

# TEM study of the alteration of interstitial glass in MORB by inorganic processes

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## Abstract

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations on a suite of mid-ocean ridge basalts (MORB) reveal abundant interstitial glass, which differs in occurrence and composition from basaltic glass at pillow rims. Interstitial glass consists dominantly of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  and is depleted in other cations, representing a highly differentiated residual material. Low-temperature alteration by seawater solutions results in the formation of saponite (Mg-rich variety of smectite) replacing the interstitial glass; the Si/Al ratio of this saponite reflects that of the source glass. Chemical changes during this transition differ from those resulting from alteration of basaltic or rhyolitic glass. Alteration of interstitial glass results in uptake of Mg and Fe and loss of Si and Al, but there is little or no leaching of alkalis. This reflects a strong control on chemical reactions by solution composition (high Na and Mg concentrations of seawater fluids). In contrast to basaltic glass at pillow rims, our observations do not reveal microbial activities in the alteration of interstitial glass. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* MORB; Glass alteration; Clay mineralogy; TEM

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## 1. Introduction

Low-temperature alteration of mid-ocean ridge basalts (MORB) through interaction between seawater and oceanic crust results in the formation of secondary minerals, especially clay minerals. MORB alteration causes changes in seawater chemistry and the composition of oceanic crust, thus affecting the chemical balance of the oceans (Edmond et al., 1979; Alt et al., 1986). The contribution of volcanic

glass has been considered to be significant in chemical exchange between seawater and oceanic crust owing to its chemical instability and abundance (Staudigel and Hart, 1983).

Alteration of glass to secondary minerals has long been studied (Bonatti, 1965; Honnorez, 1981; Staudigel and Hart, 1983). Early studies focused on the physical and chemical processes (Staudigel and Hart, 1983; Berger et al., 1987, 1994; Crovisier et al., 1987; Zhou and Fyfe, 1989; Thorseth et al., 1991). Recently, however, renewed interest has been stimulated because of the postulated role of microbial activity in the alteration of basaltic glass (Thorseth et al., 1992; Furnes and Staudigel, 1999; Furnes et al., 1996; Fisk et al., 1998; Staudigel et al., 1998).

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There are two kinds of glasses in MORB: (1) glass in pillow rims, which has a composition of average basalt, and which therefore is here called “basaltic glass”, and (2) glass that is interstitial to crystalline phases in the interiors of pillows, in massive flows and in dikes. Interstitial glass is highly differentiated in composition and usually consists of the solid equivalents of two immiscible liquids. Because the two kinds of glasses have different compositions and characteristics, they may play different roles in the chemical exchange between seawater and oceanic crust. The role of glass which is interstitial to crystalline phases is especially significant, given its relatively large volume in flows, but in contrast with basaltic glass, its alteration processes have been little studied owing to its small dimensions. In this study, we utilized scanning electron microscopy (SEM), transmission electron microscopy (TEM) and analytical electron microscopy (AEM) to determine the characteristics of MORB interstitial glass and the processes of its alteration.

## 2. Samples and analytical techniques

A suite of MORB samples was obtained which originated both through surface dredging and from drill cores obtained through the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP). They range in age from recent to 38.4 Ma, such a range being required to illustrate the range of degree of alteration. The studied samples are from lava flows, with depths within the flows at least several centimeters from the glassy margins. The drilled samples were obtained from ODP repositories and are labeled according to ODP/DSDP identification methods. The dredged samples were kindly provided by colleagues, as follows. The New Flow and Dive 2985 samples are submarine pillow lavas that erupted recently at the Juan de Fuca ridge (Johnson and Tivey, 1995). CH114 was dredged from the EPR ridge axis, and its age is < 20 ka (Kent and Gee, 1994). Sample BD10-5 was dredged from the Blanco Fracture zone and has an age of ~ 1.2 Ma. Samples of the glass rims of the two recent pillows were also chosen for study, for comparison with interstitial glass.

Polished thin sections were made for preliminary petrographic study by optical microscopy and SEM. SEM observations were made with a Hitachi S3200N SEM fitted with back-scattered electron (BSE) imaging systems and a NORAN energy-dispersive X-ray spectrographic (EDS) system for qualitative chemical analysis. Areas of thin sections found to be representative with respect to glass content were then removed from sections and ion-milled preparatory to TEM/AEM study. A Philips CM-12 TEM fitted with a Kevex Quantum EDS system and operated at 120 kV was used for TEM/AEM analyses. The compositions of the basaltic glass samples were determined by electron microprobe analysis (EMPA) with a Cameca CAMEBAX microprobe operated at

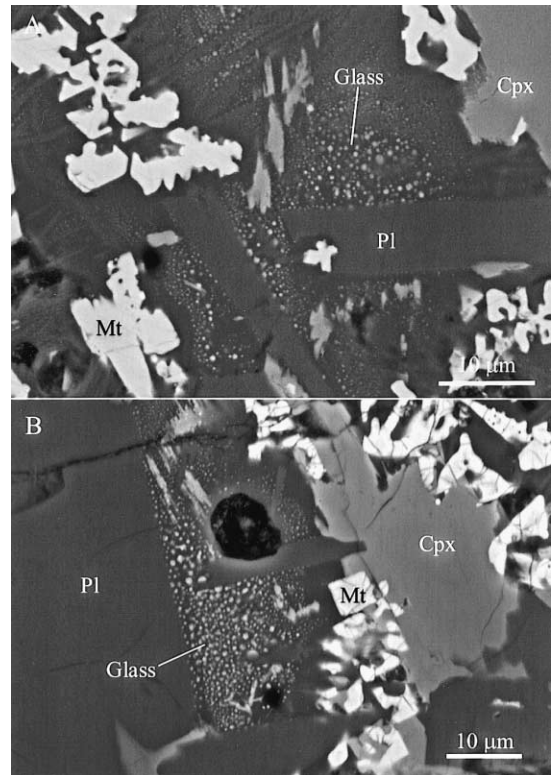


Fig. 1. SEM BSE image showing typical occurrence of interstitial glass in MORB 506-2R1 (0.54 Ma) (A) and 508-3R1 (0.85 Ma) (B). Abundant fine-grained immiscible globules with bright contrast occur in interstitial glass. Mt — titanomagnetite, Pl — plagioclase, Cpx — clinopyroxene.

15-kV accelerating voltage and 10-nA beam current. Standard laboratory minerals and the PaP correction procedure were used (Pouchou and Pichoir, 1984).

### 3. Interstitial glass in MORB

Interstitial glass occurs in polygonal areas between plagioclase and clinopyroxene crystals (Fig. 1) commonly associated with pore space (not shown). Titanomagnetite with a dendritic to cruciform shape is typically associated with interstitial areas. The interstitial glass consists of two materials. One, the enclosing groundmass, has contrast in BSE images

which is similar to that of plagioclase crystals, implying a similar average atomic number. The other consists of abundant, rounded areas with bright contrast, and therefore of atomic number greater than that of plagioclase (Fig. 1). The dimensions of interstitial glass areas increase from the submicrometer range near glassy margins to tens of micrometers or larger toward flow interiors. It is most commonly observed in samples in which the crystalline silicates are finest, being only rarely observed in massive basalts, which are more coarsely crystalline. These relations are consistent with its formation under conditions of relatively rapid cooling.

In Fig. 2, TEM images show that the interstitial glass is comprised of small globules within material

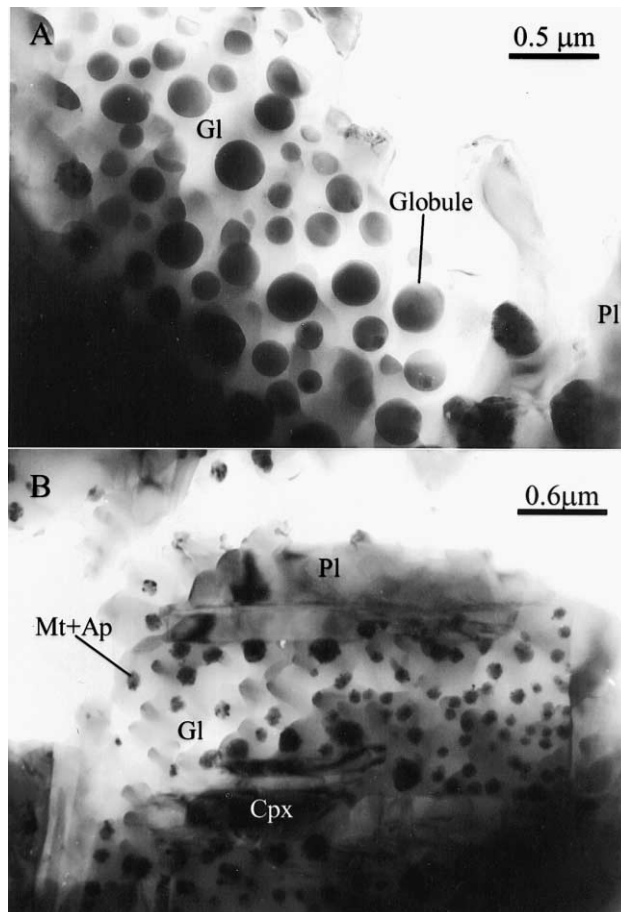


Fig. 2. TEM bright field images showing interstitial glass and immiscible globules in MORB. (A) Homogeneous globules in sample 508B-4R1 (0.85 Ma). (B) Heterogeneous globules in sample BD10-5 (1.2 Ma). The small particles in the globules are (titano)magnetite and apatite. Mt-titanomagnetite, Ap — apatite, Pl — plagioclase, Cpx — clinopyroxene, Gl — glass.

Table 1  
Chemical compositions of basaltic and interstitial glass in MORB

Sample Interval (cm)	Basaltic glass (EMPA) <sup>a</sup>		Interstitial glass (AEM)									
	New flow dredged	Dive 2985 dredged	New flow dredged	Dive 2985 dredged	CH114 dredged	506G-2R1 22–25	507C-2R3 14–20	508B-3R1 11–18	508B-4R1 3–5	BD10-5 dredged	519A-9R1 10–12	335-8R4 23–25
Age (Ma)	0	0	0	0	< 20 ky	0.54	0.69	0.85	0.85	1.2	10.1	13.8
SiO <sub>2</sub>	50.32	49.27	77.25	76.22	77.51	79.39	82.71	83.68	77.44	80.99	80.49	78.49
TiO <sub>2</sub>	1.61	2.01	0.26	0.74	0.50	0.69	0.45	0.44	0.00	0.43	0.33	0.21
Al <sub>2</sub> O <sub>3</sub>	13.56	14.40	15.46	15.92	13.89	12.01	10.38	9.24	13.78	11.84	12.43	13.79
FeO <sup>b</sup>	12.63	12.31	1.61	2.14	2.94	2.06	2.22	2.51	2.62	1.17	1.27	1.61
MnO	0.29	0.20	0.24	0.00	0.17	0.23	0.08	0.00	0.00	0.00	0.00	0.12
MgO	6.66	6.91	0.00	0.00	0.00	0.00	0.14	0.00	1.21	0.56	0.39	0.23
CaO	11.39	11.04	1.51	2.77	2.31	1.93	2.01	1.81	2.39	1.03	1.67	1.48
Na <sub>2</sub> O	2.56	2.73	1.67	1.74	1.79	1.52	1.73	1.43	1.41	2.28	1.50	1.15
K <sub>2</sub> O	0.12	0.16	2.00	0.48	0.89	2.18	0.27	0.88	1.15	1.69	1.93	2.91
P <sub>2</sub> O <sub>5</sub>	0.16	0.19	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.31	99.22	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

n.d.: below detection limit.

<sup>a</sup>Electron microprobe analyses from rim glass chips.

<sup>b</sup>Total Fe as Fe<sup>2+</sup>.

of uniform contrast. The uniform matrix gives no selected area electron diffraction (SAED) pattern, as consistent with noncrystalline material. Chemical compositions of the matrix glass as analyzed by AEM are listed in Table 1. For comparison, the EMPAs of the basaltic rim glass are also included in Table 1. The matrix glass is relatively homogeneous in composition from sample to sample, and it consists dominantly of network-forming elements SiO<sub>2</sub> (76–84%) and Al<sub>2</sub>O<sub>3</sub> (9–16%), with only minor amounts of other elements. AEM analyses could yield low alkali contents due to their loss during the analyses, which would explain some of the unusually high SiO<sub>2</sub> contents (> 80 wt.%). However, its composition differs significantly from basaltic glass. Compared to basaltic glass, the interstitial matrix glass is rich in SiO<sub>2</sub> and K<sub>2</sub>O and depleted in TiO<sub>2</sub>, FeO, MgO and CaO, implying a highly differentiated residual material. On the other hand, basaltic glass is less differentiated and represents the quenched composition of the bulk rock or magma.

AEM analyses of the globules reveal high concentrations of Fe, Ti, Ca, P, with or without S, in sharp contrast to the matrix glass. Such two-phase materials have been commonly observed in volcanic rocks

(Philpotts, 1979, 1982; Kuo et al., 1986; Zhou et al., 1997, 1999b). They are interpreted to originate through exsolution in a differentiated liquid of network-forming elements, and framework-modifying elements (e.g., Fe, Ti). Globules vary from appearing to be homogeneous to heterogeneous in TEM images (Fig. 2). Globules with homogeneous contrast give

Table 2  
AEM analyses of homogeneous globules within interstitial glass

Sample	CH114	508B-3R1	508B-4R1	507C-2R3
SiO <sub>2</sub>	38.14	36.65	43.76	35.77
TiO <sub>2</sub>	2.88	3.99	2.83	4.87
Al <sub>2</sub> O <sub>3</sub>	4.41	2.57	6.20	3.28
FeO <sup>a</sup>	40.41	42.38	33.97	41.41
MnO	1.74	0.40	1.29	1.46
MgO	0.92	0.81	0.23	0.57
CaO	6.69	8.04	6.36	7.91
Na <sub>2</sub> O	2.50	0.12	1.80	0.54
K <sub>2</sub> O	0.35	0.00	0.14	0.00
P <sub>2</sub> O <sub>5</sub>	1.96	3.57	2.18	2.19
SO <sub>3</sub>	0.00	0.66	0.28	0.73
Cl	0.00	0.81	0.96	1.29
Total	100.00	100.00	100.00	100.00

<sup>a</sup>Total Fe as Fe<sup>2+</sup>.

no SAED patterns, as consistent with glass (Fig. 2A). Typical chemical compositions are listed in Table 2. Globules with heterogeneous contrast appear to consist of many small particles (Fig. 2B). AEM analyses and electron diffraction patterns reveal that (titano)magnetite and apatite are the dominant minerals (Zhou et al., 1997). Some globules are well crystallized and consist only of a few relatively large titanomagnetite and apatite grains (Zhou et al., 1997, 1999b). Both homogeneous and heterogeneous globules can occur in the same sample. However, the ratio of homogeneous vs. heterogeneous globules varies among samples.

#### 4. Alteration of interstitial glass

The interstitial glass in recent MORB is very fresh and shows no sign of alteration, as also indicated in previous studies (Xu et al., 1997; Zhou et al., 1997). Signs of alteration of interstitial glass begin to appear in slightly older samples ( $> 1.2$  Ma) (see below). Older samples ( $> 6$  Ma) may show complete alteration, with massive replacement of interstitial glass by clay minerals (Fig. 3). The immiscible globules, however, are usually preserved; such textures can therefore be used to distinguish clay minerals altered from interstitial glass from those formed by alteration of silicates, as commonly observed in older MORB (Shau and Peacor, 1992; Teagle et al., 1996).

Because alteration of MORB is a heterogeneous process on a microscopic scale, unaltered interstitial glass can be preserved in some older samples (Zhou et al., 1999b). Two such samples, 519A-9R1 and 335-8R4, contain abundant unaltered interstitial glass in direct contact with clay. Fig. 4 shows a BSE image and low-resolution TEM images of such areas. There appears to be a relatively sharp interface between glass of uniform contrast and clay with variable contrast. The clay contains abundant lenticular void space which is typical of dehydration of smectitic clays in the vacuum of the TEM.

SAED patterns show only very diffuse and weak reflections typical of smectite; i.e., only 001 (one) reflections occur, and then only for small values of  $l$  (ell) index. The 001  $d$ -value is  $\sim 10$  Å, as consistent

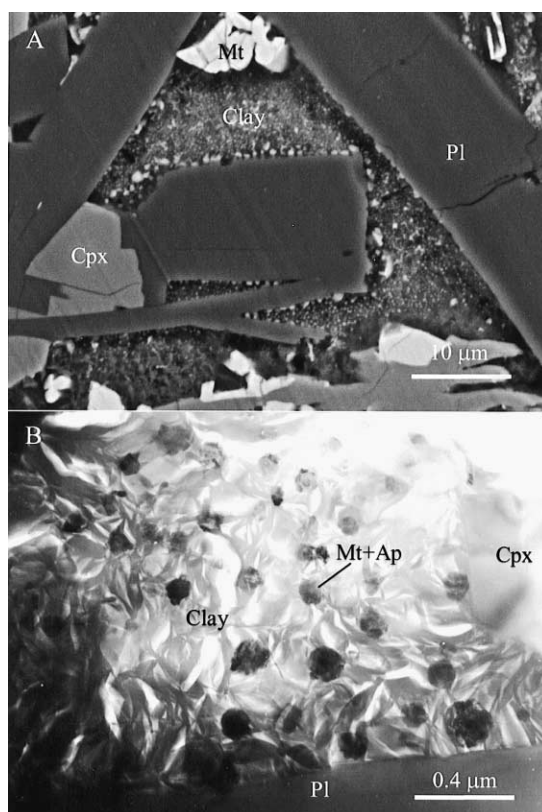


Fig. 3. SEM BSE (A) and TEM bright field (B) images showing replacements of interstitial glass by clay minerals in samples 519A-9R1 (10.1 Ma) and 522B-5R2 (38.4 Ma), respectively. The fine grains in (A) with bright contrast in the interstitial area are immiscible globules. Mt — titanomagnetite, Ap — apatite, Pl — plagioclase, Cpx — clinopyroxene.

with the spacing of dehydrated smectite. High-resolution TEM images show small sets of 001 lattice-fringes ( $\sim 10$  Å wide) arranged in subparallel packets of up to  $\sim 10$  layers (Fig. 5), some layers being curved and anastomosing. AEM chemical analyses show high concentrations of Mg and Fe (Table 3). Normalization of the data to the formula of smectite (i.e., 22 oxygen atoms), results in structural formulae compatible with that of saponite.

Fig. 5 shows thin packets of saponite in a featureless surrounding, which is similar to the development of smectite in the palagonite (Zhou et al., 1992). They may have one of two origins: (1) it may be glass which is unaltered, or (2) it may consist of clay

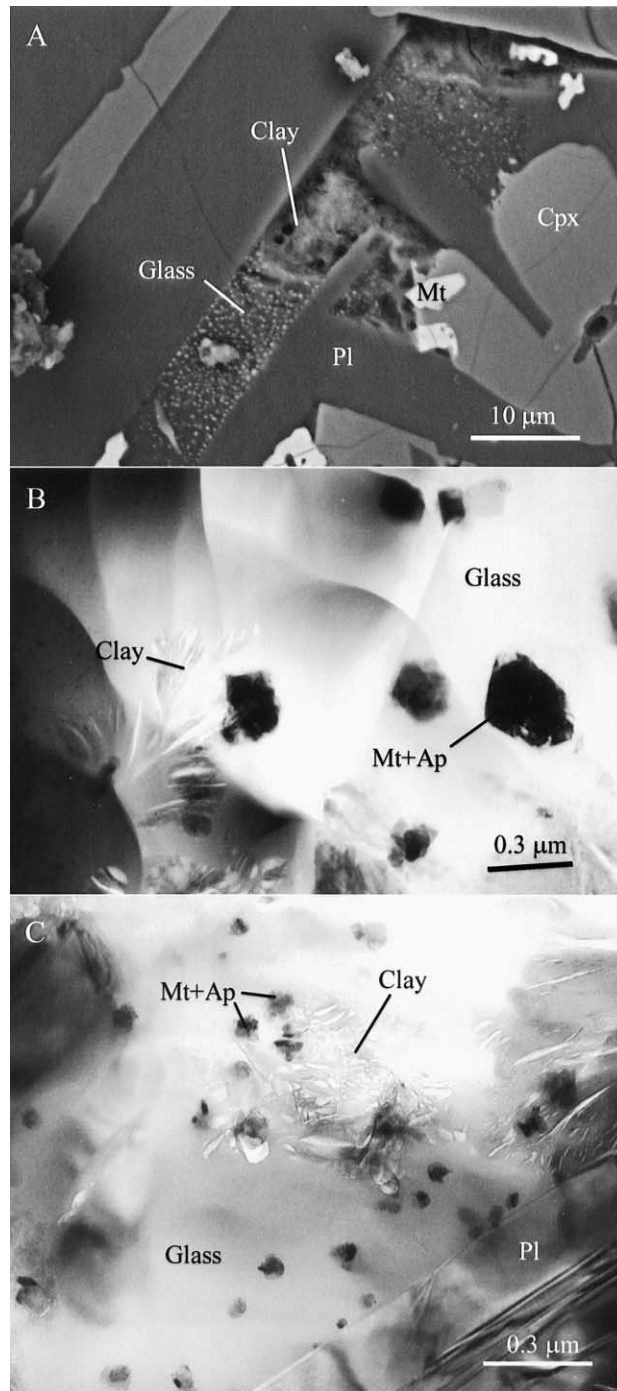


Fig. 4. SEM BSE (A) and TEM bright field (B and C) images showing interface between interstitial glass and clay minerals. A and B from 335-8R4 (13.8 Ma), C from 519A-9R1 (10.1 Ma). Mt — titanomagnetite, Ap — apatite, Pl — plagioclase, Cpx — clinopyroxene.

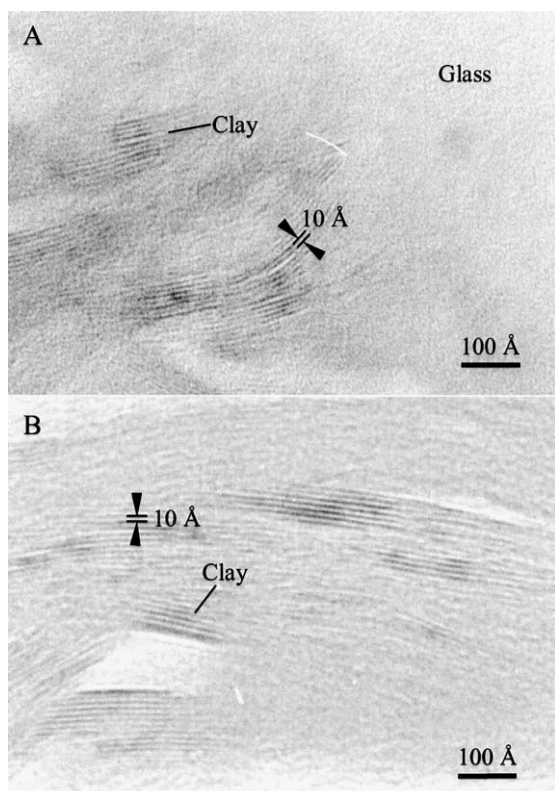


Fig. 5. TEM images showing 10 Å lattice-fringes of saponite altered from interstitial glass in samples 519A-9R1 (10.1 Ma) (A) and 335-8R4 (13.8 Ma) (B).

which, as typical of smectite, has a local orientation with layers not parallel to the electron beam, and which therefore does not contribute to fringes. In this case, however, attempts at orienting the sample at diverse angles failed to produce contrast in the featureless areas, implying that they consist of unaltered glass. In combination with the images in Fig. 4, they show, therefore, that the transformation to clay occurs across a narrow front within which islands of clay grow at the expense of glass.

## 5. Discussion

In contrast to the alteration of interstitial glass, which has received little attention, the alteration of

basaltic glass at pillow rims is relatively well studied. Basaltic glass can alter by different processes, depending on solution composition, temperature, and fluid/rock ratio (Crovisier et al., 1983, 1989; Berger et al., 1987, 1994; Dudoignon et al., 1989, 1997; Guy and Schott, 1989; Petit et al., 1990). In laboratory dissolution experiments under acid to neutral conditions, network-modifier cations (Mg, Fe, Ca, Na) exhibit incongruent behavior with respect to silica, and these cations are leached in exchange for protonation and hydration of the glass surface. Under alkaline conditions dissolution is stoichiometric, and network-forming cations (Al and Si) are lost as well. A thin (up to a few micrometers) leached layer resulting from incongruent dissolution of basalt glass has been observed or inferred in experiments (Crovisier et al., 1983, 1989; Berger et al., 1987), but has only rarely been observed in natural samples (Thorseth et al., 1991). Although high-resolution observations are scarce, natural basalt glasses typically exhibit a sharp transition from unaltered glass to alteration products (see review in Honnorez, 1981; Eggleton and Keller, 1982; Staudigel and Hart, 1983; Crovisier et al., 1987, 1992; Zhou and Fyfe, 1989). The differences can be caused by the differences in water/rock ratio between experimental and natural systems (Leturcq et al., 1999). Alteration products are mainly saponitic smectite and “palagonite” (poorly crystalline smectite  $\pm$  amorphous material), but include zeolites, carbonates, and oxides. Alteration of basaltic glass at pillow rims results in losses of essentially all major and minor cations except Ti and Fe, which can be passively accumulated, and K, which exhibits significant uptake (summary in Honnorez, 1981; Staudigel and Hart, 1983).

In contrast to basaltic glass at pillow rims, interstitial glass in flow interiors is initially already depleted in most cations (Table 1). The interstitial glass is silica-rich and poor in Fe, Mg, and Ca, similar to a rhyolite but without the high alkali contents of the latter. Rhyolitic glasses undergo processes of alteration generally similar to those acting on basaltic glasses, with leaching of alkalis in exchange for protons and water, and accumulation of heavy elements (Fe, Ti) at the surface (Petit et al., 1990). Compared to fresh interstitial glass, its alteration products are enriched in FeO and MgO and depleted in SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> (Table 3, Fig. 6). TiO<sub>2</sub> increases

Table 3  
Selected AEM analyses of clay minerals altered from interstitial glass<sup>a</sup>

Sample	504B-3R1	504B-9R1	896A-22R1	519A-9R1	335-8R4	522B-5R2
Interval (cm)	124–127	91–95	53–54	10–12	23–25	28–30
Age (Ma)	6.9	6.9	6.9	10.1	13.8	38.4
SiO <sub>2</sub>	47.63	47.60	47.14	46.02	47.06	45.65
TiO <sub>2</sub>	0.39	0.14	0.24	0.43	0.28	0.27
Al <sub>2</sub> O <sub>3</sub>	6.13	6.23	7.50	7.75	9.89	7.59
FeO <sup>b</sup>	10.32	8.51	11.23	9.17	8.60	7.21
MnO	0.13	0.13	0.05	0.05	0.19	0.26
MgO	19.29	20.33	17.71	17.48	17.83	20.82
CaO	1.99	1.38	1.77	1.27	1.03	1.63
Na <sub>2</sub> O	1.77	2.54	1.22	3.45	1.69	3.21
K <sub>2</sub> O	0.36	1.13	1.14	2.37	1.43	1.37
Total <sup>c</sup>	88.00	88.00	88.00	88.00	88.00	88.00
No. of cations on the basis of 22 oxygens						
<i>Tetrahedral</i>						
Si	7.07	7.05	7.03	6.92	6.92	6.78
Al	0.93	0.95	0.97	1.08	1.08	1.22
Total	8.00	8.00	8.00	8.00	8.00	8.00
<i>Octahedral</i>						
Ti	0.04	0.02	0.03	0.05	0.03	0.03
Al	0.14	0.13	0.35	0.29	0.63	0.11
Fe <sup>2+</sup>	1.28	1.05	1.40	1.15	1.06	0.90
Mn	0.02	0.02	0.01	0.01	0.02	0.03
Mg	4.27	4.49	3.94	3.92	3.91	4.61
Total	5.75	5.70	5.72	5.41	5.65	5.68
<i>Interlayer</i>						
Ca	0.32	0.22	0.28	0.20	0.16	0.26
Na	0.51	0.73	0.35	1.01	0.48	0.93
K	0.07	0.21	0.22	0.45	0.27	0.26
Total	0.89	1.16	0.85	1.66	0.91	1.44
Si/(Si + Al)	0.87	0.87	0.84	0.83	0.80	0.84
Fe/(Fe + Mg)	0.23	0.19	0.26	0.23	0.21	0.16

<sup>a</sup>Phosphorus below detection limit.

<sup>b</sup>Total Fe as Fe<sup>2+</sup>.

<sup>c</sup>Oxides wt.% normalized to 88.0%.

by ~0.1%, or 20% of its original concentration which could reflect accumulation of this element, but this is within the analytical uncertainty and is not significant. FeO content increases by a factor of 5, of which only a small part could be attributed to passive accumulation, assuming behavior similar to Ti. MgO contents of alteration products are a factor of 40 greater than those of interstitial glass. Such increases in Mg are not typically seen in alteration of

rhyolitic glasses, and must reflect differences in solution composition (Petit et al., 1990). This could reflect either the presence of Mg-rich seawater or the breakdown of primary ferromagnesian phases in the basalt. Similarly, the alkali content of the interstitial glass does not change appreciably during alteration, which probably reflects the inhibitory effect of Na-rich solutions (seawater) on leaching of alkalis (Petit et al., 1990).



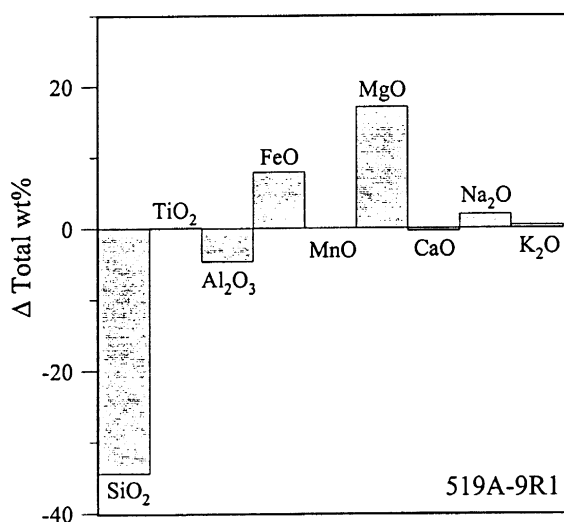


Fig. 6. Representative chemical changes resulting from the alteration of interstitial glass to clay minerals (sample 519A-9R1, 10.1 Ma).  $\Delta$ Total wt.% is the difference of compositions between the interstitial glass (Table 1) and its alteration product (Table 3). Positive sign (+) indicates elemental gain and negative (-) indicates loss during alteration.

Alteration of silicates (e.g., olivine), titanomagnetite and basaltic glass in the basalts can be a source of Fe and Mg for incorporation into secondary minerals in interstitial areas. The low-temperature alteration of titanomagnetite to titanomaghemite (maghemitization) in MORB involves a loss of iron (Ryall and Hall, 1980; Zhou et al., 1999a) and titanomagnetite in the older samples studied here shows a high degree of oxidation (Zhou et al., 1999a,b), indicating that maghemitization may be a major source of iron required by alteration of interstitial glass. The breakdown of olivine in the basalt is complementary to that of interstitial glass: the replacement of olivine by saponite releases Mg but requires the uptake of small amounts of Al, whereas alteration of interstitial glass is a sink for Mg and a source of Al. Breakdown of basaltic glass at pillow rims could also be a source of Mg, Fe, and Al, and seawater could supply additional Mg. These latter reactions are probably not important, however, because with the exception of increased H<sub>2</sub>O contents, the chemical changes exhibited by most bulk rocks containing only saponite are essentially undetectable, indicating little metasomatism by seawater or other

sources (Alt et al., 1986; Alt, 1999). Despite the relatively high K<sub>2</sub>O content of altered interstitial glass compared to the bulk basalt (similar to basaltic glass at pillow rims, Table 1), the K contents of interstitial glass exhibit little or no change during alteration (Fig. 6), again consistent with little addition from seawater other than hydration.

TEM observations show formation of smectite from unaltered glass (Fig. 5) suggesting direct replacement. The compositional changes (Tables 1 and 3, Fig. 6), however, indicate exchange of material between glass and fluids during alteration. TEM studies of such replacement mechanisms have shown that they are the ones in which dissolution occurs at a reaction front, with immediate neocrystallization across the front of a second phase. Where the product structure is closely related to that of the reactant, the replacing structure may be oriented similarly to that of the reactant. However, where reactant and product have very different structures, as with glass and smectite, the product may have a random orientation (for a review of the general relations, see Giorgetti et al., 2000). Smectite occurring as a neocrystallized product of glass therefore appears at the optical or SEM scale to be a direct replacement. Studies of glass alteration have clearly demonstrated such a relation where smectite is a product (Tazaki et al., 1989; Masuda et al., 1996).

Saponite is the most common secondary mineral in MORB altered at low temperatures, along with common celadonite and other rarer phyllosilicates (Alt, 1999). Our observations of this suite of samples of diverse age and depth indicate that saponite is the dominant secondary mineral replacing interstitial glass, although halloysite has also been reported as an alteration product of interstitial glass in old dredged MORB (Xu et al., 1997). The saponite replacing interstitial glass is generally similar in composition to those typical of altered MORB, but it contains lower amounts of Al<sub>2</sub>O<sub>3</sub> than saponitic smectites that replace basaltic glass at pillow rims (Alt, 1999). This difference reflects a compositional control of the primary substrate on the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of the secondary phase. The SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of saponites replacing interstitial glass are similar to those of the glass (5–9, Tables 1 and 3), whereas those of Al-rich saponite replacing basaltic glass at pillow rims are the same as the glass which it

replaces (~ 3–4; Melson and Thompson, 1973; Andrews, 1977; Staudigel and Hart, 1983; Teagle et al., 1996).

Alteration of basaltic glass at pillow rims has been suggested to play an important role for chemical exchange between seawater and oceanic crust (Staudigel and Hart, 1983). Given the abundance of flow interiors in the crust, the total volume of interstitial glass should be comparable to that of basaltic glass at pillow rims. The large chemical changes for Si, Al, Fe, and Mg during alteration of interstitial glass, however, appear to contribute mainly to internal redistribution of elements within the basalt. This process does not appear to have a significant effect on basalt–seawater exchange, at least for these elements, although it could be important for isotopic or trace element exchange.

The involvement of biological activity in the alteration of basaltic glass has recently received significant attention. These studies demonstrate that microbes may mediate the alteration of basaltic glass in MORB (Thorseth et al., 1992; Furnes and Staudigel, 1999; Furnes et al., 1996; Fisk et al., 1998; Staudigel et al., 1998; Torsvik et al., 1998). The presence of microbial activity is supported by alteration textures, genetic (DNA) analyses, chemical analyses and experimental studies. In particular, textures of glass alteration in MORB (pits, channels, tubes, spherulitic bodies) are similar in size and shape to those produced by bacteria (Thorseth et al., 1992; Furnes and Staudigel, 1999; Furnes et al., 1996; Fisk et al., 1998). Although not specifically sought, such alteration textures have not been observed in interstitial glass in this study. It may be that greater amounts of circulating seawater are required to support microbial activity, such as in permeable interpillow areas rather than in the interior of the rocks. Availability of rock-supplied nutrients may also be important. It has been proposed that microbes could obtain metabolic energy or nutrients (P, metals) from the basaltic glass, using reduced Fe, Mn and S as electron donors or ferric Fe as an electron acceptor (Furnes et al., 1996; Fisk et al., 1998). Basaltic glass is relatively rich in these elements, whereas initial interstitial melt is differentiated into residual glass and immiscible liquids, with Fe, Mn, S and P concentrated in the immiscible liquids rather than the glass (Tables 1 and 2).

Although our limited observations do not reveal microbial activity in the alteration of interstitial glass in MORB, the possible role of microbial activity cannot be ruled out. Further detailed studies are needed to investigate presence or absence of microbial activity in the alteration of interstitial glass as well as the alteration mechanism.

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