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Relative Roles of Source Composition, Fractional Crystallization and Crustal Contamination in the Petrogenesis of Andean Volcanic Rocks [and Discussion]

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Relative roles of source composition, fractional crystallization and crustal contamination in the petrogenesis of Andean volcanic rocks

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There are well established differences in the chemical and isotopic characteristics of the calc-alkaline basalt–andesite–dacite–rhyolite association of the northern (n.v.z.), central (c.v.z.) and southern volcanic zones (s.v.z.) of the South American Andes. Volcanic rocks of the alkaline basalt–trachyte association occur within and to the east of these active volcanic zones. The chemical and isotopic characteristics of the n.v.z. basaltic andesites and andesites and the s.v.z. basalts, basaltic andesites and andesites are consistent with derivation by fractional crystallization of basaltic parent magmas formed by partial melting of the asthenospheric mantle wedge containing components from subducted oceanic lithosphere. Conversely, the alkaline lavas are derived from basaltic parent magmas formed from mantle of 'within-plate' character. Recent basaltic andesites from the Cerro Galan volcanic centre to the SE of the c.v.z. are derived from mantle containing both subduction zone and within-plate components, and have experienced assimilation and fractional crystallization (a.f.c.) during uprise through the continental crust. The c.v.z. basaltic andesites are derived from mantle containing subduction-zone components, probably accompanied by a.f.c. within the continental crust. Some c.v.z. lavas and pyroclastic rocks show petrological and geochemical evidence for magma mixing. The petrogenesis of the c.v.z. lavas is therefore a complex process in which magmas derived from heterogeneous mantle experience assimilation, fractional crystallization, and magma mixing during uprise through the continental crust.

1. Introduction

Active Andean volcanism occurs in three distinct zones (figure 1): a northern volcanic zone (n.v.z.) in Colombia and Ecuador (5° N to 2° S), a central volcanic zone (c.v.z.) in S Peru and N Chile (16–28° S) and a southern volcanic zone (s.v.z.) in S Chile (33–52° S) (Thorpe & Francis 1979). The n.v.z. lavas are dominantly basaltic andesites and andesites (SiO_2 = *ca.* 53–63 %) with minor dacite and rhyolite. The c.v.z. lavas are dominantly andesites and dacites (SiO_2 = *ca.* 56–66 %) associated with ignimbrite sheets of dacite and rhyolite composition (SiO_2 = *ca.* 68–75 %), and the s.v.z. lavas comprise basalt, basaltic andesite and andesite lavas (SiO_2 = *ca.* 50–65 %) with minor dacite and rhyolite. The n.v.z. is built upon continental crust *ca.* 40–50 km in thickness, of Cretaceous and older age, and the s.v.z. is upon *ca.* 30–40 km thick crust of Mesozoic and younger age. By contrast, the c.v.z. is built upon thick (*ca.* 70 km) continental crust which is of Precambrian age below part or all of the volcanic zone (Cobbing & Pitcher 1972; Ziegler *et al.* 1981; Thorpe *et al.* 1981).

The three active volcanic zones are underlain by a relatively steeply dipping Benioff zone and a well-developed wedge of asthenospheric mantle (Baranzangi & Isacks 1976, 1978; Sacks 1982). The association of active volcanism with asthenospheric mantle indicates that the volcanism is a response to mantle conditions. Further the Sr-, O- and Nd- isotope characteristics of the n.v.z. and s.v.z. lavas have been interpreted in terms of derivation from mantle modified by influx of components derived from the subducted oceanic crust (Thorpe *et al.* 1976, 1981;

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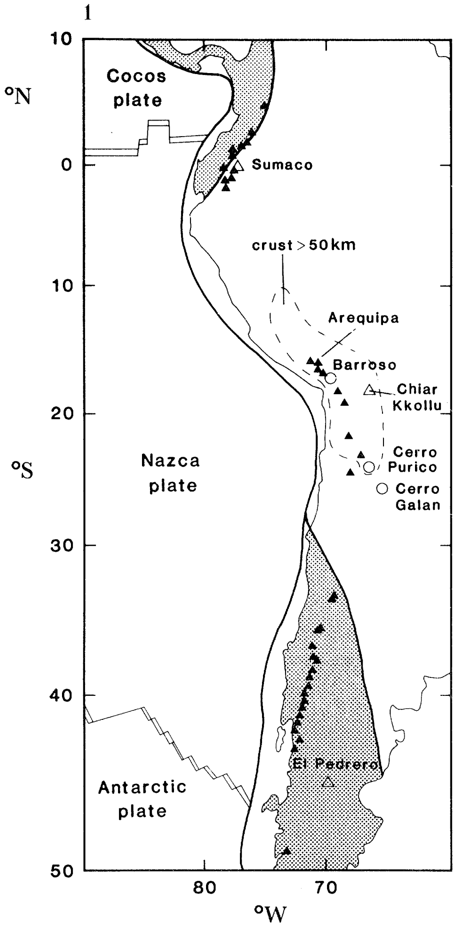
Hawkesworth *et al.* 1979; Harmon *et al.* 1981; Déruelle *et al.* 1983). By contrast, the c.v.z. lavas are more evolved (cf. above) and have higher ratios of $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ but lower $^{143}Nd/^{144}Nd$ ratios. A wide range of hypotheses has been proposed for the origin of the c.v.z. lavas including derivation from 'enriched' continental mantle (James *et al.* 1976; Hawkesworth *et al.* 1979), lower continental crust (Pichler & Zeil 1972; Hawkesworth *et al.* 1982), and subducted continental sediments (James 1981). The c.v.z. lavas may be derived from one or more of these sources and several models have been proposed for 'contamination' of mantle-derived magmas rising through thick continental crust (Francis *et al.* 1977, 1980; Briqueu & Lancelot 1979; DePaolo 1981). In this paper we review data concerning the relative roles of source composition (subducted oceanic crust, mantle and continental crust), fractional crystallization and combined assimilation–fractional crystallization processes in the petrogenesis of Andean andesites.



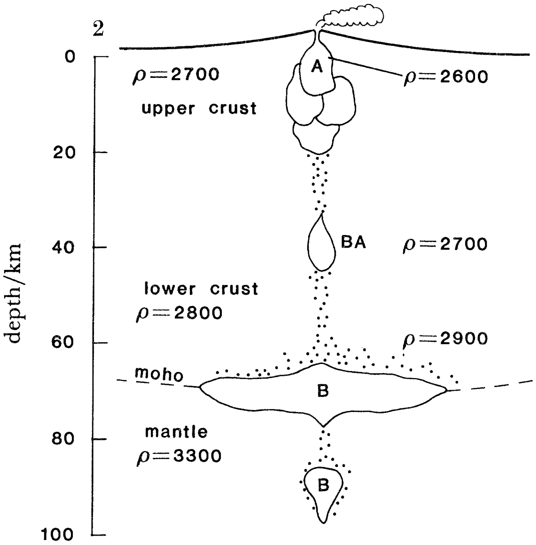


FIGURE 1. Map of western South America showing the plate tectonic framework in relation to active volcanism, crustal age and thickness. The active calc-alkaline basalt–andesite, dacite volcanoes are represented by solid triangles (MacDonald 1972). Some alkaline volcanoes are represented by open trinagles. The open circles are volcanic areas referred to in the text. The stippled areas represent continental areas underlain by crust of Palaeozoic or younger age, and other areas may be underlain by Precambrian crust (cf. Ziegler *et al.* 1981; Thorpe *et al.* 1981). The location of crust exceeding 50 km in thickness is shown (Cummings & Schiller 1971).

FIGURE 2. Density-controlled uprise of basaltic magma (B) through continental crust accompanied by assimilation–partial melting (stipple) and fractional crystallization to form basaltic andesite (BA) and andesite magma (A).

The possible sources of Andean andesites are summarized in figure 2. Before initiation of subduction the mantle may show complex chemical and isotopic heterogeneity (Bailey *et al.* 1980), upon which may be superimposed elements derived either by dehydration or by partial melting or both of the subducted oceanic slab (including subducted continental sediment returned to the mantle). Basaltic magmas derived from such mantle will be underplated at the base of the crust (figure 2), and may experience assimilation and fractional crystallization during subsequent uprise through the crust. Such 'contamination' may occur before, during or after fractional crystallization (Briqueu & Lancelot 1979; Francis *et al.* 1980; DePaolo 1981) and may result from addition of elements in a hydrous phase derived from crustal dehydration (see, for example, Patchett 1980) or a melt derived by crustal anatexis (see, for example, DePaolo 1981). In this context, there is some confusion regarding the concept of 'selective contamination' or 'selective addition' (Carter *et al.* 1978; Moorbath & Thompson 1980). Mixing of components of different composition will yield a mixture in which different proportions of each element are contributed from each component. In a restricted sense therefore each element may be contributed selectively from one component. We do not refer to 'selective' processes but attempt to assess the relative contributions of different components to the erupted magma. Contamination of magmas from different crustal or mantle sources may take place by magma mixing (cf. Eichelberger 1978, 1979).

2. Interpretation of elemental patterns

In this section we use primordial-mantle normalized trace element patterns of Andean lavas to comment on possible mantle and crustal sources for these rocks (cf. Wood 1979).

(*a*) *N.v.z. and s.v.z.* (*cf. table* 1)

The major and trace element and isotope characteristics of lavas from the n.v.z. (Francis *et al.* 1977; Hawkesworth *et al.* 1979; Harmon *et al.* 1981; Hörmann & Pichler 1982), and the s.v.z. have been described elsewhere (Lopez-Escobar *et al.* 1977, 1981; Déruelle 1982). The chemical characteristics of these basalt, basaltic andesite and andesite lavas are summarized in primordial mantle-normalized trace element patterns shown in figure 3*a*. The lavas from both volcanic zones are enriched in Rb, Ba, Th, K, Ce, Sr relative to Ta, Nb, Hf, Zr and Ti (cf. Hawkesworth *et al.* 1979; Pearce 1982). The n.v.z. lavas also show enrichment of ^{87}Sr/^{86}Sr in relation to ^{143}Nd/^{144}Nd (Hawkesworth 1982). These data indicate petrogenesis of the lavas from parent magmas produced from mantle containing a 'subduction-zone' component enriched in Rb, Ba, Th, K, Ce and Sr (and ^{87}Sr/^{86}Sr) (cf. Pearce 1983). The parent magmas may have been derived by 10–15% partial melting of such mantle followed by fractional crystallization of *ca.* 20% olivine and clinopyroxene during uprise through continental crust (Lopez-Escobar *et al.* 1977). Therefore while the n.v.z. and s.v.z. lavas are derived from magmas containing mantle and subduction-zone components, there is no evidence for the presence of a significant crustal component.

(*b*) *Alkaline lavas east of the Andes* (*cf. table* 2)

Pliocene-recent alkaline lavas occur within and to the east of the active volcanic zones. In the n.v.z., these include monogenetic cones and associated flows in Colombia which occur within an area some 30–100 km east of the active volcanic zone (Kroonenburg *et al.* 1982). In Ecuador,

Table 1. Chemical analyses of basaltic andesites from the active volcanic zones and Cerro Galan

	1†	2	3	4	5	6
SiO_2	55.72	56.18	54.22	54.88	52.41	52.33
TiO_2	0.89	1.17	0.95	1.33	2.02	1.27
Al_2O_3	16.89	16.78	16.02	16.50	16.25	15.32
Fe_2O_3	8.72	7.94	8.46	3.76	9.27	8.93
FeO	—	—	—	6.56	—	—
MnO	0.10	0.10	0.13	0.19	0.14	0.14
MgO	5.12	4.61	7.66	3.28	6.03	7.76
CaO	7.51	6.95	7.88	7.25	6.93	8.22
Na_2O	3.86	3.75	3.14	4.44	3.95	4.16
K_2O	1.14	2.05	1.19	0.84	2.50	1.76
P_2O_5	0.23	0.27	0.20	0.21	0.49	0.37
H_2O	—	0.41	0.10	0.28	—	0.26
CO_2	—				—	
total	100.18	100.24	99.95	99.52	99.99	100.52
Cr	—	35	120	12	144	385
Ni	—	11	81	40	82	129
Rb	18	46	32	17	63	47
Sr	640	584	501	485	633	528
Y	13	21	21	—	25	25
Zr	110	156	115	—	238	155
Nb	6	11	11	—	34	15
Ba	—	846	367	265	509	381
La	13.4	24.5	15.7	10.0	39.3	27.3
Ce	27.0	53.0	35.0	25.2	84.2	59.8
Nd	16.7	26.2	18.7	14.6	40.4	30.6
Sm	3.9	5.3	4.0	2.9	7.7	6.1
Tb	0.4	0.7	0.6	0.7	0.9	0.8
Yb	1.0	1.6	1.7	2.4	2.1	1.99
Hf	2.7	4.2	3.2	1.9	5.8	4.11
Ta	0.5	0.9	0.5	—	2.9	1.45
Th	2.6	3.5	2.5	2.0	6.8	5.33
$^{87}Sr/^{86}Sr$	0.7044	—	—	—	0.7059	—

† (1) n.v.z.; Cotopaxi, Ecuador (EF7; Francis *et al.* 1977, and unpublished data); (2) c.v.z.; La Porunita, N Chile (7988, unpublished data); (3) c.v.z.; Cerro Overo, Guataquina, N Chile (A 791, unpublished data); (4) s.v.z.; Cerro Condor, S Chile (511771; Lopez-Escobar *et al.* 1981); (5) Cerro Galan; NW Argentina (LO 13); (6) Cerro Galan; NW Argentina (LO 34).

the composite volcano Sumaco is composed of haüyne tephrite and trachyte, and is located *ca.* 50 km east of the active volcanic zone (Colony & Sinclair 1928, and unpublished data). To the east of the c.v.z., alkaline basalt occurs within an area of extensive Oligocene–Pliocene calc-alkaline volcanism at Chiar Kkollu. To the east of the s.v.z., alkaline lavas are known from composite volcanoes (for example, Payun-Matru; Llambias 1966) and from monogenetic cones and associated flows such as El Pedrero in NW Argentina, located *ca.* 100 km east of the s.v.z. (Déruelle 1979, 1982).

Mantle-normalized trace element patterns for two alkaline basalts are compared with the basalts and basaltic andesites of the n.v.z. and s.v.z. in figure 3*a*. In comparison with the calc-alkaline basaltic andesites, the alkaline basalts have similar Rb, Ba, and Th but are strongly enriched in Ta and Nb, and are also enriched in elements from La to Tb in figure 3*a*. The close spatial association of alkaline and calc-alkaline lavas in the active volcanic zone indicates a sharp local transition in either mantle melting conditions or composition or both. This is nterpreted to indicate the presence of a 'within-plate' component (see, for example, Pearce 1982, 1983), enriched in Ta, Nb, P and Ti, below and to the east of the active volcanic zone. The mantle below the active volcanic zone may therefore contain both subduction zone and within-plate components.

TABLE 2. CHEMICAL ANALYSES OF ALKALINE VOLCANIC ROCKS FROM VOLCANOES TO THE EAST OF THE ACTIVE VOLCANIC ZONES

	1†	2	3
SiO_2	62.61	43.49	47.88
TiO_2	0.24	2.34	2.36
Al_2O_3	18.86	13.43	15.06
Fe_2O_3	1.89	13.19	11.29
FeO	—	—	—
MnO	—	0.18	0.14
MgO	0.15	8.95	8.25
CaO	2.38	12.30	8.40
Na_2O	7.70	3.12	3.73
K_2O	5.95	1.42	1.87
P_2O_5	—	0.74	0.65
H_2O	—	—	—
CO_2	—	—	—
total	99.78	99.16	99.63
Cr	—	—	209
Ni	4	127	187
Rb	145	24	34
Sr	1189	871	714
Y	37	27	—
Zr	494	190	225
Nb	65	47	—
Ba	(2500)	—	399
La	180.0	47.5	35.6
Ce	285.1	96.1	71.0
Nd	79.2	49.0	—
Sm	9.6	8.8	—
Tb	(0.9)	1.1	0.8
Yb	3.9	2.0	—
Hf	8.7	4.5	5.1
Ta	3.1	3.5	3.1
Th	40.5	5.4	4.0
$^{87}Sr/^{86}Sr$	0.7040	0.7041	—

† (1) n.v.z., Sumaco, Ecuador (häuyne-bearing tephrite AW 587; Thorpe & Francis 1979, and unpublished data; (2) c.v.z., Chiar Kkollu, north of Salar de Uyuni, SW Bolivia (alkli basalt, B1); (3) s.v.z., El Pedrero, NW Argentina (alkali basalt, 19P, Déruelle 1982).

(*c*) *C.v.z. lavas* (*cf. table* 1)

The c.v.z. basaltic andesites (SiO_2 = *ca.* 54–56 %) occur as flows from composite volcanoes and also form monogenetic cones with associated flows. Mantle-normalized trace element patterns for two representative lavas, which bracket the variation of 4 samples, are shown in figure 3*b*. These c.v.z. lavas are enriched in Rb, Ba, K, La and Ce in comparison with the n.v.z. and s.v.z. lavas. Since the lavas are enriched in Rb, Ba and K in comparison with the alkaline lavas (figure 3*a*), the c.v.z. lavas may have either an additional within-plate or crustal component or both in comparison to that within the source of alkaline basalts. Mantle-normalized trace element patterns for upper and lower continental crust (Taylor & McLennan 1981) are shown in figure 3*d*. The upper crustal pattern is enriched in Rb, Ba and K relative to n.v.z., s.v.z. and alkaline lavas and may account for the enrichment of these elements in the c.v.z. lavas.

(*d*) *Cerro Galan basaltic andesites*

The Cerro Galan resurgent caldera in NW Argentina is located *ca.* 200 km to the east of the active volcanic zone, in a relative position similar to that of the alkaline lavas (Francis *et al.* 1978, 1983). Recent basaltic andesite lavas (SiO_2 = *ca.* 51–57 %) form monogenetic cones and flows to the west of the caldera. The petrological and chemical features of these lavas are described in §3. Mantle-normalized trace element patterns for the Cerro Galan basaltic andesites are compared with the n.v.z. and s.v.z. lavas in figure 3*c*. These lavas are: (i) enriched in Rb, Ba, Th, U and K in comparison with the n.v.z., s.v.z. *and* the alkaline lavas (cf. figure 3*a*); (ii) show Ta and Nb concentrations intermediate between the n.v.z. and s.v.z., and alkaline

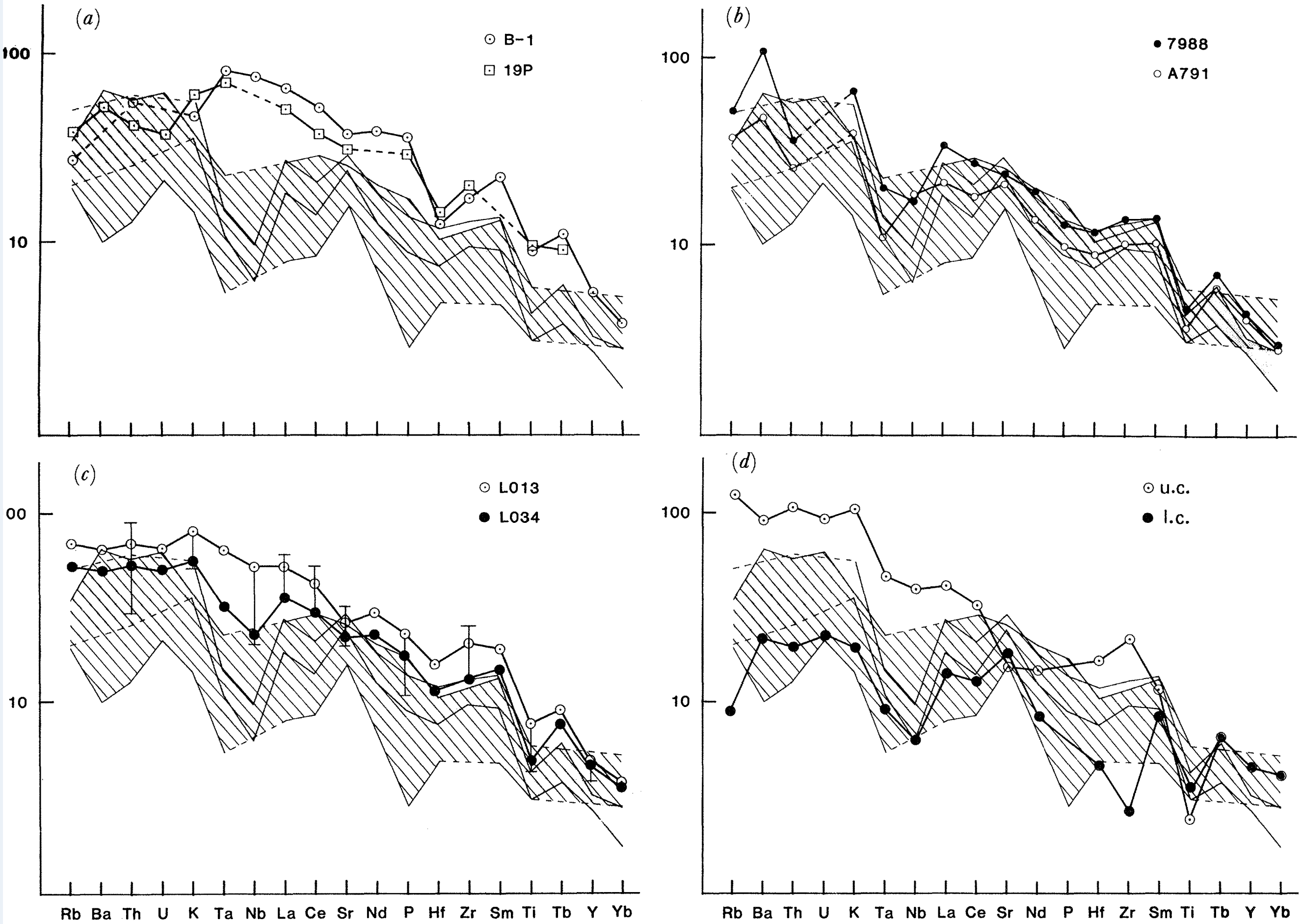


FIGURE 3. Primordial mantle-normalized, trace element patterns (Wood 1979) for Andean lavas. (*a*) Range for n.v.z. (stipple; basaltic andesites and andesites *n* = 5, SiO_2 = 56–58 %, unpublished data) and s.v.z. (basalts and basaltic andesites, *n* = 12, SiO_2 = 50–55 %, Lopez-Escobar *et al.* 1977, 1981). B-1 = alkali basalt, SW Bolivia; 19P = alkali basalt, NW Argentina (Déruelle 1979). (*b*) C.v.z. basaltic andesites (SiO_2 = *ca.* 54–56 %; unpublished data). (*c*) Cerro Galan basaltic andesites (LO13 and LO34; the vertical bars indicate the range for 12 samples (unpublished data). (*d*) Upper crust (u.c.) and lower crust (l.c.); Taylor & McLennan (1981). The stippled and lined areas in (*b*)–(*d*) correspond respectively to the n.v.z. and s.v.z. lavas described in (*a*).

lavas (cf. figure 3*a*); and (iii) have concentrations of elements from Nb to Yb generally higher than the n.v.z. and s.v.z. lavas, but similar to those in the alkaline lavas. The data are interpreted as indicating that the Cerro Galan basaltic andesites may be derived from a mantle source containing both 'subduction zone' and 'within-plate' components (cf. Pearce 1982). Further, the relatively high concentrations of Rb, Ba, Th, U and K in comparison with the n.v.z., s.v.z. and the alkaline lavas indicate the presence of either a different mantle or crustal component (figure 3*d*), the identity of which is discussed in §3.

3. COMBINED ASSIMILATION-FRACTIONAL CRYSTALLIZATION OF CERRO GALAN BASALTIC ANDESITES

The data presented here suggest that the Cerro Galan lavas are derived from a mantle source intermediate in composition between that of the n.v.z., and s.v.z., and the alkaline lavas to the east of the active volcanic zone. Although the mantle-normalized trace element patterns for the Cerro Galan lavas do not allow unequivocal identification of mantle or crustal components, we now discuss geological and petrological evidence for the occurrence of crustal assimilation combined with fractional crystallization during the evolution of the Cerro Galan basaltic andesites.

The Cerro Galan caldera (*ca.* 40 × 24 km in NW Argentina is an elliptical structure, elongated parallel to the trend of N–S faulting. The basement consists of presumed Palaeozoic and pre-Palaeozoic metamorphic rocks which include meta-igneous amphibolite, diorite and granitoid gneiss, and meta-sedimentary micaceous gneisses. These rocks form part of the 'Pampean Ranges Massif' which dates from over *ca.* 500 Ma, and was intruded by granitoids between *ca.* 475–340 Ma (Rapela & Shaw 1979; Rapela *et al.* 1982; Knüver & Miller 1982). The fault-bounded valley to the west of Cerro Galan contains monogenetic cones and associated flows of basaltic andesite composition (Francis *et al.* 1978; Hörmann *et al.* 1973). The basaltic andesites (termed lati-andesites by Hörmann *et al.* 1973) have $SiO_2 = ca.\ 51–57\%$ and $K_2O = ca.\ 2–3\%$, have normative plagioclase compositions of *ca.* $An_{37–48}$, and may therefore be classified as high-K basalts, basaltic andesites and andesites (cf. Peccerillo & Taylor 1976). They are here termed the Cerro Galan 'basaltic andesites'. The lavas have phenocrysts of olivine (Fo_{78}–Fo_{88}) and clinopyroxene (*ca.* $Ca_{42}Mg_{48}Fe_{10}$), in a glassy or microcrystalline matrix containing microphenocrysts of plagioclase (An_{55}–An_{45}), orthopyroxene (*ca.* $Ca_2Mg_{83}Fe_{15}$), clinopyroxene and Fe–Ti oxide. Many samples contain rounded xenocrysts of plagioclase and quartz showing complex reactions with the basaltic andesite lava. In addition, some cones contain ultramafic (pyroxenite) xenoliths as well as a wide range of crustal xenoliths.

The basaltic andesites contain quartz and feldspar xenocrysts and sialic xenoliths which range from microscopic size to *ca.* 10–20 cm in size. Some of these are partially fused. Microprobe analyses have been made of the melts and coexisting mineral phases in two such xenoliths. Sample LO23A is a quartz diorite containing thin veins of glass separating quartz and plagioclase (oligoclase) crystals. The melt has a composition lying to the quartz-rich side of the quartz-plagioclase cotectic surface in the quartz–albite–orthoclase–anorthite system (figure 4*a*). The second xenolith, LO23X, is a plagioclase-alkali feldspar quartz gneiss containing a highly vesiculated melt, locally segregated into rounded masses, which contains quench feldspar crystals. The alkali-rich feldspathic melt with *ca.* 6% K_2O and 4% Na_2O, coexists with plagioclase (*ca.* $Ab_{73}An_{14}Or_{13}$) and alkali feldspar (*ca.* $Ab_{34}An_1Or_{75}$), and plots close to the two-feldspar surface in the quartz–albite–orthoclase–anorthite system between the Ab–Or and Q–Ab–Or minima (figure 4*b*). Analysed whole-rock xenoliths plot close to the Q–Or–Ab minimum in the granite system. These data indicate that crustal melts with compositions near to cotectic surfaces and temperature minima within the Q–Or–Ab–An, were available in xenoliths within the Cerro Galan basaltic andesites.

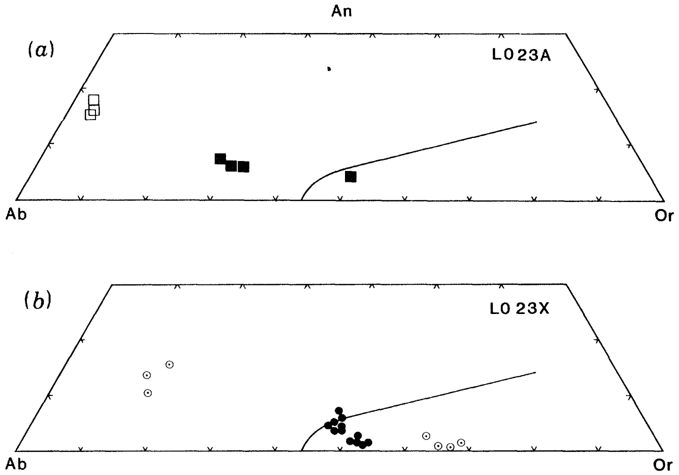


FIGURE 4. Plot of normative An–Ab–Or compositions of feldspars and glasses formed by natural fusion of xenolith samples LO23A (*a*) and LO23X (*b*) within the Cerro Galan basaltic andesites. Solid symbols refer to glass compositions and open circles refer to feldspar compositions. The compositions are compared with liquidus phase relations at 1 kbar PH_2O in the synthetic An–Ab–Or system (James & Hamilton 1969; Thompson 1981). (1 bar = 10^5 Pa.)

The role of fractional crystallization in the evolution of the Cerro Galan basaltic andesites may be evaluated by considering the behaviour of elements such as Ni and Cr which are sensitive to olivine and pyroxene fractionation but which are relatively insensitive to mantle heterogeneity (cf. Pearce 1982, figure 3). The basaltic andesites are characterized by substantial variations in Cr and Ni (*ca.* 140–420 μg/g and *ca.* 80–180 μg/g respectively) accompanied by relatively small variation in Y (20–27 μg/g). A possible model would involve derivation of the basaltic andesites from parental magmas derived by 10–20 % partial fusion of mantle, containing Cr = 2500 μg/g, Y = 4.87 μg/g (Pearce 1982) and Ni = 1500 μg/g followed by up to *ca.* 20 % fractional crystallization of olivine and clinopyroxene phenocrysts before eruption.

Figure 5 is a plot of $^{87}Sr/^{86}Sr$ against Rb/Sr for the Cerro Galan basaltic andesites. The lavas have $^{87}Sr/^{86}Sr$ of *ca.* 0.705–0.708 which pass into andesites and dacites with $^{87}Sr/^{86}Sr$ = *ca.* 0.708–0.711. Basement rocks from the Pampean Ranges Massif (Rapela *et al.* 1982; Knüver & Miller 1982) and xenoliths with the lavas (unpublished data) have $^{87}Sr/^{86}Sr$ = *ca.* 0.71–0.80. The data are in close agreement with a model of combined assimilation-fractional crystallization (a.f.c.) (cf. DePaolo 1981) and are interpreted in terms of increasing crustal assimilation during fractional crystallization (see discussion that follows). The basaltic andesites are therefore considered to contain a crustal component (cf. §2*d*) acquired through assimilation accompanying fractional crystallization.

It is clear that the Cerro Galan basaltic andesites show evidence for fractional crystallization combined with crustal assimilation–contamination. From thermal arguments these processes are likely to have occurred concurrently (Taylor 1980; DePaolo 1981). Although assimilation fractional crystallization (a.f.c.) processes have affected the range of basaltic andesites studied, the most basic lavas show petrological evidence of assimilation of crustal materials (e.g. xenocryts of quartz and plagioclase) and are unlikely on chemical grounds to represent primary magmas. The parental magmas of the basaltic andesites may be silica-saturated olivine

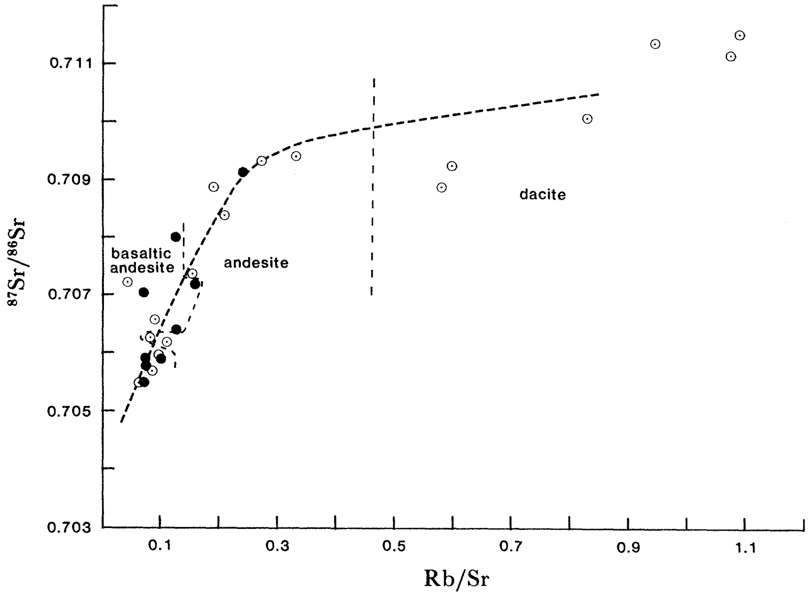


FIGURE 5. Plot of $^{87}Sr/^{86}Sr$ against Rb/Sr for Cerro Galan lavas (basaltic andesites, andesites and dacites). Solid circles are unpublished data and open circles are published data from Klerkx *et al.* (1977), 2 analyses and Francis *et al.* (1979), 17 analyses. The heavy broken line is a possible evolutionary path for a magma experiencing a.f.c. during rise through the continental crust (DePaolo 1981, figure 1).

tholeiites or silica-undersaturated basalts which have penetrated the diopside-olivine (olivine gabbro) thermal divide by assimilation of siliceous crustal material (cf. O'Hara 1968). Such magmas would be more primitive and less contaminated than the most basic basaltic andesites and would be expected to yield high $^{87}Sr/^{86}Sr$ andesites and dacite by more advanced a.f.c. processes.

4. RELATIVE ROLES OF PARTIAL MELTING AND A.F.C. IN EVOLUTION OF ANDEAN ANDESITES

We have argued that the Andean volcanic rocks are derived from varied mantle sources and locally contain a crustal component added during a.f.c. processes. We now use chemical variation diagrams to resolve the relative contributions of these mantle and crustal sources and the role of the a.f.c. processes. Figure 6*a* is a plot of TiO_2 against Zr which indicates that (i) the n.v.z., c.v.z. and s.v.z. lavas plot within the field of volcanic arc lavas, with the lower Zr contents of the s.v.z. being consistent with petrogenesis by a higher degree of partial melting or fractional crystallization from a more primitive mantle source in comparison with the c.v.z. and n.v.z. lavas; (ii) the alkaline lavas (B-1 and 19P) plot within the within-plate field; and (iii) the Cerro Galan lavas plot largely within the within-plate field and show a positive correlation of TiO_2 with Zr consistent with fractional crystallization dominated by plagioclase ± olivine ± pyroxene (cf. § 2: Pearce & Norry 1979).

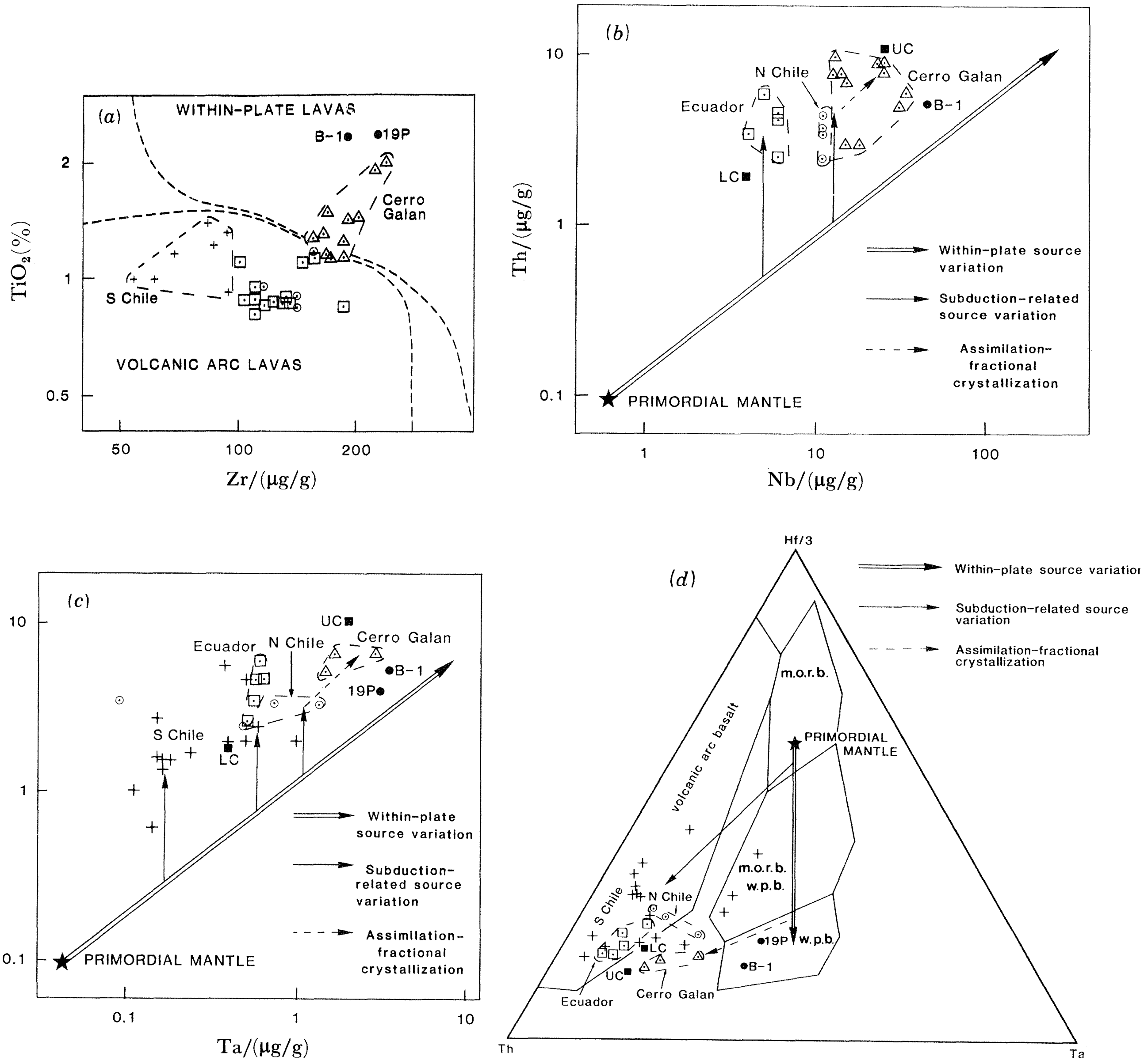


FIGURE 6. Chemical variation diagrams and possible petrogenetic schemes for Andean lavas. (*a*) TiO_2–Zr showing fields of volcanic arc and within-plate lavas (cf. Pearce 1980). (*b*) Th–Nb. (*c*) Th–Ta. (*d*) Hf/3–Th–Ta (cf. Wood *et al.* 1979). +, s.v.z. lavas (S Chile); □, n.v.z. lavas (Ecuador); ○, c.v.z. lavas (N Chile); △, Cerro Galan lavas; ●, alkaline lavas (B–1 and 19P); ■ UC, upper crust; ■ LC, lower crust (crustal data from Taylor & McLennan 1981).

Figure 6*b* and *c* are plots of Th against Nb and Ta. Although all of these elements are enriched in within-plate lavas, Th is enriched in the mantle by the subduction process, so that Th/Ta and Th/Nb are high in the source of volcanic arc lavas (Wood *et al.* 1979; Pearce 1982). The data plotted in figure 6*b* and *c* are not normalized to an element such as Yb that is supposedly unaffected by processes responsible for mantle heterogeneity, because such elements may be compatible with mantle phases such as garnet or amphibole in the mantle source region of some of the volcanic suites plotted in figure 6 (cf. Pearce 1982).

Figure 6*b* and *c* show possible petrogenetic schemes for derivation of the basaltic andesite lavas of the active Andean volcanic zones from the mantle (Wood 1979; Pearce 1982). The alkaline lavas (B-1 and 19P) are from a mantle source highly enriched in Th, Ta and Nb relative to primordial mantle and similar to the source of within-plate alkali basalts (cf. Wood 1979). The s.v.z. lavas (S Chile) require some source enrichment relative to primordial mantle before, or after, introduction of a subduction-zone component enriched in Th relative to Nb and Ta. Similarly the n.v.z. lavas (Ecuador) are from a more enriched mantle source in comparison with the s.v.z. lavas. The chemical characteristics of Cerro Galan lavas are consistent with derivation from a mantle source intermediate between the s.v.z.–n.v.z. and alkaline lavas and the scatter towards upper crustal rocks reflects a.f.c. within the crust rather than mantle heterogeneity. The c.v.z. lavas (N. Chile) plot between the n.v.z.–s.v.z. and Cerro Galan lavas on figure 6*b* and *c* and may therefore result from a.f.c. of basaltic lavas from a similar mantle source to the n.v.z.–s.v.z. lavas, or a.f.c. of such lavas within the upper crust.

The relative proportions of Ta, Hf and Th are compared for the Andean lavas in figure 6*d* (cf. Wood *et al.* 1979). The alkaline lavas plot within the w.p.b. field, consistent with derivation from a mantle source enriched in Th and Ta relative to primordial mantle. The s.v.z. lavas may be derived from mantle with a composition between that of primoridal mantle and mantle that is somewhat enriched in Ta and Th, and the n.v.z. lavas are from a mantle source more enriched in these elements. The Cerro Galan lavas plot between the volcanic arc and w.p.b. fields (cf. figure 6*a*) and approach the upper crustal composition, reflecting a.f.c. processes as argued earlier. Finally, the c.v.z. basaltic andesites (N Chile) plot in an ambiguous position between volcanic arc and w.p.b. basalt fields. This might indicate mantle derivation with or without crustal contamination. However, the association of these c.v.z. lavas with volcanic arc fields in figure 6*a* and *d* is considered more consistent with derivation from a mantle source containing subduction-related components rather than a mantle source containing within-plate components, as argued from the earlier consideration of elemental patterns.

5. Correlation of isotopic and elemental characteristics

Sr isotope data for Andean volcanic rocks have been reported by Noble *et al.* (1975), James *et al.* (1976), Francis *et al.* (1977, 1980), Klerkx *et al.* (1977) and Déruelle *et al.* (1983), and Nd and Sr data have been reported by Hawkesworth *et al.* (1979, 1982) and James (1982*a*, *b*). Oxygen isotope data have been reported by Thorpe *et al.* (1981), Harmon *et al.* (1981) and Déruelle *et al.* (1983) and Pb isotope data have been reported by Tilton & Barreiro (1980). These isotopic data have been summarized by James (1982*a*, *b*) and Hawkesworth (1982) (see figure 7). The n.v.z. and s.v.z. lavas show a relatively small range in Sr, Nd, O, Pb isotope composition generally interpreted in terms of petrogenesis by fractional crystallization of mantle-derived parent magmas with little or no crustal contamination (Déruelle *et al.* 1983; James 1982*b*; and earlier discussion).

By contrast, the c.v.z. lavas are characterized by much more varied isotope compositions with higher $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ ratios, lower $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios. These data have been used to argue that c.v.z. lavas have originated from 'enriched' mantle (Hawkesworth *et al.* 1979), crustal anatexis (Pichler & Zeil 1972; Klerkx *et al.* 1977; Hawkesworth *et al.* 1982) and bulk or 'selective' crustal contamination of mantle-derived magmas (Francis *et al.* 1977, 1980; Briqueu & Lancelot 1979; Thorpe *et al.* 1981; Harmon *et al.* 1981; James 1982*a*).

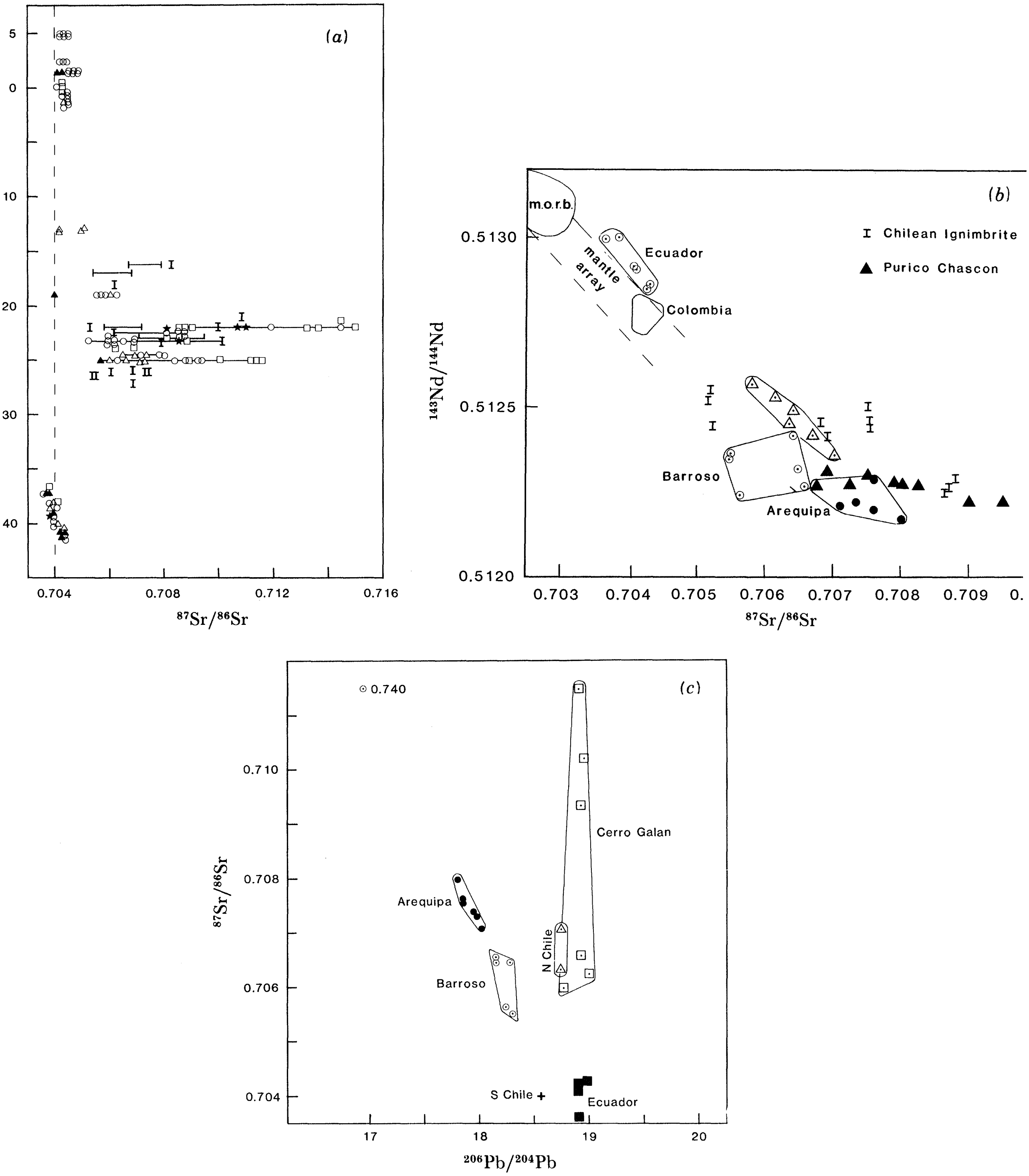


FIGURE 7. (*a*) Plot of $^{87}Sr/^{86}Sr$ against latitude for Andean lavas. Key: ▲, basalt; ○, andesite; □, dacite; ★, rhyolite lavas; I, ignimbrite (data from Noble *et al.* 1975; James *et al.* 1976; Francis *et al.* 1977, 1980; Hawkesworth *et al.* 1982; James 1982*a*, *b*; Déruelle *et al.* 1983; and unpublished data). (*b*) Plot of $^{143}Nd/^{144}Nd$ against $^{87}Sr/^{86}Sr$ for Andean lavas (data from Hawkesworth *et al.* 1979; James 1982*a*, *b*; Hawkesworth *et al.* 1982). (*c*) Plot of $^{87}Sr/^{86}Sr$ against $^{206}Pb/^{204}Pb$ for Andean lavas (data from Barreiro 1981; Tilton & Barreiro 1980). The open circle ($^{87}Sr/^{86}Sr = 0.740$) is for the Charcani gneiss (James 1982*a*).

The isotope characteristics are generally taken to indicate involvement of crustal materials with high Rb/Sr, low U/Pb and Sm/Nd and with a high $^{18}O/^{16}O$ ratio, and this corresponds to the isotope characteristics of gneisses exposed in S Peru (Shackleton *et al.* 1979; James 1982*a*). By contrast, the Cerro Galan lavas have higher $^{87}Sr/^{86}Sr$ (greater than 0.7055) higher $^{18}O/^{16}O$ ratios ($\delta^{18}O > 8.4‰$) to those of the c.v.z. lavas, and also higher $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios than the n.v.z. lavas, consistent with incorporation of late Precambrian rocks with high Rb/Sr and U/Pb (figure 7*c*). The Sr isotope characteristics correspond to the analysed basement around Cerro Galan (Rapela *et al.* 1982). This confirms the model for crustal contamination of Cerro Galan basaltic andesite magmas presented in §3.

Despite the agreement that crustal materials must be involved in the petrogenesis of some c.v.z. lavas there is no agreement on the mechanism involved. This may be accomplished by assimilation of crustal materials into either mantle-derived magmas or crustal anatexis. The Sr isotope data summarized in figure 7*a* shows that the n.v.z. and s.v.z. lavas are relatively uniform with $^{87}Sr/^{86}Sr$ ratios of *ca.* 0.704 ± 0.0005. Although this is interpreted in terms of an origin from mantle-derived parental magmas with little or no crustal contamination (cf. references above) it is important to note that the correlation of $^{87}Sr/^{86}Sr$ ratios (*ca.* 0.7035–0.7045) with $\delta^{18}O$ values (*ca.* +6.5 to +8.0‰) in Colombian basaltic andesites and andesites has been interpreted in terms of a small degree of crustal contamination (James 1982*b*).

By contrast the c.v.z. and Cerro Galan lavas, with a few exceptions (Bolivian alkali basalt, B-1, and 'low-silica latites'; Noble *et al.* 1975), have $^{87}Sr/^{86}Sr$ ratios exceeding *ca.* 0.705 and show large variations between *ca.* 0.705–0.715 (cf. Déruelle *et al.* 1983). The Sr and Nd isotope variations summarized in a plot of $^{143}Nd/^{144}Nd$ against $^{87}Sr/^{86}Sr$ (figure 7*b*) shows that the lavas fall into three groups: (i) n.v.z. (Ecuador), which is enriched in $^{87}Sr/^{86}Sr$ relative to the mantle array; (ii) the n.v.z. (Colombia) lavas which plot within the mantle array; and (iii) the c.v.z. lavas which plot at the high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ end of the mantle array.

These Sr and Nd isotope data may be used to comment on the models proposed on the basis of the elemental data discussed earlier. The Sr and Nd isotopic relations for n.v.z. (Ecuador) lavas are consistent with a derivation from mantle enriched in radiogenic Sr derived from the subducted slab. The n.v.z. (Colombia) lavas may be derived from a similar source but with minor contamination by continental crust with a low $^{143}Nd/^{144}Nd$ ratio which causes the magma to move into the 'mantle array' on figure 7*b*. The higher $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios of the c.v.z. lavas have been interpreted in terms of petrogenesis by crustal contamination of either mantle-derived magmas or crustal anatexis (see Hawkesworth 1982). For example, although none of the c.v.z. volcanic suites shown in figure 7 show good correlations of $^{87}Sr/^{86}Sr$ or $^{143}Nd/^{144}Nd$ with respectively Rb/Sr or Sm/Nd, or SiO_2, Hawkesworth *et al.* (1982) argued that the San Pedro lavas ($^{87}Sr/^{86}Sr$ = *ca.* 0.706–0.707) are mantle-derived, while the Cerro Purico lavas ($^{87}Sr/^{86}Sr$ = 0.707–0.709) are derived by crustal anatexis.

The correlation of Sr isotope composition and trace element characteristics may be summarized by a plot of $^{87}Sr/^{86}Sr$ ratio against an index of fractional crystallization such as Rb/Sr ratio. For the c.v.z., the Sr isotope ratios often show poor correlation with major and trace element chemical characteristics. (Francis *et al.* 1977; Hawkesworth 1982; Hawkesworth *et al.* 1982). Chemical variations during assimilation and fractional crystallization have been described by Taylor (1980) and DePaolo (1981). DePaolo (1981) has shown that basaltic magma rising through the crust will initially experience a balance between assimilation rate, M_a and crystallization rate, M_c, while the crystallizing mineral phases (olivine and pyroxenes)

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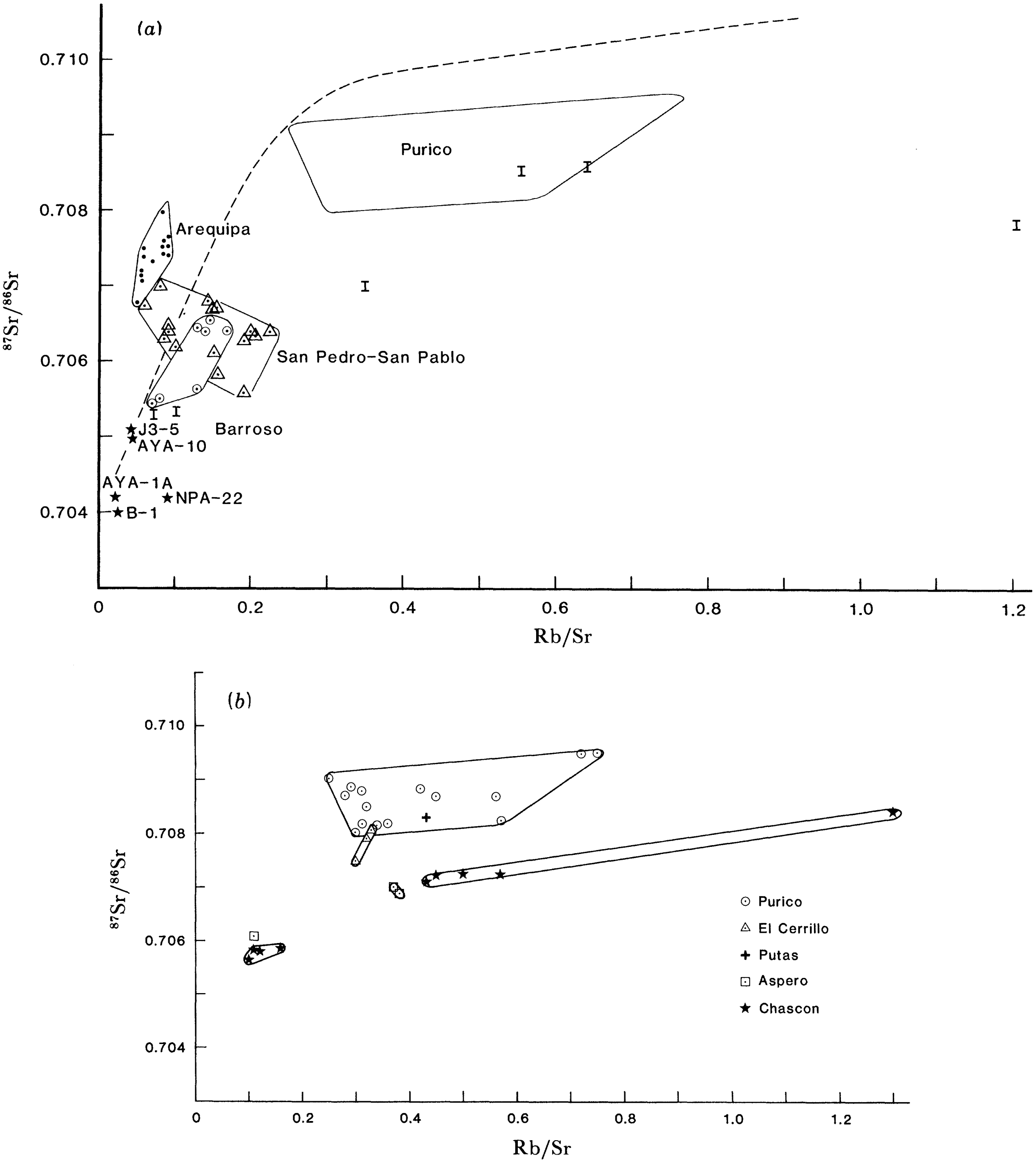

FIGURE 8. (*a*) Plot of ^{87}Sr/^{86}Sr against Rb/Sr for c.v.z. lava suites (andesites, dacites and rhyolites). (Sources of data: Noble *et al.* 1975; Francis *et al.* 1977; Thorpe *et al.* 1979; Hawkesworth *et al.* 1982; James 1982, unpublished data.) (*b*) Plot of ^{87}Sr/^{86}Sr against Rb/Sr for Cerro Purico-Chascon lavas from the c.v.z. (Hawkesworth *et al.* 1982). The heavy broken line on (*a*) and (*b*) is a possible evolutionary path for a magma experiencing a.f.c. during rise through the continental crust (DePaolo 1981, figure 4).

have D^{Sr} below 1. Higher in the crust the ratio of M_a/M_c will decrease and plagioclase (D^{Sr} over 1) may be crystallized. The variation of ^{87}Sr/^{86}Sr with Rb/Sr during such a combined a.f.c. process is shown in figure 5*a*. This shows an initial rapid increase of ^{87}Sr/^{86}Sr with Rb/Sr followed by more constant ^{87}Sr/^{86}Sr to higher values of Rb/Sr, and it should be emphasized that if only the evolved part (high ^{87}Sr/^{86}Sr–high Rb/Sr) of the trend is sampled, it may be very difficult to deduce anything about the properties of the magma source or assimilated rock.

Figure 8 compares the variation in c.v.z. lava groups with the a.f.c. model described. In §3 we described evidence that the chemical variations in Cerro Galan basaltic andesites are explicable on such a model. In §2 we argued that the c.v.z. basaltic andesites have a component enriched in Rb, Ba, K, La and Ce in comparison with mantle-derived n.v.z. and s.v.z. lavas. These lavas have major and trace element compositions that indicate that they are derived by fractional crystallization of more primitive magmas, and have $^{87}Sr/^{86}Sr \approx 0.705$–$0.706$. They may therefore be derived from either (i) a mantle source with subduction-zone components and alkaline components both different in trace element composition and enriched in $^{87}Sr/^{86}Sr$ in comparison with the alkaline mantle component in the source of Andean alkaline basalts (and Cerro Galan basalts), or from (ii) a mantle source like that of the n.v.z. and s.v.z. lavas in which primitive magma has experienced crustal contamination. Noting (*a*) the evidence of a.f.c. at Cerro Galan, (*b*) that the continental crust below the c.v.z. is more ancient and thicker than below the n.v.z. and s.v.z. (figure 1), and (*c*) some c.v.z. basaltic andesites (e.g. A791; table 1) contain partially fused xenoliths of Tertiary dacite, we tentatively suggest that these c.v.z. lavas contain a crustal component.

Figure 8*a* shows the variation in c.v.z. lava groups in comparison with the a.f.c. model described. The less-evolved c.v.z. lava groups show a good positive correlation of $^{87}Sr/^{86}Sr$ with Rb/Sr while the move evolved groups have higher $^{87}Sr/^{86}Sr$ ratios which show a poor correlation with Rb/Sr (or other indices of fractional crystallization). This is consistent with petrogenesis by a.f.c. of mantle-derived basic magma. Therefore it cannot be assumed that high $^{87}Sr/^{86}Sr$ (over *ca.* 0.706) andesite and dacite associations such as Purico-Chascon which show a poor correlation of $^{87}Sr/^{86}Sr$ with fractionation (figure 8*b*) have trace element or isotope characteristics of their source region (Hawkesworth 1982; Hawkesworth *et al.* 1982). Rather, the parental magmas of the associations plotted on figure 8 are likely to include the basaltic andesites and andesites described. On geochemical grounds (§2 and above) these may be derived by a.f.c. of more primitive basalt magma (cf. §3). Finally, some of the Chascon lavas (Aspero and Putas) show field and petrographic evidence for incomplete magma mixing and this is reflected in the distinctive linear variation shown by these lavas in figure 8*b*.

6. Summary

Active Andean volcanoes of the calc-alkaline basalt–andesite–dacite rhyolite association occur within a northern (n.v.z.), central (c.v.z.) and southern volcanic zone (s.v.z.) (figure 9). Alkaline volcanic rocks occur within and to the east of these zones. The n.v.z. and s.v.z. lavas have chemical and isotope characteristics consistent with an origin by fractional crystallization of magmas derived from mantle containing subduction zone-derived components. By contrast, the alkaline lavas result from partial melting and fractional crystallization of magmas derived from mantle enriched in within-plate components. The c.v.z. lavas contain either a distinctive mantle-derived or a continental crustal component.

The relative roles of mantle heterogeneity and crustal contamination have been evaluated by study of recent basaltic andesite lavas from the Cerro Galan area of NW Argentina (southeast of the c.v.z.). The chemical characteristics of these lavas indicate derivation from mantle with chemical characteristics intermediate between the source of the n.v.z.–s.v.z. and alkaline lavas. The basaltic andesite lavas show abundant petrologic, chemical and isotopic evidence for occurrence of crustal contamination (assimilation) combined with fractional crystallization (a.f.c.). We propose that these lavas evolved from parental olivine tholeiite magma which experienced contamination by varied crustal anatectic melts allied with fractional crystallization of olivine and pyroxene during uprise–storage within the continental crust.

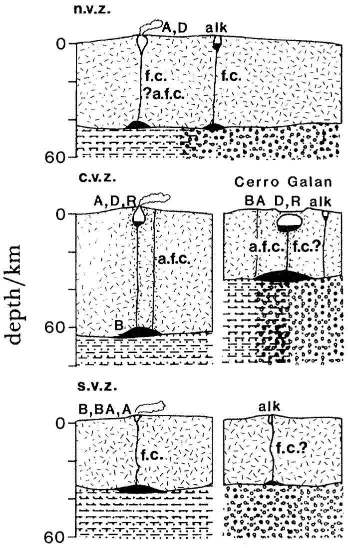

Figure 9. Summary of sources and processes involved in petrogenesis of lavas from the active n.v.z., c.v.z. and s.v.z. of the Andes. Rock types are indicated as B, basalt; BA, basaltic andesite; A, andesite; D, dacite, and R, rhyolite. The processes are f.c.: fractional crystallization and a.f.c.: combined assimilation-fractional crystallization. Subduction zone-derived mantle components have a horizontal ornament and within-plate mantle components have a circular ornament (see text for discussion).

The combined effects of contamination and fractional crystallization upon basaltic magma rising through continental crust may obscure the chemical and isotope characteristics of the parental magmas of c.v.z. and Cerro Galan basaltic andesites. However, noting that none of the analysed lavas is unfractionated and the most basic Cerro Galan lavas show evidence of crustal contamination, we tentatively suggest that the parental magmas are silica-saturated basaltic magmas with isotopic characteristics intermediate between those of the most primitive c.v.z.–Cerro Galan basaltic andesites and the n.v.z.–s.v.z. alkaline lavas. The more evolved c.v.z.–Cerro Galan andesites–dacites and rhyolites (ignimbrites) result from complex a.f.c. and magma mixing processes within the continental crust.

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Discussion

R. Hutchison (*Mineralogy Department, British Museum (Natural History), Cromwell Road, London SW7 5BD, U.K.*). It is unfortunate that the authors normalize their data to 'primordial mantle', the composition of which is unknown and model dependent. Some directly measurable standard such as chondrite or m.o.r.b. should be used.

R. S. Thorpe. The choice of normalization values does not affect the arguments presented in the paper. The elemental abundances in primordial mantle (Wood 1979) are generally 1.5–2.5 of those in the chondritic meteorites. Such primordial mantle values may be used to determine the magnitude of element fractionations involved in production of a given magma from 'undepleted' mantle (see, for example, Wood 1979; Pearce 1982). It is widely agreed that the Earth does not have chondritic values of all elements (e.g. Rb, K) and that mid-ocean ridge basalts (m.o.r.b.) are derived from a mantle reservoir depleted in certain lithophile elements in comparison with a chondritic Earth (e.g. Rb relative to Sr, Nd relative to Sm). Normalization to a 'primordial mantle' is therefore preferable to the use of either chondritic or m.o.r.b. compositions.

J. S. Turner (*Research School of Earth Sciences, Australian National University*). A previous contributor to the discussion has referred to the 'megahypotheses' used by several geochemical speakers. I should like to make a general cautionary comment from the point of view of a fluid dynamicist. It seems to me that there are major unsolved problems in this field that are dynamical ones: what exactly are the forces and mechanisms that move material through the Earth's mantle and crust? Too little is known at present to support any of the elaborate conceptual 'models' that have been proposed. An understanding of the dynamics is usually best achieved by addressing one well defined question at a time, and not expecting to solve the whole complex problem in one step.

Dr Sparks has described some of the laboratory experiments using aqueous solutions which we have used as analogues of certain processes in liquid magmas. It should be clearly understood, however, that such comparisons are valid only because both systems are fluids, and the phenomena of interest can be appropriately scaled. The results cannot immediately be applied in very different circumstances; for example partial melts, and solid state creep processes, will need to be treated separately when they are relevant to mantle convection phenomena.