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SEDIMENT YIELD DURING LATE GLACIAL AND HOLOCENE PERIODS IN THE LAC CHAMBON WATERSHED, MASSIF CENTRAL, FRANCE

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ABSTRACT

A sediment budget for the Late Glacial and Holocene periods was calculated for the Lac Chambon watershed which is located in a formerly glaciated temperate crystalline mountain area. It appears that over 15 500 years: (1) 69 per cent of eroded particles have been displaced by gravity processes and then stored within the watershed, compared to 31 per cent that have been displaced by running water and evacuated outward; (2) the mean mechanical erosion due to gravity processes on the slopes amounted to 16·1±6 m and only developed on a quarter of the watershed surface, whereas the mean mechanical erosion due to running water amounted 1·24±0·37 m and involved the whole watershed surface. The mean sediment yields due to gravity processes on slopes were 2300±1360, 1770±960 and 380±100 m^3 km^{-3} a^{-1}, respectively, for basalts, and basic and acidic trachyandesites. Values of sediment yield due to running water were 49±15, 120±36 and 79±24 m^3 km^{-2} a^{-1}, respectively, during the Bölling–Alleröd, the Younger Dryas and the Pre-Boreal–Boreal periods. They were 56±17 and 166±50 m^3 km^{-2} a^{-1} during the Sub-Atlantic period before and after 1360 a BP, respectively. These values reflect variations in the natural environment and the impact of human-induced deforestation. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Sediment yield and erosion rates are influenced by size of the watershed (Holeman, 1968; Robinson, 1978; Milliman and Syvitski, 1992), lithology (Corbel, 1959, 1964; Dietrich and Dunne, 1978; Meade, 1988; Meade *et al*., 1990b), relief and tectonics (Schumm, 1964; Ruxton and MacDougall, 1967; Ahnert, 1970; Pinet and Souriau, 1988; Meade *et al*., 1990a,b; Milliman and Syvitski, 1992), climate and vegetation (Langbein and Schumm, 1958; Corbel, 1959, 1964; Church and Ryder, 1972; Wilson, 1973; Martins, 1988) and the activities of man (Corbel, 1964; Douglas, 1967; Trimble, 1975, 1983; Kemp *et al*., 1978; Robinson, 1978; Revel and Rouaud, 1985; Meade *et al*., 1990b). Sediment yield also depends on dynamic agents such as gravity on slopes (Slaymaker, 1988) and running water (Meybeck, 1988; Meade *et al*., 1990b). The effect of these various parameters has been demonstrated by comparing data calculated for individual watersheds which differ from one another in active parameters.

Human activities heavily modify present sediment yield. It is therefore necessary to calculate ancient sediment yield values to know the real impact of natural parameters on mechanical erosion. Few data exist concerning sediment yield in relation to climate and vegetation variations during Late Glacial and Holocene periods before development of human activities; these data (Church and Ryder, 1972; Kemp *et al*., 1978) are not very accurate.

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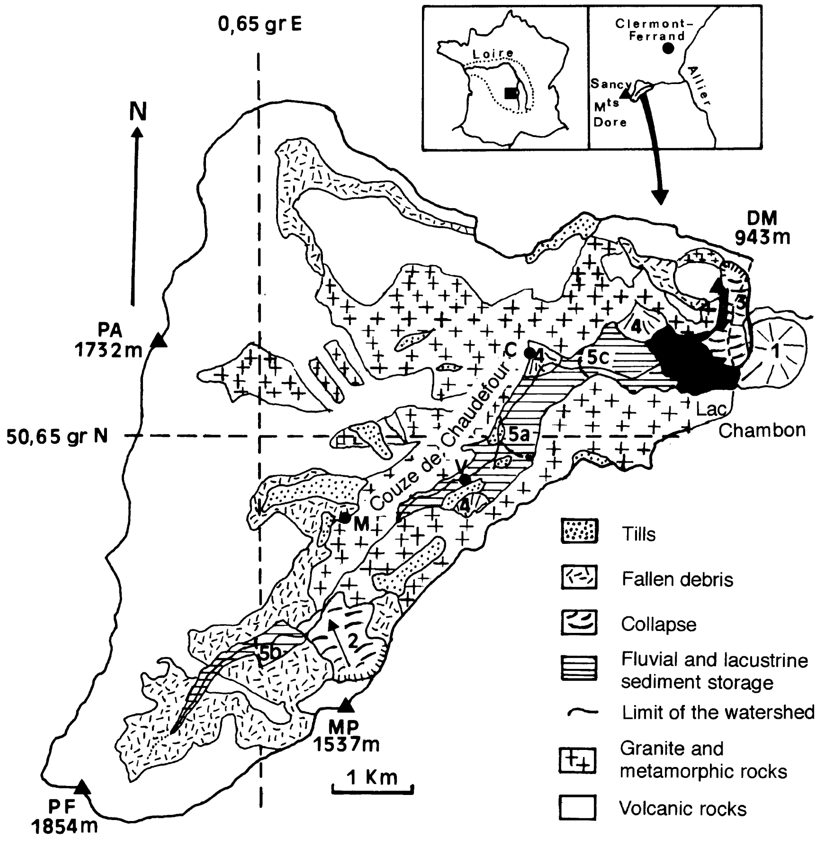

Figure 1. Location map and geological limits of source rocks and sediment storage. 1, Tartaret volcanic cone; 2, Montagne de la Plate collapse (MP); 3, Dent du Marais collapse (DM); 4, alluvial fans; 5, limits of lake extension (a) Tartaret lake; (b) Monneaux lake; (c) Lac Chambon; C, Chambon-sur-Lac; V, Voissières; M, Monneaux; PF, Puy Ferrand; PA, Puy de l'Angle

The watersheds studied are often very large (Holeman, 1968; Ahnert, 1970; Martins, 1988; Pinet and Souriau, 1988; Meade *et al.*, 1990a). Small watersheds would appear more useful in understanding the origin and flux of fluvial sediments (Milliman and Syvitski, 1992). Moreover, many works deal only with fluvial sedimentary discharge and overlook the storage on slopes of material displaced over short distances. A high proportion of this kind of material often appears in budgets (Dietrich and Dunne, 1978; Robinson, 1978; Revel and Rouaud, 1985).

An attempt was therefore made to estimate accurate sediment yield values and a whole sediment budget for the Late Glacial and the Holocene periods in a watershed in which fallen debris, collapsed materials, and pollen- and wood-rich fluvio-lacustrine deposits had been stored since the last glacier retreat. The purpose was to find the overall evolutionary characteristics of the watershed reflecting the effect of non-varying parameters (size of the watershed, lithology, relief and tectonics), and to evaluate the effect of varying parameters (climate, vegetation and human-induced deforestation) on the sediment yield values for each time period. A temporarily closed watershed was chosen, to make possible the storage of almost all the discharged sediments in a lacustrine basin. In order to calculate a complete budget, a detailed morphological analysis of the watershed and a quantification of material stored on slopes was conducted.

The chosen study area was a medium-sized watershed (36.6 km^2), located in a temperate climate, crystalline middle mountain area, currently showing homogeneous characteristics, where changes in climate and vegetation during the Late Glacial and Holocene periods were accurately known.

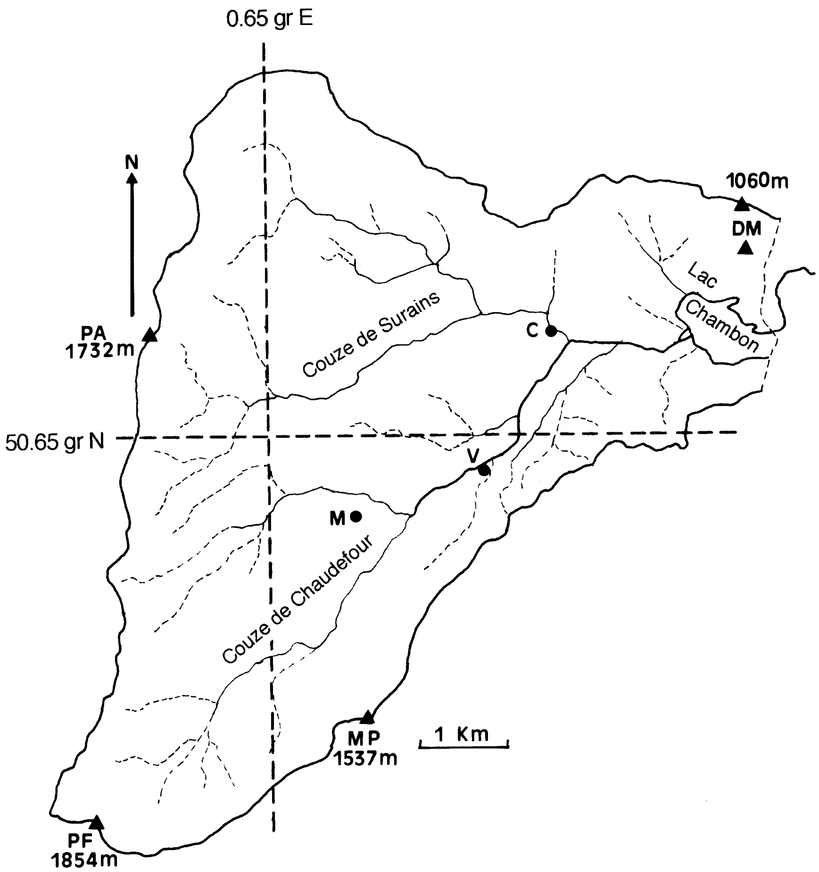

Figure 2. Hydrographic network in the Lac Chambon watershed. See Figure 1 caption for key

GEOLOGIC SETTING AND PHYSIOGRAPHIC CHARACTERISTICS

The Lac Chambon watershed (50·63°N, 0·65°E, 875 m) is located on the eastern side of the Massif du Mont Dore, in the French Massif Central (Figure 1). This is a glaciated valley through which the Couze de Chaudefour river flows, filling the lake. The basement, made of granites and metamorphic rocks (De Peyronnet, 1964; Mervoyer, 1972) is covered mainly by Mio-Plio-Quaternary basalts, and basic ('doréites') and acidic ('sancyites') trachyandesites (Brousse, 1954; Mervoyer, 1972; Besson, 1978; Lavina, 1985). Evidence of the action of ice (cirques, bars, tills) has been found in the watershed (Kieffer, 1962; Veyret, 1981). Many types of superficial sediments were stored in the watershed after the retreat of the ice: fallen debris, material from collapse of steep slope rocks, and fluvial and lacustrine sediments. Two lakes formed successively in the area (Macaire *et al.*, 1992) (Figure 1).

(1) The former *Tartaret lake* (or Tartaret system) was formed after the damming of the Couze de Chaudefour valley by the strombolian volcanic cone of the Tartaret, 12 600 a BP. The lake remained at its maximum extension (elevation 890 m) from 11 300 to about 9800 a BP and emptied totally around 8500 a BP. From 12 600 to 8500 a BP, during the closing of the basin, the solid discharge was stored in the watershed as fluvial, deltaic and lacustrine pebbles, sands and silts.

(2) The present *Lac Chambon* was formed after the damming of the valley at the same place as previously because of the collapse of the Dent du Marais, 2600 a BP. From this time, the main part of the solid discharge of the Couze was stored in the lake and upstream in the alluvial plain (Chambon system) overlying the Tartaret system sediments. The surface area of the present Lac Chambon (0·51 km^2) is half of its initial size (Figure 1). A 5900 year gap separates the Tartaret system and the Chambon system deposits.

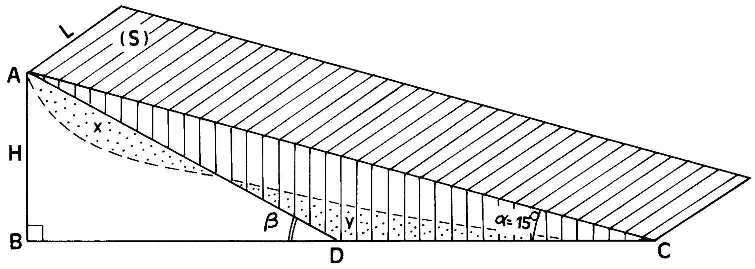

Figure 3. Geometric data used to calculate the volume of fallen debris. The dashed line represents assumed form of bed-rock surface under the fallen debris storage

A minor zone of sediment storage appeared in the ancient lac de Monneaux (Monneaux system) (Figure 1). Two ^{14}C datings from wood fragments in lacustrine sediments (Delmas, 1973; Macaire *et al.*, 1992) give a date of about 8500 a BP for the collapse of Montagne de la Plate which blocked the valley, forming this small lake. The drainage pattern is shown in Figure 2, with the rivers flowing in narrow gullies. The mean annual precipitation (1951–1980) is 1000 mm in Chambon-sur-Lac (Rapport DIREN, 1992). The mean annual temperature is about 7°C with an annual range of 15°C and frost occurs for about 150 days a year. The valley bottoms are covered with meadows or with genista heathland. The steep granitic slopes are covered with conifer plantations. Beech is also found, especially on volcanic rocks, up to 1500 m. Above 1500 m, the alpine level is characterized by bushes, genista heathland and pastures (Luquet, 1926).

METHODS

The total surface of the watershed was calculated for the real and projected surfaces. The mean slope gradients as well as the frequency of slope gradients were calculated by classes of 5° for each type of rock, using the lithologic boundaries of Bureau de Recherches Géologiques et Minières (BRGM) 1/50 000 geological maps and elevation contour lines of the Institut Géographique National (IGN) 1/25 000 maps. These data were digitized to allow the processing of both lithology and relief using BRGM's SynerGis program.

The volume of fallen debris was calculated for each type of source rock. In Figure 3, the surface S ($S = L \times AC$) is the addition of real surfaces of outcrops of a given rock type and L is the addition of lengths of slopes covered by fallen debris. The angle α is the mean slope gradient of the surface of the fallen debris. The height H is the difference in elevation between the top and the base of the fallen debris ($H = AC \sin \alpha$). The assumed concave profile of the basal layer can be inscribed in the ABC triangle and can be compared to the AD median whose gradient is β, supposing that surfaces X and Y compensate. The volume of fallen debris is $V = (L \times H \times BC)/4$. The error rate due to the field survey and to the calculation mode is estimated at ±10 per cent. There is no element in the fallen debris that makes possible an evaluation of their rates of formation. The maximum and minimum erosion surfaces correspond to the surfaces between the top of the slope and the lower and upper boundaries of the fallen debris, respectively.

The volumes of collapsed materials from the Montagne de la Plate and Dent du Marais were determined using the real surface of materials and their mean thickness estimated at 20 m in both cases from field observations. The values obtained lead to an error rate of ±10 per cent for the volumes of collapse. These collapses were assumed to have occurred instantaneously.

Twelve boreholes were drilled in the fluvial and lacustrine sediments of Tartaret and Chambon systems using an auger and two with core samplers (Figure 4). The lithology of the main sedimentary formations and the nature of the basal layer were determined (Figure 5). Fifty-two electric soundings and magneto-telluric measurements were made to ascertain the shape of sedimentary formation limits. These classic methods were described by Aubert *et al.* (1982) and Bossuet *et al.* (1993). Elevation maps of the main palaeosurfaces were drawn (Figure 6). The volumes (in m^3) of lithologic units were calculated using the Descartes Modélisation program (IGA Tours) with an accuracy of ±10 per cent. Late Glacial and Holocene chronologic phases were

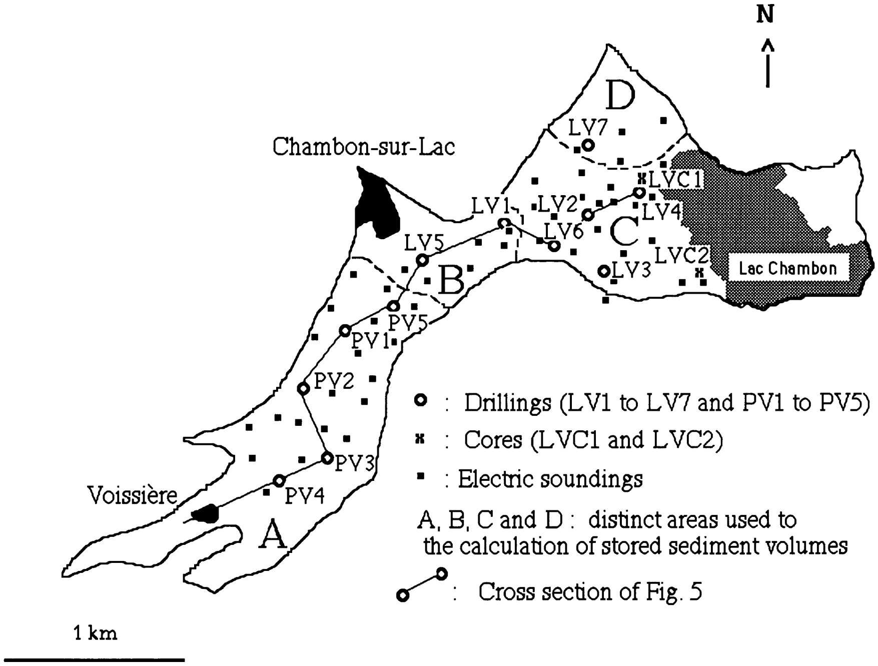

Figure 4. Location map of mechanical drillings and electric soundings used to prospect sediment storage in Tartaret and Chambon systems

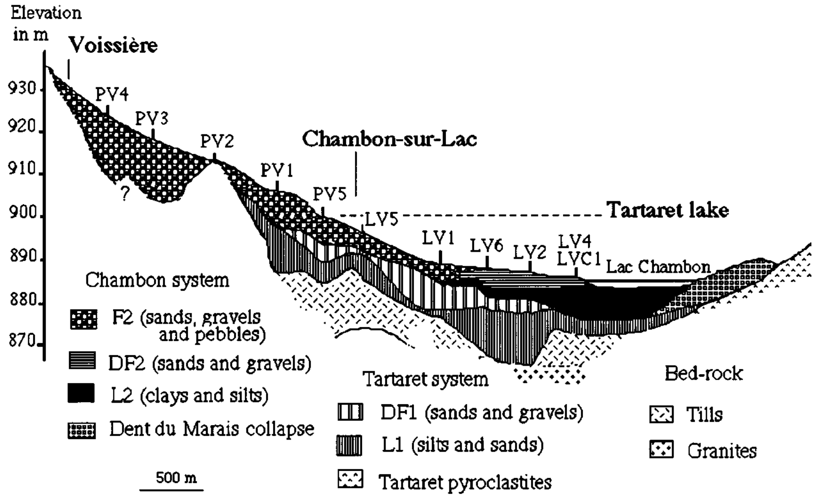

Figure 5. Facies and geometry of sediment storage in Tartaret and Chambon system. See Figure 4 for location of cross-section

recognized in seven reference boreholes using 11 ^{14}C dates, 24 palynologic analyses, interpreted after de Beaulieu *et al.* (1982, 1988a,b) and Guenet (1986), and 142 mineralogic analyses by X-ray diffraction of the <2 µm fraction of sediments (Figure 7).

For the Tartaret system, the volume of sediment for each chronologic phase was calculated by interpolation of the data obtained in the reference borehole (LV5 of B and LV7 of D) or the average value of two boreholes (PV1–PV5 of A and LV2–LV6 of C) in each area, A, B, C and D (Figures 4 and 7). For the Chambon system, the volume of sediment deposited before and after 1360 a BP was calculated from unit L2 thicknesses in borehole

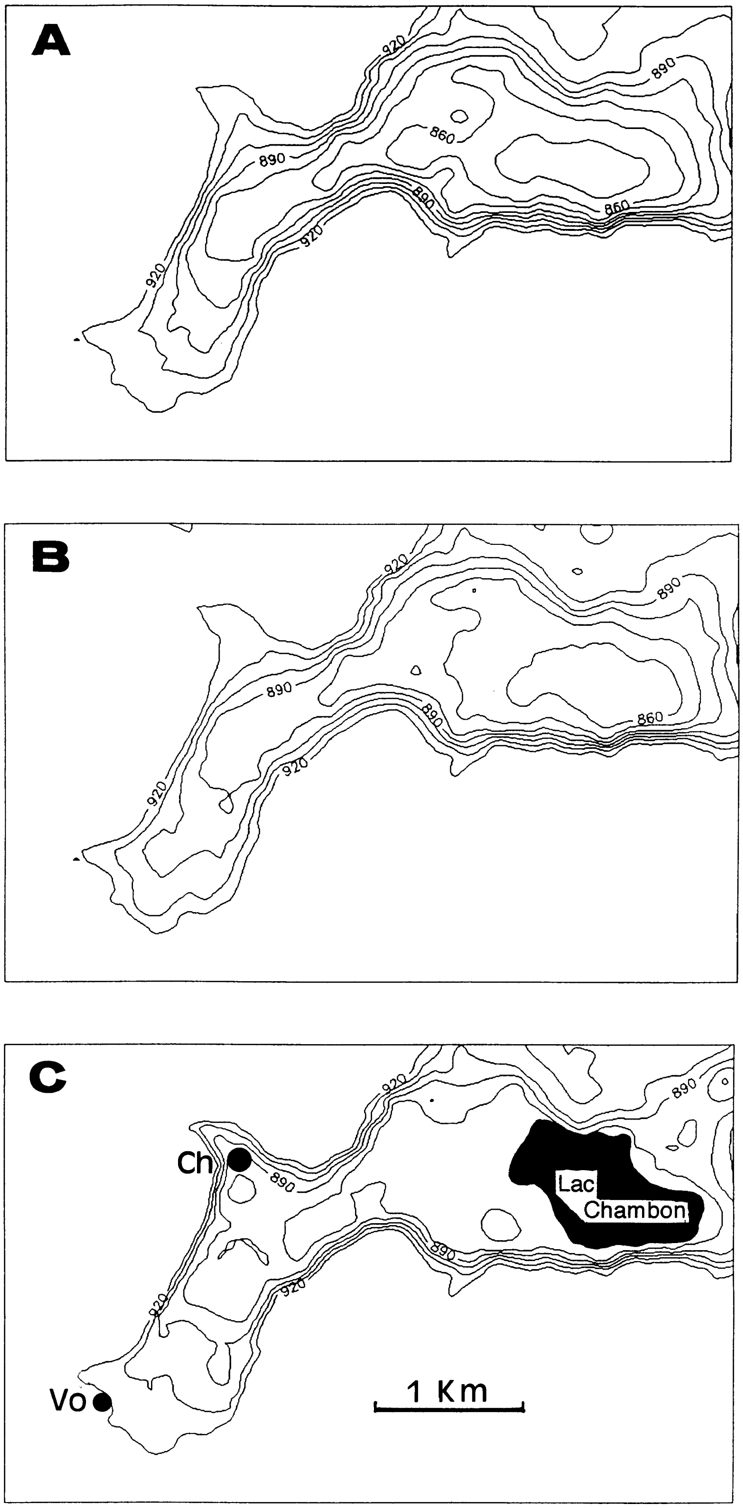

Figure 6. Elevation isolines (at 10 m intervals) above sea level of the main discontinuity surfaces in the Tartaret and Chambon system sediment storage. (A) Basal surface of the storage; (B) discontinuity surface between Tartaret and Chambon storage; (C) present topographic surface. Ch, Chambon-sur-Lac; Vo, Voissière

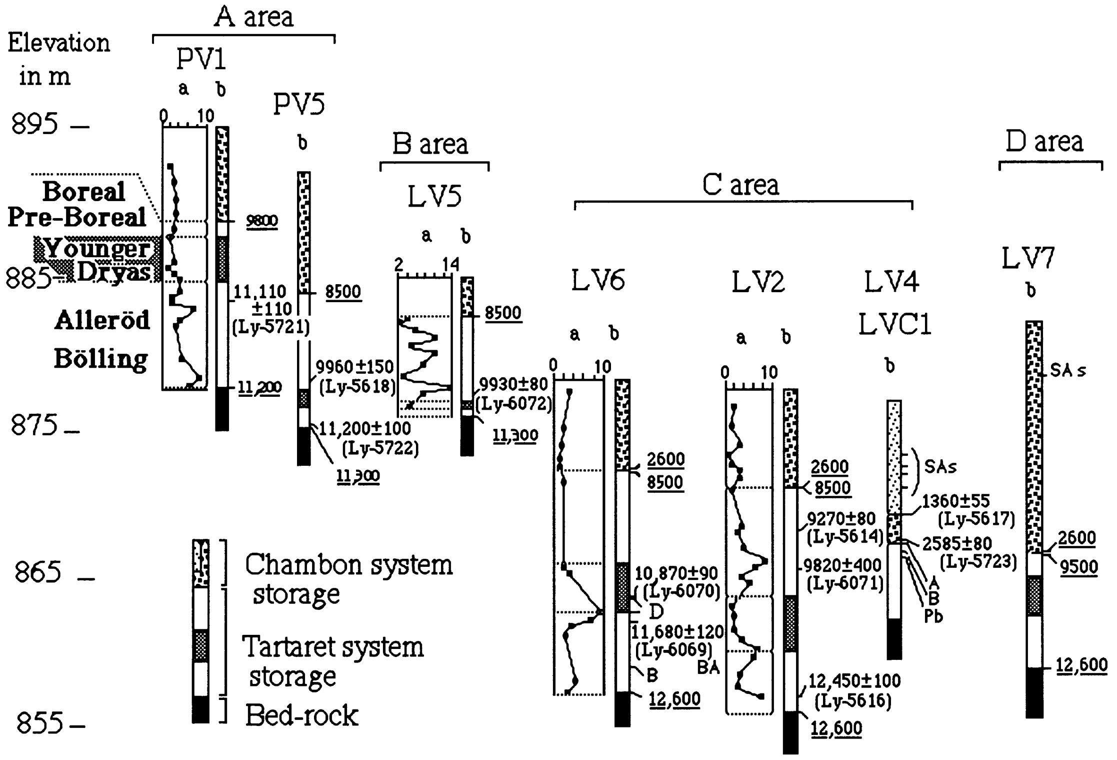

Figure 7. Chronologic limits in reference drillings in Tartaret and Chambon system storage. a, clayey mineral/primary mineral ratio in <2 µm sediment fraction; b, chronologic limits in drillings. Palynologic dates: B, Bölling; A, Alleröd; D, Younger Dryas; Pb, Pre-Boreal; B, Boreal; A, Atlantic; SA, Sub-Atlantic; s, *Secale cereale* pollens. 11110±110 (Ly−5721), ^{14}C date in years BP and laboratory number; 9800, assumed age in years BP

LV4 and core drilling LVC1. The volumes (in m^3) of chronologic units were calculated with an accuracy of ±25 per cent.

The mean sediment yield (in m^3 km^{-2} a^{-1}) and mechanical erosion rates (in mm a^{-1}) were expressed with an accuracy of 30 per cent supposing that all the watershed was affected. It was assumed that the volumetric mass of eroded materials and stored materials were identical on average, as stored materials were almost solely detrital in origin. The total volume of material eroded by running water from 15 500 a BP was estimated by adding the estimated volumes corresponding to the periods of the opening of the watershed to the actual volumes stored. The mean erosion rate chosen for the Oldest Dryas is equal to that of the Younger Dryas as climates of these periods were quite similar. For the period 8500–2600 a BP, an average rate between those of Boreal and Sub-Atlantic periods (2·5±10^3 m^3 a^{-1}) was chosen because of the evolution of climate and vegetation during the Holocene.

RESULTS

The Lac Chambon watershed is 10 km long and has a difference in elevation of 980 m, hence a relief ratio (Schumm, 1956, 1964) of 0·098. The total projected surface is 36·65 km^2 (Table I). The real surface is 39·03 km^2. As the difference between these two values is significant (6·1 per cent), real surface data will be used. The geological basal layer represents 74·1 per cent of the surface. Granitic and metamorphic rocks dominate (24·3 per cent), followed by sancyites (22·8 per cent), doréites (15·1 per cent) and basalts (9·4 per cent). The mean slope gradients for rock type are quite similar (14·9 to 18·5°). However, small slope gradients (5–15°) are frequent on basalts and doréites, showing their initial flow (Figure 8) at elevations between 1100 and 1600 m. The small slope gradients (5–15°) and the steep slopes (15–30°) show the same frequency on granitic

Table I. Main lithologic characteristics and slope values in the Lac Chambon watershed

	Lithology	Projected surface (km^2)	Slope gradient		Real surface (km^2)	Percentage of total surface of the watershed
			Average	Standard Deviation		
Bed rock	Granites and metamorphic rocks	8·88	17·7	9·6	9·48	24·3
	Basalts	3·44	14·9	10·2	3·58	9·4
	Doréites	5·51	18·5	11·1	5·92	15·1
	Sancyites	8·33	18·3	10·2	8·98	22·8
	Other rocks	0·93	17·6	9·1	1·01	2·5
	Total	27·09	17·7	10·1	28·97	74·1
Quaternary surface deposits	Fallen debris	3·83	20·6	9·6	4·22	10·4
	Collapsed materials	1·04	15·4	10	1·09	2·8
	Tills	1·22			1·24	3·3
	Fluvial and lacustrine deposits	2·96	7·5	7·4	3	8
	Total	9·05	13·9	8·5	9·55	24·5
	Lac Chambon	0·51	0	0	0·51	1·4
	Total	36·65	16·3	10·6	39·03	100

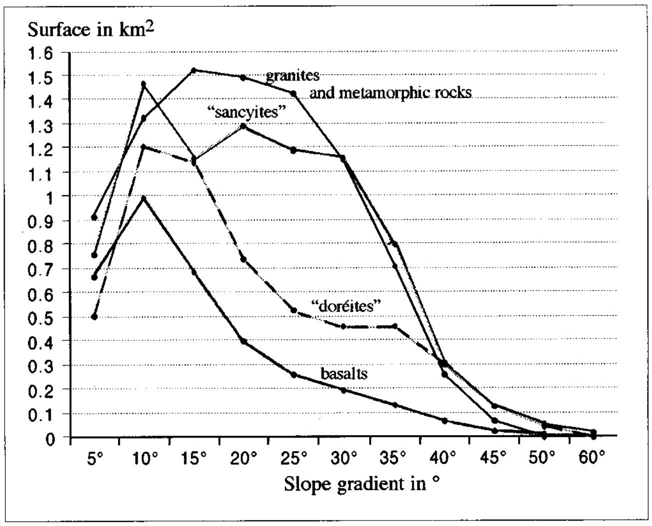

Figure 8. Surface frequency distribution in relation to slope gradient classes for the main lithologic types of bed-rock

and metamorphic rocks (elevation <1100 m) as sancyites (elevation 1500–1885 m). Granitic and metamorphic rocks are often deeply altered by hydrothermal fluids giving a soft sandy material, particularly in fault zones. Volcanic rocks are generally fresh, solid and cross-cut by frequent macrofissures. Quaternary deposits cover 24·5 per cent of the surface. Surface values and mean slope gradients for each deposit are shown in Table I.

Fallen debris is mainly supplied by basalts, doréites and sancyites (Table II). The total volume is (85·9±8·6)×10^6 m^3. Fallen doréite debris is the most abundant, at (39·0±3·9)×10^6 m^3. Fallen basalt and sancyite debris represents (23·2±2·3)×10^6 m^3 and (23·7±2·4)×10^6 m^3, respectively. The following mean sediment yields were deduced from the ratio between volumes of fallen debris and surfaces that could have fed them since the beginning of the Late Glacial period (15 500 a BP in the Massif Central: Beaulieu *et al.*, 1988a,b) 1770±960 m^3 km^{-2} a^{-1} for doréites, 2300±1360 m^3 km^{-2} a^{-1} for basalts, and 380±100 m^3 km^{-2} a^{-1} for sancyites. Maximum distances of fallen debris displacement are greater for sancyites (1·8 km) than for doréites and basalts (0·8 and 1·1 km, respectively). The volumes of collapsed materials are (14·6±1·5)×10^6 m^3 and (7·0±0·7)×10^6 m^3, respectively, in the Montagne de la Plate and Dent du Marais collapses (Figure 1). These volumes, when compared to the surfaces of tear scars, provide instantaneous sediment yields that are (60·8±6·1)×10^6 m^3 km^{-2}

Table II. Sediment yield on slopes

	Stored material	Total volume ($\times 10^6 m^3$)	Storage real surface (ssa) (km^2)	Erosion real surface (esa) (km^2) Present	Initial	Ratio ssa /initial esa (%)	Sedimentation duration (years)	Sediment yield and erosion rate ($m^3 km^{-2} a^{-1}$)	($mm a^{-1}$)	Maximum distance of displacement (km)
Fallen debris	Doréites	39·0±3·9	1·77	1·01	2·78	63·6	15500	1770±960	1·8	0·8
	Basalts	23·2±2·3	0·98	0·45	1·43	68·5	15500	2300±1360	2·3	1·1
	Sancyites	23·7±2·4	1·47	3·52	4·99	29·4	15500	380±100	3·8	1·8
	Total	85·9±8·6	4·22	4·98	9·20					
Collapsed materials	Montagne de la Plate	14·6±1·5	0·74	0·24		75·5	15500	3935±387		1·2
	Dent du Marais	7±0·7	0·35	0·13		72·9	15500	3484±322		1·3
	Total	21·6±2·2	1·09	0·37						
	Total	107·5±10·8	5·31	5·35	9·57					

and (53·8±5·4)×10^6 m^3 km^{-2}, respectively, with maximum displacement distances of materials equal to 1·3 km (Table II).

Under the materials successively stored in the Tartaret and Chambon systems, the basal layer is formed of granite or tills that form a ridge buried in the B area (Figures 4 and 5) and outcrop upstream. The sediments of the Tartaret system comprise a lower silty-clayey to sandy lacustrine unit (L1) overlain by a sandy-pebbly deltaic and fluvial unit (DF1). Sediments of the Chambon system overlie Tartaret system sediments. They comprise two units similar to the Tartaret system lacustrine (L2) and deltaic (DF2) units, which are succeeded by a fluvial unit (F2) identified upstream in the Chambon system (Figure 5).

The Tartaret system sediments cover the major part of the Bölling–Alleröd Interstadial, the Younger Dryas, the Pre-Boreal and the first half of the Boreal periods (12 600 to 8500 a BP) (Figure 7 and Table III). The Chambon system sediments correspond to the Sub-Atlantic period (2600 to 0 a BP). A ^{14}C age of 1360 ± 55 a BP obtained in the L2 unit makes it possible to separate the first part and the second part of the Sub-Atlantic period. These are marked by considerable human-induced deforestation and the abundance of cereal pollens, including rye (*Secale cereale*), in the Middle Ages and in the 'modern' period sediments.

Table III. Sediment yield from fluvial and lacustrine storage in Tartaret and Chambon systems

System	Storage: Lithologic units: Type	Storage volume ($\times 10^6 m^3$)	Chronologic units: Reference period*	Storage phase age*	Total volume ($\times 10^6 m^3$)	Lacustrine sedimentation rate ($mm a^{-1}$)	Storage rate ($\times 10^3 m^3 a^{-1}$)	Erosion: Watershed surface (km^2)†	Sediment yield ($m^3 km^{-2} a^{-1}$)	Erosion rate ($mm a^{-1}$)
				0						
Chambon (2600–0 a BP)	F2	5·3±0·5		Middle Ages and 'Modern Epoch'	8·1±2·0	4·3	6·3		166±50	0·166
	DF2	1·5±0·2	Sub-Atlantic	1360				37·7		
	L2	3·9±0·4		Beginning of clearance	2·6±0·7	1·4	2·1		56±17	0·056
				2600						
	Total	10·7±1·1			10·7±2·7					
Sediment gap: opening of the lacustrine system										
				8500						
Tartaret (12600–8500 a BP)				Boreal						
	DF1	4·0±0·4	9000		5·1±1·3	0·9 to 4·6	2·9		79±24	0·079
				Pre-Boreal						
			10250					36·5		
	L1	6·7±0·7		Younger Dryas	2·2±0·5	0·8 to 7·2	4·4		120±36	0·120
			10750							
				Bölling–Alleröd	3·4±0·9	0·4 to 2·9	1·8		49±15	0·049
				12600						
	Total	10·7±1·1			10·7±2·7					

* Age in years BP

† At the maximum lake size

Table III gives storage and erosion rates corresponding to each lithologic and chronologic unit. The Tartaret system stores $(10{\cdot}7 \pm 1{\cdot}1) \times 10^{6}\ \mathrm{m}^{3}$ of sediments over 4100 years and by coincidence the Chambon system stored the same volume over 2600 years. The volume of water in Lac Chambon is presently $(1{\cdot}53 \pm 0{\cdot}15) \times 10^{6}\ \mathrm{m}^{3}$. The deposition rates in distal lacustrine areas for thin particles ranged from 0·4 to 7·2 mm a^{-1} depending on the chronologic phases and locations considered. During the Late Glacial period and at the beginning of the Holocene, sediment yield values ranged from 49 ± 15 to $120 \pm 36\ \mathrm{m}^{3}\ \mathrm{km}^{-2}\ \mathrm{a}^{-1}$ depending on palaeoenvironmental conditions. Since 2600 a BP the mean sediment yield has ranged from $56 \pm 17\ \mathrm{m}^{3}\ \mathrm{km}^{-2}\ \mathrm{a}^{-1}$ before 1360 a BP to $166 \pm 50\ \mathrm{m}^{3}\ \mathrm{km}^{-2}\ \mathrm{a}^{-1}$ thereafter.

DISCUSSION

Initial conditions of the watershed

The glaciers which covered the major part of the study area during the last Pleniglacial Stadial (Goër de Herve, 1972; Veyret, 1978) heavily eroded the soft materials lying on the bedrock: 100 km^{3} out of the 220 km^{3} could have been carried away by glacial erosion from the Mont-Dore Massif volcanic rocks (Mervoyer, 1972). According to Veyret (1978), the last glacier retreat occurred at the beginning of the Late Glacial period and was of short duration. According to Beaulieu *et al.* (1988b), the establishment of steppe vegetation in the Oldest Dryas Stadial, following a semi-desert phase, shows an earlier glacier retreat related to the highly xeric conditions of the Late Pleniglacial Stadial. It has been assumed that morphogenetic conditions changed greatly at the Pleniglacial Stadial–Late Glacial period transition (15 500 a BP). Glacial processes were then replaced by the displacement and storage of material due to the dominant influence of gravity processes and running water. The initial bulk of tills is not known accurately, but according to Goër de Herve (1972) and Veyret (1978) it was not large. Moreover, a large amount of this soft material, that was especially prone to erosion (Church and Ryder, 1972), was probably quickly carried downstream by running water. At the present time, tills cover no more than 3·3 per cent of the watershed surface.

Mean sediment yield deduced from slope storage

The major part of the material stored within the watershed $((107{\cdot}5 \pm 10{\cdot}8) \times 10^{6}\ \mathrm{m}^{3})$ lies on the slopes. Fallen debris and collapsed materials were produced by the erosion of a limited surface (9·57 km^{2}) making up 24·5 per cent of the whole watershed surface (Table II). Among all the dynamic factors affecting slopes, the role of climate is not clearly known. Periglacial conditions during the Oldest and Younger Dryas Stadials probably increased the production of fallen debris (Carson and Kirkby, 1972; Etlicher, 1984; Valadas, 1984) for the Massif Central, but there is no quantitative evidence of this within this catchment. A large amount of fallen debris is still being produced. Moreover, the action of snow and ice have been observed to assist in the formation of fallen debris (Valadas, 1984). In order to calculate the mean sediment yield values, it was assumed that fallen debris had been produced regularly since 15 500 a BP. Collapse occurred suddenly during the Boreal and at the beginning of the Sub-Atlantic periods. This was probably induced by exceptional and brief climatic events which were not characteristic of the mean climatic conditions of the temperate dry Boreal and temperate humid Sub-Atlantic periods (Beaulieu *et al.*, 1988b).

Lithology and relief influence slope storage (Carson and Kirkby, 1972). Fallen debris and collapsed materials were supplied almost exclusively by volcanic rocks that generally disintegrated into blocks which could not be transported by running water, but could move downslope under the action of gravity. Block movement distances have not exceeded 1·8 km and almost all the blocks are stored on the lower slopes. Loss of stored materials by fluvial erosion at the foot of slopes is quite slight. Altered granites and metamorphic rocks have disintegrated into sands and gravels. These grains are easily eroded by runing water on steep slopes (Figure 8), and transported a long way downstream through the valley to the lakes.

In basaltic and doreitic areas, as erosion–storage gravity processes develop, block-transfer distances are short: 1·1 and 0·8 km maximum respectively (Table II). Basalts and doréites originated as lava flows. Their generally weak initial slope gradients did not favour the formation of fallen debris. Active slopes are located where glacial erosion has initiated steep slopes. This is why the mean slope gradients of fallen debris surfaces

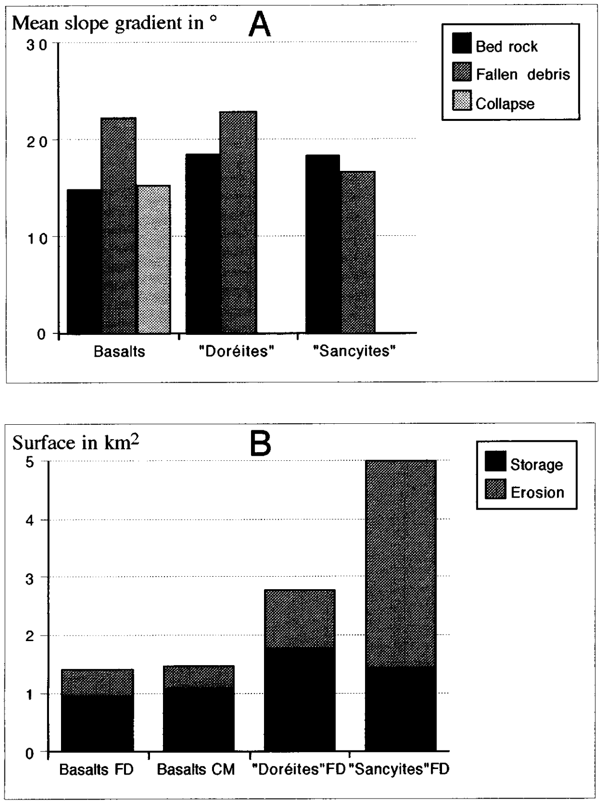

Figure 9. Characteristics of active slopes for each lithologic type: (A) comparison of mean slope gradients on bed rock and sediment storage; (B) comparison of present erosion and storage surface values. FD, fallen debris; CM, collapsed materials

are greater than the mean slope gradients of their source-rock surfaces (Figure 9A) and the storage surfaces are greater than the present erosion surfaces (Table II and Figure 9B). Fallen debris now covers 68·5 per cent of the active basaltic slopes and 63·6 per cent of the active doréite slopes. These erosion–storage systems induced high sediment yields: 2300 m^3 km^{-2} a^{-1} on basalts and 1770 m^3 km^{-2} a^{-1} on doréites.

In sancyite areas, as erosion–storage gravity processes develop, block-transfer distances are greater (as far as 1·8 km). Because sancyite slopes are generally steep (Figure 8), storage areas cover only a tiny fraction of active slopes (29·4 per cent) and have a mean slope gradient slightly lower than the sancyite mean slope gradient (16·7° and 18·3°, respectively) (Table II and Figure 9). In source areas, the sediment yield of sancyites (380 m^3 km^{-2} a^{-1}) is five times less than erosion rates of basalts and doréites. This difference could be linked to lithology, mainly because of macrofissure networks developed in volcanic lava flows (Tomkeieff, 1940; Long and Davidson, 1981). It is possible that some materials moving down sancyite slopes were not stored because changes in the slope gradient were slighter on sancyites than on basalts and doréites.

The Montagne de la Plate and Dent du Marais collapses are located in basaltic areas with initial steep slopes. The high kinetic energy that developed as collapses occurred explains why the collapsed materials were scattered over a larger area than the basaltic fallen debris. Collapse block-transfer distances (1.2–1·3 km) and storage surfaces (75 per cent) are greater, whereas slope gradients of storage surfaces are lower (15·4°) (Table II and Figure 9). The calculated mean annual sediment yield from collapse processes (3935±387 and 3484±322 m^3 km^{-2} a^{-1}; Table II) for the whole Post Glacial period (15 500 years) is about twice the fallen basaltic debris mean sediment yield.

The sediment yield values from slope induced by gravity processes are not very different from those known elsewhere on basaltic slopes (Slaymaker, 1988). They are about 100 times greater than those due to creeping and

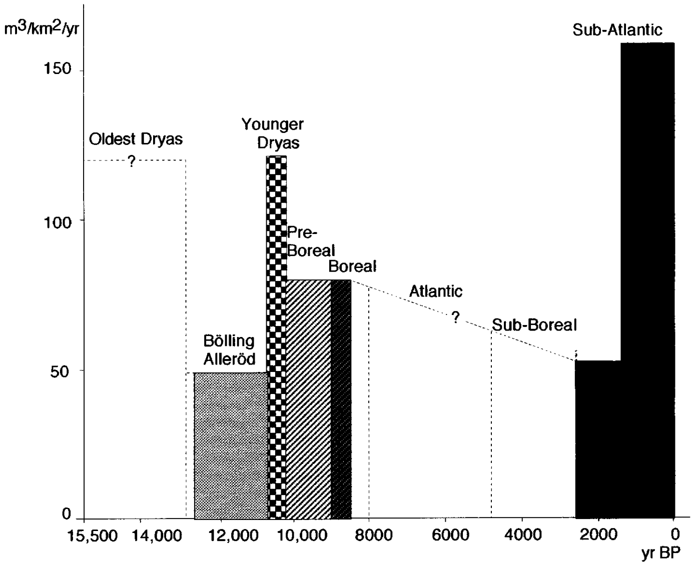

Figure 10. Fluctuation of mean sediment yield values by running water during Late Glacial and Holocene periods

solifluction (Dietrich and Dunne, 1978; Brunsden, 1979), 10 to 50 times greater than those due to running water, and do not significantly differ from those due to ice (Corbel, 1959, 1964).

Mean sediment yield deduced from fluvial and lacustrine storage

Stored sediment volumes amount to (10·7±1·1)×10^6 m^3 both in the Tartaret and the Chambon systems (Table III). Retention times of water in lakes, calculated using the present mean inflow (1·1 m^3 s^{-1}: Rapport DIREN, 1992), were about 250 days in the Tartaret lake and 50 days in Lac Chambon, at their maximum size. At present, it is 15 days in Lac Chambon. From these retention times, a sediment trap efficiency of 95±5 per cent in both lakes can be assumed (Brune, 1953). The Monneaux lake formed upstream at about 8500 a BP when the Tartaret system opened, therefore they did not notably interfere with one another. Once the Monneaux lake was completely filled with sediments at about 8000 a BP, about half the bulk of the soft stored sediments (1±10^6 m^3) was easily eroded and transported downstream. Assuming that erosion was constant in time, 0·325±10^6 m^3 of additional material stored in the Chambon system came from this source once it was closed at 2600 a BP, i.e. only 3 per cent of the whole stored material.

Lacustrine sediments could originate from different areas (Kemp and Harper, 1976, 1977; Kemp *et al.*, 1978). The materials stored at present are derived mainly from the sediment yield of the rivers that drained the whole watershed (Figure 2), as shown by the small difference between the mean chemical composition of source rock outcropping in the watershed and the mean chemical composition of the stored sediments (Gay, 1995). Spreading out the stored materials over the whole watershed surface gives sediment yield values between 49±15 and 166±50 m^3 km^{-2} a^{-1} according to climatic phases (Table III and Figure 10). The equivalent mechanical erosion rates are 10 to 100 times greater than the chemical erosion rates (Godard, 1977; Gay, 1995) and two to five times greater than the rates of thickening of saprolites derived from granitic or volcanic rock in the same environments (Tardy, 1969; Velbel, 1985). This explains why the rocks outcropping in the watershed appear slightly weathered.

The rather low sediment yield during the Bölling–Alleröd Interstadial (49±15 m^3 km^{-2} a^{-1}) may be explained by the cool to temperate climate and the sparse development of woodland with *Juniperus, Betula* and *Pinus* (Beaulieu *et al.*, 1988a,b). This protected the soil surface against significant sheet erosion, favouring pedogenesis on slopes and gully erosion (Robinson, 1978). This low sediment yield also shows that tills, which are generally strongly eroded during and soon after glacier retreat (Church and Ryder, 1972), were either initially scarce or mainly eroded during the Oldest Dryas Stadial. The return of steppe conditions at the lowest elevations and disappearance of vegetation on the tops of mountains during the cold Younger Dryas Stadial explain the strong increase in erosion ($120 \pm 36\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$), especially the sheet erosion that affected the poorly protected slopes (Robinson, 1978). The disintegration of rocks, as soils developed during the Bölling–Alleröd, and frost shattering (Corbel, 1959) during the Younger Dryas probably assisted in these erosion processes. During the Pre-Boreal and the first half of the Boreal periods, sediment yield decreased appreciably ($79 \pm 24\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$), without reaching the lower value of the Bölling–Alleröd. It suggests that both *Betula, Pinus* and then *Quercus* and *Corylus* forests and soils regenerated slowly under a temperate climate that was first cool and then dry (Beaulieu *et al*., 1988a,b).

The threefold increase in erosion rates during the Sub-Atlantic resulted mainly from human interference with the natural vegetation of the catchment (Table III and Figure 10). Indeed, from 2600 a BP, the humid temperate climate was similar to the present climate and did not vary significantly. On the other hand, the vegetation patterns showed evidence of human activity (Beaulieu *et al*., 1988a,b): firewood working, clearance for crop farming and planting. From 2600 to 1360 a BP the sediment yield was low ($56 \pm 17\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$) and close to the Bölling–Alleröd value. From 1360 a BP, a great increase in sediment yield ($166 \pm 50\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$) was observed. The abundance of rye pollens in sediments indicates that crop farming may have been responsible.

Using the mean sediment yield of the last 1360 years, we calculated that the present Lac Chambon should be completely filled with sediments in the next 255 years. However, a recession in crop farming and an increase in tree plantations since the mid-nineteenth century (Beaulieu *et al.*, 1988a,b) has probably reduced sediment loss. Delmas (1973) proposed a sediment yield of $22\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$ for the last 150 years. This is certainly an underestimate because this author only analysed present deltaic sediment storage.

Therefore, the sediment yield in the Lac Chambon watershed has been clearly influenced by climatic fluctuations and human activity, the latter inducing the highest sediment yield values, although variations of sediment yield due to climate and human activity were quite similar. The less marked anthropogenic impact (threefold increase) in the Lac Chambon watershed than in areas where crop farming was heavy (Meade *et al*., 1990) suggests a moderate land use (Saunders and Young, 1983) due to high elevations, quite steep slopes and poor quality of soils, reducing farming possibilities. Nevertheless, these data confirm the assessment of Milliman and Syvitski (1992): historic and present sediment yield values are overestimates of natural values for undammed rivers.

The climate-induced sediment yields agree with the erosion rates known elsewhere in the ancient orogenic areas (Pinet and Souriau, 1988) (Figure 11). Late Glacial and Holocene sediment yield values in the Lac Chambon catchment, especially values before 1360 a BP, are much lower than those currently observed in other mountains worldwide (1000–3000 m) (Milliman and Syvitski, 1992). This may be the result of the small watershed area where a single type of geology dominates. These low values reflect the poor erodibility of crystalline rocks in a temperate mountain area originating from Palaeozoiic orogenies, and can be extended to many similar areas in northern and western Europe.

The mean sediment yield from running water for 1360 years in the $39\,\mathrm{km}^2$ Lac Chambon catchment ($166 \pm 50\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$) was about 50 to 25 times greater than the present sediment yield in the whole $117\,000\,\mathrm{km}^2$ Loire watershed: $3\,\mathrm{m}^3\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$ (Corbel, 1959) and $13\,\mathrm{t}\,\mathrm{km}^{-2}\,\mathrm{a}^{-1}$ (Manickam *et al*., 1985). Relief rates are 0·098 in the Lac Chambon catchment against 0·001 in the whole Loire watershed. Therefore, as emphasized by Holeman (1968), Ahnert (1970), Robinson (1978), Pinet and Souriau (1988) and Milliman and Syvitski (1992), watershed area and topography appear to be the most efficient parameters in the mechanical erosion processes for both Lac Chambon and Loire catchments.

Overall sediment budget

Sediment erosion and storage can be considered within the studied limit of the watershed (internal budget), and from inside this limit to outside (external budget). These budget calculations only concern mechanical processes of erosion.

The internal budget concerns gravity-induced erosion, and the transfer and storage on slopes of materials which form 69 per cent of the whole eroded materials in the watershed. These slope processes have produced a high erosion rate (16·1 ± 6 m in 15 500 years) but this has involved only a fraction of the watershed surface (24·5

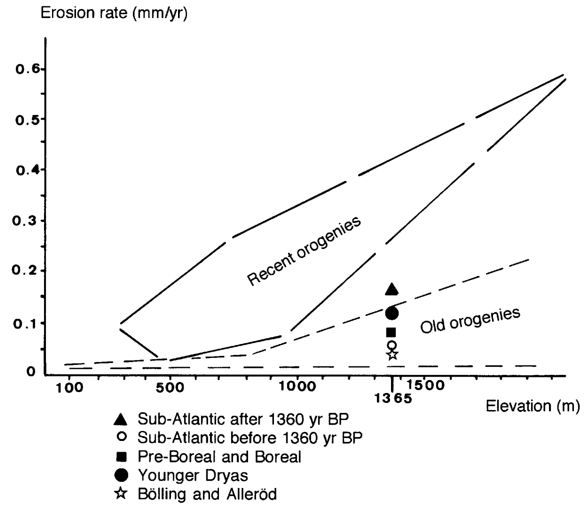

Figure 11. Relationships between erosion rates and elevations in old and recent orogenies (from Pinet and Souriau, 1988), showing situation of the Lac Chambon watershed Late Glacial and Holocene erosion rates

per cent). Recent tectonic activity has been slight in this area and therefore it appears that only the return of glacial processes, able to modify the relief and the slope gradients drastically, could result in the downstream movement of the materials presently stored.

For the external budget, extrapolating the sediment yield values from the last 15 500 years, it was calculated that rivers discharged 31 per cent of the total material derived from mechanical erosion ($(48{\cdot}8 \pm 4{\cdot}8) \times 10^6$ m^3) outside the studied watershed, about half of which was stored as lakes developed. The mean erosion rate by running water was about 13 times lower ($1{\cdot}24 \pm 0{\cdot}37$ m in 15 500 years) than the mean erosion rate by gravity without the assistance of a fluid transporting agent, but the first concerned the whole watershed surface.

The percentage of discharged material in comparison with the total amount of eroded material depends on the watershed surface (Meade, 1988). The present percentage of discharge (31 per cent) is a mean value over 15 500 years for a 39 km^2 catchment and involves both materials eroded by gravity processes and by running water. Plotting this percentage on the diagram of Robinson (1978), which involved only material presently eroded by running water (Figure 12), shows a noteworthy difference.

CONCLUSION

Computation of stored material volumes and sediment yield values from source rock during Late Glacial and Holocene periods in the Lac Chambon watershed has given accurate information not previously calculated. These data, which can be extended to temperate crystalline mountain areas formed in Proterozoiic and Palaeozoiic orogenies throughout northern and western Europe, showed that:

(1) 69 per cent of the eroded particles were displaced by gravity-induced processes and stored in slopes inside the watershed;
(2) 31 per cent of the eroded particles were transported by running water and would be completely discharged downstream beyond the limit of the watershed if it was not temporarily closed by natural dams; the material stored in the Tartaret and Chambon systems expresses the net mechanical erosion;
(3) over 15 500 years, the mean mechanical erosion capacity by slope processes ($16{\cdot}1 \pm 6$ m) was 13 times greater than the mechanical erosion capacity by running water ($1{\cdot}24 \pm 0{\cdot}37$ m), but it developed over only a quarter of the watershed surface.

This shows the impact of non-varying watershed parameters on erosion processes in a small watershed (39 km^2) of plutonic and volcanic outcropping source rocks and ancient mountain relief, without active tectonics, exhibiting forms inherited from the last glacier extension. Volumes of stored materials and the

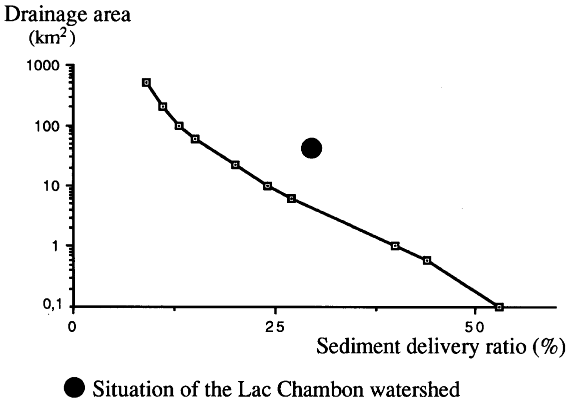

Figure 12. Effect of drainage basin size on sediment delivery ratio (adapted from Robinson, 1978), showing situation of the Lac Chambon watershed

sediment yield on slopes greatly depend on rock type and related slope gradient. Sediment yield and derived stored material volumes are greater on basalt and doréite than on sancyite.

Fluctuations in sediment storage rates in lacustrine depressions, and therefore fluctuations in sediment yield from running water during Late Glacial and Holocene periods, have resulted from environment variations (climate, vegetation and anthropogenic activities).

(1) Cold and dry climate and disappearance of vegetation during the Younger Dryas Stadial induced a 2·5-fold increase in sediment yield in comparison with the Bölling–Alleröd Interstadial. A moderate decrease in sediment yield during the Pre-Boreal and the first half of the Boreal periods shows a continuity of processes developing during the Younger Dryas period which suggests a slow regeneration of vegetation and soils.

(2) In the first half of the Sub-Atlantic period, sediment yield did not differ greatly from the sediment yield of the Bölling–Alleröd period although the vegetation of both periods was different. A threefold increase in erosion over the last 1400 years shows the impact of human-induced deforestation.

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