedimentary basins. The initial eruptions, between 13 and 7 Ma, were of basaltic lava with a peak of activity around 9 Ma. Trachyandesitic lava, minor trachyte and rhyolite were also erupted towards the end of this activity, mainly between 8.5 and 7 Ma although extending from 10 to 6.5 Ma. This trachyandesitic episode led to the construction of a high stratovolcano (higher than 3000 m above sea level) with an associated laharic piedmont. The edifice, however, collapsed several times, producing gigantic debris-avalanche deposits that are widespread all around the Cantal stratovolcano, extending as much as 35 km from the volcanic centre. The last stages of trachyandesitic activity were synchronous with the emplacement of phonolitic domes between 7.5 and 5.5 Ma, an extrusive event that was synchronous with and followed by extensive basaltic lava flows that covered most of the Cantal stratovolcano.

The emplacement ages of the debris-avalanche deposits are now well constrained by abundant radiometric ages obtained from the overlying and underlying strata, and from included blocks : several large debris avalanches were emplaced on the flanks of the Cantal volcano between 8.0 and 6.8 Ma.

Well-characterized prehistoric and historic debris-avalanche bodies have height/length ratios around 0.1. Taking this good correlation into account suggests elevations above 3000 m for the Cantal paleovolcano. This correlates with the high paleoslopes observed in its central part. Previous models required the existence of a gigantic caldera ("volcano-tectonic depression") in the central part of the volcano to account for the abundant "pyroclastic rocks" now interpreted as debris-avalanche deposits. This caldera and smaller ones were interpreted on the basis of geophysical and geochronological features but new geophysical and geological investigations have proved the absence of such structural features.

*Key words* - Alkaline, Debris avalanche, France, Lahar, Massif Central, Stratovolcano, Volcano, Volcanoclastic deposits

## I. - INTRODUCTION

The Cantal breccias, sandwiched between two thick units of lava, have always intrigued the geologists mapping the flanks of the stratovolcano, both because of the diversity of exhibited facies and because of the great volume that the breccias occupy within the volcanic massif.

During the 1960s and 1970s, whilst mapping the 1:50,000-scale geological map Riom-ès-Montagnes, Brousse (1972) revised the earlier work of Rames (1873), Fouqué (1881) and Boule (1896, 1900) and proposed a stratigraphy based on three superposed units to describe the breccia complex: *i.e.* a “lower breccia”, an “intercalated volcano-sedimentary series” and an “upper conglomeratic complex”.

This stratigraphy established on the Riom-ès-Montagnes mapsheet (Figure 1) was further developed in the western and northern regions of the Cantal, and provided a model for the 1:50,000-scale geological maps of Vic-sur-Cère, Pleaux, Aurillac and Mauriac (Brousse, 1975, 1977, 1980, 1989).

The “lower breccia” was interpreted as a pyroclastic formation, although opinions regarding its precise origin were divided between a pyroclastic flow of the type known as a *nuée à blocs* “blocky flow” (Thonon, 1967; Maury, 1968), a welded tuff or an ignimbrite (Lefèvre, 1968; Lambert 1969), and even a pyroclastic flow resulting from a Katmaian-type eruption (Dantier, 1969).

The “volcano-sedimentary” series, the middle unit, is a marker horizon of very limited thickness (10 to 30 m) relative to the two formations that define its upper and lower limits.

The upper unit was interpreted as a horizon that has been reworked by lahar-type mudflows and streamflow (Boule, 1900; Maury, 1968; Lambert, 1969; Blais, 1972; Vaziri, 1973; Pesme, 1974; Mazet, 1975).

In studying the “conglomeratic formations”, Goër and Milési (1976) and Milési (1976) noted a complete sequence of outcrops exposing the longitudinal evolution from lava flows to stratified conglomerates. They interpreted these conglomerates as the “result of the irreversible rupture of lava emulsions subjected to an “ignimbritic” process”. The same conclusions were advocated in the thesis work of Watelet (1977) and Fontaine-Vive (1981). However, the first attempt at mapping the Murat sheet, in the heart of the Cantal, in the 1970s resulted in a stalemate due to lack of consensus regarding the emplacement and correlation of these breccia formations. Later, mapping the volcanic rocks of the 1:50,000-scale St-Flour

(Goër and Tempier, 1990) and particularly the Chaudes-Aigues sheets by Goër and Burg (1991) demonstrated significant divergence from the regional stratigraphy previously established by Brousse (1972).

Unfortunately, these numerous works (some thirty theses, nine 1:50,000-scale geological maps and more than 200 publications) leave us with no satisfying general vision of the Cantal. This article presents the synthesized geological history of the volcano that has emerged from multidisciplinary geologic, geochemical, geophysical, and cartographic studies. Detailed description of the various lithologic formations, are the subject of BRGM publications in preparation (geological maps and explanatory notes of the Murat sheet at 1:50,000-scale and the Cantal volcanic massif at 1:100,000-scale; Nehlig et al., 2002a,b). In the light of the new data we are finally able to reply to some of the frequently posed questions concerning the possible presence of a broadly distributed pumice layer, a "volcano-tectonic depression", a caldera, the number of debris-avalanche events and the highest paleo-elevation reached by the Cantal volcano.

## **II. – GEOLOGIC HISTORY OF THE VOLCANIC EDIFICE**

The Cantal stratovolcano is part of the Massif Central volcanic province. Lying at the heart of the Massif Central it forms an immense and regular volcanic cone cut by radiating valleys (Figure 1). This is the largest stratovolcano in France, and one of the largest in Europe, covering presently an area almost 2,500 km<sup>2</sup> with a volume of almost 400 km<sup>3</sup>. Slightly elliptical, its dimensions are 50 km north-south, and 70 km east-west. Even though its maximum elevation is no more than 1855 m at Plomb-du-Cantal, 1400 km<sup>2</sup> lie above 1000 m.

The geological history of the Cantal can be subdivided into several broad episodes as depicted on Figures 1 and 2.

### **1) Cantal basement**

The Cantal volcanic edifice overlies an irregular topographic surface ranging in elevation from 580 to 1100 m on a “collapsed” section of crystalline granito-gneissic basement.

Widespread tilting and the horst and graben features observed beneath the Cantal, are the result of a generally extensional tectonic regime dating from the end of the Eocene, and which resulted in the formation of several sedimentary basins (Figure 1). These movements continued during construction of the Cantal volcano. For example, at about 5 Ma, uplift raised fluvial alluvium with abundant phonolite cobbles by more than 100 m (Goër and Tempier, 1990). Seismic activity continues today (Dorel *et al.*, 1994).

## **2) The first eruptions: infra-Cantal basalt**

The initial volcanic deposits of the Cantal were composed of lava flows. Based on the work of Boule (1896), these basaltic lavas have generally been grouped under the name of “Miocene basalts” or “ancient basalts”, or even “infra-Cantal basalt” (Goër, 1980). We retain the latter term for use in contrast with the term “supra-Cantal basalt”.

Because it was completely covered by later products, this initial volcanism is known only from exposures in valley bottoms and on the margins of the massif. It comprises lava flows which are mostly continuous in the northern sector but dispersed and highly eroded elsewhere, associated with varied pyroclastics such as “strombolian” ejecta, welded scoria and phreatomagmatic tuffs. This initial phase mainly took place between 11 and 9 Ma, although it may have begun as early as 13 Ma (Figure 2). The lavas are alkaline basalt and basanite and evolve toward hawaiite. The ejecta and flows have been strongly affected by a red clayey alteration.

## **3) A great stratovolcano grows**

A large part of the Cantal stratovolcano consists of breccias. Most of these are trachyandesitic, and are exposed in the centre of the massif where their thickness may be as much as 800 m, diminishing gradually towards the edge. These breccias, especially in the central part of the stratovolcano, are cut by a network of dykes, again predominantly trachyandesitic, that become increasingly abundant as one approaches the central part of the volcanic edifice. The breccias derive from several origins: pyroclastic flows, autobrecciated flows, lahars and debris avalanches. Schematically, the centre of the volcanic edifice (24 km in diameter) consists essentially of lava flows, pyroclastic flows, and autobrecciated lava flows that are replaced laterally by lahar deposits that can be found up to 17 to 25 km from

the geographic centre of the volcano, and then by debris-avalanche deposits in the most distal parts up to more than 35 km from the core of the edifice marked by the Puy Griou (Fig. 1).

In the following paragraphs, we detail two important lithologic formations associated with the constructive and destructive episodes of the volcanic edifice:

- a succession of lava flows and breccias, whose highly propylitized base contains numerous pyroclastic flows and trachyandesitic, trachytic and rhyolitic extrusives, and which develops laterally into a laharc complex;
- debris-avalanche deposits resulting from successive destabilization of the central stratocone and incorporating its laharc fans.

#### a) Construction of the volcanic edifice: succession of trachyandesitic flows and breccias

The Cantal volcano consists predominantly of trachyandesite. The lava flows are readily viewed in the central part of the volcano where thick flows alternate with breccia.

In the surrounding countryside, the lava flows form light-coloured cliffs 20 to 40 m high. The flows are trachyandesitic with abundant feldspar, pyroxene and amphibole phenocrysts  $\pm$  biotite. Where visible, the base of the flows consists of multicoloured, unsorted trachyandesitic blocks agglomerated by a scoriaceous cement.

The rest of the formation consists of breccia, in places with a zoned appearance. The zonation is very coarse and discontinuous, and results from the intercalation of finer-grained layers (max. 50 cm thick) between the thick strata of monolithic breccia. Very few flow structures or sorting features are visible in these beds. The most massive strata are composed of larger, relatively homogeneous blocks. The block granulometry generally exhibits a mode of between 10 and 20 cm.

These blocks are bound by a matrix that, in most cases, is a cement nearly as tough as the blocks themselves. Chemical analyses performed on the blocks and the cement generally indicate the same trachyandesitic chemical composition. The breccia cement consists predominantly of trachyandesite fragments, with interstices filled with plagioclase fragments sometimes bound together by carbonates. This configuration occurs in the proximal zone and in the thickest strata. In other cases, a more ash-rich pumice matrix surrounds the blocks, although the whole still retains the general characteristics described above.

The breccias mainly derive from pyroclastic flows and from autobrecciated lava flows.

The emplacement of these thick piles of flows and trachyandesitic pyroclastic flow deposits was accompanied by monzonitic and monzodioritic intrusions, dated at approximately 8.3 Ma and which are exposed in the bottom of the upper-Jordanne valley. The intrusions are contemporaneous with a widespread hydrothermal alteration of the rocks in the centre of the edifice.

The generally short flows generated by this trachyandesitic activity are to be found within less than 12 km from the geometric centre from the stratocone. It appears that trachyandesitic volcanic activity was displaced in a northerly direction toward the Puy Chavaroche, during the construction of the stratovolcano.

#### b) Trachyandesitic, trachytic and rhyolitic intrusions, and pyroclastic formations

The central part of the stratovolcano is not uniformly trachyandesitic. It also contains a suite of silicic domes and pyroclastic flows, which were previously grouped together and known by different unit names, such as “Miocene trachytes” (Boule, 1896), “lower acidic formations” (Goër, 1972; Watelet, 1977), “light-coloured lower or sub-breccia suite” (Milési, 1976), “latitic Paleocantal” (Goër, 1980). Milési (1976) completed a detailed study of these rocks in the Alagnon, between Super-Lioran and Murat. Watelet (1977) recognized them in the Santoire and the Rhue valleys. Fontaine-Vive (1981) described them in the Brezons and Epie valleys. Mapping of the volcanic edifice and the new geochronologic data show that these are not a “formation” in the strictest stratigraphic sense, as they are found at all stratigraphic levels of the trachyandesitic stratovolcano. The acid units are, however, more abundant at the base and at the centre of the edifice, where they are associated with significant hydrothermal alteration characterized by the development of paragenetic chlorite, epidote, calcite, sericite and pyrite.

They mainly form large endogenous domes, most commonly trachyandesitic or trachytic, but in places rhyolitic.

Isotopic dates obtained on the trachyte and rhyolite domes of the Cère valley yielded ages of between 9.7 and 8.4 Ma. These ages are relatively early in the development of the stratovolcano. The regional extent of their vents parallels that of the trachyandesitic products.

#### c) Distal transformation of the primary trachyandesitic breccias

The lateral evolution from trachyandesitic breccias to lahar deposits can be seen in the Santoire and Rhue valleys. Near the volcano's center abundant intercalated thick trachyandesitic flows (<20 m) can be seen and the trachyandesitic breccia is not stratified.

Farther away, to the northwest, intercalated flows are no longer visible, but a clear stratification appears, with an inverse grading at the base, normal grading in the middle and inverse grading and better sorting again at the sequence top. The blocks in the breccia become more rounded and contiguous; the proportion of matrix material is high (70%). Farther downstream, they are intercalated with sandy and gravel lenses, generally corresponding to channel-fill.

The entire sequence has an average thickness of 150 m that regularly decreases northeastward. In its proximal regions, it has the aspect of interstratified pyroclastic flow breccias with some intercalated trachyandesitic flows. In its distal regions, it exhibits debris-flow characteristics. The breccias illustrate the progressive transformation from the pyroclastic flow deposits into debris-flow deposits derived from their reworking.

A similar evolution can also be seen in the western and southern valleys of the Cantal stratovolcano, although the distal parts of the deposits have been remobilized by debris-avalanche events.

#### d) Lahar complexes

The distal parts of the pyroclastic-epiclastic transition are associated with the construction of significant lahar deposit fans. These lahar deposits can be observed within a radius of approximately 20 km about the geographic centre of the Cantal, i.e. the Puy Griou (Figure 1). Their geographic distribution is asymmetric. Nearly 2/3 of the deposits are found to the north of the volcano. To the west and east, the lahar deposits extend up to 18 km away (Maronne valley). The area of exposed lahar deposits is approximately 280 km<sup>2</sup>, with the thickest deposits being found on the northern part of the volcano, where they can be as thick as 140 to 180 m.

#### **4) Destruction of the stratovolcano: debris avalanches**

A significant part of the Cantal is composed of unstratified breccia with unsorted, angular to subangular volcanic clasts. The first to make the parallel between these breccias and analogous deposits known to result from debris avalanches was Boule (1900) who mentions



“mud flows” and compares these to the deposits of the “valley of ten thousand hills” at the foot of the Galunggung volcano in Indonesia. Lambert (1969) noted the analogy with the Bezymianny breccias (Gorschkov, 1959) but interpreted them as formed by gigantic lahars.

The first observed debris avalanche studied in detail occurred during the 1980 eruption of Mount St Helens (Voight et al. 1981). Since then, debris avalanches have been described at many large stratovolcanoes, whether terrestrial or marine. This inspired Hoskuldson (1989) and Bourdier et al. (1989) to draw parallels between the debris avalanche of Mount St Helens and the breccias of the Cantal. Next, Cantagrel (1995) proposed the first structural framework for the debris avalanches of the Cantal. Later on, Vidal (1998), Schneider and Fisher (1998) and Reubi and Hernandez (2000) studied the debris-avalanche deposits in parts of the northwestern sector of the Cantal stratovolcano.

Debris avalanches are gravity-induced slope failures resulting from structural instability. Slope failures produce extremely mobile debris avalanches that can travel at high velocities for long distances beyond the flanks of volcanoes. The characteristics and related deposits of debris avalanches have been described by Siebert et al. (1987), Crandell (1989), Glicken (1991) and McGuire et al. (1996).

The frequency of these events is low at the scale of a human lifetime, but not uncommon in the evolution of polygenetic volcanoes. In fact, when volcanic activity is sustained over long periods, the slopes of the edifice may increase through both external accretion (lava flows and pyroclastic deposits) and internal emplacement (intrusions, etc.), become unstable, and destabilize under their own weight possibly as a result of a seismic event, a volcanic eruption, the emplacement of a cryptodome, or hydrothermal alteration or a combination.

The volumes involved are of the order of a few km<sup>3</sup> (up to 47 km<sup>3</sup> for Mount Shasta, in northern California (Crandell, 1989)). Surfaces are covered over hundreds, if not thousands of km<sup>2</sup> (70 km radial distance for an avalanche at Colima in Mexico (Siebert et al., 1987)) at speeds of up to 150 m/s (Siebert, 1984), and the entire mass flows as a granular fluidised mixture.

Several events of this nature affected the Cantal over the course of its history. Debris-avalanche deposits are exposed in the sides of all the major valleys (Figs. 1 and 3) and are extensive at the northern, southern and western edges of the volcano where they form the volcanoclastic piedmont.

The recognition of debris-avalanche deposits in the Cantal is not always easy. In particular, the gigantic scale at which this phenomenon occurs can readily induce errors, especially in

the central part of the edifice, as blocks may be 100's of meters across (Figs 3-1 and 3-2). Their resistance to weathering – often greater than that of the bounding matrix means that lateral contacts commonly do not crop out, which can lead to the erroneous conclusion that these rocks are *in situ*. It is only possible to recognize their true nature by stepping back to observe geometrical relations from a distance.

As a general rule, the presence of large blocks of homogeneous composition, surrounded by a cataclastite of similar composition, and in clearly demarcated contact with components and matrices of different compositions, allows the identification of debris-avalanche deposits. Another characteristic is the presence of jig-saw cracks in blocks (Figure 3-3)(Schneider and Fisher, 1998; Vidal, 1998).

The matrix enclosing the blocks generally results from the cataclasis of the blocks themselves (Figure 3-3) to which is added components incorporated from the substratum (Figure 3-5). At thin-section scale, the microclasts are shattered in the same manner as the blocks. The matrix is composed of free minerals and lava fragments. It can also contain fossil wood, pumice and sedimentary clasts (limestone, marl) or crystalline clasts (granite, gneiss) torn from the substratum.

Megablocks range in size from ten to several hundred metres (Figure 3). They form structures with significant topographic relief in most valleys (Figures 3-1 and 3-2). Usually, these blocks themselves are composed of primary pyroclastic flow deposit breccias. They may also comprise fragments of domes or lava flows. The majority of these products are trachyandesitic. Most of the time, these "clasts" have maintained their internal structures (flow base, columnar jointing, "lahar" deposit stratification), but lost their original orientation. At the contact with the matrix, the surface of the blocks is brecciated (jigsaw cracks), with injections of matrix into the blocks.

The base of the debris-avalanche deposits varies from being clearly demarcated and erosive to well marked by a thick polygenetic basal layer. Fieldwork indicates that the nature of this sole is a function of distance from volcano centre, the nature of substratum encountered and the nature of the exposed topography that was encountered by the avalanche. Several facies types can be described as a function of these different criteria:

- thick sole, rich in underlying basement materials;
- thin cataclastic sole, resting directly on the basement;
- thick red sole, rich in basaltic components; the red colour is due to the incorporation of clays resulting from the weathering of infra-Cantalien basalts.

## **5) Supra-Cantalian phonolites and basalts**

A series of phonolitic knobs and a few hauyne-phenocryst-bearing trachyandesite flows of limited extent were emplaced between the trachyandesitic stratovolcano and the supra-Cantalian basalts. They form two zones of outcrops oriented NW-SE: one comprising the northern part of the Cantal (Varet, 1967) and the other comprising the central part of the Cantal (Vatin-Pérignon, 1966; Demange, 1974). The isotopic ages of these lavas fall between 6.5 and 7 Ma.

Subsequent to the debris avalanches, the supra-Cantalian basalts comprise the last unit of the volcanic stratigraphic series, and define deeply incised terraces in the landscape. This final phase of Cantal eruptive activity gave rise to wide basalt plateaus or “planèzes”, up to 250 m thick. Activity in the southwestern quadrant was low, but it was voluminous in the other sectors. The lavas vary between dark, basic end-members (basanite and nephelinite) and lighter, slightly evolved end-members (basalts and hawaiites), commonly doleritic in texture. Although not readily visible, there are many fissure vents and evidence of eruptive centres spread over the entire surface of the planèzes (Goër, 1972). Extrusive and strombolian events are dominant, with some lesser hydromagmatic events.

As in the initial phase, this final basaltic volcanism is dispersed relative to the centralized Cantal. After 4 Ma the Cantal centre was limited to small events, such as the summit crater plug of the Plomb-du-Cantal, the last identified event (3 Ma).

Near the end of the Pliocene (2.5 Ma), the first major global climatic cooling period ushered in a long series of glacial-interglacial cycles which, in addition to rainwash, modified the volcanic terrain into its current landscape form.

The overall slope of the planèzes rarely exceeds 5% in the central regions, and decreases to less than 1% in the peripheral zones. The general geometry of these zones indicates that the elevation of the volcanic edifice at the time was not substantially different from its current elevation. This indicates that the general form of the volcanic massif was acquired before the supra-Cantalian basalts were deposited, and owes little to subsequent erosion: the essential cause of the low topographic elevation of the Cantal stratovolcano was due essentially to the sectorial destabilizations.

### III. - VOLCANOLOGIC IMPLICATIONS

#### 1 ) How many debris avalanches?

The emplacement ages of the debris-avalanche deposits are relatively well-constrained by geochronologic data (Fig. 2) obtained either from the flows below and above the avalanche deposits, or from the blocks contained within the deposits themselves.

In chronological order, we find:

- the debris avalanche(s?) of the north and east (Rhues, Véronne, Impradine, Santoire, Alagnon and Chevade valleys) prior to 7.6 Ma; the deposits of the debris avalanche(s) were subject to significant later erosion, and commonly occur discontinuously or as thin units; they are covered by a thick laharic series providing evidence of later reconstruction of a central stratocone;
- the debris avalanche(s?) of the northwest (Marilhou, Mars, Maronne, Aspre and Bertrande valleys) have ages between 7.2 and 7.4 Ma;
- the debris avalanche(s?) of the southwest Doire and Authre valleys (between 7.2 and 7.4 Ma), the Jordanne valley (between 6.9 and 7.2 Ma), the Cère valley (between 6.8 and 7.4 Ma);
- the debris avalanche(s?) of the south : Goul, Brezons and Epie valleys; they came to rest south of the Truyère valley on basalts of the Aubrac generation, of which the youngest (Espinasse plateau, Chaudes-Aigues sheet) is dated at  $7.1 \pm 0.1$  Ma; in the Goul valley, it contains megablocks of phonolite; Geometric reconstruction leads us to date the debris avalanche(s) of the south prior to that of the Cère valley.

These chronological constraints that have been verified by geologic data (superposition, nesting) indicate the presence of at least four debris-avalanche events occurring, one prior to 7.6 Ma (to the north and the east), one between 7.4 and 7.2 Ma (to the northwest), and two later than 7.2 Ma (to the south and the southwest).

The absence of debris-flow deposits overlying the debris-avalanche deposits in the area between the Bertrande and Cère valleys suggests to us that no major volcanic edifice reconstruction occurred after this major period of destabilization. Nearly all the other debris-

avalanche deposits are covered by thick laharic complexes indicating reconstruction of the volcanic edifice.

Whether several debris avalanches have affected the western part of the Cantal stratovolcano between the Mars valley in the north and the Bertrande valley farther south remains unclear. If this is the case we should expect the local presence of an interface marked by paleosols, lava flows or pyroclastic and debris-flow deposits. However, despite an active search no discontinuity of this type has yet been mapped except locally in the northwestern part of the Cantal where two possible -and still debated- overlying debris-avalanches deposits have been distinguished by Schneider and Fisher (1998) and Reubi and Hernandez (2000).

Without being able to completely exclude the existence of a very close succession of destabilizations, as has been observed at certain volcanic edifices like Saint Augustine in Alaska (Beget and Kienle, 1992), the absence of internal discontinuities within the deposits indicates a different scenario - major destabilization events that would have affected the entire slopes of the Cantal.

However, some avalanches were clearly channelled within the valleys of the proximal zone and may correspond to “smaller” events. This appears to be the case for the Cère debris-avalanche deposit, which occurred between 7.4 and 6.8 Ma and which is confined between the massifs of Elancèze and Plomb-du-Cantal which have been dated at between 10 and 8 Ma. The total volume of debris-avalanche deposits presently preserved is around  $250 \text{ km}^3$  for a total volume of the present stratovolcano of less than  $400 \text{ km}^3$ . Under the hypothesis that a small number of debris avalanches occurred, the conclusion must be drawn that each of these was responsible for the deposition of a very large volume.

This indicates that these were in fact gigantic debris avalanches, which can be compared to prehistoric examples such as at Mount Shasta with a volume of  $47 \text{ km}^3$  (Crandell, 1989). The near-instantaneous brecciation of such rock volumes, and their reworking by erosional processes must have left a significant sedimentary signature in the downstream basins, which remains to be discovered.

## **2) What paleoelevations were achieved at the Cantal volcano?**

The present Cantal stratovolcano has the form of a very flat-shaped cone whose highest point is at 1,855 m at the Plomb-du-Cantal. The observation of flows and breccias with very steep slopes, and the discovery of large volumes of reworked formations about the volcanic edifice

have led, from the end of the 19<sup>th</sup> century, to models suggesting much higher paleovolcanoes. The erosive power of ice and water were held responsible for the flattening of this great stratovolcano. Until the end of the 1980s, this model had both supporters and challengers.

The extent of debris-avalanche deposits allows us to support the model of a major stratovolcano.

Ui et al. (1986), in a synthesis of 283 Japanese volcanoes, identified 71 debris-avalanche deposits on 52 volcanoes, of which 41 were stratovolcanoes. The maximum distances travelled by these debris avalanches ranged between 1.6 and 32 km and the vertical collapse (or drop height) ranged between 0.2 and 2.4 km. The height/length ratio was between 0.2 and 0.07 (Fig. 4). This means that the maximum distance travelled by the debris avalanche is 5 to 17 times greater than the drop height. The H/L ratio decreases slightly with a decrease in avalanche volume.

Using the good correlation between drop height and the distance travelled by the debris avalanches it is possible to establish limits on the trachyandesitic Cantal paleoelevations. Thus, for the debris-avalanche deposits found 35 km from the heart of the volcanic edifice, the drop height cannot have been less than 2400 m; calculations using the elevation of the distal debris-avalanche deposits produces an initial elevation above sea level of not less than 3000 m (Fig. 4). Taking the mean H/L ratio of 0.11 into account results in paleoelevations of over 4000 m.

These significant heights are supported by the high viscosity of the trachyandesite lava flows that are thick, short and mostly blocky, by the concentration of trachyandesitic vents within a small radius (7 km) and by the significant volcanic activity occurring within 1 Ma (8.5 to 7.5 Ma).

The destabilizations of the Cantal volcanic edifice are primarily owing to the emplacement of this large volume of extremely viscous trachyandesitic material. Little reworked by debris-flows, this material gives rise to the very steep dips (20-25°) observed in many sectors in the heart of the Cantal. Many factors may have contributed to the destabilization, such as hydrothermal alteration of the base of the volcano or the tilting of the entire structure as at the end of the Late Miocene (Merle et al., 2001). It is also possible that the emplacement of the phonolite cryptodomes in the central region (around the Puy Griou) may have caused the destabilization. However, the absence of phonolitic clasts in the debris avalanche of the west slope puts this particular cause-and-effect relationship in doubt, despite the near-contemporaneity of these events.

### 3) Stratigraphic reinterpretations

The geologic history formulated here leads to a reinterpretation of all the brecciated formations defined previously and used in many publications and maps. In particular, this concerns the “lower breccia”, the “volcano-sedimentary series” and the “conglomeratic complex”. Without entering into the details of the many nomenclatures and definitions used elsewhere, these three terms have been renamed and reinterpreted as follows.

The “lower breccia”, previously interpreted as a pyroclastic deposit corresponds essentially to debris-avalanche deposits. The hundreds of 50 m to more than 1 km-size mapped intrusions shown within this unit on the 1:50,000-scale Riom-ès-Montagnes, Mauriac, Pleaux, Aurillac and Vic-Sur-Cère maps exhibit neither roots nor chilled margins. Everywhere that we have checked the contacts of these rocks, they have corresponded to megaclasts carried within debris avalanches. This has the effect of considerably reducing the number of trachyandesitic and trachytic lava vents that were previously considered to cover the entire Cantal massif (70 km in diameter). According to our observations, these vents are concentrated at the heart of the volcanic edifice within an area of less than 15 km diameter, corresponding to the central stratocone (Fig. 1).

The “volcano-sedimentary series” corresponds essentially to reworked volcanic material deposited by aeolian, lacustrine or fluvial processes. They are essentially volcano-detrital deposits, though in some cases they may be pyroclastic flows or falls. These deposits are present at all stratigraphic levels of the Cantal, but are particularly abundant at the top of the debris-avalanche deposits where these have been covered and preserved by later formations. In general, their geometry is lenticular and discontinuous, marking small depressions filled by various materials of different types and origin. These levels have been mapped on the Riom-ès-Montagnes, Mauriac, Pleaux, Aurillac and Vic-sur-Cère geological maps as fairly continuous levels that can be correlated at the scale of the entire Cantal. The diachronous character of the debris avalanches does not permit such a stratigraphic correlation. Moreover, their differences in elevation cannot be used to prove the existence of faults, as was done on the geological maps. In fact, these deposits represent the infill of small depressions, accompanied by the subsequent debris-flow deposits which smoothed the post-debris-avalanche topography.

The “conglomeratic complex” had previously been interpreted either as a sequence of lahar deposits, or a sequence of autobrecciated flows. In the majority of cases, these are lahar deposits that contain intercalated lava flows, pyroclastic-flow and ash falls deposits.

#### **4) A great layer of pumice?**

A significant "pumice layer" covering an area of 375 km<sup>2</sup> with an average thickness of 30 m, or a volume of 11 km<sup>3</sup>, has been previously described in the Cantal (Brousse and Lefèvre, 1966). The map that was completed within the framework of the present project (Nehlig et al., 2002a) illustrates the remarkable diversity and very small volumes of these deposits, which occur at all levels of the Cantalian stratigraphy, although concentrated between 7.5 and 8.5 Ma (Platevoët et al., 2000).

In the central part of the edifice, pyroclastic deposits in places correspond with thick, slightly welded pyroclastic flows filling the paleovalleys. In the distal regions they essentially correspond to fall-out deposits, which have been severely reworked by laharcic and fluvial processes.

Our results suggest that instead of a significant layer of pumice of several km<sup>3</sup>, the Cantal contains only a few small ash and pumice pyroclastic deposits. Given the absence of a major plinian event, there is no longer any reason to continue searching the Cantal for evidence of a vast collapsed circular caldera.

#### **5) What about the Cantal caldera? The debris-avalanche caldera.**

A major programme of geochronologic dating enabled Baubron and Demange (1977) to show the existence of a significant topographic relief inversion effect in the central part of the stratovolcano, where a trachyandesitic flow dated 7.1±0.2 Ma was emplaced in a paleodepression. This depression is synchronous with the main activity of the stratovolcano and was originally interpreted as a collapse caldera, and is presented as such on the 1:1,000,000-scale Geologic Map of France (Chantraine et al., 1996). The topographic relief inversion was synchronous with the debris avalanches to the southwest, and mapping and reinterpretation of the breccias suggest that it may be related to a scar left behind by a debris avalanche.



Massive landslides create specific morphologies, e.g. horseshoe-shaped re-entrants into the edifice, and a high steep-sided breakaway scarp having an amphitheatre shape. An inventory of flank-collapse calderas conducted by Siebert (1984) demonstrated that they typically have a diameter of between one and three kilometres and are generally several hundreds of metres deep.

The flank-collapse calderas are infilled fairly rapidly by younger material and gravity slides. At Bezymianny (1956), the caldera was filled by eruption deposits within 25 years. At Bandaï-san (1888), it has remained visible. At Mount St Helens, pyroclastic flows, lahars and the development of a dome slowly modified the original 1980 flank-collapse caldera. But one phenomenon that has an important contribution to the suppression of this geomorphologic structure is the incessant crumbling of the steep sides of the caldera, whose products accumulate at the foot of the cliffs. The erosional breccias produced by these collapses exhibit characteristics common to all slope collapse deposits (little interstitial matrix, angular and poorly sorted clasts).

In ancient edifices, flank-collapse caldera scars are hard to interpret. They are generally situated near the summit of the volcano, with very steep slopes covered by slope deposits and the deposits of subsequent volcanic activity. One possible flank-collapse caldera wall was discovered on the west slope of Puy Mary (1783m) where a unit 50 to 70 m thick, and visible over a distance of 100 metres consists of steeply inclined stratified layers. The entire unit is interpreted as a paleo-breccia of slope-collapse origin, resulting from the collapse of the trachybasaltic breccia known as “the Rolland breccia”. The geometric relationships and geochronological data indicate that this unit is the likely product of the collapse of a debris-avalanche caldera wall.

## **6) A hypothetical “volcano-tectonic graben”; sedimentary basins and hydrothermal alteration.**

In 1966, the results of an electrical prospecting survey carried out by BRGM have led Vatin-Pérignon and Michel (1966) to suggest the presence of a basement collapse (a “volcano-tectonic depression”) in the central part of the Cantal volcano. New magnetic data (an aeromagnetic survey carried out in 1975 by BRGM and INAG (Roux and Senaud, 1978)), and electric and magneto-telluric data (from CNRS and INAG surveys carried out between 1974

and 1978 (Aubert et al., 1979; Aubert et al., 1982)) have helped define the geometry of this graben and the physical characteristics of its infill material.

The graben, 20 km long and oriented NW-SE, appears to be filled with low resistivity formations (5-10  $\Omega$ m), moderately magnetic (1 A/m), and interpreted (Aubert et al., 1979) as pyroclastic in nature. To date, no geological data, such as faults or pyroclastic deposits, have enabled us to confirm the existence of this collapse feature. Similarly, a geophysical profile (DC resistivity, electromagnetic, seismic reflection, gravity) established in the Cère valley (This project) has failed to show any evidence of collapse in the roof of the basement rocks. In addition, the discovery of clayey limestone within the hypothesized graben, runs counter to the proposed model. These data suggest that the electrical and aeromagnetic anomalies are not related to a "volcano-tectonic graben".

We deduce that the previously described "volcano-tectonic graben" does not exist: the cause of the significant geophysical anomalies must be sought elsewhere, probably in the hydrothermal alteration of the basement rocks and at the heart of the volcanic edifice, and to a lesser degree in the local existence of clayey Oligocene sediments. Furthermore, this "volcano-tectonic graben", the site of "pyroclastic breccia expulsion" in the models of the 1960s and 1970s, has no justified reason for existing after reinterpretation of the "lower breccia" as a debris-avalanche breccia.

#### **IV. - CONCLUSIONS**

After more than a century of geological work and sometimes lively debate that has resulted in the accumulation of an impressive quantity of data, preserved in over thirty thesis dissertations, two hundred memoirs and scientific articles, this synthesis and reinterpretation of the data, coupled with mapping in the heart of the edifice at 1:25,000-scale (Nehlig et al., 2002a) and the acquisition of new geochronological, geochemical and geophysical data (Nehlig et al., 2002b), has provided a clearer picture of the formation of the Cantal stratovolcano.

This can be sub-divided into 3 principal phases:

- an early basaltic volcanism, very widespread;
- a differentiated stratovolcano, 25 km in diameter, supplying a volcanoclastic piedmont of over 60 km in diameter;

- a late basaltic volcanism, with numerous scattered vents.

The mapping of volcanic deposits illustrates that during the differentiated period, the primary lavas and volcanoclastic material accumulated near the vents. Detrital materials were retransported by fluvial and laharc processes and built the volcanoclastic fan at the periphery of the edifice (Fig. 5). Nonetheless, this erosion was not enough to reduce the edifice significantly before it suffered several major gravity destabilizations. These contributed to the formation of a large volcanoclastic piedmont. As a result, while the central zone of the Cantal exhibits only a succession of lavas and pyroclastic breccias, the intermediate zones have lahar and debris-avalanche deposits. The latter are the only mode of deposition preserved in the distal regions. This mode of formation leads us to reinterpret previously established stratigraphies, and to reconsider their volcanologic significance. In addition, the data acquired have brought into question the existence of the “great pumice layer”, “caldera” and “volcano-tectonic graben”.

### **Acknowledgements:**

The dynamic and volcanologic interpretation of the Cantal is based on detailed 1:25,000-scale mapping of the Murat sheet, performed by V. Baudoin, F. Binet, A. Dardon, G. Durance, G. Freour, A. Jamet, C. Legendre, H. Leyrit, L. Michon, P. Nehlig, S. Pilet, O. Reubi, A. Saraceni, W. Vannier and N. Vidal. The previous mapping work carried out by G. Boudon, J. Demange, M. Fontaine-Vive, A. de Goër, H.M. Guérin, A. Lambert, P. Larroque, C. Lefevre, C. Maurizot Blanc, R. Maury, J.P. Milesi, N. Vatin-Pérignon, Y. Veyret, and P. Watelet significantly facilitated our current work. Our volcanologic interpretation also benefited from data contributed by, and discussions held with H. Bellon, G. Boudon, J.L. Bourdier, J.M. Cantagrel, R. Crahmaliuc, P. Gillot, G. Lerouge, P. Maguire, R. Maury, Ph. Mossand, R. Platevoet, G. Prouteau, J.Ph. Rançon, P. Rochette, J. Roger, J.Y. Roig, J.L. Schneider, P. Skipwith, M. Tegye, J. C. Thouret, B. Valadas and Van Wyk de Vries. To all of these colleagues, we extend our warmest thanks. We also thank J. Donnelly-Nolan, V. Neall and T. Uhlir who reviewed and greatly improved this paper. Finally, this work would not have seen the light without the prior studies carried out under the supervision of R. Brousse, A. de Goër, N. Vatin-Pérignon and P.M. Vincent, and which comprise an important part of the Cantal bibliography since 1960.

## REFERENCES

- Aubert M., Dupis A., Lenat J.F., Roux J., Senaud G. (1979) Exploration géophysique de la fosse volcano-tectonique du Cantal. C. R. Acad. Sci., D, 288, 2:215-218
- Aubert M., Dupis A., Lenat J.F., Roux J., Senaud G. (1982) Structure of the Cantal stratovolcano, French Central massif, from electric, magnetotelluric soundings and aeromagnetic data. J. Volcanol. Geotherm. Res., 12:77-99
- Baubron J.-C., Demange J. (1977) Chronologie absolue de quelques formations volcaniques du centre du stratovolcan du Cantal (Massif central français). Méthode potassium-argon. Implications volcanologiques. BRGM Report, 77, SGN, 268
- Beget J.-E., Kienle J. (1992) Cyclic formation of debris avalanches at Mount Saint Augustine volcano. Nature, 356:701-704
- Blais S. (1972) Contribution à l'étude géologique du massif du Cantal : géologie du Carladès. PhD Thesis, Orsay, France, pp 1-150
- Boule M. (1896) Le Cantal miocène. Bull. Serv. Carte géol. Fr., 8, 54:213-248
- Boule M. (1900) Géologie des environs d'Aurillac, et observations nouvelles sur le Cantal., Bull. Serv. Carte géol. Fr., 11, 76:279-358
- Bourdier J.L., Goër de Herve A. (de), Rançon J.P., Vincent P.M. (1989) Volumineux dépôts d'avalanches de débris sur les versants sud et ouest du massif du Cantal. Implications stratigraphiques et volcano-structurales. C.R. Acad. Sci., Paris, 309:2127-2133
- Brousse R., Lefevre C. (1966) Nappes de ponces du Cantal et du Mont-Doire. Leurs aspects volcanologique, pétrographique et minéralogique. Bull. Soc. géol. Fr., 7, 8:223-245
- Brousse R. (1972) Geological map of Riomès Montagne (764), 1:50,000-scale, plus explanatory notes, BRGM, French Geological Survey
- Brousse R. (1975) Geological map of Vic sur Cère (812), 1:50,000-scale, plus explanatory notes, BRGM, French Geological Survey
- Brousse R. (1977) Geological map of Pleaux (787), 1:50,000-scale, plus explanatory notes, BRGM, French Geological Survey
- Brousse, R. (1980) Geological map of Aurillac (811), 1:50,000-scale, plus explanatory notes, BRGM, French Geological Survey
- Brousse, R (1989) Geological map of Mauriac (763), 1:50,000-scale, plus explanatory notes, BRGM, French Geological Survey
- Cantagrel J.M. (1995) Avalanches et coulées de débris dans un volcan complexe intraplaque : vers un nouveau schéma volcano-structural du massif du Cantal (Massif Central, France), Bull. Soc. Géol. Fr., 166, 3:285-293
- Chantraine J., Autran A., Cavelier C. (1996) Carte géologique de la France au 1 000 000. Editions BRGM, 6<sup>ème</sup> édition
- Crandell D.R. (1989) Gigantic debris avalanche of Pleistocene age from ancestral Mount Shasta volcano, California, and debris avalanche hazard zonation. U.S. Geol. Surv. Bull, 1861, pp 1-32

- Dantier M. (1969) La vallée de la moyenne Santoire et les plateaux voisins (Cantal). PhD Thesis, Orsay, France, pp 1-200
- Demange J. (1974) Contribution à l'étude du volcanisme de la Haute-Vallée de la Cère (Cantal). PhD Thesis, Orsay, France, pp 1-231
- Dorel J., Fourvel D., Donnadiou G. (1994) Etude de la sismicité de l'Auvergne et des régions limitrophes (Massif Central Français). Bull. Soc. Géol. Fr., 166, 3:271-284
- Fontaine-Vive M. (1981) Volcanologie et pétrologie de la haute vallée du Brezons et des planèzes adjacentes (massif du Cantal). Etude de l'analogie de cristallisation des pegmatitoïdes et des lingots métalliques. PhD Thesis, Grenoble, France, pp 1-336
- Fouque F. (1881) Sur la série de roches qui constituent le sol de la Haute Auvergne. C.R. Acad. Sci., 92:1039
- Glicken H. (1991) Sedimentary architecture of large volcanic debris avalanches. Sedimentation in volcanic settings, SEPM, Spe. pub., pp 1-45
- Goër de Herve A. (de) (1972) La planèze de Saint-Flour (Massif volcanique du Cantal, France). Annales scient. Univ. Clermont-Ferrand, n° 47 et 48. Vol. I - Structure et stratigraphie, pp 1-254. Vol. II - Formes et dépôts glaciaires, pp 1-213
- Goër de Herve A. (de) (1980) Le Cantal. In Géologie des pays européens, 26<sup>th</sup> Int. Geol. Congr., Paris, t. France, Belgique, Luxembourg, Dunod Editor
- Goër de Herve A. (de), Milesi J.P. (1976) Etude préliminaire de la falaise d'Auzolles, modèle dynamique d'une origine directement éruptive des "conglomérats andésitiques" du Cantal (Massif Central français). C.R. Acad. Sci. Paris, 282:977-980
- Goër de Herve A (de), Tempier P. (1990) Carte géologique à 1/50 000<sup>e</sup> et notice, Saint-Flour (789), BRGM, Serv. Géol. Nat
- Goër de Herve A (de), Burg J.-P. (1991) Carte géologique à 1/50 000<sup>e</sup> et notice, Chaudes-Aigues (813), BRGM, Serv. Géol. Nat
- Gorshkov G.S. (1959) Gigantic Eruption of the volcano Bezymianny. Bull. Volcanol., 20:77-109
- Hoskuldsson A. (1989) Contribution à la géologie du Cantal Occidental. Master Thesis, Clermont Ferrand, France, pp 1-26
- Jamet A. (1999) Le piémont occidental du stratovolcan du Cantal (France). Master Thesis, IGAL, Cergy, France, 114, pp 1-140
- Lambert A. (1969) Géologie de la moyenne vallée du Mars et des plateaux adjacents (Massif du Cantal). PhD Thesis, Orsay, France, pp 1-200
- Lefèvre C. (1968) Géologie du massif du Cantal au niveau des vallées de la Maronne, de la Bertrande et de la Doire. PhD Thesis, Orsay, France, pp 1-285
- Mazet A.G. (1975) Une série basalte alcalin - trachyandésite à hypersthène - comendite, moyenne vallée de la Cère, Cantal, France. PhD Thesis, Orsay, France, pp 1-99
- McGuire W.J., Jones A.P., Neuberg J. (1996) Volcano instability on the Earth and other planets. Geol. Soc. London, Spec. Pub.. 110, pp 1-388
- Maury R. (1968) Contribution à la géologie du Cantal : les hautes vallées de la Petite Rhue et de la Véronne. Master Thesis, Orsay, France, pp 1-126

- Merle O., Vidal N., van Wyk de Vries B. (2001) Experiments on vertical basement fault reactivation below volcanoes. *Journal of Geophysical Research*, 106:2153-2162
- Milési J.-P. (1976) Dynamisme des écoulements pyroclastiques du Cantal oriental, sur l'exemple de ceux de la vallée de l'Alagnon. Thèse 3ème cycle, Grenoble, pp 1-197
- Nehlig P., Arnaud N., Baudoin V., Binet F., Boudon G., Dardon A., Demange J., Durance G., Fontaine-Vive M., Fréour G., de Goër de Herve A., Jamet A., Legendre Ch., Leyrit H., Maurizot Blanc Ch., Michon L., Milési J.P., Pilet S., Vatin Pérignon N., Vannier W., Watelet P. (2002a) Geological map of Murat, 1:50,000-scale, BRGM, French Geological Survey. In press
- Nehlig P., Fréour G., Goër A. de, Huguet D., Leyrit H., Maroncle J.L., Roger J., Roig J.Y., Surmely F., Thiéblemont D., Vidal N. (2002b) Geological map of Murat, explanatory Notes. In press
- Pesme M.F. (1974) Contribution à l'étude géologique du Cantal méridional et du Nord de l'Aubrac. PhD Thesis, Orsay, France, pp 1-204
- Platevoët R., Schneider J.L., Lefèvre C., Nehlig, P. (2000) Les formations pyroclastiques du volcan Cantal (France) sont-elles liées à une vaste caldeira centrale ? Apport des dynamismes volcaniques. *Géologie de la France*, 4:77-91
- Rames J.-B. (1873) Géogénie du Cantal. Bouygues Editor, Aurillac, 1, pp 1-103
- Reubi O., Hernandez J. (2000) Volcanic debris-avalanche deposits of the upper Maronne valley (Cantal volcano, France) : evidence for contrasted formation and transport mechanisms. *J. Volcanol. Geotherm. Res.*, 102, 3-4:271-286
- Roux J., Senaud, G. (1978) Le levé aéromagnétique Massif central 1975 : étude de quelques anomalies caractéristiques liées au volcanisme et au socle. PhD Thesis, Clermont-Ferrand, France, pp 1-198
- Schneider J.L., Fisher R.V. (1998) Transport and emplacement mechanisms of large volcanic debris avalanches: evidence from the northwest sector of Cantal volcano (France). *J. Volcanol. Geotherm. Res.*, 83:141-165
- Siebert L. (1984) Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruptions. *J. Volcanol. Geotherm. Res.*, 22:163-197
- Siebert L., Glicken H., Ui T. (1987) Volcanic Hazards from Bezymianny and Bandaï type eruptions. *Bull. Volcanol.*, 49:435-459
- Steiger R.H., Jäger E. (1977) Subcommittee on geochronology : convention on the use of decay constants in geo and cosmochronology. *Earth Planet. Sci. Lett.*, 36:359-362
- Thonon P. (1967) Contribution à la géologie du Cantal : la haute-vallée du Marilhou, environs de Trizac et d'Auzers. Master Thesis, France, pp 1-110
- Ui T., Yamamoto H., Suzuki-Kamata K. (1986) Characterization of debris avalanche deposits in Japan. *J. Volcanol. Geotherm. Res.*, 29:231-243
- Varet, J. (1967) Les trachytes et phonolites du Cantal septentrional. PhD Thesis, Orsay, France, pp 1-354
- Vatin-Perignon N. (1966) Pétrographie et Minéralogie des roches volcaniques et description géologique de la partie centrale du massif du Cantal. PhD Thesis, Univ. Grenoble, France, 359p.
- Vatin-Perignon N., Michel R. (1966) Présence d'une fosse d'effondrement volcano-tectonique dans la partie centrale du massif du Cantal. *Bull. Soc. Geol. Fr.*, 7, 8:308-310
- Vaziri H.M. (1973) Contribution à l'étude géologique du massif du Cantal: géologie de Mur-de-Barrez. PhD Thesis, Orsay, France, pp 1-91

- Vidal N. (1998) Les avalanches de débris volcaniques: description des dépôts et nouveau modèle de destabilisation de flanc à partir de l'exemple du stratovolcan du Cantal (Massif Central, France) : Modélisation analogique et numérique. PhD Thesis, Clermont Ferrand, France, 201, pp 1-180
- Voight B., Glicken H., Janda R.J., Douglas P.M. (1981) Catastrophic rockslide-avalanche of May 18, in Lipman P.W. and Mullineaux, D.R. eds, The 1980 eruptions of Mount St. Helens, Washington : U.S. Geological Survey Professional Paper 1250, p. 347-378
- Watelet P. (1977) Volcanisme tertiaire dans les hautes vallées de la Santoire, de l'Impradine et de la Petite Rhue. Contribution à l'étude des formations bréchiques. Massif du Cantal. PhD Thesis, Grenoble, France, pp 1-225

## List of figures

Figure 1 – Geological map of the Cantal volcano plotted on a hillshaded digital elevation model (50 m). The map was drawn after nine 1:50,000 scale geological maps (Mauriac, Riom-es-Montagnes, Massiac, Pleaux, Murat, Saint-Flour, Aurillac, Vic-sur-Cère and Chaudes-Aigues). The inset shows a map of France with the area of interest. Legend : 1-Supra-Cantalien basalts; 2-Phonolite; 3-Debris-flow deposits; 4-Debris-avalanche deposits; 5-Ash and Pumice deposits; 6-Trachyandesitic stratocone with minor trachyte and rhyolite; 7-Infra-Cantalien basalts; 8-Oligo-miocene sediments; Hercynian basement (not coloured). Principal summits : PM = Puy Mary; PG = Puy Griou; PC = Plomb du Cantal. The numbering 1, 2, 3, 4, 5 and 6 corresponds to the localization of the photographs shown in figure 3.

The E-W cross-section of the central part of the Murat map (see trace of cross-section on the map) has the same general legend then the map (from top to bottom in stratigraphic order: Supra-Cantalien basalts (light blue); Phonolite (Puy Griou, light green); Debris-flow deposits (yellow); Debris-avalanche deposits (orange); Ash and Pumice deposits (red); Trachyandesitic stratocone (light (flows) and dark green (pyroclastic breccias)) with minor trachyte and rhyolite (orange); Infra-Cantalien basalts (dark blue); Oligo-miocene sediments (pink); Hercynian basement (not colored).

Figure 2 - K-Ar and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages of the different lithostratigraphic units (Nehlig et al., 2002b). 1-Supra-Cantalien basalts; 2-Phonolites; 3-Trachyandesites; 4-Trachytes and Rhyolites; 5-Bloks in the Debris Avalanche deposits; 6-Infra-Cantalien basalts. Ages obtained before 1977 were recalculated using the new constants (Steiger and Jäger, 1977).

Figure 3 - Pictures from the western part of the Cantal stratovolcano illustrating the progressive brecciation of the debris avalanche deposits from the central to the peripheral parts of the Cantal volcano (M = matrix; B= blocks). See figure 1 for localisation.

1 – Picture showing the succession of the stratigraphic units in the central parts of the volcano (A = crystalline basement; B = debris avalanche deposits; C = debris flow deposits; D = Supra-Cantalien basalts). Note the gigantic size of the debris avalanche megablocks (several 100 meters). Mars Valley southfacing slope.



- 2 – Picture showing a large subhorizontal megablock (B). The megablock shows vertical fractures injected by a fine-grained matrix of cataclastic trachyandesitic material. Aspre Valley southfacing slope.
- 3 – Large block (B) with a puzzle structure (right of picture) included in a polygenic matrix (M). Maronne Valley southfacing slope
- 4 – Large dislocated blocks (B) with a polygenic matrix injection (M), on the road between Mauriac and Aurillac.
- 5 – Debris-avalanche deposit with injection of a polygenic matrix (M) derived from the cataclasis of the sole of the avalanche 10 meters beneath the base of the picture. Giou de Mamou quarry in the Cère valley.
- 6 – Large dislocated megablock (B) with a polygenic matrix injection (M), on the road between Mauriac and Aurillac, 23 km from the geometric center of the stratocone.

Figure 4 - Graph showing the distance covered (L) and the height of fall (H) of a selection of Japanese volcanic debris-avalanche deposits (data from Ui et al., 1986). A good correlation is observed between H and L that can be used to estimate a minimum paleoelevation for the Cantal paleovolcano. Debris-avalanche deposits 35 km from the centre of the stratovolcano imply a minimum paleo-value for H of 2,400 m. Thus we calculate an elevation above 3,000 m, taking into account that the distal parts of the western avalanche are at an altitude of 600 m. An average H/L value would provide an elevation above sea level largely above 4,000 m.

Figure 5 - Conceptual model showing the development of the Cantal stratovolcano and its laharcic and debris-avalanche volcanoclastic piedmont (modified after Jamet, 1999). The gravitational collapse of the paleovolcano and its volcanoclastic fan generates a major debris-avalanche deposit. A new volcano is built that again supplies an extensive laharcic piedmont. The succession of several phases of construction (intrusions, extrusions, pyroclastic flows, debris flows) and destruction (debris-avalanches) between 8.5 and 6.8 Ma explains the present geometry and stratigraphic successions observed in the Cantal volcano.

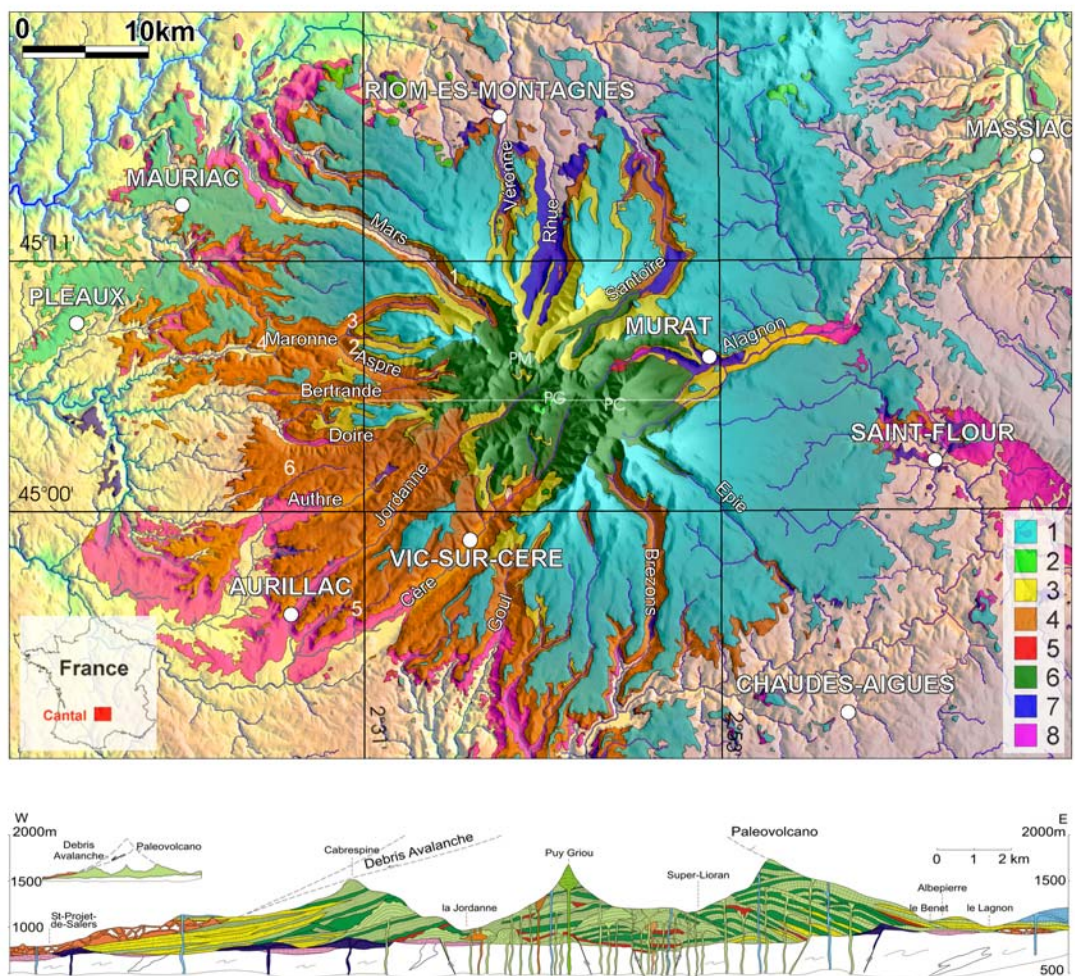
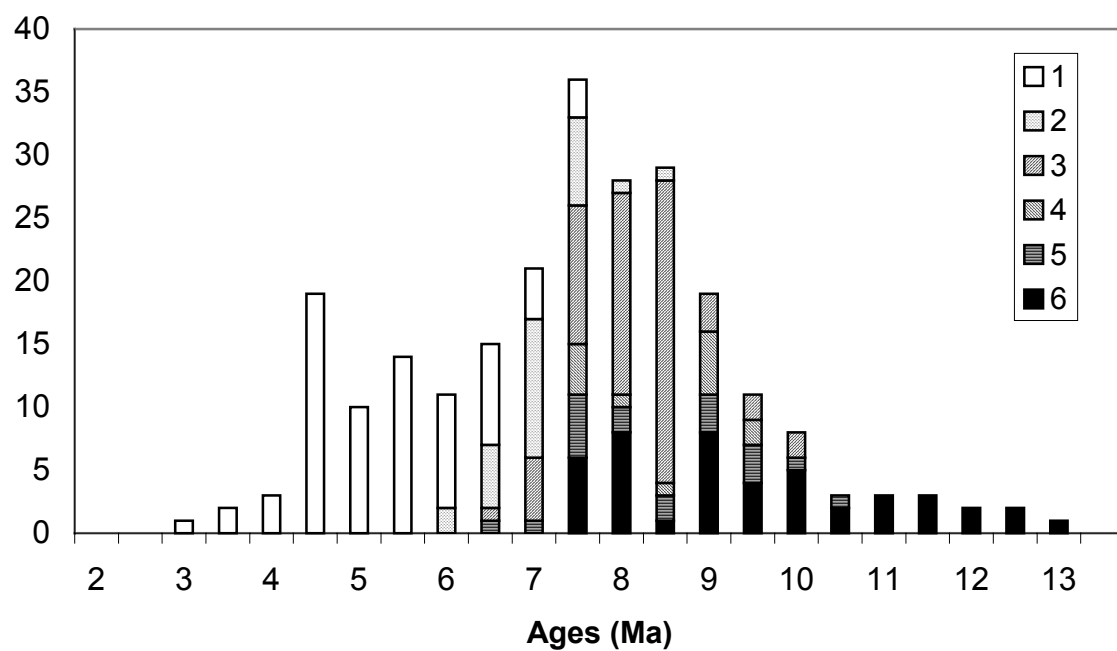
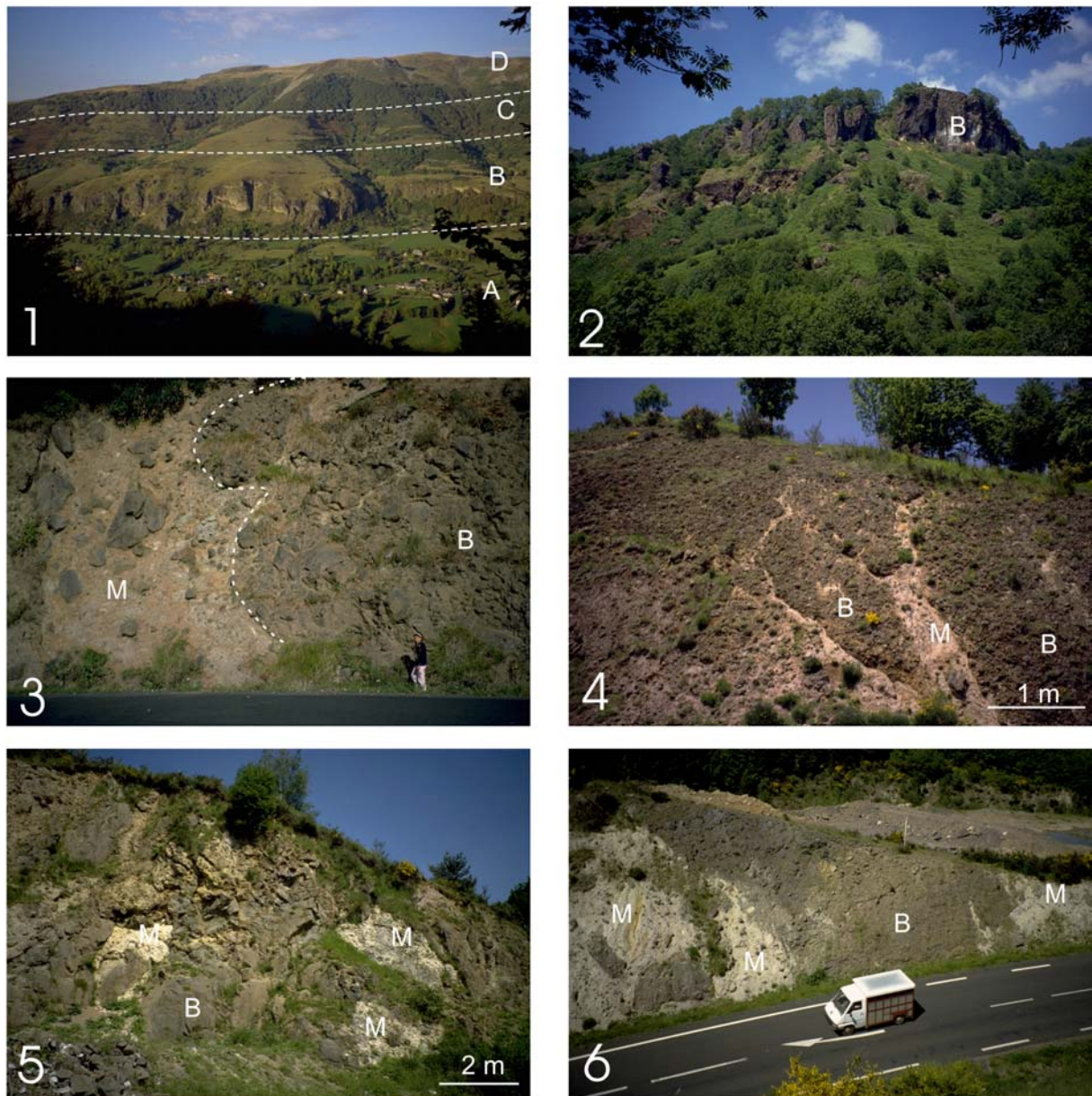


Figure 1

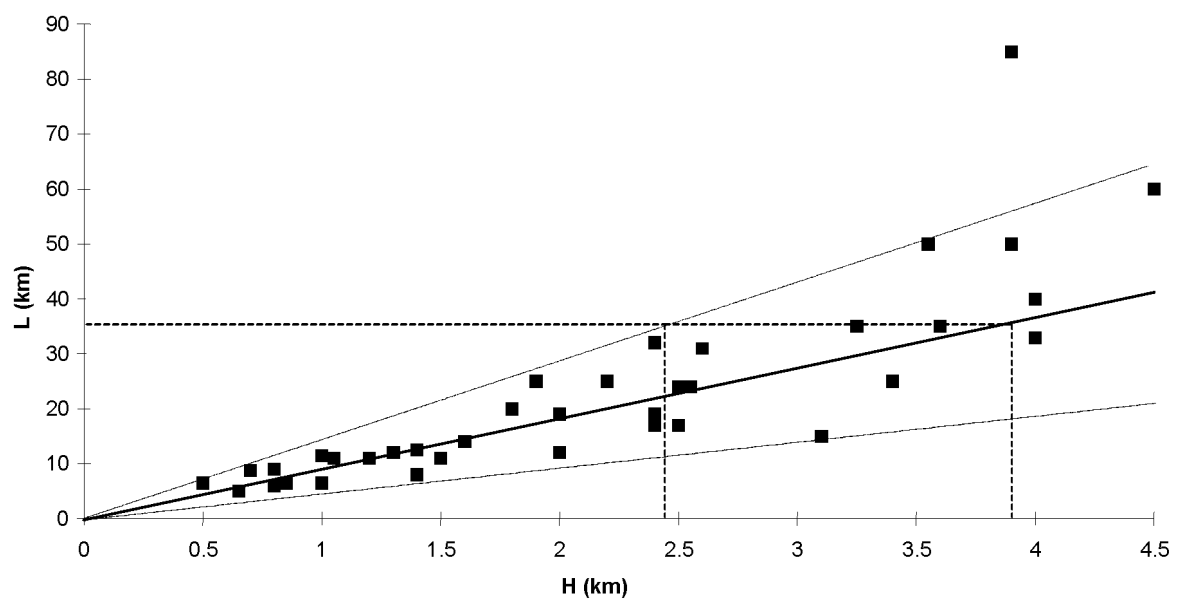


**Figure 2**

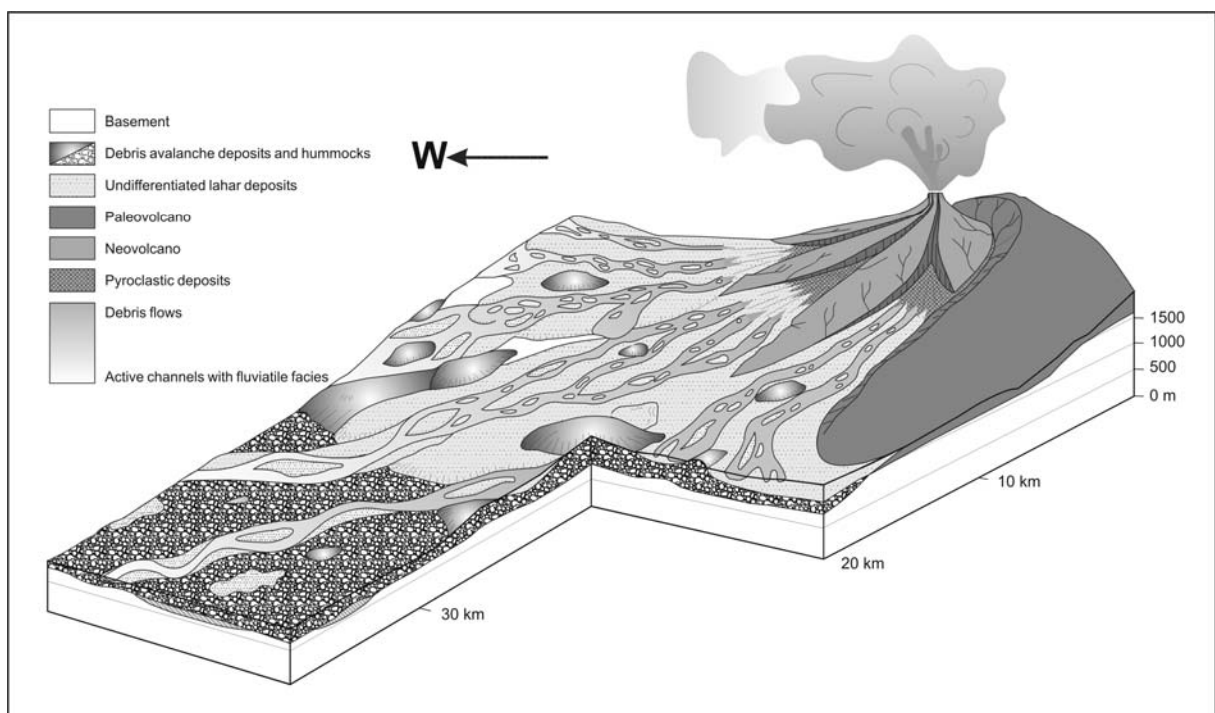




**Figure 3**



**Figure 4**



**Figure 5**