Jurassic volcanic glass from the Stonyford volcanic complex, Franciscan assemblage, northern California Coast Ranges

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ABSTRACT

Hyaloclastite breccias that occur near the top of the Stonyford volcanic complex contain abundant volcanic glass and rare basaltic clasts that have not been altered significantly by hydrothermal processes or by subsequent metamorphism. They resemble hyaloclastites observed in the summit regions of young Pacific seamounts, and appear to have formed by submarine fire fountains, during which globules of the erupting lava were fragmented by thermal shock from contact with seawater. These breccias contain the first-reported occurrence of unaltered olivine (Fo_{86}) and plagioclase (An_{63-80}) in volcanic rocks of the Franciscan complex.

The glasses are rich in K_2O, Nb, Zr, Rb, and Sr relative to both normal and enriched mid-ocean ridge basalt (MORB), and low in Y, V, and Sc. Pillow lavas intercalated with the hyaloclastites and a crystalline basalt clast have similar compositional characteristics. These magmas are similar to alkalic and transitional basalts that are common in intraplate seamounts and along oceanic spreading centers associated with large ion lithophile element (LILE)-enriched mantle plumes. Other volcanic rocks of the Stonyford complex are LILE-rich tholeiitic basalts and ferrobasalts characteristic of intraplate seamounts. A heterogeneous source region that has at least two distinct end members is suggested by the Zr-Nb systematics: depleted suboceanic asthenosphere (normal MORB-type source) and enriched asthenosphere.

INTRODUCTION

Volcanic glass is rarely preserved in most ancient volcanic rocks, but its presence implies that hydrothermal processes and metamorphism have not significantly altered the composition of the quenched lava since its eruption. As a result, ancient volcanic glass provides us with a unique perspective on the geochemistry of these lavas and their mantle source region. Volcanic glass has been reported from rocks as old as 1.1 Ga (Palmer et al., 1988), but most terrestrial glasses are younger than Miocene in age (Marshall, 1961).

The Stonyford volcanic complex comprises a thick accumulation of basaltic pillow lava and diabase of Late Jurassic age (Tithonian) exposed in serpentinite-matrix melange in the northern Coast Ranges of California (Brown, 1964; Hopson et al., 1981; Shervais and Kimbrough, 1987). The occurrence of volcanic glass in the Coast Ranges was first reported by Brown (1964), who mapped four separate horizons of glass-rich volcanic breccia in the Stonyford complex that are intercalated with pillow lava. We report here the first geochemical data on glass from these breccias, and mineral analyses of unaltered olivine, plagioclase, and Cr-spinel microphenocrysts. These unique basaltic glasses provide us with an unambiguous look at magma compositions in Jurassic ocean crust and, by inference, with the chemical systematics of their mantle source region.

FIELD RELATIONS

The Stonyford volcanic complex crops out toward the southern end of the Round Mountain serpentinite-matrix melange (Jayko et al., 1987) in the northern California Coast Ranges (Fig. 1). It forms an ovoid mass approximately 8 × 5 km in plan; its estimated stratigraphic thickness is at least 1 km and possibly as much as 2.5 km (Brown, 1964). The complex consists largely of pillow lava, but massive diabasic flows and/or sills are common near the base of the section. Chert forms a prominent horizon about

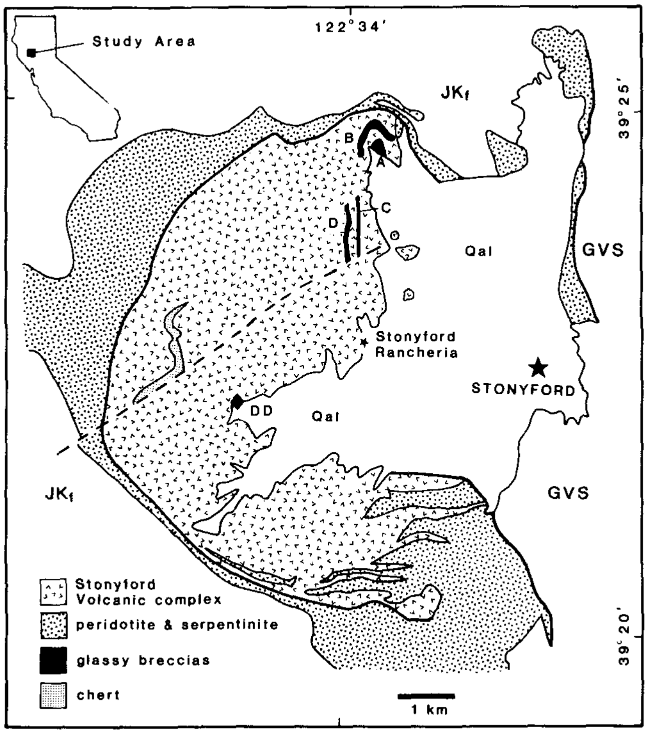

Figure 1. Simplified geologic map of Stonyford volcanic complex (after Brown, 1964). Hyaloclastite beds are shown in black and labeled A, B, C, D. Samples are from horizon A (SFVG-1, SFVG-2), horizon B (SFVG-3), and horizon D (SFVG-5). GVS = Great Valley Series; JK$_f$ = Franciscan Complex; DD = Stony Creek diversion dam; Qal = Quaternary alluvium.

signs of resorption or textural disequilibrium (Fig. 2C). Plagioclase (An_{72-80}) and Cr spinel are unaltered, but olivine microphenocrysts are commonly replaced by smectite. Olivine is preserved locally; however, it ranges in composition from Fo_{86} to Fo_{87} (Table 1).

The crystalline basalts are characterized by intersertal to vitrophyric textures; abundant plagioclase laths (An_{62-73}) enclose patches of glass and/or quench pyroxene (Fig. 2D). Microphenocrysts of olivine (replaced by smectite), plagioclase (An_{70-76}), and Cr spinel are sparse. The quench pyroxene is characterized by a branching, dendritic morphology and by unusual Ti-rich fassaite compositions, with up to 5 wt% TiO_2 and 9 wt% Al_2O_3 (Table 1).

GEOCHEMISTRY

Major Elements

All the glasses are alkali or transitional basalts that have high concentrations of Al_2O_3, Na_2O, K_2O, and P_2O_5, and low FeO*/MgO ratios relative to normal mid-ocean ridge basalts (MORB) (Table 2). These compositions are in contrast to the tholeiitic basalts and ferrobasalts that compose most of the Stonyford complex (Shervais and Kimbrough, 1987). In a plot of TiO_2 vs. FeO*/MgO, the glasses plot at the primitive end of the array defined by Franciscan metabasalts in general and by other volcanic rocks of the Stonyford complex. SFVG-5 is slightly fractionated, and least-squares mixing models show that it can be related to the other glass samples by 1%–2% fractional crystallization of the observed phenocryst phases. Pillow lavas intercalated with the hyaloclastites (SFVP-1 and SFVP-2) have major-element concentrations similar to the volcanic glass samples but are significantly more evolved, with higher TiO_2, FeO, Na_2O, K_2O, P_2O_5, and FeO*/MgO (Table 2). Least-squares mixing models show that the pillows can be related to the glasses by approximately 30% fractional crystallization of the observed phenocryst phases, with good fits for all elements except Ca (too low) and Na (too high). This suggests that the pillows lost Ca and gained Na during alteration. The single crystalline basalt clast analyzed, SFVB-3-X3, is similar in composition to the volcanic glass but has lower TiO_2 and K_2O (Table 2).

Trace Elements

All the samples studied here are characterized by high concentrations of the incompatible trace elements Nb, Zr, Sr, Rb, and Ba, and by low concentrations of Y, V, and Sc (Table 2). The latter elements are compatible with refractory mantle assemblages at low degrees of partial melting, and low concentrations are characteristic of other Franciscan alkali and transitional basalts (Shervais and Kimbrough, 1987). SFVG-5 has slightly lower Cr and Ni than the other glasses and slightly higher Zr and Rb, consistent with major-element data that suggest it is more evolved than the other glasses. The pillow lavas SFVP-1 and SFVP-2 are even higher in Nb, Zr, Y, Rb, and V and lower in Ni, Cr, and Sr than the glasses, consistent with major-element data that suggest they are related to the glass samples by crystal fractionation. The basalt clast SFVB-3-X3 is lower in the HFS elements than the volcanic glasses but shares their characteristic low concentrations of Sc, V, and Y (Table 2).

DISCUSSION

Magmatic Affinity of the Stonyford Glasses

Despite field and petrographic evidence showing that these lavas erupted in a submarine environment, the volcanic glasses studied here do not correspond to MORB formed at normal spreading centers. The glasses have moderate Na_2O concentrations, but K_2O and Nb are three to four times higher than either normal or enriched MORB. Although high K_2O is commonly associated with orogenic volcanic suites, origin of the Stonyford magmas in an island-arc setting is ruled out by their high concentrations of the HFS elements TiO_2 (~2.0 wt%), Nb (13–22 ppm), and Zr (190–212 ppm).

The Stonyford glasses seem to be most closely related to within-plate alkali basalts or enriched

TABLE 1. REPRESENTATIVE MINERAL ANALYSES, STONYFORD VOLCANIC COMPLEX, CALIFORNIA

	1	2	3	4
SiO_2	39.90	50.40	44.98	0.01
TiO_2	0.00	0.00	3.58	1.15
Al_2O_3	0.05	31.63	7.52	33.84
Fe_2O_3	0.00	0.00	0.00	7.80
FeO	12.81	0.41	9.11	13.43
MnO	0.25	0.00	0.15	0.16
MgO	46.67	0.19	11.26	16.11
CaO	0.30	14.87	22.05	0.04
Na_2O	0.00	2.37	0.38	0.00
K_2O	0.00	0.14	0.00	0.00
Cr_2O_3	0.04	0.00	0.11	27.26
	100.02	100.01	99.14	99.80

Note: Electron microprobe analyses, University of South Carolina Cameca SX-50 with natural and synthetic mineral standards, 15 kV potential, and 25 nA beam current. Column 1 = olivine microphenocryst in glass, $Fo_{86.4}$; Column 2 = plagioclase phenocryst in glass, An_{76}; Column 3 = quench pyroxene in basalt clast, Wo_{49} En_{35}; Column 4 = Cr-Spinel microphenocryst in glass, Cr/Cr + Al = 35.1.

TABLE 2. ANALYSES OF WHOLE ROCK SAMPLES FROM STONYFORD VOLCANIC COMPLEX, CALIFONIA

	SFVG-1 Glass	SFVG-2 Glass	SFVG-3 Glass	SFVG-5 Glass	SFVB-3X3 Clast	SFVP-1 Pillow	SFVP-2 Pillow
Oxides (wt %)							
SiO_2	48.20	48.30	48.70	48.11	49.06	49.10	49.69
TiO_2	1.94	2.00	1.99	2.02	1.90	2.56	2.42
Al_2O_3	17.13	17.50	17.40	17.29	19.77	17.35	16.12
FeO*	8.35	8.58	8.47	8.31	6.56	10.96	10.04
MnO	0.15	0.16	0.18	0.13	0.09	0.22	0.18
MgO	7.62	7.78	7.82	7.28	5.09	4.90	5.36
CaO	10.81	10.93	10.91	10.54	14.05	8.68	10.26
Na_2O	2.66	2.76	3.15	3.24	2.61	4.63	4.49
K_2O	0.40	0.82	0.80	0.92	0.59	0.84	0.71
P_2O_5	0.30	0.30	0.29	0.30	0.27	0.44	0.39
	97.56	99.13	99.71	98.14	99.99	99.68	99.66
LOI	n.d.	n.d.	n.d.	n.d.	n.d.	3.35	3.72
FeO*/MgO	1.10	1.10	1.08	1.14	1.29	2.24	1.87
Trace elements (ppm)							
Nb	22	17	13	16	8	29	21
Zr	193	196	194	212	145	226	214
Y	31	34	32	29	28	48	34
Sr	800	812	968	669	398	462	421
Rb	14	10	9	19	12	23	22
Ni	131	130	140	109	152	82	35
Cr	208	210	218	186	214	42	45
V	252	263	260	255	263	300	296
Sc	30	30	28	31	30	32	34
Ba	236	269	353	285	148	237	197
Zn	72	86	88	104	109	173	163
Cu	65	66	67	66	53	34	16
Ti/Zr	61.6	61.4	61.4	58.3	78.8	67.9	67.7
Ti/V	46.1	45.5	45.8	47.5	43.3	51.2	48.9
Zr/Y	6.3	5.8	6.0	7.4	5.2	4.7	6.3
Zr/Nb	9.0	11.2	15.5	12.9	17.5	7.8	10.2

NOTE: Major elements determined by electron microprobe analysis of natural volcanic glass and fused whole-rock powders of basalt using University of South Carolina Cameca SX-50 EMP with basaltic glass and natural mineral standards. Basalt clast was fused without ignition, pillow lavas were fused from ignited powders. Na_2O was first element analyzed on the light spectrometer to minimize volatilization, and five to ten separate spots were averaged for each sample. LOI = Loss on ignition at 1050°C. Trace element analyses are by X-ray fluorescence analysis using the Philips PW-1400 automated XRF spectrometer at the University of South Carolina and U.S. Geological Survey rock standards. Glass is volcanic glass and clast is crystalline basalt clast, both from hyaloclastite breccia; pillows are pillow lavas intercalated with breccias. Analytical uncertainty (one sigma): 5-10% = Zr, Sr, Rb, Ni, Cr, V; 15-25% = Nb, Y, Sc, Ba, Zn, Cu.

(E-type) MORB associated with a large ion lithophile element (LILE)–enriched mantle plume or small-scale mantle heterogeneities (e.g., Batiza and Vanko, 1984; Batiza et al., 1982, 1984; Zindler et al., 1984; Humphris et al., 1985; Dupuy et al., 1988). The glasses are strongly enriched in Zr relative to normal MORB (Zr = 200 ppm), but are low in TiO_2 and have Ti/Zr ratios of 60–65 (Fig. 3). The Stonyford glasses have Zr/Y ratios >4, which is characteristic of within-plate basalts (Pearce and Cann, 1973), and Ti/V ratios = 45–50, characteristic of alkali basalts and enriched tholeiites from seamounts (Shervais, 1982). Pillow lavas associated with the hyaloclastite beds, the crystalline basalt clast SFVB-3-X3, and basalts that directly underlie the central chert horizon have similar high Zr/Y and Ti/V ratios. Tholeiitic basalts and ferrobasalts that compose most of the Stonyford complex are enriched in both TiO_2 and Zr, and have trace-element ratios typical of enriched MORB or ocean-island tholeiite (Ti/Zr = 85, Zr/Y <4, Ti/V = 20–40; Fig. 3).

Many of the chemical systematics discussed above are consistent with variable degrees of partial melting of a single enriched source region. This simple explanation is ruled out, however, by the Nb-Zr systematics of the Stonyford volcanic series (Fig. 4). In a plot of Zr/Nb vs. Zr, the Stonyford lavas form a trend from high Zr/Nb, low Zr (i.e., depleted normal MORB characteristics) toward low Zr/Nb, high Zr compositions characteristic of alkali basalt (Fig. 4). These variations cannot arise from variable partial melting, but require preexisting variations in the mantle source region of the magmas. The trend exhibited in Figure 4 implies variable degrees of mixing between two contrasting end members, one represented by LILE-depleted asthenophere (normal MORB source), the other by an enriched mantle component. That this variation occurs within a single volcanic seamount implies that the scale of heterogeneity is smaller than the mantle source of the seamount magmas (<1–10 km^3), as proposed by Batiza and Vanko (1984).

Alkalic and transitional basalts similar to the Stonyford glasses are common in young Pacific seamounts, where they are generally associated with more abundant tholeiitic basalts and ferrobasalts (Batiza and Vanko, 1984; Batiza et al., 1984). The glasses are also similar to MORB suites found along some active and fossil spreading centers that have been contaminated by off-ridge hot spots (Humphris et al., 1985; Schilling et al., 1982, 1985). The thick radiolarian chert horizon found in the central part of the complex implies prolonged deposition during a volcanic hiatus and supports an off-axis origin for the lavas that lie above it; lavas found below the chert may have formed at a spreading center or off-axis.

Eruptive History of the Hyaloclastites

The Stonyford hyaloclastites consist almost entirely of angular to subangular glass lapilli of near-uniform composition; rounded or ovoid glass lapilli are also common, but clasts or bombs of crystalline basalt and metabasalt are rare. Thus, the virtually monomict hyaloclastites did not form by the brecciation of preexisting volcanic material, but must represent a primary eruption breccia. The lack of keystone-shaped fragments and curved glass slivers also argues against formation as a pillow-fragment breccia, as does the lack of isolated pillows within the breccia (e.g., Fisher and Schmincke, 1984; Batiza et al., 1984).

The rounded to angular shapes, surface indentations, and glassy character of the lapilli are most consistent with a submarine fire-fountain origin in which the primary mechanism of fragmentation was thermal shock of lava globules as they came into contact with seawater (Fisher and Schmincke, 1984; Lonsdale and Batiza, 1980; Batiza et al., 1984). The rarity of crystalline basalt clasts suggests that the mixing took place at or above the vent-seawater interface as the lava was erupted explosively (e.g., Batiza et al., 1984). Hyaloclastites have been found at depths as great as 2500 m on young seamounts in the Pacific, where they are commonly associated with collapse calderas (Batiza et al., 1984). The occurrence of these hyaloclastites near the top of the volcanic edifice but not at deeper levels is consistent with this association.

Tectonic and Metamorphic History of the Stonyford Complex

The preservation of unaltered volcanic glass implies that hydrothermal fluids had little access to the hyaloclastite beds prior to subduction (or obduction) of the Stonyford complex, and that

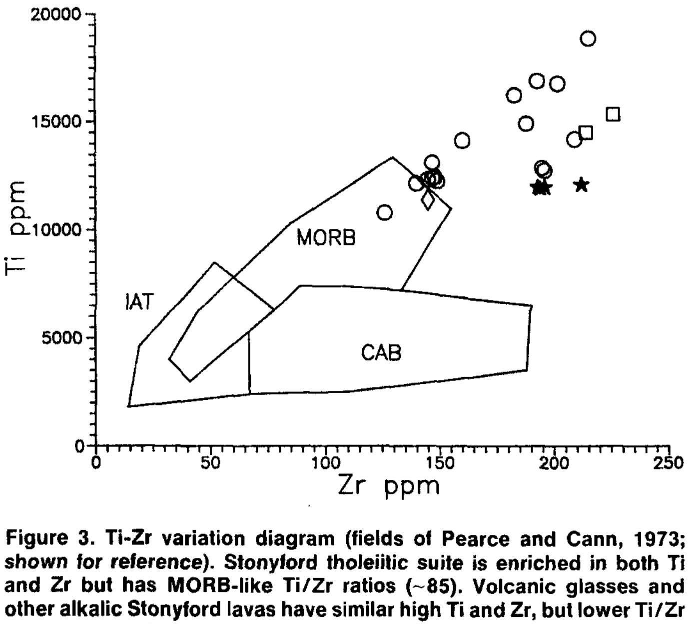

Figure 3. Ti-Zr variation diagram (fields of Pearce and Cann, 1973; shown for reference). Stonyford tholeiitic suite is enriched in both Ti and Zr but has MORB-like Ti/Zr ratios (~85). Volcanic glasses and other alkalic Stonyford lavas have similar high Ti and Zr, but lower Ti/Zr ratios. Stars = Stonyford volcanic glasses; squares = pillow lavas intercalated with hyaloclastites; diamond = basalt clast SFVB-3-X3; circles = other pillow lavas and massive flows of Stonyford volcanic complex (Shervais and Kimbrough, 1987; Shervais, unpub. data).

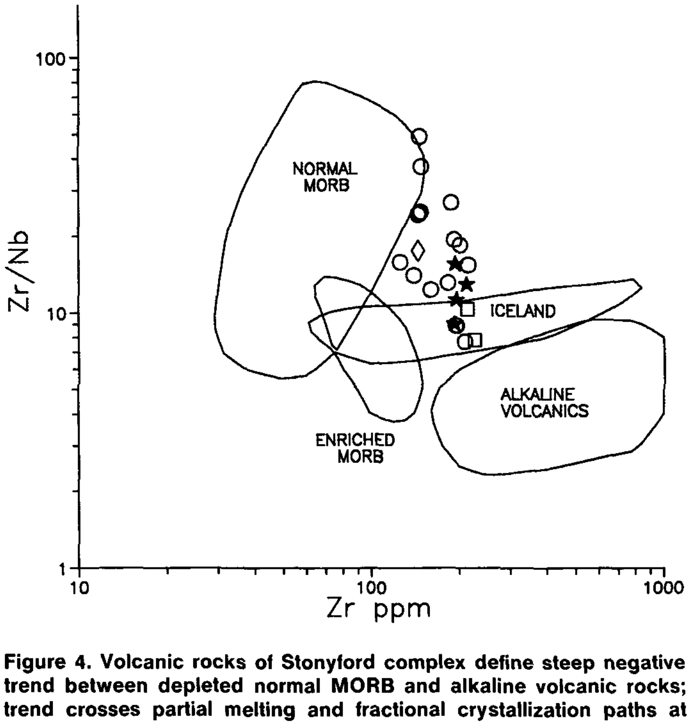

Figure 4. Volcanic rocks of Stonyford complex define steep negative trend between depleted normal MORB and alkaline volcanic rocks; trend crosses partial melting and fractional crystallization paths at nearly right angles. Trend is best explained as mixing line between depleted normal MORB asthenospheric source region and enriched mantle source. Same symbols as Figure 3.

subduction of the complex was arrested before significant metamorphism could occur. Petrographic evidence suggests that the primary mechanism which isolated the glass from hydrothermal fluids was early deposition of calcite cement in the interstices of the breccia; the calcite cement may have been deposited from cold seawater shortly after eruption. Botryoidal surfaces and subhedral crystal faces observed on calcite adjacent to analcite show that the calcite was deposited in open voids prior to compaction of the breccia. Analcite deposition and heulandite replacement of glass probably occurred at higher temperatures that did not exceed 100 °C. This estimate is based on the upper stability limits of analcite in natural systems (e.g., Boles, 1978) and on the reaction heulandite + smectite → laumontite (Evarts and Schiffman, 1983).

The lack of high-pressure mineral parageneses in the basaltic glass shows that the Stonyford complex could not have been subducted more than a few kilometres, unlike the nearby Snow Mountain Complex (MacPherson, 1983, 1986). Jayko et al. (1987) have proposed that the Round Mountain serpentinite matrix melange formed by the mixing of off-scraped oceanic crust with hydrated mantle lithosphere in the hanging wall of the proto-Franciscan subduction zone. This interpretation is supported by the occurrence of enriched oceanic basalts as tectonic blocks in the melange (Shervais and Kimbrough, 1987), which are readily distinguished chemically from the arc-related volcanics of the Coast Range ophiolite that overlies the melange (Shervais and Kimbrough, 1985; Shervais, 1988). Thus, the depth of subduction must have exceeded the thickness of crustal rocks in the overlying Coast Range ophiolite—a minimum of 2.5 km near Paskenta (Hopson et al., 1981) and 4 km at Del Puerto Canyon (Evarts, 1977). If we assume a subduction depth of 10 km, the inferred maximum temperature (100 °C) implies a metamorphic gradient of about 10 °C/km—consistent with typical high P/T series (e.g., Turner, 1981), but much lower than the 100 °C/km hydrothermal gradient estimated by Evarts and Schiffman (1983) for the Del Puerto ophiolite remnant.

CONCLUSIONS

The preservation of 150 Ma volcanic glass is an unusual event that requires isolation of the glass from hydrothermal fluids shortly after eruption and lack of any subsequent metamorphism. The distribution of incompatible trace elements in these glasses and in other basalts of the Stonyford volcanic complex requires derivation from a heterogeneous mantle source. The scale of this heterogeneity must have been smaller than the mantle source of the seamount magmas (<1–10 km^3). The Stonyford volcanic complex may have formed near an oceanic spreading center, but its protracted sedimentary history is more consistent with an intraplate origin. The glasses are currently being analyzed for rare-earth elements and Sr, Nd, and Pb isotopic compositions in order to further constrain the geochemical characteristics of the Jurassic suboceanic mantle and the origin of the Stonyford complex.

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