

Primary Basalts and Magma Genesis II. Snake River Plain, Idaho, U.S.A.

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Abstract. The Pliocene-Holocene lavas of the Snake River Plain, Idaho, U.S.A., have a bimodal composition range, consisting predominantly of basalts (olivine-tholeiites), with subordinate intercalated tholeiitic andesites but with very few analyses falling between these groups. The more-magnesian of the tholeiitic andesites contain more total Fe, alkalis, TiO_2 and P_2O_5 but less SiO_2 than the less-magnesian basalts. Derivation of the tholeiitic andesites from the basalts by low-pressure fractional crystallization or by major-element crustal contamination does not seem possible, although some minor-element exchange with ancient crust apparently has occurred. Two lavas, representative of the least-magnesian basalts and the most-magnesian tholeiitic andesites, respectively, have been subjected to anhydrous experimental studies within their melting ranges at pressures up to 35 kb. Both appear to show four-phase points on their liquid at about 8 kb and these are thought to have genetic significance. Microprobe analyses of the interstitial glasses in partially-crystalline runs on the basalt between 8 and 12 kb show that these reproduce all the characteristic features of the Snake River Plain most-magnesian tholeiitic andesites, notably their reduced Si-saturation. The compositions of the most Mg-rich Snake River Plain basalts are such that they may perhaps be primary magmas, produced by partial fusion of a relatively Fe-rich spinel-lherzolite upper mantle at 50 to 60 km depth; a proposal which accords well with the geophysics of this currently-active region. Partial crystallization of batches of this magma, delayed during ascent within the crust at depths of about 30 km, is thought to have given rise to the tholeiitic andesites.

Introduction

This is the second part of a paper concerned with investigating some aspects of the genesis and interrelationships of volcanic rocks by means of anhydrous high-pressure melting experiments on selected lavas. The first part (Thompson, 1974a) discussed the apparently fissure-erupted Eocene flood basalts and asso-

cated lavas of Skye, NW Scotland. This section is a similar study of the flood basalts and tholeiitic andesites of the Snake River Plain, southern Idaho, U.S.A. This region is one of prolonged and continuing volcanism and, as such, must play an important role in any tectonic synthesis of the western United States. Morgan (1972) has suggested that the area is of prime geodynamic significance as the surface expression of a mantle thermal convective plume, currently under the Yellowstone Plateau, which he regards as part of the driving force behind motion of the American lithospheric plate, beneath which it impinges. Smith and Shar (1974) have expanded on this theme. Several geochemical studies of the lavas produced above supposed plumes, notably Iceland, have been published recently. The authors of such works (e.g. O'Nions and Grönvold, 1973; Schilling, 1973a; Hart, Schilling and Powell, 1973; Treuil and Varet, 1973; Schilling and Noe-Nygaard, 1974) tend to emphasize the postulated role of variation of composition and degree of partial melting of the upper mantle in their schemes for magma genesis. When subsequent fractional crystallization of the magmas is considered (e.g. Treuil and Varet, 1973) it is generally supposed to have occurred in relatively near-surface magma chambers. O'Hara (1973) has pointed out that schemes of magmatic evolution based on trace element geochemistry are inclined to pay scant attention to the genetic restrictions imposed by our current knowledge of the phase chemistry of appropriate compositions. Schilling (1973b) has shown in response that the converse is true. The work reported here is intended to establish a genetic framework for the Snake River Plain lavas, based on the major element chemistry and experimental petrology, which may serve as a foundation for future geochemical studies.

Geological Setting

The Snake River Plain is an elongate arcuate structural and topographic depression which extends for 500 km across southern Idaho, from the Yellowstone Plateau at its northeastern extremity to the Columbia River Plateau at the northwest. Studies of the surface geology (Stearns, Crandall and Steward, 1938; Malde, 1959; Malde and Powers, 1962) indicate that the depression has formed since the Lower Pliocene by a combination of downfaulting and downwarping; the former predominating, at least in the west. The infill of continental detrital sediments and lavas is locally several km thick. The lava component was erupted from innumerable scattered fissures, some of which are aligned along rift zones (Prinz, 1970). Volcanism has continued in the Snake River Plain since at least the Lower Pliocene (Malde and Powers, 1962; Armstrong and Leeman, 1971). The most recent eruptions, along the Idaho Rift Zone, have taken place less than 2100 years ago (Prinz, 1970; Bullard and Rylander, 1970). With a time scale of this length in mind, the region may be described as currently active, despite the lack of historic eruptions, and geophysical data on its present crust and upper mantle may be used to assist the construction of petrogenetic models. The region forms part of the high heat flow (> 2.0 hfU) province of the western United States (Blackwell, 1971). Seismic refraction studies have shown, however,

that the crust beneath the western Snake River Plain is very different from that underlying the Basin and Range province, immediately to the south (Hill and Pakiser, 1967). The latter is relatively thin and predominantly stable, whereas beneath the western Snake River Plain the M discontinuity is at about 45 km depth. Above it most of the crust appears to be mafic ($P_n = 6.7$ – 7.0 km/sec), capped by only a thin (8–12 km) layer with lower seismic velocities ($P_n = 5.2$ – 6.0 km/sec). The relatively low velocities ($P_n = 7.9$ km/sec) and high seismic attenuation in the upper mantle immediately beneath the M discontinuity in this area fall within the range characteristic of the low velocity zone. Thus, in a seismic sense, the lithosphere here is only about 45 km thick. Gravity survey of the western Snake River Plain by Hill (1963) located three large, elongate, en echelon zones of positive Bouguer anomalies parallel to the axis of the plain. He postulated that these were sets of tension fissures injected with basalt; the tops of the dense bodies reaching to within about 2 km of the surface. The unusual gravitational and seismic features of the western Snake River Plain die out progressively towards the eastern plain, which appears to be underlain by stable crust (La Fehr and Pakiser, 1962).

Previous Studies of the Lavas

Malde and Powers (1962) established a detailed stratigraphic succession in the western Snake River Plain. Powers (1960) made a preliminary survey of the chemistry of the lavas. Subsequently, Stone (1967) completed a detailed petrological study of them, but this remains unpublished. Tilley and Thompson (1970) used a suite of samples collected by Powers for 1-atmosphere melting experiments.

The lavas fall into two distinct chemical groups. The predominant type is basalt, with MgO between 6.4 and 11.2%. Silica saturation varies considerably so that, although all the flows analyzed to date are olivine tholeiites in the classification of Yoder and Tilley (1962), they range from samples which are virtually Q-normative to some which would be *ne-normative* if their Fe_2O_3 contents were lower than as analyzed (Tilley and Thompson, 1970, Fig. 2). The basalts contain phenocrysts of olivine $\pm$ plagioclase in a groundmass of these minerals, Ca-rich clinopyroxene and Fe-Ti oxides. The olivine shows no signs of reaction to form Ca-poor pyroxene but, nevertheless, the interstices are often filled with siliceous glass.

The other lava type, which occurs sporadically throughout the Snake River Plain volcanism, has also been referred to as basalt by several authors (Tilley and Thompson, 1970; Leeman and Rogers, 1970; Muehlenbachs and Stone, 1973). The use of this term is consistent with the basalt-like SiO_2 contents (46.0–51.2 weight percent) of these rocks but fails to take account of other aspects of their chemistry: e.g. MgO, 3.0–4.4%; $\text{FeO} + \text{Fe}_2\text{O}_3$, 13.4–16.7%; CaO , 6.4–7.7%; normative plagioclase, An30–37. These features, together with their thermal behaviour (see below), indicate that such lavas resemble the postulated liquids at advanced stages of differentiation of the Skatogard intrusion, East Greenland (Wager, 1960). The cumulate rocks formed from these were called ferrogabbros by Wager and Deer (1939). The term was subsequently changed to ferrodiorite

by Wager and Vincent (1962). Its volcanic equivalent, ferroandesite, might suit these unusual lavas quite well but would involve introducing yet another term into the evergrowing volcanic nomenclature. The author has previously called these rocks "iron-rich andesite-normative lavas" (Thompson, 1972a,b, 1973a) and subsequently "tholeiitic andesites" (Thompson, 1975a). The latter term is used in this paper and is in conformity with the classification of volcanic rocks proposed by Irvine and Baragar (1971, Fig. 7A). Most, possibly all, of these Fe-rich lavas appear to have been erupted at the margins of the Plain (Leeman and Manton, 1971). They contain phenocrysts of olivine, plagioclase, titaniferous magnetite and apatite in a groundmass of these minerals, Ca-rich clinopyroxene, ilmenite and siliceous glass. Ferroaugitic phenocrysts are rare but occur in a few flows. Sparse xenocrysts and rare xenoliths of gneissic crustal rocks are found in these lavas.

The isotopic compositions of strontium, oxygen and lead in the Snake River Plain lavas have been studied by Leeman and Manton (1971, 1972), Muehlenbachs and Stone (1973) and earlier workers. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the basalts (0.706–0.708) are considerably higher than those of most ocean basin tholeiites (e.g. Hart *et al.*, 1973). However, their uniformity throughout the Plain, especially in the western part where granitic crust seems virtually absent (Hill and Parkiser, 1967), was emphasized by Leeman and Manton (1971). These authors suggested that the relative ^{87}Sr -enrichment is an original mantle-derived feature of these lavas; a view supported by oxygen isotope data (Muehlenbachs and Stone, 1973). In contrast, the Sr, O and Pb isotope values of tholeiitic andesites from the King Hill, Craters of the Moon and Cold Springs Creek suites are all anomalous for mantle-derived magmas and suggestive of contamination by ancient crustal rocks, such as outcrop around the margins of the Plain.

Tilley and Thompson (1970) found that the Snake River Plain basalts have a similar range of 1-atmosphere liquidus temperatures to those of basaltic suites elsewhere but that the tholeiitic andesite liquid fell in a much lower range, 1075–1110°C, comparable with such rocks as nepheline mugearite from Anjouan, Comores Archipelago, Indian Ocean, and benmoreite from Skye, N.W. Scotland (Thompson, 1972a). Thompson (1975a) has studied the 1-atmosphere melting behaviour of the tholeiitic andesites as a function of oxygen fugacity and deduced that, at their liquid, the fractionating magmas fell on a T/f_{O_2} curve sub-parallel to and slightly below that for the univariant assemblage Ni + NiO.

Statement of Problems

Tilley and Thompson (1970) suggested that the compositional variation within the basaltic and tholeiitic andesite groups was produced by fractional crystallization of liquids approximately represented by the most-magnesian members of each suite. They envisaged this process taking place at relatively low pressures; the precipitating phases being those forming phenocrysts in the lavas. They were reasonably certain that the basalts and tholeiitic andesites were genetically connected by some process dominated by fractional crystallization, but were unsure of its precise nature. At first sight the Sr, O and Pb isotope data may be used

to show that the tholeiitic andesites are simply basalts, heavily contaminated by assimilation of ancient crustal rocks. However, both Tilley and Thompson (1970) and Leeman and Manton (1971) rejected this hypothesis after consideration of the major-element chemistry of the lavas. If, as seems reasonable, the genetic link between the basaltic and tholeiitic andesite suites as a whole is considered to involve the relationship between the least-magnesian Snake River Plain basalts

Table 1. Estimates of crystalline fraction required to separate from Snake River Plain basalt 59-P-13 to produce tholeiitic andesite ORB2.

	Mix 1		Mix 2		Mix 3		Mix 4	
	59-P-13	Misfit	59-P-13	Misfit	59-P-13	Misfit	59-P-13	Misfit
	estm		estm		estm		estm	
SiO_2	48.41	+0.09	47.47	-0.85	48.65	+0.33	47.16	-1.16
Al_2O_3	14.20	-0.23	14.92	+0.49	14.07	-0.36	13.71	-0.72
FeO^*	13.45	-0.24	13.66	-0.03	13.46	-0.23	14.38	+0.59
MnO	0.24	0.00	0.21	-0.03	0.22	-0.02	0.24	0.00
MgO	7.25	+0.09	7.13	-0.03	7.18	+0.02	6.99	-0.17
CaO	9.30	+0.19	7.98	-1.13	8.73	-0.38	9.79	+0.68
Na_2O	2.76	+0.09	3.15	+0.48	2.96	+0.29	2.77	+0.10
K_2O	0.73	-0.02	1.46	+0.71	1.22	+0.47	1.14	+0.39
TiO_2	3.15	+0.10	3.01	-0.04	2.72	-0.33	3.13	+0.08
P_2O_5	0.52	-0.05	1.00	+0.43	0.78	+0.21	0.78	+0.21
ΣR^2		0.19		3.16		0.90		2.91

* All Fe taken as FeO.

(Components used in the mixes are:

59-P-13 = Snake River Plain olivine tholeiite (Table 2, No. 2).

ORB2 = Snake River Plain tholeiitic andesite (Table 2).

Glass = Groundmass glass of 59-P-13 (unpublished microprobe analysis).

OI pheno = Olivine phenocryst (core) in 59-P-13 (Thompson, 1972b, Table 26).

Plag pheno = Plagioclase phenocryst (core) in 59-P-13 (Thompson, 1972b, Table 26).

Pl 8 Kb, Pl 8 Kb, Cpx 8 Kb = olivine, plagioclase and Ca-rich clinopyroxene from 8 Kb/1150°C run on 59-P-13 (Table 4 below; Thompson, 1972b, Table 26).

Cpx 26 Kb, Gr 26 Kb = Ca-rich clinopyroxene (Table 4) and garnet (Thompson, 1975b) from 26 Kb/1325°C run on 59-P-13.

Mix 1: 74 Glass + 9 OI pheno + 17 Plag pheno = 100 59-P-13.

Mix 2: 71 ORB2 + 11 OI pheno + 18 Plag pheno = 100 59-P-13.

Mix 3: 55 ORB2 + 7 OI 8 Kb + 21 Pl 8 Kb + 17 Cpx 8 Kb = 100 59-P-13.

Mix 4: 55 ORB2 + 37 Cpx 26 Kb + 8 Gr 26 Kb = 100 59-P-13.

The parts of each mix are in weight percent. Estimates are obtained by a least squares computer method (Wright and Doherty, 1970).

(those with lowest 1-atmosphere liquid) and the most-magnesian tholeiitic andesites (with highest 1-atmosphere liquid), the process involves the following major element changes: going from basalt to tholeiitic andesite, SiO_2 falls slightly whilst total Fe, TiO_2 and P_2O_5 rise substantially. To produce such changes by assimilation would clearly involve dissolution of rather exotic country rock (phosphatic ironstone?) which did not yield a cotectic liquid of broadly granitic composition

when partially melted. As it happens, all the xenoliths recorded in the tholeiitic andesites are of quartz-feldspathic gneiss.

Tilley and Thompson (1970) noted that clinopyroxene was a late crystallizing phase in all the Snake River Plain lavas studied experimentally at one atmosphere by them. Thompson (1972a) suggested that this was most simply explained by postulating a genetic scheme, perhaps at moderate or high pressures, in which pyroxene was a major fractionating phase. The data in Table 1 show that separation of a pyroxene-rich precipitate, such as would crystallize at moderate pressure (8 to 12 kb), from a representative of the less-magnesian Snake River Plain basalts gives a residuum which approximates reasonably in composition to the most-magnesian tholeiitic andesite of the King Hill series, whereas separation of the phenocrysts occurring in the basalt alone is unable to accomplish this. Thompson (1972c) noted that, whatever the genetic connection between the basalts and tholeiitic andesites, it appeared to differ from the conventionally- envisaged differentiating magma chamber tapped at regular intervals, because the compositions of the lavas reaching the surface were strongly bimodal (Fig. 1).

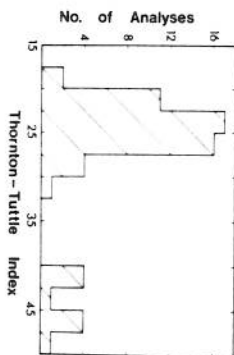


Fig. 1. Histogram of Thornton-Tuttle indices of Snake River Plain basalts and tholeiitic andesites. Data sources are Stone (1967) and Tilley and Thompson (1970).

The study reported here is an attempt to answer the following questions:

1. Can a high-pressure model be developed which successfully relates the tholeiitic andesites, with their highly characteristic major element chemistry, to the predominating basalts of the Plain?
2. Can this model explain why the tholeiitic andesites are so heavily contaminated by crustal Sr, O and Pb when there is so little evidence for large-scale bulk assimilation by them of crustal rocks?
3. Why are there so few intermediate compositions between the basalts and tholeiitic andesites at the surface?
4. What light can be shed on the genesis of the basalts?

High-Pressure Melting Experiments

High-pressure melting experiments have been carried out on one of the least-magnesian basalts (59-P-13) and the most-magnesian tholeiitic andesite (OB32) from the set of Snake River Plain lavas used by Tilley and Thompson (1970). Charges of dried finely-ground rock powder were enclosed in graphite capsules

and run in piston-cylinder apparatus. Details of experimental techniques and the methods used to analyze run products have been given elsewhere (Thompson, 1974a).

Olivine Tholeiite 59-P-13

The two analyses which previously have been made of material with this field number differ slightly in their silica saturation (Tilley and Thompson, 1970, Table 1). The particular batch of powder used for the experiments was therefore analyzed by electron microprobe, using the all-glass products of runs at 30 kb/1430° C and 35 kb/1490° C. The result is given in Table 2. The rock is extremely fresh and largely tachylitic, consisting of 9 weight percent of <2 mm olivine and 17 percent of <6 mm plagioclase phenocrysts (Table 1), together with <1 percent of dark brown spinel microphenocrysts, in a matrix of pale brown glass. Relevant mineral analyses have been published previously (Thompson, 1972b, 1973b). The zoning ranges of the phenocrysts are: olivine, $Fe^{2+}_{72.6}$ cores to $Fe^{2+}_{69.4}$ rims; plagioclase, $An_{65.3}$ to $An_{50.0}$; spinel, complex zoning from titanum chromite to chromian titanomagnetite (Thompson, 1973b).

An interpretation of thermal experiments on this lava from one atmosphere (Tilley and Thompson, 1970) to 35 kb is given in Fig. 2. Its melting interval is dominated at low pressures by the solid phases olivine, plagioclase and Ca-rich

Table 2. Chemical analyses and CIPW norms of Snake River Plain lavas used in high-pressure melting experiments

	1	2	3		1	2	3
SiO ₂	47.76	48.21	47.17	or	4.45	4.31	11.68
Al ₂ O ₃	14.93	14.38	13.34	ab	22.01	22.85	28.82
Fe ₂ O ₃	1.36	—*	2.54	an	26.69	24.96	15.01
FeO	12.37	13.55	12.93	di	13.57	13.94	11.63
MnO	0.20	0.21	0.23	by	15.49	13.44	8.02
MgO	6.70	9.41	4.42	il	8.37	13.18	9.15
CaO	9.41	7.18	7.68	mt	5.78	5.68	7.90
Na ₂ O	2.62	2.70	3.40	ap	2.09	3.71	3.76
K ₂ O	0.75	0.73	2.00	cc	1.34	1.30	—
H ₂ O ⁺	nil	nil	0.33	rest	0.03	—	0.10
H ₂ O	0.03	nil	0.15				0.10
CO ₂	0.01	nil	0.04				0.48
FeO ₂	3.03	2.99	4.15				
P ₂ O ₅	0.53	0.56	1.39				
Total	99.70	99.66	99.77				

* All Fe taken as FeO in analysis 2 and its norm.

1 Olivine tholeiite (59-P-13). McKinney Basalt, Snake River Group, mouth of Malad River, Gooding Co., Idaho. Analyst D.F. Powers (U.S. Geol. Survey).

2 Microprobe analysis of glass product of high-pressure, supra-liquidus runs on 59-P-13 (see text). Mean of 10 complete analyses by R. N. T.

3 Tholeiitic andesite (OB32). Brunen Formation, Idaho Group, 8 km W of King Hill, Elmore Co., Idaho. Analyst P. Montalto (U.S. Geol. Survey).

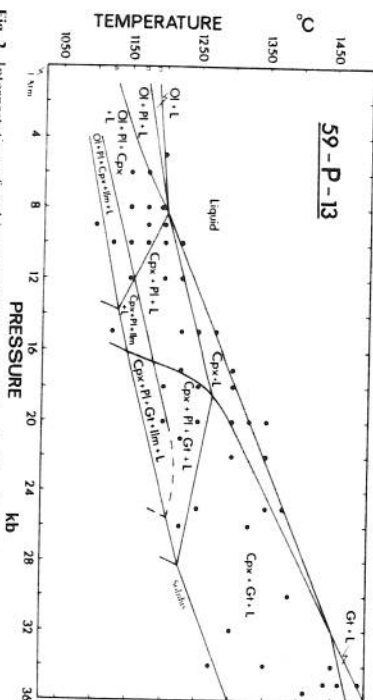


Fig. 2. Interpretation of melting experiments on olivine tholeiite 59-P-13. Runs are indicated by dots. Products of experiments correspond with labeled phase fields. Boundaries of phase fields are drawn as straight lines, wherever no positive evidence has been found for their curvature. Key to phases: *Ol*, olivine; *Cpx*, "Ca-rich" clinopyroxene (including subcalcic augite); *Pl*, plagioclase; *Gr*, garnet; *Ilm*, ilmenite. Open symbols at one atmosphere are first appearance temperatures of phases upon cooling: $\circ$, olivine; $\square$, plagioclase; Δ , Ca-rich clinopyroxene.

clinopyroxene and at high pressures by Ca-rich clinopyroxene and garnet. Ilmenite appears in small quantities near the solidus at pressures below about 25 kb. No Ca-poor pyroxene was detected. Olivine is the liquidus phase up to about 8 kb, where it is replaced at higher pressures by pyroxene. A surprising feature of this *P-T* diagram is that the field of plagioclase precipitation also appears to reach the liquidus at the intersection of the olivine and pyroxene melting curves, thus generating a four-phase point. The known errors in the quoted pressures and temperatures of the experiments (Thompson, 1974a) are too large for this interpretation of the 6 to 10 kb near-liquidus region of Fig. 2 to be regarded as certain. However, it is consistent with all the available data.

Tholeiite Andesite OB32

This near-aphyric holocrystalline lava consists of < 2 mm phenocrysts of olivine (0.1 volume percent), plagioclase (0.7 percent) titanomagnetite (0.6 percent) and a trace of apatite in a groundmass of these phases, augite and ilmenite. A chemical analysis of the rock is given in Table 2. Relevant mineralogical data are given in Table 3. An interpretation of melting experiments from one atmosphere (Thompson, 1975a) to 35 kb is given in Fig. 3.

The *P-T* diagram for this composition is similar to that for the basalt (Fig. 2), except that it is displaced towards somewhat lower temperatures. The appearance of a liquidus 4-phase point (olivine + plagioclase + Ca-rich clinopyroxene + liquid) at 8 kb in this *P-T* diagram is, as with the basalt (Fig. 2) an unexpected relationship which cannot be explained convincingly as merely the coincidental crossing of

Table 3. Microprobe analyses of minerals in OB32.

	1	2	3	4	5	6	7
SiO ₂	36.1	56.0	64.2	48.4	0.19	0.21	0.19
Al ₂ O ₃	0.07	26.9	18.9	3.36	2.45	1.33	0.15
Fe ₂ O ₃	—	0.03	0.02	0.00	0.17	0.07	0.02
FeO*	31.8	—	0.57	—	21.0	18.8	4.53
MnO	0.52	0.00	0.05	12.6	48.3	50.3	40.9
MgO	31.0	0.07	0.02	11.0	0.55	0.63	0.67
CaO	0.27	10.2	1.88	20.4	2.84	1.53	2.07
Na ₂ O	—	5.30	6.26	0.50	—	—	—
K ₂ O	—	0.66	6.84	0.01	—	—	—
TiO ₂	0.06	0.12	0.25	2.43	23.6	24.5	50.2
Total	99.8	99.9	99.0	99.0	99.1	97.4	98.7

(Cation proportions)

	0=4	0=32	0=32	0=6	0=32	0=32	0=6
Basalt	0.4	0.32	0.32	0.6	0.32	0.32	0.6
Si	0.99	10.14	11.74	1.86	0.05	0.06	0.01
Al	0.00	5.74	4.07	0.15	0.85	0.47	0.01
Cr	—	0.00	0.00	0.00	0.03	0.01	0.00
Fe ³⁺	—	0.09	0.08	—	4.57	4.28	0.17
Fe ²⁺	0.73	—	—	0.40	11.90	12.76	1.73
Mn	0.01	0.00	0.01	0.01	0.13	0.16	0.03
Mg	1.27	0.02	0.01	0.63	1.24	0.68	0.16
Ca	0.01	1.98	0.37	0.84	—	—	—
Na	—	1.86	2.22	0.04	—	—	—
K	—	0.15	1.99	0.00	—	—	—
Ti	0.00	0.02	0.03	0.07	5.23	5.57	1.90
Σ	3.01	20.00	20.12	4.00	24.00	23.99	4.01

*All Fe taken as FeO in olivine and pyroxene, Fe₂O₃ in feldspar and allocated assuming stoichiometry in Fe-Ti oxides.

1. Most Mg-rich olivine phenocryst core. Groundmass olivines range to Fe_{0.45}.
2. Most Ca-rich plagioclase phenocryst core. Groundmass plagioclases range to An₄₂.
3. Alkali feldspar. Interstices of groundmass.
4. Ca-rich pyroxene. Interstices of groundmass.
5. Most Al and Mg-rich titanomagnetite phenocryst core. Zoned to rims with Al₂O₃ = 1.98%, MgO = 2.39% and TiO₂ = 24.7%.
6. Titanomagnetite. Groundmass. Very slight zoning detected.
7. Ilmenite. Groundmass. No zoning detected. Calculated equilibration conditions for groundmass Fe-Ti oxides (Buddington and Lindsay, 1964) are: temperature = 1090°C and log *f*_{O₂} = -9.7.

three melting curves. The preferred interpretation, that these liquidus 4-phase points result from pre-eruption cotectic crystallization of both the basalt and the tholeiite andesite at about 8 kb, will be discussed in detail below.

Fe-Ti oxides are more prominent amongst the solid phases in the lower part

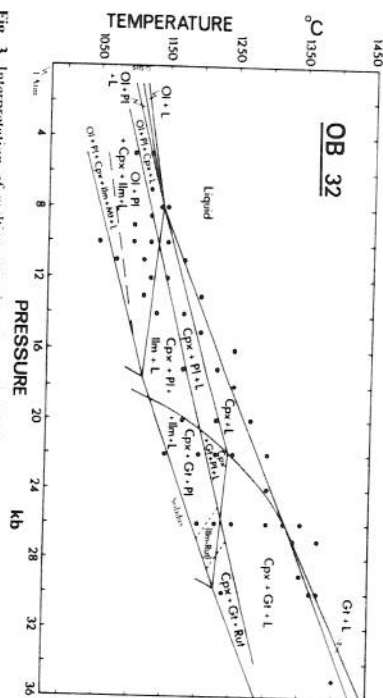


Fig. 3. Interpretation of melting experiments on tholeiitic andesite OB32. Symbols as in Fig. 2. Additional phases: *Mt* titaniferous magnetite, *Rut* rutile.

of the melting range of OB32 than in the basalt. Ilmenite is the main opaque mineral. It appears to be replaced by rutile at near-solidus temperatures above about 25 kb, but the details of this part of Fig. 3 are unclear. Titanomagnetic is only stable near the solidus and at pressures below about 13 kb. This is in accord with the results of a study on the stability of iron oxides within graphitic capsules by Thompson and Kushiro (1972), who showed that the containers buffered their contents at oxygen fugacities within the stability field of wüstite in the system Fe-C-O, at temperatures above the titanomagnetic field in Fig. 3. The extension of the near-solidus stability field of plagioclase to between 25 and 30 kb in both Figs. 2 and 3 reflects the relatively high alkali contents of both OB32 and 59-P-13.

Mineral Compositions

Representative microprobe analyses of minerals crystallizing within the melting intervals of both lavas are given in Table 4.

None of the analyzed olivines are from near-liquidus runs. They are therefore all considerably more Fe-rich than the phenocrysts in the rocks. Analyses are available (Table 5) of liquids (interstitial glasses) coexisting with olivine in four runs on 59-P-13. If the total iron contents are all assumed to be FeO, it is possible to calculate a distribution coefficient for Fe and Mg between olivines and liquids in the form $K_D = X_{Fe}^{Oli} \cdot X_{Mg}^{Liq} / X_{Mg}^{Oli} \cdot X_{Fe}^{Liq}$ where X_{Fe}^{Oli} = mole fraction of FeO in olivine etc. The value for this ranges from 0.209 to 0.336 and shows a marked negative correlation with the temperature difference between that of each run and the liquidus of 59-P-13 at the run pressure. This is probably the effect of ignoring increasing a_{FeO} in the liquids as the crystallization of this bulk composition progresses. If so, the minimum estimate of the true value of K_D will be the highest value of this coefficient obtained (0.336). This agrees

Table 4. Representative microprobe analyses of minerals crystallized in high-pressure experiments

specimen no.	59-P-13													
Pressure kb	8	10	10	12	8	10	10	12	25	25	26	26	34	
Temperature (°C)	1150	1150	1125	1150	1150	1150	1125	1150	1350	1250	1325	1225	1350	
Mineral	Ol	Ol	Ol	Ol	Cpx	Cpx	Ol	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	
Coexisting	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	
Solid phases	Cpx	Cpx	Ilm	Ilm	Ilm	Pl	Ilm	Ilm	Ilm	Ilm	Ilm	Ilm	Ilm	
SiO ₂	36.1	35.8	35.0	35.6	49.3	49.1	48.2	46.6	48.9	49.9	48.6	49.3	50.7	
Al ₂ O ₃	0.14	0.14	0.17	0.14	6.34	4.63	6.37	7.68	11.2	10.4	12.5	9.86	11.4	
Fe ₂ O ₃	0.06	0.06	0.07	0.06	0.13	0.09	0.09	0.07	0.09	0.03	0.02	0.01	0.00	
TiO ₂	33.4	30.8	36.4	34.9	14.0	16.4	17.7	19.6	10.6	11.5	11.6	14.5	9.98	
MnO	0.45	0.39	0.46	0.44	0.34	0.37	0.36	0.37	0.17	0.19	0.20	0.17	0.16	
MgO	30.2	32.0	27.3	28.9	14.6	16.8	12.6	13.3	9.87	13.0	11.7	10.1	9.57	
CaO	0.47	0.41	0.43	0.41	13.3	9.88	10.9	8.67	12.1	13.5	13.5	10.8	13.2	
Na ₂ O	0.06	0.02	0.06	0.05	0.50	0.44	0.63	1.02	1.49	2.21	2.39	2.38	3.42	
K ₂ O	0.03	0.02	0.04	0.02	0.05	0.00	0.36	0.20	0.02	0.02	0.05	0.13	0.02	
Fe ₂ O ₃	0.19	0.19	0.20	0.17	2.16	1.71	2.77	2.39	1.28	1.94	1.75	2.50	1.47	
Total	101.1	99.8	100.1	100.7	100.7	99.4	99.9	99.9	98.9	101.4	100.7	99.8	99.9	
Molar proportions														
Basalt	0 = 4	0 = 4	0 = 4	0 = 4	0 = 6	0 = 6	0 = 6	0 = 6	0 = 6	0 = 6	0 = 6	0 = 6	0 = 6	
Si	0.99	0.98	0.98	0.98	1.83	1.85	1.82	1.77	1.80	1.82	1.78	1.83	1.86	
Al	0.00	0.00	0.01	0.00	0.27	0.21	0.28	0.34	0.49	0.45	0.54	0.43	0.49	
Ti	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	
Mn	0.76	0.71	0.85	0.81	0.43	0.52	0.56	0.62	0.33	0.35	0.36	0.45	0.31	
Mg	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	
Ca	0.01	0.01	0.01	0.01	0.53	0.40	0.44	0.35	0.48	0.53	0.55	0.56	0.52	
Na	0.00	0.00	0.00	0.00	0.04	0.03	0.05	0.07	0.11	0.16	0.17	0.17	0.24	
K	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.01	0.00	
Fe _T	0.00	0.00	0.00	0.00	0.06	0.05	0.08	0.07	0.04	0.05	0.05	0.07	0.04	
Fe ₂	2.99	3.01	3.00	3.00	3.98	4.01	3.97	3.99	3.96	4.00	3.99	3.95	3.98	
(Fe,Mg+Fe)	0.62	0.65	0.57	0.60	0.65	0.65	0.56	0.55	0.69	0.64	0.61	0.55	0.63	
Fe ₂	0.34	0.22	0.21	0.21										

well with the average of recent values (0.33) found for K_D over a wide range of bulk compositions, pressures and temperatures (Cawthorn *et al.*, 1973; Thompson, 1974a).

Chemical variation in the pyroxenes as a function of pressure and temperature is complex and has been described elsewhere (Thompson, 1974b). The representative analyses given in Table 4 show the main features of these high-pressure pyroxenes and contrast with the groundmass augite of OB32 (Table 3). The garnets in Table 4 are typical of the 17 available analyses, which will be published elsewhere (Thompson, 1975b). They are essentially pyrope—almandines and show the following chemical trends: with decreasing temperature at constant pressure the values of Mg/(Mg+Fe) and Cr fall, whilst Ti rises. The behaviour of Ca

Table 4 (continued)

Specimen no.	59-P-13	OB32									
Pressure kb	34	12	10	11	26	8.5	26				
Temperature (°C)	1450	1150	1100	1075	1325	1125	1225				
Mineral	Gr	Ilm	Ol	Ol	Gr	Ilm	Rut				
Coeexisting solid phases	Cpx	Cpx	Pl Cpx	Pl Cpx	Cpx	Ol Pl	Cpx Gr				
SiO ₂	40.3	0.29	33.2	33.1	38.8	0.23	0.26				
Al ₂ O ₃	21.1	0.79	0.14	0.21	20.5	0.57	0.36				
Cr ₂ O ₃	0.10	0.13	0.07	0.06	0.01	0.04	0.01				
Fe ₂ O ₃	—	3.10	—	—	—	0.65	—				
FeO*	15.7	37.8	46.6	47.8	20.3	38.1	1.17				
MnO	0.41	0.32	0.71	0.84	0.63	0.44	0.01				
MgO	12.5	4.49	18.4	17.3	9.93	5.26	0.00				
CaO	8.31	—	0.52	0.50	7.27	—	—				
Na ₂ O	0.11	—	0.08	0.09	0.15	—	—				
K ₂ O	0.00	—	0.05	0.06	0.01	—	—				
TiO ₂	1.10	51.0	0.26	0.27	1.90	53.2	98.2				
Total	99.6	97.9	100.0	100.2	99.5	98.5	100.0				

Cation proportions

Basalt	0=24	0=6	0=4	0=4	0=24	0=6	0=2
Si	6.01	0.01	0.99	0.99	5.92	0.01	0.00
Al	3.71	0.05	0.00	0.01	3.69	0.03	0.01
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	—	0.12	—	—	—	0.02	—
Fe ²⁺	1.95	1.57	1.16	1.19	2.59	1.57	0.01
Mn	0.05	0.01	0.02	0.02	0.09	0.02	0.00
Mg	2.78	0.33	0.82	0.77	2.26	0.39	0.00
Ca	1.32	—	0.02	0.02	1.19	—	—
Na	0.03	—	0.00	0.01	0.04	—	—
K	0.00	—	0.00	0.00	0.00	—	—
Ti	0.12	1.91	0.01	0.01	0.22	1.96	0.99
Σ	15.98	4.00	3.02	3.02	16.00	4.00	1.01

* All Fe taken as FeO, except in Fe-Ti oxides, where stoichiometry is assumed.

K_D is a distribution coefficient for Fe and Mg between olivine and liquid, as defined in text.

Key to phases: Ol = olivine; Pl = plagioclase; Cpx = Ca-rich clinopyroxene; Gr = garnet; Ilm = ilmenite; Mt = magnetite; Rut = rutile.

is far from distinctive. It shows a slight tendency to fall with falling temperature at constant pressure and to rise with rising pressure at constant temperature, but this is not always the case in the set of analyses available. The distribution of Al, Ca, Fe and Mg between coexisting garnets and pyroxenes crystallized from 59-P-13 and OB32 is discussed by Thompson (1974b).

An analysis of *plagioclase* precipitated from 59-P-13 at 8 kb has already been published (Thompson, 1972b). The *P-T* variation of this phase was not studied in detail. However, the available data show clearly that the plagioclase becomes progressively more sodic with rising pressure.

The *clinopyroxene* which appears near the solidus of OB32 at low pressure is richer in Ti and Al and poorer in Cr and Mn than the magnetite in the rock. The near-solidus *ilmenite* crystallizing from 59-P-13 and OB32 is richer in Al and Mg and poorer in Mn than that in the groundmass of the tholeiitic andesite. Details of the variation of this phase as a function of pressure and temperature will be reported elsewhere. Finally, the *rutile* crystallizing near the solidus of OB32 at high pressures is close to pure TiO₂ in composition.

Discussion

Origin of the Tholeiitic Andesites

The Snake River Plain tholeiitic andesites have Mg/Fe ratios much too low for them to be considered as possible direct melts from any currently-envisioned upper mantle material, other than oceanic crust in subduction zones. Hypotheses that they originated by low-pressure fractional crystallization or major element crustal contamination of the associated basalts have been rejected for reasons detailed above. The *P-T* diagrams for 59-P-13 and OB32 (Figs. 2 and 3) may be used to assess possible high-pressure connections between the basalt and tholeiitic andesite, providing that the latter have reached the surface essentially unmodified from the depth at which they were interrelated, other than dissolving their high-pressure phenocrysts during leisurely uprise. It must be stressed that the two compositions studied experimentally are not to be thought of as a possible parent and daughter; the tholeiitic andesite (OB32) is considerably older (Malde and Powers, 1962) than the basalt (59-P-13). These two samples are chosen simply to illustrate the general relationship between the Snake River Plain lava groups.

The *P-T* liquidus curves of 59-P-13 and OB32 are subparallel, with the latter about 60° C below the former (Figs. 2 and 3). At two pressures, 8 and 26 kb, the liquidus phases of OB32 are the same as those crystallizing at that pressure and temperature from 59-P-13. Microprobe analyses of the interstitial glasses in runs made on 59-P-13 at these pressures and temperatures are given in Table 5 (Nos. 2 and 9). Neither composition fits that of OB32 precisely. However, the 8 kb glass is in equilibrium with olivine (Fo_{61.6}) very close in composition to that forming the cores of phenocrysts in OB32 (Fo_{63.5}) and shows all the main features of the most-magnesian Snake River Plain tholeiitic andesites. Relative to the least-magnesian Snake River Plain basalts, the tholeiitic andesites contain less SiO₂, Al₂O₃, MgO and CaO and more total Fe, alkalis, TiO₂ and P₂O₅. The most marked characteristic of the latter is that they are *less silica saturated* than the least-magnesian basalts. This feature is examined in Fig. 4, a normative plot of several analyzed interstitial glasses (Table 5) from runs on 59-P-13. These are divided into two groups: those from the 8 to 12 kb range,

Pressure	8	8	10	10	12	22	25	25	26	30	32	34
Temp. (°C)	117.5	11.50	11.50	11.25	11.50	1.300	1.350	12.50	12.25	1.385	1.300	1.350

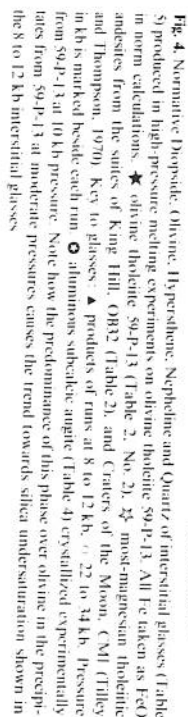
Pressure Temp (°C)	8 1175	8 1150	10 1150	10 1125	12 1180	22 1300	25 1350	25 1250	26 1325	30 1385	32 1400	34 1350
SiO ₂	47.2	46.4	43.9	39.1	40.0	48.6	47.7	55.1	50.9	49.6	55.5	52.0
Al ₂ O ₃	13.5	13.2	13.5	9.72	11.5	15.0	15.0	13.4	14.4	13.5	13.3	12.9
Fe ₂ O ₃	15.6	17.4	19.0	25.2	25.4	14.3	15.1	9.63	13.5	13.9	9.75	10.8
MnO	0.25	0.40	0.31	0.47	0.32	0.24	0.23	0.32	—	0.13	—	—
MgO	6.16	5.58	5.28	3.88	3.97	4.12	4.79	6.04	2.56	3.80	4.85	1.73
CaO	8.78	8.37	8.12	8.31	7.53	7.91	7.63	6.30	7.22	8.07	5.22	5.90
Na ₂ O	2.80	2.64	2.84	2.62	3.03	3.24	2.79	4.13	3.41	3.33	3.61	3.36
K ₂ O	0.92	0.75	0.67	1.21	1.48	1.09	0.89	2.23	1.43	1.18	3.05	4.10
TiO ₂	3.82	4.66	5.37	6.66	5.25	3.73	3.45	4.12	4.13	4.03	5.55	4.57
P ₂ O ₅	0.78	0.91	1.18	2.02	2.57	0.80	0.67	1.40	1.00	0.86	1.58	0.98
Total	99.8	100.5	99.2	99.3	99.3	99.7	99.6	99.2	99.8	99.5	99.3	100.0

Q	5.44	7.30	3.96	7.15	8.75	6.44	5.26	13.2	8.45	6.97	18.0	10.5	2.69
Sub	23.7	22.3	24.0	17.3	20.3	27.4	23.6	35.0	28.9	28.2	30.6	28.4	5.97
am	21.6	20.5	22.2	11.2	13.4	23.3	25.9	11.5	19.8	18.4	10.0	17.1	
one	14.2	12.7	8.83	14.5	6.20	9.05	10.9	8.99	7.99	13.5	3.86	19.8	
ly	11.1	11.5	10.3			14.8	13.5	13.3	23.4	17.9	11.1	15.5	
ly	14.8	15.1	17.1	20.2	31.8	9.81	12.5		4.81				
ly	7.26	8.85	10.1	12.7	9.97	7.08	6.55	7.82	7.84	7.65	10.5	8.17	
P	1.81	2.11	2.73	4.68	5.95	1.85	1.55	3.24	2.32	1.99	3.66	2.27	

Note close correspondence between modes of 0.15 and 0.23

correspondence between mode of 8 kb/1.50°C run and Mix 3 of Table 1.

59-613 intercept the most significant different between OB37 and the 8 to 12 Kt interstitial glasses is that CaO is lower and Na₂O higher in the former than the latter. This may simply be the result of a slightly inappropriate choice of parent composition in what is, self-evidently, an extremely simplified genetic



model. Alternatively, it may reflect a difference of conditions between the anhydrous experiments and the small P_{H_2O} that occurs in natural basaltic magmas. Studies of appropriate hydrous systems (Yoder and Tilley, 1962; Yoder, 1969; Green and Hibbeson, 1970) have shown that even a low P_{H_2O} in a crystallizing basic magma, such as 59-P-13 at 8 kb, would raise the clinopyroxene/plegiclastics ratio of the precipitate, the Ca content of the clinopyroxene and the Ca/Na ratio of the plagioclase. These effects would bring the residual extremely close to the compositions of the more mafic Snake River Plain tholeiitic andesites. The genesis of the less-magnesian King Hill and Craters of the Moon tholeiitic andesites was considered by Tilley and Thompson (1970) to have involved fractional crystallization, with precipitation of olivine, plagioclase, titaniferous magnetite and apatite; of the more mafic compositions in these suites. This proposal has not been investigated further during the present study, because experimental control of f_{O_2} to specified values would become critical within the stability field of titaniferous magnetite. However, detailed 1-atmosphere work by Thompson (1975) has shown that the tholeiitic andesites evolved along a $T-f_{O_2}$ curve subparallel to and slightly below that for the univariant assemblage Ni + NiO. The melting behaviour of plagioclase in the 1-atmosphere runs indicates that P_{H_2O} rose progres-

sively, probably to values of about 0.5 kb, during evolution of the less-magnesian tholeiitic andesites.

Origin of the Basalts

Although the main objective of this study has been to investigate the relationship between the Snake River Plain tholeiitic andesites and basalts, the results have some bearing on the origin of the latter. It was proposed above that the magma liquid at about 25 to 30 km depth: a mechanism consistent with the liquidus 4-phase point in the P - T diagram (Fig. 3) of this lava at 8 kb. As the basalt at about 8 kb, it seems reasonable to suppose that this magma also attained its final bulk composition deep in the Snake River Plain crust and was erupted from about 25 to 30 km depth, unchanged except for dissolution of tellurite and losses of gaseous components. Clearly further studies are required to determine whether other less-magnesian Snake River Plain basalts have evolved at similar depths.

Insufficient is known about the chemical range of the Snake River Plain lavas to provide a sound factual basis for comprehensive discussion of the genesis of the more-magnesian basalts and, hence, of the ultimate origin of the magmas. Any final model must take into account the widely varying Si-saturation in basalts at constant values of MgO in this province (Stone, 1967). This feature also characterizes the basalts of Skye, NW Scotland, and has recently been discussed at length in that context (Thompson, Esson and Dunham, 1972; Thompson, 1974a).

If the currently-available analyses are a representative sample (Stone, 1967; Tilley and Thompson, 1970; Leeman and Rogers, 1970), the most-magnesian basalts (11 percent MgO) reaching the surface of the Snake River Plain are very similar to the most-magnesian basalts of Skye, except that the latter are slightly less Si-saturated. It is therefore possible to make tentative predictions about the high-pressure melting behaviour of Snake River Plain magnesian basalts by analogy with the experimental study of Skye magnesian basalt 66018 (Thompson, 1974a, Fig. 4). Thus, although the former contain only olivine phenocrysts (when sparsely porphyritic) and lie in the field of primary olivine precipitation at one atmosphere (Tilley and Thompson, 1970), it is probable that Ca-poor pyroxene is a major phase within their crystallization interval in the 12 to 20 kb was to show a liquidus 4-phase point (olivine + Ca-rich pyroxene + Ca-poor pyroxene + liquid), like that of Skye basalt 66018 (Thompson, 1974a, Fig. 4), it would probably occur between about 15 and 20 kb. The significance of this speculation to Snake River Plain basalt genesis is shown in Fig. 5. Here the calculated geothermal gradient for the Plain (Blackwell, 1971), which is part of the Basin and Range high heat flow province, is plotted together with the liquidus P - T curve for Skye basalt 66018, serving as an analogue for Snake River Plain magnesian

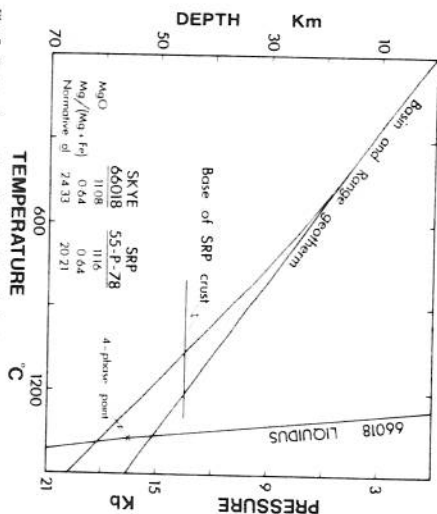


Fig. 5. Comparison of predicted melting behaviour of the most-magnesian Snake River Plain basalt (55-P-28) recorded amongst published analyses (see text) with geophysical data for the Plain. Limiting values of Basin and Range geotherm from Blackwell (1971). Depth to base of Snake River Plain crust from Hill and Pakiser (1967). Liquidus of Skye magnesian basalt 66018 from Thompson (1974a). Significant chemical similarities between this and 55-P-28 are tabulated on the diagram. See text for arguments supporting use of Skye basalt 66018 as an analogue for the likely high-pressure melting behaviour of Snake River Plain magnesian basalts.

basalts. The 4-phase point on the liquidus of 66018 at 16.5 kb was taken by Thompson (1974a) to indicate that this lava was a primary magma, generated by partial melting of lherzolite upper mantle at about 55 to 60 km depth beneath Skye. It is clear from Fig. 5 that a genetic model in which the Snake River Plain magnesian basalts are also generated by upper mantle partial fusion at about 50 to 60 km depth is consistent with the heat flow in that area. It carries the implication, again by analogy with the Skye lavas, that the source lherzolite in equilibrium with the basaltic melts has an Mg/(Mg + Fe) ratio of approximately 0.85 (Thompson, 1974a).

A Genetic Model

The proposal that the most-magnesian basalts on the surface of the Snake River Plain may be primary magmas generated within a comparatively Fe-rich spinel-lherzolite upper mantle only 10 km or so beneath the base of the crust is in accord with the relatively low seismic velocities and high seismic attenuation in this zone recorded by Hill and Pakiser (1967). It seems generally to be agreed that the Snake River Plain occupies a zone of tension in the crust of the Western U.S.A. (Hamilton and Myers, 1966; Christiansen and Lipman, 1972). Discussion of how the tectonics of this region may have evolved is outside the scope of

the present paper. If it is presumed that the Plain was originally an area with normal continental granitic crust, then the geophysical data of Hill (1963) and Hill and Pakiser (1967) imply that extensive wedging apart of this crust by basaltic magma has taken place. Weertman (1971) has given a theoretical analysis of how such wedging might occur in a lithospheric plate undergoing tension. Isostatic adjustment of the developing mafic crustal zone would result in sinking, giving the thick crust (Fig. 5) and the subsidence features seen at the surface.

The factors currently influencing the range of magmas erupted on the Snake River Plain appear to be:

1. After generation by upper mantle partial fusion, some of the batches of magmatic basalt magma are at sufficient overpressure (Maaloe, 1973) to rise immediately to the surface.
2. Other magmatic basalt batches at lower overpressures are delayed for varying lengths of time deep in the crust, evolving by partial crystallization into compositions such as 59-P-13 (Table 2).
3. Some magma batches rise from beneath the margins of the Plain and enter the flanking granitic crust. The comparatively low density of this acts as a severe barrier to the denser mafic magma, which halts and commences to crystallize in sill-like bodies. During this process water is drawn into the residual magma from surrounding ancient crustal rocks. Such movement of water (and other volatile species) between granitic crust and developing tholeiitic andesitic magmas provides a possible explanation for the "crustal" Sr, Pb and O isotopic ratios of the latter. Eventually the residua of these delayed magma batches are expelled from their deep-crustal residences and proceed to the surface. It has been suggested previously that rising P_{H_2O} may be the impelling agent and that the requirement that this exceeds a critical value before the deep-crustal magma bodies are ruptured could explain the bimodality of lava compositions reaching the surface (Thompson, 1974a).
4. It is apparent from comparison of Figs 2 and 5 that, if the lower crust beneath the western Snake River Plain is composed of basic rocks similar in composition to 59-P-13, these may well be undergoing incipient refusion and therefore could be the source of the sporadic acid magmas erupted at the surface.

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