Geology and Geochemical Evolution of Lavas on the Island of Pohnpei, Federated States of Micronesia

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ABSTRACT

Pohnpei is one of three volcanic islands in the Caroline Island group in the southwest Pacific. Previous K-Ar dating of the lavas on these three islands suggests that they are products of hot-spot type activity which persisted on two of the islands (Pohnpei and Truk) for an extended duration compared to other hot-spot volcanoes on the Pacific plate**.** The Caroline Island group represents the only sub-aerial hot-spot chain on the Pacific Plate in the northern hemisphere besides the well documented Hawaiian Chain.

Geologic mapping on Pohnpei conducted during this study led to the subdivision of volcanism into three separate stages of activity. A representative suite of sixty rock samples collected from the three volcanic states was analyzed for chemical and isotopic (Sr, Nd, Pb) composition. The main shield-building stage of volcanism, centered near the town of Kolonia, persisted for roughly one million years. Lavas of this stage are predominantly relatively thin, gently dipping flows of olivine-phyric alkali olivine basalt, which are commonly intruded by numerous dikes. Chemical trends are consistent with the fractionation of olivine and lesser amounts of clinopyroxene in the more differentiated members of the series. Lavas of the Awak Volcanics series unconformably overlie the shield-building lavas and range in composition from basanite to trachyte. Hawaiite is the most common rock type in this volcanic series and major element abundance variations can be explained by fractional crystallization of the observed phenocryst assemblages. The Kupwuriso Volcanics series constitute the most recent eruptive products on Pohnpei. Lavas of this series are all nepheline normative and range from nephelinite to basanite. Chemical trends within this series are largely controlled by variations in the degree of partial melting.

The shield-building lavas and dikes on Pohnpei are compositionally similar to the slightly alkalic lavas erupted during the waning stages of shield building volcanism on Hawaiian volcanoes. The Awak Volcanics have a similar, although somewhat greater range of composition, than alkalic

capping stage lavas of Hawaiian volcanoes. The final Kupwuriso stage on Pohnpei is compositionally similar to the post-erosional lavas on some Hawaiian volcanoes.

Isotopic data for Pohnpei fall within the modern-day oceanic island or hot-spot field. Data for the three volcanic series lie along distinct trends in Pb isotope diagrams, indicating these series did not originate from an isotopically homogeneous source. Comparison of the Pohnpei data with isotopic data for basalt from Ontong Java Plateau suggests that little or no mixing occurred between Pohnpei magmas and the thick plateau crust atop which the island was built. In general, the Pohnpei lavas are more radiogenic in $^{208}Pb/^{204}Pb$ than the overall Hawaiian. The general trend toward less radiogenic 87Sr/86Sr values going from shield-building to alkalic capping to post-erosional stages observed in many individual Hawaiian Volcanoes is not seen in the Pohnpei data set. The comparatively limited range of Sr and Nd isotopic variability coupled with the extended persistence of volcanic activity after migration of the island away from the "hot-spot" places bounds on the nature of geochemical heterogeneities present within the source region for this intra-plate volcano.

INTRODUCTION

The island of Pohnpei, Federated States of Micronesia is situated at 6°54'N and 158°14'E. Pohnpei has a land area of 338 km^2 and is almost completely surrounded by a barrier reef, which averages 3.2 km in width, and a lagoon, which varies in depth from 0 to 100 m. The island is roughly circular in shape and is characterized by steep mountains in the deeply dissected interior. There are eleven peaks higher than 600 m, the highest being Nanalaud (760 m). The general steepness of the island is reflected in the fact that about half of the area (47%) of Pohnpei is on slopes of more than 30 percent (Laird, 1982). Large coastal plains of alluvium are not present on Pohnpei, as coastal alluvial sediments have apparently been drowned by interglacial rises in sea level (Bloom, 1970) and by island subsidence (Spengler, 1990). The perimeter of the island is fringed instead with mangrove forests growing on the seaward part of the coastline and with Nipa palm, Phragmites reed, or domestic swamp taro growing in the inner-margin, where the salinity is lower. Raised reefs are not found on Pohnpei, although modern growth in the shallow fringing coral reef offshore is vigorous.

Pohnpei is a member of the Caroline Island group which consists of three sub-aerial volcanic islands and numerous atolls and reefs. Figure 1 is a general location map and also depicts the relative size of the islands in the Caroline group. The three volcanic islands (Truk, Pohnpei, Kosrae) become smaller in size and geomorphologically younger to the east. Truk has reached a near-atoll stage of development, with topographic highs of the original volcano today exposed as numerous islets enclosed within a surrounding barrier reef. Pohnpei has attained an intermediate stage of atoll development with a central, main volcanic island that is almost completely surrounded by a barrier reef. Kosrae, the youngest island in the chain, is surrounded by a narrow fringing reef.

The geology of the islands in the Caroline group has received little previous attention, with the exception of Truk (Stark and Hay, 1963). As a result, previous geochemical investigations of Pohnpei (Mattey, 1982; Keating et al., 1984; Dixon, 1984) were conducted without the benefit of a detailed understanding of the geology of the island. The identification of magmatic series among rock samples collected during these previous studies was based solely on the measured compositions of the rocks; the relative stratigraphic positions of the samples analyzed were unknown, and thus a comprehensive geologic context in which to interpret the geochemical data was lacking.

This paper describes the results of reconnaissance geologic mapping of Pohnpei conducted by the first author as well as the results of chemical and isotopic analysis conducted on a comparatively extensive suite of rock samples collected from the three volcanic series delineated by field mapping. The advantage of this study over previous geochemical studies on Pohnpei is that observed changes in lava composition and isotopic ratios can be associated clearly with stages in the island's volcanic development established during field mapping.

Characterization of the variation in geochemistry of the lavas on Pohnpei is important because the Caroline Island group represents the only subaerial hot-spot chain in the northern Pacific besides the well-documented Hawaiian chain. Thus, isotopic and chemical compositions measured for the volcanoes are valuable in characterizing non-MORB mantle sources under this vast portion of the Pacific. The isotopic data are also useful in evaluating the contribution of various mantle sources in light of the extended duration of volcanism (relative to other hot-spot volcanoes on the Pacific Plate) on Pohnpei.

Previous Investigations

The earliest geologic studies of Pohnpei were parts of regional surveys of the South Sea islands conducted during the periods of German and Japanese administration (Kaiser, 1903; Yosii, 1936; Iwao, 1941). These studies provided brief petrographic descriptions of samples and noted that the rocks on Pohnpei are alkalic in composition. Tayama (1936) collected a suite of rocks from Pohnpei and briefly described the island’s geomorphology, geology, and coral reefs. He also produced a rough geologic map of the island’s perimeter. Five major terraces were identified, which he associated with alternating events of uplift and subsidence on the island. Bloom (1970) studied the stratigraphy and morphology of the tidal swamps that fringe the Eastern Caroline Islands and concluded that deposition was consistent with a history of shoreline progradation associated with decelerating submergence during the Holocene. Four radiocarbon dates on intertidal peat layers overlying former hillslopes of weathered volcanic rocks on Pohnpei demonstrated a submergence of about five meters over the last 5,500 to 6,000 yr.

Yagi (1960) provided petrographic and chemical data on fourteen of the rocks collected by Tayama (1936). The rock types analyzed included olivine basalt, nepheline basalt, trachyandesite, and trachyte. Yagi (1960) noted the chemical similarity of rocks from Pohnpei, Truk, and Kosrae and suggested that the East Caroline Islands constitute an alkalic province geochemically distinct from the Marianas and Palau, the calc-alkalic islands located to the west. Ishikawa and Yagi (1969) presented limited trace element data on the same suite of samples.

The bathymetry and quasi-linear trend observed in the Eastern Caroline Islands (Fig. 1) led Jarrard and Clague (1977) to propose a hot-spot origin for these islands. Epp (1978) showed that this linear trend is co-polar with the Hawaiian chain from 0 to 14 Ma. Pollitz (1986) suggested that the convex-northward configuration of the island trend from Pohnpei to Kosrae was consistent with a minor change in the absolute motion of the Pacific Plate between 5.0 and 3.2 Ma observed in other Pacific hot-spot traces.

Mattey (1982) described the mineralogy and geochemistry of volcanic rocks from the three subaerial volcanic edifices in the Caroline chain (Truk, Pohnpei, and Kosrae). The systematic decrease in volume of these islands (Figure 1) was found to be coupled with systematic increases in silica-undersaturation, absolute abundance of incompatible (IC) elements, and observed ratios of more-IC to less-IC elements (e.g., Ce/Y). This secular variation in lava chemistry along the Caroline chain was attributed to gradually changing conditions during partial melting, resulting in a gradual decline in magma production. On Pohnpei, the rocks analyzed were predominantly from the island's perimeter, where the most accessible exposures are found. Mattey sub-divided the lavas on Pohnpei into three series based on differences in chemical composition. The shield-building lavas on Pohnpei were sub-divided into a dominant main lava series that encompassed rock types ranging from basalt to trachyte (Pohnpei Main Lava Series; PMLS) and a geochemically less-alkalic transitional lava series (Pohnpei Transitional Lava Series; PTLS). The chemical variation observed in these shield-building lavas was attributed to low-pressure fractional crystallization of the observed phenocryst assemblages. A third geochemical series (Pohnpei Basanite Series; PBS) was associated with a post-erosional phase of volcanism. The compositional trends observed in these near-primary post-erosional PBS lavas were interpreted to reflect variable degrees of partial melting.

Keating et al. (1984) provided K-Ar age, paleomagnetic and geochemical data for the Caroline Islands which suggested a hot-spot origin for the island chain. Dixon et al. (1984) analyzed eleven rocks for major and trace elements and reported five additional K-Ar ages of Pohnpei lavas. They proposed that this suite of lavas was produced by multi-stage (polybaric) fractional crystallization and that the observed geochemical variation was controlled by variable amounts of an incompatible-element-rich phase in the mantle source. The five K-Ar ages obtained during this study ranged from 0.9 to 8.7 Ma. Dixon argued that the age data are not consistent with a simple

hot-spot model owing to the overlap in K-Ar ages for these widely spaced volcanoes and the extended duration of volcanism (~8-11 Ma.) on Pohnpei and Truk. Rather, they proposed that volcanism along the chain was related to the interaction between the Caroline Plate and the Pacific Plate beginning in early Miocene times and continuing to the present. Figure 2 shows that the duration of volcanism on Pohnpei and Truk is more typical of hot-spot volcanoes on slow-moving plates as in the Atlantic (e.g., Canary Islands and Tristan de Cunha).

A limited amount of previous isotopic data has been published for Pohnpei lavas. Hedge (1978) analyzed two Pohnpei lavas for Sr isotopic ratios while Dixon et al. (1984) reported Sr and Nd isotopic data for four samples. More recently, isotopic compositions (Pb,Nd,Sr) for three Pohnpei lavas were measured by Hart (1988) whose data are incorporated with ours after correction for inter-laboratory differences.

Methods

A total of six months of field work were completed on Pohnpei between January 1988 and August 1989. A geologic map was produced based on all available roadcuts, drill logs, and natural outcrops present on the island (Fig. 3). Because of the dense vegetation in the island's interior, geologic contacts were typically mapped in stream beds and in the faces of waterfalls in the steep-sided, elongated ridges (dolens) found in the interior. In the course of this study, the stream beds of all major rivers were followed as far as possible into the interior. Elevations were estimated by reference to the 1983 USGS 1:25 000 topographic map for Pohnpei and by use of a pocket altimeter. Completion of the circum-island road in the late 1980s also provided numerous invaluable outcrops in the southern half of the island.

It is difficult to find a continuous stratigraphic sequence of lava flows on Pohnpei because of the dense vegetation, thick soil, and colluvial cover that commonly separate exposures of bare rock. Individual outcrops can usually be traced for only short distances horizontally along strike. In addition, a sequence of flows found in one vertical section can be quite different from a sequence observed in a section only a hundred meters away. This is a result of the tongue-like projections of individual flows, as well as the dissection that occurs in the individual flows between pulses of eruptive activity. Adding to the difficulty of tracing individual flow units from outcrop to outcrop is the relatively aphyric character of many of the post-shield lava flows, which often are indistinguishable in hand-sample. As a result of the large distances between mappable outcrops and the need to extrapolate a contact between these localities, the location of the contacts delineated on the geologic map (Fig. 3) should be considered approximate.

GENERAL GEOLOGY

The volcanic rocks on Pohnpei are subdivided into two major units on Figure 3: the shield-building lavas and the overlying post-shield deposits. The island's roughly circular outline and the gentle dip of the shield-building lavas suggest that the original volcano possessed a shield-like morphology. Limited K-Ar age data suggest that the shield building stage occurred around 8.5 Ma. Volcanic activity became more explosive toward the end of this constructional stage, blanketing the southern half of the island with extensive ash deposits and the northern half with stratified deposits of volcanic breccia. A quiescence in volcanic activity followed, during which time significant erosion of the island occurred. Sporadic eruptive activity resumed at roughly 7 Ma and persisted to the last 1 Ma (Keating et al., 1984; Dixon et al., 1984). These post-shield deposits are subdivided into two groups, the Awak Volcanics and the Kupwuriso Volcanics, based on differences in age, general flow morphology, and chemical composition. These two units are not distinguished on the geologic map, however, because the contact between them is observed at only a few isolated localities (typically in exposures on the faces of waterfalls and steep cliffs). This post-shield activity generated thick flows, which repeatedly capped, and thus protected, the more easily eroded shield-building lavas. Based on K-Ar ages (Keating et al., 1984; Dixon et al., 1984) the Awak stage lasted from about 3.0 to 7.0 Ma and the Kupwuriso stage extended from less than 1.0 Ma to 2.1 Ma.

SHIELD-BUILDING LAVAS. Exposures of the shield-building lavas are concentrated around the island perimeter and in valleys where erosion has cut through the capping post-shield volcanics (Figure 3). Olivine-phyric alkali olivine basalt is the predominant rock type, with lesser amounts of clinopyroxene and plagioclase appearing in the more evolved lavas in this series. Individual flow units range in thickness from 0.6 to 9 m (average of 3 m) and are predominantly aa flows containing clinker zones above and below a dense interior. Pahoehoe flows are also observed, but much less frequently. The flows have relatively shallow dips, ranging from 3° to 11° at the few localities where individual flows can be followed for appreciable lateral distances. The lavas are almost always weathered. At many outcrops, the original rock has been completely altered to clay, but the original flow morphology usually can still be discerned.

The volcanic center during the main constructional stage of volcanic activity was located by gravity survey and from the observed variation in intensity and strike of dikes in the shield-building lavas. A free-air anomaly contour map for Pohnpei was constructed based on a total of 189 gravity measurements made on the island and the surrounding reef, using a portable Lacoste-Romberg gravimeter (Fig. 4). The free-air gravity high is centered over the northern end of the island near the town of Kolonia. The free-air contours are roughly concentric around this gravity high, in contrast to the typically elongate free-air contours that characterize well-developed rift systems (Strange et al. 1968). This is consistent with the variation in measured dike orientations

illustrated in Figure 4. The divergence in the strike of dikes around the gravity high suggests that the shield lavas were erupted from a radially distributed dike swarm centered near the location of the gravity high. Exposures of shield-building lavas near the gravity high are intruded with up to 95% dike material, further evidence that this area was close to the original eruptive center. Outcrops of shield-building lavas located within the area of greater than 40% dike intensity (roughly coincidental with the 325 Mgal free air anomaly on Figure 4) have undergone pervasive greenschist-facies alteration, with chlorite, epidote, and pyrite being the dominant secondary minerals.

Volcanic breccia and ash deposits blanketed much of the island at or near the end of the shield-building stage. The breccia deposits (Parem Breccia) are best exposed in the barrier islands of Parem and Mwahnd Peidi in the northeastern end of Pohnpei while the ash deposits (Rohi Ash) are best exposed in the southern half of the island along the circum-island road.

AWAK VOLCANICS. The Awak Volcanics rest unconformably above the shield-building volcanics and the Parem Breccia in the northern half of Pohnpei. The type locality occurs at Kepin Mahu, near the village of Awak, where a near-continuous 170-m section of these volcanics is exposed (Fig. 5). Individual flow units are relatively thick (average of 15 m) and commonly have moderately steep dips (8°–13°). The thicker flow units often possess well-developed columnar jointing. In addition, many flows of this stage appear to have been discharged into rivers or other standing bodies of water, producing a highly fragmental rock (hyaloclastite) as the fluid basalt suddenly chilled and granulated upon entering the water. Relatively long periods elapsed between individual eruptions of this stage, as evidenced by the relatively thick (up to 15 m) conglomerate and stream deposits often found between individual flow units. The oldest flows exposed at the type locality are basanitic in composition, with increasing amounts of more evolved hawaiites occurring up-section. Several trachytic domes found in the southern half of the island are also associated with this volcanic stage.

Dolen Net and Paipalap, the two impressive ridgelines that flank the town of Kolonia, are composed of flows of hawaiitic composition from this stage of volcanism. These structures are examples of inverse topography, where the relatively viscous hawaiite flows ponded within paleo-valleys cut into the original, shield-building lavas. As erosion removed the less resistant shield-building lavas that made up the valley walls, the more resistant, ponded alkalic lavas remained, forming the vertical escarpments seen today.

The mineralogy present within these lavas varies as a function of differentiation within the series. The more evolved alkali basalts and hawaiites are typically aphyric, with a sugary texture due to the presence of microscopic laths of plagioclase. The basanites often have minor amounts of modal olivine in the groundmass with subordinate amounts of clinopyroxene. A few flows of

ankaramite are found near the top of the section. These ankaramites contain abundant modal amounts of both olivine and clinopyroxene (15%–30%) and were a common building stone used in the construction of the archaeological site at Nan Madol. The more evolved hawaiites and mugearites are relatively aphyric, with minor amounts of olivine, clinopyroxene, and magnetite present in the groundmass. The even more differentiated trachyte samples contain magnetite and plagioclase phenocrysts.

KUPWURISO VOLCANICS. The last stage of volcanism on Pohnpei is best exposed below the peak at Kupwuriso, where a 110-m-thick section is partially visible in the walls of the ridge (Fig. 5). Relatively thick (10–25 m on average), columnar jointed lava flows with intervening thinner layers of sedimentary material are exposed in this type section. Around the perimeter of the island, these flows often became very thick (up to 60 m) as the relatively fluid lava ponded in paleo-valleys. The majority of flows associated with this stage have well-developed columnar jointing at their base and tops. Another distinguishing characteristic of these flows is the common occurrence of xenoliths. Dunite is the most common xenolith observed, along with smaller amounts of gabbro and harzburgite.

The lavas of this stage range in composition from alkali olivine basalt to nephelinite. These lavas commonly contain phenocrysts of olivine, with subordinate amounts of titanaugite microphenocrysts present in the groundmass. From two stratigraphic sections that have been sampled and chemically analyzed, it appears that the basanites were erupted first, followed by the nephelinites. In general, the earlier phases of activity during this stage were more voluminous than the later phases.

Temwen Island is probably the youngest volcanic feature on Pohnpei. It is a tuff cone that formed as a result of the explosive interaction between hot magma and either shallow groundwater or seawater. A small nephelinitic lava flow emanated from near the center of the cone and flowed west. The fact that this easily eroded tuff cone still retains much of its original morphology in such an intense chemical weathering environment attests to its relative youthfulness.

Lavas of the Kupwuriso stage are mapped together with the Awak Volcanics in Figure 3 since the contact between these two units is so infrequently exposed around the island. In the section near Kupwuriso, the contact lies at around an elevation of 450 m. In a drill hole near the town of Kolonia, a 75-m-thick section, composed of a minimum of four flows, overlies a 35-m section of Awak hawaiite flows. The major distinguishing features of these two stages are the generally larger volumes of individual Kupwuriso flows, the common occurrence of xenoliths in the Kupwuriso Volcanics, and the distinct chemical composition of the lavas.

In summary, volcanism on Pohnpei may be subdivided into two distinct phases of activity. The main constructional shield-building phase consisted of the repeated eruption of relatively thin, gently dipping lava flows of alkali olivine basalt. Volcanic activity became more explosive toward the end of this stage, blanketing portions of the island with extensive ash and volcanic breccia deposits. Volcanic activity ceased for roughly one million years, during which the original shield volcano was heavily eroded. Sporadic volcanic activity then resumed and persisted over a period of roughly six million years. This post-erosional activity generated thick lava flows, which repeatedly capped, and thus protected, the more easily eroded shield-building lavas. The post-erosional activity was subdivided into two volcanic series, the Awak Volcanics and Kupwuriso Volcanics, on the basis of differences in age, general low morphology, and chemical composition. The Awak Volcanic Series and ranged in composition from basanite to trachyte while the Kupwuriso Volcanic Series ranged in composition from alkali olivine basalt to nephelinite.

ANALYTICAL METHODS

Stratigraphically controlled sets of rock samples were collected during mapping from both accessible portions of steep cliff faces and from cuttings recovered during drilling of several deep water supply wells near the town of Kolonia. Sixty of these samples, representing the full stratigraphic range sampled, were selected for chemical analysis.

The majority of outcrops of the shield-building lavas were in a highly weathered condition, rendering them unsuitable for chemical study. This fact probably led to the shield-building stage being poorly represented in previous geochemical studies (i.e. Mattey et al., 1982; Dixon et al., 1984; Keating et al., 1984). The deep weathering of these shield lavas is due to a combination of their old age, the environment (i.e., in excess of 500 centimeters/year rainfall along the coast), and the relatively thin and highly vesicular nature of individual lavas. Because of the heavily weathered character of the lavas, over half of the shield-building stage samples analyzed in this study were recovered from less weathered dikes that intrude these lavas (see Table 1). The sampling localities are illustrated in Figure 3.

Rocks chosen for analysis were broken into small chips from which the freshest material was hand-picked. Selected chips were powdered in an alumina mill for XRF (X-ray fluorescence) analysis. Material analyzed for isotopic composition was powdered separately in agate.

Major and trace element compositions were determined for sixty samples by XRF spectrometry at the University of Hawaii (40 samples) and at Washington State University (24 samples) (Table 1). A Rh anode X-ray tube was used to determine major and trace elements. Replicate analyses were run on separate pellets for samples analyzed at the University of Hawaii. Instrumental drift was

minimized by reanalyzing the same standard repeatedly after every ninth sample. Based on replicate analyses of standards BCR-1 and ARCO-1 at the University of Hawaii, the precision for the major elements is estimated to be better than 1% for SiO_2, TiO_2, FeO, 2% for CaO, MgO, K_2O, 5% for Al_2O_3 and 15% for Na_2O and P_2O_5. The reported precision of trace element data for standards BCR-1, BHVO and W1 is better than 1% for Sr, Zr, Rb and 2% for Nb and Y.

Splits of four samples were run at both labs. The major element data from both labs agree within the estimated precision of the UH XRF for most elements with only Al displaying a consistent bias between data sets. The trace element data shows a consistent bias in three of five elements analyzed. Measured Sr and Zr abundances are consistently higher in the Hawaii data set while Nb abundances are consistently lower with a maximum difference of 4 to 8% between data sets. The Washington State XRF trace element data (Sr, Zr and Nb) and major element data (Al) reported in Table 1 have been normalized to the University of Hawaii data.

Isotopic analyses were performed at the University of Hawaii on a VG Sector mass spectrometer. Chemical separation and mass spectrometric procedures used were as described by Mahoney and Spencer (1991). The total range for NBS 987 Sr is ± 0.000022 and for La Jolla Nd ± 0.000012. Total Pb isotopic ranges for the NBS 981 standard were ± 0.008 for $^{206}Pb/^{204}Pb$, ± 0.008 for $^{207}Pb/^{204}Pb$ and ± 0.03 for $^{208}Pb/^{204}Pb$. Uncertainties in the Pb abundances determined by isotope dilution are better than 1% whereas values for Sm and Nd are better than 0.2%. Values are reported relative to $^{143}Nd/^{144}Nd = 0.511855$ for La Jolla Nd, $^{87}Sr/^{86}Sr = 0.71024$ for NBS 987 Sr, and the NBS987 Pb values of Todt et al. (1984). Thirteen samples were chosen for isotopic analysis to represent the three volcanic series. All were analyzed for Sr and Nd isotopic ratios; a subset of nine were analyzed for Pb isotopes. Three of the rock samples analyzed for isotopes were from the shield-building stage, five were from the intermediate Awak stage and five were collected from the Kupwuriso volcanic stage. Isotopic ratios are listed as present-day values in Table 1.

ALTERATION

Some of the rocks showed macroscopic evidence of low-temperature alteration, which potentially could have affected chemical and isotopic composition. The relatively high volatile loss on ignition (LOI) values (0.06-4.95 wt.%) of some of the samples are substantially greater than values typically associated with fresh volcanic rock. However, thin-section study of several samples with high LOI values revealed only minor secondary mineralization. Dixon et al. (1984) observed that despite the high H_2O contents in some samples, neither the oxygen isotopic compositions nor the Fe_2O_3/FeO ratios deviated greatly from values associated with unaltered oceanic alkalic basalts, suggesting that their samples had not exchanged oxygen appreciably with meteoric water or seawater.

Of the samples analyzed in this study, the shield-building samples were the most likely to have been affected by post-melting processes. As discussed earlier, the majority of outcrops of the main shield-building lavas encountered during mapping were so highly weathered that suitable samples for chemical study were often unattainable. As a result of this weathering, the abundances of some highly mobile element such as K and Rb exhibit relatively large amounts of scatter within this series. Samples from the Kupwuriso and Awak series are generally much less altered and have lower LOI values than the shield-building lavas. Element abundances within these series are not expected to have been affected greatly by weathering or hydrothermal alteration processes.

MAGMATIC SERIES

Variation diagrams of major and trace element data for rock samples analyzed during this investigation are presented in Figures 6 and 7. The samples were associated with a volcanic stage based on stratigraphic relations deduced during mapping. A wide range of chemical compositions is found, here illustrated using the chemical classification scheme of Irvine and Baragar (1971) (Fig. 8). Based on the major element data, the shield-building samples range from picrite basalt to alkali olivine basalt. The four shield-building samples that plot within the picrite basalt field contain between 12 and 25 modal percent olivine. The Awak Volcanic Series ranges from basanite to trachyte, with hawaiite being the most common rock type present among the analyzed samples. Samples from the Kupwuriso Volcanic Series range from nephelinite to alkali olivine basalt.

Mattey (1982) found the variation in Nb versus Zr to be particularly useful for delineating the three chemical series present on Pohnpei. In general, Mattey's PTLS data plot within the field defined by our shield-building lava and dike samples whereas his PMLS suite generally plot within the field described by the post-shield-building Awak volcanic series (see Figure 7). Data for the Kupwuriso volcanic series correspond to Mattey's PBS series. Mattey (1982) and Keating et al. (1984) suggested that the shield-building lavas of the Caroline Islands (Truk, Pohnpei, Kosrae) are similar to typical Hawaiian alkalic basalts. Mattey's PMLS is indeed chemically similar to lavas erupted during the alkalic capping stage on Hawaiian volcanoes. However, the mapping conducted in this study shows that rocks of similar chemical compositions as Mattey's PMLS series actually correspond to the post-shield Awak Volcanic Series. The shield-building lavas and dikes on Pohnpei are actually more similar chemically to the slightly alkalic lavas erupted late in the shield-building stage of some Hawaiian volcanoes (i.e., Kohala, Haleakala, Waianae, East Molokai, and West Maui [Macdonald et al. 1983]). This is illustrated in Figure 9 where the compositional fields for Kohala Volcano, Hawaii (Spengler and Garcia, 1988) are superimposed on the Pohnpei data on a silica versus total alkali diagram. The field labeled Upper Pololu corresponds to samples collected from the upper 100 m of the shield-building section from Kohala which are distinctly more alkalic than the lavas of the main shield-building stage of activity (the Lower Pololu

field). The Hawi field corresponds to the alkalic-capping stage on Kohala. The majority of Pohnpei shield-building compositions either overlap or plot along linear extensions of the Upper Pololu field. Lavas of the Awak series on Pohnpei mostly plot within or along extensions of the Hawi field.

A more detailed description of the geochemical variation observed in each volcanic stage is given below.

Main Shield-Building Stage

The non-porphyritic shield-building samples vary little in MgO content (5-7%) yet have a relatively wide range in K_2O abundance (0.48 to 1.24%). Some of this variability is probably due to mobilization of K_2O during weathering and hydrothermal alteration. Low potassium abundances at a given MgO content are most commonly observed in shield-building samples collected near the original volcanic center of the island where the intensity of these secondary processes was apparently the greatest. Less mobile incompatible elements such as phosphorous vary much less within this series. The four shield-building lavas with high MgO contents (12-18%) contain much higher modal amounts of olivine (12%-35%) than the other samples from this stage (typically 1%-3%). As a result, the trends observed within these high MgO lavas are largely consistent with olivine control.

The main shield lavas form relatively linear trends in the trace element variation diagrams (Figure 7). Some scatter is observed in the K_2O and Rb trends which are likely to have been affected by variable amounts of alteration, as mentioned previously. The overall trends are consistent with the fractionation of the observed phenocryst assemblage (olivine and lesser amounts of clinopyroxene) in the more differentiated members of the series.

Awak Volcanic Stage

The Awak data form broadly linear trends consistent with fractional crystallization, although there is substantial scatter within the major element data (Figure 6). The P_2O_5 data are, in particular, quite scattered, with four samples having much higher P_2O_5 contents at a given MgO content than the other samples in the group. Apatite is observed within the groundmass of these lavas but not as a cumulus phase and thus could not have produced the chemical differences observed between these two groups of data. The effect of apatite fractionation is observed, however, in the mugearite and trachyte samples (MgO<3.5%), where phosphorous decreases to very low concentrations. Fractionation of a titanium-bearing phase (Ti-rich clinopyroxene and minor magnetite) is suggested by the steadily decreasing TiO_2 concentration in the more differentiated members within the series.

The Awak trace element data form broadly scattered trends, particularly in the Nb and Sr versus Zr diagrams (Figure 7). The scatter partly reflects the presence of porphyritic ankaramite lavas and

relatively aphyric hawaiite/mugearite lavas within the same volcanic series. The presence of variable amounts of modal clinopyroxene and plagioclase within these samples would be expected to affect the trends of elements such as Sr, which can reach high concentrations within these mineral phases. However, the abundances of other normally incompatible elements (Nb, K_2O) do not co-vary with Zr as would be expected if fractional crystallization alone controlled the composition of the lavas. In addition, the Zr versus P_2O_5 diagram reveals two samples which have significantly lower P_2O_5 contents at a given Zr content than the rest of the Awak data plotted. This suggests that either the source is heterogeneous in abundances of these elements or that these samples were produced by different degrees of partial melting of a source containing phases which retain these elements during melting.

Kupwuriso Volcanic Stage

Within the Kupwuriso data set, two distinct chemical sub-groups are apparent based on the major element data; One group being characterized by low TiO_2 and K_2O contents and high Al_2O_3 contents at a given MgO content while the other group has higher TiO_2 and K_2O contents and lower Al_2O_3 contents at a given MgO content. The abundance of P_2O_5 increases with increasing MgO content within both groups in the Kupwuriso series. The two subgroups within the Kupwuriso stage can not be related by fractionation of the dominant mineral phases (olivine and lesser amounts of clinopyroxene) observed in the Kupwuriso series lavas.

The observed range in abundances of incompatible elements in the Kupwuriso series is much greater than can be produced by fractional crystallization between the low and high MgO (12%-17%) samples within the series. Thus it appears that the chemical variability within this series was largely controlled by variations in the degree of partial melting. The observed ranges in incompatible elements such as P_2O_5 suggest that the degree of melting varied by a factor of approximately 2.5 within the series. The Rb abundance varies by a factor of 5.5 within the series but this large variation may partially reflect post-melting, secondary processes, such as variable enrichment by an alkali-rich, mobile fluid phase. This phenomena is observed within the Honolulu Volcanic Series where multiple samples collected from a single flow unit can yield widely variable alkali-metal abundances (Clague and Frey, 1982), presumably resulting from the presence of abundant pegmatoid segregations within the flow.

Figure 10 plots the primitive mantle normalized element ratios (Sun and McDonough, 1991) of moderately to highly incompatible elements for the three volcanic series on Pohnpei. The mean trace element concentrations of eleven of the thirteen lava samples analyzed by mass spectrometry for isotopic content (producing Nd, Sm, Sr, Pb and Rb data by isotopic dilution) were averaged and plotted. Two Awak Series samples (a mugerite and trachyte sample) were not plotted since these samples had undergone a large degree of fractionation which skewed the resultant trace element

concentrations. The averaged Kupwuriso and Awak data show a relative depletion of K and Rb in comparison to typical Ocean Island Basalt profiles. The relative depletion of these incompatible trace elements has been atributed o the presence of residual phlogopite in the source for post erosional lavas in other hot-spot volcanos (Clague and Frey, 1982). Some of the observed relative depletion of Rb and Ba in the averaged main shield data is believed to be related to the weathering of the rock (the mobility of the trace elements during weathering of the samples). Watson (1993) also concluded from the inversion of rare earth element data for Hawaiian post-erosional lavas that these lavas require an amphibole-bearing source which had been enriched by post-shield magma.

ISOTOPIC COMPOSITION

A total of thirteen rock samples collected during the field mapping were analyzed for Sr, Nd and Pb isotopes. Three of the rock samples analyzed were from the shield-building stage, five were from the Awak Volcanic stage, and five were from the Kupwuriso Volcanic stage. In addition to the isotopic data collected in this study, Hart (1988) analyzed three rock samples collected in 1983 by Mike Robinowitz on Pohnpei for Sr, Nd and Pb isotopes. The locations from which these samples were collected (S.R. Hart, Personal Communication) are shown in Figure 3. Major element data provided by Hart for these three additional samples can be found in Table 1. Samples 1 and 2 were collected from areas where lavas of the Awak stage outcrop. Sample 4 was collected from the site of a rock crushing plant located in the back of Nett Valley which quarries rock from a nearby thick, ponded Kupwuriso stage lava flow.

The isotopic ratios measured in the thirteen Pohnpei lavas analyzed during this study vary over a narrow range in $^{87}Sr/^{86}Sr$ (0.70319-0.70339), $^{143}Nd/^{144}Nd$ (0.51294-0.51299), $^{206}Pb/^{204}Pb$ (18.41-18.83), $^{207}Pb/^{204}Pb$ (15.46-15.54) and $^{208}Pb/^{204}Pb$ (38.15-38.62). Figure 11 illustrates the variation in Sr, Nd and Pb isotopic values measured, including the three values reported by Hart (1988). Data from the three volcanic series on Pohnpei have overlapping Sr and Nd isotopic ratios with the overall trend of the data paralleling the oceanic mantle array. The ranges in isotopic ratios for samples within the three volcanic stages are greater than analytical uncertainty, although the absolute variation is nonetheless small. The Pb isotopic ratios for the three volcanic series in Pohnpei plot in discrete fields in $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagrams and are overall more radiogenic in $^{208}Pb/^{206}Pb$ than the overall Hawaiian field. Isotopic data for two post-shield lavas collected from the island of Truk, the oldest volcanic island in the Caroline group, are also included in Figure 11. The Truk lavas are somewhat elevated in $^{87}Sr/^{86}Sr$ but have overlapping Pb and Nd isotopic ratios in comparison to the Pohnpei isotopic data.

Present day isotopic data for tholeiiitic basalts recovered from two Deep Sea Drilling Project Sites (807 and 803) located on the northern portion of the Ontong Java Plateau (OJP) are also plotted in Figure 11 (Mahoney et al., 1993). Pohnpei is located just to the north of these two DSDP sites. The

OJP was formed by the eruption of voluminous submarine flood basalts during two discrete periods in the Cretaceous. Seismic measurements suggest that the crust reaches a thickness of up to 40 kilometers under the central portions of the plateau (Hussong et al., 1979). The OJP data were included in Figure 11 to test for evidence of contamination of the Pohnpei lavas by plateau lithosphere during their ascent through this massive volcanic pile. The OJP data, collected from these two DSDP sites and from basement exposures on the islands of Malaita and Small Malaita approximately seven hundred miles to the south, suggest involvement of a uniform, relatively low $^{143}Nd/^{144}Nd$, low $^{206}Pb/^{204}Pb$, high $^{87}Sr/^{86}Sr$ mantle source (Mahoney et al., 1993; Tejada et al., 1996) which is not seen in the Pohnpei data. Significant contamination of Pohnpei magma by plateau lithosphere appears to be precluded by the different trends of the two data sets, especially evident in the $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ isotopic diagram. In addition, there is no evidence of an enriched source within the Pohnpei data similar to that found within the Samoa, Tahiti, Marquesas and Cook/Austral island chains in the South Pacific. Thus the DUPAL anomaly originally identified by Hart (1984) does indeed appear to be largely confined to the South Pacific mantle.

It is instructive to compare the isotopic variation observed in Pohnpei shield to post-shield building stage lavas with the isotopic variation observed in Hawaiian Volcanoes, since the islands of the Caroline chain are the only other sub-aerial example of hot-spot volcanism in the northern Pacific. Shield building lavas in individual Hawaiian Volcanoes typically have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than associated post-shield lavas (Figure 12). Early workers attributed this temporal variation in isotopic geochemistry, along with associated variations in trace element composition, to mixing of incipient melts generated from a MORB source with undepleted plume material (Chen and Frey, 1985; Tatsumoto et al., 1987). According to this model, the MORB component was generated by partial melting of the depleted upper mantle wall rock during plume ascent. The chemical and isotopic composition of the shield building lavas are dominated by the plume component due to the high relative percent volume of this component in relation to the component produced by melting of the lithosphere during this robust phase of activity. However, after the volcano migrates away from the axis of the hot spot, very small (1%) degrees of melting of the wall rock produce high concentrations of trace elements which dominate the composition upon mixing with the ascending small-volume plume melts. This produces the shift towards MORB-like lavas observed during the post-shield stages of volcanism in Hawaiian lavas.

Recent fluid dynamic models (Hauri et al., 1994) predict that significant entrainment of ambient mantle occurs during plume ascent and that the range of entrainment is negatively correlated with the buoyancy flux. Most of the entrained fraction is believed to originate in the lower mantle yielding the FOZO (‘focal zone’) isotopic component which appears in hotspots around the world (Hart et al., 1992). In addition, ambient mantle outside the plume boundary will ascend as a result of viscous coupling to the flow in the plume conduit. As the viscously coupled ambient mantle ascends, it undergoes adiabatic decompression generating a partial melt with a MORB isotopic

signature. During the shield building stage, Hauri et al. (1994) hypothesized that this alkalic MORB-like component is diluted by large volumes of plume melt, generating lavas of tholeiitic composition. As the volcano migrates away from the hot-spot, the flux of plume component diminishes and the relative contribution of this MORB-like component increases. The difference between this fluid dynamic model and earlier models is that late-stage magmas primarily reflect melting of depleted mantle entrained by the plume rather than melting of the lithosphere.

Duncan et al. (1994) used a similar model to explain the chemical variation observed in Tahiti lavas. The observed variation in chemical and isotopic composition is attributed to chemical zonation of the source plume; the inner core of the plume, which contains relatively large amounts of entrained lower mantle, is the source material during the shield building phase while the volcano is positioned directly over the plume, while the post-shield lavas are generated by melting form the outer zone of the plume which contains relatively large amounts of entrained upper mantle. Lassiter (1995) proposed that the compositional differences between Loa-trend (Loihi, Mauna Loa, Hualalai) and Kea-trend (Kilauea, Mauna Kea, Kohala) volcanoes in Hawaii may be explained by a compositionally zoned mantle centered beneath the Loa-trend volcanoes.

The three stages of volcanism on Pohnpei do not show a similar temporal variation in Sr and Nd isotopic content as is typically observed in Hawaiian volcanoes. The fact that the shield building stage lavas on Pohnpei are alkalic in composition may indicate that the flux of plume component may have been lower than typically occurs in Hawaiian volcanoes as the volcano passes over the hot spot. In this scenario, the relative contribution of the MORB-like component (whether generated by melting of the lithosphere or upwelling of viscously coupled depleted upper mantle) would have been greater during the shield building stage than is typical for Hawaiian volcanoes producing shield lavas of alkalic composition and overlapping isotopic content with the post-shield lavas. Alternatively, the overlapping Nd and Sr isotopic content of the Pohnpei lavas could indicate that the upper and lower mantle in the vicinity of Pohnpei have similar overlapping isotopic compositions with respect to these two elements. Hawaiian volcanoes also typically exhibit a shift to higher $^{87}Sr/^{86}Sr$ at a given $^{206}Pb/^{204}Pb$ during the transition from shield building to young post-shield and/or post-erosional lavas (Chen et al., 1991). No such shift is observed in the Pohnpei isotopic data. The $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ data for the three volcanic series on Pohnpei plot in discrete fields (Figure 12). The lack of correlation between Pb isotope ratios and Sr and Nd isotope ratios rules out a simple two component mixing model for generation of Pohnpei lavas. The fact that the lead isotopic data plot in three discrete fields suggests the presence of a minimum of three discrete source components with discrete Pb contents but overlapping Nd and Sr contents.

As previously discussed, the duration of volcanism on Pohnpei was longer than observed on other hot spot volcanos erupted atop the Pacific Plate. The field mapping conducted during this study demonstrates that the long duration of volcanism on Pohnpei was related to extended post-shield

volcanism rather than a prolonged shield-building stage. Because the underlying plate velocity in the vicinity of the Caroline Islands and other hot spot chains in the Pacific is similar, the island of Pohnpei must have been comparatively far away from the "focus" of the hot-spot during eruption of the post-shield Awak and Kupwuriso volcanic stages. If the volcanic evolution of hot-spot volcanoes is controlled by passage over a chemically zoned plume, the extended duration of post-erosional volcanism suggests that the lateral dimension of the viscously coupled mantle component that was entrained by the plume underlying Pohnpei was exceedingly large. This is an unexpected result due to the relatively old age of the oceanic crust underlying the Caroline Island chain. The lateral dimension of the plume might have been anticipated to be relatively small due to the fact that the underlying lithosphere was relatively cool.

Hauri et al. (1994) concluded that the amount of ambient plume entrainment during upwelling of the plume is negatively correlated with the buoyancy flux. Because of the extended duration of volcanism on Pohnpei (relative to the overlying plate velocity), the post-shield lavas would be expected to contain a relatively high percentage of entrained upper mantle due to the presumably low flux rate (e.g. extended volcanic duration) of the melt which produced these post-shield lavas. However, in the region of Pohnpei, where the upper 20 to 40 kilometers of the underlying lithosphere is believed to be composed of Ontong Java Plateau lavas, no evidence for mixing with this component is observed in the isotopic data. Specifically, mixing trends towards the Ontong Java Plateau isotopic field would be expected in the Awak and Kupwuriso trends if such assimilation of upper mantle had occurred (Figure 11). The lack of such a trend in the isotopic data suggests that there is little interaction with material present in the underlying upper lithosphere.

Figure 13 shows the range of isotopic variability measured at individual Hawaiian hot spot volcanos plotted versus volcanic duration. The "amplitude ratio" as described by Zindler and Hart (1986) was used to describe isotopic variability for all oceanic basalts (mid-ocean ridges and oceanic islands). The isotopic range for oceanic basalts was taken from the data presented in Hofmann (1997). The variation in $^{206}Pb/^{204}Pb$ was used to calculate the amplitude ratio for lead. Since the plate velocity of the Pacific Plate over the Hawaiian and Caroline hot-spot is similar (Minster and Jordan, 1978), the volcanic duration roughly corresponds to the distance away from the original hot-spot plume that the final post-shield volcanic event occurred. If thermal factors controlled the degree of isotopic variability produced during post-shield volcanism (e.g. variations in partial melting, degree of wall rock interaction), a correlation between isotopic variability and volcanic duration would be expected. There appears to be a crude correlation between Sr isotopic variability and eruptive duration but no correlation between eruptive duration and Nd and Pb isotopic variability (Figure 13). The isotopic variability for all three isotopes is limited on Pohnpei. despite the extended duration of volcanism. The absence of a strong correlation between these variables indicates that isotopic variability observed in hot-spot volcanoes is most likely controlled by variations in source composition rather than from variable degrees of mixing of isotopically distinct sources. Lassiter (1995) has also

concluded that the temporal variation in isotopic composition observed in Mauna Kea lavas reflects an evolution in source composition rather than involvement of lithospheric components. The observation of large-scale isotopic variations within lavas erupted over 0.1 Ma on Pitcairn with similar major and trace element composition (Woodhead and McCulloch, 1989) also argues for source control of isotopic variability rather than the variation being generated by variable degrees of mixing or partial melting. The island of Pohnpei represents the opposite extreme; a hot-spot volcano with chemically distinct lavas, generated over a wide range in degrees in partial melting, having limited and overlapping isotopic content (Sr and Nd), which erupted over an extended period of time.

CONCLUSIONS

Field-mapping led to the sub-division of volcanism on Pohnpei into three stages of activity. Volcanic activity during the shield-building stage was centered near the northern half of the island based on the results of an island wide gravity survey and from the measurement of dike trends on the island (Spengler, 1990). Throughout much of the island, the shield-building lavas are covered by flows from the later volcanic stages. In the northern half of the island, the shield lavas are intruded by numerous dikes which are typically less altered than the shield-building lavas themselves. Individual flow units within the shield-building lavas are typically 1.5 to 3.0 meters thick and contain highly weathered rubble zones above and below a dense, more resistant interior (aa morphology). The two oldest K-Ar age dates reported for Pohnpei (8.5 and 8.7 Ma; Keating et al., 1984; Dixon et al., 1984) were obtained on rocks collected near areas mapped as shield-building stage in this study.

The Awak volcanics unconformably overlie the shield-building volcanics. Individual flow units tend to be thicker (2.5-10.0 meters) and more massive than the shield-building flows. Sedimentary deposits are often found between individual flow units, suggesting that eruptive activity during this stage was sporadic. This is further suggested by the apparently long duration of this volcanic stage, with K-Ar dates ranging from 3.1-7.1 Ma (Keating et al., 1984; Dixon et al., 1984).

The final stage of volcanism on Pohnpei (Kupwuriso volcanic series) was characterized by high-volume eruptions of lava which often contained abundant entrained xenoliths. Individual flow units are often quite thick (up to 40 meters) owing to ponding of the low viscosity nephelinite and basanite flows of this stage within stream valleys and other pre-existing erosional features. K-Ar age dating of Kupwuriso flows yields ages ranging from 1.0-2.1 Ma (Keating et al., 1984; Dixon et al., 1984). Additional dating of morphologically younger volcanic vents, such as the tuff cone which forms Temwen Island, would probably extend this range to younger ages.

Lavas of alkali olivine basalt composition dominate the shield-building stage of volcanism on Pohnpei. This contradicts the assertion by Mattey (1982) that the shield-building stage was characterized by lavas ranging in composition from basalt to trachyte. Mattey's PMLS series is in

fact related to the Awak volcanic series which post-date the shield-building series by roughly 2 Ma. The Kupwuriso volcanic series, which is equivalent to Mattey's PBS series, ranges in composition from nephelinite to basanite and represents the most recent volcanic activity on Pohnpei. Thus, the geochemical evolution of lavas on Pohnpei is similar to the changes in composition observed within Hawaiian volcanoes, with the exception that the shield-building-stage lavas on Pohnpei are overall dominated by lavas of alkali olivine basalt rather than tholeiitic basalt composition

Fractional crystallization controls much of the chemical variation observed within the main shield series, although a compositionally heterogeneous source is required to explain the observed variation in some trace element ratios. The overall chemical variation within the Awak volcanic series is controlled by fractional crystallization. Variable degrees of melting of a source which is slightly compatible for the elements Nb, K_2O and Sr is required, however, by the trace element data. The Kupwuriso volcanics were produced by variable degrees of melting.

Data from the three volcanic series on Pohnpei have overlapping Sr and Nd isotopic ratios with the overall trend of the Sr and Nd data paralleling the oceanic mantle array. The temporal trend in isotopic composition typically observed in Hawaiian volcanoes during the transition from shield to post-shield volcanism is not observed on Pohnpei. The Pb isotopic ratios for the three volcanic series in Pohnpei plot in discrete fields and are overall more radiogenic in $^{208}Pb/^{206}Pb$ than the overall Hawaiian field. The isotopic data appear to preclude significant mixing between Pohnpei lavas and the underlying lithosphere of the Ontong Java Plateau. The isotopic data indicates that a minimum of three discrete source components with discrete Pb contents but overlapping Nd and Sr contents were required to produce the isotopic variation observed on Pohnpei.

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FIGURE 1
General Location Map

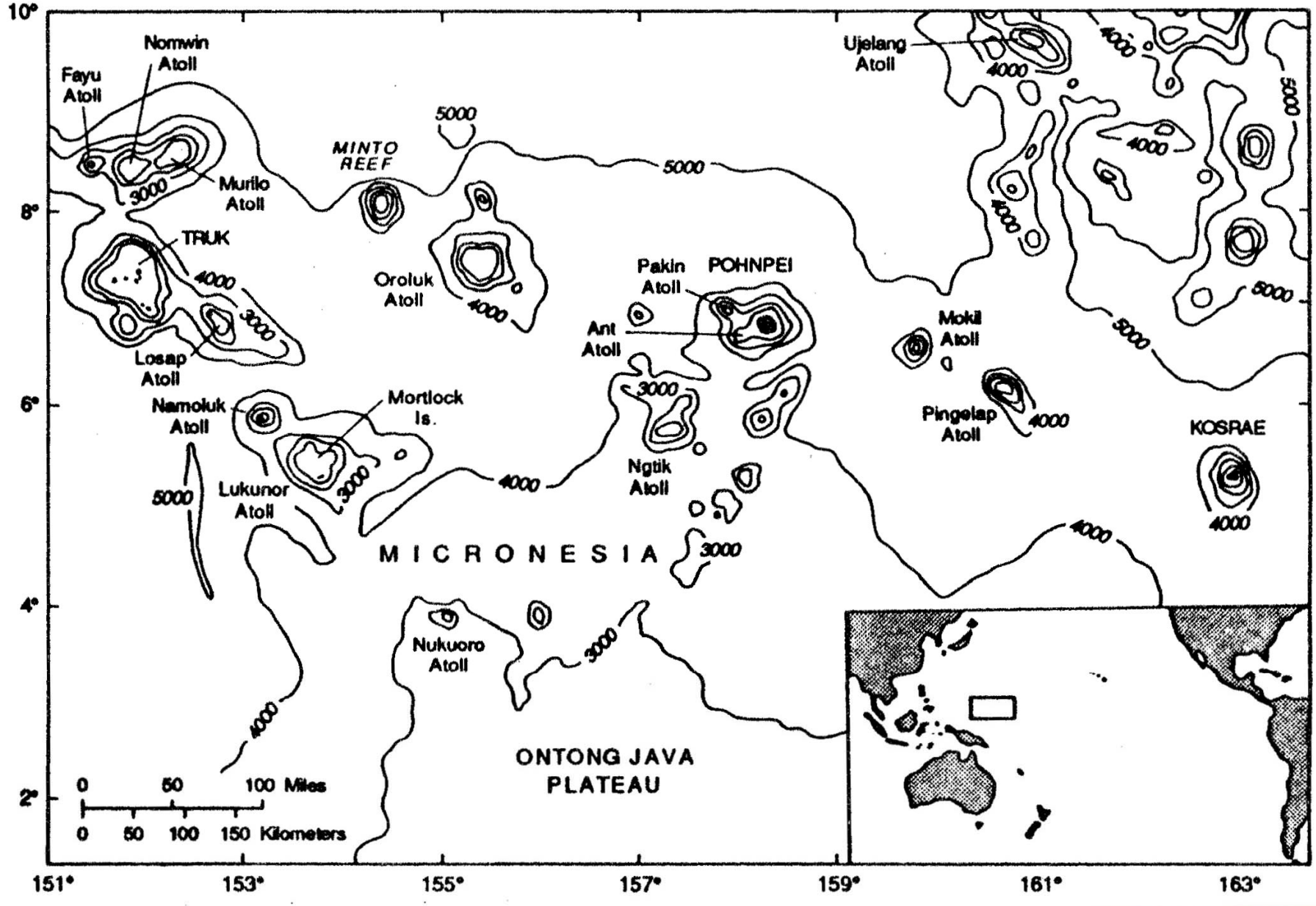


FIGURE 2
Volcanic Duration on Hot-Spot Volcanoes Versus Plate Velocity

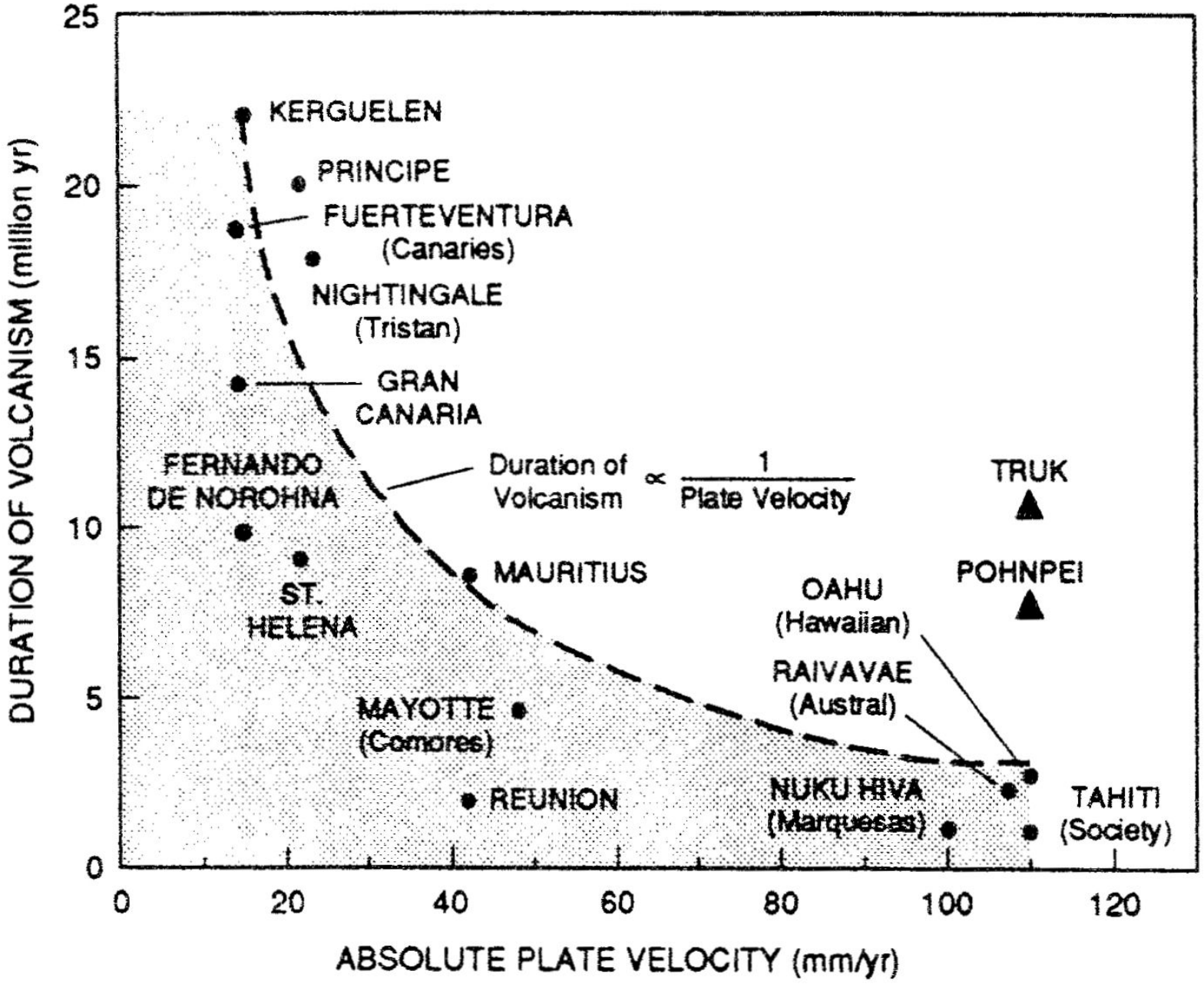
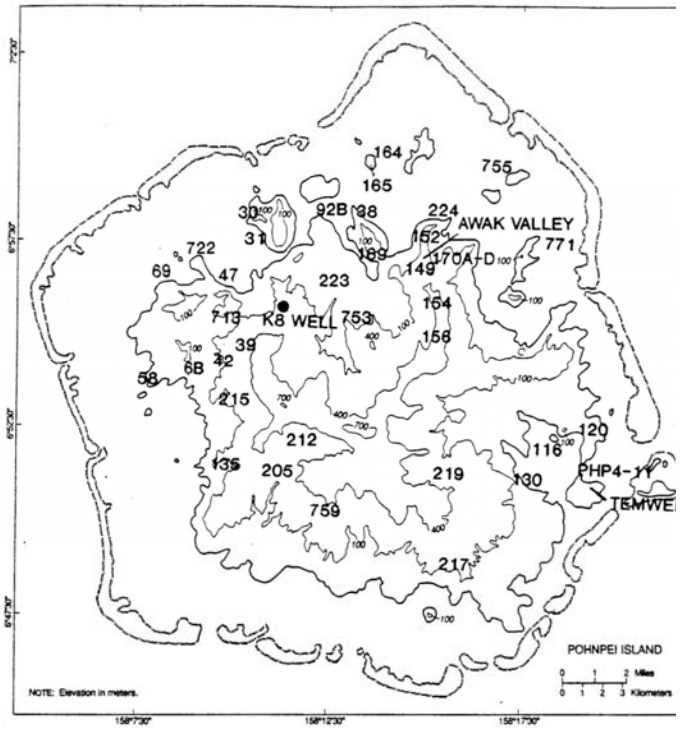


FIGURE 3
Geologic Map of the Island of Pohnpei and Sample Locations



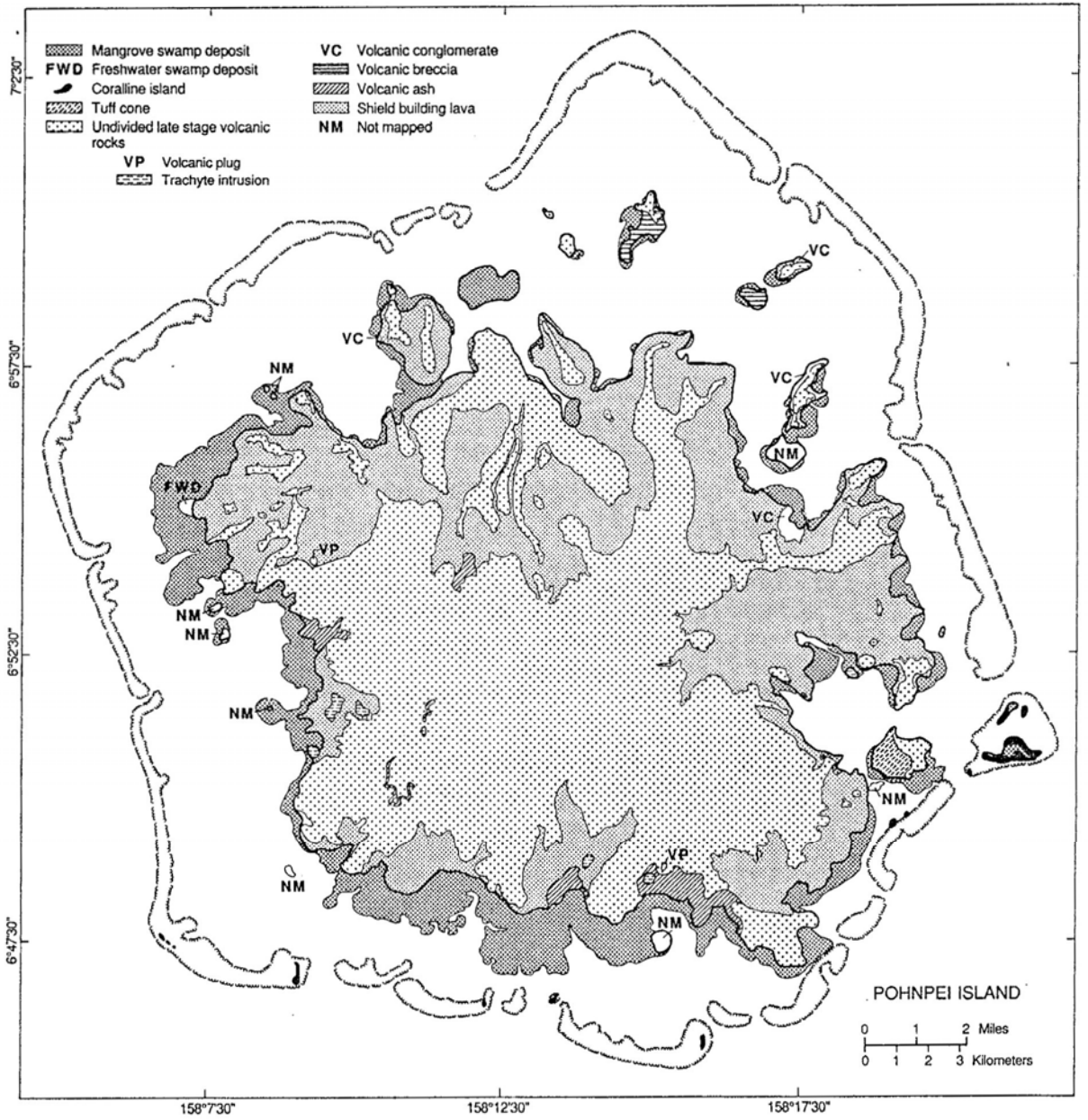
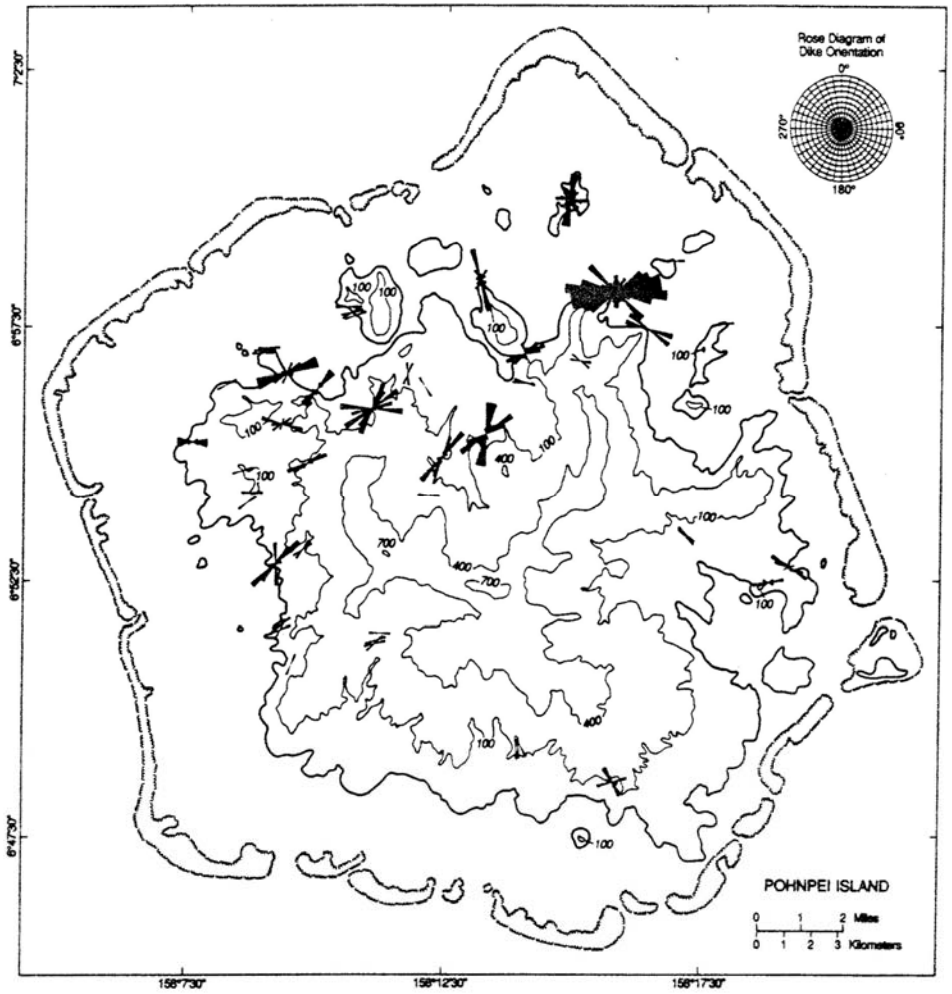


FIGURE 4

Measured Dike Orientation and Free-Air Gravity Anomaly Map



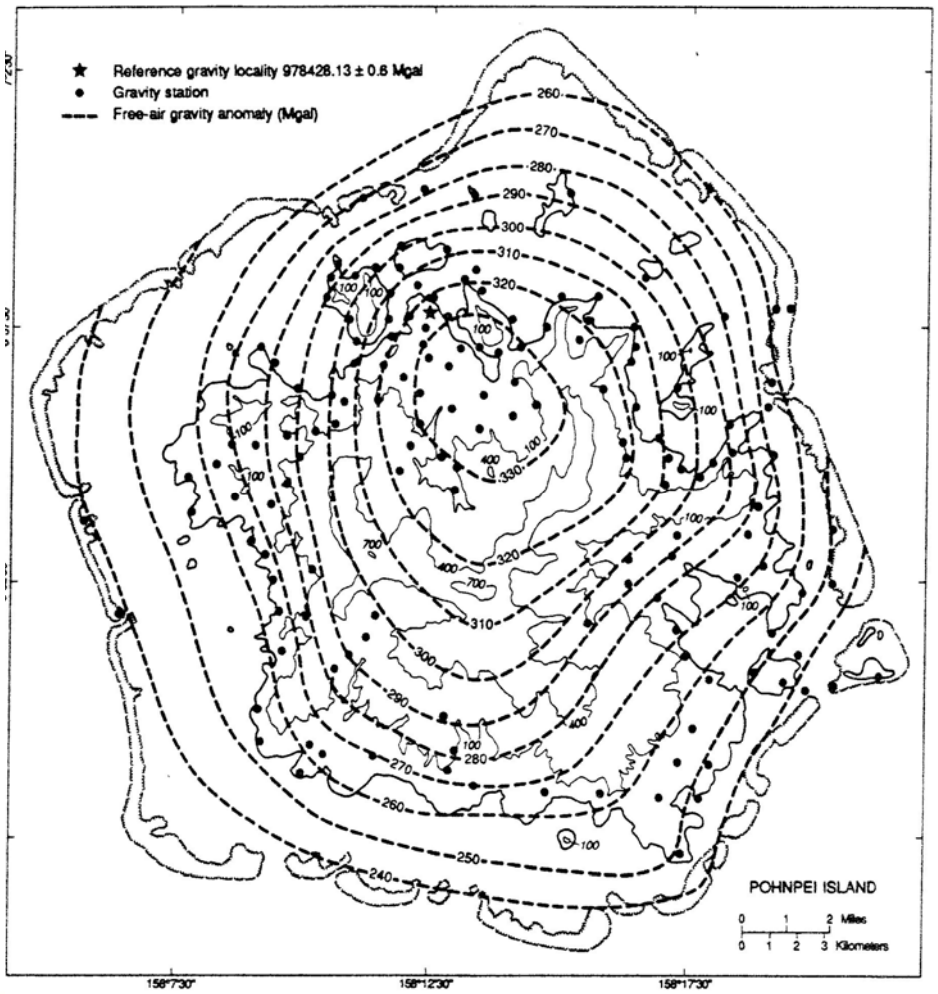


FIGURE 5
Type Section of Awak and Kupwuriso Volcanics

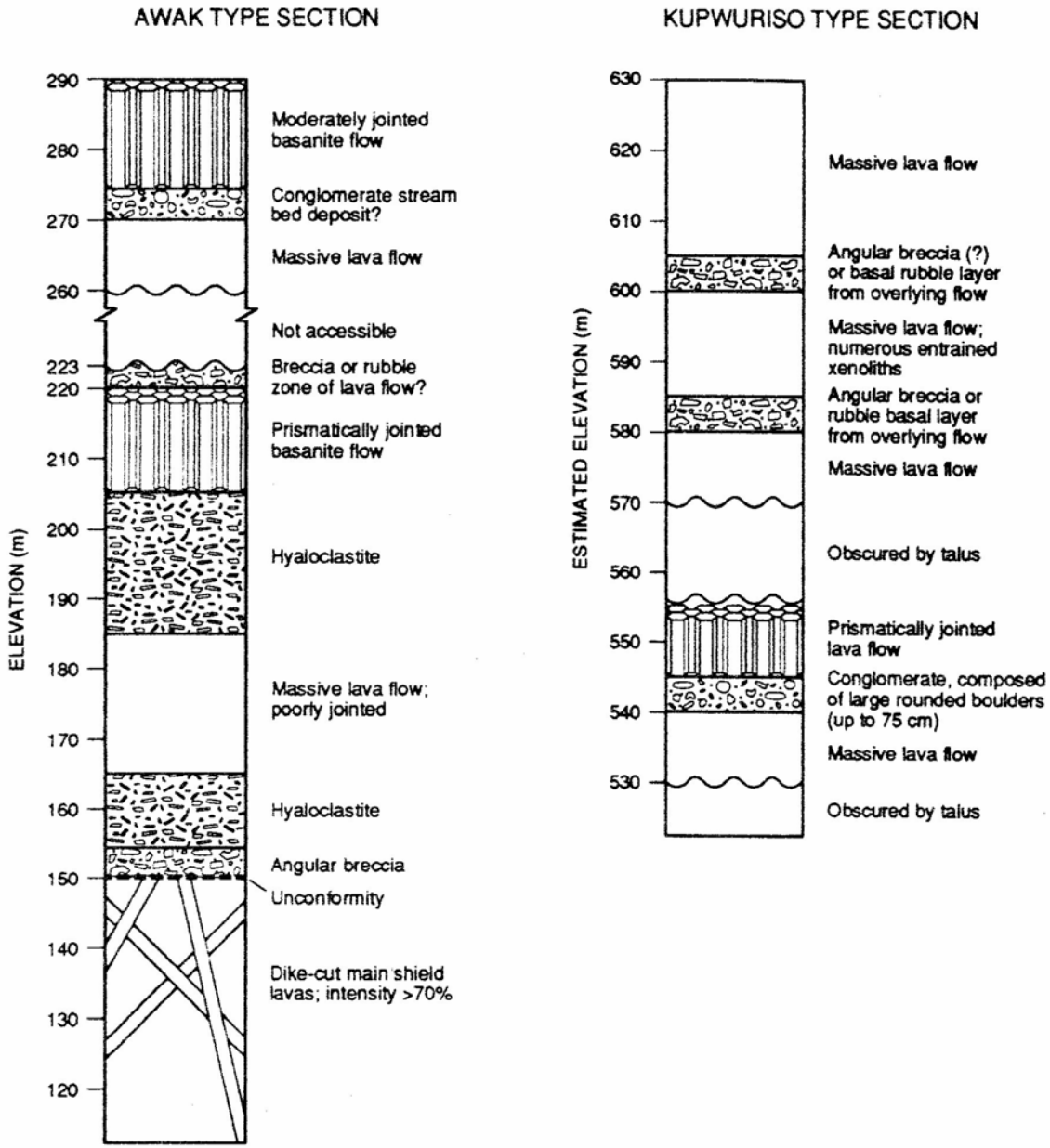
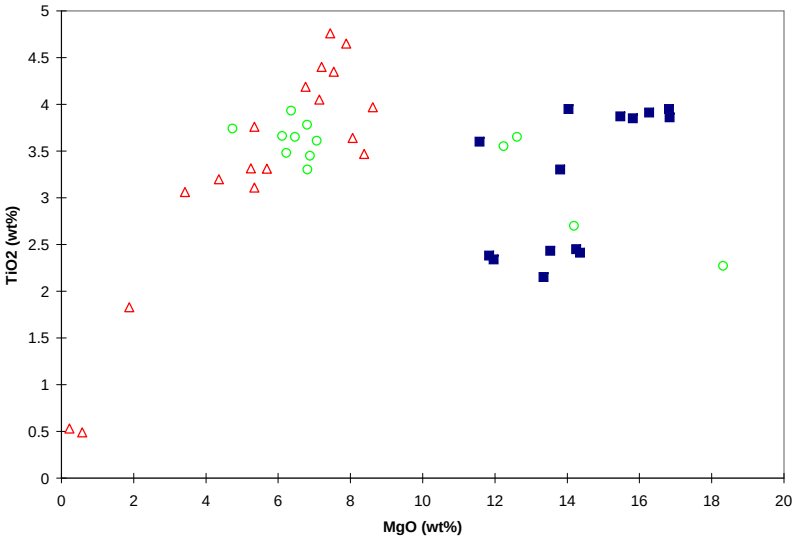
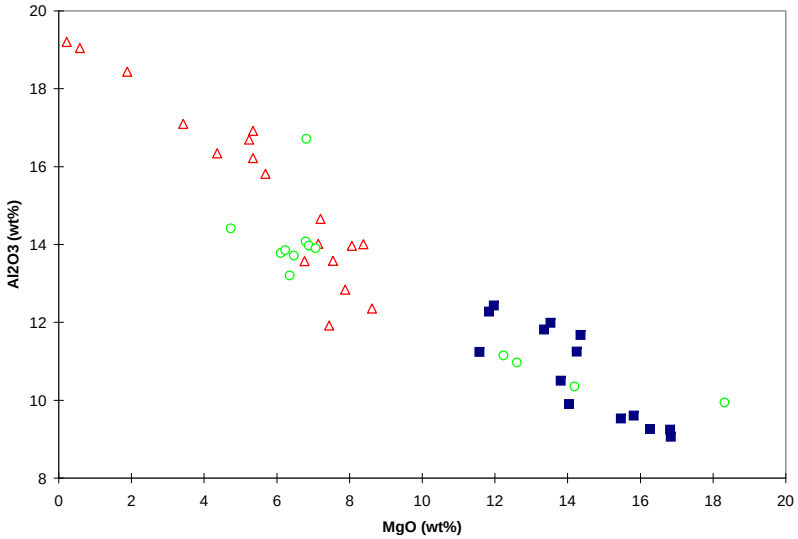
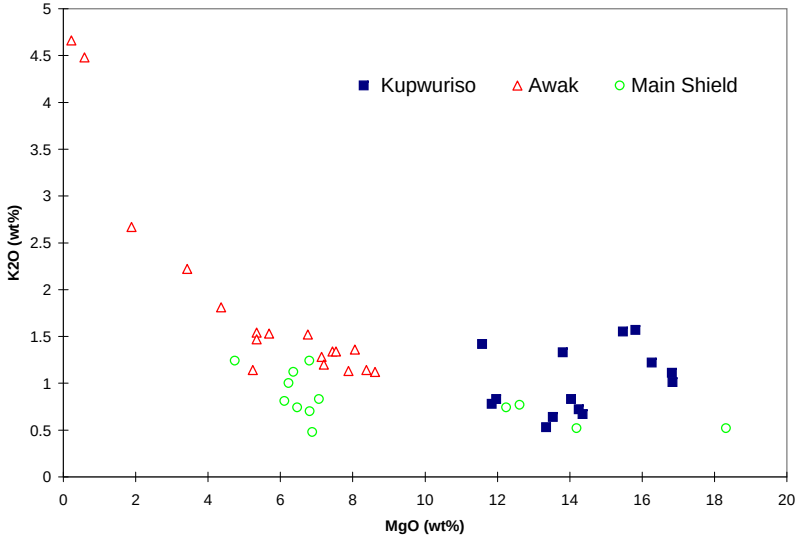


FIGURE 6:
Major Element Data







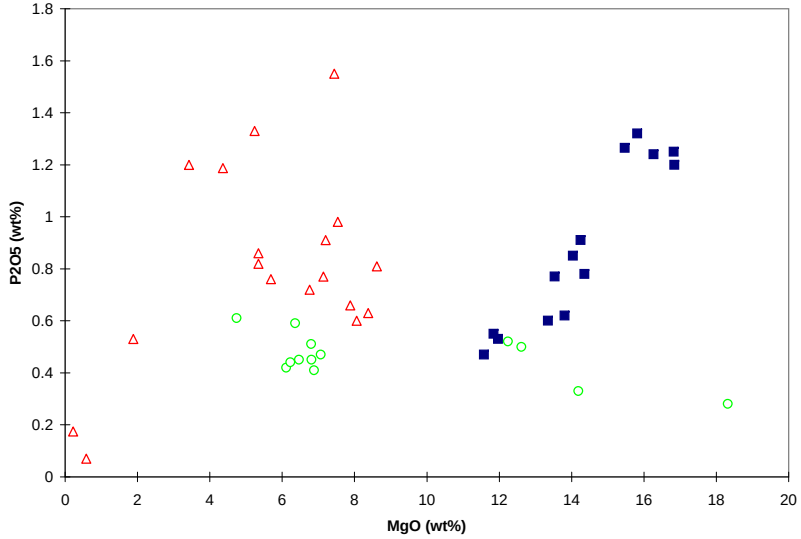


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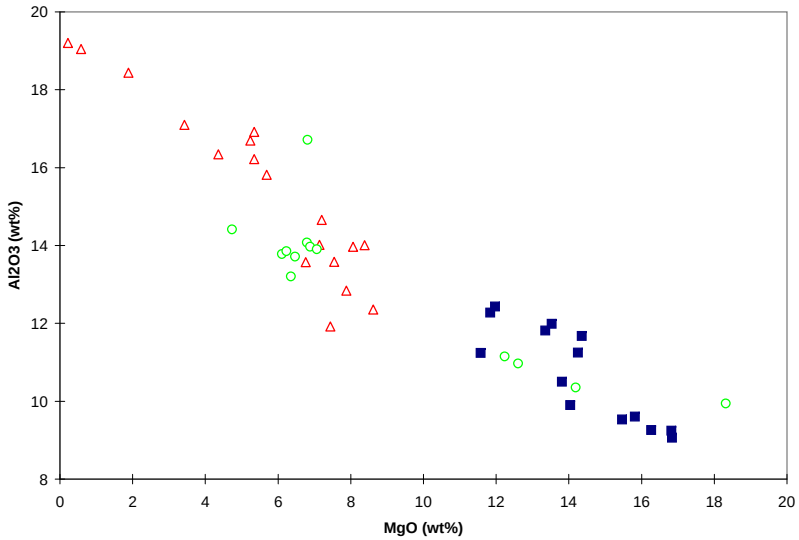
FIGURE 6:
Major Element Data



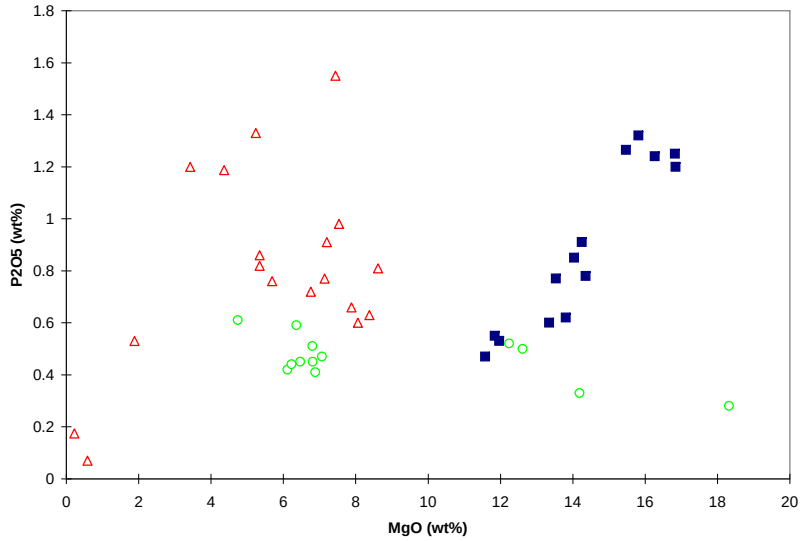


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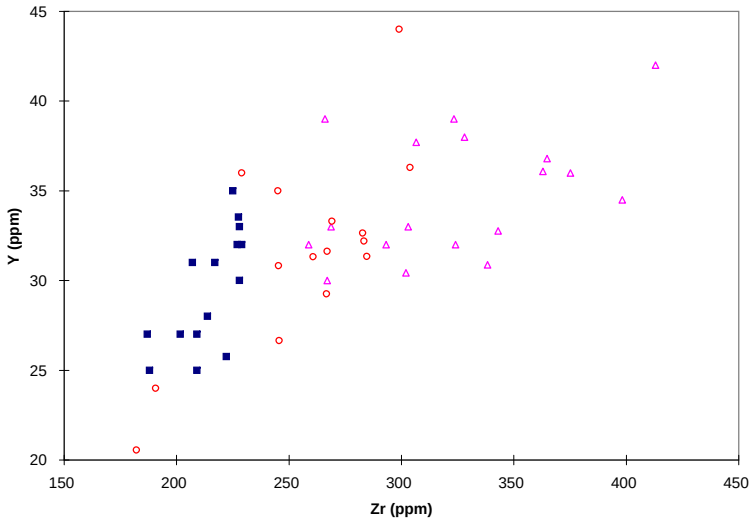
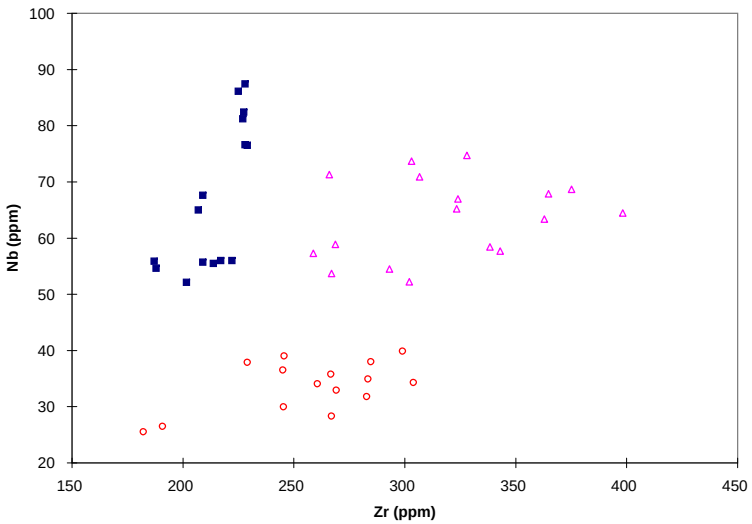
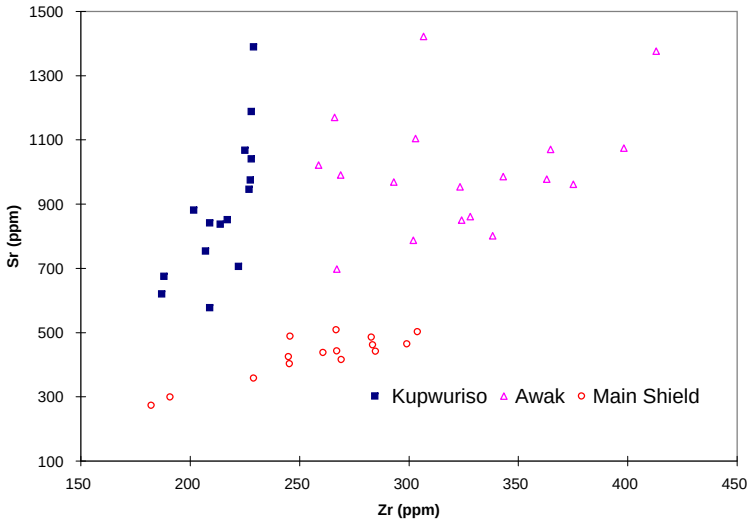
FIGURE 7:
Trace Element Variation Diagrams







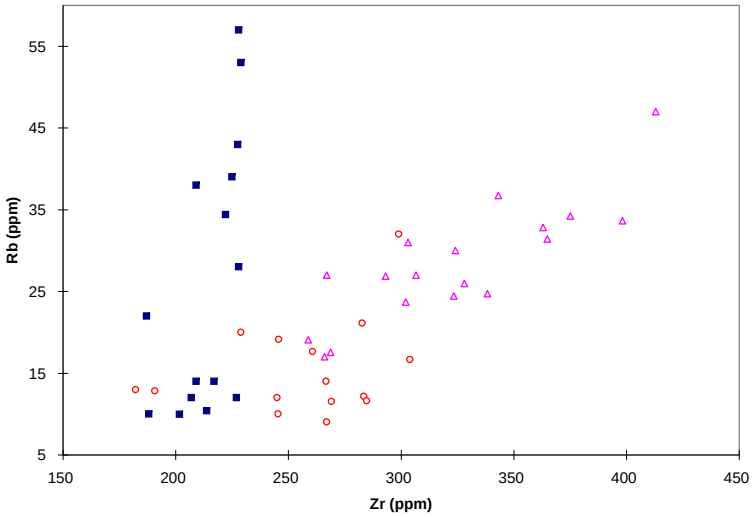


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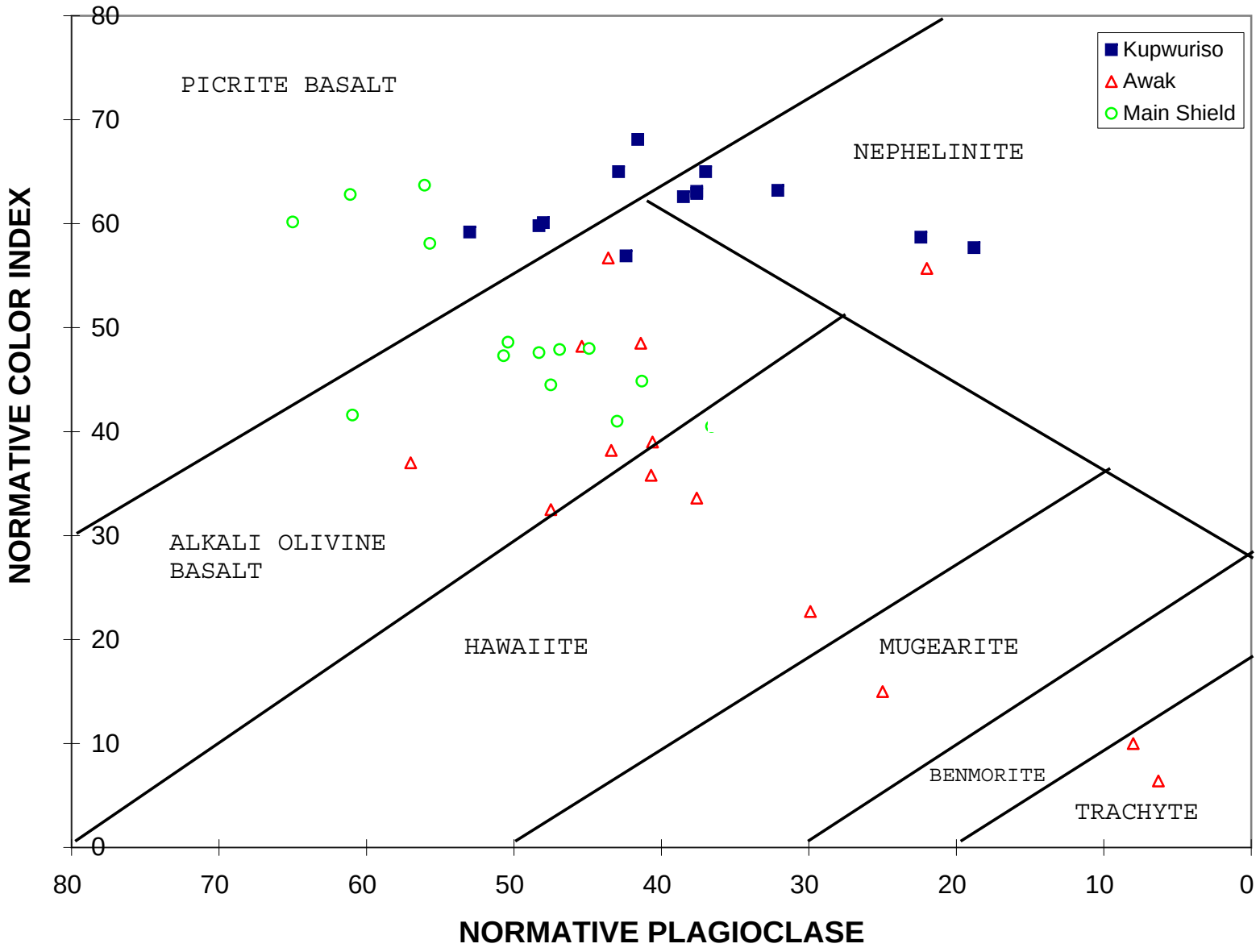
FIGURE 8
Irvine Bargar Chemical Classification Scheme



Note: Nomenclature from Irvine and Baragar (1971).

FIGURE 9
Si Versus Total Alkali

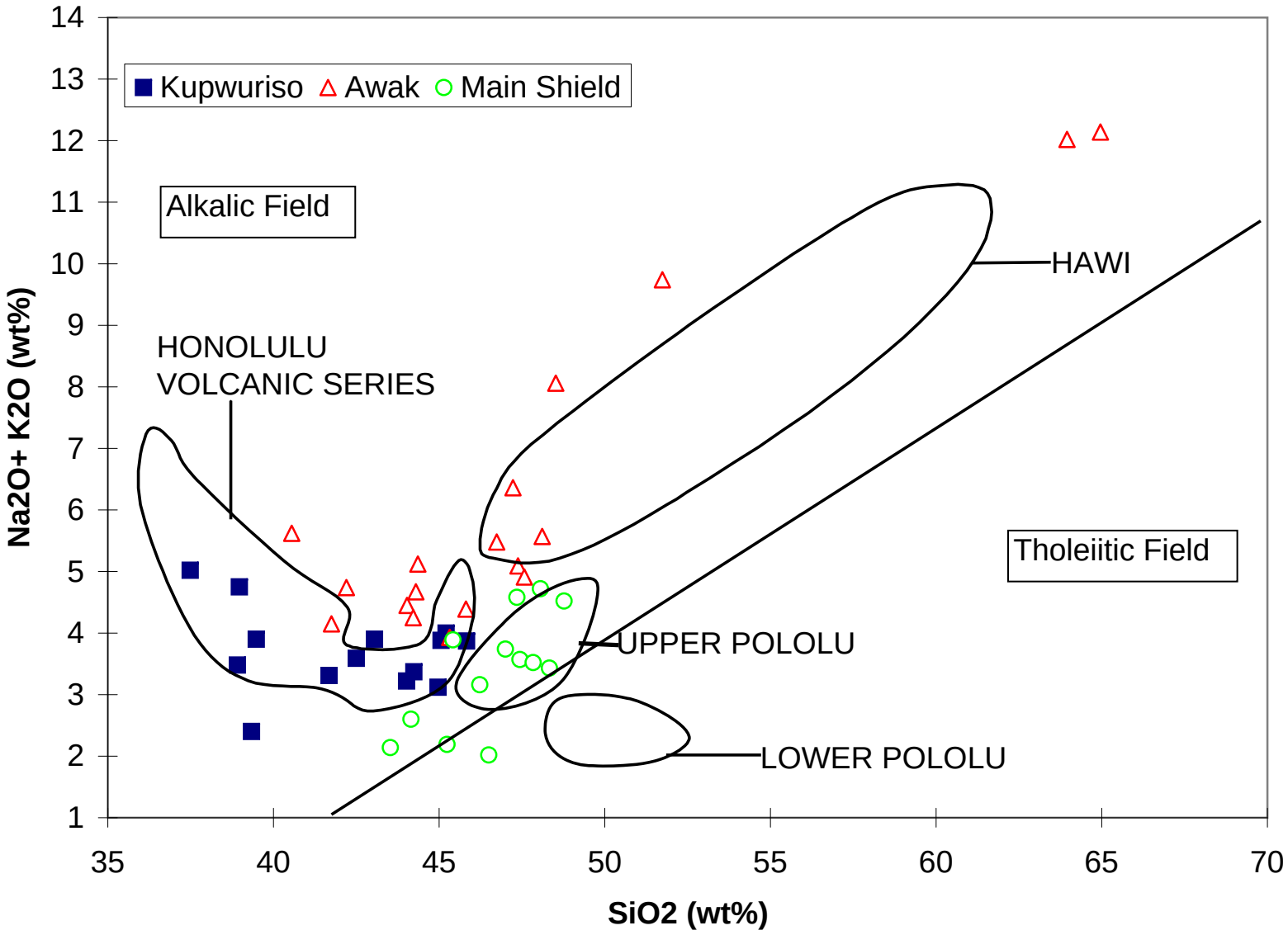
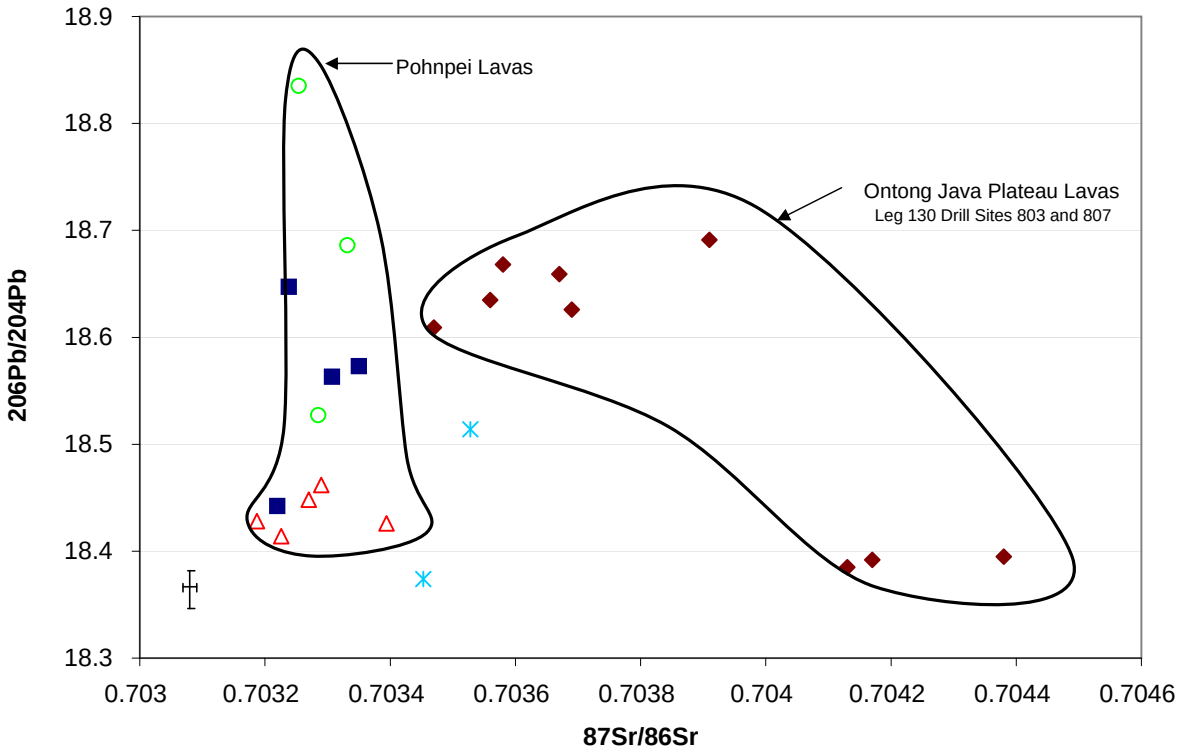


FIGURE 11
Pohnpei, Truk and Ontong Java Plateau Isotopic Data



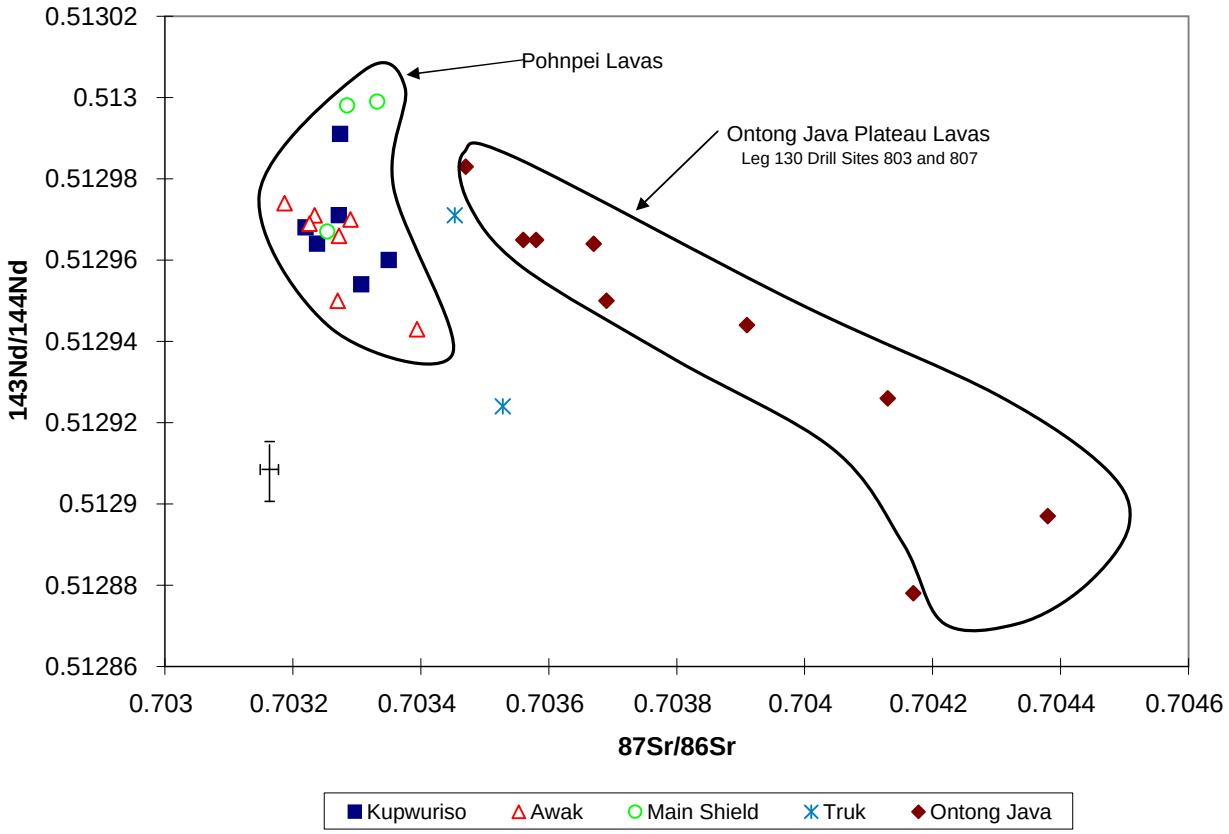


FIGURE 12

Variation in Isotopic Content of Shield and Post-Shield Building Lavas: Hawaiian Volcanoes and Pohnpei

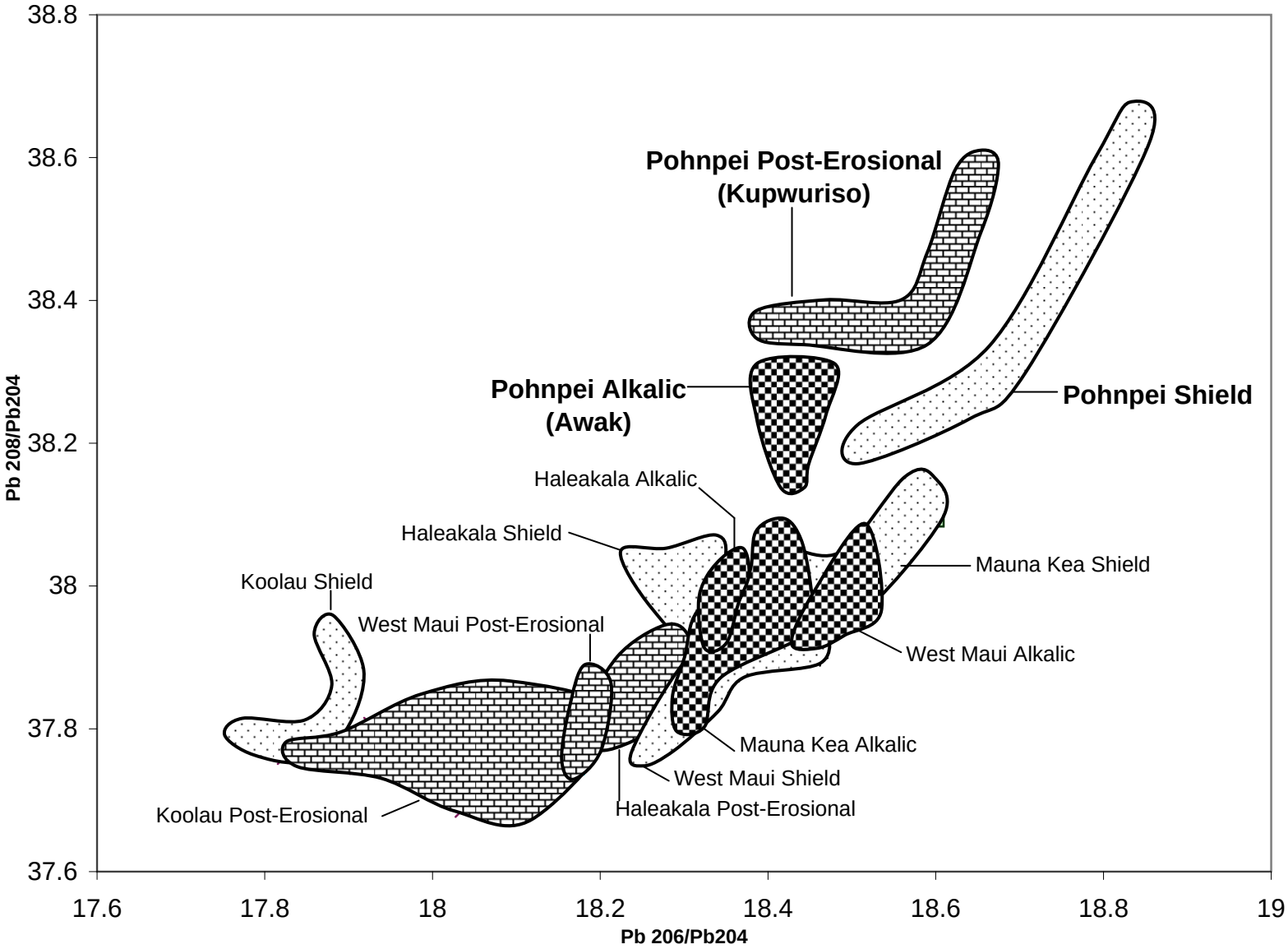


FIGURE 13

Pohnpei and Hawaiian Volcanoes Isotopic Variability versus Eruptive Duration

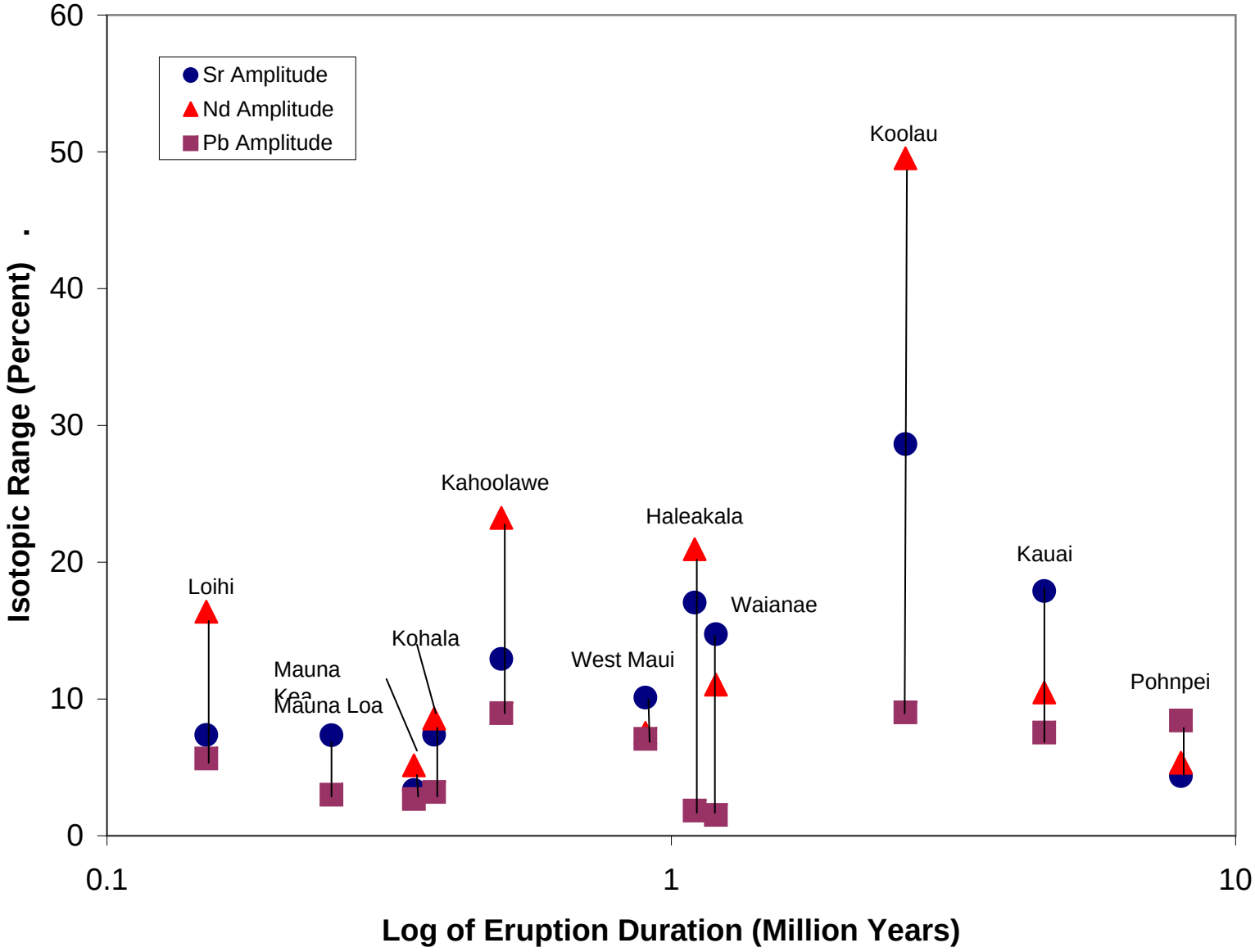


TABLE 1

STAGE	KUPWURISO	KUP	KUP	KUP	KUP	KUP	KUP	KUP	KUP	KUP	KUP	KUP	KUP
XRF LAB	W	W	W	W/H	H/W	HART	W	W	W	W	W	W	W
SAMPLE #	SS-130	SS-156	212	217	SS-111	4	PHP-4	PHP-7	PHP-8	PHP-11	92-B	219	223
SiO2	43.05	44.02	41.68	44.24	45.21	45.06	38.97	38.91	39.48	39.34	44.97	42.5	45.83
Al2O3	11.25	11.99	9.9	11.24	10.5	12.27	9.53	9.24	9.26	9.06	11.81	11.67	12.43
TiO2	2.45	2.43	3.95	3.6	3.3	2.38	3.87	3.95	3.91	3.86	2.15	2.41	2.34
FeO	12.22	11.94	12.79	13.85	11.91	12.74	12.34	12.6	12.76	12.53	11.38	11.77	11.51
MnO	0.19	0.2	0.19	0.17	0.18	0.18	0.19	0.19	0.19	0.18	0.18	0.195	0.18
CaO	12.38	11.88	12.89	10.65	11.21	11.35	13.76	13.25	13.21	14.09	11.94	12.33	11.19
MgO	14.25	13.53	14.04	11.58	13.81	11.84	15.47	16.82	16.27	16.84	13.35	14.36	11.97
K2O	0.72	0.64	0.83	1.42	1.33	0.78	1.55	1.11	1.22	1.01	0.53	0.67	0.83
Na2O	3.18	2.58	2.48	1.95	2.67	3.1	3.2	2.37	2.68	1.39	2.59	2.92	3.04
P2O5	0.91	0.77	0.85	0.47	0.62	0.55	1.265	1.25	1.24	1.2	0.6	0.78	0.53
LOI	ND	ND	ND	0.38	0.06	ND	ND	ND	ND	ND	ND	ND	ND
TOTAL	100.6	99.98	99.6	99.16	100.74	100.26	100.14	99.68	100.22	99.5	99.5	99.6	99.85
Ni	309	319	302	291	370		405	398	445	466	302	317	265
Cr	486	426	479	452	579		488	500	533	546	504	519	372
Sc	29	31	30	19	27		33	31	30	38	20	20	19
V	243	243	302	297	266		318	317	243	294	236	248	218
Ba	648	439	850	453	558		1007	1003	519	1220	405	541	437
Rb	12	14	57	38	34		39	28	12	53	10	14	22
Sr	946	851	1041	577	706		1068	1188	754	1389	675	841	620
Zr	227	217	228	209	222		225	228	207	229	188	209	187
Y	32	31	30	25	26		35	33	31	32	25	27	27
Nb	81	56	77	56	56		86	87	65	76	55	68	56
Ga	19	20	19	21	16		16	17	13	16	20	20	21
Cu	32	75	69	74	74		118	89	68	90	82	75	74
Zn	105	101	106	111	110		101	97	103	98	107	103	102
Pb	4.26	3.13	3.11										
Nd	61.07	47.37	54.44	32.43	39.53								
Sm	11.44	10.01	11.03	7.42	8.55								
87/86Sr	0.703307	0.70322	0.703238	0.703274	0.703272	0.70335							
143/144Nd	0.512954	0.512968	0.512964	0.512991	0.512971	0.51296							
206/204Pb	18.563	18.442	18.647			18.573							
207/204Pb	15.523	15.541	15.511			15.516							
208/204Pb	38.372	38.367	38.561			38.366							

TABLE 1

STAGE	KUP	KUP	KUP	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK
XRF LAB	H	H	H	H	H	W	W	W	HART	HART	W	H/W	W
SAMPLE #	TEMWEN	K8:30-40	K8:100-110	K8:150-160	K8:200-210	116	152	169	1	2	149	164	SS-6B
SiO2	37.49					64.96	46.74	48.11	44.36	45.32	47.23	51.74	45.81
Al2O3	9.6					19.05	16.22	16.7	13.57	14.01	16.34	18.44	13.97
TiO2	3.85					0.49	3.76	3.316	4.19	3.47	3.2	1.83	3.64
FeO	12.28					2.47	12.24	11.8	14.08	13.99	11.64	6.76	11.99
MnO	0.18					0.19	0.202	0.208	0.19	0.21	0.245	0.26	0.19
CaO	12.57					1.52	9.55	8.61	10.94	10.41	9.47	6.8	10.52
MgO	15.82					0.58	5.34	5.24	6.76	8.38	4.36	1.88	8.06
K2O	1.57					4.48	1.54	1.14	1.52	1.14	1.81	2.67	1.36
Na2O	3.45					7.66	3.94	4.43	3.6	2.79	4.55	7.07	3.03
P2O5	1.32					0.07	0.82	1.33	0.72	0.63	1.187	0.53	0.6
LOI	1.25					ND	ND	ND	ND	ND	ND	2.2	ND
TOTAL	98.13					101.46	100.35	100.89	99.93	100.33	100.03	97.98	99.17
Ni		331	361	214	196	10	13	6			9	7	99
Cr						0	0	5			7	0	259
Sc						3	20	18			21	0	23
V						19	247	180			187	123	305
Ba						1591	545	601			791	1282	355
Rb	43	10	10	18	19	131	31	17			47	63	27
Sr	975	837	881	991	1022	428	1104	1170			1376	2265	698
Zr	228	214	202	269	259	790	303	266			413	849	267
Y	34	28	27	33	32	37	33	39			42	65	30
Nb	82	56	52	59	57	171	74	71			107	232	54
Ga						23	23	13			33	27	22
Cu		67	75	66	57	5	25	13			18	12	68
Zn		103	104	126	122	121	134	133			151	181	116
Pb						8.81	2.65	2.26			5.92		
Nd						56.18	46.41	59.69			73.3	129.43	
Sm						8.69	10.07	12.39			14.77	22.89	
87/86Sr						0.703394	0.703226	0.703187	0.70329	0.70327	0.703234	0.703272	
143/144Nd						0.512943	0.512969	0.512974	0.51297	0.51295	0.512971	0.512966	
206/204Pb						18.426	18.414	18.428	18.462	18.448			
207/204Pb						15.489	15.514	15.456	15.489	15.483			
208/204Pb						38.239	38.288	38.152	38.289	38.263			

TABLE 1

STAGE	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK	AWAK
XRF LAB	W	H	H	W	W	H	H	H	H	H	H	H	H	H
SAMPLE #	120	858	154	135	SS-58	205	30	165	755	759	771	69	170A	170D
SiO2	44.03	42.52		63.95	47.38	47.57	44.3	40.55	42.2	48.52	41.75	44.22		
Al2O3	12.36	14.88		19.2	15.82	16.92	14.02	11.92	13.58	17.1	12.84	14.66		
TiO2	3.97	2.75		0.53	3.31	3.11	4.05	4.76	4.35	3.06	4.65	4.4		
FeO	14.57	12.42		2.91	11.54	11.24	12.92	15.74	14.87	10.42	15.05	13.61		
MnO	0.203	0.19		0.095	0.2	0.22	0.19	0.25	0.21	0.18	0.21	0.19		
CaO	11.65	11.65		0.64	9.22	8.5	11.04	10.98	11.64	7.4	12.07	9.92		
MgO	8.62	12.19		0.22	5.69	5.34	7.14	7.44	7.54	3.42	7.88	7.2		
K2O	1.12	0.38		4.66	1.53	1.47	1.28	1.34	1.34	2.22	1.13	1.2		
Na2O	3.33	1.67		7.36	3.56	3.44	3.39	4.28	3.4	5.84	3.02	3.05		
P2O5	0.81	0.51		0.175	0.76	0.86	0.77	1.55	0.98	1.2	0.66	0.91		
LOI	ND	1.19		ND	ND	3.75	1.74	1.36	0.35	4.95	1.27	4.69		
TOTAL	100.67	99.16		99.74	99.01	98.67	99.1	98.81	100.11	99.36	99.26	99.36		
Ni	124		111	15	31								12	75
Cr	219			1	70									
Sc	29			1	17									
V	354			8	239									
Ba	457			1504	423									
Rb	26	37	27	68	30	25	34	45	33	53	24	21	24	34
Sr	861	986	969	141	850	801	1075	1318	978	1165	788	759	954	962
Zr	328	343	293	873	324	338	398	633	363	550	302	371	323	375
Y	38	33	32	77	32	31	35	54	36	46	30	38	39	36
Nb	75	58	55	136	67	58	64	117	63	107	52	63	65	69
Ga	24			28	24									
Cu	84		56	7	50								28	55
Zn	139		125	124	132								126	135
Pb														
Nd														
Sm														
87/86Sr														
143/144Nd														
206/204Pb														
207/204Pb														
208/204Pb														

TABLE 1

STAGE	AWAK	AWAK	MAIN DIKE	MD	MD	MD	MD	MD	MD	MD	MD	MAIN LAVA	ML
XRF LAB	H	H	H/W	H	H	H	H	H	H	H	H	W	W
SAMPLE #	K8:260-270	K8:300CLN	224	VILLAGE	39	713	753	31	38	47	714	215	K8-390
SiO2			48.77	47.35	45.24	44.15	45.42	43.53	47	47.44	46.23	48.33	48.06
Al2O3			14.41	14.07	9.94	11.15	13.2	10.97	13.97	13.78	16.71	13.71	13.85
TiO2			3.74	3.78	2.27	3.55	3.93	3.65	3.45	3.66	3.3	3.65	3.48
FeO			12.39	13.77	12.83	14.11	12.58	14.4	12.15	12.94	11.74	12.52	12.18
MnO			0.19	0.17	0.19	0.19	0.17	0.2	0.12	0.17	0.2	0.18	0.16
CaO			9.09	9.26	8.42	10.59	11.09	10.81	11.29	11.45	11.49	10.96	7.97
MgO			4.74	6.8	18.32	12.24	6.36	12.61	6.88	6.11	6.81	6.47	6.23
K2O			1.24	1.24	0.52	0.74	1.12	0.77	0.48	0.81	0.7	0.74	1
Na2O			3.28	3.34	1.67	1.86	2.77	1.37	3.26	2.76	2.46	2.69	3.72
P2O5			0.61	0.51	0.28	0.52	0.59	0.5	0.41	0.42	0.45	0.45	0.44
LOI			2.38	4.63	2.06	1.59	3.89	2.97	3.92	1.46	1.57	ND	ND
TOTAL			98.46	100.29	99.68	99.1	97.23	98.81	99.01	99.54	100.09	99.7	97.08
Ni	112	101	29									72	60
Cr			9									111	57
Sc			26									33	33
V			360									353	367
Ba			198									135	156
Rb	27	31	32	21	13	14	17	19	10	12	9	12	20
Sr	1422	1071	465	486	273	508	502	489	403	462	443	425	358
Zr	307	365	299	283	182	267	304	246	245	283	267	245	229
Y	38	37	44	33	21	29	36	27	31	32	32	35	36
Nb	71	68	40	32	26	36	34	39	30	35	28	37	38
Ga			24									22	22
Cu	49	59	82									84	110
Zn	126	130	129									109	118
Pb										1.54	1.81	1.61	
Nd										36.19	36.1	33.76	
Sm										8.3	8.41	7.97	
87/86Sr										0.703285	0.703332	0.703254	
143/144Nd										0.512998	0.512999	0.512967	
206/204Pb										18.527	18.686	18.835	
207/204Pb										15.46	15.469	15.521	
208/204Pb										38.197	38.307	38.619	

TABLE 1

STAGE	ML	ML	ML	ML	TRUK	TRUK	BRECCIA	CONG DIKE	CONG DK	ASH DIKE	ASH DIKE	ASH CLAST
XRF LAB	H	H	H	H	H	H	H	H	H	H	H	H
SAMPLE #	K8:300ZEOL	K8:350-360	42	722	1	3	PAREM BR	308	309	9	748	20
SiO2			46.5	47.84			44.01	46.81	44.24	43.72	42.93	42.88
Al2O3			10.35	13.9			13.65	12.16	10.68	13.44	11.05	14.79
TiO2			2.7	3.61			4.53	4.27	4.25	4	3.35	4.25
FeO			12.35	11.46			14.08	13.46	14.12	14.01	13.55	13.68
MnO			0.18	0.16			0.19	0.19	0.19	0.22	0.17	0.18
CaO			10.69	11.39			11.34	11.59	11.36	10.19	12.43	10.75
MgO			14.19	7.07			2.76	8.25	11.05	8.43	13.12	7.81
K2O			0.52	0.83			0.95	0.94	1.02	1.14	0.7	1.15
Na2O			1.5	2.69			2.76	2.22	2.3	2.91	1.95	2.72
P2O5			0.33	0.47			0.62	0.4	0.46	0.9	0.58	0.61
LOI			2.13	1.9			1.1	3.38	0.69	2.54	1.26	1.51
TOTAL			99.31	99.42			94.89	100.29	99.67	98.96	99.83	98.82
Ni	237	114										
Cr												
Sc												
V												
Ba												
Rb	18	12	13	12	153	10.39	20	27.53	25.1	28.53	14.35	23.55
Sr	438	416	299	442	694	511.3	667	331.8	523.51	835.38	596.63	829.91
Zr	261	269	191	285			327	192.9	262.76	380.75	193.51	260.52
Y	31	33	24	31			36	30.6	26.52	35.43	22.9	29.28
Nb	34	33	26	38			42	31.68	44	60.68	40.49	48.89
Ga												
Cu	94	119										
Zn	121	129										
Pb					2.89	0.53						
Nd					82.3	5.72						
Sm					15.63	1.97						
87/86Sr					0.703528	0.703453						
143/144Nd					0.512924	0.512971						
206/204Pb					18.514	18.374						
207/204Pb					15.479	15.497						
208/204Pb					38.237	38.133						