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VOLCANISM IN THE EASTERN ALEUTIAN ARC: LATE QUATERNARY AND HOLOCENE CENTERS, TECTONIC SETTING AND PETROLOGY

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by

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ABSTRACT

Calc-alkaline volcanism and oceanic plate subduction are intimately linked in the eastern Aleutian arc. The volcanic arc is segmented. Larger caldera-forming volcanic centers tend to be located near segment boundaries. Intrasegment volcanoes form smaller stratocones. Of the 22 volcanoes that make up the 540 km long volcanic front in the eastern Aleutian arc ten have erupted in recorded history and another six show active hydrothermal activity.

The geometry of the Benioff zone in the eastern Aleutian arc has been defined by earthquake data from a local, high-gain short-period seismograph network. The Benioff zone dips at an angle of about 45° beneath the volcanic arc and reaches a maximum depth of 200 km. Based on the alignment of volcanoes, the eastern Aleutain arc can be subdivided into two main segments, the Cook and Katmai segments. A disorientation of 35* of the two segments reflects a change in strike of the underlying Benioff zone and implies a lateral warping of the subducting plate, The Cook segment volcanoes line up closely on the 100 km isobath of the Benioff zone. The Katmai segment volcanoes lie on a cross-cutting trend with respect to the strike of the underlying Benioff zone. Depths to the dipping seismic zone beneath volcanoes of the Katmai segment vary by 25% from 100 to 75 km. In the Katmai segment there is also good geophysical evidence that crustal tectonics plays an important role in localizing volcanism. Narrowly spaced linear groups of volcanoes appear to be positioned over crustal faults that extend laterally along the volcanic front. Transverse arc elements localize larger magma reservoirs at shallow levels in the crust.

Intrasegment volcanoes in both the Cook and Katmai segments erupt. andesite and minor dacite of remarkably uniform composition despite the difference in their tectonic setting. Segment boundary volcanoes erupt lavas with a wider range of compositions (basalt to rhyolite) but are still talc-alkaline in contrast to volcanoes in similar tectonic settings near segment boundaries in the central Aleutains. Greater crustal thickness in the eastern Aleutian arc coupled with structural traps in the crust allow magma pending at shallow crustal levels and further differentiation to yield dacite and even rhyolite.

INTRODUCTION

The Aleutian arc stretches 2,600 km westward from Hayes Volcano (152.5° W) (Miller and Smith, 1976) to a small island volcano, Buldir, in the western Aleutians (176° E). Figure 1 shows the location of the about 80 Quarternary volcanoes that make up the Aleutian arc (Coats, 1962; Smith and Shaw, 1975; Simkin et al., 1981). Forty of the recent volcanoes have erupted in recorded history (which began with the discovery of Alaska by Vitus Bering in 1741).

The volcanoes of the Aleutian arc are not very well studied and in fact new Quaternary volcanic centers are still being discovered today. Because of the remoteness of many of the volcanoes, eruptions still go unnoticed and most of the volcanoes have not been mapped in any detail. To date, the Aleutian arc is one of the few volcanic areas in the world for which no catalogue exists in the series "Active Volcanoes of the World" published by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). T. P. Miller and J. R. Riehle of the U.S. Geological Survey are now compiling such a catalogue.

This paper begins with a discussion of the distribution of Late Quarternary and Holocene volcanic centers in the eastern Aleutian arc (Katmai and Cook Inlet regions), where the University of Alaska has concentrated its efforts over the past years.. We will then try to relate arc volcanism to subduction tectonics and finally discuss petrologic trends in the eastern Aleutian arc.

VOLCANOES OF THE EASTERN ALEUTIAN ARC

The eastern Aleutian-arc as defined here includes principally the volcanoes of Katmai and Cook Inlet from Ugashik Caldera (names of volcanic centers are unofficial and are given in Tables 1 and 2) to Hayes Volcano (Figure 2). This easternmost section of the Aleutian arc is 540 km long and contains 22 Late Quaternary and Holocene volcanoes. Young volcanoes are still being identified in this heavily glaciated region. For example, Miller and Smith (1976) have recently reported on two new volcanoes southwest of Ugashik Caldera (Kialagvik and Yantarni) and another one (Hayes) north of Mt. Spurr volcano. Ugashik Caldera has also only recently been recognized as separate volcanic center (T. P. Miller, personal communication). Kienle et al. (1982) have recently completed a reconnaissance field study in Katmai National Park and Cook Inlet to identify Late Quaternary and Holocene volcanic "centers and to collect a first suite of rock samples from many of these remote volcanoes. In the course of this work we positively identified 5 new volcanic centers in Katmai National Park, Fourpeaked Mtn., Devils Desk, Mt. Stellar, Snowy Mtn. and Kejulik Volcano. Based on their morphology, the first four peaks were previously thought to be of volcanic origin, but no mapping or sampling had been done.

Volcanoes of Cook Inlet and Katmai

Little is known about the eruptive history and geologic evolution of many of the volcanoes of the eastern Aleutian arc. In Cook Inlet, reconnaissance and photo-geologic maps have been or are being prepared for Redoubt (A. Till, U.S. Geol. Survey, in prep.), Iliamna (Juhle, 1955) and Augustine (Detterman, 1973; Kienle and Swanson, 1980). To date, Spurr remains unmapped. A series of papers have dealt with eruptions of Spurr (Juhle and Coulter, 1955), Redoubt (Wilson et al., 1966; Wilson and Forbes, 1969; Riehle et al., 1980) and Augustine (Davidson, 1884; Detterman, 1968; Kienle and Forbes, 1976; Meinel et al., 1976; Stith et al., 1977; Johnston, 1978; Kienle and Shaw, 1979; Kienle and Swanson; 1980).

In Katmai National Park much of the previous work has concentrated around Mt. Katmai and specifically on the 1912 eruption that formed the Valley of Ten Thousand Smokes (VTTS). Griggs (1920, 1922) and Fenner (1920, 1922, 1923, 1926, 1930, 1950) in their studies of the 1912 eruption identified several volcanic centers in the area including Mt. Katmai, Novarupta, Knife Peak (now renamed Mt. Griggs), Mt. Mageik, Mt. Martin, Trident Volcano and Mt. Peulik. Curtis (1968) also studied the 1912 eruption and made a detailed examination of the tephra deposits. Hildreth (1982) has recently been working on the petrology of the 1912 ejects.

Few studies of other volcanic centers in this region are available. Muller and et al. (1954) reported on the volcanic activity in the Katmai area during the summer of 1953, which included the 1953 eruption of Trident.' Muller et al. also noted fumarole activity on six other vo"lcanoes: steam issued in 1953 from several vents on the side of a crater lake on Douglas and steam vents were observed at Kukak, Griggs, Novarupta, Mageik and Martin. Snyder (1954) gave the first detailed report of the new activity at Trident. Ray (1967) studied the mineralogy and petrology of the lavas formed during the 1953-1963 eruptions of Trident. Kosco (1981a, and b) reported that the lavas of Griggs, Katmai, Trident and Mageik are dominately dacites and andesites (SiO_2 = 54 to 68%) and that disequilibrium phenocryst assemblage (olivine + quartz + orthopyroxene) is suggestive of magma mixing in some of these lavas. Keller and Reiser (1959) presented a regional geologic map far the area from Cape Douglas to the Kejulik Mtns. and showed the distribution of volcanic rocks, but most of their effort was devoted to the Mesozoic and Tertiary sedimentary rock units. Keller and Reiser (1959) did comment that Martin, Mageik, Novarupta, Knife, Kukak and Douglas were steaming with varying intensities and that Trident was steaming and extruding blocky lava. An important summary of volcanic activity in Katmai National Monument from 1870 to 1965 was prepared by Ward and Matumoto (1967). Just outside the Park boundary Kienle et al. (1980) and Self et 'al. (1980) described the formation (in 1977) of two maars near Mt. Peulik, which they named Ukinrek Maars. Because"no IAVCEI volcano catalogue currently exists for the Aleutian arc and because much of the previous work on volcanoes in Cook Inlet and Katmai is generally only available as abstracts, unpublished theses or not easily accessible reports. Tables 1 and 2 summarize the principal facts about the volcanoes of Cook Inlet and Katmai based on the literature and recent field studies (Swanson et al., 1981; Kienle et al., 1981; Kienle et al., 1982).

Ten of the 22 volcanic centers of probably Late Quaternary and Holocene age in the eastern Aleutian arc have erupted in recorded history. Figures 3 and 4 summarize the most important eruptive events in Cook Inlet and Katmai in historic times. Spurr, Redoubt, Iliamna, Augustine, Trident, Mageik and Peulik had vulcanian eruptions. A Plinian eruption of Novarupta in 1912 lead to the formation of the Valley of Ten Thousand , Smokes ash flow and the collapse of the summit of Mt. Katmai, producing 20 km3 of air-fall tephra and 11-15 km3 of ash-flow tuff within - 60" hours (Hildreth, 1982). The Ukinrek eruption was phreatomagmatic/

Strombolian. Six volcanoes that have not erupted in historic times show hydrothermal activity (Douglas, Kaguyak, Kukak, Snowy, Griggs, Martin). Four of the eastern Aleutian volcanoes have advanced to caldera stage: Kaguyak, Katmai, Novarupta (a possibility proposed by Hildreth, 1981), and Ugashik (Miller, personal communication), Both Kaguyak and Katmai have well developed summit calderas occupied by deep (~ 200 m) lakes. Most of the volcanoes in Katmai and Cook Inlet are composite cones. Domes and pyroclastic flows are common at Augustine Volcano, Kaguyak Crater and Novarupta.

Glaciers are found on all the eastern Aleutian volcanoes except for the very young centers such as Augustine, Kaguyak, Novarupta and Ukinrek. Glacial dissection can be used as a means to crudely classify the volcanic centers with regard to their relative age. Extensive erosion of Kejulik, Denisen, Devils Desk, Fourpeaked and Hayes, and current lack of hydrothermal activity, suggest that these volcanoes have not been active since the last period of extensive glaciation, ending - 10,000 years ago in this region (Karlstrom, 1964; Péwé, 1975). On the other end of the spectrum Griggs, Kaguyak, Augustine, and of course Novarupta and Ukinrek have not been affected by glacial erosion and have all been recently active or show hydrothermal activity. The bulk of these volcanic structures was most likely built in the past 10,000 years. The remaining volcanoes are still active, have erupted recently or show surface hydrothermal activity; but these centers have also been extensively modified by glacial erosion. Here, construction of the volcanic edifices could not keep up with glacial dissection.

PRESENT-DAY TECTONIC FRAMEWORK

Quarternary volcanism in the Aleutians is the result of plate convergence between the American and Pacific plates. Figure 5 shows directions and rates of relative plate motion along the arc calculated from Minster and Jordants (1978) model RM2 that describes present-day global plate motions (this model averages global plate motions over the past 3 m.y.). Slip rates increase regularly from east to west along the Aleutian volcanic arc as the angular distance to the pole of rotation for the Pacific-American plates increases. However, the component of convergence normal to the arc decreases from east to west as plate motion becomes more and more oblique to the arc. Also shown in Figure 5 is the seismicity based on worldwide teleseismic data between 1962 and 1969 and the approximate 150 km isobath to the Benioff zone (after Jacob et al., 1977). The Aleutian volcanic front is developed over a distance of 2,600 km between Hayes and Buldir Volcanoes along that section of the arc which is underlain by a dipping seismic zone, This illustrates the intimate relationship between active arc volcanism and the presence of a down-going oceanic slab in the Aleutian arc. This connection is further emphasized by the fact that Quaternary volcanism ceases in the Kommandorsky section of the arc (between Buildir Volcano and Sheveluch Volcano in Kamchatka), where the slip vector between the two plates is tangential to the arc. Lack of intermediate depth seismicity and strike slip mechanisms for large earthquakes (McKenzie and Parker, 1967; Stauder, 1968) imply that the Pacific plate is currently not subducting beneath the Kommandorsky section of the arc and that this section acts as a transform plate boundary (Cormier, 1975). Sheveluch Volcano, the northernmost Quarternary Volcano in Kamchatka, marks the next transition back to near normal plate convergence against the Kamchatka Peninsula with its well developed chain of active volcanoes, Kamchatka is again underlain by a seismically well defined down-going oceanic slab (e.g. Fedotov and Tokarev, 1973),

The volcanic front in the Aleutian arc lies generally over the 100 to 150 km depth contour to the Benioff zone (see Figure 2). Marsh and Carmichael (1974) presented the interesting hypothesis that the regular spacing of 60 to 70 km between large volcanic centers observed along the Aleutian arc could be explained by mantle diapirism of magma rising in regularly spaced plumes from a gravitationally unstable ribbon of melt that has developed at some critical depth (100-150 km) along the strike of the down-going plate. Bogoslof and Amak Islands are the only volcanic centers that have developed behind the primary volcanic front above greater depths to the dipping seismic zone. These two volcanoes also erupt more potash-rich lavas (Marsh, 1979). Both Bogoslof and Amak are very young, probably less than 10,000 years old. Marsh and Leitz (1 979) and Marsh (1979, 1982) proposed that this embryonic secondary volcanic front may be the result of mantle diapirism above a ribbon of melt that has now developed downdip from the main volcanic front along the surface of the subducting plate.

At the eastern end of the Aleutian arc there are two apparent anomalies in the relationship of volcanism to plate subduction. (1) No major Late Quaternary or Recent volcanic center has yet been found north of Hayes Volcano (Figure 5), even though northwesterly subduction is well defined by intermediate depth earthquakes into the interior of Alaska, extending 300 km beyond the last Aleutian arc volcano. (2) A group of voluminous Pleistocene volcanoes, which represent the culmination of past mid-Miocene andesitic volcanism in the Wrangell Mountains (Nye, 1982) lies some 350 km east of the Aleutian trend (Figure 1). This group of volcanoes is not underlain by a currently active Benioff zone.

SUBDUCTION DEFINED BY SEISMICITY

The geometry of the subducting Pacific plate in the eastern Aleutian arc is now quite well defined through earthquake studies. A series of theses (Davies, 1975; Lahr, 1985; Estes, 1978), various reports (Pulpan and Kienle, 1979; Lahr et al, 1974), and a recent paper by Kienle et al. (1982) have analyzed the configuration of the Benioff zone in the area.

Since 1976, the University of Alaska has operated a high resolution seismographic network with some 30 short-period stations in the lower Cook Inlet-Katmai-Kodiak Island region, where the relationship of volcanism to a well developed down-going plate is quite clear. All stations have single component, vertical, short-period (natural period 1 see) seismometers. Figure 6 shows the current configuration of the seismic network and the location of an additional 4 stations operated by other agencies, which are routinely used for our earthquake locations. Data from all stations are radio-telemetered to 3 data gathering points, located in King Salmon, Kodiak, and Homer. Details of our routine procedure for location of hypocenters have been discussed by Pulpan and Kienle (1979) and Kienle et al. (1982).

Epicenters

Figure 7 is a map of epicenters in the eastern Aleutian arc. For this figure we selected a data file of 1,881 events from the period July 1977 to June 1981. These events were recorded on at least 6 stations, had vertical and horizontal location errors of less than 10 km, and had a root mean square travel time error of less than 0.4 sec. These quality factors describe the relative location uncertainties. The earthquake detection threshold within the network is about magnitude 2, but can be as low as magnitude 1 in some portions.

Hypocentral Cross Sections

In Figure 8 earthquake hypocenters within 3 individual blocks shown on the epicenter map (Figure 5) have been projected on vertical planes indicated by lines A-A′, B-B′ and C-C′. The orientations of the planes were chosen by trial and error to minimize the thickness of the Benioff zone and thus correspond to the best-fit plunge direction of the subducting plate. Two types of data are plotted on Figure 8: hypocenters for events with a depth greater than 50 km are closely constrained (crosses). We required that an event was recorded on at least 6 stations, had a vertical (ERZ) and horizontal (ERH) location error of less than 10 km, had a root mean square (RMS) travel time error of less than 0.3 sec and the distance from the epicenter to the nearest station was within twice the depth to the hypocenter. The last requirement insures fairly good depth control, Since these constraints filtered out too many of the shallow events (O to 50 km depths), we re'laxed the selection criteria, requiring that the event be recorded on at least 5 stations and had an RMS travel time residual of less than 0.5 see, and an ERH and ERZ of less than 10 km (triangles).

The seismicity shown in the cross section defines four distinct tectonic regions:

(1) A shallow thrust zone dips at an angle of about 10° landward from the Aleutian trench over a distance of several 100 km. This thrust zone widens from southwest to northeast (bottom to top in Figure 8).

Great earthquakes (M > 7.8), such as the 1964 Alaskan earthquake, rupture this plane of. generally strong plate coupling. -

(2) A Benioff zone, about 20 to 30 kin thick, reaches a maximum depth of 200 km, and dips at an angle of 35-40" beneath the Katmai Volcanoes (BB' and CC'), steepening to 45 to 50° beneath the Cook Inlet Volcanoes (AA'). The continental and oceanic lithosphere decouple at depths of 50 to 100 km.

(3) An aseismic wedge of hot, ductile asthenosphere is located above the cold subducting slab and below the overriding plate.

(4) A brittle top layer of the overriding plate is characterized by generally diffuse seismicity that does not correlate with mapped faults. Cross sections BB' and CC' show shallow clusters of earthquakes beneath certain volcanic centers, e.g. Douglas-Fourpeaked and Ukinrek. The pipe-like cluster of events beneath Ukinrek is associated with the formation of the 2 maars in the course of the April, 1977 eruptions (Kienle et al., 1980). The cluster beneath Douglas-Fourpeaked may be associated with hydrothermal activity (Pulpan and Kienle, 1979). Had we used data recorded before 1977, extending back to 1975, a dense cluster of very shallow (0-5 km) seismicity would have been plotted directly beneath Augustine Volcano, which erupted explosively in 1976.

Frontal View

Figure 9 is a sectional view of the hypocenter distribution looking toward the volcanic arc. All the data shown in Figure 8 were plotted onto two vertical planes, one oriented parallel to the stike of the volcanic front in Katmai (DO', for location of projection, see Figure 7), the other oriented parallel to the strike of the volcanic front in Cook Inlet (EE', compare Figure 7). As in Figure 8, the data set is split into shallow events (0-50 km depth, triangles) and deeper events (depths greater than 50 km, crosses).

Shallow events in the 30 to 50 km depth range give a good picture of the seismicity in the thrust zone. Very shallow earthquakes generally scatter in a diffuse manner but are sometimes concentrated beneath certain volcanoes as we have just discussed.

Earthquakes in the 50 to about 100 km depth range are fairly uniformly distributed along the arc. However, earthquakes deeper than about 100 km appear to cluster near the lower end of the Benioff zone behind certain volcanoes. Fairly well defined clusters of intermediate depth earthquakes occur beneath Peulik (100-150 km deep), landward of Kaguyak-Douglas-Fourpeaked (100-150 km deep), and slightly south of Augustine (100-150 km deep). A very intense, persistent cluster of intermediate depth earthquakes occurs in the vicinity of Iliamna. This 100 km diameter and 70 to 180 km deep cluster frequently produces earthquakes in the magnitude 3-4 range and some larger events up to magnitude 5. We have as yet no explanation why these deeper clusters of events occur spatially beneath and behind certain active volcanoes but such clusters have also been observed beneath some of the volcanoes in the central Aleutians (Engdahl, 1977).

TECTONIC SETTING OF VOLCANISM

Segmentation of the Volcanic Front

The front of Late Quaternary and Holocene volcanoes in the eastern Aleutian arc is clearly segmented as shown in Figure 10. A similar segmentation of the volcanic front has been observed elsewhere in the

Aleutian arc (Marsh, 1979; Kay et al. , 1982), and also in other cirum - Pacific areas such as for example the Cascades (Hughes et al., 1980) and the central American arc (Stoiber and Carr, 1973; Carr et al., 1982). Linear segments of volcanoes are often separated by transverse offsets, which have been correlated in the Aleutians with fracture zones or breaks in the downgoing oceanic plate (Van Wormer et al., 1974; Spence, 1977) or with apparent transverse arc boundaries mapped out by the boundaries of aftershock sequences of great thrust earthquakes (Holden and Kienle, 1977) , Intrasegment volcanoes that form the volcanic fronts are characterized by talc-alkaline fractionation patterns and commonly erupt two-pyroxene andesite (Hughes et al., 1980). Volcanoes near the offsets often erupt a variety of lavas that range from basalt to rhyolite (Hughes et al., 1980) and may show tholeitic fractionation trends (Kay et al., 1982).

In Figure 10 we distinguish two major arc segments defined on the basis of volcano alignment, the Cook and Katmai segments. A third segment formed by Kialagvik, Chiginagak and Yantarni Volcanoes is offset seaward by 40 km from the Katmai front across a transarc boundary that also marks the southern boundary of the 1964 great Alaskan earthquake rupture zone (compare Figure 5 and 9). That boundary passes through Ugashik, Peulik, and Ukinrek that have erupted a variety of lavas ranging from basalt to rhyolite (Table 2).

The Katmai segment consists of several en echelon subsegments, each one characterized by a very close volcano spacing. Volcanoes with more fractionated magmas occur near the subsegment boundaries (Novarupta/Katmai, Kaguyak). On the average, volcanoes of the Katmai segments have a narrow spacing of 13 ± 7 km [11 pairs between Kejulik and Douglas), Volcanoes within in the Cook segment form a single N 20°E trending front that diverges from the average Katmai trend of N 55°E by 35°. in marked contrast to the Katmai segment, volcano spacing in Cook Inlet is much wider, 70 ± 18 km (3 pairs, Spurr to Augustine). The northern end of the Cook segment arbitrarily has been chosen to pass between Spurr and Hayes, because Hayes is offset to the west from the Cook Inlet trend. Van Wormer et al. (1974) discussed seismologic evidence for a break in the down-going slab that coincides with the end of the Aleutian volcanic front near Hayes. The location of the southern boundary of the Cook segment is not clear, Kien'e et àl. (1982) chose a line south of Augustine (dashed line in Figure 10). That boundary coincides with a broad zone of deformation in the overr·ding plate (stippled zone in Figure 10) proposed by Fisher et al. (1981). Based on volcanic alignment alone, one could equally well group the Douglas/Fourpeaked pair of volcanoes with the Cook segment, thus drawing the Cook segment boundary through Kaguyak (Marsh, 1982). There are petrologic/geochemical arguments for this as we will discuss below. If we include the Douglas/Fourpeaked pair of volcanoes in the Cook segment, volcano spacing becomes 66 ± 18 km (4 pairs, Spurr to Douglas).

Subduction and Volcanism

Based on the epicentral data presented in Figure 7, it is possible to contour isobaths to the Benioff zone. Three isobaths (50, 100 and 150 km) are shown in Figure 10. Comparing volcano positions to the Benioff zone isobaths we find: (1) the 35* change in volcanic alignment between the Katmai and Cook segments reflects a gradual lateral warping of the down-going oceanic plate to a more northerly strike in Cook Inlet.

(2) We find no evidence for a break or hinge fault in the subducting plate in the vicinity of Douglas Volcano, a result that corroborates the findings of Estes (?978) who analyzed an earlier earthquake data set for the region. The lateral warping of the subducting plate in lower Cook Inlet appears to occur smoothly without failure of the slab. (3) Volcanoes of the Cook segment are closely aligned above the 10CI km isobath of the Benioff zone. Volcanoes of the Katmai segment lie on a trend that is disoriented by about 20" with respect to the strike of the Benioff zone. In Katmai the depth to the Benioff zone decreases by 25% from Kejulik to Douglas Volcanoes, from 100 to 75 km.

Crustal Tectonics and Volcanism

Tranverse arc boundaries: Fisher et al. (1981) have recently defined crustal tectonic boundaries at the northeastern and southwestern end of the Kodiak Islands that extend further inland across the Aleutian volcanic arc. These boundaries are not single faults but consist of broad zones of disruption that began to form during the late Miocene or Pliocene (stippled zones in Figure 10). The southern zone of disruption coincides with the southern boundary of the Katmai Volcano segment as we defined it based on the 40 km offset of the volcanic front across a line drawn through Ugashik, Peulik and Ukinrek. According to Fisher et al. the northern zone of crustal disruption is less clearly defined than the southern one and passes between the Kenai Peninsula and the Kodiak Islands into lower Cook Inlet. This zone coincides with the Cook-Katmai segment boundary proposed by Kienle et al. (1982) but passes about 50 km north of Kaguyak. In this paper we consider Kaguyak to be the segment boundary volcano based on its evolved composition and mineralogy.

Evidence cited by Fisher et al. to define the transverse arc boundaries includes regional changes in geology, terminations of structural trends, cross-arc trends of young tectonic elements on the continental shelf at the two boundaries, changes in sign of long-wave length gravity anomalies representing regional changes of crustal structure, and the discrete nature of the southern boundary of the aftershock zone of the 1964 great Alaskan earthquake (compare Figure 5). Fisher et al. also regard offsets in the volcanic front as strong indicators of transverse tectonic boundaries,

The question arises whether or not the transverse tectonic boundaries in the overriding plate can be correlated with tectonic features on the down-going plate such as seamount chains and fracture zones. In the central Aleutians Marsh (1979) correlated offsets in the volcanic front with subducting fracture zones. However, since subduction is oblique in the eastern Aleutian arc tectonic elements on the down-going plate would sweep along the continental margin with time and hence could not give rise to any stationary zones of disruption in the overriding plate. Specifically, Fisher et al. calculated that the intersection of the Kodiak seamount chain with the continental margin near the southern transverse arc boundary must have swept ~ 180 km northward in the past 3 my. (based on Jordan and Minster's 1978 model RM2. Similarly oceanic fracture zones near the northern boundary would have swept - 160 km northward for the sane time period.

Crustal control of volcanic alignment in the Katmai segemnt: There is geologic and geophysical evidence that the northeasterly alignment of the volcanic front between Mageik and Kaguyak may be structurally controlled. Two anticlines mapped by Keller and Reiser (1959) on or near the crest of the volcanic arc between Martin and Katmai and between Kaguyak and Devils Desk clearly trend toward each other. Keller and Reiser propose that these anticlines may be the manifestation of a deep-seated fault that provides a zone of crustal weakness for magma migration.

There is geophysical evidence for such a fault. Kubota and Berg (1967) and Berg et al. (1 967) found that the active volcanic front is located along a steep 35 regal gravity gradient. Kienle {1969) showed that this gravity gradient extends from about Martin to Kaguyak along 90 km of the volcanic front (Figure 11, top). Figure 11 (bottom) shows a two-dimensional crustal density model derived from the gravity data for section A-A' which crosses the volcanic range between Snowy Mtn. and Mt. Denisen. The steep gravity gradient can, at least in part, be attributed to a deep-seated crustal fracture beneath the volcanic front. Based on seismic data, Berg et al. (1 967) also found distinctly different average crustal thicknesses on either side of the volcanic front. This implies the existence of a crustal boundary or fault that may extend at least to the base of the crust. Northeast of the Katmai volcanoes the crust has an average thickness of 38 km, southeast of the chain of volcanoes average crustal thickness decreases to 32 km.

In addition to these regional trends there is also good evidence from gravity and seismic data that major magma accumulations may exist in the crust beneath several volcanoes of the Katmai segment. Matumoto (1971) was able to show based on body wave attenuation patterns from local earthquake that large magma bodies may underlie Martin-Mageik, Griggs-Katmai-Trident-Novarupta-Gri ggs, and Snowy at depths of less than 10 km. Two magma reservoirs have been identified by Matumoto beneath the Katmai group of volcanoes. A shallow chamber lies at a depth of less than 10 km and has a dimension of, about 10 x 30 km. A deeper magma chamber beneath the shallow one has a similar size and lies near the base of the crust at a depth of 20-30 km. A local negative gravity anomaly, about 7-8 km wide, with an amplitude of nearly 20 regal has been mapped by Decker (1963), Berg and Kienle (1966) and Kienle (1969). It is centered in the volcanic triangle defined by Mageik-Trident-Novarupta (Figure 11, top). The anomaly has been interpreted by Kubota and Berg (1967) and Kienle (1969) as a shallow magma body beneath the recent Trident cone (Table 2). It may be part of the Katmai body defined by Matumoto (1971). The crustal density model and gravity profile shown in Figure 11 (bottom) also shows a small gravity low beneath the volcanic axis near Snowy, model led as a shallow low density magma body with a density of 2.46 g/cc. That body also coincides with a shallow region of anomalous body wave attenuation identified by Matumoto (1971) near Snowy.

Another piece of evidence that suggests that fairly large magma bodies and associated hydrothermal systems may be present in the shallow crust beneath the Katmai volcanic front is microearthquake activity. Microearthquake studies carried out in Katmai National Park at various times during the past 15 years consistently showed a fairly intense clustering of microearthquakes in the Martin-Snowy section of the Katmai volcanic front (Kubota and Berg, 1967; Berg et al., 1967; Matumoto and Ward, 1967; Matumoto, 1971). Continuous earthquake data acquired by the University of Alaska over the past few years clearly showed the episodic nature of the shallow seismicity beneath the Katmai volcanic front. Earthquakes typically occur in swarms of short duration. Pulpan and Kienle (1979) and Kienle et al. (1982) proposed that this seismicity may be associated with volcanic and hydrothermal activity beneath several Katmai segment volcanoes. In recent years Snowy Mtn. has been the most consistent source region for shallow earthquake swarms.

PETROLOGY OF THE EASTERN ALEUTIAN LAVAS

Petrologic studies of volcanic centers in the eastern Aleutian arc range from none or only the shortest reconnaissance survey to detailed studies that utilize major and minor element analyses, electron microprobe analyses, and isotropic studies. Tables 1 and 2 include a summary of petrology in the eastern Aleutian arc and also identify the data source for each volcanic center. Obviously conclusions based on a few samples from a volcanic center (such as Denisen or Martin, Table 2) may change as more samples are collected and the discussion that follows is based on a somewhat limited and uneven distribution of data in the eastern Aleutian arc. However, the data base used here is the largest and most complete for volcanic centers in this region and should be useful in identifying regional patterns of variation, although the story for individual volcanic centers may change with the accumulation of more data.

Prophyritic andesite containing abundant phenocrysts of plagioclase and lesser amounts of hypersthene and augite is the most common rock type in the eastern Aleutian arc. Dacite, often containing hornblende, is found as a minor constituent at several of the volcanic centers and a quartz-bearing dacite is the dominant lava type at Kaguyak Crater (Swanson et al., 1981). Dacite is also an important component of the 1912 VTTS deposits (Hildreth, 1982). Quartz-bearing rhyolite is present in the basal portions of the VTTS deposits and at Novarupta (Fenner, 1950; Curtis, 1968; Hildreth, 1982). Basalt has been analyzed from Katmai

(Fenner, 1926; Kosco, 1981b) and olivine-bearing basalt has been found on Iliamna, Augustine (Johnston, 1979) and at Ukinrek (Kienle et al., 1980).

Mineralogy

Plagioclase forms most of the phenocrysts in the eastern Aleutian arc, The phenocrysts are complexly twinned and zoned. Normal compositional zoning from Ca-rich cores to Na-rich rims is commonly observed, but reversed zoning is also widespread, especially in grains with abundant glass inclusions that form a sieve texture. Plagioclase commonly shows a wide range in compositions within a particular volcanic center, often almost the entire compositional range is found in a single thin' section, Hildreth (1982) found the plagioclase in the VTTS deposits ranged from An_{25} to An_{94}. A less extreme, but probably more typical range of plagioclase compositions (An_{37} to An_{86}) is shown in the dacites and andesites of Kaguyak.

Hypersthene is more abundant than augite in most of the lavas from the eastern Aleutian arc. The orthopyroxene forms slightly pleochroic phenocrysts that range in composition from W03 en45 fs52 (VTTS; Hildreth, 1982) to W03 en81 fs17 (Kaguyak). Some hypersthene grains are rimmed by clinopyroxene.

Augite is present in moderate to trace amounts in most lavas of the eastern Aleutian arc. Clinopyroxene shows a more resticted compositional range than the coexisting hypersthene. Kosco (1981b) reports a range of augite compositions from the volcanic centers around the VTTS of W045 en51 fs6 to W044 en36 fo20.

Olivine is an accessory phase in some of the andesites of the eastern Aleutian arc. Reaction rims of pyroxene often surround the olivine grains. Kosco (1981b) reports a range of olivine compositions in the volcanoes around VTTS of Fo_{68} to Fo_{80}. Olivine phenocrysts are a major component in the basalts from Augustine (Johnston, 1979) and Iliamna.

Amphibole, either edenite or edenitic hornblende according to the classification of Leake (1978), is a minor accessory phase in some andesites and dacites and is a major phase in some dacites from Kaguyak. The amphibole shows the common green to brown pleochroic color scheme. Oxidation of some hornblende grains has resulted in opaque pseudomorphs after amphibole. Other amphiboles are surrounded by reaction coronas of pyroxene and plagioclase, apparently formed by dehydration of the amphibole at low pressure.

Quartz is found as phenocrysts in the rhyolite and dacite of the VTTS deposits (Fenner, 1920; Hildreth, 1982) and in the dacites of Kaguyak (Swanson et al., 1981). Reaction coronas of pyroxene and plagioclase are found around some quartz grains and the rounded and embayed form of some quartz crystals also suggests the quartz may be unstable.

Fe-Ti oxides are common accessory phases in the lavas of the eastern Aleutian arc, Titanomagnetite is generally more abundant than members of the ilmenite-hematite solid solution series. Kosco (1981b) used Fe-Ti oxide compositions to estimate temperature (780-940°C) and oxygen fugacity (log f_{O_2} = -10.7 to -14,8) in lavas from the region around the VTTS. Similar results are reported by Hildreth (1982) for the VTTS deposits and reconnaissance studies we have done at Kaguyak are also consistent with this estimate.

Chemistry

Lavas of the eastern Aleutian arc are talc-alkaline and their pattern of chemical variability is similar to other talc-alkaline volcanic provinces. FeO*, MgO and CaO decrease with increasing SiO_2, while Na_2O and K_2O

increaes (Figure 12). Al_2O_3 shows little change with increasing SiO_2 until bulk compositions reach basaltic andesite (about 57% SiO_2) then there is a progressive decrease in Al_2O_3 with increasing SiO_2. Scatter in the variation patterns of some basalts indicates fractionation of olivine and plagioclase, but generally crystal fractionation does not appear to be important in producing the variation patterns. Most of the volcanic centers show similar patterns of variation and are grouped together in Figure 12. Augustine is slightly higher in MgO and CaO than other Cook Inlet volcanoes, Kaguyak is higher in FeO* than most of the volcanoes, lower in MgO and CaO than the Cook Inlet volcanoes and lower in K20 than the Katmai volcanoes. Griggs is higher in Na20 and K20 than other Katmai volcanoes and this is consistent with its position behind the main volcanic front. The alkaline basalts (nepheline = 1.2 in the norm) of Ukinrek do not seem to follow the same compositional trend as the other Katmai volcanoes (Figure 12) and this is consistent with the anomalous character of the Ukinrek relative to the calderas and composite volcanoes of Katmai.

Katmai shows a large range of lava compositions, but other volcanoes show a much more restricted range of compositions (Figure 12). Figure 13 further illustrates the restricted compositional range for lavas of the eastern Aleutian arc. The diverstiy of the Katmai lavas and the 1912 pumices from the VTTS suggests some common source for both sites. Fenner (1930), Curtis (1968) and Hildreth (1982) all suggest a magmatic connection between Novarupta (the supposed source of the 1912 pumices) and Mt. Katmai. The 1912 trends in Figure 13 are consistent with this argument. Other volcanoes in the eastern Aleutian show a much more restricted compositional range. It might be argued that the restricted compositional ranges shown on Figure 13 are an artifice of the limited number of available analyses and this may be true for centers such as Martin (n = 2) or Devils Desk (n = 4). Howev er, volcanoes such as Augustine (n = 21) and Trident (n = 36) also show restricted compositional ranges and the restriction here is clearly not related to a limited number of samples.

Igneous fractionation in the Aleutian arc follows either a calc-alkaline or tholeiitic trend. Kay et al. (1982) have successfully used FeO*/MgO vs. SiO_2 plots to distinguish between these differentiation trends and Figure 14 shows the results for the eastern Aleutian lavas. Increases in FeO*/MgO with increasing SiO_2 are characteristic of tholeiitic lavas while talc-alkaline differentiation shows little, if any, increase in FeO*/MgO with increasing SiO_2. A number of volcanic centers in the eastern "Aleutian arc show similar overlapping trends on Figure ?4 and these enters have been combined, none of these centers show FeO*/MgO increases with increasing SiO_2. In fact, only Kejulik could be characterized as tholei itic based on Figure 14. Other volcanic centers (such as Kaguyak or Katmai) have individual analyses that plot in the tholeiitic field, but lack the pattern of iron-enrichment with increasing SiO_2. Volcanoes of the Katmai and Cook segments appear to be uniformly talc-alkaline with the exception of Kejulik.

PETROLOGY AND VOLCANIC ARC GEOMETRY

Magmas of the eastern Aleutain arc show little compositional variation along the trace of the arc. The two major segments, Katmai and Cook (Figure 10), are quite similar in their patterns of variation (Figures 12, 13 and 14). Both arc segments are dominated by andesites that show a rather restricted range of variation (Figure 14). Cook lavas are slightly higher in CaO and MgO, but lower in Na20 and K20 relative to the Katmai samples (Figure 12). The variation of K20 (at a particular Si02 value) along the eastern Aleutian. arc is shown on Figure 15. Generally volcanic centers in the Katmai segment are richer in K_2O than the Cook Inlet volcanic centers. Kaguyak, located at the segment boundary has the lowest K20 content in the eastern Aleutian arc, while Mt. Katmai, another volcano that may lie on a arc segment boundary, is not abnormally low in K_2O.

Volcanic centers in the Katmai segment are aligned at an oblique angle to contours on the Benioff zone seismicity (Figure 10), Attempts to relate the chemical variation to the depth to Benioff zone have not been successful. Kienle et al. (1982) present data on the relation of K20 to depth to Benioff zone. In other volcanic arcs a good correlation is often found between K20 content (at a particular Si02 value) and depth to the, seismic zone (Dickinson, 1975). However, only a poor correlation between seismicity and variation in lava chemistry could be found for the eastern Aleutian arc. No correlation between depth to Benioff zone and other chemical components could be demonstrated for the eastern Aleutian lavas.

Volcanic centers that lie along segment boundaries in the eastern Aleutian arc seem to be characterized by a higher degree of fractionation within the lava suite resulting in a diversity of rock types or more evolved mineral assemblage. Kaguyak is characterized by dacites that contain phenocrysts of quartz and relatively abundant hornblende, The prevalence of this mineral assemblage is unique in the eastern Aleutian arc. Katmai and Ugashik, volcanic centers that seem to mark segment boundary volcanoes along the arc, are characterized by a diverse suite of lavas (Table’s 1 and 2, Figure 13).

DISCUSSION

Segmentation in the eastern Aleutian arc is generally well-defined (Figure 10), but the exact position of the Cook Inlet-Katmai segment boundary is a problem. Based upon the alignment of the volcanic front Kienle et al. (1982) drew the boundary between Augustine and Douglas. Fisher et al. (1981) propose a segment boundary in the same region based on anomalies in crustal geology and tectonics, Based solely on volcanic alignment Marsh (1982) proposed the segment boundary is through Kaguyak Crater, a model which explains the anomalous character of the dacites of Kaguyak. A third possibility is that both models are correct. Then segment boundaries are located between Augustine and Douglas and also through Kaguyak resulting in a subsegment that contains Fourpeaked and Douglas (Figure 10). In any case, if a segment boundary is located between Augustine and Douglas, it is not associated with any known segment-boundary volcano with anomalous lavas.

The boundary volcanoes, Kaguyak, Novarupta/Katmai and Ugashik appear to be characterized by talc-alkaline fractionation that has taken place at shallow levels in the crust. Kaguyak lavas are dominated by quartz- and hornblende-bearing dacite prior to the caldera-forming eruption. Dacitic pumices erupted during the caldera-forming event contain quartz and hornblende in a glassy groundmass. Post-caldera andesites at Kaguyak contain neither quartz nor hornblende. Swanson et al. (1981) interpret this eruptive sequence as the draining of a zoned magma chamber under Kaguyak. The quartz- and hornblende-bearing dacites represent the top of the chamber while the post-caldera andesites represent a lower level of the magma chamber. Hildreth (1981) notes a similar eruptive sequence from many zoned magma chambers. Fractionation within the Kaguyak lavas apparently took place at shallow levels because the phenocrysts and groundmass minerals have similar compositions (Figure 16).

Hildreth (1982) studied the stratigraphy and petrology of the 1912 VTTS deposits and concluded that the 1912 Novarupta eruption partially drained a shallow zoned magma chamber. The VTTS deposits have a rhyolite at the base and become dacitic and andesitic toward the top. Magma mixing, as evidenced by extensive banded pumices, is common in the upper portions of the deposits. Hildreth (1982) reports distinct compositional breaks between the rhyolite, dacite and andesite in the VTTS deposits, suggesting the presence of 3 distinct lavas in the magma chamber prior to eruption. Temperatures calculated from Fe-Ti oxides in the VTTS deposits show a continuum from rhyolite through dacites to andesites suggesting that the 1912 lavas were comagmatic. Therefore, the mixing evidenced in the 191.2 products are probably the result of internal mixing of more and less-fractionated magmas prior to eruption. Results of seismic and gravity studies (Kubota and Berg, 1967; Berg et al., 1967; Matumoto and Ward, 1967; Kienle, 1969; Matumoto, 1971) are consistent with the presence of a large shallow-level (< 10 km deep) magma chamber under the entire Griggs-Novarupta-Trident-Katmai area.

Ugashik (Table 2) is another segment boundary volcano (Figure 10) that has erupted a suite of lavas that range from rhyolite to andesite. However, little is known about the petrology of this volcanic center. Only the abundance of dacite and rhyolite suggests a similarity to the Kaguyak and Novarupta/Katmai systems.

Segment-boundary volcanoes in the eastern Aleutian arc (Kaguyak and Katmai) are characterized by talc-alkaline differentiation in contrast to the tholeiitic segment-boundary volcanoes in western Aleutian arc (Kay et

51., 1982) Based upon the results of trace-element analyses, parental magmas for the talc-alakal.ine and tholeiitic appear to be the same (Kay et al., 1982), but the fractionation mechanisms are different. Kay et al. (1982) suggest that tholeiitic lavas fractionate at shallower levels than calc-alkaline lavas. Perhaps the ascent of tholeiitic lavas to shallower levels is aided by zones of crustal weakness at transverse arc boundaries. As discussed previously, transverse arc boundaries in the eastern Aleutian arc appear to be related to changes in crustal geology, but here these zones of weakness do not promote tholeiitic volcanism.

Volcanic centers of the Cascade Range are segmented (Hughes et al., 1980) and the segment boundary volcanoes are not associated with tholeiitic differentiation. Instead, the segment-boundary volcanoes of the Cascades show talc-alkaline fractionation as do the intrasegment volcanoes. However, the intrasegment volcanoes are typically andesitic while the boundary volcanoes range from rhyolite to basalt (McBirney, 1968; Hughes et al., 1980). This same pattern of chemical variation is found in the eastern Aleutian arc.

A rather thick section of continental crust uderlies both the Cascade Range and the eastern Aleutian arc, while the central Aleutian arc is underlain by either oceanic crust or relatively thin continental crust. The presence of thick continental crust seems to control whether the segment boundary volcanoes are talc-alkaline or tholeiitic. Marsh (1982) related the presence of rhyolite on the Alaska Peninsula to the presence of continental crust and suggested the rhyolite formed by the melting of the continental crust. However, Sr-isotope studies cited by Hildreth (1982) on the rhyolite of the VTTS deposits show no evidence for crustal contamination in the VTTS rhyolites. Thus, whatever the role of the continental crust is in controlling fractionation in the segment-boundary volcanoes, it apparently does not involve partial melting or chemical interaction of the crust with the rising magmas.

Kosco (1981b) recognized that the continental crust was not involved in magma generation in the Katmai area. Instead he felt the density similarity between the continental crust and the rising magma would stagnate the magma near the base of the crust (about 30-35 km under Katmai) and fractionation would begin. Fractionation at such moderate pressure would produce hornblende and Kay et al, (1982) believe this fractionation would follow a talc-alkaline trend. Structural traps higher in the crust beneath the Katmai volcanoes may result in fractionation at still shallower levels thus accounting for the textural disequilibrium observed for some phenocryts [decompositions of amphibole, reaction coronas on some quartz and hypersthene).

Geophysical evidence indicates a discontinuity in the crust that extends along the strike of the volcanic arc from the VTTS region to about Kaguyak. This discontinuity may provide a structural trap for the accumulation of magma at shallow depths in the crust. Since the discontinuity extends laterally along the volcanic arc, magma may accumulate to form elongate bodies that feed several closely-spaced volcanic vents. This may account for some of the close spacing of volcanic vents in the Katmai segment (such as Devils Desk-Kukak-Denisen/Stellar and the line of 3 peaks forming Snowy). Intersection of this lateral structural discontinuity with a subsegment boundary near the VTTS may explain the abnormally large magma chamber that exists at shallow depths in this region. The differences between the eruptive products at Katmai (greater diversity, more K_2O) and Kaguyak '(less diversity and K20) shown on Figure 13 and 15 may be related to the shallow level, structurally controlled differentiation at Katmai as opposed to fractionation of Kaguyak lavas deeper in the crust.

CONCLUSIONS

Subduction in the eastern Aleutain arc is marked by a smooth, continuous Benioff zone and a segmented volcanic arc. Transverse arc boundaries offset the volcanic front and correspond to some change in crustal topography and regional geology. Back-arc volcanic centers (Ukinrek and Griggs) are sometimes found behind the main volcanic front along the transverse boundaries. The strike of the Benioff zone and trend of the volcanic arc cross-cut in the Katmai segment, but are generally parallel in the Cook Inlet segment.

Despite the difference in the tectonic setting between the Katmai and Cook segments, the chemistry of the eruptive products between the two areas is remarkably uniform andesites. Only the segment boundary volcanoes Ugashik, Katmai/Novarupta, and Kaguyak are significantly different and contain a wider range of compositions from rhyolite to basalt. Mineralogic and petrologic trends suggest initial fractionation of the magmas near the base of the crust. Intrasegment volcanoes tap this lower crust magma body and erupt the magma with little further fractionation. Segment boundary volcanoes tap the same magma source but discontinuities higher in the crust allow pending of the magma promoting further fractionation, resulting in a wider diversity of lava types.

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TABLE 1

VOLCANIC CENTERS IN COOK INLET

Name Latitude (N) Longitude (W) (of Indicated feature) Highest Point (ft)	Type of Feature	Last Eruption	Current Activity	Historic Eruptions	Comments	Petrology/SiO_2 Range (n: No. of samples analyzed)
Hayes Volcano 61°37.2' 152°?8.9' (remnant) 5,400	remnant of unconsolidated. ash fall and avalanche deposit	no historic activity	not active	none	young vent, probably Holocene, original vent covered by Hayes Glacier	hornblende-biotite dacite (Miller and Smith, 1976)
Mt. Spurr (Crater Peak) 61°16.0' 152°12.7' (highest peak) 11,070	complex volcano, covering about 25 km²	1953, major eruption. ash spread over Anchorage, damage to equipment (Juhle and Coulter, 1955; Wilcox, 1959)	50 m diameter, hot. acid lake within Crater Peak; fumaroles on south rim of crater at boiling point in 1982 (94.1°C) (R. Motyka, pers. comm.)	1953	heavily glaciated, deeply dissected	?
Iliamna Volcano 60°01.9' 153°05.4' (highest peak) 10,016	complex volcano, consisting of four peaks aligned in a N-S direction (Juhle, 1955)	1876, major eruption spreading ash to Kenai Peninsula (Rymer and Sims, 1976)	two vigorous, sulfurous fumaroles, one just below the summit of Iliamna on upper east face above Red Glacier, the other near the saddle between Iliamna and North Twin	eruptions in 1876, 1867, 1843, deposit-ing ash 160 km to the ENE in Skilak Lake, ash eruption in 1778/79; "smoke" reported in 1947, 1933, 1?93 1786, 1779, 1778, 1768. Active in 1978, 1952/53.	heavily glaciated, deeply dissected	olivine basalt and two-pyroxene andesite; SiO_2 = 51 to 61% (n = 9) (Juhle, 1955; Kienle et al., 1982)
Redoubt Volcano 60°29.3' 152°45.5' (highest peak) 10,197	stratocone	1966/67/68, major eruptions (Wilson et al., 1966; Wilson and Forbes, 1969) producing 2 flash floods in Drift River Valley because of excessive ice melt in summit crater (Post and Mayo, 1971)	healed ground; weak steam vents in ice calves at northern rim of summit crater	eruptions in 1966-68, 1902 (ash 200 km to the E, to Nope, Knik Sunrise); smoke reported in 1933 and 1819: active in 1770.	extensive lahar deposits in Crescent River Valley (Riehle et al., 1900); heavily glaciated	two-pyroxene andesite, widespread hornblende; SiO_2 - 55 to 60% (n = 9) (Forbes et al., 1965; Kienle et al., 1982)
Augustine Volcano 59°21.7' 153°25.9' (highest peak) 4,100	Island, stratocone and dome complex with pyroclastic flow apron	1976, major eruption, eruption columns to 14 km (Kienle and Shaw, 1979); emplacement of pyroclastic flows; ash dispersal 300 km to the NNE (Talkeetna) and 1100 km to the ESE (Sitka).	cooling lava dome, extruded in 1976, vigorous summit fumaroles, 354°C in 1979 (O. Johnston, pers. comm.), 464°C in 1902 (R. Motyka, pers. comm.)	major eruptions in 1976, 1963/64. 1935, 1883, 1812, producing high eruption columns and pyroclastic flows; eruptions often end with dome intrusions. the 1003 eruption was tsunamigenic (Doroshin, 1070; Davidson, 1884; Detterman, 1968, 1973; Johnston, 1978; Kienle and Swanson, 7900); ash to Skilak Lake, 200 km to the NC, 1963/64, 1935, 1812 (Rymer and Sims, 1976)	not glaciated	two-pyroxene andesite and dacite, minor hornblende and olivine; SiO_2 . 57 to 69% (n = 21) (Detterman, 1973; Kienle and Forbes, 1976; Kienle et al., 1902)

TABLE 2

VOLCANIC CENTERS IN KATMAI NATIONAL PARK AND ON THE UPPER ALASKA PENINSULA

Name Latitude (N) Longitude (W) (of indicated feature) Highest Point (ft)	Type of feature	Last Eruption	Current Activity	Historic Eruptions	Comments	Petrology/SiO_2 range (n: No. of samples analyzed)
Mt. Douglas 58°51.3' 153°32.4' (crater lake) 7,020	stratocone	no historic activity	200 m diameter crater lake at 25°C, pH < 1, fumaroles at boiling point in 1982 (93.4°C) (R. Motyka, pers. comm.)	none	heavily glaciated	two-pyroxene andesite, some olivine; SiO_2 = 59 to 62% (n = 7) (Kienle et al., 1982)
Fourpeaked Mtn. 58°46.1' 153°40.8' (center of four peaks) 6,903	stratocone	no historic activity	not active	none	hydrothermally altered summit, but no apparent solfataric activity, heavily glaciated and dissected	two-pyroxene andesite, minor hornblende; SiO_2 = 57 to 58% (n = 5) (Kienle et al., 1982)
Kaguyak Crater 58°36.8' 154°03.5' (island in crater lake) 2,956	caldera, 2.4 km diameter, contains 189 m deep lake	no historic activity	weak solfataric activity on central island, no elevated temperature in lake	none	pyroclastic flow apron, several lava domes within and outside caldera; not glaciated	two-pyroxene dacite, and minor andesite, some hornblende and quartz; SiO_2 = 59 to 66% (n = 14) (Swanson et al., 1901; Kienle et al., 1902)
Devils Desk 58°28.5' 154°17.9' (highest peak) 6,410	central vent and dike complex	no historic activity	not active	none	deeply dissected, few small glaciers	two-pyroxene andesite, minor olivine and hornblende; SiO_2 = 55 to 61% (n = 4) (Kienle et al., 1982)
Kukak Volcano 58°27.6' 154°20.9' (fumarole field on northernmost peak) 6,710	stratocone	no historic activity	vigorous fumarole field, with steam excaping through holes in ice	none	heavily glaciated	two-pyroxene andesite, and dacite; SiO_2 = 59 to 66x (n = 6) (Kienle et al. 1982)
Mt. Denison 58.25.1' 154°26.9' (highest peak) 7,520	stratocone, includes Mt. Stellar, an erosional remnant	no historic activity	not active	none	heavily glaciated and dissected	two-pyroxene andesite; SiO_2 = 57 to 63% (n = 2) (Kienle et al., 1902)
Snowy Mtn. 58°20.1' 154°41.0' (highest peak) 7,090	complex volcano, consisting of 3 peaks aligned in a NE-SW direction	no historic activity	heated ground and weak steam vents on peak 6,875, 89° C in 1982 (R. Motyka, pers. comm.)	none	heavily glaciated	olivine, two-pyroxene andesite, hornblende dacite; SiO_2 = 56 to 64% (n = 4) (Kienle et al., 1982)
Mt. Katmai 58°15.8' 154.58.5' (center of crater lake) 6,715	caldera, 2 km x 2.5 km, ~ 600 m deep, contains 200 m deep lake	1912, caldera formation	lake has elevated temperature, there is a zone of upwelling gas, indicating fumarolic activity at lake bottom; lake level rising at ~ 3m/yr (average 1975-1977, Motyka, 1978)	1912	glaciated	andesite dominant, minor basalt, dacite and rhyolite (Fenner, 1926, 1950; Kosco, 1981b)
Mt. Griggs 58°21.2' 155.06.2' (summit crater) 7,650	stratocone	no historic activity	summit crater with heated ground and weak steam vents, high pressure fumarole on W-flank	none	heavily mantled with 1912 tephra from Novarupta; few small glaciers	andesite, minor dacite (Fenner, 1926; Kosco, 1981b)
Novarupta 58°16.0' 155°09.4' (dome) 2,760	dome, ~ 250 m diameter, located within buried, ~ 2.8 km diameter, caldera (Hildreth, 1981)	1912, paroxysmal explosion, source vent of Valley of 10,000 Smokes ash flow	heated ground, weak steam vents	1912		rhyolite and dacite (Hildreth, 1982)

Trident volcano 58°13.8' 155°07.2' (summit of new flank cone) 3,800	cinder cone with lava flows and block avalanches, formed in 1953/54, 57, 58, 59/60, 63 (Snyder 1954; Decker, 1963), located on SW flank of ancestral group of 3 volcanoes, the Tridents	1968, normal explosion	fumaroles at boiling point within and outside summit crater	vent plugs emplaced in 1961, 66, 74 (74 plug subsided again by 1975); normal explosions in 1953, 60, 61, 62, 63, 64, 67, 68 with plumes to 6-14 km, former vent plugs destroyed during 62, 67 eruptions no vent plug in 1982.		two-pyroxene andesite; minor dacite (Ray, 1967; Kosco, 1981b)
Mt. Mageik 58°11.8' 155°14.6' (summit crater lake) 7,140	stratocone	1936, explosion	small crater lake at 70°C, P_H ~ 1 (Hildreth, personal communication, 1981), weak steam plume can be seen frequently	1936; questionable event in 1946; 1929, small explosion; 1927, small explosion (Jaggar, 1927)	heavily glaciated	dacite and andesite (Fenner, 1926; Kosco, 1981b)
Mt. Martin 58°10.2' 155°21.0' summit crater solfatara field 6,110	stratocone	1951, questionable ash eruption	almost continuous steam plume fed from vigorous solfatara field in crater floor, small acid lake	none	glaciated	two-pyroxene andesite and dacite, some olivine; SiO_2 61 to 64% (n = 2) (Fenner, 1926)
Kejulik Volcano 58°01.7' 155°40.0' (center of complex) 5,510	central vent and dike complex	no historic activity	not active	none	deeply dissected, few small glaciers	two-pyroxene andesite; SiO_2 56 to 60% (n = 6) (Kienle et al., 1982)
Mt. Peulik --587S73" 156"22.2" (highest peak) 5,030	stratocone	1814, normal explosion	not active	1814; "smoke" reported in 1852	summit crater occupied by large dacitic dome, not glaciated	andesite (T. Miller, pers. comm.)
Ukinrek Maars 57°50.1' 156°23.2' (eastern maar) 250	2 maars, 170 and 600 m in diameters	formed March 30 to April 9, 1977	hot springs in dry west maar, east maar occupied by ~ 70 m deep lake	none		alkali-olivine basalt (normative Ne . 1.2%): SiO_2 . 40% (n . 2] Kienle et al., 1980)
Ugashik Caldera 57°42.9' 156°23.2' (dome in center of caldera) 2,600	caldera, 4 km diameter, containing nested dome complex (T. Miller, pers. comm.)	no historic activity	not active	none	not glaciated	dacite to rhyolite (T. Miller, pers. comm.)

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Figure Captions:

Figure 1: Quarternary volcanic centers in the Aleutian arc.

Figure 2: Location of Late Quarternary and Holocene volcanoes in the eastern Aleutian arc. Relative motion vectors between Pacific and North American plates after Minster and Jordan (1978, model RM2). Line AA', BB' and CC' indicate locations of seismic cross sections shown in Figure 8.

Figure 3. Types of volcanic edifices, major historic eruptions and generalized volcanic hazards in Cook Inlet. Numbers within plume symbols refer to the Volcanic Explosivity Index (VEI), described by Simkin et al. (1981).

Figure 4. Types of volcanic edifices, major historic eruptions and generalized volcanic hazards in Katmai National Monument and on the upper Alaskan Peninsula. Numbers within plume symbols refer to the Volcanic Exposivity Index (VEI), described by Simkin et al. (1981),

Figure 5. Relative motion vectors between Pacific and North American plates after Minster and Jordan (1978, model RM2), and seismicity of the Aleutian arc (WWSSN teleseismic locations 1962-69). Pacific-North American plate boundary and 150 km depth contour to Benioff zone shown by solid lines (Figure modified from Jacob et al., 1977).

Figure 6. Cook Inlet-Alaska Peninsula-Bristol Bay-Kodiak seismic network, of the University of Alaska, 1981 configuration (from Kienle et al., 1982).

Figure 7. Epicenters, volcanoes, isobaths of Benioff zone (50, 100, 150 km) and location of projection volumes for cross sections and frontal views shown in Figures 8 and 9. Epicenters from local network data, July 1977 to June 1981; selection criteria: Recorded on at least 6 stations, RMS travel time residual < 0.4 see, relative vertical and horizontal location error (ERZ and ERH) < 10 km. Epicenters are coded according to magnitude and depth range, A: 0-25 km, B: 26-50 km, C: 51-100 km, etc. (from Kienle et al., 1982).

Figure 8. Cross sectional views of Benioff zone along lines A-A', B-B', C-C' shown in Figures 2 and 7. No vertical exaggeration. Landmasses (solid. black), the position of the trench and location of-volcanoes are also-shown. Shallow thrust zone is added schematically. Selection criteria for events at 0-50 km depth (triangles): Recorded on at least 5 stations (STA > 5), relative horizontal and vertical location error (ERZ and ERH) < 10 km, RMS travel time residual < 0.5 sec. Selection criteria for events > 50 km depth (crosses): STA > 6, ERH ' and ERZ c 10 km, RMS < 0.3 see, and distance from epicenter to nearest station < 2 x depth. (modified from Kienle et al., 1982)

Figure 9. Same data as in Figure 8 projected on two vertical planes oriented along the strike of the Benioff zone (along lines D-D'and E-E'., Figure 7). Position of volcanoes also shown. Deep clusters of seismicity cross-hatched. Vertical line in section D-D' marks rupture zone boundary of 1964 (M_w 9.2) and 1938 (M_w 98.2) shallow thrust earthquakes.

Figure 10. Segmentation of the eastern Aleutain arc. 50, 100 and 150 km isobaths to the Benioff zone are also shown. Arc-tansverse tectonic boundaries shown as stippled *zones* (after Fisher et al. (1981).

Figure 11. Top: Simple Bouguer (2.67) gravity map of Katmai National Monument, showing gravity stations (solid dots) and volcanoes (modified from Kienle, 1969).

Bottom: Two-dimensional crustal density section (g/cc) along profile AA' (see top of figure). Terrane corrected and geologically corrected gravity data and computed anomalies are also shown. Jnch + Jn: Upper Jurassic sandstone arid shales' (Naknek Form.); QTu: Tertiary/Quaternary igneous rocks undifferentiated; Tv: Ecocene volcanic rocks (all units after Keller and Reiser, 1959). Upper crustal layer: 2.67 g/cc; lower crustal layer: 2.9? g/cc (modified from Kienle, 1969).

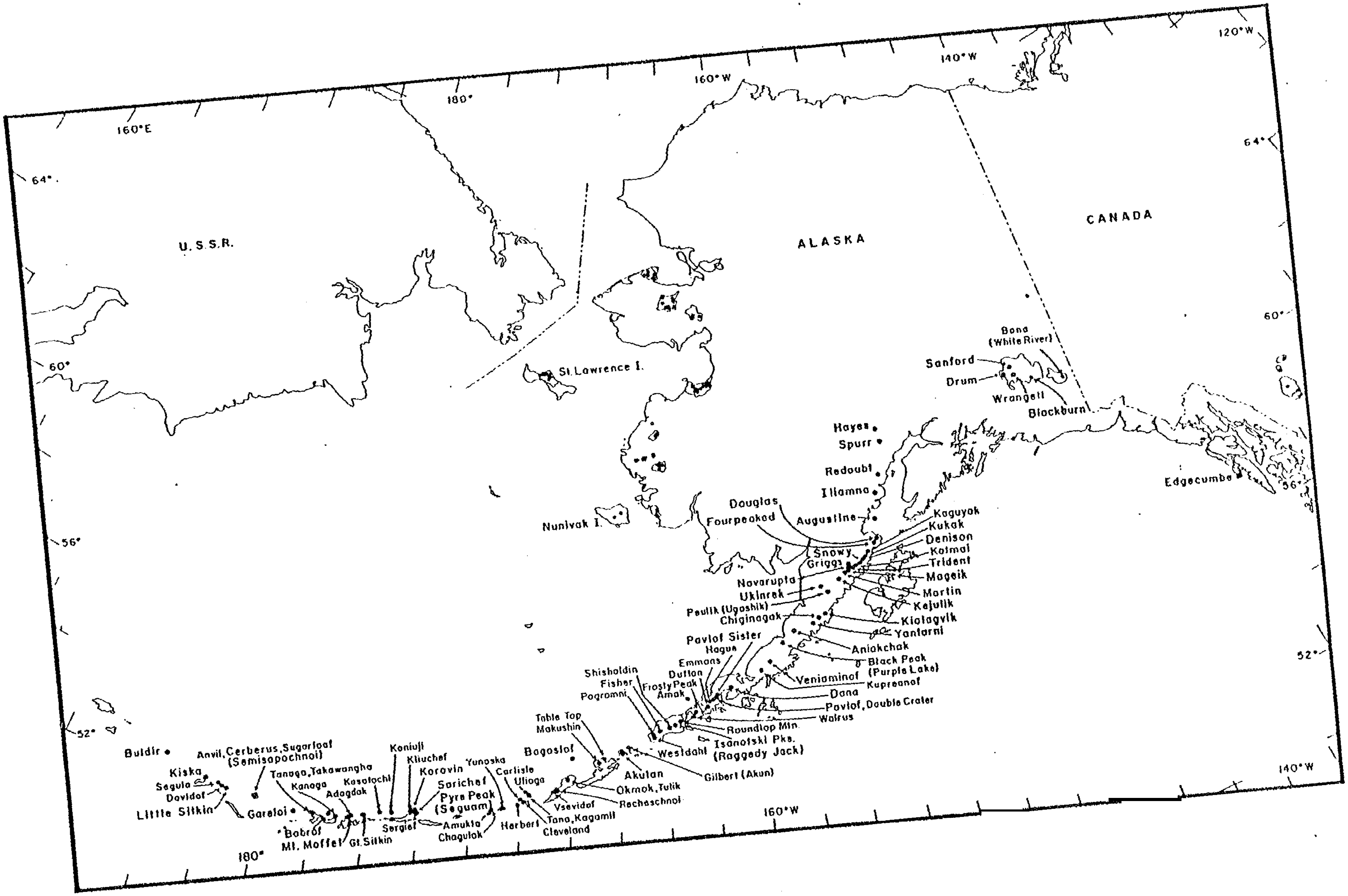
Figure 12. Harker variation diagrams for the Cook Inlet volcanoes (Iliamna, Redoubt, etc.) and the Katmai volcanoes (Kaguyak, Katmai, etc.). Note that Kaguyak is given on both diagrams for comparison. Data from Becker (1898), Fenner (1926, 1950), Juhle (1955), Forbes et al. (1965), Ray (1967), Detterman (1973), Kienle and Forbes (1976), Kosco (1981b) and Kienle et al. (1982).

Figure 13. A (Na_2O + K20), F (FeO + 0.899 Fe203), M (MgO) diagrams for volcanic centers in the eastern Aleutian arc. Data sources listed in the caption for Figure 12.

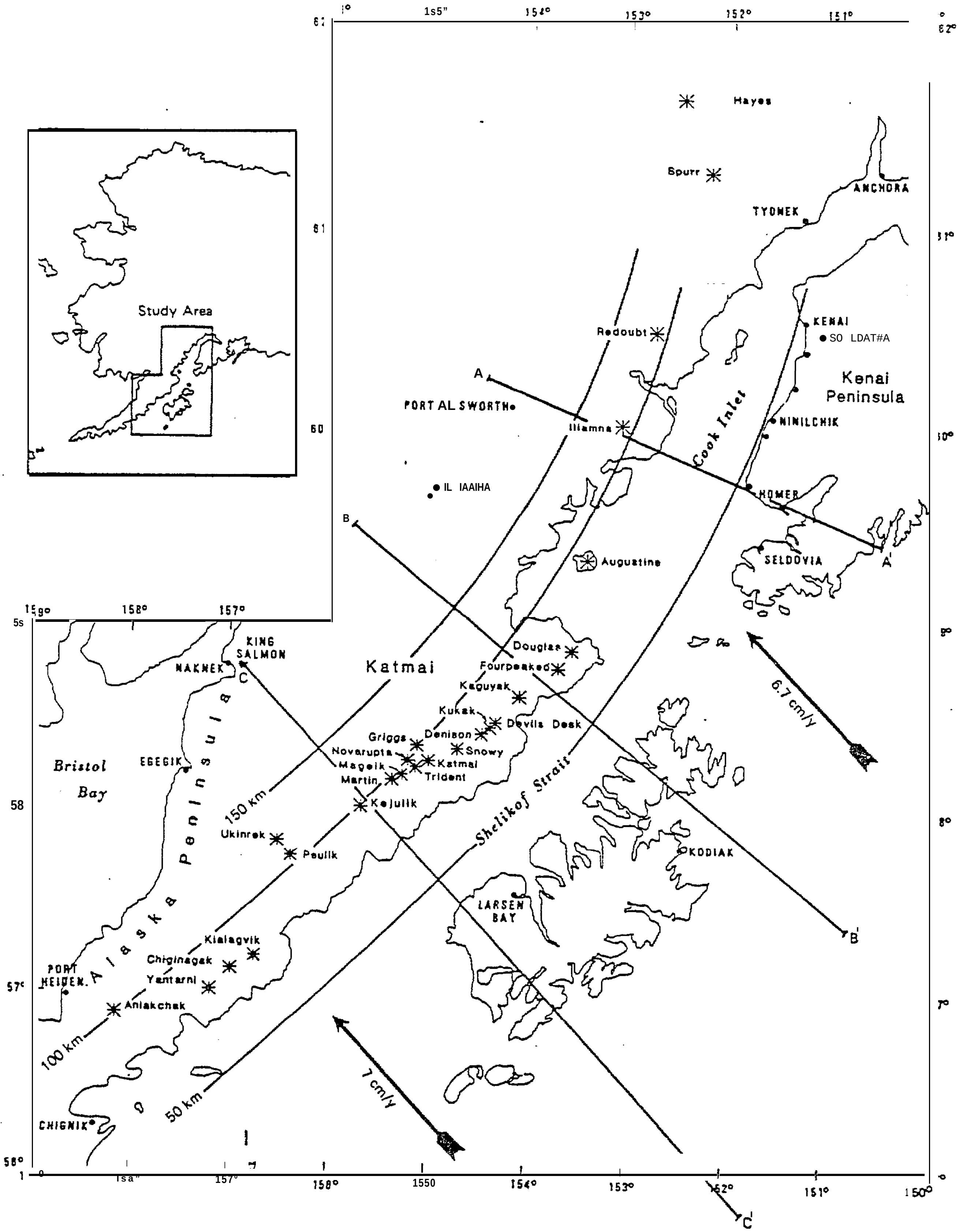
Figure 14. FeO*/MgO vs. SiO_2 variation diagram, where FeO* = FeO + 0.899 Fe_2O_3. CA/TH is the talc-alkaline/tholeiitic trend for island arcs from Miyashiro (1974). Data from Cook Inlet (Kaguyak, Augustine, etc.) and Katmai (Kaguyak, Katmai, etc.) are on separate diagrams with Kaguyak being repeated for comparison.

Figure 15. Variation of K_{60} (K20 content at 60% SiO_2) along the strike of the eastern Aleutian arc. The stippled bar marks a transverse arc break at Kaguyak. KE = Kejulik, M = Mageik, T = Trident, KA = Katmai, S = Snowy, DE = Devils" Desk, F = Fourpeaked, ' DO - Douglas, A = Augustine, R = Redoubt, and I = Iliamna.

Figure 16. Comparison of phenocryst and groundmass p"lagioclase compositions from Kaguyak Crater,



U.S.S.R.
ALASKA
CANADA
160°E
180°
160°W
140°W
120°W
64°
60°
56°
52°
St. Lawrence I.
Nunivak I.
Bona (White River)
Sanford
Drum
Wrangell
Blackburn
Hayes
Spurr
Redoubt
Iliamna
Douglas
Fourpeaked
Augustine
Edgecumbe
Kaguyak
Kukak
Denison
Katmai
Trident
Mageik
Martin
Kejulik
Kialagvik
Yantarni
Snowy
Griggs
Novarupta
Ukinrek
Peulik (Ugashik)
Chiginagak
Aniakchak
Black Peak (Purple Lake)
Veniaminof
Kupreanof
Dana
Pavlof, Double Crater
Walrus
Pavlof Sister
Hague
Emmons
Dutton
Frosty Peak
Amak
Shisholdin
Fisher
Pogromni
Roundtop Mtn.
Isanotski Pks. (Raggedy Jack)
Westdahl
Gilbert (Akun)
Akutan
Okmok, Tulik
Recheschnoi
Vsevidof
Tana, Kagamil
Cleveland
Table Top
Makushin
Bogoslof
Yunaska
Carlisle
Uliaga
Herbert
Sarichef
Pyre Peak (Seguam)
Amukta
Chagulak
Korovin
Kliuchef
Koniuji
Kasatochi
Sergief
Gt. Sitkin
Adagdak
Kanaga
Tanaga, Takawangha
Mt. Moffet
Bobrof
Gareloi
Anvil, Cerberus, Sugarloaf (Semisopochnoi)
Buldir
Kiska
Segula
Davidof
Little Sitkin


Study Area
Hayes
Spurr
ANCHORA
TYONEK
KENAI
Kenai
Peninsula
Redoubt
A
PORT ALSWORTH
Iliamna
Cook Inlet
NINILCHIK
HOMER
SELDOVIA
A'
B
Augustine
KING
SALMON
NAKNEK
C
Katmai
Douglas
Fourpeaked
Kaguyak
Kukak
Devils Desk
Denison
Griggs
Snowy
Novarupta
Mageik
Katmai
Trident
Martin
Kejulik
6.7 cm/y
Bristol
Bay
EGEGIK
Alaska Peninsula
150 km
Shelikof Strait
Ukinrek
Peulik
KODIAK
LARSEN
BAY
B'
Kialagvik
Chiginagak
Yantarni
Aniakchak
PORT
HEIDEN
100 km
50 km
7 cm/y
CHIGNIK
C'
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157°
155°
154°
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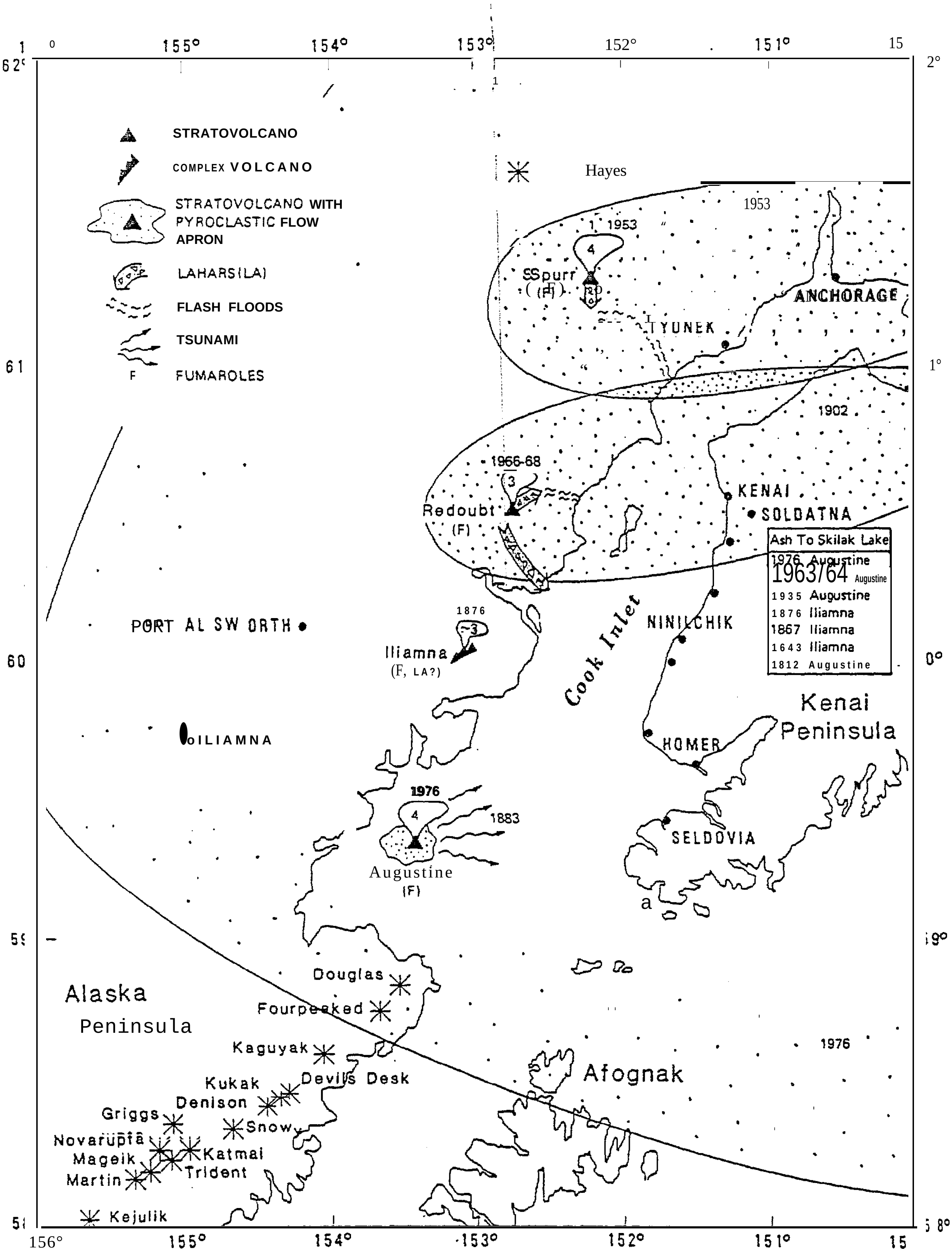
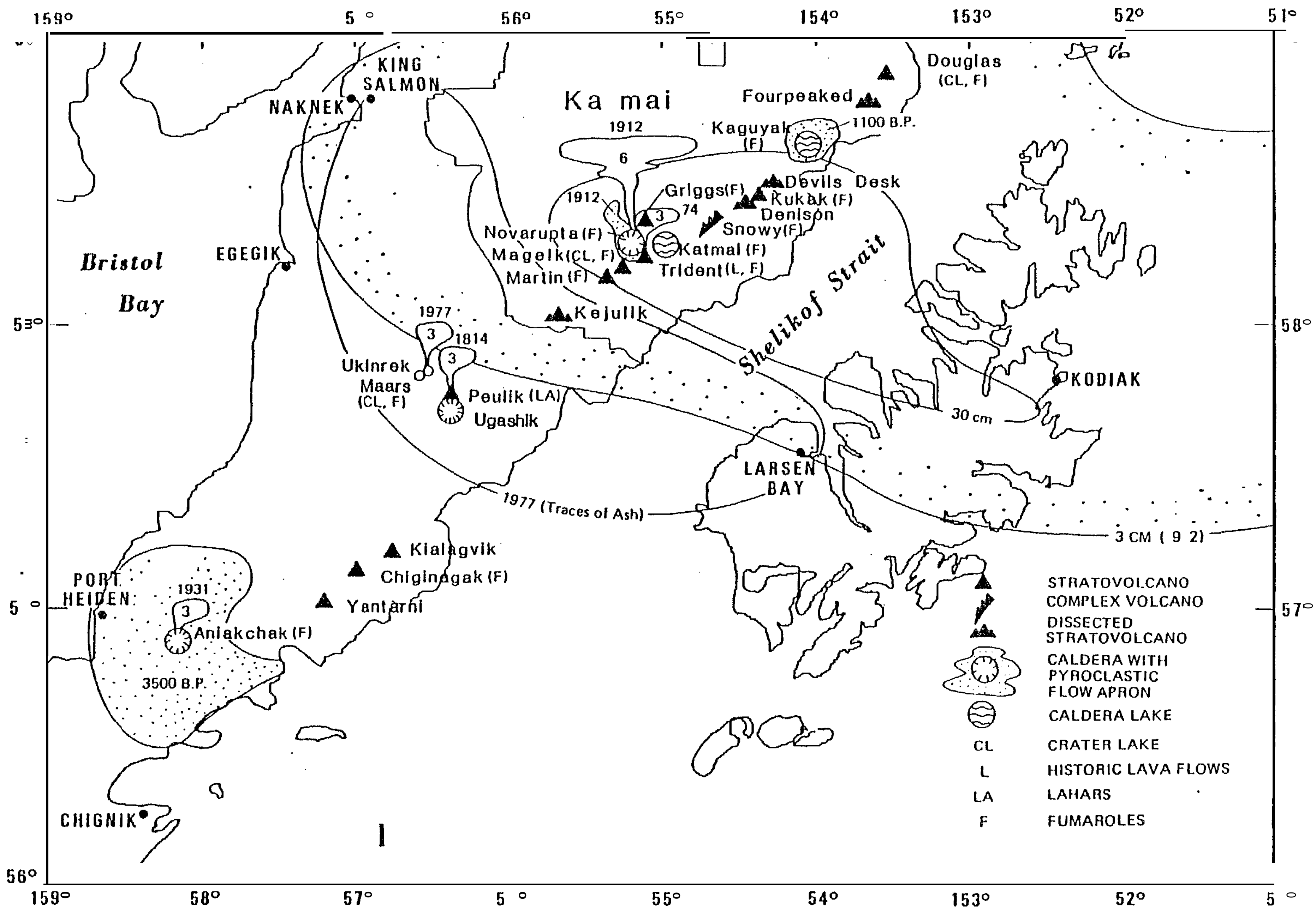
56°
60
61
62°



155°
154°
153°
152°
151°
62°
61°
60°
59°
58°
156°
STRATOVOLCANO
COMPLEX VOLCANO
STRATOVOLCANO WITH PYROCLASTIC FLOW APRON
LAHARS (LA)
FLASH FLOODS
TSUNAMI
F FUMAROLES
Hayes
1953
Spurr (F)
TYUNEK
ANCHORAGE
1902
1966-68
Redoubt (F)
KENAI
SOLDATNA
Ash To Skilak Lake
1976 Augustine
1963/64 Augustine
1935 Augustine
1876 Iliamna
1867 Iliamna
1643 Iliamna
1812 Augustine
PORT ALSWORTH
1876
Iliamna (F, LA?)
Cook Inlet
NINILCHIK
Kenai Peninsula
ILIAMNA
HOMER
1976
1883
Augustine (F)
SELDOVIA
Douglas
Fourpeaked
Alaska Peninsula
Kaguyak
1976
Kukak
Devils Desk
Afognak
Denison
Griggs
Snowy
Novarupta
Mageik
Katmai
Martin
Trident
Kejulik



159°
56°
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154°
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52°
51°
58°
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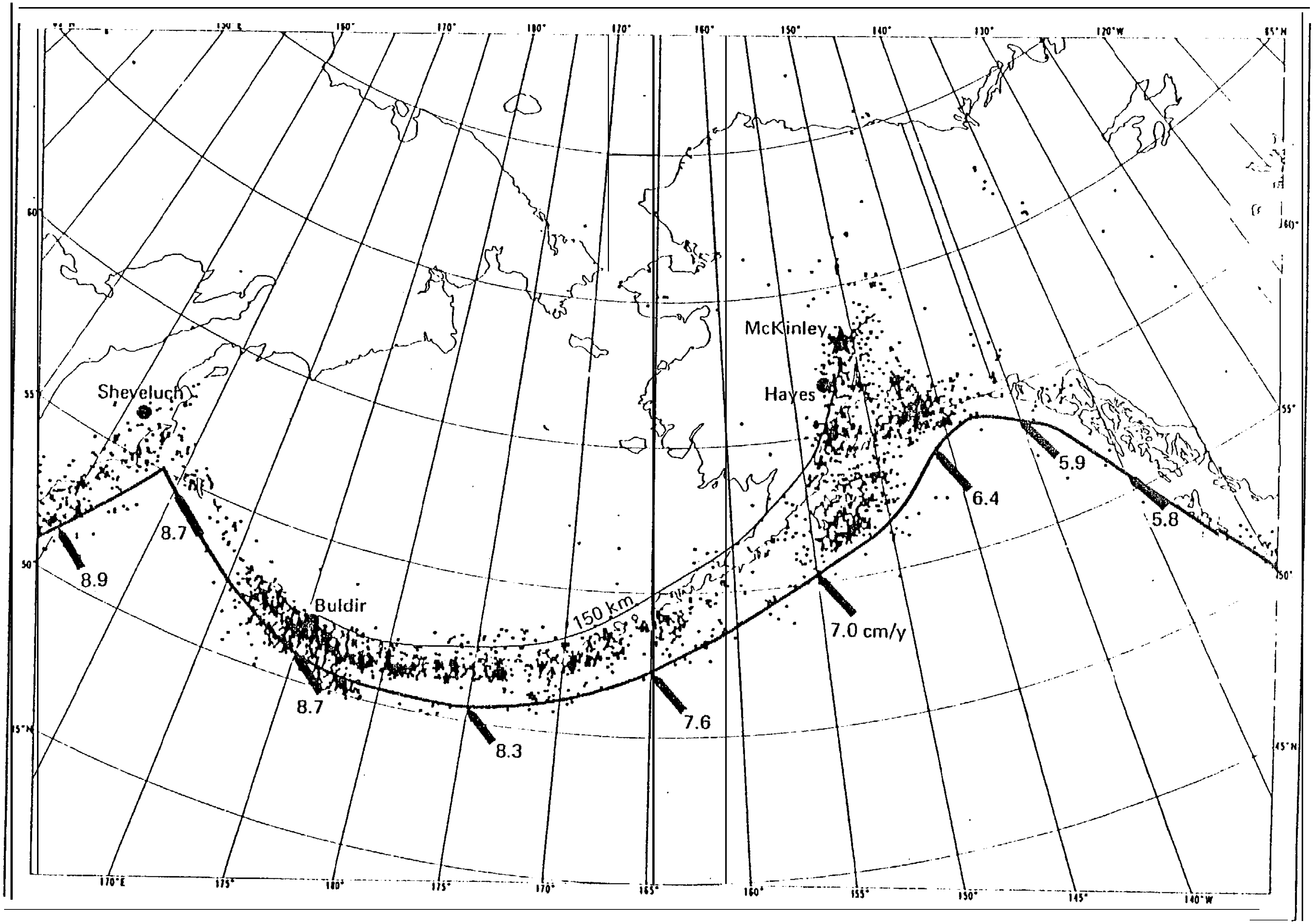
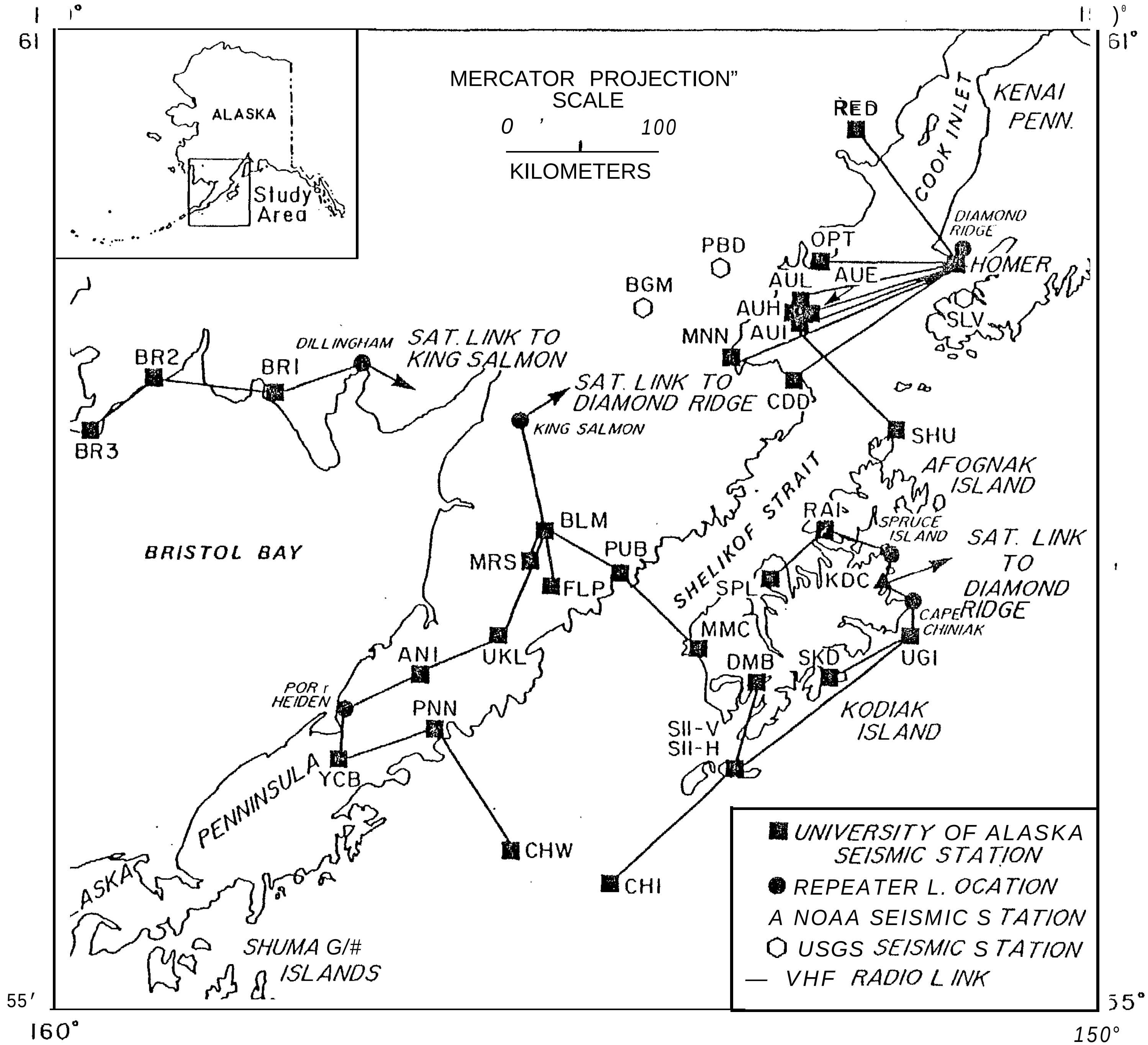
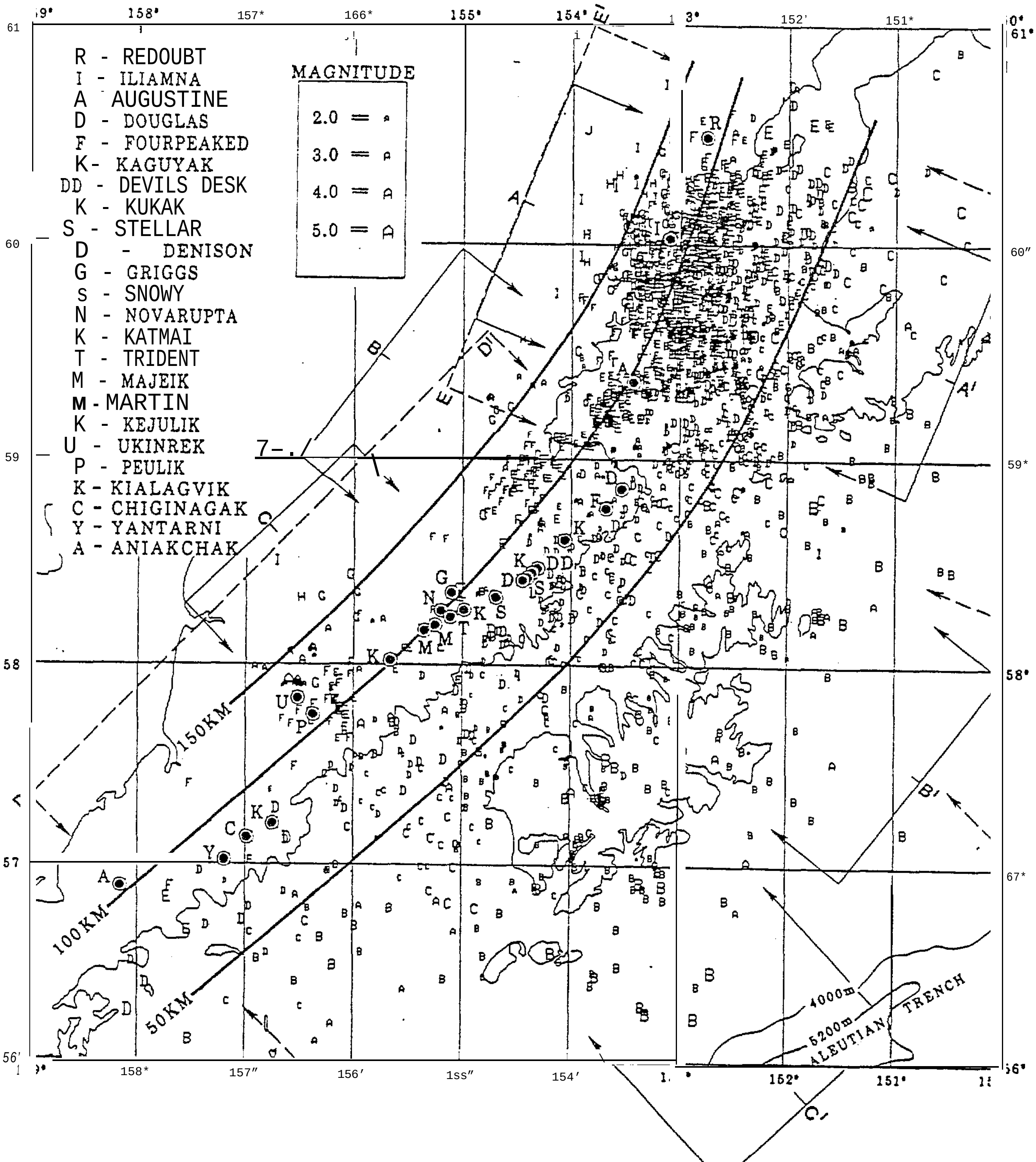
56°
Douglas (CL, F)
Fourpeaked
KING SALMON
NAKNEK
Ka mai
1912
6
Kaguyak (F)
1100 B.P.
Devils
Desk
Kukak (F)
Denison
Griggs(F)
74
3
Snowy(F)
1912
Novarupta (F)
Magelk(CL, F)
Katmal (F)
Trident(L, F)
Martin (F)
Bristol
Bay
EGEGIK
Shelikof Strait
Kejulik
1977
1814
Ukinrek Maars (CL, F)
Peulik (LA)
Ugashik
KODIAK
30 cm
LARSEN BAY
1977 (Traces of Ash)
3 CM (9 2)
Kialagvik
Chiginagak (F)
Yantarni
PORT HEIDEN
1931
Aniakchak (F)
3500 B.P.
CHIGNIK
STRATOVOLCANO
COMPLEX VOLCANO
DISSECTED STRATOVOLCANO
CALDERA WITH PYROCLASTIC FLOW APRON
CALDERA LAKE
CL CRATER LAKE
L HISTORIC LAVA FLOWS
LA LAHARS
F FUMAROLES

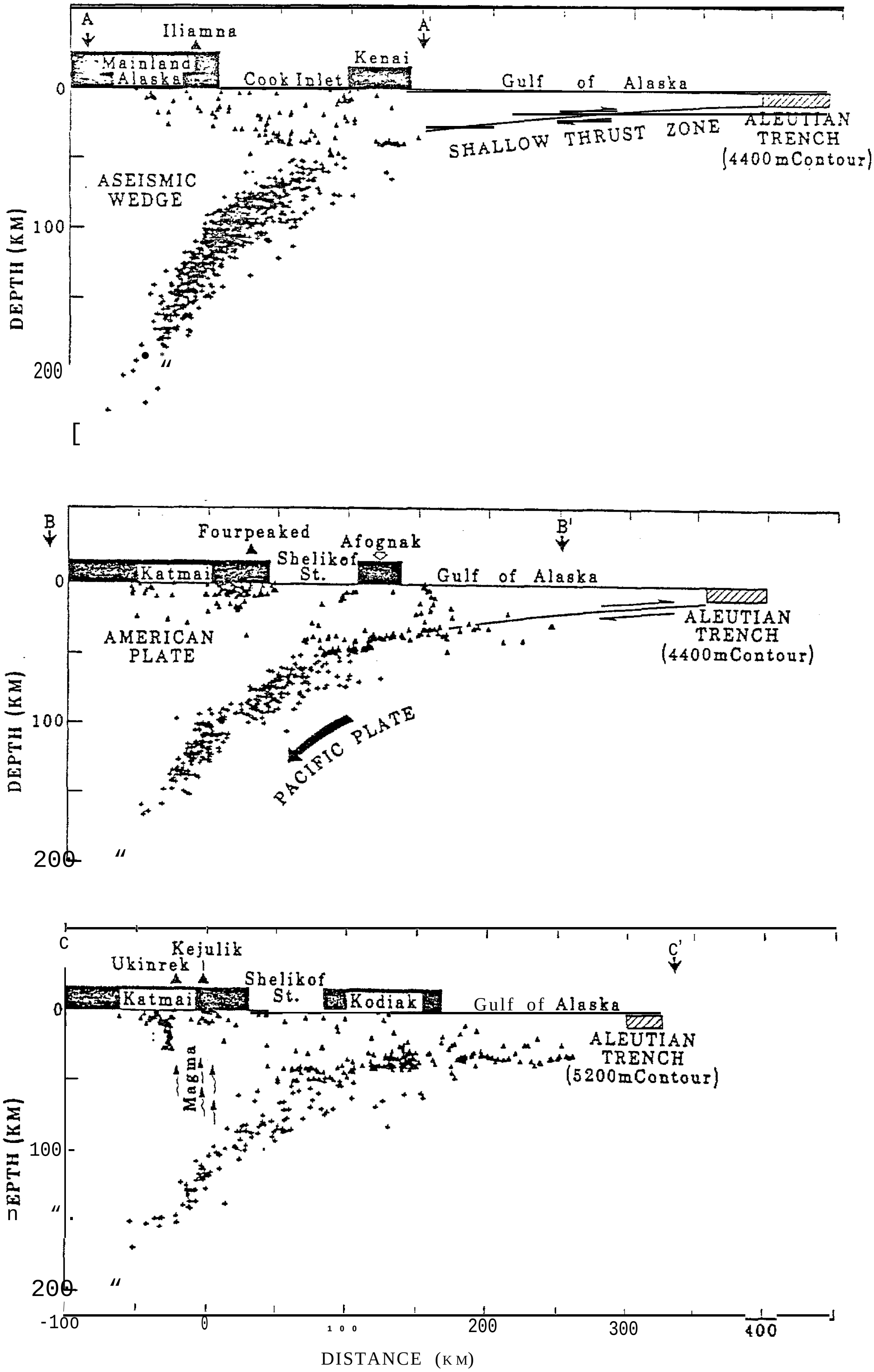


McKinley
Hayes
Sheveluch
Buldir
150 km
8.9
8.7
8.7
8.3
7.6
7.0 cm/y
6.4
5.9
5.8

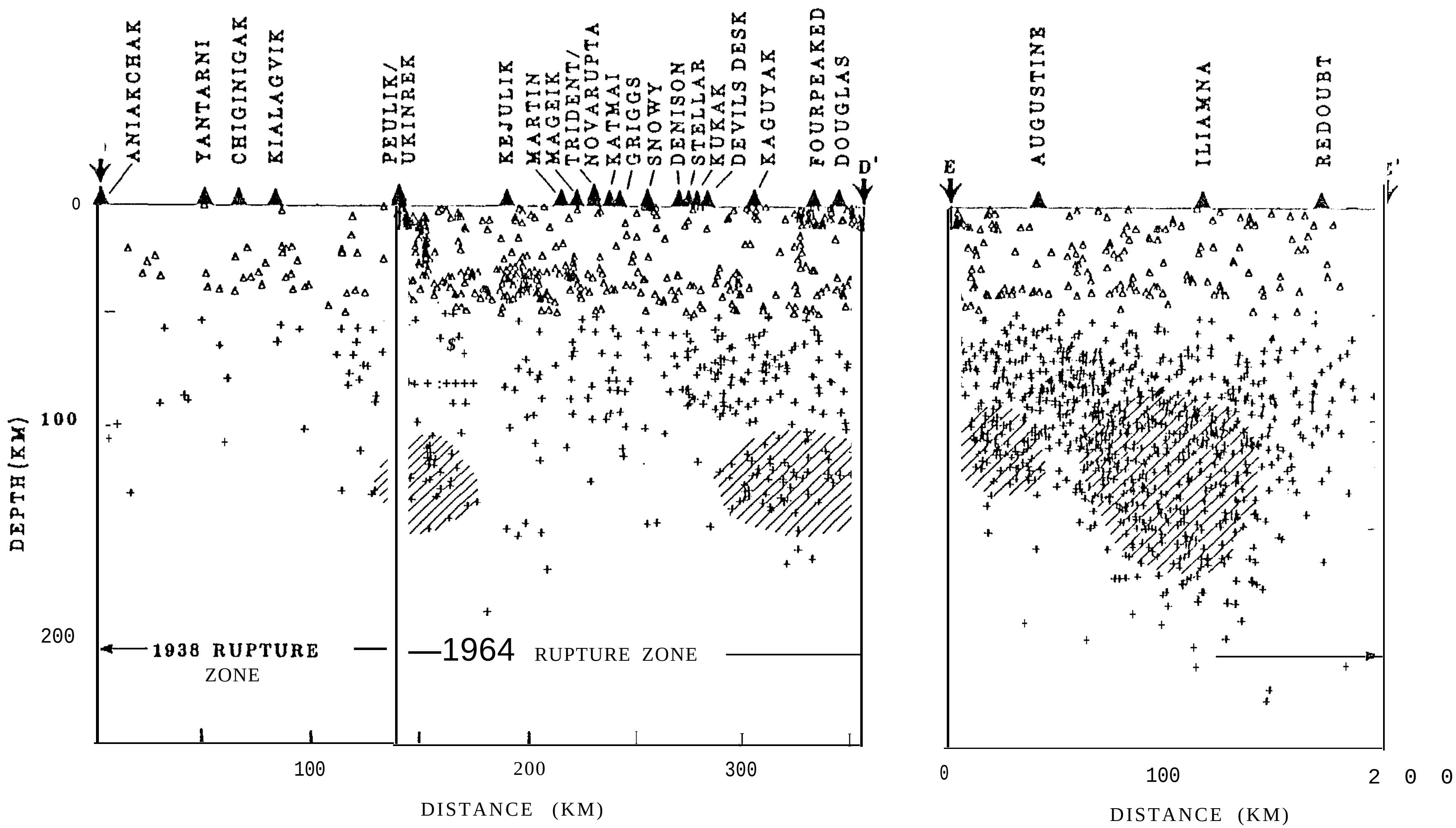


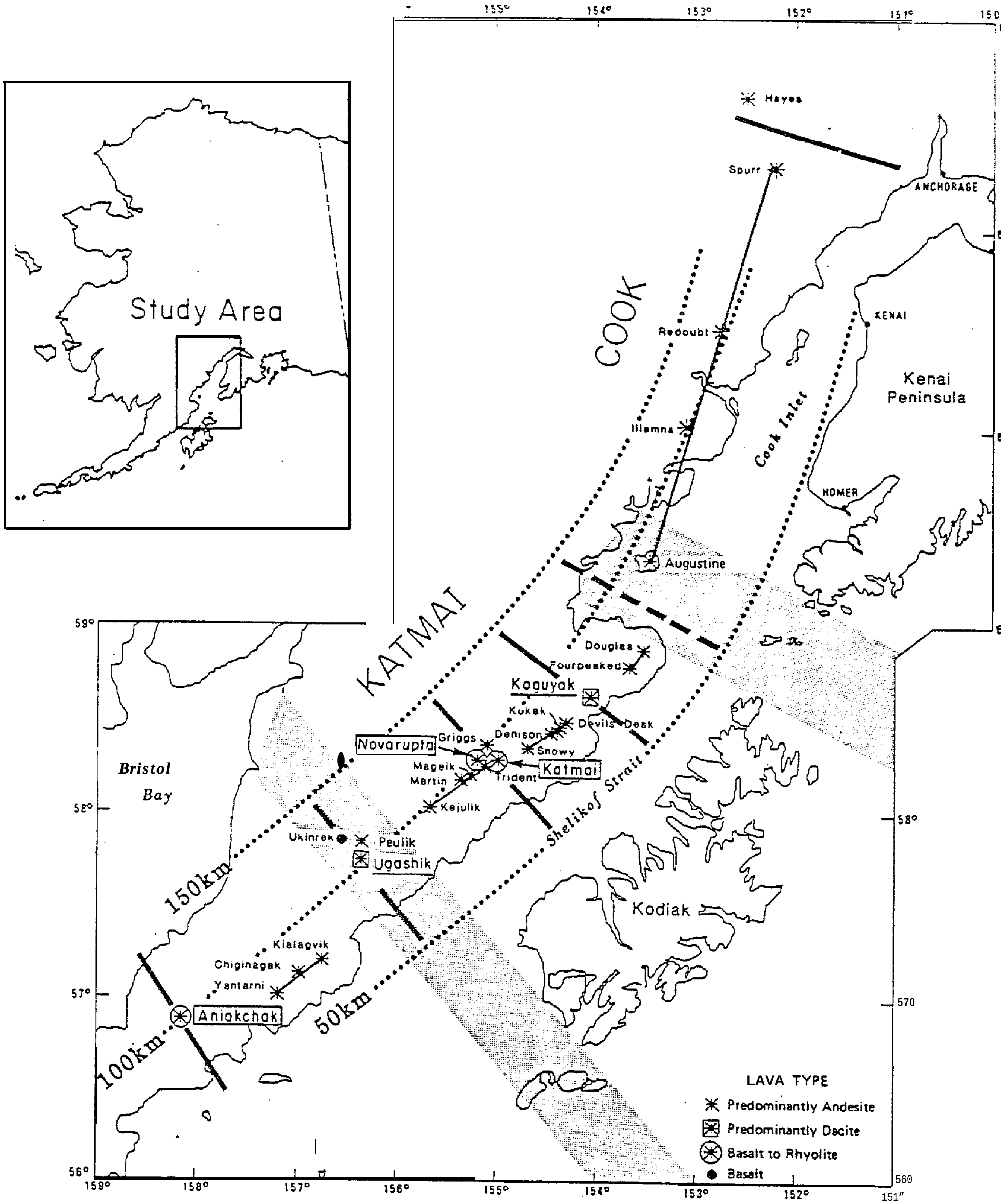
61°
61°
55°
55°
160°
150°
ALASKA
Study Area
MERCATOR PROJECTION"
SCALE
0
100
KILOMETERS
COOK INLET
KENAI PENN.
RED
DIAMOND RIDGE
HOMER
OPT
PBD
BGM
AUL
AUE
AUH
AUI
MNN
SLV
CDD
DILLINGHAM
SAT. LINK TO KING SALMON
BR2
BRI
BR3
SAT. LINK TO DIAMOND RIDGE
KING SALMON
SHU
AFOGNAK ISLAND
SHELIKOF STRAIT
BRISTOL BAY
BLM
MRS
PUB
FLP
RAI
SPRUCE ISLAND
SAT. LINK TO DIAMOND RIDGE
SPL
KDC
CAPE CHINIAK
MMC
UGI
ANI
UKL
DMB
SKD
PORT HEIDEN
PNN
KODIAK ISLAND
SII-V
SII-H
YCB
PENNINSULA
ASKA
CHW
CHI
SHUMA G/# ISLANDS
UNIVERSITY OF ALASKA SEISMIC STATION
REPEATER L. OCATION
A NOAA SEISMIC S TATION
USGS SEISMIC S TATION
VHF RADIO L INK

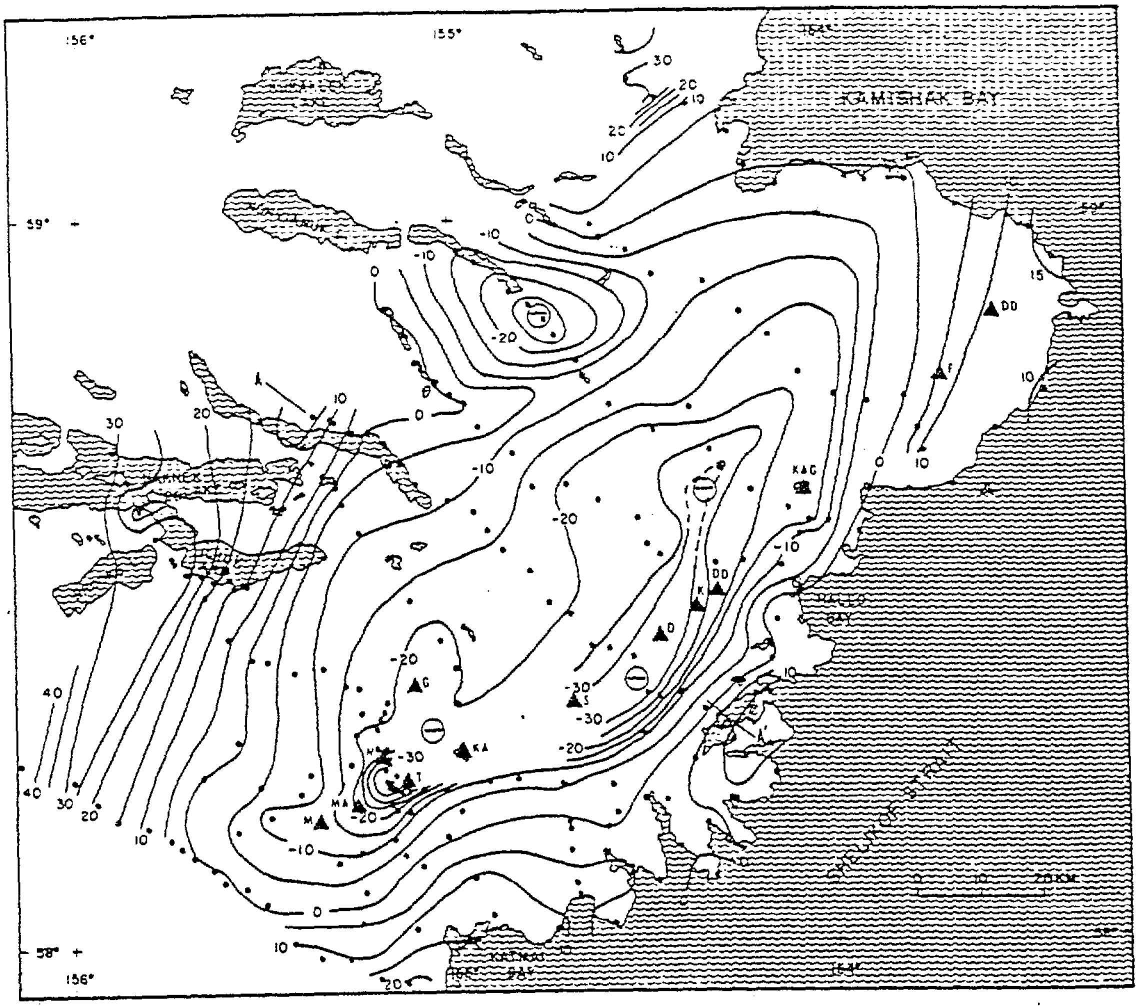

R - REDOUBT
I - ILIAMNA
A AUGUSTINE
D - DOUGLAS
F - FOURPEAKED
K- KAGUYAK
DD - DEVILS DESK
K - KUKAK
S - STELLAR
D - DENISON
G - GRIGGS
S - SNOWY
N - NOVARUPTA
K - KATMAI
T - TRIDENT
M - MAJEIK
M - MARTIN
K - KEJULIK
U - UKINREK
P - PEULIK
K - KIALAGVIK
C - CHIGINAGAK
Y - YANTARNI
A - ANIAKCHAK
MAGNITUDE
2.0 =
3.0 =
4.0 =
5.0 =
158°
157°
155°
154°
153°
152°
151°
61°
60°
59°
58°
57°
56°
150KM
100KM
50KM
4000m
5200m
ALEUTIAN TRENCH
A'
B'
C'

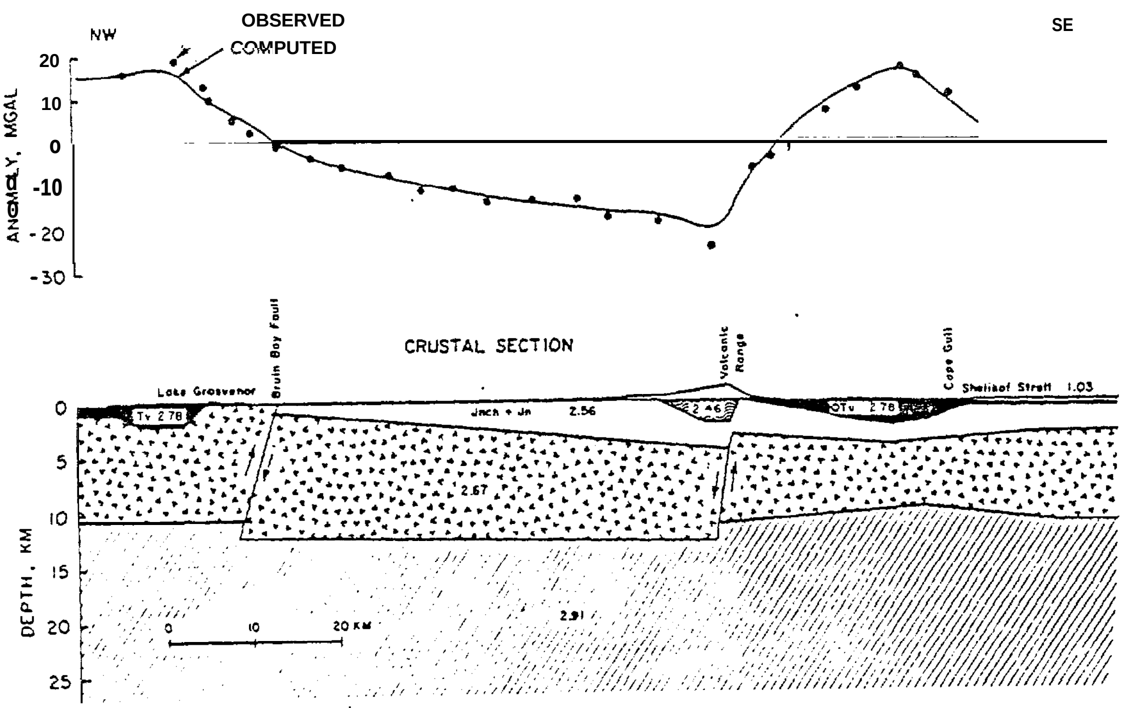


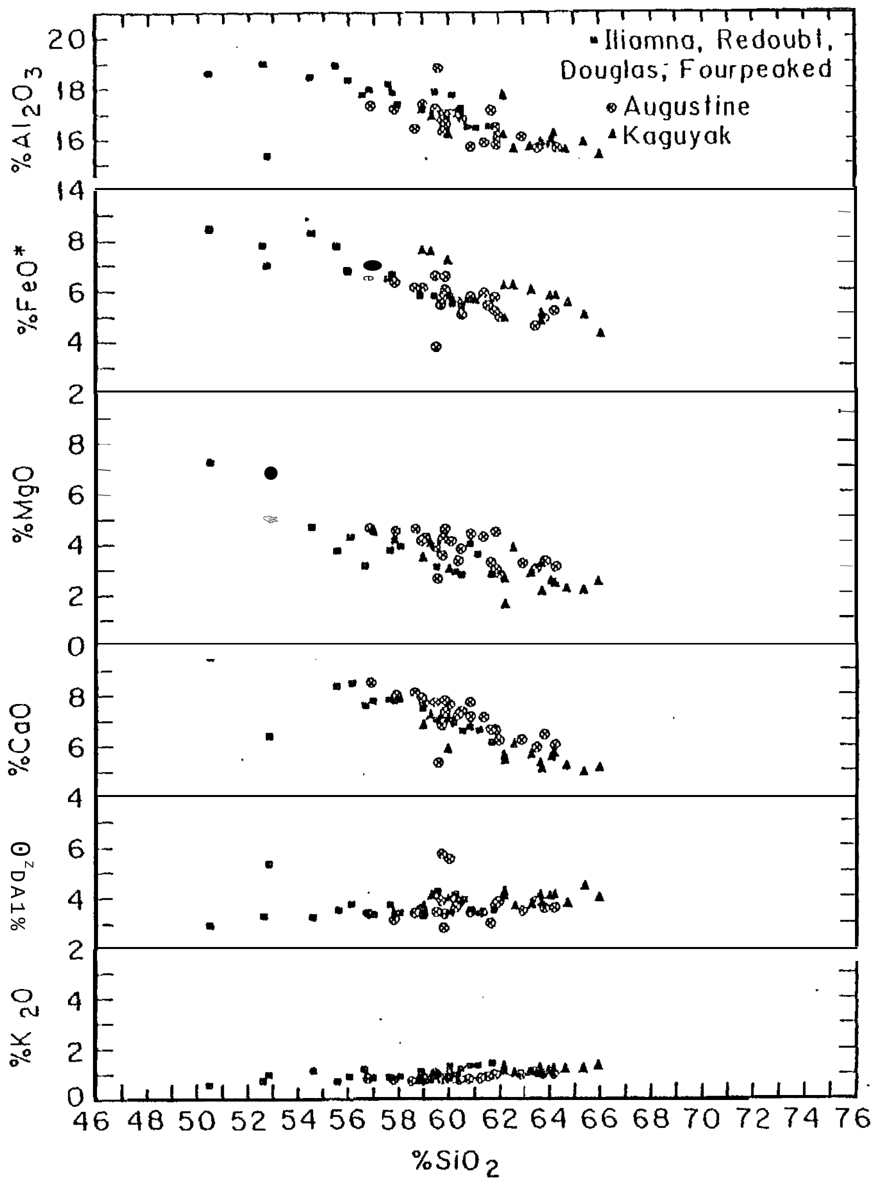
A
Iliamna
A'
Mainland Alaska
Kenai
Cook Inlet
Gulf of Alaska
SHALLOW THRUST ZONE
ALEUTIAN TRENCH
(4400mContour)
ASEISMIC WEDGE
DEPTH (KM)
0
100
200
B
Fourpeaked
Afognak
B'
Shelikof St.
Katmai
Gulf of Alaska
AMERICAN PLATE
ALEUTIAN TRENCH
(4400mContour)
PACIFIC PLATE
DEPTH (KM)
0
100
200
C
Kejulik
Ukinrek
C'
Shelikof St.
Katmai
Kodiak
Gulf of Alaska
ALEUTIAN TRENCH
(5200mContour)
Magma
DEPTH (KM)
0
100
200
-100
0
100
200
300
400
DISTANCE (KM)

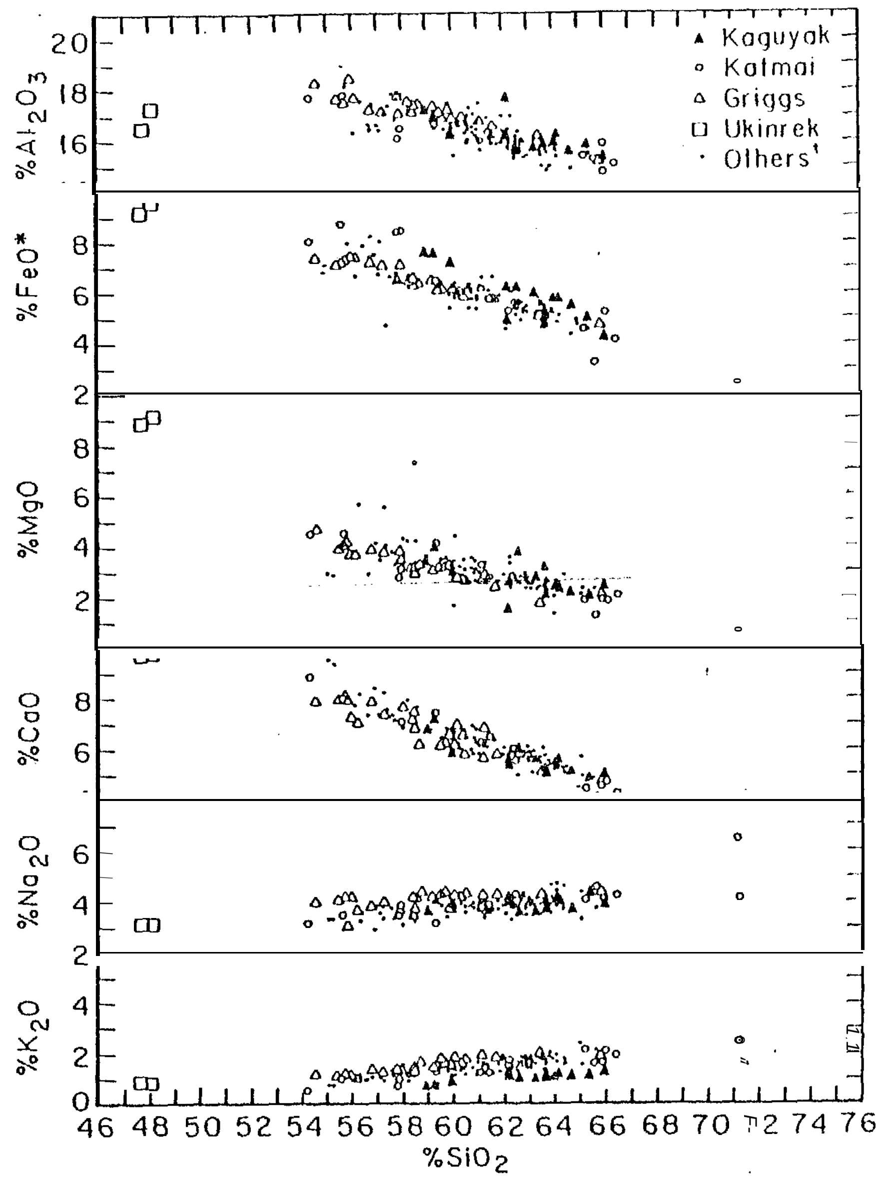

ANIAKCHAK
YANTARNI
CHIGINIGAK
KIALAGVIK
PEULIK/
UKINREK
KEJULIK
MARTIN
MAGEIK
TRIDENT/
NOVARUPTA
KATMAI
GRIGGS
SNOWY
DENISON
STELLAR
KUKAK
DEVILS DESK
KAGUYAK
FOURPEAKED
DOUGLAS
D'
E
AUGUSTINE
ILIAMNA
REDOUBT
DEPTH (KM)
0
100
200
1938 RUPTURE
ZONE
1964 RUPTURE ZONE
100
200
300
DISTANCE (KM)
0
100
200
DISTANCE (KM)


Study Area
Hayes
Spurr
ANCHORAGE
KENAI
Kenai Peninsula
COOK
Redoubt
Iliamna
Cook Inlet
HOMER
Augustine
KATMAI
Douglas
Fourpeaked
Kaguyak
Kukak
Devils Desk
Denison
Griggs
Novarupta
Snowy
Mageik
Martin
Trident
Katmai
Kejulik
Shelikof Strait
Bristol
Bay
Ukinrek
Peulik
Ugashik
150km
Kodiak
Kialagvik
Chiginagak
Yantarni
Aniakchak
50km
100km
LAVA TYPE
Predominantly Andesite
Predominantly Dacite
Basalt to Rhyolite
Basalt

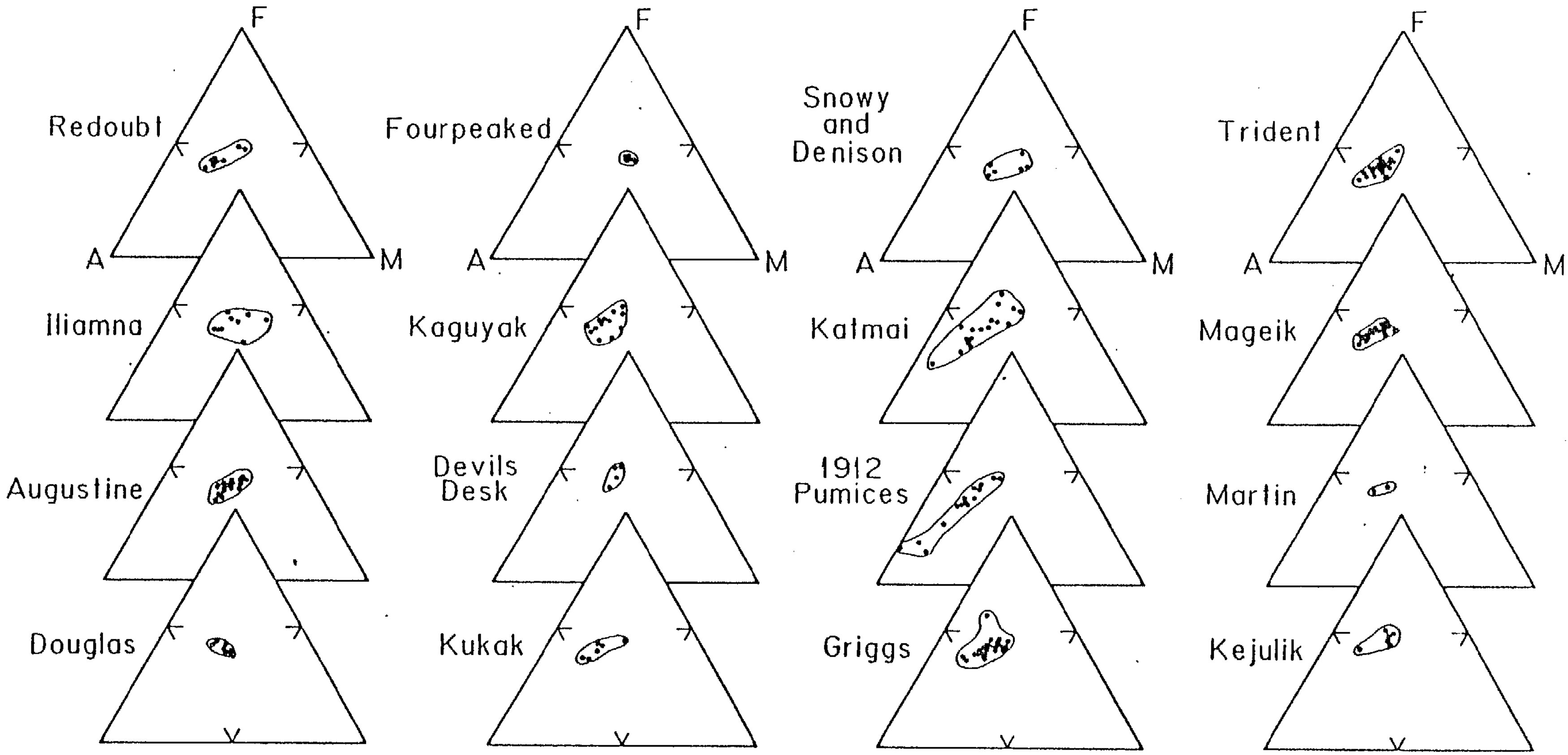

156°
155°
KAMISHAK BAY
59°
58°
156°
KATMAI BAY
0 10 20 KM

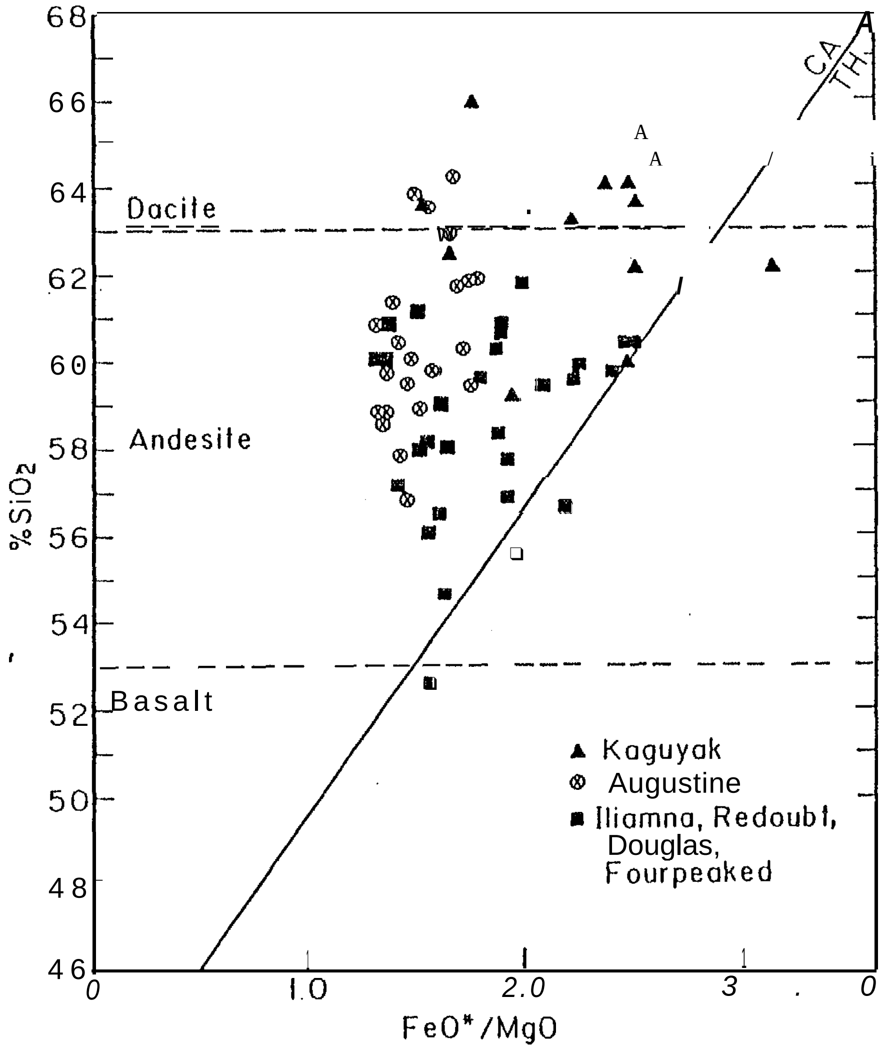

NW
OBSERVED
COMPUTED
SE
ANOMALY, MGAL
20
10
0
-10
-20
-30
CRUSTAL SECTION
Bruin Bay Fault
Volcanic Range
Cape Gull
Lake Grosvenor
Shelikof Strait 1.03
Tv 2.78
Jnch + Jn 2.56
2.46
QTv 2.78
2.67
2.91
DEPTH, KM
0
5
10
15
20
25
0 10 20 KM



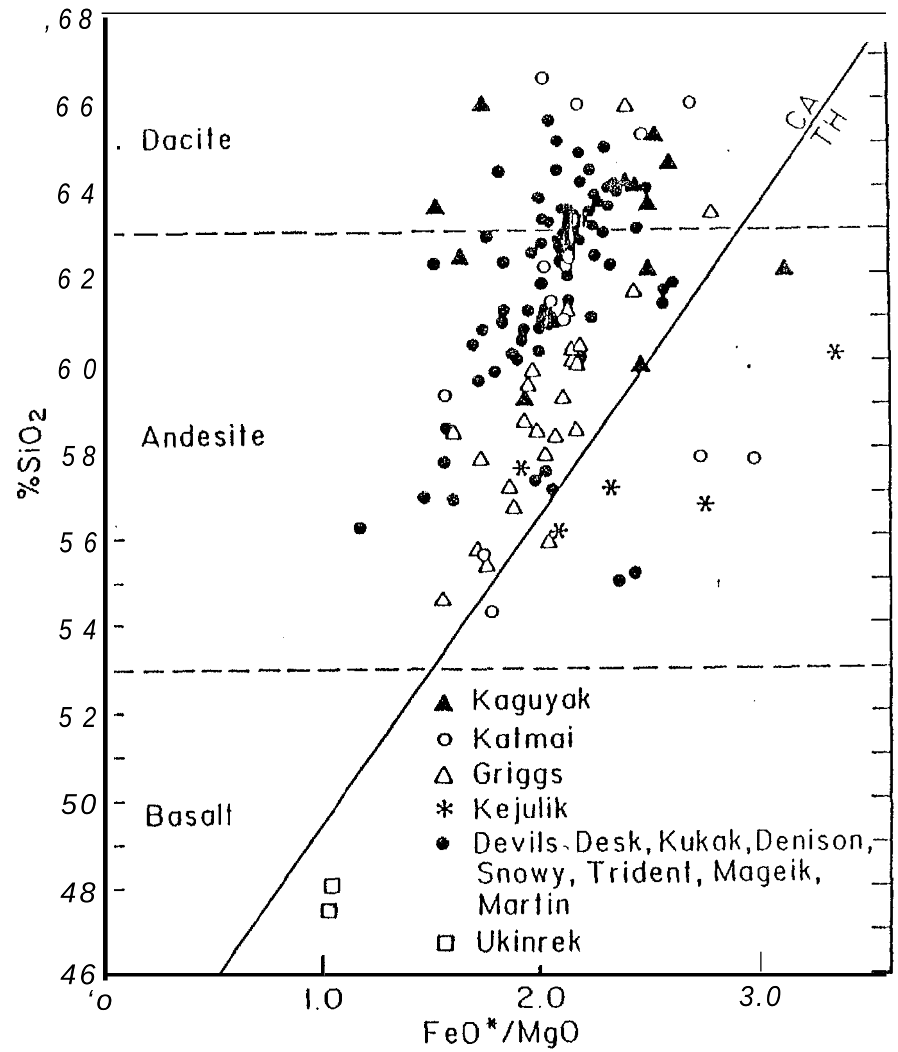


[1]Others: Devils Desk, Kukak, Denison, Snowy, Trident, Mageik, Martin

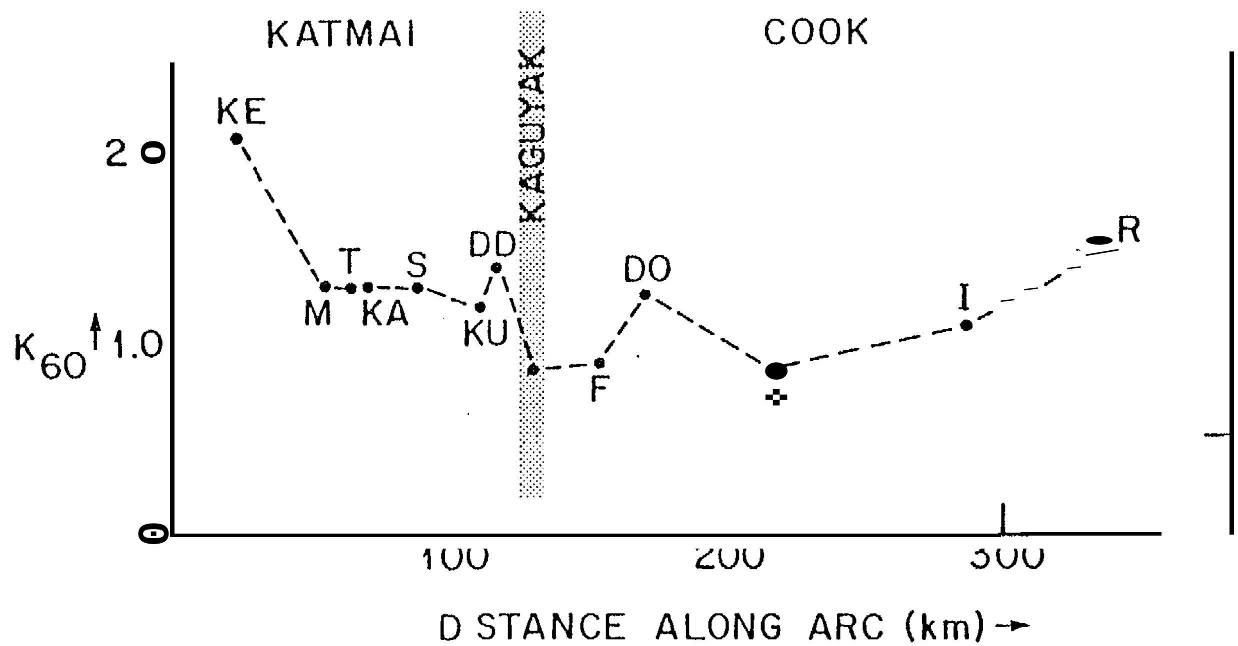

F
A
M
Redoubt
Iliamna
Augustine
Douglas
Fourpeaked
Kaguyak
Devils Desk
Kukak
Snowy and Denison
Katmai
1912 Pumices
Griggs
Trident
Mageik
Martin
Kejulik

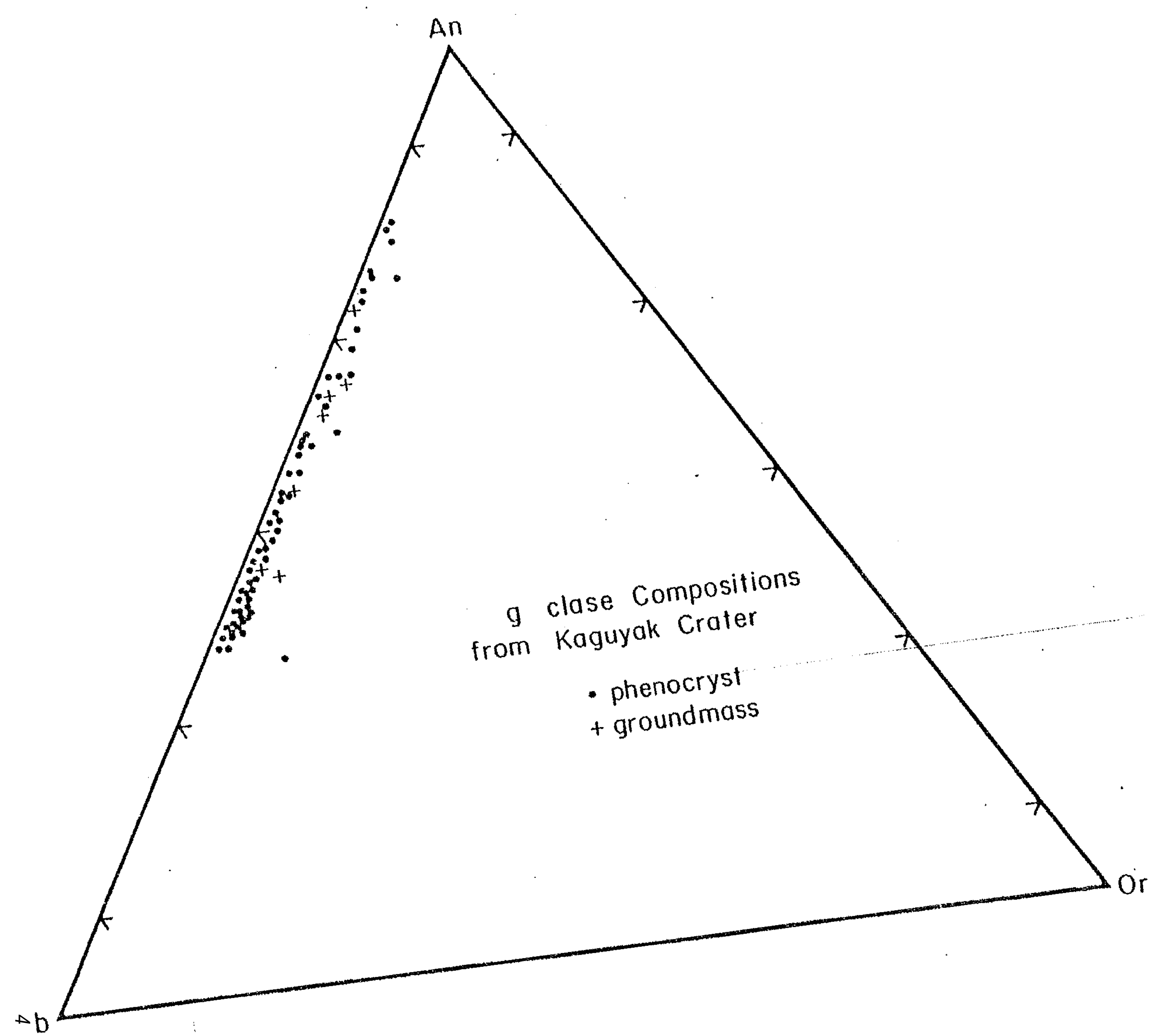


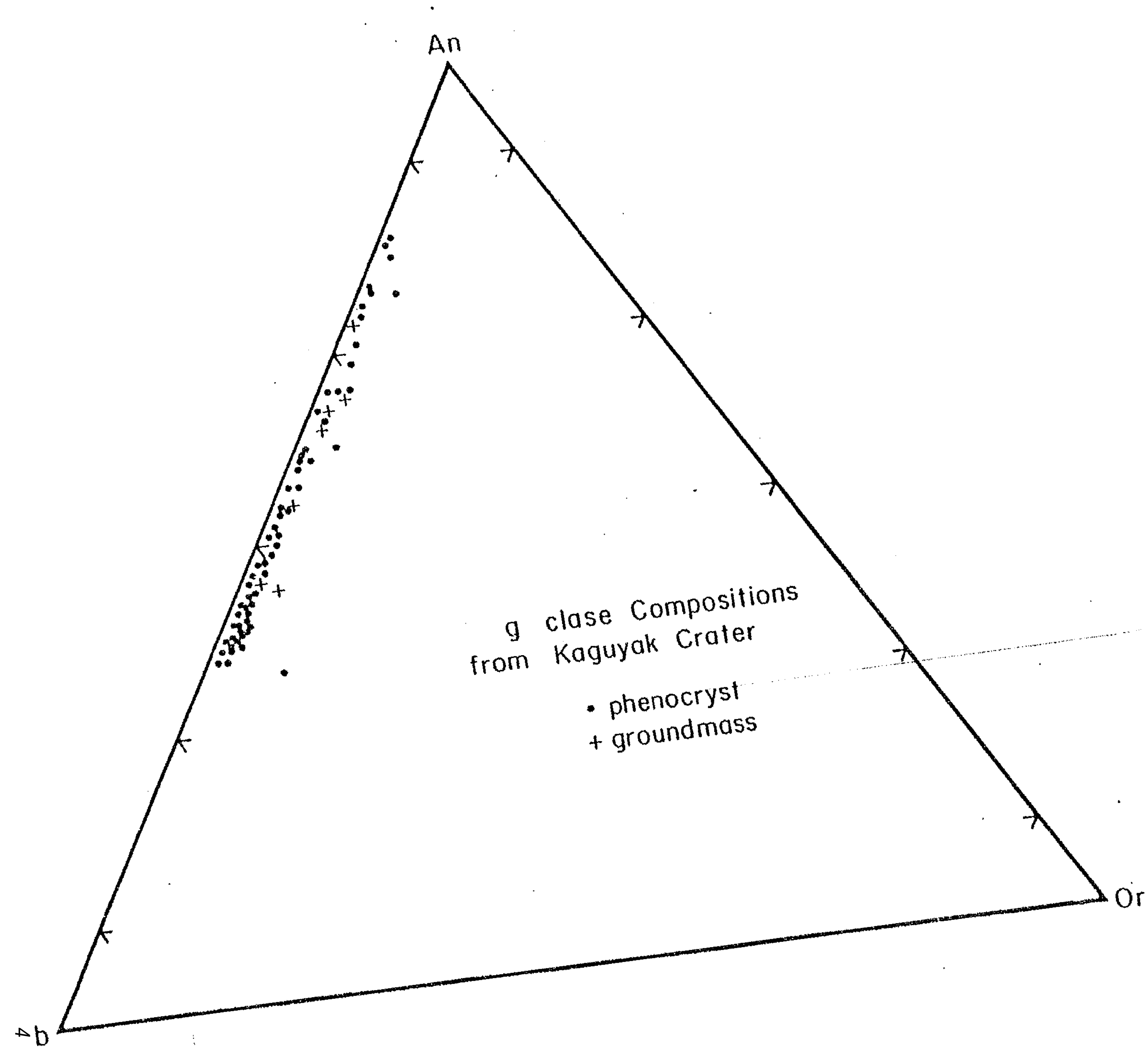
CA
TH
Dacite
Andesite
Basalt
%SiO2
FeO*/MgO
Kaguyak
Augustine
Iliamna, Redoubt, Douglas, Fourpeaked



CA
TH
Dacite
Andesite
Basalt
%SiO2
FeO*/MgO
Kaguyak
Katmai
Griggs
Kejulik
Devils, Desk, Kukak, Denison, Snowy, Trident, Mageik, Martin
Ukinrek


KATMAI
COOK
KAGUYAK
KE
M
T
KA
S
KU
DD
F
DO
I
R
2 0
1.0
0
100
200
300
K60
D STANCE ALONG ARC (km)


An
Or
b
g clase Compositions
from Kaguyak Crater
• phenocryst
+ groundmass


An
Or
b
g clase Compositions
from Kaguyak Crater
• phenocryst
+ groundmass