

### 13. PETROGRAPHIC AND GEOCHEMICAL PROPERTIES OF TEPHRAS IN DEEP SEA DRILLING PROJECT CORES FROM THE NORTH PHILIPPINE SEA

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#### ABSTRACT

Refractive index and chemical composition were determined for glass shards contained in more than 100 tephra layers in DSDP Leg 58 sediment cores collected in the Shikoku Basin, North Philippine Sea. The refractive index is consistent with chemical composition. Refractive index and total iron show a linear relationship. Tephra in Pleistocene and Pliocene sediments is mostly rhyolitic and dacitic (non-alkali), whereas tephra in the Miocene shows wide composition variations in the eastern part of the basin. Basaltic tephra is recognized in Miocene sediments at Sites 443 and 444, but not at Site 442, west of the other two sites. This indicates that the basaltic tephra came from eruption relatively close to those drill sites (perhaps the Kinan Seamounts and the Shichito-Iwo Jima volcanic arc), although the exact source has not been identified.

#### INTRODUCTION

Recent mineralogical and chronological studies of deep-sea tephra layers in DSDP and piston cores have enabled us to consider the geological and geophysical problems related to volcanism in and around island arcs and oceanic islands.

During DSDP Leg 58, three sites were drilled in the central part of the Shikoku Basin (Figure 1). Abundant tephra layers in deep-sea sediments were identified clearly in sediments from the lower Miocene to Holocene. Volcanic glass shards in these tephra layers are heterogeneous in chemical composition, as determined by electron-microprobe analyses and measurement of refractive index, so that correlation between these tephra layers and their sources is possible.

DSDP tephra layers and their correlation with sub-aerial volcanic materials have been investigated extensively (Jones, 1973; Scheidegger and Kulm, 1975; Scheidegger et al., 1978; Ninkovich, 1979; Fujioka et al., in press; Furuta and Arai, in press). Scheidegger et al. (1978), using data from 33 analyzed tephra layers of the Pleistocene and Pliocene at DSDP Site 192 in the northwestern Pacific, demonstrated that glass shards have been subjected to progressive hydration, with minor exchanges of  $K_2O$ ,  $MgO$ , and  $CaO$ . They also suggested that hydration occurs rapidly and leads to a uniform water content of 4.5 to 5.0 per cent during exposure to seawater over several hundred thousand years. Scheidegger and Kulm (1975), using chemical composition of glass shards, showed that the tephra layers at DSDP Site 178 in the Gulf of Alaska correlate with the volcanic activities of the Aleutian and Alaska arcs. Ninkovich (1979) analyzed tephra layers of deep-sea

piston and DSDP cores from the northeastern Indian Ocean and suggested that three distinct provinces can be recognized from chemical data. He also demonstrated that hydration in glass shards reaches a "saturation point" of 4 to 5 per cent in 250,000 to 400,000 years.

This paper describes petrographic and geochemical properties of tephra layers from the Shikoku Basin. We do not attempt to discuss the petrogenetic implications of the analyzed data, although we do give some idea of the sources of tephra. We present results of microprobe analyses of glass shards and constituent minerals in 32

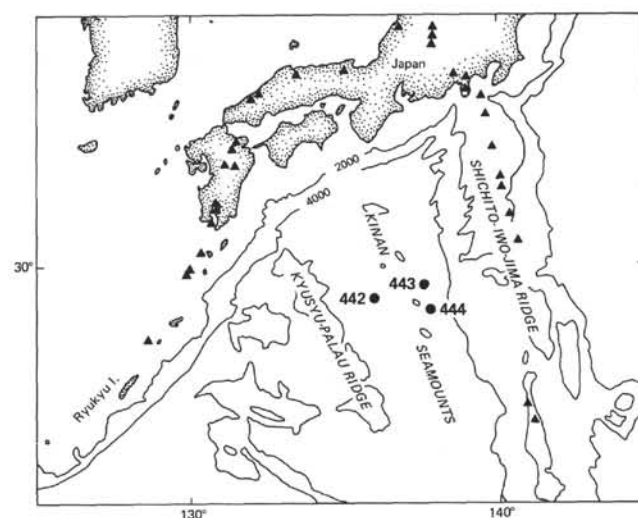


Figure 1. Location of Leg 58 drill sites in the Shikoku Basin and Quaternary volcanoes (triangles). Bathymetry in meters.

tephra layers from the early Miocene to Holocene and measurements of refractive index of glass shards in all tephra layers.

It is worth emphasizing that at two sites (443 and 444), tephra of basaltic composition was recovered from Miocene sediments. Tephra found so far in DSDP cores has been mostly rhyolitic to andesitic; it is seldom that basaltic tephra, such as in the Shikoku Basin, has been recognized. Therefore, examination of these tephra layers is of great interest from the viewpoint of the sedimentary environments and tectonic developments of the Shikoku Basin.

Twenty-three tephra layers of late-Eocene to Holocene age were also sampled at Site 445, at the crest of the Daito Ridge. However, only petrographic characters are presented (Appendix, this chapter), because their features have not been examined in detail.

### PETROGRAPHIC FEATURES

Tephra layers in deep-sea sediments of the Shikoku Basin range from early-Miocene to Holocene in age. Twenty layers from Site 442 (Holes 442A and 442B), 30 layers from Site 443, and 60 layers from Site 444 (Holes 444 and 444A) were investigated. Table 1 shows the numbers of tephra layers from the three sites. Techniques used for preparation of tephra samples for refractive index and chemical analysis are the same as described by Furuta and Arai (in press).

Refractive indexes of tephra layers are shown in Table 2 and Figure 2. Volcanic glass shards are classified as pumice, bubble-wall, and scoria types by their shapes. Plate 1 illustrates typical examples.

At Site 442, refractive indexes of glass shards in early-Miocene to Holocene tephra layers range from 1.498 to 1.512. The glass is colorless, with the exception of one layer at 442-3-6, 48-50 cm. Glass shards from this site are pumice and (or) bubble-wall type (Table 2). The refractive index for the layer at 442-3-6, 48-50 cm is somewhat higher than that of shards from other layers, with values from 1.518 to 1.521.

At Site 443, approximately 100 km east of Site 442, refractive indexes of glass shards show a wide range, from 1.499 to 1.599. Basaltic tephra predominates in late-Miocene sediments. Glass shards at this site are pumice and (or) bubble-wall and scoria types. The first and second types have relatively low refractive indexes, while the third has high indexes. Glass shards with relatively low refractive indexes are colorless, and those with high indexes are brown. At Site 444, 70 km south-

east of Site 443, petrographic features and refractive indexes of glass shards appear to be similar to those for Site 443 tephra layers.

At this site, the highest refractive indexes, 1.600 to 1.610, are found at 444A-10-1, 92-94 cm. Refractive index and color of glass shards seem to be controlled by the abundance of transition metals (FeO, TiO<sub>2</sub>, MnO, etc.).

### CHEMICAL COMPOSITION OF VOLCANIC GLASS

Five samples from the Site 442 tephra layers, 16 from Site 443, and 11 from Site 444 were chemically analyzed by electron microprobe. The results are shown in Table 3. SiO<sub>2</sub> content ranges from 47 to 74 per cent, corresponding to compositions from basalt to rhyolite. Al<sub>2</sub>O<sub>3</sub> content varies from 11 to 16 per cent, values consistent with those reported for normal volcanic rocks with the same SiO<sub>2</sub> contents. FeO (total iron as FeO) varies from 0.9 to 13 per cent. This variation is mainly responsible for the changes in refractive index of glass shards. MgO content also varies considerably and is inversely related to SiO<sub>2</sub> content. CaO, Na<sub>2</sub>O, and K<sub>2</sub>O contents vary considerably. Such variation in CaO and alkalis can be explained by magmatic differentiation, as well as by hydration of glasses after deposition. In particular, the alkali contents are likely to vary significantly as a result of hydration (Aramaki and Lipman, 1965; Aramaki and Haramura, 1966; Jezek and Noble, 1978).

In order to test whether the analyzed glass shards belong to alkali or non-alkali rock series, total alkalis are plotted against SiO<sub>2</sub> (Figure 3) (Kuno, 1965). In this diagram, data were recalculated on a water-free basis. Most values from Pleistocene and Pliocene glass shards are fitted to the non-alkali rock series (Figure 3a), but data from Miocene glass shards are scattered (Figure 3b). Miocene glass shards from three tephra layers at Site 444 with low SiO<sub>2</sub> contents, and three from Site 443 with high SiO<sub>2</sub> contents, belong to the alkali rock series. This suggests that two different types of volcanic activity occurred during the same time in the Shikoku Basin or adjacent areas.

In the upper Miocene, different rock series, alkalic and non-alkalic, are represented by the deep-sea tephra layers. Figure 3 shows that the compositions of glass shards from different sites are well clustered. Such similarity of chemical composition is very useful for correlation of tephra layers.

Data from each tephra layer are plotted in an AFM diagram in Figure 4. This diagram indicates the fractionation evidenced by glass-shard compositions. The Miocene tephra layers show patterns of high iron concentration, typical of the tholeiitic fractional crystallization trends, with three exceptions (Figure 4b); these are from Miocene tephra layers at Site 444 and belong to the alkali rock series. These samples have a high alkali content (4-5%), in spite of an SiO<sub>2</sub> content lower than 50 per cent and are very similar to typical alkali olivine basalt. From Figures 3 and 4, it is inferred that tephra layers from the Shikoku Basin originated from at least two different volcanic activities.

TABLE 1  
Numbers of Tephra Layers Cored at  
the Shikoku Basin Sites

| Age         | Site 442 | Site 443 | Site 444 |
|-------------|----------|----------|----------|
| Pleistocene | 11       | 4        | 12       |
| Pliocene    | 2        | 3        | 13       |
| Miocene     | 7        | 23       | 35       |
| Total       | 20       | 30       | 60       |

TABLE 2  
Petrographic Characters of Tephra Layers

| Age                        | Sample (interval in cm)        | Sub-bottom Depth (m)    | Volcanic Glass                    |                   |          |             |                        |             |        |
|----------------------------|--------------------------------|-------------------------|-----------------------------------|-------------------|----------|-------------|------------------------|-------------|--------|
|                            |                                |                         | Constituent Minerals <sup>a</sup> | Type <sup>b</sup> | Color    | Size (mm)   | Refractive Index Range | Mean Range  | Mode   |
| Pleistocene                | 442A-2-5, 100-102 <sup>c</sup> | 16.00                   | pl ++, hb +                       | pm≈bw             | clear    | 0.3         | 1.499-1.501            |             | 1.500  |
|                            | 3-3, 66-68 <sup>c</sup>        | 22.66                   | pl ++, hb ++, hy +, op +          | pm≈bw             | clear    | 0.4         | 1.500-1.502            | 1.500-1.501 | 1.5005 |
|                            | 3-6, 48-50 <sup>c</sup>        | 26.98                   | pl ++, hy +, au +, op +           | pm                | p. brown | 0.6         | 1.517-1.522            | 1.518-1.521 |        |
|                            | 5-3, 30-32 <sup>c</sup>        | 41.30                   | pl +, hb +                        | pm<bw             | clear    | 0.2         | 1.500-1.505            | 1.501-1.504 |        |
|                            | 5-3, 132-134                   | 42.32                   | pl +, hb +                        | pm≈bw             | clear    | 0.3         | 1.500-1.502            |             | 1.501  |
|                            | 5-4, 75-77                     | 43.25                   | pl +, hb +                        | pm≈bw             | clear    | 0.3         | 1.500-1.505            | 1.500-1.503 |        |
|                            | 5-5, 104-106                   | 45.04                   | pl +, op +                        | pm>bw             | clear    | 0.2         | 1.499-1.501            |             | 1.4995 |
|                            | 7-1, 98-100 <sup>c</sup>       | 57.98                   | pl +, hb +                        | pm≈bw             | clear    | 0.3         | 1.501-1.503            |             | 1.502  |
|                            | 7-4, 48-50                     | 61.98                   | pl +, hb +, bi +, px +            | pm≈bw             | clear    | 0.3         | 1.500-1.503            |             |        |
|                            | 10-4, 31-33                    | 90.31                   | pl +, op +                        | pm>bw             | clear    | 0.3         | 1.504-1.509            | 1.506-1.508 | 1.507  |
| 13-2, 80-82                | 116.30                         | pl ++, hy +, au +, ho + | pm≈bw                             | clear             | 0.4      | 1.500-1.502 |                        | 1.501       |        |
| Pliocene                   | 20-1, 25-27                    | 180.75                  | pl +, op +                        | pm>bw             | clear    | 0.2         | 1.503-1.505            |             | 1.504  |
|                            | 21-3, 84-86                    | 193.84                  | pl ++, bi ++                      | pm>bw             | clear    | 0.4         | 1.498-1.500            |             | 1.499  |
| Miocene                    | 28-3, 117-119                  | 260.67                  | pl +, bi +                        | pm≈bw             | clear    | 0.3         | 1.500-1.501            |             | 1.5005 |
|                            | 29-1, 145-147                  | 267.45                  | pl +, op +                        | pm≈bw             | clear    | 0.1         | 1.500-1.501            |             |        |
|                            | 29-2, 66-68                    | 268.16                  | pl ++, qt +, bi +, hb +           | pm≈bw             | clear    | 0.4         | 1.500-1.504            | 1.500-1.503 |        |
|                            | 442B-1-1, 70-72                | 268.20                  | pl +, hy +, au +                  | pm<bw             | clear    | 0.5         | 1.504-1.508            |             | 1.506  |
|                            | 1-2, 96-98                     | 269.96                  |                                   | bw                | clear    | 0.4         | 1.504-1.511            |             |        |
| 1-2, 134-136               | 270.34                         | pl +, op +              | pm<bw                             | clear             | 0.3      | 1.508-1.512 | 1.509-1.511            |             |        |
| 1, CC                      | 270.80                         | hb +, au +, bi +        | pm≈bw                             | clear             | 0.5      | 1.500-1.503 | 1.500-1.501            |             |        |
| Pleistocene                | 443-1-4, 64-66 <sup>c</sup>    | 5.14                    | pl +, hy +, au +, op +            | pm<bw             | clear    | 0.2         | 1.499-1.501            |             | 1.500  |
|                            | 4-2, 80-82 <sup>c</sup>        | 33.44                   | pl +, hy +, au +, op +            | pm>bw             | p. brown | 0.3         | 1.518-1.525            | 1.519-1.522 | 1.520  |
|                            | 8-5, 26-28 <sup>c</sup>        | 70.26                   | pl ++, op +                       | pm>bw             | clear    | 0.2         | 1.499-1.501            |             | 1.500  |
|                            | 11-5, 55-57 <sup>c</sup>       | 99.05                   | pl +                              | pm>bw             | clear    | 0.3         | 1.500-1.503            |             | 1.502  |
| Pliocene                   | 18-1, 118-121                  | 160.18                  | ho ++, pl +, hy +                 | pm>bw             | clear    | 0.3         | 1.504-1.508            | 1.504-1.507 | 1.505  |
|                            | 18-3, 110-112                  | 163.10                  | pl +, hy +, au +, op +            | pm>bw             | clear    | 0.2         | 1.503-1.506            |             | 1.505  |
|                            | 22-2, 139-141 <sup>c</sup>     | 199.89                  | pl +, hy +, ho +, op +            | pm>bw             | clear    | 0.3         | 1.504-1.510            | 1.505-1.508 |        |
| Miocene                    | 31-3, 29-31 <sup>c</sup>       | 285.79                  | pl ++, au +, ol +                 | sco               | brown    | 0.5         | 1.580-1.592            | 1.585-1.590 |        |
|                            | 31-4, 6-8 <sup>c</sup>         | 287.06                  | pl +                              | sco               | brown    | 0.3         | 1.584-1.592            |             |        |
|                            | 32-1, 106-108 <sup>c</sup>     | 293.06                  | pl ++                             | sco               | brown    | 0.3         | 1.583-1.595            |             |        |
|                            | 32-2, 105-107                  | 304.05                  | pl +, op +                        | pm>bw             | clear    | 0.1         | 1.502-1.505            |             |        |
|                            | 34-2, 43-45                    | 312.93                  |                                   | sco               | brown    |             | 1.583-1.588            |             |        |
|                            | 39-2, 69-71 <sup>c</sup>       | 360.69                  | pl +                              | pm                | clear?   | 0.4         | 1.519-1.525            | 1.520-1.524 | 1.522  |
|                            | 40-2, 22-24 <sup>c</sup>       | 369.72                  | pl +, hy +                        | pm                |          | 1.0         | 1.538-1.546            |             |        |
|                            | 40-2, 139-140 <sup>c</sup>     | 370.89                  | pl +                              | pm≈bw             | clear    | 0.2         | 1.507-1.510            |             | 1.508  |
|                            | 42-1, 22-24                    | 387.22                  |                                   | sco               | brown    | 0.2         | 1.592-1.599            |             |        |
|                            | 42-1, 92-94                    | 387.92                  | pl +, hy +                        | pm<bw             | clear    | 0.5         | 1.499-1.500            |             | 1.4995 |
|                            | 43-1, 30-32                    | 396.80                  | pl +                              | pm                | clear    | 1.0         | 1.505-1.508            |             | 1.506  |
|                            | 43-1, 69-71                    | 397.19                  | pl ++, hy +                       | pm<bw             | clear    | 0.3         | 1.500-1.502            |             | 1.501  |
|                            | 43-2, 22-24                    | 398.22                  | pl ++, bi +                       | pm>bw             | clear    | 0.5         | 1.501-1.506            |             | 1.503  |
|                            | 43-2, 36-38                    | 398.36                  |                                   | pm                | p. brown | 0.4         | 1.528-1.547            |             |        |
|                            | 45-1, 92-94 <sup>c</sup>       | 416.12                  | pl +, au +                        | pm<bw             | p. brown | 0.4         | 1.507-1.513            |             | 1.510  |
|                            | 45-1, 106-108 <sup>c</sup>     | 416.56                  |                                   | pm>bw             | p. brown | 0.2         | 1.530-1.543            |             |        |
|                            | 45, CC <sup>c</sup>            | 417.28                  | pl +                              | pm>bw             | p. brown | 0.3         | 1.518-1.550            | 1.518-1.525 |        |
|                            | 46-1, 98-99                    | 425.98                  | pl ++, hy +                       | pm≈bw             | clear    | 0.2         | 1.503-1.515            |             |        |
|                            | 46-1, 106-108                  | 426.06                  |                                   | pm>bw             | clear    | 0.3         | 1.503-1.505            |             | 1.504  |
|                            | 46-1, 111-113                  | 426.11                  | pl +, au +                        | pm>bw             | clear    | 0.3         | 1.501-1.555            | 1.501-1.505 |        |
| 46-2, 181-183 <sup>c</sup> | 428.31                         |                         | sco                               | brown             | 0.3      | 1.582-1.590 |                        |             |        |
| 48-1, 85-87 <sup>c</sup>   | 444.85                         | pl +, au +              | pm>bw                             | p. brown          | 0.4      | 1.527-1.533 |                        |             |        |
| 49-1, 76-78                | 454.26                         | au ++, hy +, op +       | pm>bw                             | clear             | 0.2      | 1.508-1.520 | 1.508-1.514            |             |        |
| Pleistocene                | 444-2-1, 10-12                 | 6.10                    | pl ++, hb +, au +                 | pm>bw             | clear    | 0.2         | 1.499-1.501            |             | 1.500  |
|                            | 2-1, 80-82                     | 6.80                    | pl ++                             | pm>bw             | clear    | 0.15        | 1.499-1.501            |             | 1.500  |
|                            | 2-2, 116-118                   | 8.66                    | pl ++, hb +                       | pm>bw             | clear    | 0.15        | 1.500-1.501            |             | 1.5005 |
|                            | 2-3, 112-114                   | 10.12                   | pl ++, hb +                       | pm>bw             | clear    | 0.2         | 1.500-1.501            |             | 1.5005 |
|                            | 4-5, 54-56 <sup>c</sup>        | 31.54                   | pl +                              | pm                | p. brown | 0.3         | 1.543-1.549            |             | 1.546  |
|                            | 4-5, 106-108 <sup>c</sup>      | 32.06                   | pl ++, hb +, bi +                 | pm<bw             | clear    | 0.5         | 1.500-1.501            |             | 1.5005 |
|                            | 5-1, 6-8 <sup>c</sup>          | 34.56                   |                                   | pm≈bw             | p. brown | 0.2         | 1.518-1.520            |             | 1.519  |
|                            | 5-1, 11-13                     | 34.61                   | pl ++, qt +, hb +                 | pm≈bw             | p. brown | 0.3         | 1.499-1.518            | 1.500-1.504 | 1.502  |

TABLE 2 - Continued

| Age                        | Sample<br>(interval in cm) | Sub-<br>bottom<br>Depth<br>(m) | Constituent Minerals <sup>a</sup> | Type <sup>b</sup> | Color                | Volcanic Glass |             |                                |        |
|----------------------------|----------------------------|--------------------------------|-----------------------------------|-------------------|----------------------|----------------|-------------|--------------------------------|--------|
|                            |                            |                                |                                   |                   |                      | Size<br>(mm)   | Range       | Refractive Index<br>Mean Range | Mode   |
| Pleistocene                | 444-5-4, 34-36             | 39.34                          | pl ++, op +                       | pm≈bw             | clear                | 0.8            | 1.500-1.501 |                                | 1.5005 |
|                            | 5-5, 14-16                 | 40.64                          | pl ++, hb +, hy +                 | pm>bw             | clear                | 0.7            | 1.500-1.501 |                                | 1.5005 |
|                            | 5-5, 53-55                 | 41.03                          | pl ++, hb +                       | pm>bw             | clear                | 0.2            | 1.499-1.501 |                                | 1.500  |
|                            | 6-1, 18-20                 | 42.18                          | pl ++, hy +                       | pm≈bw             | clear                | 0.2            | 1.508-1.513 |                                | 1.511  |
| Pliocene                   | 444-7-2, 19-21             | 55.19                          | pl +                              | pm>bw             | clear                | 0.3            | 1.505-1.509 |                                | 1.508  |
|                            | 7-2, 111-113               | 56.11                          | pl ++, hb +                       | pm>bw             | clear                | 0.4            | 1.506-1.508 |                                | 1.507  |
|                            | 7-3, 57-59                 | 57.07                          | pl ++, hb +                       | pm>bw             | clear                | 0.2            | 1.506-1.508 |                                | 1.507  |
|                            | 7-3, 139-141               | 57.89                          | pl ++, hy +, hb +                 | pm>bw             | clear                | 0.3            | 1.506-1.509 |                                | 1.508  |
|                            | 7-4, 145-147               | 59.45                          | pl +                              | pm>bw             | clear                | 0.1            | 1.506-1.509 |                                | 1.508  |
|                            | 7-5, 80-82                 | 60.30                          | pl +, hy +                        | pm>bw             | clear                | 0.13           | 1.506-1.509 |                                | 1.508  |
|                            | 7-6, 17-19                 | 61.17                          | pl ++, hy +, au +                 | pm                | p. brown             | 0.2            | 1.523-1.530 | 1.525-1.528                    |        |
|                            | 9-1, 125-127 <sup>c</sup>  | 73.75                          | pl ++, hy +, au +, hb +           | pm>bw             | clear                | 0.4            | 1.501-1.505 | 1.502-1.504                    |        |
|                            | 10, CC                     | 82.00                          | pl ++, hy, au, op, ol, hb +       | pm                |                      |                | 1.510-1.520 |                                |        |
|                            | 444A-1-1, 137-139          | 83.37                          | pl ++, op +, bi +                 | pm>bw             | clear                | 0.2            | 1.500-1.535 | 1.505-1.515                    |        |
|                            | 1-3, 10-12                 | 85.10                          | pl +                              | pm>bw             | p. brown             | 0.1            | 1.502-1.553 | 1.515-1.535                    |        |
|                            | 1-3, 38-40                 | 85.38                          | pl +                              | pm>bw             | clear                | 0.2            | 1.505-1.551 | 1.510-1.535                    |        |
|                            | 1-5, 44-46                 | 88.44                          | pl +                              | pm>bw             | clear                | 0.25           | 1.505-1.510 |                                | 1.507  |
|                            | Miocene                    | 2-2, 72-74                     | 93.72                             | pl +, op +        | pm≈bw                | clear          | 0.45        | 1.505-1.509                    |        |
| 2-2, 115-117               |                            | 94.15                          | pl +, hy +, au +                  | pm>bw             | clear                | 0.5            | 1.505-1.509 |                                | 1.507  |
| 2-3, 36-38                 |                            | 94.86                          | pl +                              | pm>bw             | clear                | 0.2            | 1.501-1.504 | 1.502-1.504                    | 1.503  |
| 8-1, 98-100                |                            | 149.48                         | pl ++, hy +, au +, op +           | pm≈bw             | clear                | 0.4            | 1.506-1.510 |                                | 1.507  |
| 9-1, 115-117               |                            | 159.15                         | pl +, au +                        | sco               | brown                | 0.1            | 1.583-1.590 | 1.585-1.589                    |        |
| 9-2, 7-9                   |                            | 159.57                         | pl +, hy +                        | sco               | brown                | 1.5            | 1.585-1.590 |                                |        |
| 9-2, 38-40                 |                            | 159.88                         | pl +, au +                        | sco               | p. brown             | 0.7            | 1.552-1.583 |                                |        |
| 9-2, 82-84                 |                            | 160.32                         | pl ++, bi, au, hb +               | pm≈bw             | clear                | 0.3            | 1.500-1.525 | 1.500-1.510                    |        |
| 9-2, 112-114 <sup>c</sup>  |                            | 160.62                         | pl ++, au +, hy +                 |                   | brown                | 0.5            | 1.528-1.578 |                                | 1.577  |
| 9-3, 70-72                 |                            | 161.70                         | pl ++, au +                       | sco               | p. brown             | 0.3            | 1.528-1.595 | 1.585-1.590                    |        |
| 9-4, 17-19                 |                            | 162.67                         | pl +++                            | sco               | brown                | 0.7            | 1.510-1.590 |                                |        |
| 9-4, 41-43                 |                            | 162.91                         | pl ++, au +                       | sco               | brown                |                | 1.508-1.577 | 1.520-1.570                    |        |
| 9-4, 86-88                 |                            | 163.36                         | pl ++, au +                       | sco               | brown                | 0.3            | 1.507-1.573 |                                |        |
| 9-5, 5-7                   |                            | 164.05                         | pl ++, hy +                       | sco               | brown                | 0.3            | 1.540-1.585 | 1.570-1.580                    |        |
| 10-1, 92-94 <sup>c</sup>   |                            | 168.42                         | pl ++, au +                       | sco               | brown                | 0.2            | 1.580-1.615 | 1.600-1.610                    |        |
| 10-2, 0-2                  |                            | 169.00                         | pl ++, au +                       | pm                | p. brown             | 0.1            | 1.525-1.532 |                                | 1.528  |
| 10-2, 30-32                |                            | 169.30                         | pl +++                            | pm                | p. brown<br>clear    | 1.0            | 1.523-1.531 |                                | 1.528  |
| 10-2, 114-116              |                            | 170.14                         | pl ++, au +                       | pm                | p. brown<br>to clear | 0.8            | 1.510-1.550 | 1.515-1.535                    |        |
| 10-2, 130-132              |                            | 170.30                         | pl ++, hy +                       | pm                | p. brown             | 1.0            | 1.520-1.530 |                                |        |
| 11-2, 68-70                |                            | 179.18                         | pl ++, hy +                       | pm>bw             | clear                | 0.25           | 1.509-1.514 | 1.510-1.512                    | 1.511  |
| 11-3, 83-85                |                            | 180.83                         | pl ++ au +                        | pm>bw             | p. brown             | 0.4            | 1.508-1.522 | 1.509-1.514                    |        |
| 12-1, 59-61                |                            | 187.09                         | pl ++, hy +, au +                 | sco               | clear to<br>brown    | 0.1            | 1.508-1.590 |                                |        |
| 12-1, 119-121 <sup>c</sup> |                            | 187.69                         | pl ++, hy +                       |                   | brown                | 0.7            | 1.584-1.589 |                                | 1.587  |
| 12-2, 45-47 <sup>c</sup>   |                            | 188.45                         |                                   |                   | p. brown             | 0.4            | 1.584-1.588 |                                | 1.586  |
| 13-2, 0-2 <sup>c</sup>     |                            | 197.50                         | pl ++, au +                       | sco               | brown                | 0.2            | 1.531-1.583 | 1.578-1.583                    |        |
| 13-3, 74-76 <sup>c</sup>   |                            | 199.74                         | pl ++, au +                       | sco               | brown                | 0.3            | 1.575-1.590 |                                |        |
| 14-1, 50-52                |                            | 206.00                         | pl ++, au +                       | pm>bw             | p. brown             | 0.3            | 1.526-1.535 | 1.527-1.531                    | 1.528  |
| 14-2, 30-32                |                            | 207.30                         |                                   | pm>bw             | p. brown             | 0.4            | 1.519-1.530 | 1.520-1.524                    | 1.523  |
| 14-4, 40-42                |                            | 210.40                         | pl +, au +                        | pm>bw             | clear                | 0.2            | 1.508-1.512 |                                | 1.510  |
| 15-1, 20-22                |                            | 215.20                         |                                   | pm>bw             | clear                | 0.4            | 1.507-1.510 |                                | 1.508  |
| 15-1, 97-99                | 215.97                     | pl ++, hy +, au +              | pm>bw                             | clear             | 0.3                  | 1.507-1.510    |             | 1.509                          |        |
| 15-2, 77-79                | 217.27                     | pl ++, au +                    | pm>bw                             | clear             | 0.4                  | 1.506-1.512    | 1.507-1.510 | 1.509                          |        |
| 22-1, 82-84 <sup>c</sup>   | 282.32                     | pl ++                          | pm>bw                             | p. brown          | 0.4                  | 1.537-1.539    |             | 1.538                          |        |
| 22-5, 36-38                | 287.86                     | pl ++, bi +                    | pm≈bw                             | clear             | 0.3                  | 1.497-1.500    |             | 1.498                          |        |
| 22-5, 58-60                | 288.08                     | pl ++, au +                    | pm>bw                             | clear             | 0.3                  | 1.499-1.502    | 1.500-1.501 | 1.5005                         |        |

<sup>a</sup> pl = plagioclase, au = augite, hy = hypersthene, hb = hornblende, bi = biotite, ol = olivine, op = opaque minerals, +++ = very abundant, ++ = abundant, + = common.

<sup>b</sup> pm = pumice type, bw = bubble-wall type, sco = scoria type.

<sup>c</sup> Chemical analysis in Table 3.

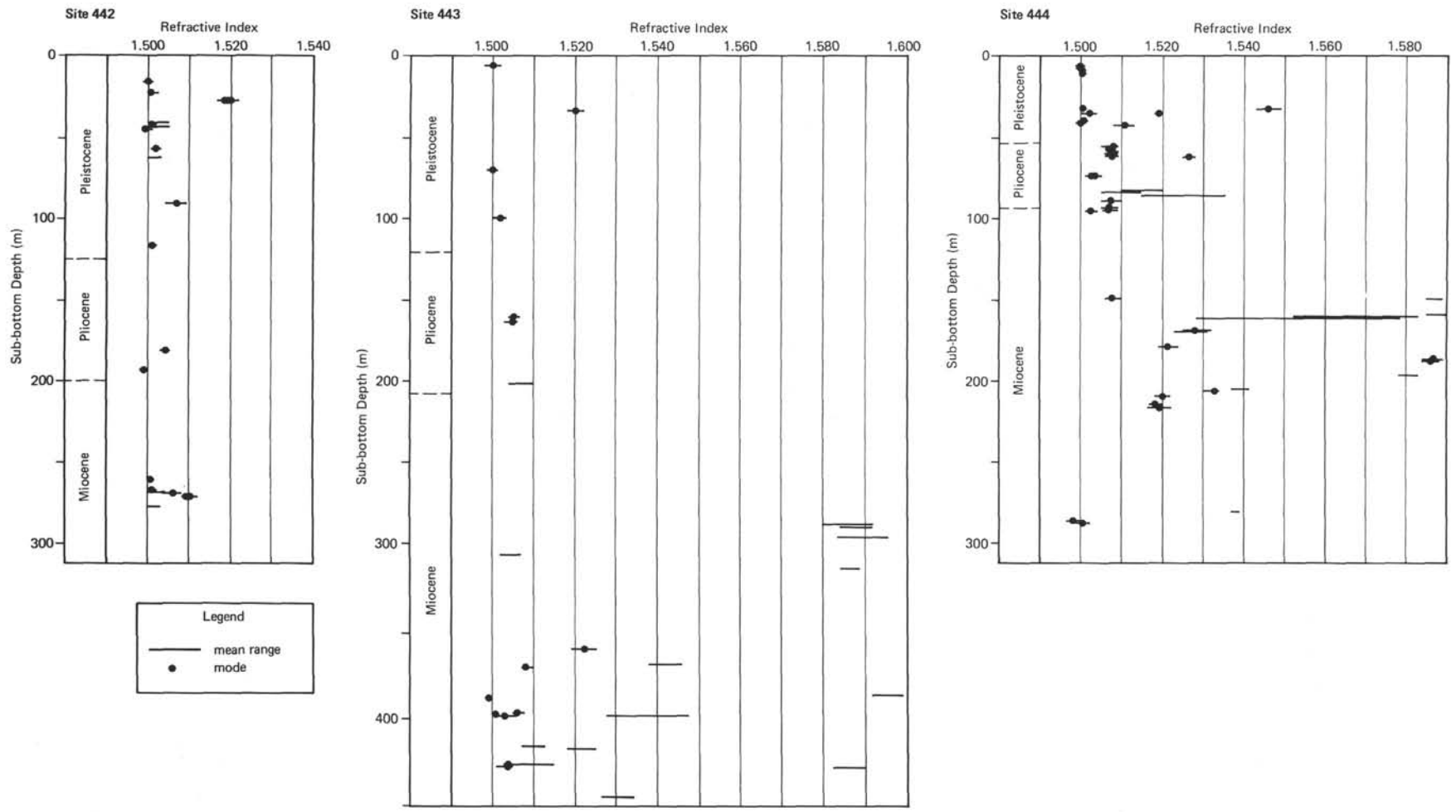


Figure 2. Refractive index of volcanic glass shards.

TABLE 3  
Chemical Composition of Volcanic Glass, Sites 442, 443, and 444

| Component                      | Sample (interval in cm) |                    |                    |                    |                     |                   |                   |                   |                    |                      |                    |
|--------------------------------|-------------------------|--------------------|--------------------|--------------------|---------------------|-------------------|-------------------|-------------------|--------------------|----------------------|--------------------|
|                                | 442A-2-5,<br>100-104    | 442A-3-3,<br>66-68 | 442A-3-6,<br>48-50 | 442A-5-3,<br>30-34 | 442A-7-1,<br>98-100 | 443-1-4,<br>64-66 | 443-4-2,<br>80-82 | 443-8-5,<br>26-28 | 443-11-5,<br>55-57 | 443-22-2,<br>139-141 | 443-31-3,<br>29-31 |
| SiO <sub>2</sub>               | 71.75                   | 73.45              | 70.86              | 72.70              | 73.39               | 74.73             | 72.20             | 77.27             | 74.82              | 74.10                | 54.11              |
| Al <sub>2</sub> O <sub>3</sub> | 11.64                   | 11.51              | 13.26              | 11.45              | 11.39               | 11.17             | 12.50             | 11.61             | 12.35              | 12.29                | 14.13              |
| TiO <sub>2</sub>               | 0.07                    | 0.12               | 0.63               | 0.20               | 0.22                | 0.24              | 0.45              | 0.13              | 0.10               | 0.15                 | 0.96               |
| FeO*                           | 0.90                    | 0.87               | 3.25               | 1.04               | 0.92                | 0.90              | 3.16              | 0.75              | 1.40               | 1.66                 | 12.29              |
| MnO                            | 0.03                    | 0.05               | 0.17               | 0.06               | 0.05                | 0.04              | 0.13              | 0.07              | 0.05               | 0.03                 | 0.25               |
| MgO                            | 0.17                    | 0.15               | 0.63               | 0.23               | 0.15                | 0.17              | 0.54              | 0.15              | 0.04               | 0.13                 | 4.40               |
| CaO                            | 1.19                    | 1.21               | 2.53               | 1.21               | 0.99                | 1.05              | 2.73              | 0.87              | 0.91               | 1.30                 | 8.92               |
| Na <sub>2</sub> O              | 3.66                    | 3.72               | 3.74               | 2.87               | 3.15                | 3.64              | 3.66              | 3.68              | 3.62               | 4.08                 | 2.31               |
| K <sub>2</sub> O               | 2.86                    | 2.19               | 1.74               | 2.86               | 4.23                | 3.27              | 1.88              | 3.19              | 4.25               | 2.72                 | 0.27               |
| Total                          | 92.26                   | 93.99              | 96.81              | 92.62              | 94.49               | 94.85             | 97.25             | 97.72             | 97.54              | 96.46                | 97.64              |
| Refractive index               | 1.499-1.501             | 1.500-1.501        | 1.518-1.521        | 1.501-1.504        | 1.501-1.503         | 1.499-1.501       | 1.519-1.522       | 1.499-1.501       | 1.500-1.503        | 1.505-1.508          | 1.585-1.590        |

| Component                      | Sample (interval in cm) |                      |                    |                    |                      |                    |                      |               |                    |                    |                   |
|--------------------------------|-------------------------|----------------------|--------------------|--------------------|----------------------|--------------------|----------------------|---------------|--------------------|--------------------|-------------------|
|                                | 443-31-4,<br>6-8        | 443-32-1,<br>106-108 | 443-39-2,<br>69-71 | 443-40-2,<br>22-24 | 443-40-2,<br>139-140 | 443-45-1,<br>92-94 | 443-45-1,<br>106-108 | 443-45,<br>CC | 443-46-2,<br>81-83 | 443-48-1,<br>85-87 | 444-4-5,<br>54-56 |
| SiO <sub>2</sub>               | 54.23                   | 52.95                | 69.40              | 60.19              | 73.34                | 73.64              | 70.63                | 67.85         | 56.59              | 72.21              | 60.50             |
| Al <sub>2</sub> O <sub>3</sub> | 14.39                   | 13.59                | 11.96              | 15.09              | 11.01                | 11.22              | 12.33                | 13.96         | 13.16              | 12.89              | 14.55             |
| TiO <sub>2</sub>               | 1.07                    | 1.03                 | 0.61               | 0.93               | 0.32                 | 0.36               | 0.16                 | 0.52          | 1.35               | 0.75               | 1.09              |
| FeO*                           | 12.85                   | 12.91                | 3.80               | 6.17               | 1.92                 | 2.29               | 1.78                 | 3.13          | 13.63              | 4.15               | 7.49              |
| MnO                            | 0.21                    | 0.24                 | 0.12               | 0.17               | 0.05                 | 0.06               | 0.05                 | 0.10          | 0.27               | 0.18               | 0.23              |
| MgO                            | 4.16                    | 5.60                 | 0.78               | 1.50               | 0.29                 | 0.35               | 0.03                 | 0.52          | 3.45               | 0.91               | 2.15              |
| CaO                            | 9.74                    | 9.56                 | 3.37               | 4.62               | 2.07                 | 2.48               | 0.55                 | 2.06          | 8.79               | 4.14               | 5.71              |
| Na <sub>2</sub> O              | 2.19                    | 2.24                 | 3.30               | 4.24               | 3.19                 | 3.53               | 4.16                 | 5.15          | 2.36               | 4.02               | 4.06              |
| K <sub>2</sub> O               | 0.25                    | 0.27                 | 0.99               | 1.17               | 1.00                 | 1.16               | 4.89                 | 2.91          | 0.39               | 0.74               | 0.76              |
| Total                          | 99.09                   | 98.08                | 94.33              | 94.80              | 93.19                | 95.09              | 94.58                | 95.72         | 97.69              | 95.20              | 96.54             |
| Refractive index               | 1.584-1.592             | 1.583-1.595          | 1.520-1.524        | 1.538-1.546        | 1.507-1.512          | 1.507-1.512        | 1.530-1.543          | 1.518-1.525   | 1.582-1.592        | 1.527-1.533        | 1.543-1.549       |

| Component                      | Sample (interval in cm) |                 |                   |                      |                     |                       |                     |                   |                     |                     |  |
|--------------------------------|-------------------------|-----------------|-------------------|----------------------|---------------------|-----------------------|---------------------|-------------------|---------------------|---------------------|--|
|                                | 444-4-5,<br>106-108     | 444-5-1,<br>6-8 | 444-7-6,<br>17-19 | 444A-9-2,<br>112-114 | 444A-10-1,<br>92-94 | 444A-12-1,<br>119-121 | 444A-12-2,<br>45-47 | 444A-13-2,<br>0-2 | 444A-13-3,<br>74-76 | 444A-22-1,<br>82-84 |  |
| SiO <sub>2</sub>               | 73.95                   | 71.04           | 70.89             | 47.74                | 51.00               | 46.81                 | 47.79               | 55.47             | 56.19               | 62.20               |  |
| Al <sub>2</sub> O <sub>3</sub> | 11.69                   | 12.26           | 11.98             | 15.36                | 12.44               | 16.00                 | 15.78               | 13.16             | 14.21               | 13.46               |  |
| TiO <sub>2</sub>               | 0.18                    | 0.58            | 0.37              | 1.82                 | 1.10                | 1.63                  | 1.67                | 0.89              | 0.93                | 0.95                |  |
| FeO*                           | 0.88                    | 3.15            | 1.41              | 7.58                 | 13.05               | 7.89                  | 8.08                | 11.89             | 10.61               | 5.23                |  |
| MnO                            | 0.06                    | 0.18            | 0.04              | 0.22                 | 0.35                | 0.20                  | 0.19                | 0.27              | 0.21                | 0.13                |  |
| MgO                            | 0.19                    | 0.60            | 0.34              | 6.23                 | 4.44                | 7.36                  | 7.67                | 2.54              | 3.23                | 1.24                |  |
| CaO                            | 1.28                    | 2.74            | 1.33              | 11.09                | 10.48               | 11.23                 | 11.10               | 7.94              | 9.83                | 3.64                |  |
| Na <sub>2</sub> O              | 3.71                    | 3.69            | 3.49              | 3.41                 | 1.91                | 2.98                  | 2.81                | 2.11              | 2.54                | 3.53                |  |
| K <sub>2</sub> O               | 2.79                    | 1.91            | 3.21              | 1.59                 | 0.26                | 1.30                  | 1.25                | 0.35              | 0.43                | 3.31                |  |
| Total                          | 94.73                   | 96.15           | 93.06             | 95.04                | 94.83               | 95.40                 | 96.34               | 94.62             | 98.18               | 93.69               |  |
| Refractive index               | 1.500-1.501             | 1.518-1.520     | 1.525-1.528       | 1.577-1.580          | 1.600-1.610         | 1.584-1.589           | 1.584-1.588         | 1.578-1.583       | 1.575-1.590         | 1.537-1.539         |  |

\*Total iron as FeO.

### RELATIONSHIP BETWEEN REFRACTIVE INDEX AND CHEMICAL COMPOSITION OF GLASS SHARDS

According to Williams et al. (1955), SiO<sub>2</sub> content of glass from artificial fusion of volcanic rocks and that of natural glass can be estimated from the refractive indexes. Recently, many investigators have reported the relationship between refractive index and SiO<sub>2</sub> content: it is well known that as SiO<sub>2</sub> content increases, refractive index decreases, although the relationship between the two parameters has not been established in detail yet.

In Figure 5, the mean ranges of refractive indexes from individual tephra layers (the range within which 80

per cent of the measurements fall) are plotted against average SiO<sub>2</sub> content. The correlation between refractive index and SiO<sub>2</sub> content is consistent, as a whole, with the trend given by Williams et al. (1955). In Figure 6, the mean ranges of refractive indexes are plotted against the mean of total iron content of glass shards. The relation between refractive index and FeO content is quite linear. Because the refractivity of the transition-metal oxides is higher than that of SiO<sub>2</sub> and other oxides, the refractive index seems to be affected primarily by the content of the transition-metal oxides, such as FeO, TiO<sub>2</sub>, and MnO. In volcanic glass shards, FeO (or Fe<sub>2</sub>O<sub>3</sub>) predominates over the other transition-metal oxides, so that the refractive index of volcanic glass shards

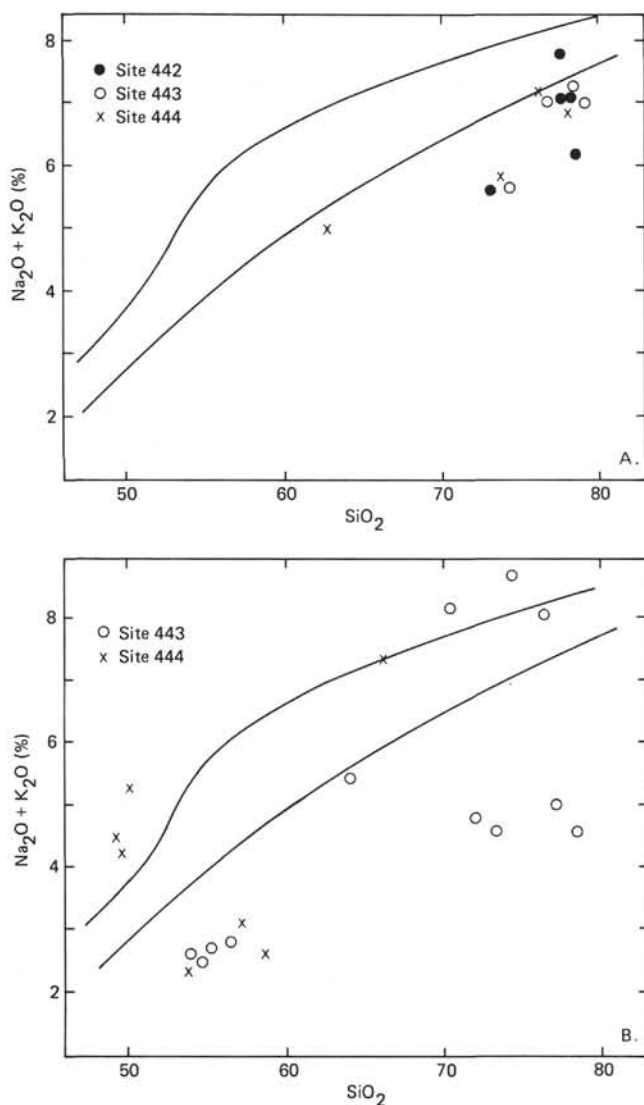


Figure 3. Total alkalis-SiO<sub>2</sub> relation for glass shards of tephra layers from the Shikoku Basin. A. Pleistocene and Pliocene tephra layers. B. Miocene tephra layers. The two lines mark the general boundaries between the fields of the tholeiitic series, the high-alumina series, and the alkali series (Kuno, 1965).

can be determined by the content of the iron oxides alone.

The refractivity of ferric oxide is about 1.6 times greater than that of ferrous oxide, so that as ferric-oxide increases over ferrous oxide, the refractive index of glass shards increases. In Figure 6, some of the plotted data are off the general trend. In these exceptional samples, the ferric-iron content may be much higher than in glass which plots on the trend, because the total alkali-SiO<sub>2</sub> relation of these samples show that they belong to the alkali rock series.

### INTERPRETATIONS

On the basis of petrographic characteristics, chemical composition, and paleontological age, the tephra layers

from the Shikoku Basin are divided into the following groups: (1) non-alkali rhyolitic tephra layers in the Pleistocene and Pliocene at Sites 442, 443, and 444; (2) non-alkali rhyolitic tephra layers in the Miocene at Site 444; (3) non-alkali tholeiitic basalt tephra layers in the Miocene at Sites 443 and 444; (4) alkali rhyolitic tephra layers in the Miocene at Site 443; and (5) alkali basaltic tephra layers in the Miocene at Site 444.

It is clear that most Pleistocene and Pliocene tephra layers originated from non-alkali volcanism, whereas Miocene tephra layers originated from two different, simultaneous volcanic activities, as described below.

### Hydration of Glass Shards

Hydration of volcanic glass shards has been discussed by many investigators (Aramaki and Lipman, 1965; Aramaki and Haramura, 1966; Jezek and Noble, 1978; Scheidegger et al., 1978; Ninkovich, 1979). Glass shards in deep-sea tephra layers are commonly subjected to hydration after deposition (Scheidegger et al., 1978; Ninkovich, 1979). In this study, glass shards of tephra layers from three sites seem to be hydrated, but visible alteration or hydrated rims of glass shards cannot be detected by optical observation. Electron-microprobe analysis of glass shards shows that most shards with the chemical composition of rhyolite and basalt are homogeneous from rim to core. In a few samples, shards are inhomogeneous: Na<sub>2</sub>O and K<sub>2</sub>O increase slightly from rim to core. In the present work, we omitted these samples.

### Relation Between Refractive Index and Some Oxides

As shown by Williams et al. (1955), there is a close correlation between refractive index and SiO<sub>2</sub> content in volcanic glass shards. This relation is summarized as follows: (1) with a SiO<sub>2</sub> content of 72 to 73 per cent, the refractive index is about 1.50; (2) as the SiO<sub>2</sub> content decreases, the refractive index increases proportionately, but the trend is slightly curved at SiO<sub>2</sub> contents between 55 and 65 per cent. The same correlation between refractive index and SiO<sub>2</sub> content of glass shards is established for deep-sea tephra in the Shikoku Basin.

The correlation between refractive index and total iron oxide is shown in Figure 6. This linear relationship is better than that between refractive index and SiO<sub>2</sub> content.

The refractive index of volcanic glass shards primarily depends upon the contents of transition-metal oxides, because the refractivity of transition-metal oxides is higher than that of SiO<sub>2</sub> and other chief constituent oxides (Larsen and Berman, 1943). Because the predominant constituent of transition-metal oxides is usually iron oxide, refractive index of glass shards is closely correlated to total iron. Although TiO<sub>2</sub> has the highest refractivity among the transition-metal oxides in glass, its content is considerably smaller than that of iron oxide. In Figure 6, some data plot off the trend of correlation. The TiO<sub>2</sub> content in these glass shards is larger than that in glass shards with a normal refractive index. If the total content of transition metal oxides in glass is plotted

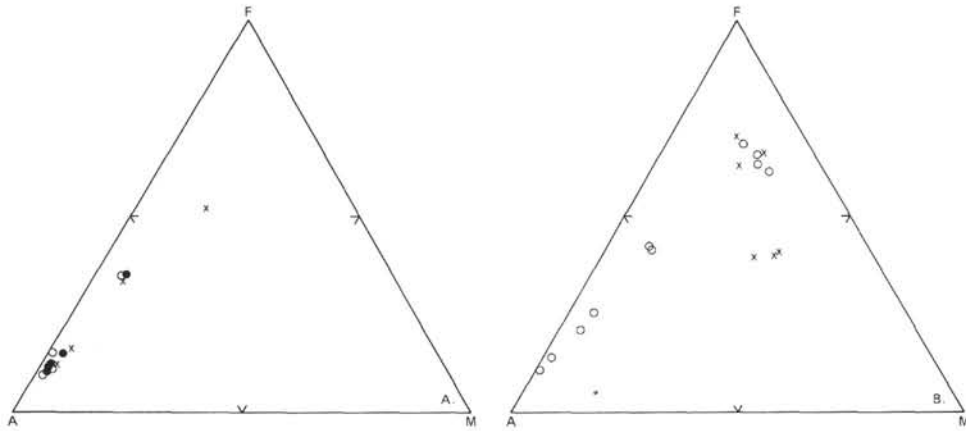


Figure 4. AFM (total iron-total alkali—MgO) diagram, showing the fractionation trend from basaltic to rhyolitic glass shards of tephra layers from the Shikoku Basin. Symbols as in Figure 3.

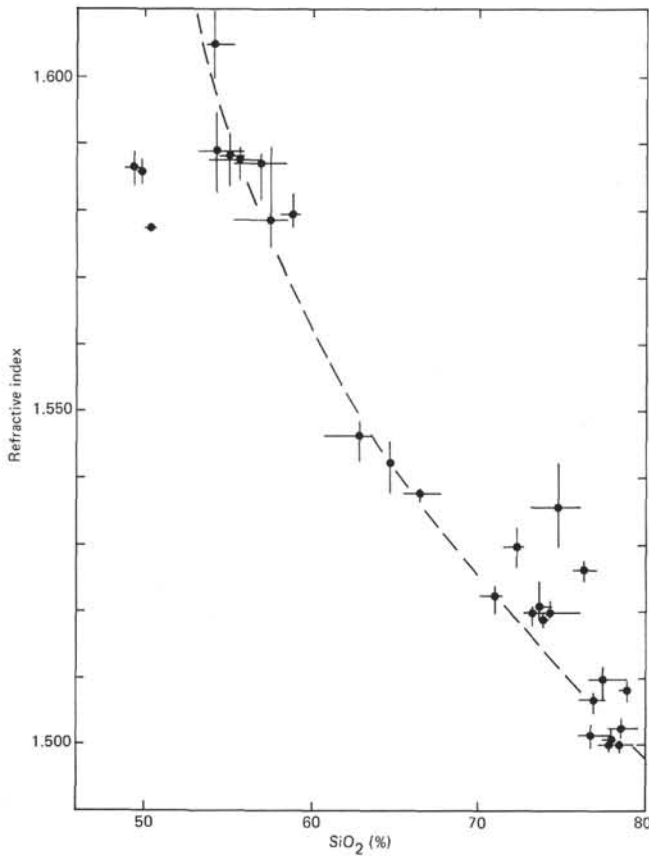


Figure 5. Relationship between refractive index and SiO<sub>2</sub> content of volcanic glass shards. Horizontal bars denote the ranges of SiO<sub>2</sub> content, and vertical bars denote the mean ranges of refractive index. Data are recalculated on a water-free basis.

against the refractive index, the correlation will be better. Another cause of this deviation seems to be the relatively large amount of ferric iron.

**Origins of the Deep-Sea Tephra Layers**

As noted, it is clear that the tephra layers from the central part of the Shikoku Basin have been derived

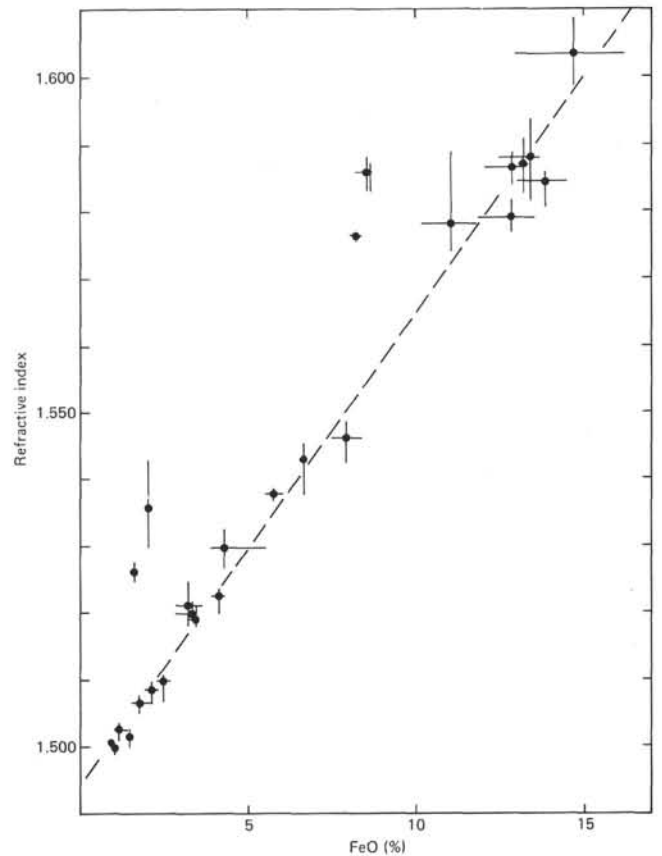


Figure 6. Relationship between refractive index and total iron oxide content. Horizontal bars denote the ranges of total iron oxide contents, and vertical bars denote the mean ranges of refractive index. Data are recalculated on a water-free basis.

from different volcanic sources with different rock series. Most of the Pleistocene and Pliocene tephra layers in this region are rhyolitic to dacitic (non-alkali series). These tephra layers presumably are ejecta produced by relatively large-scale eruptions in an island arc and transported toward the east: the grain size of shards in a well-correlated late-Pleistocene layer (442A-3-6, 48-50



cm; 443-4-3, 80-82 cm; 444-5-1, 6-8 cm) is greater in the westernmost site (442) than at the two eastern sites (443 and 444).

In contrast, the Miocene tephra layers are from rhyolitic to basaltic and belong to both the non-alkali and alkali rock series. In these tephtras, the grain size of basaltic glass shards is usually greater than that of rhyolitic shards. This implies that sources of basaltic tephtra were closer to the drilling sites than those of rhyolitic and andesitic tephtra. Moreover, it is well known that the eruption columns of basaltic volcanoes are much smaller than those of felsic volcanoes, and the altitude attained by the ejecta is much lower. This results in much shorter distances of transport for basaltic ash falls, as compared with felsic ash falls. Therefore, the source of these basaltic tephtra layers is assumed to have been close to the drilling sites.

A pillow basalt was dredged from one of the seamounts of the Kinan seamount chain in the central part of the Shikoku Basin; it was identified as tholeiitic basalt of late-Miocene age (Tokuyama and Fujioka, 1976). Petrographic study of basement basalts from the Shikoku Basin DSDP sites indicates that most are abyssal tholeiite, but a few sills belong to the alkali series (Dick et al., this volume). Tephtra with high total alkali may be from such alkali volcanism. Another possible source is the Izu-Shichito-Iwo Jima volcanic arc, east of the drilling sites, although its history is not well understood. The activity of this arc probably ranges from the early Miocene to the Holocene (Kaneoka et al., 1970).

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APPENDIX  
Petrographic Characteristics, Site 445 Tephra Layers<sup>a</sup>

| Sample<br>(interval in cm) | Sub-<br>bottom<br>Depth<br>(m) | Constituent Minerals         | Volcanic Glass |                      |              |                  |             |       |
|----------------------------|--------------------------------|------------------------------|----------------|----------------------|--------------|------------------|-------------|-------|
|                            |                                |                              | Type           | Color                | Size<br>(mm) | Refractive Index |             | Mode  |
|                            |                                |                              |                |                      |              | Range            | Mean Range  |       |
| 445-1-5, 33-35             | 6.33                           | pl +                         | pm<bw          | clear                | 0.2          | 1.500-1.512      | 1.509-1.511 |       |
| 2-3, 48-50                 | 11.98                          | pl++, hy +, au +, hb +, op + | pm<bw          | clear                | 0.4          | 1.502-1.503      |             |       |
| 3-3, 114-116               | 22.14                          |                              | bw             | clear                | 0.4          | 1.500-1.504      |             |       |
| 8-4, 59-61                 | 70.59                          |                              | bw             | clear                | 0.2          | 1.501-1.512      |             |       |
| 10-5, 90-92                | 91.40                          | pl ++, hy +, au +, op +      | pm>bw          | p. brown             | 0.5          | 1.505-1.540      | 1.518-1.530 |       |
| 12-3, 31-33                | 106.81                         | pl ++, hb +, hy +, op +      | pm>bw          | clear                | 0.1          | 1.508-1.512      |             |       |
| 12-4, 105-107              | 109.05                         | pl ++, hb ++, au +, op +     | pm>bw          | clear                | 0.1          | 1.503-1.509      | 1.503-1.505 |       |
| 13-4, 118-120              | 118.68                         | pl +, op +                   | pm>bw          | clear to<br>p. brown | 0.2          | 1.515-1.550      | 1.515-1.530 |       |
| 23-2, 53-55                | 210.03                         | bi ++, pl +                  | pm>bw          | clear                | 0.1          | 1.501-1.503      |             | 1.502 |
| 23-3, 9-11                 | 211.09                         | pl +, hb +                   | pm             | clear                | 0.1          | 1.504-1.505      |             |       |
| 26-1, 99-101               | 237.49                         | pl ++, bi ++, hy +, op +     | pm>bw          | clear                | 0.2          | 1.499-1.501      |             | 1.500 |
| 32-2, 61-63                | 295.61                         | pl ++, hy +, au +, op +      | pm<bw          | p. brown             | 0.3          | 1.506-1.521      | 1.506-1.508 | 1.507 |
| 46-2, 7-8                  | 428.07                         | pl ++, hy +, au +, op +      | pm             | p. brown             | 0.1          | 1.522-1.528      | 1.523-1.525 |       |
| 55-6, 30-32                | 518.30                         | pl ++, op +                  | pm             | p. brown             | 0.2          | 1.520-1.540      |             |       |
| 56-2, 144-146              | 524.44                         | pl ++, hy +, au +            | pm>bw          | clear to<br>p. brown | 0.2          | 1.512-1.514      |             | 1.513 |
| 57-7, 40-42                | 540.40                         | pl ++, bi ++, hy +           | pm>bw          | clear                | 0.5          | 1.501-1.503      |             | 1.502 |
| 62-1, 110-112              | 579.60                         | pl ++                        | pm>bw          | clear to<br>p. brown | 0.1          | 1.504-1.506      |             | 1.505 |
| 62-2, 89-90                | 580.89                         | pl ++, au +                  | pm             | clear                | 0.1          | 1.508-1.515      | 1.508-1.511 |       |
| 64-4, 92-93                | 602.92                         | pl +                         | pm>bw          | p. brown             | 0.2          | 1.518-1.521      |             | 1.520 |
| 64-4, 114-115              | 603.14                         | pl +                         | pm             | p. brown             | 0.1          | 1.517-1.558      | 1.525-1.540 |       |
| 64-6, 76-77                | 605.76                         | pl ++, au +, op +            | pm≅bw          | p. brown             | 0.2          | 1.509-1.511      |             | 1.510 |
| 64-6, 78-79                | 605.78                         | pl ++, au ++, op +           | pm<bw          | p. brown             | 0.5          | 1.509-1.512      |             | 1.511 |
| 66-4, 144-146              | 622.44                         | pl ++, hy +, au +, op +      | pm>bw          | clear                | 0.1          | 1.507-1.510      |             | 1.508 |

<sup>a</sup>Symbols as in Table 2.

PLATE 1

- Figure 1 442-A-3-6, 48-50 cm. Glasses are almost pumice type. Refractive index = 1.517 to 1.522.
- Figure 2 443-1-4, 64-66 cm. Glasses are bubble-wall type. Refractive index = 1.499 to 1.501.
- Figure 3 443-11-5, 55-57 cm. Clean pumice-type glasses are predominant in this sample. Refractive index ranges from 1.500 to 1.503.
- Figure 4 443-31-4, 6-8 cm. Glasses are brown scoria type. Refractive index = 1.584 to 1.592. Dark-brown devitrified glasses have numerous inclusions.
- Figure 5 443-45-1, 92-94 cm. Glasses are clear bubble-wall type. Refractive index = 1.507 to 1.513.
- Figure 6 443-46-2, 81-83 cm. Glasses are brown scoria type and have acicular crystallites. Refractive index = 1.582 to 1.589.
- Figure 7 444A-12-1, 119-121 cm. Glasses are flake-shaped brown shards. Refractive index = 1.584 to 1.588.
- Figure 8 Closeup of shard with crystallites from sample shown in Figure 7. This glass shard includes many crystallites, including scopulite and globulite.

PLATE 1

