Comparison of volcanic production rates and subduction rates in the Lesser Antilles and Central America

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ABSTRACT

The volumes of volcanic products erupted in both the Lesser Antilles and Central America are estimated for the past 300 yr and the past 100 000 yr, and for the past 10 000 yr for the Lesser Antilles alone. From these data, volcanic production rates are calculated for unit lengths of the two subduction zones: 5 (Lesser Antilles) and 62 (Central America) $km^3 \cdot Ma^{-1} \cdot km^{-1}$ for the past 300 yr; 3 (Lesser Antilles) $km^3 \cdot Ma^{-1} \cdot km^{-1}$ for the past 10 000 yr; and 4 (Lesser Antilles) and 31 (Central America) $km^3 \cdot Ma^{-1} \cdot km^{-1}$ for the past 100 000 yr. Volcanic productivity and plate-tectonic slip rates are both significantly greater for Central America than for the Lesser Antilles. The Central America:Lesser Antilles ratio of volcanic productivity rates is two to three times the ratio of plate-tectonic slip rates, but the level of uncertainty in the volume estimates means that this result may not be significant.

INTRODUCTION

If the relative rate of motion at a convergent plate boundary is twice as great at one place than it is at another, will twice as much magma be produced at one as at the other? We currently cannot answer this question. If there were accurate data on the rate at which magma reaches the surface above subduction zones, this would supply part of the answer. We know that unless a subducted plate descends fast enough and steeply enough, volcanism does not occur on the overlying plate. At subduction zones where there is associated volcanism, the relationship between volcanic vigor and the rate of plate convergence is uncertain (Kay, 1980), but the data show a bias in favor of a positive correlation (Karig and Kay, 1981; Sample and Karig, 1982).

This report briefly presents the results of a comparative study of the rates at which volcanoes have produced magma at two convergent plate boundaries: the Lesser Antilles and Central America. These two volcanic chains are well suited to this type of study because they are of similar lengths (Lesser Antilles = 700 km; Central America = 1050 km), the quality of volcanological research on both is compara-

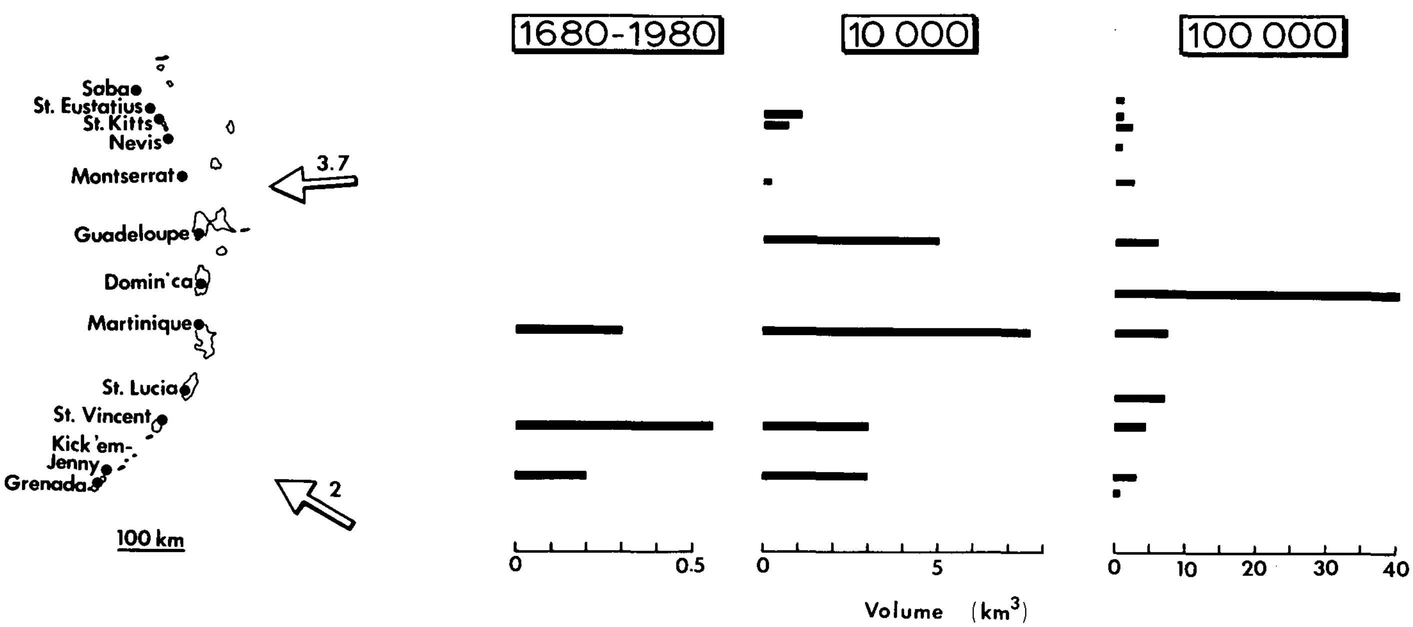

Figure 1. Histograms of volumes of magma erupted at specific volcanoes (solid circles) in Lesser Antilles for periods 1680–1980, past 10 000 yr and past 100 000 yr. Note that this does not include total tephra budget for 100 000 yr. More than one volcano has been active in Dominica in past 100 000 yr, but for clarity only one is shown. Abscissa is drawn radial to mid-point of arc (250°). Arrows indicate mean vectors of relative plate convergence of North American/South American plate(s) with Caribbean plate, and corresponding rates are in centimetres per year. Vector labeled 2 is from RM2 model of Minster and Jordan (1978), and vector labeled 3.7 is from model of Sykes et al. (1982).

ble, and they have different rates of plate convergence beneath them.

VOLCANIC PRODUCTION RATES

The volumes of volcanic rocks produced during three periods: 300 yr, 10 000 yr, and 100 000 yr have been estimated. Ideally, a continuous chronological record of volumes erupted would be most useful for analysis, but data of this type are not available for long periods. The longest historical period for which we can be certain that most major eruptions were documented in both regions is about 300 yr (1680–1980). The choice of 100 000 yr is partly dictated by the recovery of piston cores of this maximum age around the Lesser Antilles (Sigurdsson and Carey, 1981). Because of a lack of data for Central America, volume estimates for 10 000 yr were made solely for the Lesser Antilles.

Most of the volumes used to compute the production rates are illustrated in Figures 1 and 2. Details of the individual volume estimates and the method of accounting are presented in the appendix[1] to this paper. For the historical period, volumes of well-studied, recent eruptions were used to crudely estimate the volumes of older eruptions for which only qualitative contemporary descriptions are available. For the 100 000-yr period, the Lesser Antilles estimates rely heavily on the marine tephrochronological studies of Sigurdsson and Carey (1981) and Sigurdsson et al. (1980) and correlation of the marine record with the subaerial deposits.

[1]Appendix, Volume Estimates and Method of Accounting, GSA Data Repository item 8425, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

In contrast, the 100 000-yr deposits in Central America are predominantly subaerial, and a different method of accounting was used. The volumes of the volcanic front stratovolcanoes (Carr, 1984), subaerial tephra deposits (Rose et al., 1981), and submarine tephra were counted separately and added. The volumes were converted to dense rock equivalent volumes (Table 1) and probably have uncertainties of tens rather than hundreds of percent. The stratovolcano volume total for Central America for 100 000 yr is less certain than this for reasons discussed in the appendix (see footnote 1). From these volumes, production rates were calculated in units of cubic kilometres per million years and length-normalized production rates in units of cubic kilometres per million years per kilometre of arc.

Figure 2 shows the dominant influence that two plinian eruptions (Cosiguina in 1835, and

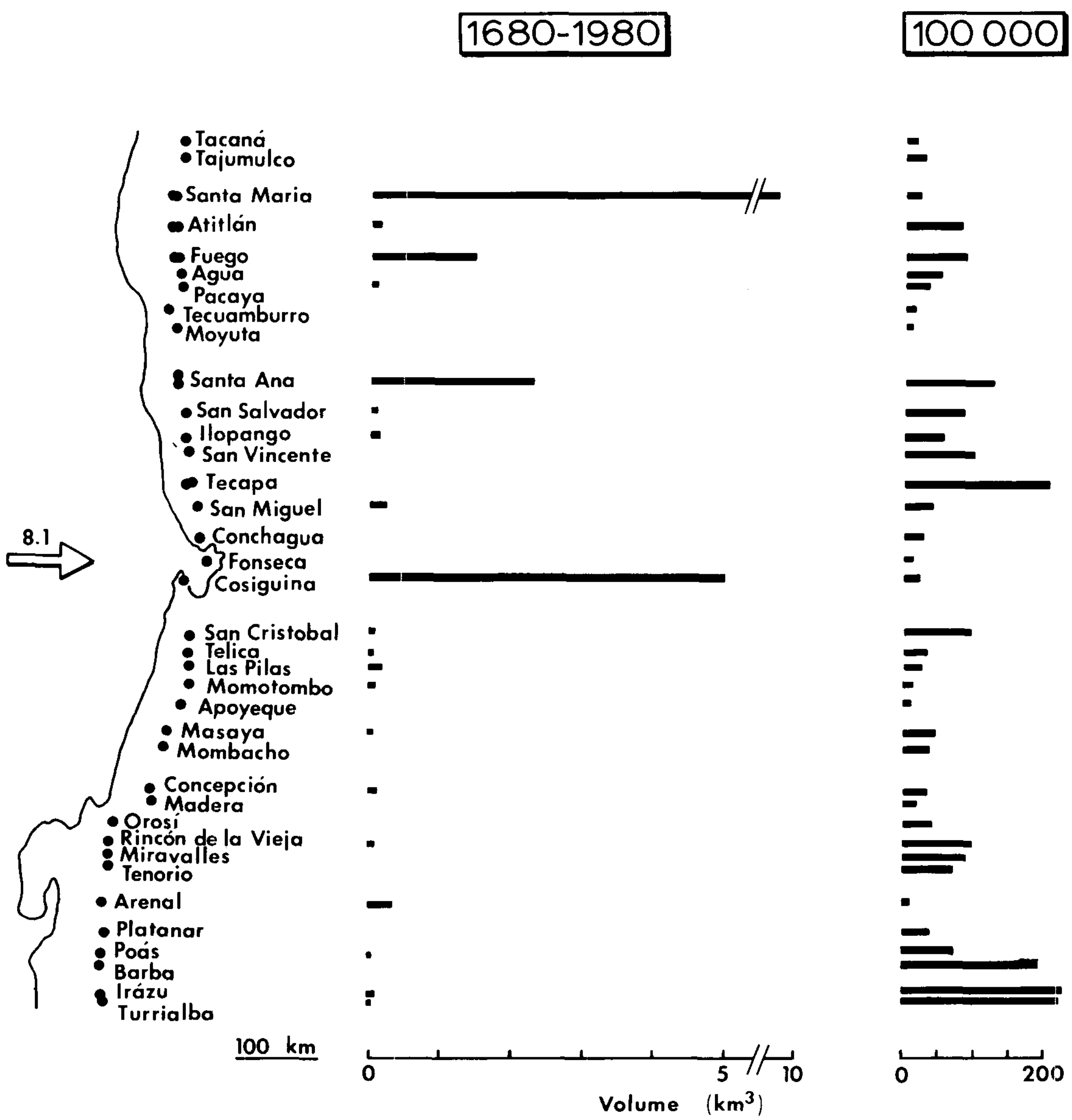

Figure 2. Histograms of volumes of magma erupted at specific volcanoes (solid circles) in Central America for periods 1680–1980 and past 100 000 yr. Abscissa is drawn parallel to mean direction of plate convergence (026°; rate = 8.1 cm/yr; RM2 model, Minster and Jordan, 1978). Note that volumes for 100 000 yr are only stratovolcano component of budget. Currently, only a limited number of major tephra deposits can be attributed to specific volcanic centers; hence, no attempt to illustrate them is made here.

Santa Maria in 1902) have had on historical volcanic production in Central America. This fact in itself does not negate the significance of the historical production rate but illustrates the need to compare rates based on more than one period. Volcanism in the Lesser Antilles shows higher productivity in the central part of the arc over the longer periods. The linear Central American chain does not show a similar pattern. Two important results can be seen in Table 1: (1) The production rates for the Lesser Antilles differ by a factor of <2 over three time periods, and the Central American rates differ by a factor of ~2 over two time periods. This suggests that these figures do represent meaningful rates of volcanic production and are not spurious artifacts of individual volcanic histories. (2) The length-normalized rates show that Central America has been twelve times as productive over the past 300 yr and about seven times as productive over 100 000 yr as the Lesser Antilles. Despite the crude nature of the data the differences between the subduction zones appear to be significant.

PLATE-TECTONIC SLIP RATES

Central America is being underthrust from the southwest by the Cocos plate, while the Lesser Antilles is being underthrust from the east by the North/South American plate(s) (Molnar and Sykes, 1969; Jordan, 1975). Minster and Jordan's (1978) model of relative plate motion, RM2, predicts slip rates beneath Central America of about 7–9 cm/yr and slip rates beneath the Lesser Antilles of about 2 cm/yr. This model is based on mean spreading rates over 3 Ma.

Two problems associated with the slip rates beneath the Lesser Antilles must be stated: (1) The most important constraint for the Caribbean–North American relative motion in any model is the sea-floor spreading rate in the Cayman Trough which is 2.0 ± 0.2 cm/yr for 0–2.4 Ma and 4.0 ± 0.2 cm/yr for 2.4–6.0 Ma (Macdonald and Holcombe, 1978). Unlike Minster and Jordan (1978), who used the 2.0 ± 0.2 cm/yr directly in their model, Sykes et al. (1982) argued that when the Cayman Trough spreading rate was halved at 2.4 Ma, the remaining 2 cm/yr of relative motion was taken up by plate-boundary deformation along the northern boundary of the Caribbean plate and that the slip rate beneath the Lesser Antilles remained constant at about 4 cm/yr (3.7 ± 0.5 cm/yr). Thus, although the RM2 slip rate of 2 cm/yr is used here, this figure could be as high as 4 cm/yr. (2) A North American–South American plate boundary must lie between lat 10° and 20°N, and the most probable position bisects the arc. RM2 predicts a South American–Caribbean slip rate of about 2 cm/yr, almost identical to the vector for the North American–Caribbean motion. Any difference in slip rate across the boundary is small enough (<1 cm/yr) to be neglected.

DISCUSSION

The Central American subduction zone is more vigorous per unit length than the Lesser Antilles subduction zone in terms of volcanic productivity and plate convergence. However, the ratios of volcanic production rates at the two zones (Central America:Lesser Antilles) of 12:1 and 7:1 are greater than the ratio of plate-tectonic slip rates of 4:1. Are these twofold to threefold differences significant? Because of the uncertainties associated with the volume estimates, particularly for Central America over 100 000 yr, it is prudent to attach only marginal significance to this result. I discuss here some of the other factors that may affect the relationship between volcanic production rate and subduction rate at these two subduction zones.

It is possible that the latest Pleistocene slip rates have been different from the average Quaternary rates used in plate-tectonic models. So far as can be judged qualitatively from the pre-100 000-yr Pleistocene record of Central American volcanism from Deep Sea Drilling Project site 502 (Ledbetter, 1982) and from the Lesser Antilles volcanism (Sigurdsson and Carey, 1981), there has been no change in the vigor of volcanism that might correspond to such a change in slip rates. There is no independent source of data for calculating plate-tectonic slip rates on the time scale 10^5–10^6 yr, but there is a source of data for the historical period: seismicity. Seismic slip rates have been calculated for both Caribbean plate subduction zones. When the data sets of instrumentally recorded seismicity for the past 80 yr from Central America (McNally and Minster, 1981) and the Lesser Antilles (Dorel, 1981) are treated in a standard format, the seismic slip rates become 2.2 cm/yr (Central America) and 0.2 cm/yr (Lesser Antilles). Comparison of the seismic and plate-tectonic slip rates shows that a greater proportion of the total slip is aseismic beneath the Lesser Antilles than beneath Central America. This is consistent with the idea of Ruff and Kanamori (1980) that a lower convergence rate and a greater age of subducted lithosphere (~100 Ma in the Lesser Antilles; <50 Ma in Central America) decrease the degree of coupling of the plates. However, the significance of the seismic slip rates is clouded by two factors. (1) No large thrust earthquakes (M_s >7.5) have occurred in the Lesser Antilles, whereas there have been about seven such events in Central America during the sample period. Even in Central America the recurrence intervals of the very large magnitude events are probably greater than the 80-yr sample period. Hence, both slip rates are probably underestimates of the longer term seismic slip rates. (2) As Stein et al. (1982) have pointed out, the focal mechanisms of the largest recent Lesser Antilles earthquakes give normal fault-plane solutions, suggesting that lithosphere flexure rather than underthrusting is the dominant contributor to seismicity.

Along-arc variations in volcanic productivity have been noted for the Marianas (Sample and Karig, 1982) and the western Bismark Sea (McKee and Lowenstein, 1981). In the former, Sample and Karig (1982) suggested that the local rate of volcanic productivity varied roughly as the local rate of subduction. The higher productivity of the central islands of the Lesser Antilles arc appears to be a function of the local angle of convergence (Fig. 1). The local angle of convergence depends on the plate-tectonic model: RM2 predicts a slip vector with an azimuth about 280° near the center of the arc (Dominica), whereas the Sykes et al. (1982) model predicts a corresponding azimuth of about 245°, and it depends on the position on the island chain, which from Saba to Grenada describes almost 90° of arc. Perhaps magma production is reduced in the peripheral parts of the arc, where convergence is more oblique. The increase in convergence rate from

TABLE 1. VOLUME ESTIMATES AND PRODUCTION RATES

Period (yr)	Subduction Zone	Volumes of volcanic products: Subaerial*	Submarine+ (km³)	Total	Production rate (10^3 km^3/Ma)	Production rate per km of zone ($km^3 \cdot Ma^{-1} \cdot km^{-1}$)
300	Central America	-	-	19	65	62
	Lesser Antilles	-	-	1	4	5
10 000	Lesser Antilles	-	-	20	2	3
100 000	Central America	2420/607	208	3235	32	31
	Lesser Antilles	74	194/27	295	3	4

* Volumes of stratovolcanoes/volumes of tephra, largely from calderas.

\+ Tephra layers/dispersed tephra in piston cores.

6.9 cm/yr in the northwest to 9.4 cm/yr in the southeast predicted by RM2 for Central America has no known correlative increase in volcanic productivity.

There are also differences in the character of the plates involved. Considerably more oceanic sediment lies on the American plate(s) in front of the Lesser Antilles (0.8 km in the north, >4 km in the south; Westbrook, 1982) than on the Cocos plate in front of Central America (a few hundred metres). In both zones a considerable fraction of the sediment is apparently being subducted (Westbrook et al., 1982; Aubouin et al., 1982). An increased flux of oceanic sediments in subduction zones may increase the rate of magma production (Karig and Kay, 1981). However, there is little indication that the south-to-north decrease in sediment thickness in front of the Lesser Antilles has any effect on volcanism (Hawkesworth and Powell, 1980).

The most obvious distinction between the Caribbean plate in Central America and in the Lesser Antilles is the presence of continental crust beneath at least part of the Central American volcanic chain. The crust beneath the Lesser Antilles is typical of older ensimatic volcanic arcs, with a Moho at about 30 km and relatively high upper-crustal seismic velocities (Boynton et al., 1979). In contrast, the crust beneath the Central American volcanoes, where measured, is thicker (~40 km) and has much lower seismic velocities at equivalent depths (Kim et al., 1982). The thicker, lighter crust in Central America should enhance the ability to trap and freeze buoyantly rising magma within it (Elder, 1978/79), despite the generation of crustal-level anatectic melts. Hence, the major upper-plate variable within the two subduction zones should tend to reduce more the volcanic production rate compared to the total magmatic production rate in Central America.

Along the length of the Lesser Antilles the surface of the upper-crustal layer has relief that rises beneath the islands and dips between them, apparently the result of successive intrusions reinforcing the old pathways of magma ascent (Boynton et al., 1979). At the surface the volcanic centers of the Lesser Antilles have been restricted to a zone no more than about 10 km wide for several million years. This pattern of long-lived loci of magma rise is not seen in Central America. On the time scale of millions of years, the Central American volcanic chain has migrated transversely over a zone 50–100 km wide (Carr et al., 1982; Reynolds, 1980). Many more individual pathways through the upper crust appear to be available to magma ascending from the subduction zone in Central America than in the Lesser Antilles. Whether this is produced by or the cause of the higher rate of volcanism is open to debate.

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