Rates of production of the main magma types in the central Andes

P. W. FRANCIS *Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA England*
C. C. RUNDLE *Geochemical Division, Institute of Geological Sciences, Gray's Inn Road, London WC1X 8NG England*

ABSTRACT

Six new K-Ar dates for young volcanic rocks in the area between lat 21° and 22°S in the Andes of northern Chile have been determined. Two groups of volcanic rocks are present: extrusive lava flows and domes of andesitic composition and extensive sheets of ignimbrite. Both groups are less than 10 m.y. old. We estimate that 2×10^3 km^3 of andesitic rocks and 1.5×10^3 km^3 of ignimbrite lie within the study area. Andesitic rocks have been erupted at an estimated rate of between 1.7×10^{-6} km^3 and 2.9×10^{-6} km^3/yr/1 km of length of the active belt, and ignimbrite at a rate of 1.3×10^{-6} km^3/yr/1 km of length. The total volume of ignimbrite is less than is suggested by the huge area covered by ignimbrite sheets.

In order to estimate the volume and rate of production of a comparable strip of the Coastal batholith of Peru, two extreme models were used for the shapes of batholiths in depth: one assumes a tabular shape with a thickness of 5 km, the other an inverted teardrop shape extending to a depth of 30 km. Rate of production estimates for these two models range from 2.9×10^{-6} km^3/yr/1 km to 9.9×10^{-6} km^3/yr/1 km of length. Whichever model is used, the rate of production is broadly comparable with that of the Sierra Nevada batholith in California.

The rate of extrusive volcanism is about two orders of magnitude less than that at the Icelandic constructive plate margin and several times less than the rate of intrusion of batholithic material. Volumetric data do not explicitly support any particular one of the many hypotheses for the genesis of destructive plate margin magma types. *Key words: Andes, andesites, ignimbrites, batholiths, volumes, ages, production rates.*

INTRODUCTION

The Andean plate margin is widely quoted as the standard example of an oceanic-continental destructive plate margin, and as such has figured prominently in many recent studies, such as that of James (1971), who has presented a useful synthesis of the plate tectonic evolution of the central Andes. Others have dealt with examinations of individual topics such as the batholithic rocks of Peru (Cobbing and Pitcher, 1972), the dates of volcanic, plutonic, and tectonic events (Clark and others, 1967; Noble and others, 1974; Stewart and others, 1974), the geomorphological evolution of the cordillera (Mortimer, 1973), and the nature of metallogenic processes (Sillitoe, 1973). We present some new isotopic age data on andesitic extrusive rocks and ignimbrite sheets from northern Chile and estimate the relative volumetric abundances of andesitic, ignimbritic, and batholithic rocks in representative segments of the central part of the Andean plate margin. The evolution of these three rock suites is of fundamental importance to the understanding of igneous processes at destructive plate margins and has been much discussed in this context, but until now there have been few attempts to quantify the amounts of material involved, or the rates of its production.

Our study was made on the Tertiary-Holocene volcanic activity in the area between lat 21° and 22°S, along the border between Bolivia and Chile (Fig. 1). Within this area, the belt of active and recently active andesite volcanoes is well defined, and there are several major volcanoes more than 6,000 m high. Three of them are regarded as active, although none has experienced a major eruption in historic times (Casertano, 1962). The area also forms part of the immense ignimbrite plateau of the central Andes, estimated by Zeil and Pichler (1967) to cover some 150,000 km^2. The study area is a representative segment of the volcanic cordillera and therefore provides a starting point for assessing the volumes of andesitic and ignimbritic rocks. The volume of batholithic material is derived from a section across the Peruvian Coastal batholith.

VOLUME OF ANDESITIC ROCKS

The area studied contains 16 major (named) andesitic volcanoes and many minor ones (Fig. 1). These rise above a platform composed of ignimbrite sheets which slopes gently away to the Rio Loa in the west. The volcanic rocks overlie a basement that consists of Mesozoic metamorphic and igneous rocks. It has been suggested that the ignimbrite platform is older than the andesitic stratovolcanoes (Bruggen, 1950; Zeil and Pichler, 1967), but there is good evidence that at least some of the ignimbrite sheets were erupted while construction of the andesite volcanoes was going on. The stratigraphic relationships of the major volcanic units and their geochemistry have been discussed by Francis and others (1974). In this paper, the term "andesitic" is applied to all extrusive lava flows and domes in the area, notwithstanding the fact that the most basic members are strictly basaltic andesites and the most acidic members are dacites. Although the andesitic extrusives and ignimbrites from the central Andes as a whole appear to form separate populations when plotted on variation diagrams (Zeil and Pichler, 1967; Pichler and Zeil, 1969), there is a continuous gradation in composition between them. The volume of andesitic rocks in the area was estimated by defining the base levels of the volcanoes on a 1:250,000 topographic map, measuring the areas contained within successive contour intervals, and integrating. The total volume of andesitic material established by this method is 2×10^3 km^3. This figure is thought to be within 25 percent of the correct value.[1]

RATE OF ERUPTION OF ANDESITIC ROCKS

In an attempt to define more closely the span of time available for the production of these rocks, K-Ar age determinations have been made on four lava and two pyroclastic flows from the area under investigation (Table 1). Errors quoted are the standard error on the mean and are compounded

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[1] Brief notes on the principal sources of errors in this method are in GSA supplementary material 76-8. Copies may be ordered from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

Geological Society of America Bulletin, v. 87, p. 474–480, 2 figs., March 1976, Doc. no. 60317.

from the errors on the mass spectrometric isotopic ratio measurements, the spike volume, and the percent K results and include an error magnification associated with the correction for contaminating atmospheric argon. They represent an estimate of analytical precision only and do not incorporate errors in the decay constants or geological errors due to argon loss or excess argon. (Notes on the K-Ar technique employed are in GSA supplementary material 76-8; see footnote 1.)

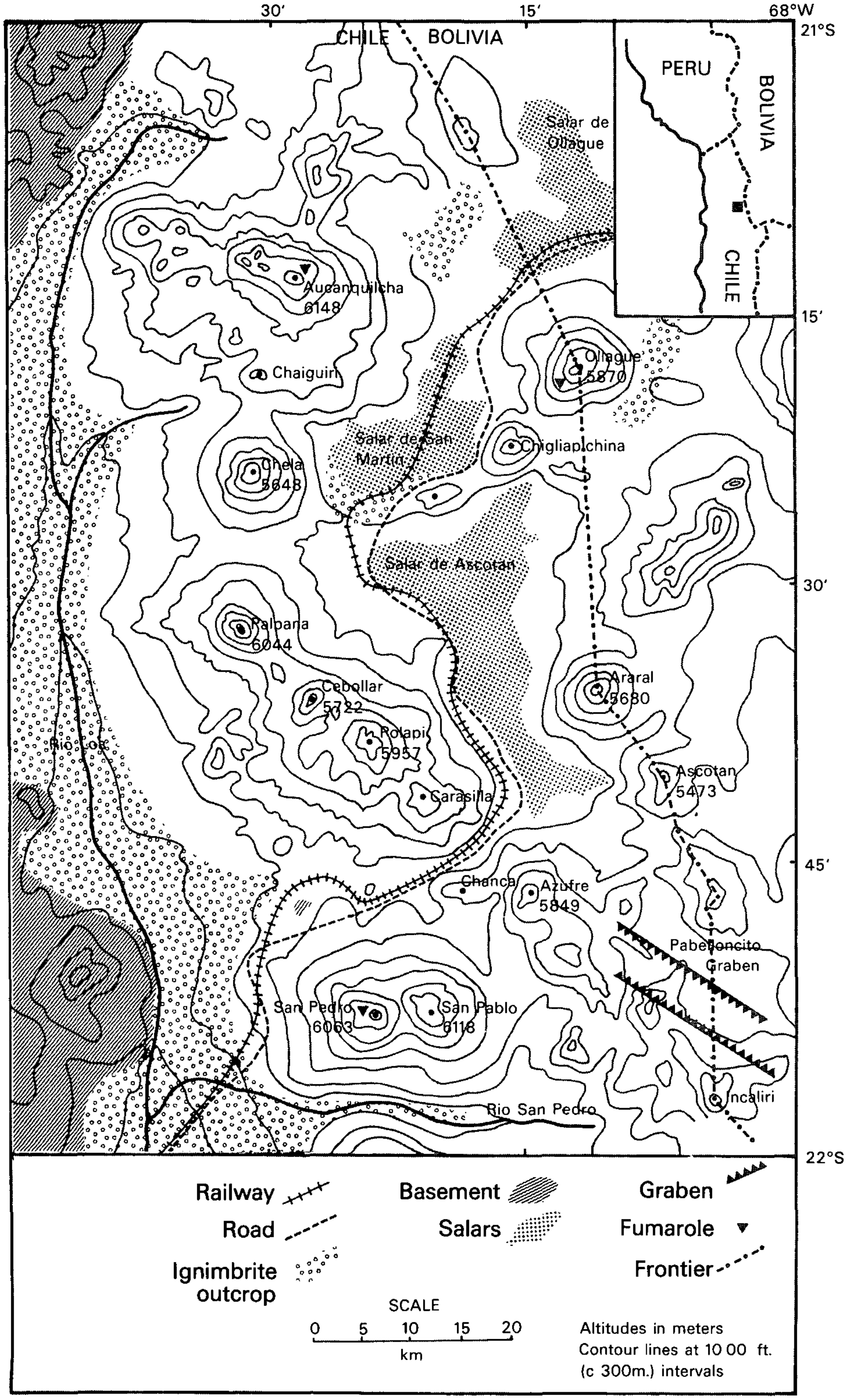


Figure 1. Sketch topographic map of volcanic area between lat 21° and 22° S. Volumetric data used in this paper were obtained from 1:250,000 version of this map. Inset: location of study area in Andes.

Age Data

While a K-Ar determination provides a minimum estimate of the age and represents the time of formation of a rock only if cooling time was rapid and there was no subsequent heating event, we can consider as a working hypothesis that for the young, fresh biotites in this study the dates obtained are reasonable estimates of the ages of these rocks. However, it must be noted that several of these samples have an unusually high percentage of contaminating atmospheric argon, and this is reflected in the high errors associated with our results.

Although a large number of dates have been obtained from north Chilean volcanic rocks by other workers (Dingman, 1965; Rutland and others, 1965; Clark and others, 1967, 1973; Mortimer, 1973), the new data are significant because this is the first time that dates have been obtained for andesitic extrusive rocks (as opposed to pyroclastic flows), and since several of these are available for a relatively small area, it is possible to establish a well-defined radiometric chronology for some of the volcanic events in this area. The oldest extrusive rock dated (sample no. 362) is an ignimbrite exposed around the base of Ollague volcano (Fig. 1) which has yielded a date of 6.2 m.y. Field evidence suggests that the volcano has been built up on top of the ignimbrite sheet. A lava flow and an extrusive dome on Ollague were also dated, both of them among the youngest products of the volcano. Both yielded ages less than 1 m.y. Thus it appears that most of the Ollague volcano was built up in the period between about 6 and 1 m.y. ago. Field relations and other age data still in preparation suggest that the other volcanoes in the area were built up within the same general period.

On the basis of a large number of unpublished dates, Clark and others (1973) concluded that there was a major breakout of volcanic activity in the Chilean Andes between lat 26° and 29°S between 12 and 7 m.y. ago. The compilation of published age data by Noble and others (1974) for the central Andes as a whole also indicate the initiation of volcanic activity about 10 m.y. ago.

Taken together, the field evidence, the small number of dates from the area examined, and the much larger number of dates from the central Andes as a whole make it reasonable to assume that none of the andesitic volcanoes shown in Figure 1 is older than about 10 m.y. The evidence from Ollague suggests that the oldest parts of the major cones are unlikely to be much more than 6 m.y. old. This means that the minimum average rate of production of andesitic rocks in the area must be of the order of 2 × 10^{-4} km^3/yr, and the maximum average rate is of the order of 3.3 × 10^{-4} km^3/yr.

VOLUME OF IGNIMBRITES

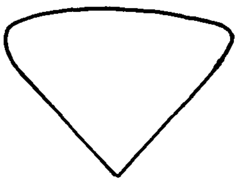
Ignimbrite sheets crop out over large parts of the area shown in Figure 1 and are magnificently exposed in some gorges, notably along the Rio Loa. A single ignimbrite sheet was traced for more than 100 km along the gorge of the Rio Loa. Despite these exposures, it is difficult to make a good estimate of the volume of ignimbrite in the area, for four reasons: First, the bases of major ignimbrite sheets are often not exposed, so it is not possible to measure their total thicknesses. Second, as many as five ignimbrite sheets can be seen in some sections, and some show evidence of erosion prior to their being covered by younger ignimbrite sheets or by alluvial material; this makes it difficult to establish their original thicknesses. Third, although most of the studied ignimbrite outcrops are in the gorges of the Rio Loa and its tributaries, it is known that ignimbrites extend over the Chile-Bolivia border into the flat ground of the Bolivian altiplano. This area is unmapped. Fourth, crystal concentration studies have shown that ignimbrites may lose as much as 50 percent of their initial material in the ash and clast clouds to which they give rise (Lipman, 1967).

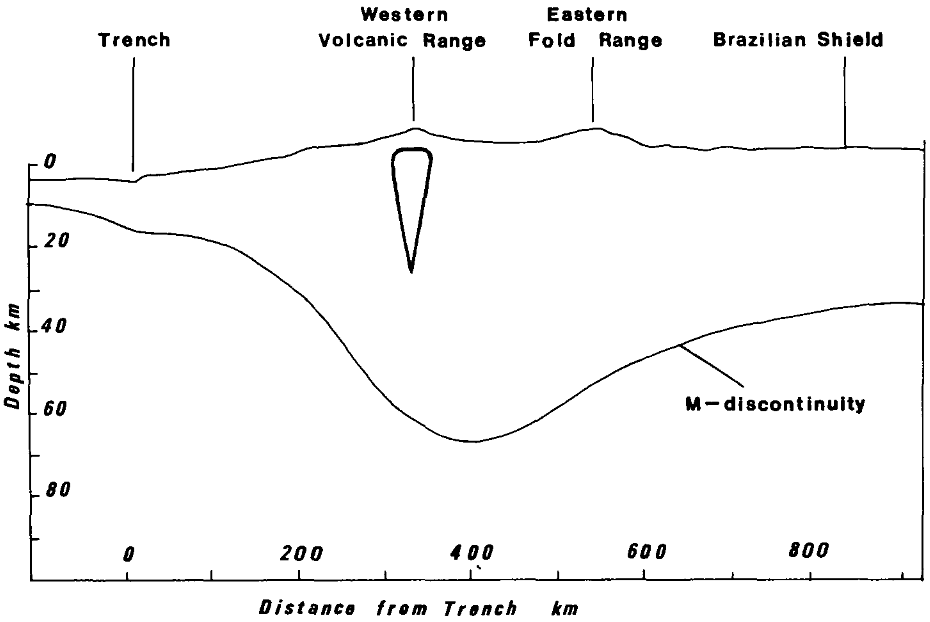
TABLE 1. NEW K-Ar AGE DETERMINATIONS OF NORTHERN CHILE VOLCANIC ROCKS

Sample no.	Rock type	Material analyzed	K-Ar reference no.	K (%)	Atmos Ar (%)	Scc/g Rg ^{40}Ar	Age and error (m.y.)
175	Pumice	Hornblende	73/45	0.99	88.9	1.016 × 10^{-7}	2.6 ± 0.6
354	Andesite	Biotite	73/46	5.35	82.3	1.755 × 10^{-7}	0.8 ± 0.1
362	Ignimbrite	Biotite	73/47	5.36	43.7	1.324 × 10^{-6}	6.2 ± 0.2
364	Dacite	Biotite	73/48	5.95	94.5	1.469 × 10^{-7}	0.6 ± 0.1
443	Andesite	Biotite	73/49	3.42	76.7	3.393 × 10^{-7}	2.5 ± 0.1
492	Dacite	Biotite	73/50	4.87	79.1	2.831 × 10^{-7}	1.5 ± 0.1

Note: Decay constants: $\lambda^{\beta} = 4.72 \times 10^{-10} yr^{-1}$; $\lambda^{e} = 0.584 \times 10^{-10} yr^{-1}$; % 40 K = 0.0119.

Figure 2. Right, Simple inverted teardrop profile used in estimating batholith volume. Below, Teardrop batholith with same height:width ratio as profile above set in cross section through central Andes, with different vertical and horizontal scales. Batholith drawn here would have surface outcrop about 50 km wide and would be rooted at depth of about 30 km. Cross section based on one by James (1971).





It is, however, possible to estimate the maximum volume of ignimbrite present, despite these difficulties. In the area of Figure 1, ignimbrite sheets are known to be exposed or to underlie an area of some 5,000 km^2 on the Chilean side of the Bolivia-Chile frontier. In some outcrops along the Rio Loa, ignimbrite sheets totaling more than 50 m in thickness are present. Dingman (1965) used an average thickness of 50 m when assessing the total volume of ignimbrite in northern Chile, whereas James (1971) suggested that the average thickness of the ignimbrite plateau is 0.5 km, ten times greater than the figure used by Dingman or that estimated for the area we studied. Ignimbrite thicknesses of 0.5 km or more do occur locally, especially where older valleys are infilled, but these are not typical. To obtain a maximum estimate of the volume of ignimbrite, an average thickness of 150 m was assumed. On this basis, the volume of ignimbrite on the Chilean side of the Bolivia-Chile border is 0.75 × 10^3 km^3. The frontier is defined by a line drawn through the summits of the major volcanoes constituting the linear volcanic belt. Assuming that equal volumes of ignimbrite were erupted on each side of the volcanic axis, the total volume of ignimbrite present in the 1° of latitude strip under consideration would be 1.5 × 10^3 km^3. Even though no allowance has been made for erosion or ash losses during eruption, this figure still represents a maximum estimate, because it is most unlikely that the average ignimbrite thickness is as great as 150 m, and there is likely to be more ignimbrite on the west (Chilean) side of the volcanic axis than on the east, since the plateau slopes toward the west. The maximum estimate of 1.5 × 10^3 km^3 is useful because it reveals a relationship not otherwise obvious: the volume of ignimbrite is of the same order of magnitude as that of the andesitic rocks. Jenks and Golditch (1956) estimated that the proportion of silicic sillar (ignimbrite) in southern Peru was less than 1 percent of the volume of andesitic lavas, but many other workers have been misled by the enormous areal extent of the ignimbrite sheets in the central Andes into considering that ignimbrite represents much the greatest proportion of volcanic rocks in the area. It is often overlooked that a single 2,000-m-high conical andesite volcano has a volume of the order of 100 km^3.

RATE OF ERUPTION OF IGNIMBRITE

The sets of age data on northern Chilean volcanic rocks discussed above, together with those presented in Table 1, suggest that ignimbrite eruptions commenced in this part of northern Chile about 10 m.y. ago. The youngest date obtained so far for an ignimbrite sheet is 2.6 ± 0.6 m.y. (sample no. 175). However, there has been recent activity in the area, so we have assumed production of material until the present. Thus the 1,500 km^3 of ignimbrite in the area was erupted at a maximum average rate of 1.5×10^{-4} km^3/yr. It is likely, however, that the rate of eruption was not uniform and that it was at its greatest 10 m.y. ago, when the breakout described by Clark and others (1967) occurred. Noble and others (1974) also implied that activity has waned since 10 m.y. ago.

VOLUME OF BATHOLITHIC MATERIAL

It is clearly impossible to demonstrate conclusively that the active volcanic belt of the central Andes is underlain by a batholith, although this has been convincingly argued by Hamilton (1969), Hamilton and Myers (1967), and Dickinson (1970). Hamilton, in particular, drew close parallels between the present situation in northern Chile and that which prevailed in Peru during the formation of the Coastal batholith. Cobbing and Pitcher (1972) have demonstrated that the Peru batholith does indeed penetrate upward into an envelope of older volcanic rocks, which include extensive sequences of ignimbrites. The Peruvian batholith is thus used here as a model, so that an estimate can be made of the volume of rocks contained within a typical section of batholith, for comparison with the Chilean volcanic data. Such comparisons are of some intrinsic interest but are also useful in consideration of the various petrogenetic models that have been advanced for the origin of magmas at destructive plate margins (see, for example, Presnall and Bateman, 1973). It is, however, difficult to estimate the volume of batholithic material for two reasons: First, the Coastal batholith is not a simple body but is composed of a large number of individual plutons of different compositions; for this reason, the term "batholithic material" has been used consistently in preference to "granite" or any other more specific term. Second, and more important, there is no consensus on what the subsurface shapes of batholiths are. Many contrasted models exist. Hamilton and Myers have stated that "batholiths form from magmas, generated largely in the mantle, which typically rise completely through the crust, spread out, and crystallize beneath covers several kilometres thick, consisting mostly of their own volcanic ejecta. . . . batholiths are tabular aggregates, only 5 km or so thick, of coalesced plutons. . . ." (Hamilton and Myers, 1974, p. 365). More conventional models for batholiths are considered to be steep sided and to extend downward to considerable (usually unspecified) depths. This model has found some support in the work of Klepper and others (1971), also on the Boulder batholith.

In this paper, estimates for the volume of material in the Peru batholith are presented for two extreme models: the Hamilton and Myers model, in which a thickness of 5 km is assumed, and another model, in which the batholith is assumed to be composed of plutons that were produced by partial melting at the lowest temperatures and shallowest depths consistent with the prevailing thermal gradient. Such plutons are likely to have the shapes of inverted teardrops (Fig. 2; Cobbing and Pitcher, 1972) and to be rooted to depths of about 30 km (Brown, 1973). Inward dips of the margins of plutons in Peru are, however, not often observed (W. S. Pitcher, 1974, personal commun.). The Coastal batholith crops out in a fairly regular strip some 50 km wide. On the Hamilton and Myers model, the volume of batholithic material contained within a strip of 1° of latitude in length is of the order of about 3×10^4 km^3. The more conventional teardrop model has a volume of about 1×10^5 km^3.

Gilletti and Day (1968), Farrar and others (1970), Levi (1973), and Clark and others (1973) have all demonstrated an apparent eastward younging in the age of intrusive rocks in the Andes. In Peru, the Coastal batholith is paralleled to the east by the younger Cordillera Blanca batholith. The axes of the two batholiths are about 50 km apart, and the outcrop of the Cordillera Blanca batholith is about 16 km wide. On the Hamilton and Myers model, a 1° strip of this batholith has a volume of about 9×10^3 km^3; on the teardrop model, it has about 2.7×10^4 km^3.

RATE OF PRODUCTION OF PERUVIAN BATHOLITHIC ROCKS

The oldest parts of the Coastal batholith are about 100 m.y. old, and the youngest are about 10 m.y. old (Stewart and others, 1974). Thus, the rate of accumulation of batholith material for a 1° strip ranges from 3.3×10^{-4} km^3/yr for the Hamilton and Myers model to about 1.1×10^{-3} km^3/yr for the teardrop model. It seems probable, however, that different components of the batholith were intruded in distinct episodes, just as Kistler and others (1971) have shown for the Sierra Nevada batholith. The Cordillera Blanca batholith appears to have been intruded between about 12 and 3 m.y. ago (Stewart and others, 1974), suggesting a rate of production ranging from 1×10^{-3} km^3/yr for the Hamilton and Myers model to about 3.3×10^{-3} km^3/yr for the teardrop model. There is considerable doubt, however, as to the significance of the very young ages obtained from this batholith.

DISCUSSION

The data presented have been summarized in Table 2, and recalculated so that the rates of production are expressed in terms of cubic kilometres per kilometre length of plate margin per year.

Rate of Volcanic Activity

It is instructive to compare the rate of volcanism along the Andean plate margin with that at a constructive plate margin. The data of Bodvarsson and Walker (1964) and Thorarinsson (1967) suggest that between 0.025 and 0.04 km^3 of material is erupted annually in Iceland, along the 50-km length of the active volcanic belt. This corresponds to a mean value of about 6.5×10^{-4} km^3/yr/1 km of length of ridge axis. This rate is probably several times greater than that along the submarine part of the Mid-Atlantic Ridge. Assuming a spreading rate of 3 cm/yr and a thickness for the oceanic plate of 8 km, the amount of new material added annually to the oceanic crust must be of the order of 2.4×10^{-4} km^3/1 km of length of ridge axis. For the central Andes, the *total* rate of eruption of volcanic material (ignimbrites plus andesitic rocks) is, at greatest estimate, about 4.2×10^{-6} km^3/yr/1 km of length of plate margin — two orders of magnitude less. This represents the average over the past 10 m.y.; the *present* rate could be much less. This is supported to some extent by the fact that few of the volcanoes in the area we examined exhibit evidence of significant activity since the last glacial episode, which ended some 10,000 to 15,000 yr ago. It is not, however, meaningful to estimate the rate of eruption over short periods, because eruptions are infrequent but may be of large magnitude. Several of the lava flows in the area mapped have volumes greater than 1

TABLE 2. SUMMARY OF DATA

	Volume in 1°-lat strip (km^3)	Age range (m.y.)	Rate of production in 1°-lat strip (km^3/yr)	Rate of production per 1-km length of plate margin (km^3/yr)
Andesitic rocks (maximum estimate)	2×10^3	6.0–0	3.3×10^{-4}	2.9×10^{-6}
Andesitic rocks (minimum estimate)	2×10^3	10.0–0	2×10^{-4}	1.7×10^{-6}
Ignimbrites (maximum estimate)	1.5×10^3	10–0	1.5×10^{-4}	1.3×10^{-6}
Coastal batholith (Hamilton and Myers model)	3×10^4	100–10	3.3×10^{-4}	2.9×10^{-6}
Coastal batholith (teardrop model)	1×10^5	100–10	1.1×10^{-3}	9.9×10^{-6}
Cordillera Blanca batholith (Hamilton and Myers model)	9×10^3	12–3	1×10^{-3}	8.9×10^{-6}
Cordillera Blanca batholith (teardrop model)	2.7×10^4	12–3	2.9×10^{-3}	2.6×10^{-5}

km^3, and one, slightly to the south, has a volume of no less than 24 km^3 (Guest and Sanchez, 1969). It is not possible to make any *simple* estimate of the overall rate at which new material is being added to the continental crust in the central Andes, because this requires that one knows where the magmas originate.

Rate of Production of Batholiths

Data on the rates of production of different batholiths are scarce. Considering only the Hamilton and Myers model, it is clear that there is some agreement between the rates of production of the Peruvian Coastal batholith and the Cordillera Blanca batholith, assuming that the age data for the very young Cordillera Blanca rocks are valid. Rough estimates on the Sierra Nevada batholith in California, however, show that a 1-km strip of it has a volume of about 400 km^3, and that, according to the age data of Evernden and Kistler (1970) the rate of production over a 130-m.y. period averaged 3.1×10^{-6} km^3/yr/1 km of length, very close to the figure of 2.9×10^{-6} km^3/yr/1 km of length obtained for the Coastal batholith.

Evernden and Kistler (1970) have shown that the Sierra Nevada batholith was formed not continuously but in five separate episodes of intrusion, each between 10 and 20 m.y. long, and further work on the Peruvian batholith may demonstrate the same kind of chronology. Overall, however, it is likely that a figure close to 3×10^{-6} km^3/yr/1 km of length may be one that is generally representative for the rate at which batholiths form. Conceivably, this rate may be related to the rate at which plutonic diapirs rise within the crust. (A similar argument, of course, could be used throughout for the teardrop model, with different figures.) The possibility that batholiths in similar settings are generated at broadly similar rates has interesting implications, but these cannot be satisfactorily explored until better data on the shapes of batholiths in depth are available.

Petrogenetic Implications

The origin of the igneous rock suites characteristic of destructive plate margins is the subject of considerable controversy. There are good grounds for believing that "granitic," "andesitic," and "ignimbritic" magmas all share a common origin. In particular, Cobbing and Pitcher (1972) have suggested that the centered complexes occurring in the Peruvian batholith could be the "basal wrecks" of volcanic calderas that gave rise to andesitic lavas, and both Hamilton (1969) and Sillitoe (1973) have stressed the intimate links that exist between major andesite stratovolcanoes and underlying plutonic masses. There are, however, considerable differences of opinion as to whether the three rock suites are derived from the upper mantle, from the downgoing lithospheric plate at the subduction zone, or by fusion of the continental crust. For the andesitic rocks and ignimbrites of southwestern Bolivia, Fernandez and others (1973) have suggested an origin in the upper crust, at a depth between 9 and 26 km. Pichler and Zeil (1969, 1972) have consistently argued that both the andesites and ignimbrites of northern Chile were derived from the lower crust, whereas Roobol and Francis (1976) showed that trace-element data are consistent with derivation at the subduction zone.

For the Sierra Nevada batholith, Kistler and others (1971) postulated a source in the upper mantle or lower crust, with varying degrees of assimilation of upper-crustal material, whereas Presnall and Bateman (1973) suggested that upward transport of andesitic and basaltic magmas generated along a Mesozoic subduction zone beneath the Sierra Nevada would have provided sufficient additional heat to make fusion of the lower crust unavoidable, and therefore the present batholith was derived from the lower crust. Volumetric considerations can cast some light on these issues.

James (1971) discussed briefly the origin of the Andean crust and suggested that "if the magma . . . was derived entirely by partial melting of a non-circulating mantle above the Benioff Zone, 18–36% partial melting is required," and "if the magma is generated within the lithospheric plate . . . the volumetric requirements could be satisfied if 1–2 km of the slab was melted." Assuming that the oceanic crust is the only part of the lithosphere that takes part in partial melting processes, that the total thickness of the crustal layers is 8 km (Cann, 1970), and that subduction has been taking place along the central Andean plate margin at an average rate of about 6 cm/yr (Le Pichon, 1968), then 4.8×10^{-4} km^3 of material is subducted annually for each 1 km of length of the plate margin. The data presented in this paper suggest that even if the *maximum* rate of generation of each of the three rock suites is considered, the total of andesitic plus ignimbritic plus granitic material (nearly 2×10^{-5} km^3/yr/1 km of length) represents less than 5 percent of the volume of subducted lithospheric plate. This indicates that volumetric considerations need not be a constraint even if the lithospheric plate is advocated as the origin of all three major rock types. This is not, however, evidence that all three rock types *were* derived from the lithospheric plate. Volumetric data could be used to support many hypotheses but are probably more useful in eliminating impossibilities. For example, had the rates of production of andesitic magmas proved to be orders of magnitude lower than that of batholithic material, then it would seem infeasible to argue that upward-moving andesitic magmas could transfer enough heat to mobilize significant quantities of the lower crust, as Presnall and Bateman (1973) suggested.

General Considerations

Many workers have suggested that continental accretion occurs through the production of magmas from mantle material at subduction zones. Brown (1973) suggested a global rate of accretion of about 1.1 km^3/yr, simply by dividing the volume of continental crust by the age of the Earth. (This estimate makes no assumptions about the mechanisms of generation of continental material.) There appears to be about 50,000 km of active destructive plate margin in the world at present. Thus if the rate of production of andesitic rocks suggested here is typical of destructive plate margins generally, then the annual increment at greatest would be of the order of 0.15 km^3/yr. If the volumes of ignimbritic and batholithic material are added, then the total annual increment would be of the order of about 1.0 km^3/yr, a figure curiously close to that suggested by Brown (1973).

The volumetric data presented here are too tentative to make this matching of figures more than a subject for speculation, but it does emphasize their usefulness. A further example is provided by the central Andes themselves. The present thickness of the crust beneath the Andean cordilleras is about 70 to 75 km (James, 1971), whereas in Jurassic time it is likely to have been no more than 30 to 40 km, because the presence of marine sediments near the crestal regions indicates that they were at sea level or below at that time. (We are grateful to D. E. James for bringing this point to our notice.) Thus the crust beneath the Andes has increased in thickness by some 30 km since Jurassic time. This could have been accomplished only by extrusion, intrusion, underplating, or crustal shortening. If activity at the Andean plate margin had been continuous since the end of Jurassic time some 135 m.y. ago, each 1-km length of the plate margin would have yielded 2.7×10^3 km^3 of material. Since the volume of a unit cross section across the present central Andes is about 2×10^4 km^3, it seems that the rates of magma production presented here are inadequate to account for the increase in thickness of the continental crust. This discrepancy may result from a number of causes, most obviously the assumption that rates of production have been constant over a period of more than 100 m.y., but it also suggests that both the models used for the shapes of batholiths are too small, and this in turn suggests that the Hamilton and Myers model, which may be applicable to a few shallow examples, is not typical of batholiths generally.

SUMMARY

The data presented here show that (1) The volcanic rocks in the area studied were erupted during the past 10 m.y. (2) The overall rate of extrusive volcanism (andesitic lavas plus domes plus ignimbrite sheets) in the central Andes is nearly two orders of magnitude less than that of the Icelandic constructive plate margin. (3) The rate of extrusive volcanism is several times less than the rate of intrusion of batholithic material. (4) Similarities between rates of production of the Sierra Nevada batholith and the Peru batholiths indicate that a figure of around 3×10^{-6} km^3/yr/1 km of length may be generally representative of the rate at which batholiths form and may be related to the rate at which diapirs rise within the crust. (5) Although the data do not support any particular petrogenetic models, they could be used to eliminate impossible hypotheses. (6) The rates of magma production deduced here are apparently not consistent with the increase in thickness of the Andean crust since Jurassic time. This may indicate that models for batholiths that have low volumes (such as the Hamilton and Myers model) may not be applicable. (7) There is an overwhelming need for more simple volumetric data and for information on the rates of geologic processes. This field of study has fallen far behind the sophistication of modern petrologic and geochemical techniques, but it could be of considerable value in testing models derived from such studies.

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