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EVOLUTION OF LINEAR VOLCANIC RANGES IN MARIE BYRD LAND, WEST ANTARCTICA

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Abstract. The Marie Byrd Land volcanic province consists of a regionally extensive foundation of subhorizontal alkaline basaltic rocks, surmounted by 18 shield volcanoes of predominantly trachytic and other felsic compositions. Eleven of the felsic volcanoes occur in three N-S and E-W oriented chains. In each of these, chronologic data and morphology suggest systematic migrations of felsic activity along linear paths 90-154 km long. Basaltic rocks show no migration patterns, although they are the most abundant and widespread rocks in the province. Plate motion is a very unlikely cause for the migrations of felsic activity because of the opposing and orthogonal directions of contemporaneous migration and because geophysical evidence indicates that the Antarctic plate has remained stationary in late Cenozoic time. Fracture propagation is a more likely mechanism, but wedging by forcible injection of magma is difficult to reconcile with an apparent lack of mixing between closely adjacent magma reservoirs. The pronounced space-time patterns of felsic volcanism coupled with the lack of pattern in mafic activity suggest a more complex process. We propose a twostage mechanism in which the rise of mafic magma from the mantle is random in space and time, but passage through the crust has been controlled by a relict system of N-S and E-W fractures that have been systematically reactivated by crustal doming.

Introduction

The recognition and interpretation of spatial and chronologic patterns of volcanism are critical to understanding the tectonic environment and petrologic evolution of a volcanic province. Several such patterns have been recognized in the late Cenozoic alkaline province of Marie Byrd Land (Figure 1). In each case the geometry and timing of pattern development and the strongly alkalic nature of volcanism suggest a close relationship to the West Antarctic rift system [LeMasurier, 1978; Cooper et al., 1982; LeMasurier and Rex, 1982, 1983; Futa and LeMasurier, 1983] and provide a path to understanding the cause of rifting in this environment.

The most conspicuous patterns are found in linear volcanic chains, which are the main focus of this paper. Doumani [1964] first described the Executive Committee Range (ECR) volcanic chain, and proposed a southward younging of activity based on morphologic criteria. Subsequently the Flood Range (FR), Ames Range (AR), Crary Mountains, and Toney Mountain were described in reconnaissance [Gonzalez-Ferran and Gonzalez-Bonorino, 1972; LeMasurier, 1972], but no patterns of activity were clear from the available radiometric ages. This paper follows more extensive field work and K-Ar age determination. We report on spatial and chronologic patterns over the entire province, with more detailed descriptions of the contemporaneous migrations of activity in the ECR, FR, and AR. The latter are unusual in that they have taken place in opposing directions, they have involved only felsic and intermediate rocks and not the more abundant basalts, no evolutionary sequence is repeated during the migrations (as in Hawaiian volcanoes), and abrupt changes in composition from one volcano to the next are commonplace. The rates of migration are all around 1 cm/yr.

Perhaps the most unusual characteristic of the Marie Byrd Land (MBL) patterns is that they developed on a stationary plate. Seafloor spreading and paleomagnetic data provide no evidence for Antarctic plate motion during the period of felsic activity (18.6 Ma to present), and some studies indicate no motion in the past 80 m.y. [Herron and Tucholke, 1975; Weissel et al., 1977; Barron and Harrison, 1979; Grindley and Oliver, 1983; Stock and Molnar, 1987]. Duncan's [1981] analysis of the global hotspot framework suggests that the Antarctic plate is "barely moving," but the data presented below suggest that the plate has been completely immobile for the past 25-30 m.y., with respect to the hotspot defined by MBL volcanism. The dominant tectonic factor associated with volcanism during this time has been intraplate block faulting, resulting in a structural relief of about 5000 m, accompanied by extension and crustal thinning [LeMasurier and Rex, 1982, 1983]. This environment provides an opportunity to study a mechanism that is apparently independent of plate motion and is able to produce linear volcanic chains and migrations of activity that mimic hotspot traces. It is likely that this mechanism has operated elsewhere, in environments where plate motion is an important factor. We hope that the example presented here will help clarify the respective roles of plate motion and intraplate tectonics in those cases.

Tectonic, Stratigraphic and Spatial Relationships

The Marie Byrd Land province lies on the north flank of the West Antarctic rift system (Figure 1). We describe it as a rift system because it is underlain by 25 km of continental crust [Bentley et al., 1960]; others have represented this region

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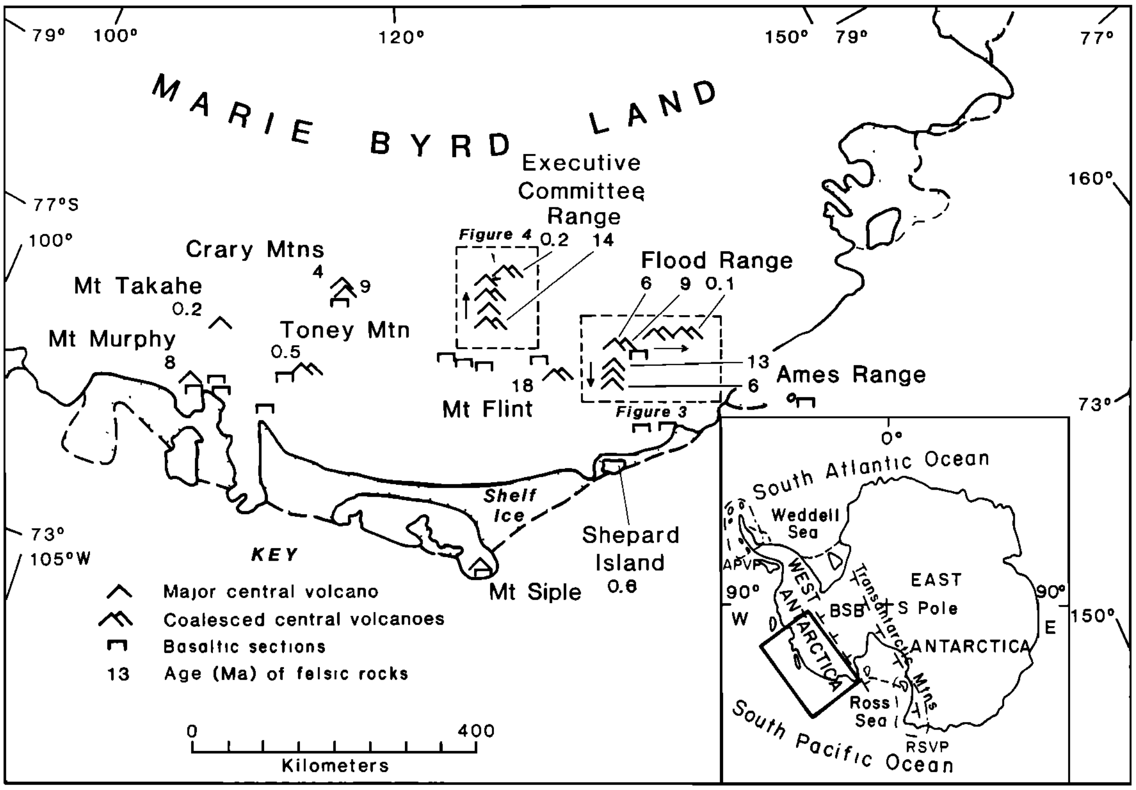

Fig. 1. Index map of the Marie Byrd Land volcanic province. Hachures on inset figure show the inferred position of the West Antarctic rift system, and flanking positions of the MBL volcanic province (box) and Ross Sea volcanic provinces (RSVP). Bedrock lies 1000-2500 m below sea level over a large area of the Byrd Subglacial Basin (BSB), which lies along the rift axis. On the large-scale map, selected ages of felsic rocks are shown for reference, and arrows indicate directions of younging for the Executive Committee Range, Ames Range, and Flood Range. Note youngest ages at the periphery of the province. See text for discussion.

as a plate boundary [e.g., Herron and Tucholke, 1975; Duncan, 1981; Grindley and Oliver, 1983]. Over the past 25-30 m.y., much of the volcanic and tectonic activity on the Antarctic continent has occurred along the flanks of this rift (Cooper and Davey, 1985).

Basement rocks in MBL are exposed mainly in fault block ranges near the coast, where the ice sheet surface descends to within a few hundred meters above sea level. The basement is dominated by two suites of granitic rock, late Cretaceous and Devonian in age, that intrude highly deformed Paleozoic metaclastic rocks. It is an old and complex magmatic arc terrain with close geological affinities to the New Zealand continental block [Cooper et al., 1982]. Basement cored ranges are all truncated by a single, very flat, early Cenozoic erosion surface of regional extent [LeMasurier and Rex, 1983]. The late Cenozoic volcanic suite rests on this surface and both have been displaced to a variety of different elevations by block faulting [LeMasurier and Rex, 1982, 1983]. The Cenozoic volcanic rocks consist predominantly of basanite, tephrite, basalt, and hawaiite (hereafter referred to as basaltic rocks), with subordinate amounts of mugearite, benmoreite, peralkaline trachyte, phonolite, pantellerite and comendite (classification follows LeBas et al. [1986]). Basaltic rocks rest on the basement wherever the base of the volcanic section is exposed and occur mainly as subhorizontally stratified lava flows, hydroclastic deposits and Strombolian tephra. The two thickest exposed sections are 1800 m and 1000 m, underlying the felsic rocks at Mount Murphy and the Crary Mountains, respectively (Figure 1). However, a single seismic traverse suggests a subglacial thickness of 5000 m for the basaltic section that underlies felsic rocks at Toney Mountain [Bentley and Clough, 1972; LeMasurier and Rex, 1982]. It appears that the greatest thicknesses of mafic rocks occur beneath felsic shield volcanoes. The ages of the basaltic sections vary from place to place, as shown in Figure 2.

The felsic (trachyte, phonolite, pantellerite, comendite) and intermediate (benmoreite, mugearite) rocks have been found almost exclusively in shield volcanoes that either comprise the summit section, or the entire exposed portion, of the 18 large central volcanoes shown in Figure 1. Felsic rocks overlie basaltic sections at Toney Mountain, the Crary Mountains, Mount Bursey (Flood Range), and the uppermost part of Mount Murphy (Figure 1). At Mount Siple, a basaltic section is exposed near sea level, but the upper part of the volcano, where felsic rocks are likely to occur, has never been visited. Occurrences of felsic rock outside of the

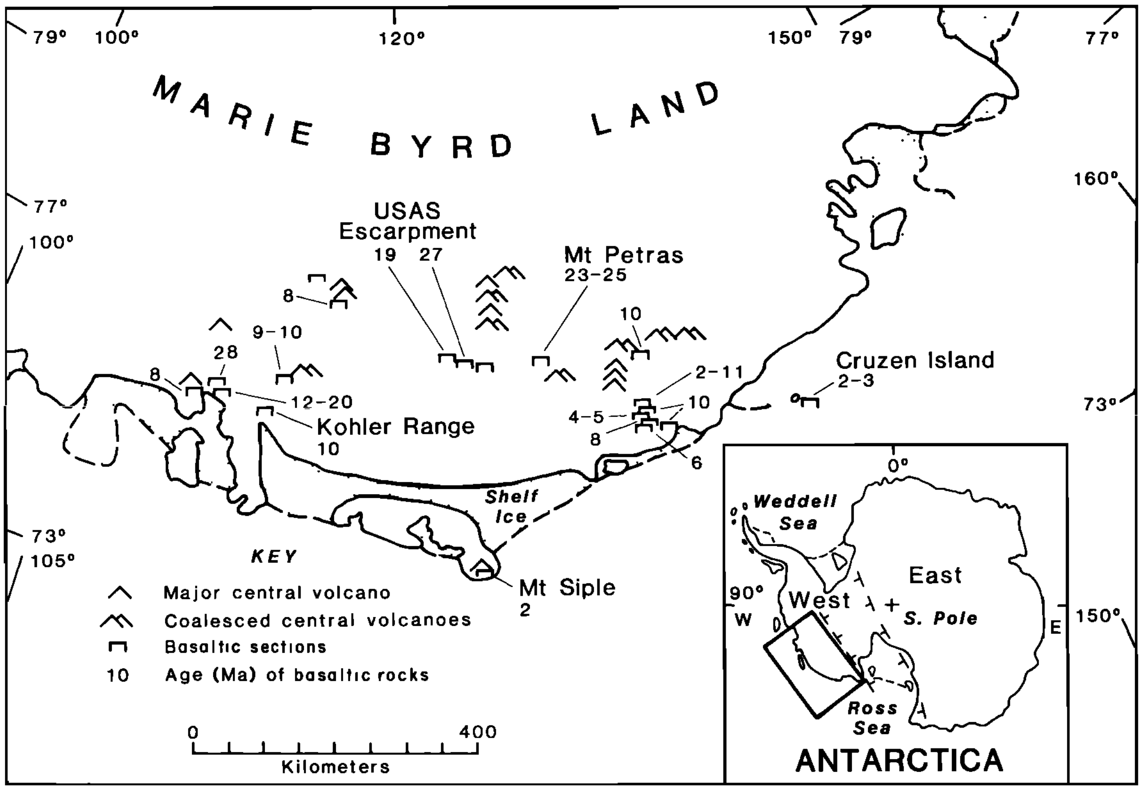

Fig. 2. Index map showing locations and K-Ar ages of basaltic sections. Locations of central volcanoes, which are predominantly felsic, are shown for reference.

shield volcanoes are limited to a small center at Shepard Island, and a single trachyte flow resting on basement rock 80 km southwest of Shepard Island. These field relationships suggest that volcanism was initially basaltic at nearly all localities and was followed by felsic volcanism in a more restricted number of centers. Basanite and hawaiite volcanism commonly recurred at a late stage, in small parasitic cones, sometimes following the end of felsic activity by as much as 5-10 m.y. These are not included in Figure 2. The only occurrences of ultramafic nodules found in MBL are in these small cones.

The spacings between calderas in the ECR, and to a lesser extent the AR and FR, are systematic (Figures 3 and 4). In the ECR, Mount Hampton, Mount Hartigan, and Mount Waesche are each paired volcanoes in which the distance between caldera centers is 6-7 km. The distances along the range from one caldera center to another are 18-20 km. Spacings between calderas in the AR and FR are similar in scale to those in the ECR, but less systematic. In conjunction with the chemical data summarized below, these spacings help constrain the sizes of magma chambers.

Fault control of volcanism is suggested by the preferential alignments of most central volcanoes in N-S and E-W chains (Figures 3 and 4). Block faulting is also suggested by conspicuous N-S and E-W scarps along the flanks of basement-cored mountain blocks [LeMasurier and Rex, 1983]. The erosion surface that truncates the summits of these ranges occurs at different levels in each, ranging from 600 to 2700 m above sea level, presumably as a result of fault displacement. The systematic increase in age with increasing elevation, of the basaltic rocks on these surfaces, suggests a close relationship between volcanic activity and fault displacement [LeMasurier and Rex, 1983].

Chronologic Data

K-Ar Procedures

Whole rock samples were crushed and sieved, and the -265 +180 μm fraction was then washed and dried. This fraction was used for both potassium and argon determinations (with very small rock samples a -530 +132 μm size fraction was used). Potassium was determined in triplicate, using a Corning-eel 450 flame photometer with Lithium internal standard.

Argon was extracted in a glass vacuum system using ^{40}Ar tracer from an aliquoting system. Special attention was given to the purity of the gas sample before analysis. A two stage clean up procedure was used, stage one incorporating a Ti-sponge furnace and a liquid nitrogen trap. The purified gases were then drawn into a second clean up section, on activated charcoal containing a Ti/Zr sponge furnace. A small aliquot of the gas was then tested on the mass spectrometer for purity, before analysis. Argon isotopes were measured on a modified AEI MS10 mass spectrometer fitted with automatic peak switching and digital output [Rex and Dodson, 1970]. Errors were estimated by taking the percentage difference between replicate argon determinations, on samples less than 20 Ma, plotted as a function of radiogenic ^{40}Ar, and the best fit estimate of the two errors in individual

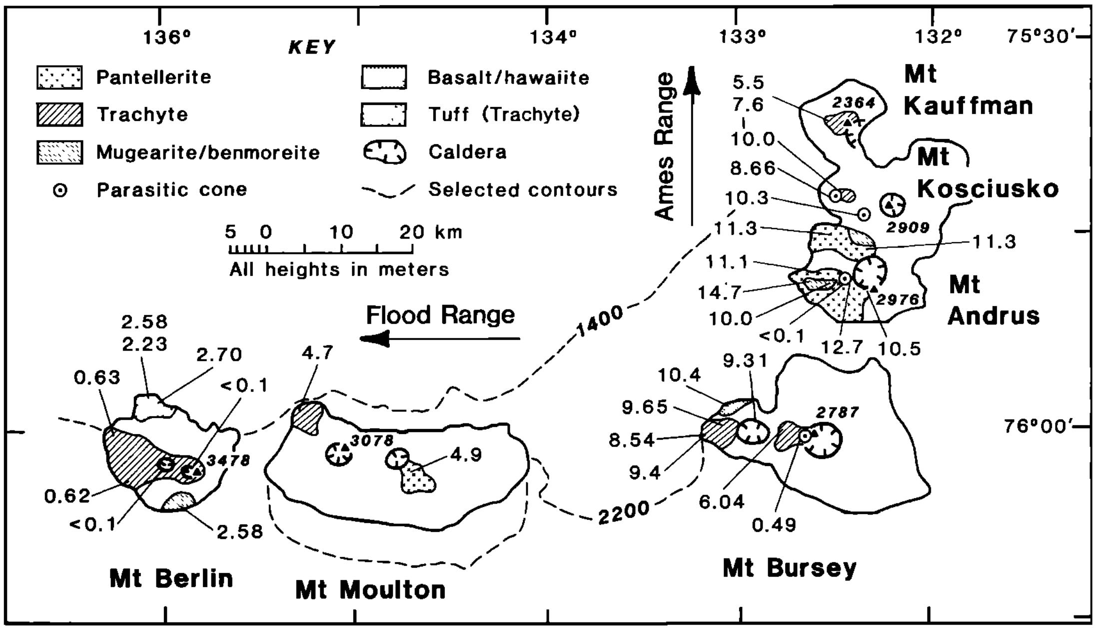

Fig. 3. Geologic map of the Ames and Flood ranges showing locations of K-Ar ages from Table 1 and from previously published sources. Selected contours illustrate relief on the surface of the continental ice sheet as well as topographic relief to the summit of each volcano. Approximate limit of topographic expression of each volcano is indicated by solid line boundary. Arrows indicate directions of younging.

analyses. This method was developed by analysis of over 100 duplicate Ar measurements on volcanic rocks between 0.1 and 20 Ma, with varying amounts of atmospheric argon contamination, and found to give the most realistic error estimates for samples in this age range. Most of the larger errors (especially in Ar measurements) are found in analyses of feldspar separates. We believe this is due to limited sample size, which diminished the chances for complete homogeneity of the feldspar separate, and sometimes resulted in too little material for a completely satisfactory series of replications. International standards were analyzed and atmospheric argon ratios were determined on a regular basis. Further details are presented by Briden et al. [1979].

All samples were selected for age determination after careful petrographic examination and bulk chemical analysis, to ensure freshness and lack of contaminants. Armstrong [1978] has thoroughly described the problems of atmospheric contamination and excess argon that are inherent in dating young volcanic rocks in Antarctica, especially those that may have been subjected to rapid quenching in a glacial environment. We have discussed similar concerns in the context of the MBL environment [LeMasurier and Rex, 1982]. Specifically, we avoid specimens that are vitric or that contain complexly zoned feldspars, abundant ultramafic nodules, crustal xenoliths, or deuteric zeolites.

Wherever possible, samples with stratigraphic control have been analyzed so that relative ages could be used to judge gain or loss of radiogenic argon. Stratigraphic tests of sections ranging between 150 and 2000 m thick have shown either rapid accumulation, with the ages of tops and bottoms falling within the limit of a 5% dating error (e.g., Mount Murphy and Toney Mountain), or a good stratigraphic correlation, as in the 11.7 to 2.34 Ma range from bottom to top, shown by 12 radiometric ages from the Coleman Nunatak section [LeMasurier and Thomson, 1989; W. E. LeMasurier and D. C. Rex, unpublished data, 1988]. The latter is represented in Figure 2 by the 2-11 Ma age range of one of the unnamed basalt sections between Mount Siple and Cruzen Island.

Basaltic Sections

Averages of 14 unpublished and 33 published ages of basaltic rocks [LeMasurier, 1972; LeMasurier and Rex, 1982, 1983] are shown in Figure 2. No basaltic sections are exposed in ECR, FR, and AR, with the exception of the 10.4 Ma basalt at the base of Mount Bursey (Figure 3). Figure 2 illustrates the absence of any regional pattern in basaltic activity during the past 28 m.y. The oldest basaltic rocks lie along an E-W line between Mount Petras, the USAS Escarpment, and the area around the Kohler Range, but no systematic change is evident along that line or away from it. A comparison of Figure 2 with Figure 1 illustrates random shifts of basaltic activity back and forth along a 40-km line between the AR and Shepard Island, during the 11 to 2 Ma interval in which most of the shifts in felsic activity in the ECR, AR, and FR were taking place. The chronology of basaltic volcanism schematically represented in this portion of Figure 2 is documented by 28 radiometric ages from seven localities.

Even where basaltic sections are exposed beneath felsic rocks, there is no clear chronologic relationship between the two. For example, the ages of basaltic sections and overlying felsic rocks at Mount Murphy are within their respective limits of error, but at Toney Mountain, the felsic rocks are

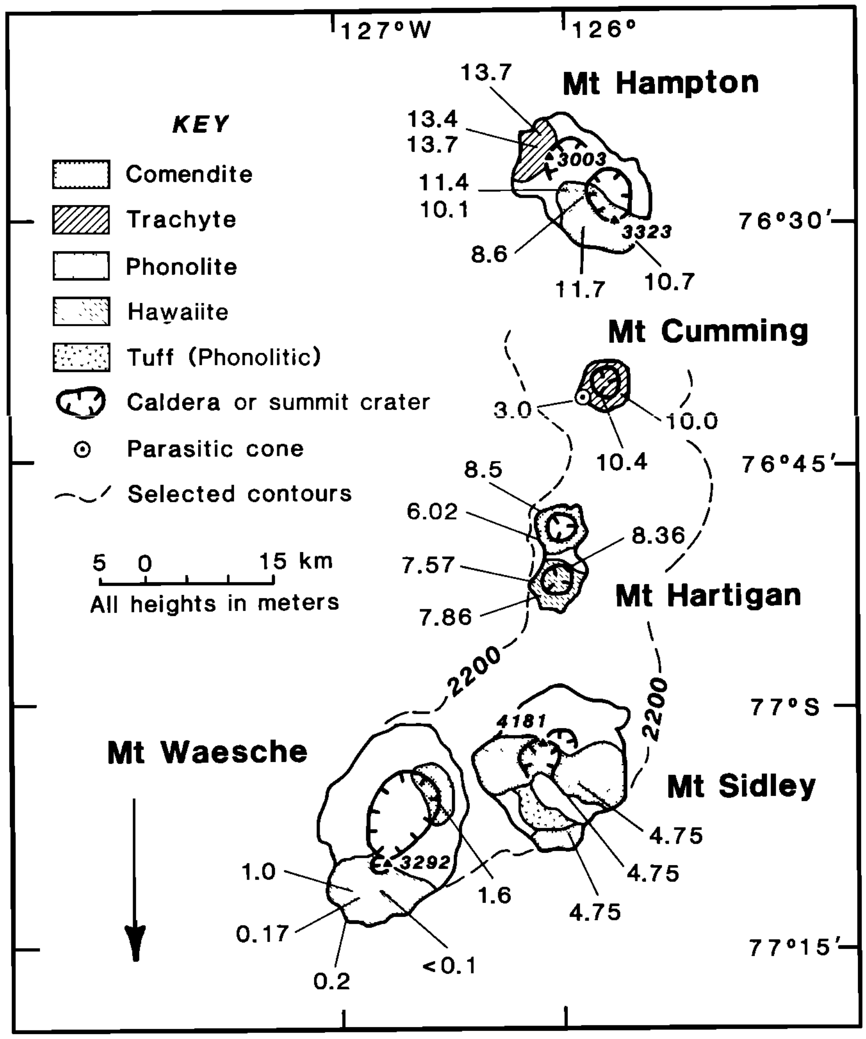

Fig. 4. Geologic map of the Executive Committee Range showing locations of K-Ar ages from Table 1. Symbols are as in Figure 3.

9-10 m.y. younger than the underlying hawaiites (Figures 1 and 2).

Felsic Shield Volcanoes

Twenty-five previously unpublished K-Ar age determinations are presented in Table 1, and these plus 28 published ages [LeMasurier and Rex, 1983] are shown in Figures 3 and 4. Based on these data, volcanic activity in ECR (Figure 4) appears to have migrated 96 km southward, from Mount Hampton to Mount Waesche, within the past 13.7 m.y., at an average rate of 0.7 cm/yr. During this period, the only contemporaneous activity at two individual centers appears to have occurred at Mount Hartigan (both north and south calderas), at roughly 8 Ma, and at Mount Cumming and Mount Hampton south, at roughly 10 Ma.

Volcanic migrations in the AR and FR (Figure 3) were contemporaneous with those in the ECR. AR volcanism began at Mount Andrus and apparently shifted northward a distance of 19 km in 7.1 (14.7-7.6) to 4.5 (10.0-5.5) m.y., if one compares oldest to oldest, and youngest to youngest activity. However, it is not unlikely that Quaternary volcanism at Shepard Island (Figure 1), 135 km north of Mount Kaufman, represents renewed felsic activity along the AR line and that Shepard Island (SI) center is in an early stage of shield volcano evolution. SI consists of trachyte, mugearite, and hawaiite flows and hydroclastic deposits that have yielded K-Ar ages of 0.4, 0.6, and 1.5 Ma [LeMasurier, and Thomson, 1989]. Migration from Mount Andrus 154 km northward to SI in 9.6 -13.2 m.y. yields a migration rate of 1.2-1.6 cm/yr.

In the FR (Figure 3), activity shifted 80 km westward, from Mount Bursey to Mount Berlin, within 7.0 to 8.5 m.y. (0.9-1.1 cm/yr). During this interval there was also a shift eastward, apparently, from the west to east caldera of Mount Bursey.

The Crary Mountains and Toney Mountain (Figure 1) are linear ranges with N-S and E-W orientation, respectively, that are not described in detail because of scarce data. In the former there is a suggestion of southward younging of felsic activity, contemporaneous with that in the ECR but it is based on only two K-Ar age determinations. Two age determinations on felsic rocks at Toney Mountain give no indication of a migration of activity [LeMasurier and Thomson, 1989].

The dominant chronologic pattern that emerges

TABLE 1. K-Ar Data Executive Committee Range and Ames Range

Sample Number	Locality	Comments	K,%	^{40}AR rad.	Vol. ^{40}Ar, rad. cm^{3}STP/g x 10^{-5}	Age, Ma
41A	Mount Waesche	hawaiite	1.07	0	0.0	± 0.1
35A	Mount Waesche	benmoreite cinder con	1.84	3.5 1.9	0.0015 0.0010	0.17 ± 0.03
39A'	Mount Waesche	benmoreite	2.12	4.3	0.0017	0.2 ± 0.2
33C	Mount Waesche	hawaiite	1.12	8.5	0.0049	1.0 ± 0.1
32A	Chang Peak	comendite vitrophyre, dated on sanidine	5.13	24.7 21.3	0.0300 0.0360	1.6 ± 0.2
53C	Mount Sidley	dated on anorthoclase	2.59	35.7 34.4 36.3	0.0443 0.0481 0.0512	4.75 ± 0.30
50A	Mount Sidley	benmoreite	2.01	13.2 9.8	0.0368 0.0376	4.75 ± 0.28
52A	Mount Sidley	benmoreite, dated on anorthoclase	2.74	41.0 27.9	0.0475 0.0538	4.75 ± 0.40
43A	Mount Hartigan north peak	comendite, dated on sanidine	5.52	40.7 36.3	0.1310 0.1279	6.02 ± 0.25
45C	Mount Hartigan, south peak	mugearite	1.45	45.7 45.3	0.0428 0.0427	7.57 ± 0.30
46B	Mount Hartigan, south peak	mugearite	1.11	48.3 50.8	0.0350 0.0330	7.86 ± 0.50
48	Mount Hartigan, south peak	hawaiite	3.8	14.9 14.8	0.1262 0.1214	8.36 ± 0.41
42B	Mount Hartigan, north peak	trachyte, dated on feldspar	5.9	33.2	0.1956	8.50 ± 0.33
28	Mount Cumming	trachyte	3.22	74.4	0.1301	10.4 ± 0.5
20D	Mount Hampton	phonolite, dated on anorthoclase	5.34	68.1	0.1780	8.6 ± 0.5
22B	Mount Hampton	phonolite, dated on feldspar	4.56	56.5	0.1790	10.1 ± 0.4
25	Mount Hampton	phonolite	3.75	74.8 74.0	0.1567 0.1558	10.7 ± 0.4
22D	Mount Hampton	basanite/basalt parasitic cone	1.36	59.1 65.6 60.1	0.0576 0.0640 0.0597	11.4 ± 0.6
19C	Mount Hampton	phonolite	3.15	59.3 58.4	0.1395 0.1491	11.7 ± 0.5
23A	Mount Hampton, Whitney Peak	benmoreite	2.64	44.4 49.8	0.1368 0.1386	13.4 ± 0.5
24A	Mount Hampton, Whitney Peak	trachyte, dated on anorthoclase	5.49	47.3 42.1	0.2957 0.2922	13.7 ± 0.5
23C	Mount Hampton, Whitney Peak	trachyte, dated on feldspar	4.61	30.9 38.2	0.2425 0.2521	13.7 ± 0.5
AR39B	Mount Kaufman, Ames Range	trachyte	4.31	67.3 67.4	0.1257 0.1285	7.6 ± 0.3
AR41A	Mount Andrus, Ames Range	pantellerite	4.18	69.8 69.4	0.1825 0.1850	11.3 ± 0.4
AR60E	Mount Andrus, Ames Range	benmoreite	3.73	71.4 77.1	0.1827 0.1859	12.7 ± 0.4

Constants: ß = 4.962 x 10 -10 yr^{-1}; E = 0.581 x 10 -10 yr^{-1}; ^{40}K = 0.01167atom %.
All dated materials are whole rock unless noted otherwise under comments.

from these data is the systematic and continuous migration of felsic activity in three different directions during the past 13 m.y. In a regional context, there appears to have been a shift in felsic activity from the oldest felsic volcano (Mount Flint, 18.6 Ma) toward the perimeter of the province (Figure 1). The youngest felsic and intermediate rocks are found at Mount Waesche (ECR), Mount Berlin (FR), Shepard Island, Toney Mountain, and Mount Takahe, with an additional possibility at the summit of Mount Siple. The absence of any regional pattern in mafic activity, either prior to or during the period of felsic migrations, seems well documented by a total of 47 K-Ar dates.

Chemical Characteristics

Systematic stratigraphic sampling of the felsic volcanoes has been difficult because of their inaccessibility and because polar erosion rates inhibit dissection [Andrews and LeMasurier, 1973]. However, K-Ar data indicate that the oldest rocks occur around the basal perimeter of each volcano and that successively younger flows did not cover their distal edges. Thus a good range of oldest to youngest samples has been obtained for Mount Berlin and Mount Andrus (Figure 3) by sampling from base to caldera rim. Caldera wall sections 1200 m thick at Mount Sidley (Figure 4) and 300 m thick at Mount Berlin and Mount Andrus have also been sampled and studied in reconnaissance.

Forty major element analyses are presented in Table 2, from among 91 available. These represent the range of rock types that have been found in each of the 11 volcanoes in the ECR, AR, and FR. The analyses illustrate that each volcano is composed of felsic and intermediate rocks that lie within a narrow compositional range and that the range is distinctive of each volcano. For example, a phonolitic suite has been found only at Mount Hampton (southeast volcano) and Mount Sidley; moreover, these rock types are the only ones found there except for basanite in parasitic cinder cones on Mount Hampton. Pantellerites and related rocks have been found only at Mount Moulton, Mount Andrus, and Mount Kosciusko, and comendite only at Mount Hartigan (north caldera) and Mount Waesche (north caldera). In the latter two, the southern volcano in each doublet appears to be composed mainly of hawaiite and mugearite with no evidence of transition between the two contiguous comenditic volcanoes. Both volcanoes are unusual in having large proportions of hawaiite, but the compositional spectrum remains narrow. Figures 3 and 4 illustrate the predominant rock types in each volcano.

Little or no evidence of sequential chemical change has been found in any single volcano. For example, at Mount Berlin the oldest trachyte is a little more undersaturated than the youngest, while at Mount Waesche (south), the oldest flows are not as undersaturated as the youngest [LeMasurier and Thomson, 1989]. Elsewhere, no sequential changes have been found.

Discussion

The migrations of activity in MBL differ markedly from the more familiar examples in oceanic settings, for example, Hawaii [Clague and Dalrymple, 1986] and the Marquesas Islands [McDougall and Duncan, 1980; Duncan and Clague, 1985]. The major lithologic and evolutionary differences are the following. (1) Migrations in MBL involve felsic and intermediate rocks only. No migration pattern in basaltic volcanism has been observed, even though these are the most abundant and widespread rocks in the province. (2) Volcanoes in MBL chains commonly differ greatly in composition, even between closely coalesced pairs. (3) There are few sequential chemical changes, either within individual MBL volcanoes or along the lengths of chains.

Spatial and chronologic contrasts include the orthogonal and diametrically opposing directions of contemporaneous migration in MBL, as well as a migration rate of roughly 1 cm/yr, compared with 9.4 ± 0.3 or 9.2 ± 0.3 cm/yr for the Hawaiian chain [McDougall, 1979; Clague and Dalrymple, 1986], 10.4 ± 1.8 cm/yr for the Marquesas, and 10.9 ± 1.0 for the Society Islands [McDougall and Duncan, 1980; Duncan and Clague, 1985]. The spacings between volcanoes and lengths of MBL chains are roughly 20% of those between Kilauea and Kauai but similar to the 3-4 km and 30-km wavelengths of some volcanic features in the Galapagos rift [Crane, 1979].

In continental settings, felsic rocks commonly occur in large proportions compared with ocean basins, and they seem to be involved wherever migrations are recognized; but the involvement of associated mafic rocks varies from one province to another. In eastern Australia, "central volcano provinces" that include felsic rocks define a pattern of southward migration during the past 35 m.y., while contemporaneous volcanic fields composed only of mafic rocks show no evidence of migration [Wellman and McDougall, 1974]. In the Yellowstone-Snake River Plain region, rhyolitic volcanism preceded basaltic volcanism and systematically migrated 400 km eastward within the past 15 m.y. [Eaton et al., 1975; Armstrong et al., 1975].

Diverse directions of migration seem more common in continental than oceanic settings. In eastern Australia, felsic volcanism migrated 2000 km southward at 66 ± 5 mm/yr, but a contemporaneous westward shift of activity, which trailed the southward migration, took place at 5 mm/yr [Wellman and McDougall, 1974]. A more pronounced disparity in the directions of migration took place in the Yellowstone-Snake River Plain, where the familiar northeastward migration was accompanied by a contemporaneous 200-km northwestward migration of rhyolite dome activity in adjacent eastern Oregon [MacLeod et al., 1976].

Plate motions have been called upon to explain migrations of activity, either as a consequence of the plate moving over an immobile diapiric hotspot [Wilson, 1963; Morgan, 1971; Presnall and Helsley, 1982] or, alternatively, plate motion coupled with fracture propagation [Shaw and Jackson, 1973; Turcotte and Oxburgh, 1973]. In most cases the rates and directions of migration are reasonably consistent with plate motions, especially in oceanic settings. Numerous hypotheses to explain the origin of the hotspots themselves are discussed by Presnall and Helsley [1982] and by Clague and Dalrymple [1986].

In MBL, plate motions are not likely to have been a cause, or even a factor, in the migrations of activity. No sensible direction of plate motion can be resolved from the migration pattern, and the paleomagnetic, seafloor spreading, and hotspot data all suggest no perceptible motion of the Antarctic plate during the past 19 m.y., as noted earlier. Furthermore, the Quaternary volcanoes in MBL can be interpreted to define a hotspot 550-650 km in diameter. Nearly all of the older volcanoes in the province, mafic and felsic, lie within the perimeter of this hotspot, suggesting that the plate has remained stationary for the past 25-30 m.y.

We favor a fracture propagation mechanism to explain the MBL migrations because it is compatible with diverse directions of contemporaneous migration, and it is consistent with the evidence for fracture control of MBL volcanic activity. Two important constraints on this mechanism apply to MBL migrations, however: (1) the mechanism must accommodate abrupt and large compositional changes

TABLE 2. Major Elements and CIPW Norms of Felsic and Intermediate Rocks,

Oxides	Mount Waesche 33C	Mount Waesche 41A	Mount Waesche 34BA	Mount Waesche 35A	Chang Peak 32A	Mount Sidley 49A	Mount Sidley 50A	Mount Sidley 54A	Mount Sidley 53B	Executive Mount 45B
SiO2	48.17	49.46	55.50	54.00	71.69	53.85	55.34	56.74	61.51	48.59
TiO2	2.18	1.82	1.30	1.75	0.25	0.47	0.90	0.28	0.38	2.49
Al2O3	18.58	18.48	17.20	16.40	10.79	21.06	16.79	18.95	16.03	19.61
Fe2O3	5.25	4.82	3.00	3.10	2.02	4.44	9.84	4.31	4.26	3.84
FeO	6.22	5.94	6.50	7.00	2.60	1.38	1.08	1.63	2.34	6.92
MnO	0.21	0.16	0.13	0.13	0.10	0.19	0.25	0.18	0.14	0.18
MgO	3.93	3.69	1.60	2.20	2.04	1.01	1.15	0.13	0.22	3.20
CaO	9.62	9.39	4.60	5.50	0.77	1.51	4.02	1.18	1.45	8.40
Na2O	4.12	4.26	7.20	7.00	5.51	9.64	6.39	9.37	6.93	3.99
K2O	1.36	1.28	2.80	2.40	4.56	5.87	3.01	5.55	5.20	1.85
P2O5	0.62	0.44	0.34	0.50	0.02	0.18	0.59	0.06	0.06	0.32
H2O+	0.12	0.64	0.00	0.00	0.24	0.91	0.00	0.00	1.73	0.35
H2O-	0.08	0.33	0.00	0.00	0.00	0.19	0.32	0.84	0.00	0.03
F	0.11	0.07	0.16	0.18	0.32	0.10	0.06	0.14	0.24	0.08
CO2	0.	0.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.57	100.45	100.33	100.16	100.91	100.80	99.74	99.36	100.49	99.85
Q	0.00	0.00	0.00	0.00	23.48	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
or	8.07	7.56	12.23	14.38	26.94	34.68	17.79	32.80	30.72	10.93
ab	30.49	33.73	38.08	42.34	30.11	18.69	53.40	26.14	53.35	30.55
an	28.19	27.52	14.18	6.25	0.00	0.00	8.24	0.00	0.00	30.14
ne	2.37	1.26	5.88	9.15	0.00	30.85	0.37	21.90	0.08	1.74
ac	0.00	0.00	0.00	0.00	5.84	5.20	0.00	11.20	4.51	0.00
ns	0.00	0.00	0.00	0.00	2.30	0.00	0.00	0.00	0.00	0.00
di	12.44	13.01	12.13	14.88	3.04	4.92	6.11	4.78	4.37	7.73
wo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hy	0.00	0.00	0.00	0.00	8.13	0.00	0.00	0.00	0.00	0.00
ol	5.53	5.13	6.45	4.21	0.00	0.17	0.02	0.25	0.00	7.26
mt	7.61	6.99	4.31	4.50	0.00	3.71	1.69	0.64	3.92	5.57
hm	0.00	0.00	0.00	0.00	0.00	0.09	8.68	0.00	0.00	0.00
il	4.14	3.46	3.48	3.32	0.48	0.89	1.71	0.53	0.72	4.73
ap	1.44	1.02	1.55	1.18	0.05	0.43	1.37	0.12	0.14	0.74
fr	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00
cc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Initial $^{87}Sr/^{86}Sr$		0.7029							0.7034	0.7033

Analyst P. K. Harvey, XRF Laboratory, Department of Geology, University of Nottingham. Samples are: 33C, hawaiite, Mount Waesche; 41A, hawaiite, Mount Waesche; 34BA, benmoreite, Mount Waesche; 35A, benmoreite, Mount Waesche; 32A, comendite, Chang Peak; 49A, phonolite, Mount Sidley; 50A, benmoreite, Mount Sidley; 54A, phonolite, Mount Sidley; 53B, trachyte, Mount Sidley; 45B, hawaiite, Mount Hartigan, south caldera; 44A, mugearite, Mount Hartigan, south caldera.

from one volcano to the next, and (2) it must control the sequential eruption of felsic and intermediate lavas but have no effect on mafic lavas. The first constraint can be accommodated if fractures are propagated by tectonic extension. Abrupt changes in composition between volcanoes only 18 km apart (e.g., Mount Sidley to Mount Waesche, Figure 4) suggest that the fracture systems were not sufficiently open to allow migration and mixing between magma chambers. Each magma chamber appears to have been small (<9 km) and isolated. This characteristic is difficult to reconcile with fracture propagation if the fractures advanced along each range by forcible injection of magma [e.g., Spence and Turcotte, 1985]. Such a process would very likely have had a homogenizing effect on magma compositions, or produced systematic lateral variations. A dilatent rise of magma in response to tectonic fracture propagation seems more capable of preserving the compositional distinctiveness of each magma body.

The exclusive involvement of felsic rocks in MBL migrations is difficult to explain, but surely the origin of the rocks must be a significant factor.

Executive Committee Range, Flood Range, and Ames Range

Committee Range

Hartigan				Mount Cumming		Mount Hampton			Mount Whitney	
South		North								
44A'	46B	42A	43A	28	27A	20B	25	21	23Ca	24B
50.37	53.00	61.98	69.00	60.80	64.20	55.49	55.60	56.21	62.08	62.89
1.37	2.30	0.53	0.25	0.58	0.50	0.20	0.75	0.43	0.58	0.45
21.01	15.90	15.51	12.80	14.40	12.60	19.01	17.80	18.43	15.66	15.97
6.69	3.80	5.02	4.10	4.40	6.90	4.97	4.60	4.31	3.72	3.22
4.36	7.40	2.45	0.04	5.50	1.30	2.47	2.50	2.79	3.37	3.88
0.21	0.11	0.23	0.02	0.17	0.06	0.21	0.10	0.23	0.20	0.19
2.31	3.20	0.62	0.02	0.22	0.09	0.08	0.99	0.27	0.20	0.11
5.62	7.10	2.51	0.52	2.60	1.30	1.23	2.10	1.53	2.32	1.24
5.06	4.70	5.87	6.30	6.30	6.90	10.14	9.20	8.85	6.10	6.10
2.51	2.20	4.73	5.10	4.40	5.20	4.95	4.80	5.28	5.02	4.83
0.48	0.50	0.08	0.00	0.09	0.02	0.06	0.13	0.09	0.12	0.07
0.20	0.00	0.34	0.50	0.50	0.50	1.50	0.50	0.00	0.00	1.02
0.05	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.61	0.00	0.11
0.10	0.11	0.00	0.24	0.00	0.23	0.13	0.20	0.04	0.11	0.18
0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.30	0.00	0.00	0.00
100.34	100.43	99.72	100.19	100.04	99.80	100.44	99.57	99.07	99.48	100.26
0.00	0.00	5.80	16.36	2.26	7.47	0.00	0.00	0.00	3.50	5.29
0.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.82	13.07	27.95	30.41	26.00	30.72	29.25	28.36	31.20	29.68	28.54
40.16	39.77	49.65	37.45	49.56	35.85	22.77	28.35	29.43	51.62	51.59
24.74	15.79	2.01	0.00	0.00	0.00	0.00	0.00	0.00	0.52	1.94
1.44	0.00	0.00	0.00	0.00	0.00	25.71	19.76	19.49	0.00	0.00
0.00	0.00	0.00	11.86	3.28	19.83	13.70	11.44	8.35	0.00	0.00
0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	13.01	3.33	0.11	10.34	3.57	5.06	5.21	6.07	5.83	3.31
0.00	0.00	2.67	0.75	0.00	0.23	0.00	0.00	0.00	1.46	0.00
0.00	4.63	0.00	0.00	1.87	0.00	0.00	0.00	0.00	0.00	2.60
4.50	2.67	0.00	0.00	0.00	0.00	1.48	2.12	0.50	0.00	0.00
9.70	5.51	7.11	0.00	4.74	0.07	0.34	0.94	2.06	5.39	4.67
0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.60	4.37	1.01	0.35	1.10	0.95	0.38	1.42	1.42	1.10	0.86
1.00	1.05	0.19	0.00	0.21	0.05	0.14	0.31	0.21	0.28	0.17
0.00	0.00	0.00	0.00	0.16	0.47	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7036						0.7047				

Samples are 44A', mugearite, Mount Hartigan, south caldera; 46B, hy-mugearite, Mount Hartigan, south caldera; 42A, trachyte, Mount Hartigan, north caldera; 43A, comendite, Mount Hartigan, north caldera; 28, pantelleritic trachyte, Mount Cumming; 27A, pantelleritic trachyte, Mount Cumming; 20B, phonolite, Mount Hampton; 25, phonolite, Mount Hampton; 21, phonolite, Mount Hampton; 23Ca, trachyte, Whitney Peak; 24B, quartz trachyte, Whitney Peak.

Did they form independently of mafic rocks, by partial or complete fusion of the crust, or is there a genetic relationship between felsic and mafic magmas? Detailed petrogenetic modeling is not completed; but preliminary work suggests that the latter is more likely. The following points are relevant. (1) The initial $^{87}Sr/^{86}Sr$ ratios of felsic and intermediate rocks are low (e.g., Table 2, samples 53B, 20B, 44A', and 45B), especially when compared with the initial ratios of the basement granitic rocks [LeMasurier and Wade, 1976]. (2) Rare earth element analyses of eight felsic samples from the ECR show large negative europium anomalies, indicating extensive feldspar fractionation for all but one trachyte sample [LeMasurier et al., 1976]. (3) All of the felsic rocks are alkaline and most are peralkaline, with a wide variety of silica saturation characteristics. Products of crustal melting are likely to be uniformly oversaturated and either metaluminous or peraluminous, especially in MBL, given the age and composition of the crust represented by the basement complex. The origins of peralkaline rocks are complex but very likely involve open system fractional crystallization of basaltic magma plus alkali transfer [Bailey, 1974]. The case for extreme fractionation

TABLE 2.

									Flood
	Mount Berlin					Mount Moulton		Mount	
Oxides	67A35	BN31E	BN4C	BN23C	BN22B	1A	2A	BU28B	BU29B
SiO2	54.55	62.21	58.09	60.71	61.63	60.54	69.80	60.56	58.91
TiO2	1.78	0.52	0.31	0.50	0.51	0.26	0.37	0.58	0.67
Al2O3	18.59	13.11	17.63	14.97	12.88	15.45	10.87	16.32	16.08
Fe2O3	0.45	2.59	3.46	5.94	6.92	5.24	4.03	3.47	4.62
FeO	7.96	6.07	4.01	2.66	2.57	2.25	3.08	3.48	4.10
MnO	0.21	0.27	0.23	0.21	0.28	0.23	0.22	0.18	0.25
MgO	2.01	0.00	0.15	0.30	0.00	0.00	0.65	0.42	0.42
CaO	4.72	1.09	2.13	1.30	1.09	0.92	0.29	1.63	2.72
Na2O	5.92	8.75	7.82	7.66	8.00	8.84	6.20	8.06	6.11
K2O	3.13	4.71	4.52	4.61	4.69	5.00	4.53	4.59	4.47
P2O5	0.86	0.05	0.11	0.04	0.05	0.03	0.03	0.12	0.25
H2O+	0.10	0.00	0.00	1.11	0.00	0.00	0.10	0.00	0.00
H2O-	0.03	0.00	0.48	0.00	0.24	0.47	0.00	0.25	0.58
F	0.13	0.08	0.00	0.00	0.11	0.02	0.11	0.07	0.04
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.44	99.45	98.93	100.01	98.97	99.25	100.28	99.74	99.20
Q	0.00	3.09	0.00	0.00	2.02	0.00	20.62	0.00	0.97
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
or	18.49	27.44	26.71	27.24	27.72	29.55	26.76	27.13	26.42
ab	42.71	41.21	46.11	48.50	40.14	40.69	30.69	46.23	51.70
an	14.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.28
ne	3.99	0.00	10.59	1.53	0.00	5.93	0.00	6.55	0.00
ac	0.00	7.49	0.58	11.87	20.02	15.16	11.66	8.64	0.00
ns	0.00	5.66	0.00	0.00	1.12	1.39	1.98	0.00	0.00
di	2.45	4.53	8.67	5.34	4.53	3.90	1.07	6.34	7.38
wo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hy	0.00	8.38	0.00	0.00	1.99	0.00	6.52	0.00	0.33
ol	11.61	0.00	0.30	0.70	0.00	1.59	0.0C	2.37	0.00
mt	0.65	0.00	4.73	2.64	0.00	0.00	0.00	0.70	6.70
hm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
il	3.38	0.99	0.59	0.95	0.97	0.49	0.70	1.10	1.27
ap	2.04	0.10	0.25	0.09	0.11	0.06	0.07	0.25	0.53
fr	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00
cc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Analyst P. K. Harvey, XRF Laboratory, Department of Geology, University of Nottingham. Samples are 67A35, benmoreite/mugearite, Mount Berlin, Wedemeyer Rock; BN31E, pantelleritic trachyte, Mount Berlin, Merrem Peak; BN4C, phonolite, Mount Berlin, Brandenberger Bluff; BN23C, peralkaline trachyte, Mount Berlin, summit; BN22B, pantellerite/trachyte, Mount Berlin, summit; 1A, phonolitic trachyte, Mount Moulton, Edwards Spur; 2A, pantellerite, Mount Moulton; BU28B, Mount Bursey, Hutt Peak, summit; BU29B, trachyte/benmoreite, Mount Bursey, NW flank.

of basaltic magma is especially strong for phonolites and trachytes [Price et al., 1985]. The peralkaline rocks whose origins are most likely to involve large crustal melt components appear to be the high silica (73.5-75.5%), low-iron (1.5-2.5% FeO_t) comendites, but even here the heat and volatiles from basaltic magma emplaced in the crust are called upon to produce the melting [Davies and Macdonald, 1987; Macdonald et al., 1987]. Based on considerations of the above, and on the close field association between felsic and mafic rocks in MBL, our interpretation of chronologic patterns assumes only that felsic magmas formed as a result of the entrapment of mafic magma in the crust, an assumption that seems unlikely to be invalidated by future petrogenetic studies.

The field relationships and chronology of basaltic sections suggest that eruptions of mafic magma were random in time and space but volumes of individual batches were highly variable. Lherzolite nodules, up to 30 cm across, are found only in cinder cones, suggesting that the small-volume

(Continued)

Range		Ames Range							
Bursey		Mount Andrus				Mount Kosciusko			Mount Kaufman
67A7	BU25B	67B4	3B	AR41C	AR44C	AR40B	67B6	AR44D2	67B8
61.40	63.10	51.00	62.74	64.72	68.47	59.78	62.50	68.61	61.00
0.44	0.76	2.00	0.56	0.68	0.48	0.30	0.65	0.50	0.27
14.90	10.23	15.10	14.32	8.62	9.00	16.78	14.20	9.33	16.60
6.80	6.00	8.00	2.89	3.18	2.58	6.19	6.60	2.79	4.60
1.80	5.63	5.50	5.48	7.87	5.71	0.72	1.60	5.79	1.60
0.06	0.34	0.18	0.24	0.34	0.21	0.21	0.06	0.21	0.04
0.14	0.10	3.20	0.14	0.00	0.00	0.34	0.25	0.00	0.18
2.20	1.00	5.30	1.19	0.59	0.31	1.91	1.40	0.42	1.40
6.60	7.26	5.50	7.60	8.21	7.06	7.14	7.00	7.20	8.30
5.50	4.35	2.30	4.51	4.35	4.39	4.88	5.40	4.31	5.70
0.04	0.07	1.40	0.07	0.05	0.02	0.10	0.04	0.01	0.02
0.20	0.00	0.00	0.58	0.00	0.00	0.00	0.50	0.00	0.50
0.00	0.17	0.00	0.00	0.00	0.00	0.77	0.00	0.00	0.00
0.13	0.14	0.15	0.14	0.09	0.10	0.06	0.52	0.18	0.07
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
00.22	99.14	99.63	100.46	98.70	98.33	99.18	100.72	99.35	100.28
1.94	10.82	0.00	1.31	18.08	24.50	0.00	3.60	23.16	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32.50	25.71	13.59	26.65	25.71	25.94	28.84	31.91	25.47	33.68
46.01	28.40	46.52	48.54	20.12	21.85	53.58	42.97	24.00	37.22
0.00	0.00	9.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	3.02	0.00	0.00	8.90
8.64	17.36	0.00	8.36	9.20	7.46	1.08	14.30	8.07	13.31
0.00	3.10	0.00	1.45	9.06	6.85	0.00	0.00	6.46	0.34
0.75	4.00	5.31	4.83	2.32	1.25	1.83	2.36	1.80	5.49
3.64	0.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00
0.00	7.85	4.52	7.38	12.73	9.42	0.00	0.06	9.24	0.00
0.00	0.00	1.05	0.00	0.00	0.00	0.00	0.00	0.00	0.13
4.74	0.00	11.60	0.00	0.00	0.00	2.14	2.40	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	4.33	0.00	0.00	0.00
0.84	1.44	3.80	1.06	1.29	0.91	0.57	1.24	0.95	0.51
0.11	0.15	3.32	0.17	0.11	0.04	0.21	0.11	0.02	0.05
0.26	0.00	0.18	0.00	0.00	0.00	0.00	1.06	0.00	0.14
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Samples are 67A7, trachyte, Mount Bursey, Starbuck Crater; BU25B, trachyte, Mount Bursey, Starbuck Crater; 67B4, mugearite, Mount Andrus, SW tip; 3B, trachyte/pantellerite, Mount Andrus, S. side; AR41C, pantellerite, Mount Andrus, N. side; AR44C, pantellerite, Mount Andrus; AR40B, trachyte, Mount Kosciusko; 67B6, trachyte, Mount Kosciusko; AR44D2, Mount Kosciusko; and 67B8, nepheline trachyte, Mount Kaufman.

batches were able to rise rapidly to the surface from mantle source regions [Futa and LeMasurier, 1983]. Felsic rocks, by contrast, are associated with large volumes of basaltic rock, but if they are derived from mafic magma, they must represent cases where the magma was trapped during ascent and stored in crustal reservoirs. These relationships suggest that only a fraction of the large- volume batches of mafic magma reached the surface before channelways became blocked, and the remaining magma was trapped in the crust.

Field relationships also suggest that mafic and felsic eruptions were both closely related to faulting, but the nature of the relationship seems to differ between the two. Basaltic volcanism was accompanied by vertical offsets of the erosion surface, with the oldest basalts now resting on the highest surfaces but no lateral pattern was produced. Felsic volcanism was accompanied by propagation (extension) of the same N-S and E-W fracture systems, and patterns of linear migration are conspicuous. We suggest therefore that the two fault-related eruption mechanisms are different and that a two-stage process produced the migrations.

During the first stage, we infer that basaltic lava was able to reach the surface wherever it rose, guided by the orthogonal fracture system. This stage ended with the exhaustion of small-volume batches or by blockage of channelways at some stage in the eruption of large-volume batches. Stage two was initiated when sealed fractures were reopened by tectonic fracture propagation. This was apparently a systematic process and led to the sequential release of residual magma trapped in crustal reservoirs. In this context, the abrupt shift from a phonolitic volcano to a comendite-mugearite/hawaiite doublet is most easily explained by random emplacement of mafic magma within an established grid, with a relatively fixed release time independent of the stage of magmatic evolution. The doublets (Mounts Waesche and Hartigan) may represent the rise of two separate mafic magma batches along the same conduit, with the emplacement of one taking place long enough before access was opened to the surface to allow extensive differentiation, and emplacement of the second just before access to the surface was made possible.

The provincewide radial migration pattern in MBL is not likely to represent a mantle flow pattern [e.g., Bonatti, 1985] because if this were the case, it would be reasonable to expect a chronologic pattern in mafic as well as felsic activity. A pattern that appears to be propagated tectonically, involves only products erupted from crustal magma chambers, and proceeds radially away from a center, is suggestive of crustal doming. In some environments, doming might be expected to produce a radial fracture system, but in a complex continental setting, reactivation of old fracture sets seems more likely.

Doming has been attributed to the diapiric rise of the asthenosphere/lithosphere boundary in rift environments such as the Rio Grande rift [Eaton, 1979] and East Africa [Baker et al., 1972; Gass et al., 1978], and it is an attractive possibility in MBL, where the isotopic composition of mafic rocks suggests an asthenospheric source [Futa and LeMasurier, 1983]. Furthermore, the most tectonically elevated basement horst occurs at Mount Petras (Figure 1), 18 km southeast of Mount Flint (Figure 2), at the center of the postulated dome. We suggest therefore that the fundamental cause of MBL migrations is doming of the lithosphere accompanied by systematic centrifugal extension of a relict fracture system in the brittle part of the crust.

Summary

The major chronologic pattern of late Cenozoic volcanism in MBL is the systematic migration of felsic activity toward the perimeter of the province, over the past 18 m.y., superimposed on the nearly random provincewide eruption of mafic rocks during the past 30 m.y. Rather than follow a truly radial pattern, however, felsic activity has followed north-south and east-west lines in migrating away from the province center. The evolution of this pattern seems to have involved the following steps.

1. The rise of mafic magma from mantle source regions has been nearly random in space and time over the past 30 m.y., but volumes have been highly variable. The rise of individual magma batches through the crust has followed a relict orthogonal fracture system, accompanied by vertical tectonic displacements.

2. Portions of the larger volume batches of mafic magma became trapped in the crust during ascent, sealing channelways and leading to the evolution of intermediate and felsic magmas in crustal reservoirs.

3. Broad crustal doming produced renewed tectonic extension and reopening of the relict fracture sets, which followed crudely centrifugal paths along reactivated fractures, rather than developing a new radial fracture system.

4. Magmas trapped in the crust were sequentially released, resulting in the formation of linear ranges of felsic volcanoes that become younger toward the perimeter of the province.

5. Quaternary volcanoes in MBL define a hotspot 550-650 km in diameter. Nearly all the older volcanic rocks in the province lie within the perimeter of this hotspot, suggesting that the plate was stationary during the development of the linear chains.

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References

Andrews, J. T., and W. E. LeMasurier, Rates of Quaternary glacial erosion and corrie formations, Marie Byrd Land, Antarctica, Geology, 1, 75-80, 1973.

Armstrong, R. L., K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica, N. Z. J. Geol. Geophys., 21, 685-698, 1978.

Armstrong, R. L., W. P. Leeman, and H. E. Malde, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, Am. J. Sci., 275, 225-251, 1975.

Bailey, D. K., Experimental petrology relating to oversaturated peralkaline volcanics: A review, Bull. Volcanol., 38, 637-652, 1974.

Baker, B. H., P. A. Mohr, and L. A. J. Williams, Geology of the eastern rift system of Africa. Spec. Pap. Geol. Soc. Am., 136, 67 pp., 1972.

Barron, E. J., and C. G. A. Harrison, Reconstruction of the Campbell Plateau and the Lord Howe Rise, Earth Planet. Sci. Lett., 45, 87-92, 1979.

Bentley, C. R., and J. W. Clough, Antarctic subglacial structure from seismic refraction measurements, in Antarctic Geology and Geophysics, edited by R. J. Adie, pp. 683-691, Universitetsforlaget, Oslo, 1972.

Bentley, C. R., A. P. Crary, N. A. Ostenso, and E. C. Thiel, Structure of West Antarctica, Science, 131, 131-136, 1960.

Bonatti, E., Punctiform initiation of seafloor spreading: The Red Sea during transition from a continental to an oceanic rift, Nature, 316, 33-37, 1985.

Briden, J. C., D. C. Rex, A. M. Faller, and J. F. Tomblin, K-Ar geochronology and paleomagnetism of volcanic rocks in the Lesser Antilles island arc, Philos. Trans. R. Soc. London, 291, 485-528, 1979.

Clague, D. A., and G. B. Dalrymple, The Hawaiian-Emperor volcanic chain, U.S. Geol. Surv. Prof. Pap. 1350, 5-53, 1986.

Cooper, A. K., and F. J. Davey, Episodic rifting of Phanerozoic rocks in the Victoria Land Basin, western Ross Sea, Antarctica, Science, 229, 1085-1087, 1985.

Cooper, R. A., C. A. Landis, W. E. LeMasurier, and I. G. Speden, Geologic history and regional patterns in New Zealand and West Antarctica--Their paleotectonic and paleogeographic significance, in Antarctic Geoscience, edited by C. Craddock, pp. 43-53, University of Wisconsin Press, Madison, 1982.

Crane, K., The Galapagos rifts at 86°W: Morphological wave forms; Evidence for a propagating rift, J. Geophys. Res., 84, 6011-6018, 1979.

Davies, G. R., and R. Macdonald, Crustal influences in the petrogenesis of the Naivasha basalt--comendite complex: Combined trace element and Sr-Nd-Pb isotope constraints, J. Petrol., 28, 1009-1031, 1987.

Doumani, G. A., Volcanoes of the Executive Committee Range, Byrd Land, in Antarctic Geology edited by R. J. Adie, pp. 666-675, North-Holland, Amsterdam, 1964.

Duncan, R. A., Hotspots in the southern oceans--An absolute frame of reference for motion of the Gondwana continents, Tectonophysics, 74, 29-42, 1981.

Duncan, R. A., and D. A. Clague, Pacific plate motion recorded by linear volcanic chains, in The Ocean Basins and Margins, vol. 7A, pp. 89-121, Plenum, New York, 1985.

Eaton, G. P., A plate-tectonic model for late Cenozoic crustal spreading in the western United States, in Rio Grande Rift: Tectonics and Magmatism, edited by R. E. Riecker, pp. 7-32, AGU, Washington, D. C., 1979.

Eaton, G. P., R. L. Christiansen, H. M. Iyer, A. M. Pitt, D. R. Mabey, H. R. Blank, Jr., I. Zietz, and M. E. Gettings, Magma beneath Yellowstone National Park, Science, 188, 787-796, 1975.

Futa, K., and W. E. LeMasurier, Nd and Sr isotopic studies on Cenozoic mafic lavas from West Antarctica: Another source for continental alkali basalts, Contrib. Mineral. Petrol., 83, 38-44, 1983.

Gass, I. G., D. S. Chapman, H. N. Pollack, and R. S. Thorpe, Geological and geophysical parameters of mid-plate volcanism, Philos. Trans. R. Soc. London, Ser. A, 288, 581-597, 1978.

Gonzalez-Ferran, O., and F. Gonzalez-Bonorino, The volcanic ranges of Marie Byrd Land between long. 100° and 140° W, in Antarctic Geology and Geophysics, edited by R. J. Adie, pp. 261-276, Universitetsforlaget, Oslo, 1972.

Grindley, G. W., and P. J. Oliver, Palaeomagnetism of Cretaceous volcanic rocks from Marie Byrd Land, Antarctica, in Antarctic Earth Science, edited by R. L. Oliver, P. R. James, and J. B. Jago, pp. 573-578, Australian Academy of Science, Canberra, 1983.

Herron, E. M. and B. E. Tucholke, Seafloor magnetic pattern and basement structure in the southeastern Pacific, Initial Rep. Deep Sea Drill. Proj., 35, 263-278, 1975.

LeBas, M. J., R. W. LeMaitre, A. Streckeisen, and B. Zanettin, A chemical classification of volcanic rocks based on the total alkali-silica diagram, J. Petrol., 27, 745-750, 1986.

LeMasurier, W. E., Volcanic record of Cenozoic glacial history of Marie Byrd Land, in Antarctic Geology and Geophysics, edited by R. J. Adie, pp. 251-260, Universitetsforlaget, Oslo, 1972.

LeMasurier, W. E., The Cenozoic West Antarctic rift system and its associated volcanic and structural features (abstract), Geol. Soc. Am. Abstr. Programs, 10, 443, 1978.

LeMasurier, W. E. and D. C. Rex, Volcanic record of Cenozoic glacial history in Marie Byrd Land and Western Ellsworth Land: Revised chronology and evaluation of tectonic factors, in Antarctic Geoscience, edited by C. Craddock, pp. 725-734, University of Wisconsin Press, Madison, 1982.

LeMasurier, W. E., and D. C. Rex, Rates of uplift and the scale of ice level instabilities recorded by volcanic rocks in Marie Byrd Land, West Antarctica, in Antarctic Earth Science, edited by R. L. Oliver, P. R. James, and J. B. Jago, pp. 663-670, Australian Academy of Science, Canberra, 1983.

LeMasurier, W. E., and J. W. Thomson, (Eds.), Volcanoes of the Antarctic Plate and Southern Oceans, Antarc. Res. Ser., AGU, Washington, D. C., in press, 1989.

LeMasurier, W. E., and F. A. Wade, Volcanic history in Marie Byrd Land: Implications with regard to southern hemisphere tectonic reconstructions, in Andean and Antarctic Volcanology Problems, edited by O. Gonzalez-Ferran, pp. 398-422, International Association of Volcanology and Chemistry of the Earth's Interior, Rome, 1976.

LeMasurier, W. E., P. R. Kyle, and P. C. Rankin, Rare-earth element geochemistry of volcanic rocks from the Executive Range, Marie Byrd Land, Antarct. J. U. S., 11, 263-267, 1976.

Macdonald, R., G. R. Davies, C. M. Bliss, P. T. Leat, D. K. Bailey, and R. L. Smith, Geochemistry of high-silica peralkaline rhyolites, Naivasha, Kenya rift valley, J. Petrol., 28, 979-1008, 1987.

MacLeod, N. S., G. H. Walker, and E. H. McKee, Geothermal significance of eastward increase in age of late Cenozoic rhyolite domes in southeastern Oregon, in Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Potential, vol. 1, pp. 465-474, U.S. Govt. Printing Office, Washington, D. C., 1976.

McDougall, I., Age of shield-building volcanism of Kauai and linear migration of volcanism in the Hawaiian Island chain, Earth Planet. Sci. Lett., 46, 31-42, 1979.

McDougall, I. and R. A. Duncan, Linear volcanic chains-Recording plate motions?, Tectonophysics., 63, 275-295, 1980.

Morgan, W. J., Convection plumes in the lower mantle, Nature, 230, 42-43, 1971.

Presnall, D. C. and C. E. Helsley, Diapirism of depleted peridotite--A model for the origin of hot spots, Phys. Earth Planet. Inter., 29, 148-160, 1982.

Price, R. C., R. W. Johnson, C. M. Gray, and F. A. Frey, Geochemistry of phonolites and trachytes from the summit region of Mount Kenya, Contrib. Mineral. Petrol., 89, 394-409, 1985.

Rex, D. C., and M. H. Dodson, Improved resolution and precision of argon analysis using an MS 10 mass spectrometer, Eclogae Geol. Helv., 63, 275-280, 1970.

Shaw, H. R., and E. D. Jackson, Linear island chains in the Pacific: Result of thermal plumes or gravitational anchors?, J. Geophys. Res., 78, 8634-8652, 1973.

Spence, D. A., and D. L. Turcotte, Magma-driven propagation of cracks, J. Geophys. Res., 90, 575-580, 1985.

Stock, J., and P. Molnar, Revised history of early Tertiary plate motion in the south-west Pacific, Nature, 325, 495-499, 1987.

Turcotte, D. L. and E. R. Oxburgh, Mid-plate tectonics, Nature, 244, 337-339, 1973.

Weissel, J. K., D. E. Hayes, and E. M. Herron, Plate tectonic synthesis: Displacements between Australia, New Zealand and Antarctica since the late Cretaceous, Mar. Geol., 25, 231-277, 1977.

Wellman, P., and I. McDougall, Cainozoic igneous activity in eastern Australia, Tectonophysics, 23, 49-a65, 1974.

Wilson, J. T., A possible origin of the Hawaiian islands, Can. J. Phys., 41, 863-870, 1963.

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