somatism ultimately reflects plate tectonic processes or merely the interaction of magmas with wall-rock is subject to debate. However, it is suggested that the existence of the brucite/calcite assemblages described here resolves the contradiction of compelling experimental evidence for the presence of carbonate in the mantle with its apparent paucity in mantle xenoliths.

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Lahars initiated by the 13 November 1985 eruption of Nevado del Ruiz, Colombia

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The eruption of Nevado del Ruiz in Colombia on 13 November 1985 was accompanied by the formation of four lahars (mud flows) triggered by the melting of glacial ice near the summit of the volcano. The lahars began as flows of water, sand and gravel, but they incorporated clay by eroding the soil along the steep valleys through which they passed. The largest flow was a cohesive debris flow, more than 45 m deep and moving at ~12 m s^{-1} when it debouched from the canyon of the Rio Lagunilla 2.5 km from Armero, where it killed 25,000 people. The continuing volcanic activity and abundant remaining glacial ice create an extremely high risk of future destructive flows.

At 5,400 m, Nevado del Ruiz is the highest of a cluster of five volcanic peaks in the Cordillera Central of north-central Colombia (Fig. 1) and is capped by a glacier 2–5 km wide. A major eruption of Ruiz occurred in 1595, and in 1845, Ruiz was the source of a lahar which killed more than 1,000 people at Ambalema (Fig. 1) on the Magdalena River (refs 1–3 and J. B. Tomblin, unpublished work). The recent activity of Ruiz began with earthquakes in November 1984, followed by a small phreatic eruption on 22 December (refs 4, 5, 6 and J. B. Tomblin, unpublished work). A second eruption occurred on 11 September 1985 (ref. 7).

On 13 November 1985, a minor eruption at ~15:00 local time produced a light ashfall north-east of the volcano[8]. Between 21:00 and 21:15 a larger eruption occurred, producing small pyroclastic flows and surges near the summit[9,10] and melting a small part of the summit glacier, which generated four major lahars[8] (Fig. 1). The two most destructive lahars moved eastwards down the Rio Lagunilla and its tributary, the Rio Azufrado, toward Armero; a third moved northeastwards down

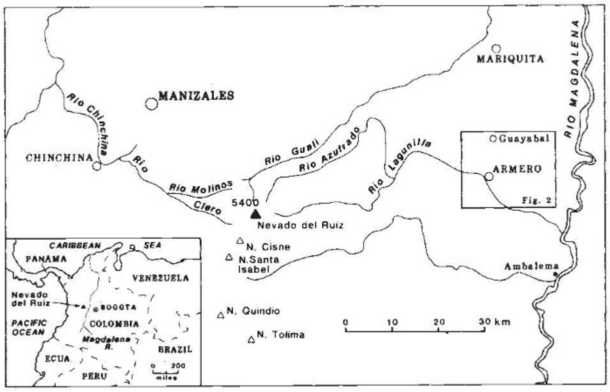

Fig. 1 Generalized location map of Nevado del Ruiz and vicinity, and (inset) Colombia.

the Rio Guali toward Mariquita; and a fourth moved northwestwards down the Rio Molinos into the Rio Claro and thence to the Rio Chinchiná toward Chichiná (Fig. 1).

Examination of the Rio Guali lahar deposits on the north-east slope of Ruiz, ~5 km from the summit, indicates that the initial flow was a mixture of sand, gravel, water and probably ice, but contained little clay. The main effects of the flow at this point were to strip away a 0.5–2-m-thick layer of vegetation, soil and older pumice overlying massive volcanic rock and to deposit units of coarse, moderately-to-poorly sorted, well-stratified gravel and sand. Most of the clay in the lahars that emerged from the canyons below was evidently derived by erosion of soils along the steep, V-shaped valleys through which the flows passed.

The valleys on the east and north-east side of Ruiz descend from elevations of ~5,300 m to only 400 m, where they enter the Magdalena River valley over river distances of 60–80 km. Headward slopes are generally 10–15°; slopes near the base are generally 3–4°. The lahars stripped vegetation and soil from the canyon walls to heights commonly exceeding 50 m and eroded many older alluvial deposits from the valley bottoms. The Rio Lagunilla flow travelled ~60 km before debouching just west of Armero. Based on a 2-h travel time (initiation at ~21:30 to passage through Armero at 23:30), the estimated mean flow velocity was 8.3 m s^{-1}. The course of the Rio Azufrado flow was 12 km longer than that down the Rio Lagunilla, giving a mean velocity of 10.0 m s^{-1}. Examination of the river valleys, as well as eye-witness reports, indicate that the Rio Azufrado flow was considerably more voluminous than the flow in the Rio Lagunilla, and that the former carried the bulk of the rocky debris. The differences in path-length and composition of these flows suggest that, downstream from the junction of the two rivers, the flows may have passed as a series of two or perhaps more discrete surges. Cross-cutting relationships at the junction of the Rio Lagunilla and Rio Azufrado indicate that the Azufrado flow reached the junction first[11], and may have formed the first surge to inundate Armero. The passage of a small lahar in the Azufrado in September 1985 (ref. 12) may have facilitated the movement of the later lahar.

About 1 km upstream from the canyon mouth, 2.5 km west of Armero, the Rio Lagunilla flows followed a sharp bend to the right, banking high onto the left (north) wall of the canyon (Fig. 2). The mean velocity (w) of debris flows at maximum discharge can be calculated indirectly from their superelevation around bends:

$$w = [g \cos\beta \tan\delta\, R]^{1/2} \qquad (1)$$

where g is the acceleration of gravity, β is the slope of the stream bed, δ is the slope of the banked flow surface (here measured from differential levels of scour on opposite sides of the river) and R is the radius of curvature of the bend[13,14].

Around this bend, $g = 9.8$ m s^{-2}, $\beta = 4°$, $\delta = 7.5°$ and $R = 110$ m, yielding a mean flow velocity of 11.9 m s^{-1}. The flow was ~45 m deep at mid-channel and had a cross-sectional area of nearly 4,000 m^2. The calculated discharge (Q) was ~47,500 m^3 s^{-1}. Similar flows at Mt St Helens in the United States in 1980 had peak velocities of 3.2–40 m s^{-1} and peak discharges of 2,440 to >190,000 m^3 s^{-1} (ref. 15). Most lahars and debris flows attain their maximum depths near the flow fronts[13]. The conditions calculated above probably characterized the first surge of debris to leave the Rio Lagunilla canyon.

The difference between estimated mean flow velocities and that of the initial surge immediately upstream from Armero may reflect imprecise estimates of the times of flow initiation and arrival; down-slope changes in channel geometry and resistance; and down-slope flow evolution from friction-dominated gravel-sand-water slurries to cohesive gravel-sand-clay-water debris flows.

When the lahars left the canyon of the Rio Lagunilla, they emptied onto the gently sloping surface of the west side of the Magdalena River valley (Fig. 3). Within 2 km of the canyon mouth, the Rio Lagunilla is incised 10–15 m below this surface. The initial flow, however, was sufficiently deep that it spread radially from the canyon mouth and split into three main lobes. The northern lobe moved to the ENE, left the Rio Lagunilla, swept through northern Armero following a broad distributary valley, and then turned northward and flowed as a series of anastomosing lobes to within 1.5 km of Guayabal (Fig. 3).

Most of the debris flowed southeastwards, following the broad valley of the Rio Lagunilla. Because the present river lies along the southern edge of this valley, and was too small to accommodate the volume of the lahar, most of the southern lobe moved north of the river, inundating and obliterating the low-lying southern half of Armero. The only parts of the city not completely destroyed were the slightly elevated central and eastern areas between the two main flow lobes. The inertia of the flow carried all but a small part of the debris away from the present river to the south-east and east for nearly 16 km, along a broad alluvial valley which may be an abandoned river course or a route of previous lahars (Fig. 3). A much smaller amount of debris followed the course of the Lagunilla, forming a small third lahar lobe.

Early reports from Armero indicated that many victims were burned, suggesting the possibility that the lahars were hot. Although virtually everyone caught in the flow suffered extensive lacerations because of the abrasive power of the coarse debris, we saw no evidence that the flows were hot. One victim interviewed several weeks after the disaster states that the flows were cold but still burned. The high sulphate content of the flow deposits[16] suggests that the 'burning' was actually caused by the acidity of the flow.

The Lagunillas-Azufrado lahar deposits are generally between 1 and 2 m thick and mantle, rather than fill, pre-flow topography. They cover an area of nearly 32 km^2, which, for an average depth of 1.5 m, implies a volume of ~4.8×10^7 m^3. The deposits consist of grey, dense, massive, extremely poorly sorted clayey gravelly sand. Granulometric analysis of one sample from the upper part of the proximal flow deposits 0.5 km south-east of the canyon mouth shows (by weight) 47.9% sand, 27% gravel, 17.5% silt and 7.6% clay. All the coarser debris is composed of lithic volcanic rock types; fresh pumice was not identified. Clasts ≥50 cm in diameter are generally rounded and probably eroded from older alluvial deposits. Clasts <15 cm in diameter are commonly matrix-supported.

The grain-size structuring of the deposits indicates that, within the debris flows, the mixture of fluid and granular materials ≤10 cm in diameter behaved as a homogeneous phase in which there was no separation or differential settling of constituents. Clasts ≥15 cm across, locally reaching 10 m in diameter, occur only at the base of the lahar deposits. They were either transported at the bases of the flows or settled as the flows decelerated.

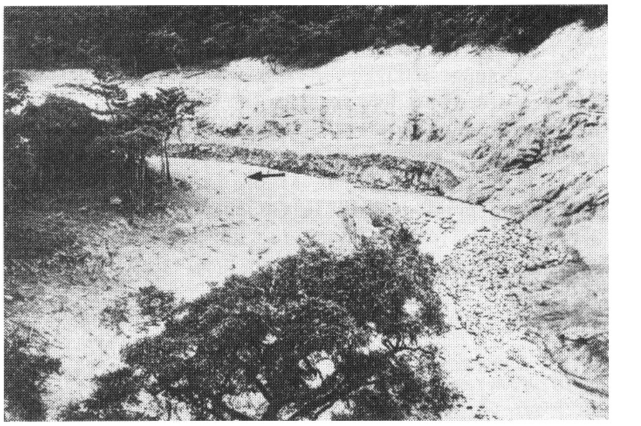

Fig. 2 Photograph of the Rio Lagunilla canyon looking upstream, ~2.5 km from Armero and 1.5 km upstream from the mountain front. Lahars generated by the 13 November 1985 eruption of Nevado del Ruiz have stripped vegetation and soil from the lower parts of the canyon walls and deposited a thin veneer of mud. A man (arrowed) gives the scale. The superelevation of the flow along the north bank (the right bank in the photograph) can be seen.

As a result, many of the deposits show normal grading of the coarsest constituents.

The observations that the flow deposits mantle, rather than fill, the topography and show differential settling of larger clasts suggest that the strength of the flow was relatively low. Flow strength (k) can be estimated by[13]:

$$k = T\rho_f g \sin \alpha \quad (2)$$

where T is the deposit thickness, ρ_f is the flow density and α is the slope of the deposit surface[13]. Over broad areas, $T \simeq$ 100–150 cm and $\alpha < 1.4°$, and ρ_f is taken as 2.2 g cm^{-3}. For these deposits, $k \simeq (5.3\text{–}8.0) \times 10^3$ dyn cm^{-2}, which is comparable to that of many other debris flows[13,17].

The large volume of glacial ice remaining on Nevado del Ruiz after 13 November, the abundance of debris around the summit, and the precipitous, narrow gorges leading downward to river valleys around the volcano collectively represent ideal conditions for the formation and long-distance movement of lahars.

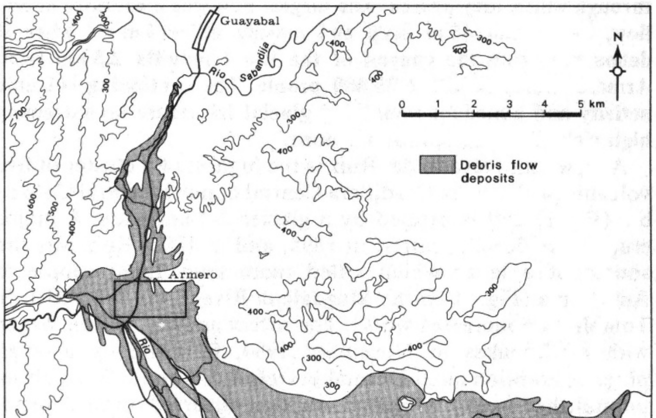

Fig. 3 Map of the Armero region (box in Fig. 1), showing the distribution of the deposits of the Rio Lagunilla lahar.

It is clear that the volcano is presently active and the probability of future eruptions is high. Even minor volcanic activity would inevitably trigger new lahars. Appropriate measures for early detection and hazard mitigation should be taken.

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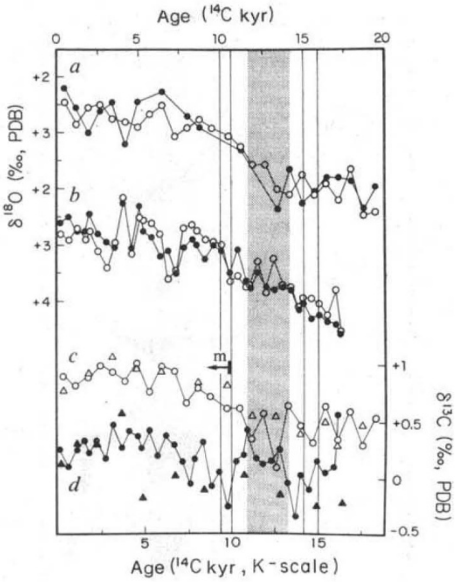

Fig. 1 Oxygen and carbon isotopes in the shells of benthic foraminifera from deep-sea sediments in the central Atlantic and western equatorial Pacific. Age scales are based on radiocarbon datings of bulk sediment (top-scale, refs 7, 8) and on correlation of planktonic oxygen isotope signals with the Norden (radiocarbon-) timescale (bottom scale, ref. 18). *a*, $\delta^{18}O$ values for *Cibicidoides wuellerstorfi* (○) and *Oridorsalis umbonatus*, adjusted by −0.6‰ (●), in core INMD 115 Bx, Atlantic. *b*, $\delta^{18}O$ values for *C. wuellerstorfi* (○) and *O. umbonatus*, adjusted by −0.75‰ (●) in core ERDC 112 Bx, Pacific. *c*, $\delta^{13}C$ values for *C. wuellerstorfi* in cores INMD 115 Bx (○) and INMD 113 Bx (△), Atlantic; m over arrow, appearance of *Globorotalia menardii*. *d*, $\delta^{13}C$ values for *C. wuellerstorfi* in cores ERDC 112 Bx (●) and ERDC 123 Bx (▲), Pacific. Atlantic data from Table 1, Pacific data from ref. 6.

Sporadic shutdown of North Atlantic deep water production during the Glacial–Holocene transition?

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Pulsations in the production of North Atlantic deep water (NADW) have been implicated in generating drastic climatic fluctuations during the Glacial–Holocene (G/H) transition[1–3]. The stable isotope record of benthic foraminifera in high-resolution cores from the Norwegian Sea suggests that such pulsations did occur[4]. Although the question of exact timing (and mechanism) is still open there is little doubt that NADW pulsations were important in climatic history because the rate of NADW production influences the rate of advection of heat to the northern North Atlantic[5]. Here we report that a sporadic shutdown of NADW may be recognizable in deep-sea carbonates with normal (low) sedimentation rates. Hence the possibility arises that relatively short-lived events (~1,000–2,000 yr) in deep circulation can be mapped over large areas of the sea floor, despite the detrimental effects of bioturbation on signal resolution.

The overall pattern of deep circulation in the present ocean is characterized by the asymmetry in deep-water properties of the Pacific and the Atlantic, which reflects the difference in age between sub-thermocline waters and, in essence, results from NADW production. We have chosen four cores to reconstruct the sequence of deep-water age difference in the two oceans since maximum glaciation (Fig. 1): ERDC 112 Bx, ERDC 123 Bx, INMD 113 Bx, and INMD 115 Bx. The ERDC box cores are from the Ontong Java Plateau in the western equatorial Pacific, from depths of 2,169 m and 2,948 m, respectively. Isotope stratigraphies and details on sedimentation rates and physical properties have been given elsewhere[6,7]. The INMD box cores are from the Mid-Atlantic Ridge, at 15.5 and 17.4° S, and from depths of 3,471 m and 3,427 m, respectively. Core data are given in ref. 8 and isotope data are listed in Table 1. Core ERDC 112 Bx and the INMD cores are close to the present two-degree potential temperature level[9]. The INMD sites are within the high-salinity-core layer of (lower) NADW. The ERDC sites sample general Pacific deep water with average salinity.

The benthic foraminifera analysed are *Cibicidoides wuellerstorfi* and *Oridorsalis umbonatus*. Both species were used for plotting $\delta^{18}O$ values, but only *C. wuellerstorfi* was used for the carbon isotope record. We believe[10,11], as do others[12–16], that this species best reflects the $\delta^{13}C$ content of deep waters, with a minimum of interference from vital effects and contamination by interstitial values of $\delta^{13}C$. Analyses were carried out as described in ref. 17.

The oxygen isotope record in the deep Atlantic (INMD 115 Bx, Fig. 1*a*) shows the rise from heavy to light oxygen isotope values during the G/H transition, which is largely due to the addition of meltwater. The change occurs mostly between 14,000 and 8,000 yr BP; the G/H range is between 1.3 and 1.4‰. Of the two foraminifera, *C. wuellerstorfi* is plotted as measured, while the values for *O. umbonatus* are adjusted by −0.6‰ to make them congruent. Exact ages cannot be assigned because of the effects of resedimentation and bioturbation on radiocarbon dates; a measure of uncertainty is