ORIGIN OF CORUNDUM IN BASALT

by

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Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Geology

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

Socorro, New Mexico

May, 1975

TABLE OF CONTENTS

	Page
ABSTRACT	v
ACKNOWLEDGEMENT	vii
I. INTRODUCTION	1
II. GEOGRAPHIC DISTRIBUTION	4
A. Basalt	4
B. Corundum in Rocks other than Basalt	15
C. Corundum in Basalt	21
III. GEOLOGIC OCCURRENCES	26
A. Corundum in Rocks other than Basalt	26
B. Corundum in Basalt	37
C. Summary of Geologic Occurrences	62
IV. STRUCTURE, FABRIC AND MINERALOGICAL COMPOSITION OF CORUNDUM-BEARING BASALTS AND RELATED ROCKS	64
A. Host Rock	64
B. Xenocrysts, Xenoliths and Megacrysts	70
V. GEOCHEMISTRY OF CORUNDUM-BEARING BASALTS	82
VI. DEPTH OF ORIGIN OF ALKALINE BASALTS CONTAINING MEGACRYSTS AND MAFIC XENOLITHS	97
VII. ORIGIN OF CORUNDUM IN BASALT	103
VIII. ENUMERATION OF PROBLEMS IN SOLVING THE ORIGIN OF CORUNDUM IN BASALT	122
IX. SUMMARY AND CONCLUSIONS	125
X. SUGGESTIONS FOR FURTHER INVESTIGATION	127
REFERENCES	129
APPENDIX	141
Appendix 1. Some corundum occurrences in the world exclusive of basalts	142
Appendix 2. The occurrences of corundum in basalts and related rocks of the world	149

Appendix 3. Chemical Composition of Basalts from Thailand. 155

Appendix 4. Calculated oxide of basalts from Thailand. 157

Appendix 5. Chemical composition of basalts from other areas of the world. 161

Appendix 6. Calculated oxide of basalt from other areas of the world. 162

Appendix 7. Chemical analyses of clinopyroxene from Thailand and other areas. 164

TABLE OF ILLUSTRATIONS

		Page
Figure 1.	Map showing some localities of basaltic Islands in the Pacific Ocean	5
Figure 2.	Map showing some localities of basaltic Islands in the Atlantic Ocean	6
Figure 3.	A plot of K_2O-SiO_2 for oceanic basalts	13
Figure 4.	General map showing location of corundum deposits in the United States	16
Figure 5.	Map showing the gemstone localities and zones of sapphire and ruby of eastern (southeastern Thailand)	22
Figure 6.	Map of eastern North America showing the distribution of peridotite and corundum	27
Figure 7.	Ideal cross-section of a peripheral or border vein of corundum at Corundum Hill mine, Macon county, North Carolina	29
Figure 8.	Ideal cross-section of an interior vein of corundum at Corundum Hill mine, Macon county, North Carolina	30
Figure 9.	Index map showing location of Montana corundum deposits	32
Figure 10.	Map of Thailand showing distribution of basalt	38
Figure 11.	Locality map, New England District, New South Wales, showing outcrops of Tertiary basalt	54
Figure 12.	A plot of $(Na_2O + K_2O)$-Al_2O_3 and (Na_2O+K_2O)-SiO_2 of corundum-bearing basalts from Thailand	83
Figure 13.	A plot of $(Na_2O + K_2O)$-SiO_2 of corundum-bearing basalts and corundumless basalts from Thailand	86
Figure 14.	A plot of MFA diagram showing corundum-bearing and corundumless basaltic fields from Thailand	87

Page

Figure 15. Showing reaction rim between garnet and basalt from Ban Nong Bon, Trat province, Thailand 91

Figure 16. Showing reaction rim between garnet and basalt from Ban Nong Bon, Trat province, Thailand 92

Figure 17. Showing oxide content (from electron microprobe analysis) in alteration zone between garnet and basalt from Thailand 93

Figure 18. Interpreted conditions of formation for suites of ultramafic xenoliths from alkaline basalts and kimberlite 101

Figure 19. Diagram showing path of rising of alkali olivine basaltic magma 113

Figure 20. A plot of mole proportion of MgO-SiO_2-Al_2O_3 in a modal basalt system showing how basaltic magma increases in Al_2O_3 with relatively constant SiO_2 content 115

Figure 21. Showing the equilibrium curve of kyanite= corundum + quartz intersects liquidus curve of alkali olivine basalt 118

Figure 22. Showing the equilibrium curve of kyanite = corundum + quartz intersects liquidus curve of eclogite 119

ABSTRACT

Corundum in basalt has been found in Thailand, Cambodia, Australia, Germany, France, Hungary, Madagascar, Scotland and Nigeria. The rocks from the first three countries yield large quantities of corundum and also good gem quality whereas those from the last six countries yield only a minor amount of corundum.

The chemical and mineralogical composition of corundum-bearing basalts indicates that alkaline basalt is the most common type that contains corundum, especially alkali olivine basalt. Corundum-bearing tholeiitic basalt is uncommon.

Corundum-bearing basalts are often characterized by lower silica, higher iron and rather higher titanium content as compared to tholeiite. The rocks are generally dark, dense and have fine-grained or glassy groundmass. Dunite, peridotite and pyroxenite xenoliths are commonly found in the areas of corundum-bearing basaltic terrains.

Corundum is usually found in alluvial deposits in or near basaltic terrains. The most commonly associated minerals in alluvial deposits are spinel, sodic plagioclase, olivine, aluminous clinopyroxene, zircon, ilmenite, pyropic garnet, and less commonly biotite. From the evidence of mineralogical characteristics of the associated minerals, they have been interpreted as megacrysts which form at high pressure and temperature.

The available data indicate that corundum could crystallize in the lower crust or upper mantle from basaltic magma generated at depths of approximately 35-70 km by partial melting of mantle materials and then could move to depths of approximately 25-30 km. Fractionation processes result in increasing the Al_2O_3 content while SiO_2 content remains constant. Magma must be kept in a holding chamber long enough for large crystals of corundum to crystallize and then be erupted to the surface and quenched.

ACKNOWLEDGEMENT

This study was initiated at the suggestion of Dr. Payome Aranyakanon of the Department of Mineral Resources, Bangkok, Thailand. The author expresses his sincere thanks to Dr. Jacques R. Renault who served as his advisor on this study and made many valuable contributions to the investigation. Deeply appreciated is the assistance of Dr. Richard E. Beane and Dr. Marshall A. Reiter of the Geoscience Department and Dr. Clifford R. Keizer of the Chemistry Department.

A deep feeling of appreciation and gratitude is also extended to Dr. Payome Aranyakanon of the Department of Mineral Resources, Bangkok, Thailand, who kindly provided valuable data and offered valuable suggestions.

Dr. N. L. Markham, Director of the Geological Survey of New South Wales, and Dr. J. T. Woods, Chief Government Geologist of the Geological Survey of Queensland, Australia, kindly provided much useful information on corundum deposits in New South Wales and in Queensland, Australia.

Acknowledgement is also made to Mrs. Lynn A. Brandvold and Mr. Joseph Taggart of the Bureau of Mines and Mineral Resources for willingly giving their time to analyze the samples of garnet and pyroxene.

Very special thanks go to Mrs. Oragool Onsuwan, Miss Theeranee Poonwiwat, Mr. Wichai Kokcharoensup, Mr. Somsak Pothisat and Mr. Piphop Wasuwanich of the Department of

Mineral Resources, Bangkok, Thailand, for their assistance in providing some valuable data from Thailand.

The author is further grateful to the Department of Mineral Resources, Bangkok, Thailand, for financial support during his study in the U.S.A.

The author also wishes to thank Jill Collis for typing the report.

I. INTRODUCTION

Basalts are extrusive igneous rock which consist principally of plagioclase and clinopyroxene. They may carry olivine, nepheline, melilite, hypersthene, or quartz, as well as other minor phases (Yoder and Tilly, 1962).

Corundum* is a type oxide of aluminum and is included in the hematite group. It generally contains 52.91% of aluminum and 47.09% of oxygen. Corundum is characterized by its great hardness (H=9), high luster (adamantine), high specific gravity (3.99-4.08), and basal parting ({0001}). Corundum is found in various colours, ranging from red, blue and green or various shades of these colours to colourless.

Corundum is found to occur in many rock types such as nepheline syenite, syenite, gabbro, schist, and gneiss. Basalt is not a common rock in which corundum has been found. Thailand, Australia, Cambodia, Scotland, Germany, France, Nigeria and Austria-Hungary are the countries that have corundum in basaltic terrains. The first three countries exclusively yield high concentrations of corundum from weathered basalts.

In Thailand and Australia, corundum is found as a product of weathering and erosion in or near basaltic terrains, but corundum in fresh basaltic rocks is extremely

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* The word "corundum" in this report refers to all types of corundum including emery and gem quality, sapphire and ruby; unless otherwise specified.

rare. Sapphires embedded in basalt boulders have been reported from Australia (MacNevin, 1971, 1972) and Thailand, but never found in outcrops.

Very few data concerning the genesis of corundum in basalts are available. Some of the authors (for example: Thomas and Radley, 1922 and MacNevin, 1971, 1972) report that the crystals of corundum are of xenolithic or xenocrystic origin. Mathias and others (1970) reported corundum-bearing ultramafic xenoliths in kimberlites of Lesotho, Rhodesia in South Africa and Tanzania. Corundum is found in the eclogite association. Wright (1971, 1972) and Irving (1974) mentioned that corundum, spinel, garnet, diopside, ilmenite, and zircon are found as megacrysts in association with alkaline or alkali olivine basaltic rocks.

In Thailand, large grains of clinopyroxene, sodic feldspar, magnetite, spinel and garnet are found in alluvial deposits associated with corundum in basaltic terrains. The unusually large crystals of these minerals have been accepted as megacrysts and widely interpreted as high pressure minerals formed in the deep crust or the upper mantle (for example: Wilshire and Binns, 1961; Green and Ringwood, 1967; Green and others, 1968; Binns, 1969; Kutolin and Frolova, 1970; Wright, 1971, 1972; MacGregor, 1974 and Irving, 1974).

From the above discussion, it can be seen that corundum which is found in basalts may be (1) of xenocrystic or xenolithic origin and (2) of high pressure cognate origin as megacrysts which suggest source in the deep level (deep crust or upper mantle). The genesis of corundum in basalt still needs to be solved especially in Thailand.

The purpose of this study is to determine the genetic relationship of corundum to basalt. The result of this study may be useful in prospecting for corundum in the future especially in Thailand.

In the absence of rock investigation, this report attempts to bring together the pertinent geographical, geological and geochemical data in the literature in order to define the conditions under which basalt and corundum can occur together.

The method of solving the problem is to study, (1) the geographic distribution, (2) the geologic occurrence, (3) the petrology, and (4) the physical chemistry of corundum and basalt as reported in the literature. A review of the results of this study and a brief statement interpreting possible genesis of corundum in basalt are presented in the following chapters.

II. GEOGRAPHIC DISTRIBUTION IN THE WORLD

A. Basalts

Basalts are the most abundant and widely distributed of volcanic rocks and are members of all typical volcanic associations (Turner and Verhoogen, 1951). Among the extrusives, basalt probably has at least five times the total volume of all the other extrusives combined. Basalt and pyroxene andesite together have at least fifty times the volume of all other extrusives combined (Daly, 1933). In this study, basaltic provinces will be summarized briefly into two types, one as oceanic basalt and the other as continental basalt.

1. Oceanic basalt

Oceanic basalt occurs in the volcanic associations of three regions: the intra-Pacific, the Atlantic and the Indian ocean provinces.

In the intra-Pacific province, there are two typical regions, the Hawaiian Islands and Tahiti. Other intra-Pacific islands are Maquesas, Austral, Samoa, Galapagos, Easter, anc Cocos islands. Some of these islands are shown in figure 1.

In the Atlantic province, major islands that have an occurrence of basaltic rock are found along or near the Mid-Atlantic Ridge such as Saint Helena, Ascension, Gough, Azores and Bouvet etc. Some of these islands are shown in figure 2.

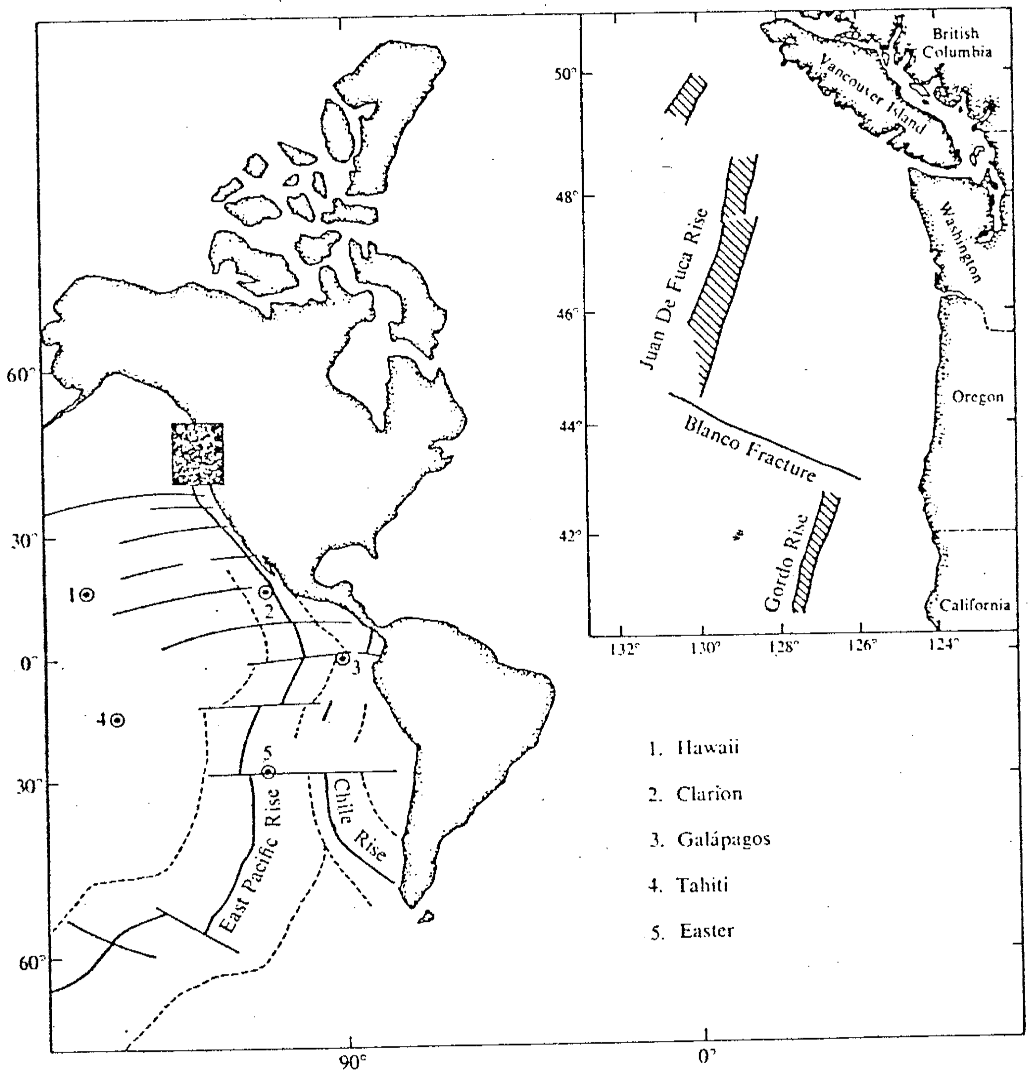


Figure 1. Map showing some localities of basaltic Islands in Pacific ocean. After Carmichael and others, 1974.

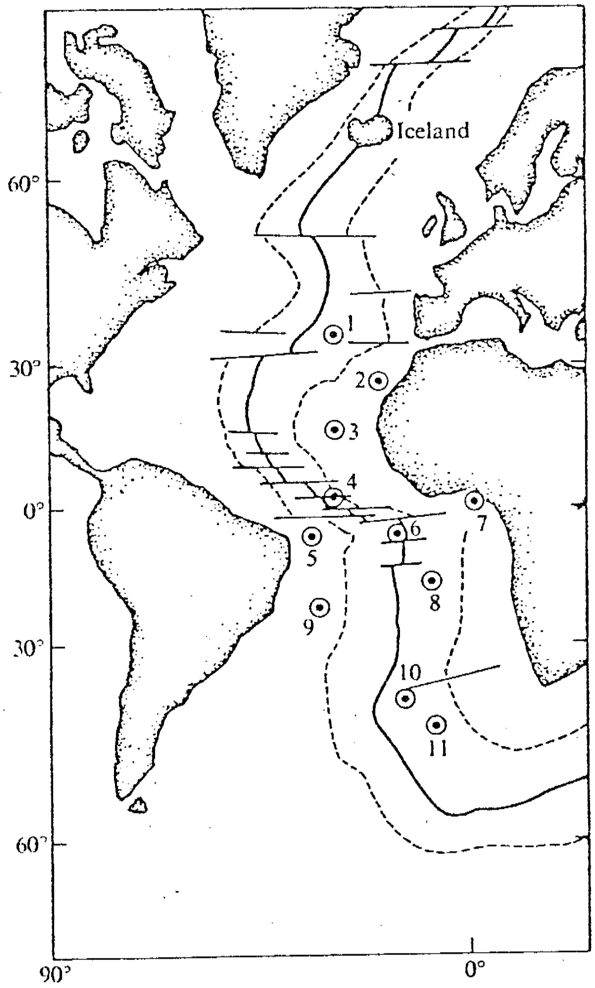


Figure 2. Mid-Atlantic ridge (outer borders dashed) and Atlantic islands: (1) Azores; (2) Canaries; (3) Cape Verde; (4) St. Paul's Rocks; (5) Fernando de Noronha; (6) Ascension; (7) Gulf of Guinea; (8) St. Helena; (9) Trinidade; (10) Tristan da Cunha; (11) Gough. After Carmichael and others, 1974.

Several volcanic basaltic islands situated in the Indian Ocean are reported from Kerguelen archipelago, Mauritius, Rodriquez, Réunion, Possesion and Heard. The Kerguelen archipelago is the largest of several volcanic island groups, situated in the southern Indian ocean.

The basaltic rocks of the three provinces seem to cover a wide range of composition. Alkaline basaltic magma seems to be most widespread. Olivine tholeiite dominates in some provinces such as Hawaii and Iceland (Carmichael and others, 1974).

Kuno (1960) classified all rocks from oceanic islands as alkaline basalt, except the Hawaiian Islands which are composed both of tholeiitic and alkalic basalts. Some alkali olivine basalt associations in the Pacific, Atlantic, and Indian oceans are shown in Table 1.

Basalts are found not only on the oceanic islands, but also in the deeper parts of the three oceans. Barth (1962) estimated that basaltic rocks from ocean basins occupy an area of one-half the total surface of the earth. According to Engel and others (1965), the distinctive basalt is the principal igneous rock encrusting the deeper parts of the oceans. They mentioned that "Tholeiitic basalts appear to exist in great volume in the ocean: along scarplike ridges of oceanic rift zones where diabasic textures are well developed; on the deeper flanks of the vast oceanic ridge and rise system; in the large Hawaiian and Icelandic archipelagic aprons; in deep oceanic trenches;

TABLE 1. Some alkali olivine basalt associations

Locality	Principal basaltic rocks
PACIFIC OCEAN	
Hawaiian Islands	Alkali olivine basalt, nepheline basanite, olivine nephelinite, olivine melilite nephelinite
Samoan Islands	Olivine basalt; "some picritic basalts"
Tahiti	Dominantly basanites, with subordinate ankaramites and oceanites
Ponape	Alkali olivine basalt, nepheline basanite, olivine nephelinite
Iki Islands (Japan)	"Trachybasalt"
Tasmania	Alkali olivine basalt, limburgite, nepheline basanite, olivine nephelinite, olivine melilite
Victoria	Alkali olivine basalt, limburgite, olivine nephelinite
North-east New South Wales	Alkali olivine basalt, analcime basanite, olivine analcimeite, nepheline basanite, olivine nephelinite, ankaramite
North Island, New Zealand	Alkali olivine basalt, augite-rich picrite basalt, nepheline basanite
South Island, New Zealand	Alkali olivine basalt, ankaramite, limburgite, nepheline basanite, olivine nephelinite
INDIAN OCEAN	
Mauritius	Alkali olivine basalt, grading into oceanite and ankaramite
Kerguelen Archipelago	Alkali olivine basalt, nepheline basanites, analcime basanites

TABLE 1 (continued)

Locality	Principal basaltic rocks
INDIAN OCEAN (cont.)	
Possession Island	"Limburgite basalt"
Heard Island	Olivine basalt, limburgite
ATLANTIC OCEAN	
Gough Island	Alkali picrite basalt, alkali olivine basalt
Ascension Island	Olivine basalt
Saint Helena	Olivine basalt

After Wilkinson, 1967

and as sill(?) beneath the abyssal sea floor as cored in the Experimental Mohole, Guadalupe Site."

2. Continental basalt

Basalts are the most voluminous continental lavas, and the most extensive of these basalts are tholeiitic (Carmichael and others, 1974). In general, three basaltic types; alkaline, tholeiite and high alumina, are reported from many areas of the nonorogenic and orogenic continental regions. According to Kuno (1969), tholeiite is a type of basalt, comparatively high in SiO_2 and low in alkalies ($Na_2O + K_2O$); alkali olivine basalt is comparatively low in SiO_2 and high in alkalies; and high alumina basalt is intermediate between the two types in SiO_2 and alkalies but higher in Al_2O_3 (>16.5%).

Alkaline basalts are reported from many areas such as in the western part of the United States (e.g. from Nye County, Nevada; Upper Cenozoic basaltic rocks in and near the northern Rio Grande depression, Southern Colorado and Northern New Mexico; Davis Mts., west Texas, San Juan Mts., Colorado and San Quintin, Baja California) by Vitaliano and Harvey (1965); Lipman (1969); Bacon and Carmichael (1973); and Schwarzer and Rogers (1974); at Minusa and Trans baikalian regions in Siberia, USSR (Kutolin and Frolova, 1970); in the Tertiary volcanic provinces of Eastern Australia (Wilkinson, 1966; Green and Ringwood, 1967); from Afar in Ethiopia; Central Kenya; Kenya Rift valley; Scotland Tertiary province and Hebrides; Southern Arabia and Dariganga in Mongolia etc. (Schwarzer and

Rogers, 1974) and also from Nigeria's Cenozoic volcanic province in Nigeria (Wright, 1971).

Tholeiite is by far the most common basalt among the Plateau or flood basalts. The two largest plateau basalt units are the Deccan plateau of western India and the Columbia-Snake River plains of Northwestern U.S.A. (Turner and Verhoogen, 1960; Kuno, 1969). Other examples are the Keweenawan lavas of Lake Superior, the Stormberg lavas of South Africa, the Parana' basalts of South America (southern Brazil and Uruguay), the basalt lavas associated with Karroo dolerite sills in New Jersey, Tunguska basin in Siberia, lavas of northern Michigan and Minnesota, basalt of Lesotho, Rhodesia in South Africa and Tertiary basalts in Western Australia (Turner and Verhoogen, 1960; Kuno, 1969; Hyndman, 1972; Carmichael and others, 1974). Tholeiite is also reported from Scotland in the Non-Porphyritic Central Magma Type, and basalt of Iceland, the Faeroes, Greenland and at New Zealand (Kuno, 1960, 1966).

High alumina basalt is reported from the southern Cascade Range in the western United States, Mexico, Japan, Manchuria, Taiwan, and Greenland (Kuno, 1960, 1966). It is said to be absent from the plateau basalts (Kuno, 1969). However, they are reported from the plateau south of Tung-ning, eastern Manchuria-Soviet border and Modoc basalt, Medicine Lake Highland, northern California of the eastern Oregon plateau province (Kuno, 1969; Carmichael and others, 1974).

According to Kuno (1969), there is a complete gradation from tholeiite to alkali olivine basalt among the plateau basalt. For example, the plateau basalts of western Scotland and Southern Vietnam, the Columbia River (transition occurs in the lower part - the Picture Gorge basalt), the Deccan and the Brito-Arctic Province (Kuno, 1960, 1969; Turner and Verhoogen, 1960; Hyndman, 1972). In the Huzi volcanic zone, Japan, Kuno (1960) classified basalts into three types: tholeiite with low Al_2O_3 and alkalis; alkaline basalt with variable Al_2O_3 and higher alkalis; and high alumina basalt with higher Al_2O_3 and intermediate alkalis.

In comparison, the continental basalt is distinguishable from oceanic basalt by their high potassium content (Engel and others, 1965). The average K_2O content of oceanic tholeiite is about 0.2 but most continental tholeiites contain more than 0.5 weight per cent K_2O and the average is almost 0.9 (see figure 3). According to them, most continental tholeiites contain more Si, K, Ba, Cs, Pb, Rb, Sr, Th, U, and Zn, as well as generally higher ratios of Sr^{87}/Sr^{86} and Pb^{206}/Pb^{204} than do the oceanic tholeiites.

Basalts in general, are characterized by mafic or ultramafic xenoliths. Spinel peridotite or lherzolite is the most common among the xenoliths (inclusions) in basalts and is very similar in mineral composition, structure and mineral content everywhere in the world (for example: Ross and others, 1954; Kutolin and Frolova, 1970). Other xenoliths in alkaline basaltic types or

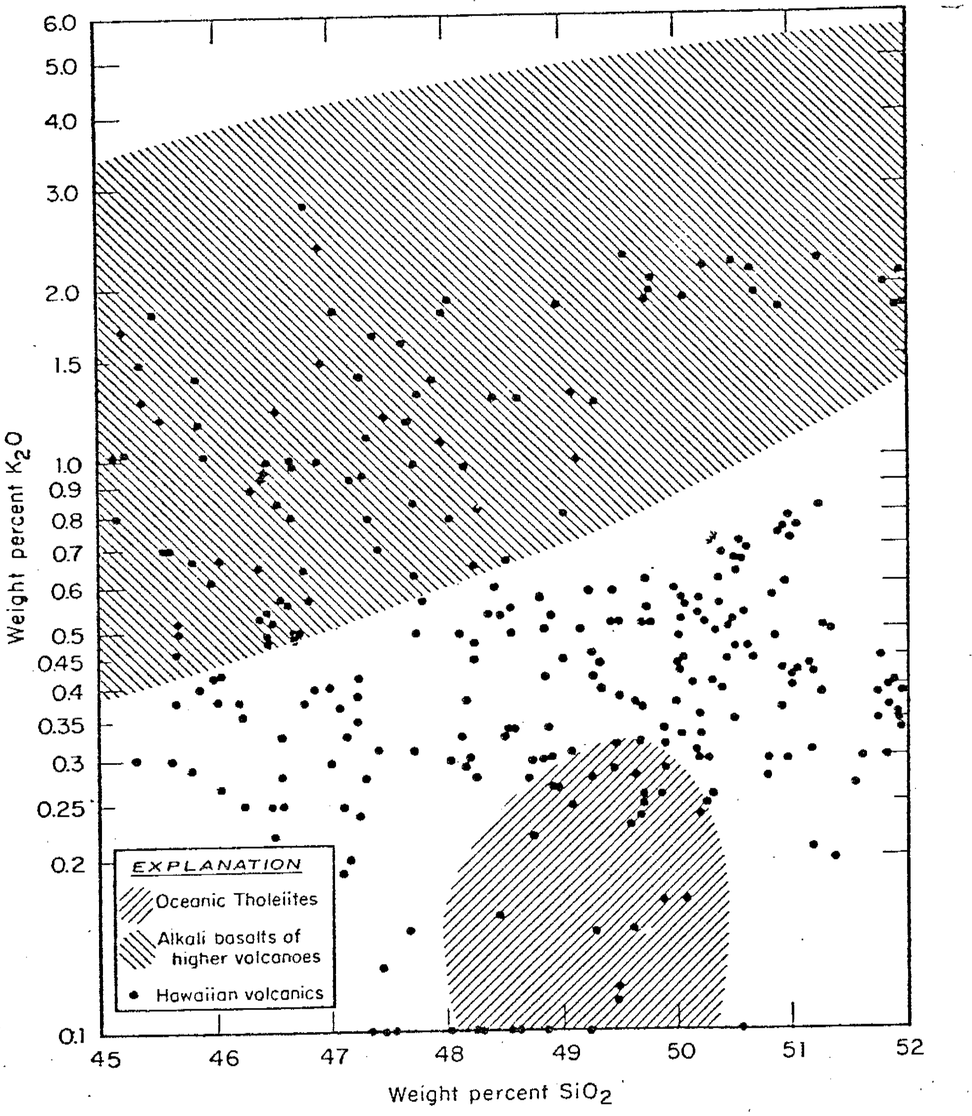


Figure 3. A plot of K_2O-SiO_2 for oceanic basalts. After Engel and others, 1965.

related rocks are pyroxenite, gabbro, dunite and sometimes eclogite and so forth (Kuno, 1969; Wilshire and Binns, 1961; Green and Ringwood, 1967; Green and others, 1968; Aoki, 1968; Macgregor, 1968, 1974; Binns, 1969; Kutolin and Frolova, 1970). Tholeiite generally contains gabbro zenoliths. Peridotite is reported by Kuno (1959) to be absent in this rock. Recently, it was noted by Sutherland (1974) that the spinel lherzolite xenoliths are found in olivine tholeiite from the Tasmanian Tertiary volcanic province. Mafic and ultramafic xenoliths have been widely interpreted to originate in the upper mantle (for example: Wilshire and Binns, 1961; Green and Ringwood, 1967; Green and others, 1968; Macgregor, 1968, 1974; Kutolin and Frolova, 1970; Bacon and Carmichael, 1973; Wilkinson, 1973; and Sutherland, 1974).

Megacrysts or high pressure phenocrysts are reported to be found in basalts by many authors (Wilshire and Binns, 1961; Vitaliano and Harvey, 1965; Binns, 1969; Binns and others, 1970; Bacon and Carmichael, 1973; Wilkinson, 1973; Carmichael and others, 1974; Irving, 1974). Megacrysts of tschermakitic clinopyroxene, aluminous orthopyroxene, kaersutitic amphibole, sodic feldspar, olivine, spinel, and titanomagnetite are widely found in association with alkaline basaltic rocks. More rarely pyropic garnet, ferromagnesian mica, apatite, zircon and corundum are found. Such megacrysts have been interpreted by many authors (Irving, 1974) as phase crystallized at high pressure. The detail of mafic and ultramafic xenoliths and megacrysts will be discussed later (pages 97-102).

B. Corundum in Rocks other than Basalt

Corundum deposits have been found in many places in the world, such as in the United States and Canada (Pratt, 1901, 1906; Pratt and Lewis, 1905; Barlow, 1915; Clabaugh, 1952; Carlson, 1957; Bauer, 1968; Lang and others, 1970 and Richter, 1970), Southern Africa and Madagascar (Barlow, 1915; Kun, 1965), Burma, Ceylon, Australia, Japan, Afghanistan, India, England, Norway, Sweden, Finland, Switzerland, Italy, Germany, Naxos, Samos and other Greek islands, France, Portugal, Spain, Eastern Europe, Russia, Mexico, Turkey and Greenland etc. (Barlow, 1915; Palache and others, 1946; Wells, 1955; Oliver and Jones, 1965; Sinkankas, 1967; MacNevin, 1972).

1. U.S.A. and Canada

Many corundum localities in the United States, such as in Montana, Alabama, Georgia, North Carolina, New York and so forth have been reported by Pratt (1901, 1906); Pirsson (1897); Pratt and Lewis (1905) and Clabaugh (1952). See figure 4. It can be seen that all varieties of corundum that are found in the United States, are especially abundant in two particular regions, namely the eastern and western parts of the country.

In the eastern part, corundum occurs throughout the Appalachian belt from Alabama to New York (see figures 4 and 6). In the western part, corundum is found in Montana, Colorado, Nevada, Utah and California (Pratt, 1901, 1906; Pratt and Lewis, 1905; Clabaugh, 1952; Bauer, 1968). A corundum

CATION OF CORUNDUM DEPOSITS IN THE UNITED STATES. (After Pratt, 1906) occurrence in the eastern Alaska Range, Alaska is reported by Richter (1970).

In the southern portion of the Appalachian belt (North Carolina and Georgia), the greatest quantity of corundum has been found (Pratt and Lewis, 1905; Bauer, 1968), for example in Michell, Madison, Buncombe, Haywood, Jackson, Macon, Clay and Burke counties in North Carolina. Almost all the precious corundum of various colors (blue, green, yellow and red) found in this region come from Macon and Jackson counties in North Carolina (Pratt and Lewis, 1905; Bauer, 1968). Pine Mountain, Rabun county in Georgia, is perhaps the most famous corundum mine in this country; good quality commercial corundum has been obtained from this area (Pratt and Lewis, 1905).

Emery deposits have been worked at Chester, Massachusetts. Large deposits of emery are at the neighborhood of Peekskill, Westchester county, New York (Palache and others, 1946).

In the western part of the U.S.A., the region especially rich in precious corundum is at Yogo Gulch, Fergus county in Montana (Pratt and Lewis, 1905; Clabaugh, 1952; Bauer, 1968). Blue sapphire is reported from this area.

In Canada, corundum is found in Ontario, especially at Craigmont, Raglan Township, and Renfrew county. The other deposits are found at Bancroft, Hastings county, and Bathurst Township, and Lanark county (Palache and others, 1946). According to Barlow (1915), corundum in Ontario, Canada appears to be included in three distinct belts which are the Northern, the Middle and the Southern belts.

The largest or Northern belt is a somewhat sinuous belt having a general northeasterly strike which extends from the Township of Lutterworth to the Township of South Algona. This represents a distance of about 103 miles with a maximum width of nearly 6 miles.

The Methuen-Burleigh or the Middle belt extends from the Township of Burleigh to the Township of Methuen in the NE-SW direction. The total length is more than 8.5 miles.

The Lanark-Frontenac or Southern belt extends in the same direction as the first two belts for a distance of about 12 miles, reaching from the northeast corner of the Township of Hinchinbrooke, across the southeast corner of Oso Township, Frontenac county, and into the Township of South Sherbrooke in Lanark county.

2. Asia and Africa

In Burma, ruby and sapphire are found in the district around Mogok, in the neighborhood of Sagyin, and at a place further north of Mogok, near the village of Nanyetseik, between Mogaung and the jadeite mines of Sanka. Another locality is also found on the Upper Irrawaddy. In all of these localities, sapphire is found to a minor extent (Bauer, 1968).

In Ceylon, the regions which are especially rich in corundum are Ratanapura, Rakwana and the district at the foot of Adam's Peak (Wells, 1955; Bauer, 1968). Pratt (1906) also reported corundum deposits at Balangoda. Another important locality where sapphires in large numbers have been found, is the Zanskar range of Kashmir, in the north-west Himalayas. Rubies have been found at Jagdalak, Afghanistan (Palache and others, 1946; Bauer, 1968).

Corundum in Asia is also reported from Kinta district at Perak in Malaysia; from Kwangtung in China; Onogori in Bungo in Japan; near Mambulao and Paracale in the Philippines (Barlow, 1915).

In Southern Rhodesia, five corundum areas can be distinguished (Kun, 1965): 1) the Mazoe drainage in the northeastern corner of the country, extending into the Tete district of Mozambique; 2) near Amandas, north of Salisbury; 3) between Marandella, Mangwendi and Rutape, southeast of Salisbury; 4) the upper Sabi, west of Umtali and 5) between Singwasi and Beitbridge, connecting with the northern Transvaal district.

In South Africa, the deposits of the northern and northeastern Transvaal are extensive (Kun, 1965). The largest fields include: 1) Louis Trichardt, Pietersburg, the Magabeen Mountains and Blouberg; 2) Lilliput and Tatchankop, and 3) the Leydsdorp-Malelane belt. Besides this, many localities of corundum deposits in Africa are also reported by Kun (1965) and Palache and others (1946) such as in Madagascar at Vatondrangy and other localities southeast of Antsirabe and in Ghana etc.

3. Europe

In Russia, corundum deposits are found at Umptek, the Kola peninsula in the province of Archangel and in the Ural mountains. In the Urals, principally corundum is found at

Kyshtym and also at Zlatoust, Miask, near the village of Kaltaschi about 50 miles north of Jekaterinburg and near the village of Palkina from 9 to 12 miles west and northwest of Jekaterinburg (Barlow, 1915; Palache and others, 1946).

In Greece, the largest and best known emery deposits are located on the Island of Naxos. The deposits are in the northern or eastern part of the island. Emery is also reported from the Island of Nicaria, Islands of Heraklia and Sikinos to the south and southwest of Naxos (Barlow, 1915).

In Turkey (Asia Minor), emery is obtained from the village or province of Aidin. The chief supplies come from the Gumuch Dagh and Ak Sivri. It is also mentioned in the vicinity of Smyrna at Baltizik, Azizich, Cosbunar and Kulluk (Barlow, 1915).

In Germany, sapphire is found in the basin of the Rhine at various localities in the Siebengebirge and in the Eifel district (Barlow, 1915).

In Eastern Europe, corundum is found at Bohemia, Moravia, Ausrrian, Silesia, Hungary, Siebenburgen, Austria and Tyrol (Barlow, 1915).

In Italy, corundum is reported from Venice; on the Italian slopes of Adamello in Lombardy at Monte Aviolo; on Monte Muffeto near Bovegno in the province of Brescia; in the district of Biella, especially near Mosso Santa Maria (Barlow, 1915).

In Switzerland, corundum is found at Ticino and Campo Longo (Palache and others, 1946); in Portugal in the vicinity of Lisbon; at southeast coast of Spain in Andalusia in the province of Almenia and at Ronda in the province of Malaga; at Arignac in Ariège, Le Croustet in France; at Dartmoor near South Brent in Devonshire, England; at Wicklow, Ireland; at Clova, Haddo House, Aberdeenshire in Scotland (Read, 1931); at Gellivare-mamberg in Sweden; at Ammankallio, Finland; at Mulale, German East Africa; near Deschenet in in Persia (Barlow, 1915).

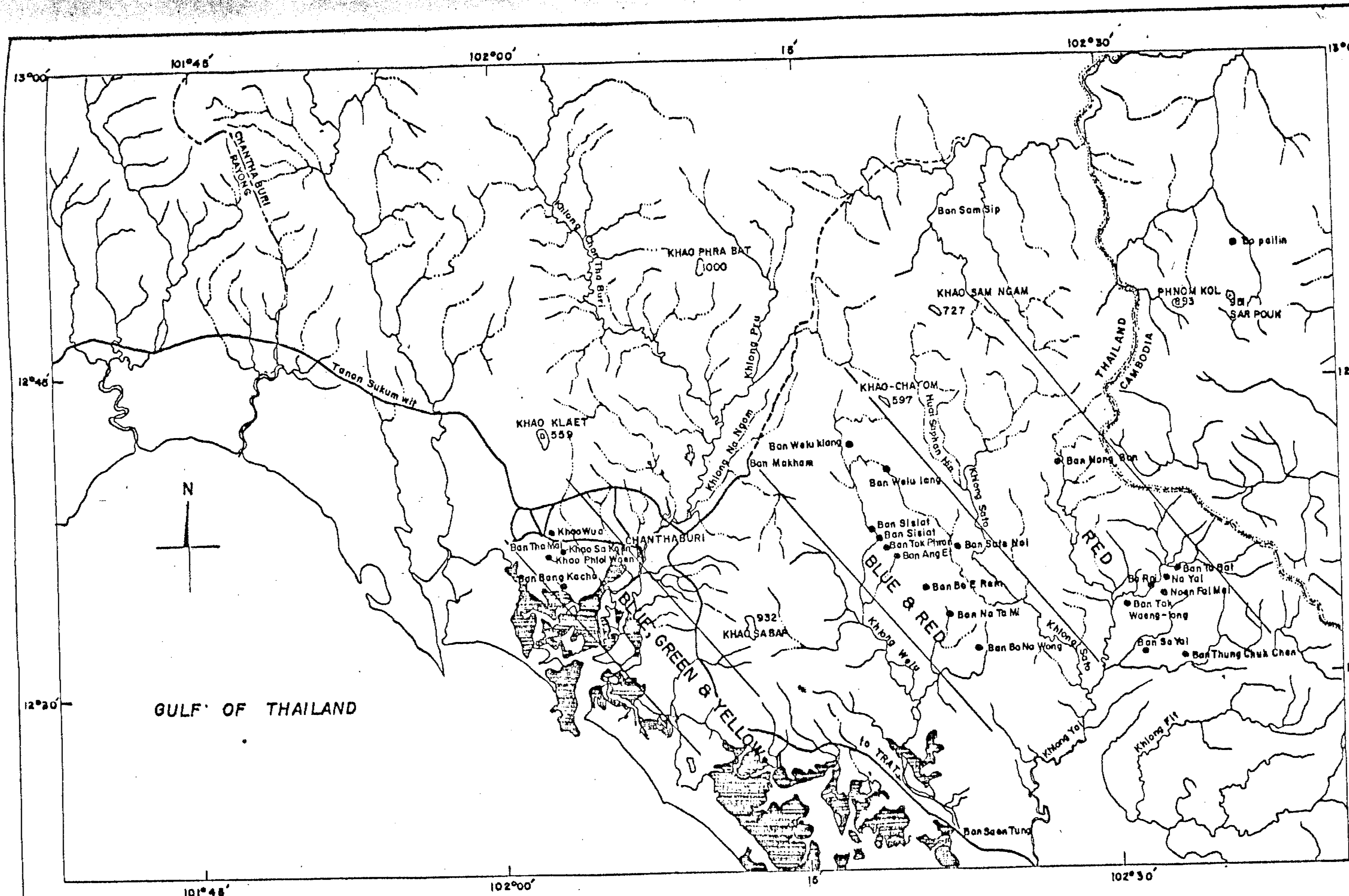
Exclusive of Europe, corundum is also reported from Back Creek near Rimu in New Zealand, in Borneo (Barlow, 1915); and at the Rio Mayo and Platayaco in Columbia, South America (MacNevin, 1972).

C. Corundum in basalts

A survey of the literature indicates that corundum deposits in basaltic terrains in the world have only been found in Thailand, Cambodia, Australia, Germany, France, Eastern Europe (Hungary), Madagascar, Scotland and Nigeria.

In Thailand, they are found at Ban Bo Kaeo, Denchai in Phrae province; at Ban Sum Bon in Petchaboon province; at Kantaraluk and Nam Yuen subprovince in Srisakate and Ubol Ratchatanee provinces; at Bo Ploi in Kanchanaburi province and at many localities in Chantaburi and Trat provinces (see figure 5).

In Cambodia, corundum is found in the basaltic area



MAP SHOWING THE GEMSTONE LOCALITIES AND ZONES OF BLUE-GREEN-YELLOW SAPPHIRE
BLUE SAPPHIRE-RUBY AND RUBY OF EASTERN THAILAND

5 0 5 10 15 20 25 30 Kilometers.

at Bo Pailin. It is well known among gemmologists that blue sapphire from Cambodia is of good gem quality. This deposit is about 10 km from the border of Thailand and Cambodia. In other words, it is about 60 km in the north-east direction from Chantaburi.

In Australia, sapphire is found at the Anakie gem fields and Cooktown in Queensland. At Anakie, sapphire occurs in the river gravels and were probably derived from the Tertiary Hoy basalt (Olgers, 1972). At Cooktown, sapphire was reported from alluvial deposits in the Annan River Tin Field, and from gullies north of Butchers Hill and the McLean basalt (Lucas and Keyser, 1964).

Sapphire is found in many streams in the Inverell-Glen Innes-Glencoe area and in Snowy Creek near Ebor, New England District, New South Wales (MacNevin, 1972). The main producing streams are Frazers Creek, Horse Gully and Mary Ann Creek, near the town of Sapphire, Wellinggrove Creek and Camerons Creek, north of Wellinggrove, Reddestone Creek near Bullock Mountain; Copes Creek near Tingha (by reworking old tin wash); and the Michell River near Glencoe. The sapphire of New England district occur for the most part in the alluvial gravels of the present stream system, but are also found on the surface (usually in basaltic soil) well above present stream deposits (MacNevin, 1972). For detail localities see Barrie (1965), Lucas and Keyser (1965), Keyser and Lucas (1968), Olgers (1968) and MacNevin (1972).

In Nigeria, corundum is found in alluvial deposits near basaltic terrain of Nigeria's Cenozoic volcanic province, according to Wright (1971, 1972). Corundum is thought to be derived from the Gimi basalt flow (Wright, 1972).

Thomas and Radley (1922) reported sapphire-bearing xenoliths in a composite sills in the Island of Mull, Scotland which were found at Mullach Glac an t'Sneacha, on the shore of Carsaig Bay, southwest of Carsaig village and in the peninsular region south of Loch Scridain. In general, the sills are of tholeiitic and andesitic character and penetrate the western part of Tertiary lava field (Thomas and Radley, 1922).

In Germany, corundum has been found occurring in silicate inclusions in basalt in the basin of the Rhine at various localities in Siebengebirge and in Eifel district (Barlow, 1915). Pirsson (1897) also mentioned the occurrence of small blue sapphires enclosed in the fresh basalt at Unkel on the Rhine and Steinheim near Frankfort on the Main. Barlow (1915) reported another locality which sapphire was noticed in the basalt of the Calvarienberg at Fulda.

In Eastern Europe, pieces of grayish blue corundum, about 7 mm long and 1.5 to 2 mm thick, occur in basalt near Ajnacsko, Hungary (Barlow, 1915).

In France, Lacroix (Barlow, 1915) described the occurrence of corundum in the trachytes, andesite, and basalts of the volcanic district of the Auvergne mountains in the "Plateau Central." At Le Croustet and volcano Le Coupet and many other places in the region, bluish corundum occurs in basalts or enclosed within the tuff and breccias. Corundum is also found in basaltic tuffs of the vicinity of Diego-Suarez in Madagascar (Barlow, 1915).

The detail of corundum-bearing basalts in Thailand, Australia, Scotland, and Nigeria will be discussed later. No detailed data about the corundum deposits in Germany, France, Austria-Hungary and Madagascar, have been found by the author.

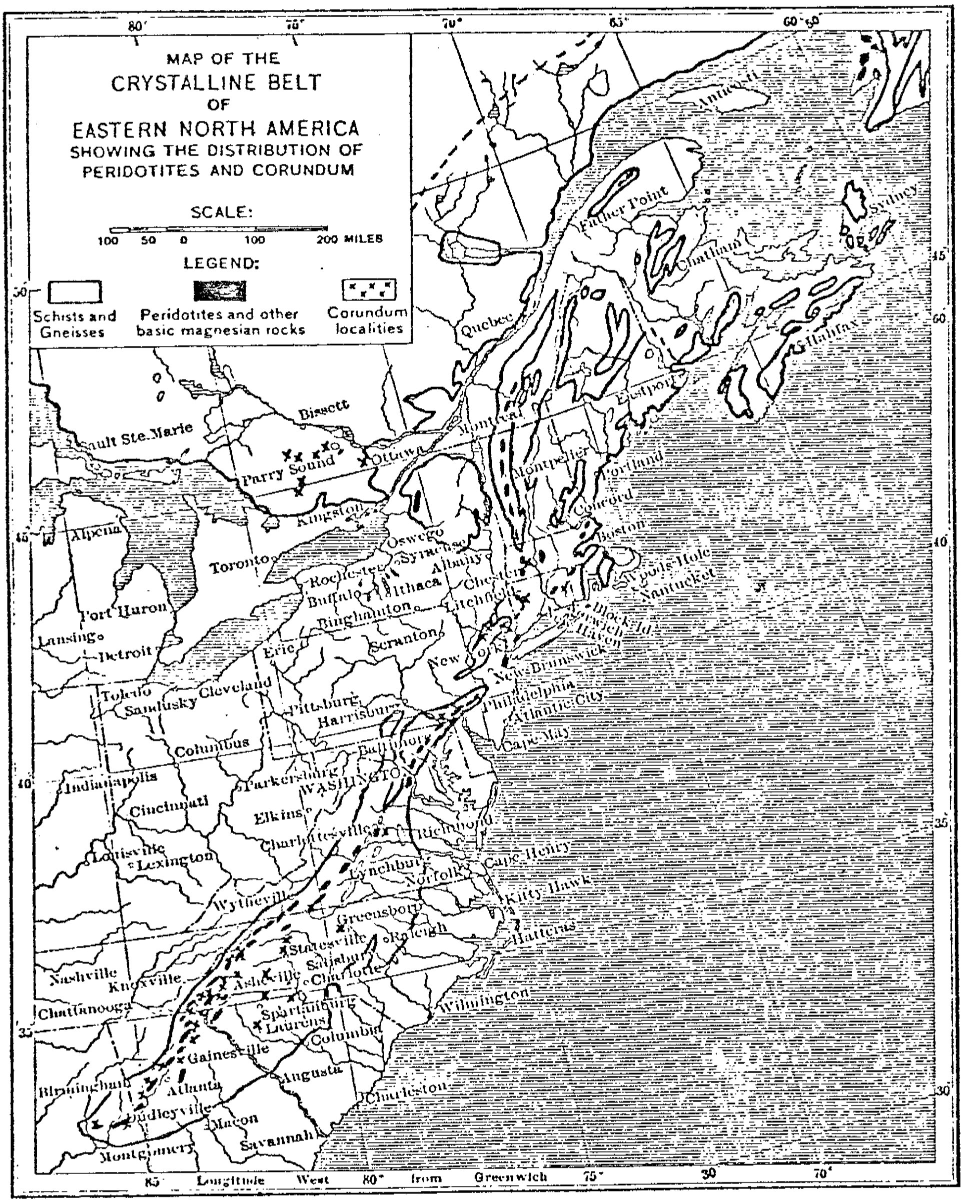
III. GEOLOGIC OCCURRENCES

Corundum occurs in a wide variety of rocks and owes its existence in different types of deposits to different genetic processes. The deposits can be classified into two types: one as primary and the other as secondary. The first type of deposit is generally found in igneous and metamorphic rocks such as peridotite, pyroxenite, syenite, amphibolite and various types of gneiss. The secondary deposit is found in alluvium and eluvium near the original sources of the first type.

Because of a large number of rock types in which corundum has been found, all the occurrences of the corundum cannot be described in detail. Only some examples of deposits which may lead to the genesis of corundum-bearing basalt, will be discussed. Corundum-bearing rocks exclusive of basalt is shown in Appendix 1. Details of each of the corundum-bearing rocks can be obtained from the list of references at the end of this report.

A. Corundum in rocks other than basalt

In the United States, as indicated on pages 15 to 17 corundum is confined to the eastern and western parts of the country. In the eastern part or Appalachian belt, corundum is found along the peridotite belt (see figure 6). For details of each of the corundum deposits in this belt see Pratt (1901, 1906), Pratt and Lewis (1905), Barlow (1915), Hadley (1949), Pearre (1958), Furcron (1960) and Hartley (1973).



MAP OF EASTERN NORTH AMERICA, SHOWING THE DISTRIBUTION OF PERIDOTITES AND OTHER BASIC MAGNESIAN ROCKS.

Figure 6.

After Pratt and Lewis, 1905.

Corundum-bearing rocks in the Appalachian belt are peridotite, dunite, harzburgite (saxonite), amphibole-peridotite and troctolite. They are confined to the belt of ancient crystalline gneisses and schists of the Appalachian orogenic belt. This belt of ultrabasic rocks is very narrow, being 10 miles in average breadth and extending from Alabama to Newfoundland for a distance of 1,800 miles (Jahn, 1967; Hartley, 1973).

The greatest concentrations of corundum are in peripheral veins* or dikes located along contacts between the peridotite and country rocks. Smaller veins (interior veins) occur in the main bodies of some of the peridotites. Type sections of peripheral and interior veins are shown in figure 7 and 8 respectively.

Corundum-bearing plagioclase was also mentioned by Pratt and Lewis (1905). It was found either in the corundum-bearing zone of chlorites and vermiculites or entirely replacing this zone. The thickness varies from a few centimeters to several meters. It was indicated that feldspar crystallizes contemporaneously with corundum. When feldspar is present there is a marked decrease in chlorite.

Spinel (pleonaste and picotite) has been found in many corundum veins and some is intimately associated with corundum. Other minerals which were found in corundum

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* According to Pratt and Lewis (1905), this term is applied for convenience, without implying any particular character or origin.

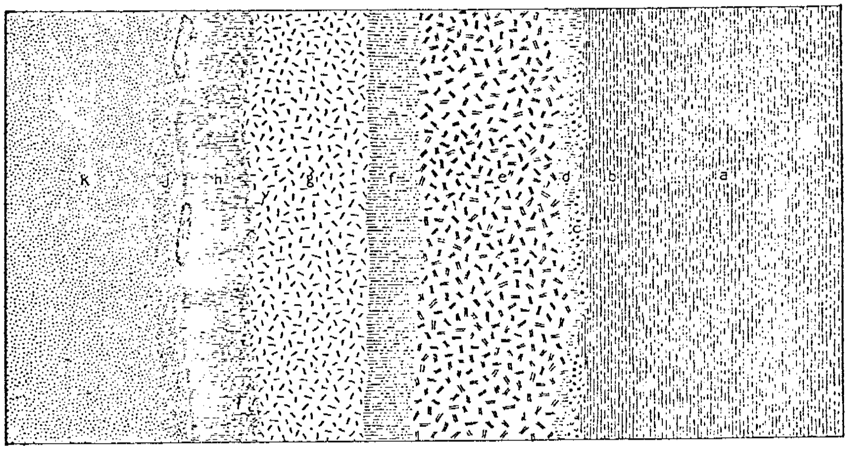


Figure 7. Ideal cross-section of a peripheral or border vein of corundum at Corundum Hill mine, Macon county, North Carolina. After Pratt and Lewis, 1905.

a. Gneiss, hornblendic or micaceous, apparently unaltered.
b. Gneiss of same general appearance as a, but so decomposed that the particles readily separate from one another.
c. Yellowish vermiculites, varying considerably in thickness, with a maximum of 6 or 8 inches, often merging gradually into d; sometimes entirely absent, so that b and d are in contact.
d. Green chlorites, varying in thickness, much like c, and sometimes entirely absent.
e. Chlorites and corundum, often with some vermiculites, varying in thickness from a few inches to 12 or 15 feet. This is the "corundum-vein" of the miners, and in places consists largely of corundum.
f. Green chlorites, 1 inch to 12 inches in thickness; so far as observed, always present.
g. Enstatite, in places hard and compact, several feet thick, and usually merging into h.
h. Talcose rock, usually fibrous, and varying from a few inches to several feet in thickness.
i. A seam of yellowish clay a few inches in thickness, often carrying masses of quartz or chalcedony. This seam is frequently absent altogether.
j. Dunite, more or less altered, friable and stained with ferric oxide.
k. Fresh dunite, usually exhibiting no alteration visible to the unaided eye. This constitutes the main mass of the peridotite.

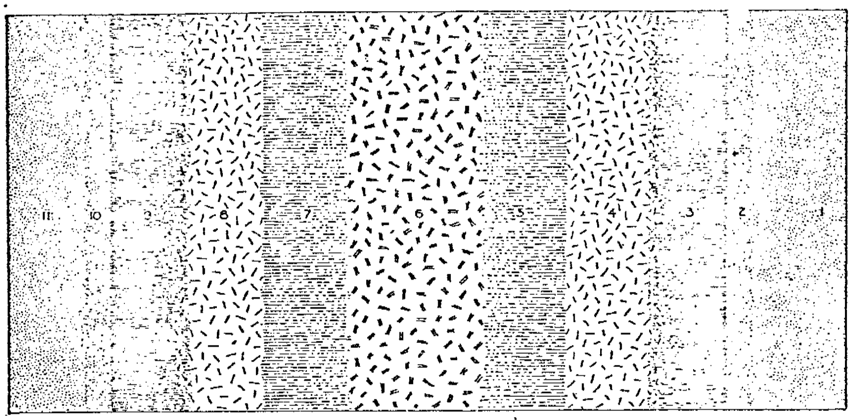


Figure 8 Ideal cross-section of an interior vein of corundum at Corundum Hill mine, Macon county, North Carolina. After Pratt and Lewis, 1905.

1 and 11	Normal dunite
2 and 10	Dunite, somewhat friable and discolored, passing into 3 and 9.
3 and 9	Fibrous talcose rock, merging into 4 and 8
4 and 8	Grayish enstatite, somewhat fibrous
5 and 7	Green chlorites, 6 and 15 inches in thickness
6	Central corundum-bearing zone, consisting of chlorite, corundum, and spinel, 6 to 8 feet thick

veins are enstatite, diopside, magnetite and garnet (almandine and andradite). Pratt and Lewis also noted that where there is an increasing amount of corundum, there is a decreasing amount of chromite. Almandine was found abundantly at many corundum deposits, especially where corundum occurs in gneiss and schist. Andradite was occasionally found with corundum in mica-schist; some andradite has been observed with the corundum in peridotite at Bad Creek Mine, North Carolina (Pratt and Lewis, 1905). Corundum is also found in gneiss, mica-schist, amphibole-schist, quartz-schist and altered peridotite (Pratt and Lewis, 1905; Clabaugh, 1952). The origin of corundum in peridotite is attributed to crystallization from peridotitic magma near the contact between magma and country rocks.

In the western part of the U.S.A., corundum is mainly found in Montana. Clabaugh (1952) located many corundum localities in this state as shown in figure 9. The most important deposit is at Yogo Gulch, in Fergus county. Sapphire-bearing dikes cut through limestone of the upper part of Madison limestone of Mississippian age. The lower and middle parts of the formation contain numerous thin beds of shale or clay. According to Clabaugh, most of the igneous rocks in the area are believed to be of Tertiary age and sapphire-bearing dike is probably post Pennsylvanian. The most common inclusion (xenoliths) in the dike are limestone fragments and several small inclusions of kyanite and quartz. The igneous dike was reported as altered

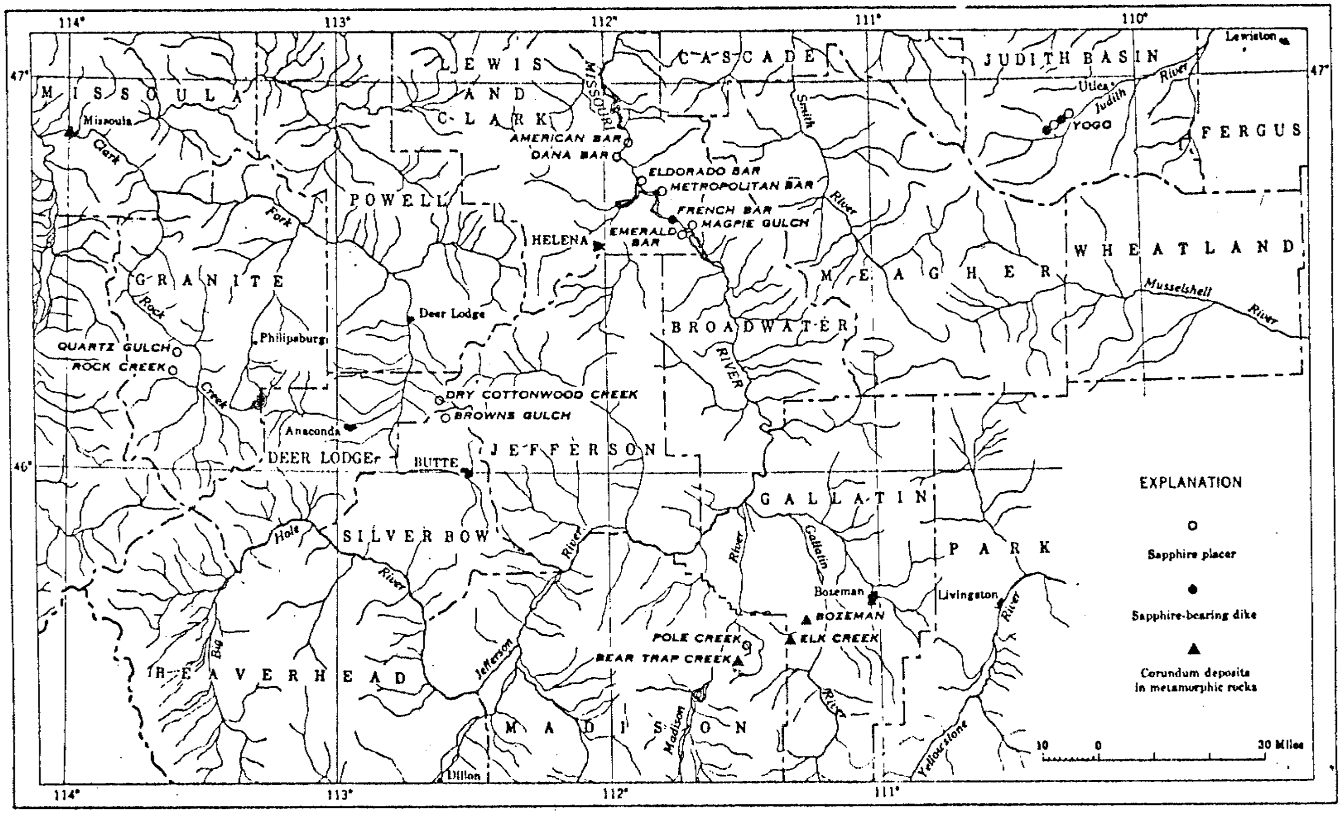


Figure 9. Index map showing location of Montana corundum deposits. After Clabaugh, 1952.

analcime basalt or ouachitite. This dike will be discussed later in detail under the heading "Structure and Fabric of Corundum-bearing Basalt and Related Rocks."

In Canada, as discussed on page 17 and 18 the corundum deposits have been located in three belts. The first belt is of three main types; nepheline gneisses, plagioclase-rich rock (white alkali syenite) and red alkali syenite (Carlson, 1957). The rocks of these three groups grade imperceptibly into one another. According to Barlow (1915), the second belt is corundiferous syenites; the third belt is largely made up of anorthosite (variety-plumasite), but, toward the southeast end, corundum has been found in the more usual syenite pegmatite.

The associated alkali syenites are generally found either along the contact of the granite or the limestone itself near the granitic contact (Barlow, 1915). These corundum-bearing alkaline rocks form part of Grenville sub province of the Precambrian Canadian Shield.

Corundum production in Canada chiefly comes from the Craigmont and Klondike workings, Renfrew county. Corundum occurs in irregular, discontinuous, isolated zones and patches in a banded scapolite-andeclase-nepheline gneiss complex (andecalse=andesine-oligoclase-rich rock) and in large amounts in altered facies of this complex along its contacts with a younger hybrid alkali syenite (Carlson, 1957).

According to Carlson, the plagioclase in the hybrid zones ranges in composition from An_{20} to An_{80}, whereas in the andeclase rock, the plagioclase ranges in composition from An_{20} to An_{37}, with most of it about An_{30}. In some specimens of andeclase and scapolite rocks, a few small grains of green spinel are intergrown with magnetite and corundum. Garnet of andradite-grossularite variety and epidote are quantitatively unimportant in the scapolite. Hornblende and pyroxene are concentrated in thin local lenses and have a random distribution in scapolite and andeclase rocks. They are not found in nepheline gneiss. Corundum is not found in those portions of the complex that contain pyroxene and/or hornblende. The pyroxene is ferroaugite. In nepheline gneiss, corundum was found to be enclosed by nepheline in many specimens. The origin of corundum in scapolite-andeclase-nepheline gneiss complex is attributed to the transformation of sediments locally rich in alumina into the corundum bearing portions of the complex either by metasomatic replacement or by magmatic assimilation. The hybrid alkali syenite formed by the metasomatic alteration of this complex (Carlson, 1957).

In Africa, corundum in kimberlite has been reported by Du Toit (1954) and by Mathias and others (1970). Corundum is found only to a minor extent. According to Mathias and others (1970), eclogite associations such as garnet-corundum and clinopyroxene-garnet-kyanite-corundum are found. Their interpretation is that calcium-aluminum enrichment operates in the lower regions within the upper mantle resulting in the series: Eclogite -----→ Kyanite eclogite -----→ Corundum eclogite. Several kinds of crystals precipitate from a melt formed by partial fusion of garnet peridotite.

Aramaki (1961) reported sillimanite, cordierite and corundum in volcanic xenoliths in andesite (found as bombs) at Asama volcano, about 140 km northwest of Tokyo, Japan. The sedimentary xenoliths contain phenocrysts of augite, hypersthene, plagioclase, magnetite and small amounts of olivine and is calc-alkali andesite in composition. The glass contains cordierite, detrital quartz, magnetite, andalusite and corundum in a general order of decreasing amount.

Aramaki concluded that both sillimanite and cordierite reflect the high temperatures and low pressures. Hydrothermal experiments showed that the glass formed by partial fusion of sediments, becomes fluid at a temperature range between 945 and 1005°C and water pressure of about 200 bars.

So far we have been concerned about the occurrences of corundum in rocks other than basalt. Other corundum deposits are reported from Pratt (1901, 1906), Pratt and Lewis (1905), Barlow (1915), Palache and others (1946), Clabaugh (1956), Deer and others (1962), and Bauer (1968). Corundum-bearing rocks in some areas of the world are summarized after Pratt (1906) in Table 2.

TABLE 2. Corundum-bearing rocks in some areas in the world

Igneous....	Anorthosite
	Andesite
	Basalt
	Carbonatite
	Diorite
	Gabbro
	Kimberlite
	Nepheline-syenite
	Quartz-porphyry
	Syenite-pegmatite
	Tonalite
	Trachyte
Metamorphic....	Corundum-schist
	Corundum-sillimanite
	Crystalline limestone
	Chlorite schist
	Dolomite
	Garnetiferous enstatite-amphibolite
	Hornblende gneiss
	Kyanite
	Micaceous gneiss
	Talc schist
Alluvial and Eluvial..	Gravel deposits, lateritic soil

Modified after Pratt (1906)

B. Corundum in Basalt

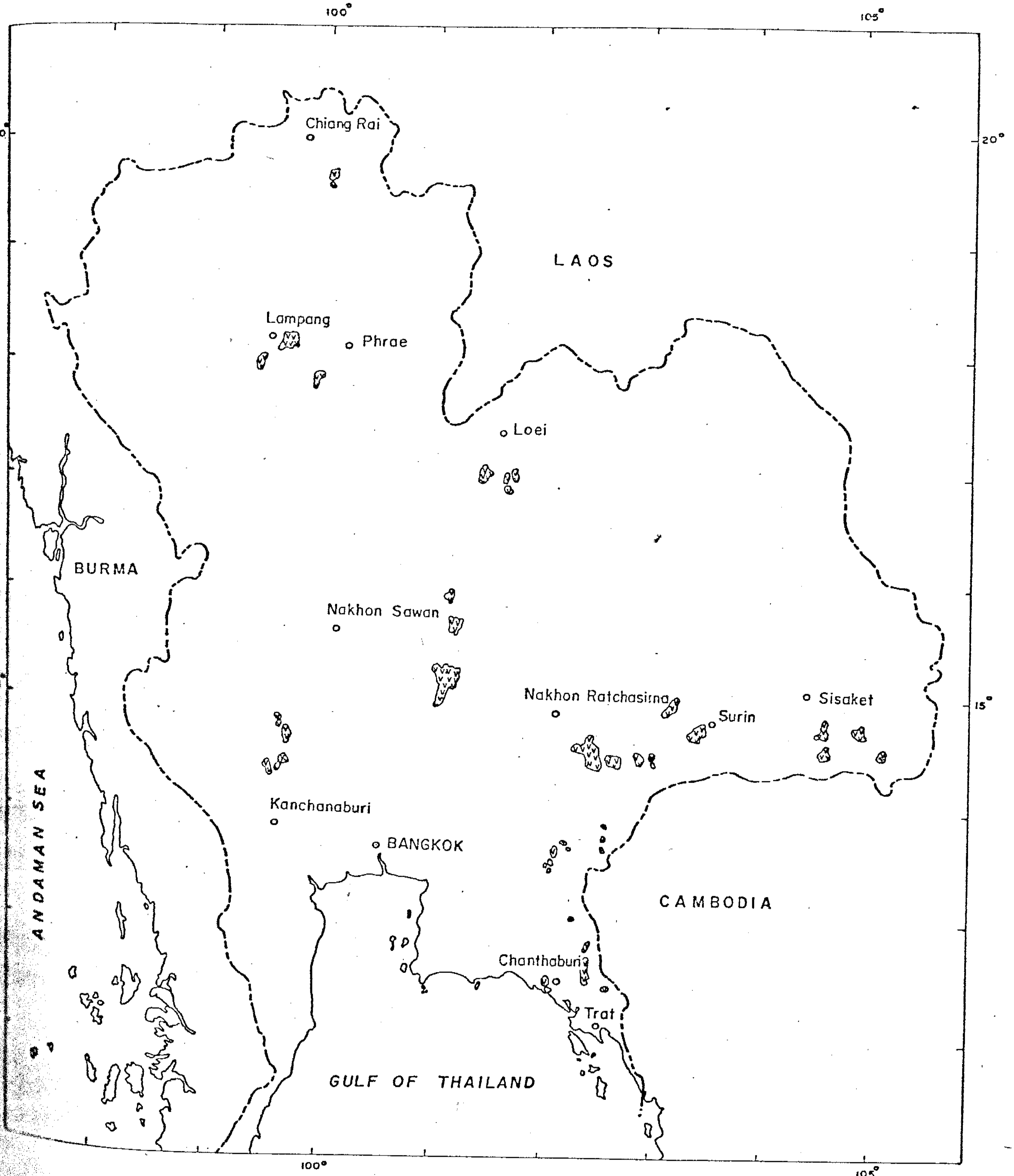
1. Thailand

Corundum localities in basaltic terrains have been discussed in previous pages. The map showing distribution of basalts in Thailand is shown in figure 10. It was drawn from field observation and airphotos of reddish brown soil which is the weathering product of basalt. Most of the deposits are found in eluvial or alluvial placer and residual soil associated with Tertiary(?) basalt flows.

a. Phrae, Petchaboon, and Chiang Rai provinces

At Phrae, the general geology of the area is of Permian rocks overlaid by Tertiary(?) basalt flows. Permian rocks are composed of slate, limestone lenses, conglomerate, phyllite, chert beds and silicified shale (Charoenprawat, 1968). This basalt erupted in the upthrown block. It is situated on the east side of Mae Paeng fault which is approximately 35 km long.

Basalts cause only little contact metamorphic effect on the country rocks. The alteration zones which are well exposed at road-cuts, along Srisatchanalai-Ban Bo Khaeo-Denchai Highway, are only one foot thick. Most of the basalts are olivine basalts and probably alkali olivine basalts (see later under the heading "Geochemistry of Corundum-bearing Basalt"). The thickness of this basalt flow usually varies from 10 to 30 m, but is never greater than 100 m. Basalts generally contain dunite or peridotite



MAP OF THAILAND SHOWING DISTRIBUTION OF BASALT

Figure 10.

xenoliths.

All of the deposits being exploited here are recent alluvial gravels in the streams, e.g. at Huai* E-Taur, Huai* Si-Siat and Huai* Wao Daeng at Ban Bo Khaeo, Denchai. Sapphires are found associated with black spinel, albite-oligoclase, olivine, magnetite, aluminous clinopyroxene, zircon and ruby spinel. Ruby is found only in trace amounts. The average grain size of sapphire is about 3-5 mm and never greater than 1 cm.

Corundum is also reported from Chiang Khong in Chiang Rai and from Ban Sum Bon, 20 km east of Kan Cha district, Wicheanburi in Petchaboon province. It was mentioned to be found in basaltic area (Aranyakanon, personal communication, 1974). Unfortunately, the investigation has not been made because the political situation is unsettled there. No detailed data are known to the author.

b. Srisakate and Ubol Ratchatanee provinces

These provinces are included in the eastern or northeastern part of Thailand. This part of the country is known as the Khorat Plateau. Srisakate and Ubol Ratchatanee are situated in the SE quadrant of the Khorat Plateau, near the border between Thailand and Cambodia.

Sapphires are found at Huai Ta-Ak (Lum-Som) and Plan-Thung-Yao, Kantaraluk subprovince in Srisakate; at Ban None Yang, Ban Kok Sa-Ard, Ban Ta-Koy, Ban Ta-Kao, Ban

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* Huai means creek or stream in Thai language.

Don-Mok and Ban Nong Ngarm, Nam Yuen subprovince in Ubol Ratchatanee.

Generally the northeastern part of Thailand is covered with the rocks of Khorat Series of Mesozoic age. The areas of gem deposits are composed of the rocks of Khok Kruat (Jurassic) and Phu Pan (Triassic) formation which are included in the Khorat Series. No basaltic outcrops are found in the vicinity of sapphire deposits there. However, basalts crop out at many localities in Srisakate; and Burirum and Surin provinces in the west half of Srisakate, near the edge of Khorat plateau. These basalts erupted in the upthrown block or on the western side of an extensive fault which occurs along the border between Thailand and Cambodia (Aranyakanon and others, 1970).

Gem deposits are recovered from the stream gravels, along the banks of the stream, and in laterite (e.g. at Plan Thung Yao). The gems recovered consist of at least 80% zircon (hyacinth), blue and green sapphires, and accessory minerals such as garnet, magnetite, hypersthene-pigeonite (aluminous clinopyroxene?), ilmenite (with high percentage of manganese), black spinel, nepheline, and olivine (Aranyakanon and others, 1970).

Stream gravels are composed of rocks of Khok Kruat and Phu Phan formations which are conglomerate, sandstone, and siltstone. Gravels of basalts were noted by Aranyakanon and others (1970). They are olivine basalts which are composed of phenocrysts of olivine and augite embedded in the groundmass of labradorites. Some feldspars have altered to kaolinite. Magnetite is found as an accessory mineral.

Sapphire embedded in basalt has not been found in these provinces. Since the corundum deposits of the country generally occur in basaltic areas, and since sapphire in the rocks of Khorat Series has also not ever been found, Aranyakanon and others (1970) believe that sapphire has more tendency to be derived from basalts which erupted through Khorat Series in Tertiary time rather than from other rock-types.

c. Chantaburi and Trat provinces

Gem deposits of the eastern or more specifically southeastern part of Thailand have been well known for many years. The mines at Khao Ploi Wean and Bang Ka-Cha in Chantaburi have been worked intermittenly for more than one hundred years by local inhabitants (Taylor, Jr., and Buravas, 1951).

There is a variation of gem colours in three distinctive geographic zones characterized by blue, green, and yellow corundum; blue and red corundum; and red corundum. These three geographic zones of corundum fall in two provinces - Chantaburi and Trat.

The first zone of gem deposits is located at Khao*Wao, Khao* Ploi** Waen, Bang Ka Cha, and Khao*Sra Khaeo in the western part of Chantaburi town (Vichit, 1973a).

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* Khao means mountain or hill in Thai language

** Ploi means gem.

The second or middle zone is situated between Chantaburi and Trat provinces. Gem deposits are located at Ban Welu Klang, Ban Welu Lang, Ban Si Siat, Ban Tok Phrom, Ban Sato Noi, Ban Ang Et, Ban Bo I-Ram, Ban Na Ta Mi and Ban Bo Na Wong (Pothisat, 1972; Vichit, 1973a).

The third zone of gem deposits is located at Ban Nong Bon, Ban Ta Bat, Bo Rai, Na Yai, Noen Fai Mai, Ban Tak Waeng Lang, Ban Sa Yai, and Ban Thung Chuck Chan in Trat province (Pothisat, 1972).

The first area is about 5 kilometers west of Chantaburi. It has been covered with Tertiary(?) basalt of an area approximately 7x3 kilometers. The rocks which lie underneath this basalt are composed of phyllite, quartzite, and schist. They were mapped as argillaceous series of Devonian-Carboniferous age by Hughes and Bateson (1967). Generally, basalts become red and reddish brown soil by deep weathering. No solid basaltic rocks have been found in this area except at Khao Ploi Waen and Kkao Wao where some vesicular basalts and olivine basalts have been found. In some places basalts show scoriaceous appearance. Olivine basalts sometimes contain aluminous clinopyroxene(?) and black spinel especially in the areas of corundum deposits.

It should be noted that at Khao Ploi Waen, where the surrounded-gem deposits are located, there is thought to be a volcanic plug (Taylor, Jr. and Buravas, 1951). The elevation of the top of this small hill (Khao Ploi Waen) is about 129 meters above sea level.

Another basalt flow is located at Khao Klat on the southwestern tip of the Khao Klat granite batholith which is about 5 km north of the former basaltic lava. The granite is overlaid by basalt which is approximately 1 km long and 1/2 km wide (Taylor, Jr. and Buravas, 1951; Hughes and Bateson, 1967). Most of this basalt has become red soil. However, fresh basaltic outcrops can be found at Klong Song Phi Nong at the western edge of the flow. It is a extremely hard, dense, greyish-black rock. Columnar jointing is also well-developed.

The second and the third geographic zones of corundum deposits form part of the Triassic rocks which are overlaid by Tertiary(?) basalts. These two zones include the Eastern Sector of southeastern Thailand which is defined by Hughes and Bateson (1967). They state that "the sediments of the major portion of the Eastern Sector are arenaceous with subordinate argillaceous members. Medium-grained sandstone is the main rock type encountered with individual beds often containing small pebbles and fragments of mudstone and other fine-grained material. Angular fragments of feldspar are also common in some units..."

Pothisat (1972) in describing the general geology of the third zone (the area around Bo Rai deposits) reports that there are argillaceous rocks interbedded with volcanic wacke(?) and volcanic agglomerate which seem to be of Triassic age. Lenses of conglomerates are found in some places in this formation.

The area of the second zone of corundum deposits is mostly confined to a basaltic lava flow which trends in the north-south direction. This flow is about 27 km long and 3 to 4 km wide. The basaltic lava seems to flow from the north to the south. No evidence has been found of the vents from which the basaltic lava flows issued (Hughes and Bateson, 1967).

Basalts usually weather first to red soil and then to lateritic soil. Solid basaltic outcrops are rarely found except at Natami, north of Ban Nong Bon in Trat and at Neon Chang near Sa-To temple (Aranyakanon, personal communication, 1974).

In the third zone, most of the basalts have become red soil and in some places they have become laterite. Solid basaltic rocks are found as gravel associated with corundum in the deposits at Ban Nong Bon, Bo Rai and Ban Thung Chuck Chan. Pothisat (1972) found an outcrop of basalt which covers an area 100 x 30 square meters at Neon Lin Hoi, Ban Nong Bon (Grid 22320,140530). He also noted the difference between basalts of Ban Nong Bon and basalts of Ban Na Yai and Ban Thung Chuck Chan as follows:

1. NongBon basalts are characterized by conspicuous magnetite with grains of about 2 mm to 10 mm in size. But, Ban Na Yai and Ban Thung Chuck Chan basalts contain lesser amount and finer grains (2-5 mm) of magnetite.
2. Nong Bon basalts are more vesicular than the

other two basalts.

In general, minerals associated with corundum in the three geographic zones are black spinel, albite-oligoclase, ilmenite, olivine, zircon, aluminous clinopyroxene, pyropic garnet, hematite (specular type) and quartz. Garnet associated with ruby in the third zone is reported to be found only at Ban Nong Bon, Trat province. X-ray analyses of three samples of pyroxene from Khao Ploi Waen indicated that they are iron-rich pyroxene. Pothisat (1972) reported pyroxene from the third geographic zone as pigeonite.

Very coarse grained biotite is found associated with sapphire deposits at Khao Ploi Waen and Khao Wao in Chantaburi (Vichit, 1973a). The grain size varies from a fraction of a cm to 6 cm in diameter. It is not reported to be found in other areas of corundum deposits in the southeastern part of the country. Biotite is used as a guide in searching for sapphire in that area. If there is a large amount of biotite in the top soil, sapphire will be found at depths about 30-60 cm under that soil layer. Sometimes, all of the minerals including sapphire are found in the same layer (Vichit, 1973a).

The thickness of the deposits varies from place to place; it depends on the nature of bed rock and the slope of the deposits. In general, the average depth to paydirt is about 1-3 m and its thickness varies from 30 cm to 1 m.

Aranyakanon and others (1970) note that the amount of zircon associated with sapphire deposits at Srisakate and Ubol Ratchatanee is greater than in the other corundum deposits of the country. At Chantaburi and Trat the first zone contains more zircon than the second and the third zones. Pyropic garnet is also found to a greater extent in the first zone than the other two zones except at Ban Nong Bon where a large number of pyropic garnets are found associated with ruby deposits. The first zone also contains good gem quality garnets and better than the other two.

It should be noted that corundum-bearing basalts of Chantaburi and Trat provinces were erupted on the eastern side of the two major transcurrent faults (Ranong and Khlong Marui faults). These have a total sinistral displacement of at least 200 km (Garson and Mitchell, 1970). Basalts are probably related genetically to these two transcurrent faults. At present there are no detailed data to support this hypothesis.

d. Kanchanaburi province

Sapphire deposits are located at Bo Ploi, about 25 km by the dirt road to the north of Kanchanaburi town. Considerable mining both by local residents and by foreign companies was reported through 1940 (Charaljavanaphet, 1951). At present, activity has diminished with the increasing paucity of gem recovery. There are only a few local residents who are still pitting and panning for gems.

Sapphire is found in red soil or alluvial placer in or near the basaltic terrain. The basalts are believed to be of Tertiary(?) age. They are reported as nepheline-olivine basalt by Charaljavanaphet (1951). In general, basalt was reported as olivine basalt. Pothisat (personal communication, 1975) mentioned that this basalt contains nepheline and iron spinel.

Basalts in this area are found forming low hills and show columnar jointing near the top and sheetlike structure near the base (Charaljavanaphet, 1951). Weathered basalts usually develop red or reddish brown soil which can be seen around the gem area. Sapphire is usually found associated with black spinel (Sensu stricto), magnetite, sodic feldspar, and minor amounts of quartz in the red soil or alluvial deposits.

In terms of gem quality, sapphires from Thailand have better colour and transparency than those from Australia, Ceylon, Montana, India and Burma. Some of the blue sapphires from Kanchanaburi and Phrae show colour and transparency as good as those from Bo Pailin in Cambodia. In terms of hardness, sapphires from Thailand and Australia are slightly harder than sapphires from other areas of the world, especially the yellowish green sapphires. Sapphires are found in various colours such as blue, green and yellow or a combination of these colours. Colour zoning is also common. Some may show gradation in colour from deep blue to yellowish or colourless. Star sapphire is found to a great extent in all areas of the deposits of Thailand.

Aranyakanon (personel communication, 1974) noted that where there are large numbers of phenocrysts (megacrysts?) of feldspar embedded in basalts, there is corundum in the stream, residual soil, or alluvial deposits near that basaltic terrain. This fact suggests that there is a close genetic relationship between corundum and feldspar.

It can be noted that basaltic soil in or near the places which have corundum deposits, usually has a more pronounced red colour than in the places which contain no corundum deposits. The pronounced colour in this case may or may not be taken into account as evidence of the genetic relationship of corundum to basalt. It may only be the result of the difference in climatic condition in different places. In other words, the corundum-basalt association may be made conspicuous by deep weathering.

2. Australia

In Australia, corundum has been found in Victoria, South Australia, Queensland, New South Wales, and Tasmania. The Anakie field in Queensland and the Inverell district of New South Wales are the most important deposits in Australia where an attempt has been made to recover sapphire on commercial scale. The Anakie field and Inverell district are the areas where corundum is found in basaltic areas. Other corundum-bearing basaltic areas are reported from alluvial deposits in the Annan River Tinfield and from gullies north of Butchers Hill and the McLean Basalt at

Cooktown (Cooktown sheet area). Only corundum deposits in basaltic terrains will be discussed below.

a. The Anakie field in Queensland

The Anakie field is situated in central Queensland. According to Barrie (1965), Anderson (1965), and Olgers (1969), sapphires are found scattered over an area of 350 square miles, and mostly north of the railway between Anakie and Willow sidings. The main working areas are at Sapphire town and Rubyvale.

Generally, sapphire deposits are found in the Anakie Inlier (Anakie Structural High or Anakie complex) which extends from Ukalunda in the north to Anakie in the south and continues to the south-southwest under the Bowen and Surat Basins as the Nebine Ridge (Olgers, 1972). The Anakie Inlier lies between Drummond Basin in the west and Bowen Basin in the east. The rocks in the areas of corundum deposits are composed of the pre-Devonian Anakie Metamorphic (which were intruded by Upper Devonian Retreat granites) and the Undifferentiated group of gravels and sands. A large number of olivine basalt plugs, the Hoy Basalt, intruded the Anakie Inlier and Drummond Basin sequence (Olgers, 1969, 1972). The Hoy Basalt is thought to be emplaced mainly in basement rocks between the Chinaman and Copperfield megashears, and possibly intruded along zones of weakness created by the coupling effect of the megashears (Olgers, 1972).

The Hoy Basalt is Tertiary in age. It is composed of porphyritic olivine basalt, olivine dolerite, and olivine gabbro containing xenoliths of ultrabasic rocks, corundum and spinel.

Sapphires are found in the river gravels as water worn fragments which are said to be derived from the Hoy Basalt plugs and probably associated flows. The flows have been completely eroded in the areas of the deposits. However, some specimens have been obtained from the remnant plugs (Olgers, 1969).

The thickness of sapphire-bearing wash varies from a few centimeters to many meters. Many of the deposits are covered by recent alluvium, but in places they rise high above present watercourses. They have been worked down to the depth of about 15 m. Most of the corundum specimens are blue, green, yellow, orange-yellow or white. Associated minerals are zircon, pleonaste, garnet, topaz and tourmaline. Some diamonds have also been recorded (Barrie, 1965; Olgers, 1969, 1972).

b. Cooktown, Queensland

Other sapphire deposits in Queensland are at Cooktown (Cooktown sheet area SD/55-13). This area is situtated in the N-NW direction of Anakie gem field or in other words in the northern part of Queensland. Corundum of various colours is reported from alluvial tin deposits in the Annan River Tinfield, south of Cooktown, and blue sapphire comes from gullies north of Butchers Hill and the McLean Basalt (Lucas and Keyser, 1965, 1968).

Few data about corundum deposits in Annan River Tinfield are found in the literature. Data from Keyser and Lucas (1968) indicate that the stanniferous gravel and siltstone in this area are overlaid by remnants of McLean Basalt. This basalt crops out in some places on the eastern side of Annan River. In general, most of the area is composed of Hodgkinson formation (Greywacke, slate, minor volcanic and limestone) of Middle Devonian to Lower Carboniferous(?) age which is intruded by Finayron Granite of Permian age. The tin mineralization in the Annan River is associated with this granite. Sapphire is probably derived from this McLean Basalt.

Other sapphire deposits are reported from gullies north of Butchers Hill and the McLean Basalt. The data of sapphire deposits in this area are not known to the author. However, all of the streams which contain sapphire cut through the McLean Basalt and the composition of this basalt is similar to the Hoy Basalt which is thought to yield sapphire in the Anakie field. It is possible that sapphire is derived from McLean Basalt.

Sapphire and ruby are also reported from Jordan Creek and Russel Goldfield, Herberton, and the Tully River south of Herberton by Barrie (1965) and Keyser and Lucas (1968). No details of the deposits are given for these areas.

It should be noted according to Morgan (in Keyser and Lucas, 1968) that "the basalts in north Queensland belong to the alkali olivine basalt association of Yoder and

Tilley (1962). The basalts are poor in silica and rich in alkalis, and many of them contain analcite or, less commonly, some nepheline. Olivine basalts predominate; olivine nephelinite, nepheline basanite and olivine analcitite have also been recorded."

c. New England District, New South Wales

Sapphire was first recorded by Clark (MacNevin, 1972) in New England district associated with stream tin in the neighborhood of Inverell. At present, sapphires are found in large numbers in the Inverell-Glen Innes-Glencoe area which is situated near the northeast corner of New South Wales.

All of the corundum deposits are found in alluvial gravels in the present stream system, especially in every creek in the Inverell-Glen Innes-Glencoe area. They are also found on the surface (usually in basaltic soil) well above present stream deposits (MacNevin, 1972). MacNevin has reported many sapphire localities in this area but, the remarkable sapphire concentrations are located at Reddestone Creek, Frazer Creek, and Hose Gully. Details of the localities are given by MacNevin (1972). It should be noted that all of the data of sapphire deposits in New England district come from MacNevin (1972), unless otherwise specified.

The Inverell-Glen Innes-Glencoe area is the area of Permian granites, porphyry and acid volcanics, and Permo-Carboniferous meta-sediments, overlaid by large areas of

Tertiary basalt (see figure 11). The basaltic areas show terrace topography controlled by the multiple flows which make up the basaltic mass. The average thickness of these flows is about 6 to 15 m, and can be up to 30 m. The basalts which extend from south of Armidale north to Glen Innes and west to Inverell area belong to the Central Volcanic Province of northeastern New South Wales. It is indicated by Wilkinson (1966) that the most common lava is alkali olivine basalt. The associated volcanic rocks include nepheline-basanites and olivine-nephelinites, analcime-basanites and olivine-analcimites and ankaramitic types (Wilkinson, 1966). Tholeiite is also found in the Inverell area (Wilkinson, 1966, 1973). Peridotite and pyroxenite are reported from the basalt of Armidale (Wilshire and Binns, 1961) and from alkali trachybasalts in Glen Innes area (Wilkinson, 1973).

According to MacNevin (1972) the Tertiary basalt flows of the Inverell-Glen Innes-Armidale area have been grouped into two main periods of volcanicity. The Older Series are of Oligocene-Miocene age and the Newer Series are of Pliocene age. In between these two basalt series, there is a laterite-bauxite horizon which formed from the Older basalt in late Miocene. In some places such as near Bukkulla, and near the MacIntyre River at Byron, thin beds of gravel, sand and clay accumulated on the laterite surface before the outflow of the younger lavas (Owen, 1954).

The presence of a laterite-bauxite horizon indicates

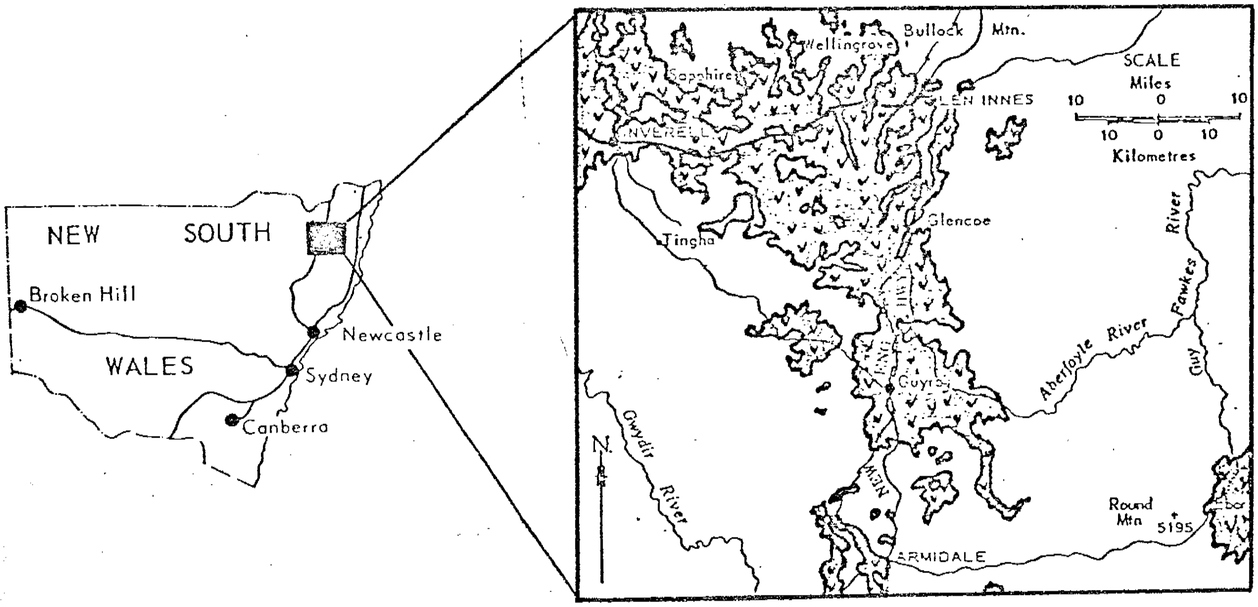

FIGURE 11 LOCALITY MAP, NEW ENGLAND DISTRICT SHOWING OUTCROP OF TERTIARY BASALT

(After MacNevin, 1972)

a very long interval of time between the two periods of volcanism (Owen, 1954; MacNevin, 1972).

Sapphires are found in all streams which cut through the basaltic flow. The bed rocks which underly the gravels are the Permian granites, porphyry and Permo-Carboniferous meta-sediments. The average thickness of sapphire-bearing wash is about 1.2 and 1.8 m; it usually occurs beneath a clayey black soil overburden which is about 0.3-1.2 m thick.

Sapphire seems to be concentrated in irregular pockets and horizons in the wash. The very bottom of the wash often yields the highest concentration of sapphire. Most of sapphire deposits are recovered down to the bedrock, as much as 6 m deep, where fine sapphire-bearing gravels are embedded in a yellow clayey matrix surrounding boulders up to 1 m in diameter.

The coarse gravel is composed of pebbles, cobbles, and boulders from 1 cm up to 1 m in diameter, and predominantly of subrounded porphyry, rounded granite, subrounded basalt, angular indurated mudstone and angular quartzite. The minerals associated with sapphire are pleonaste, zircon, tourmaline, enstatite, ilmenite and quartz.

Specimens of <u>sapphire embedded in basalt</u> have been found in the wash from Frazers Creek and the Waterloo Valley. Pleonaste has been found as xenocrysts in basalt near Reddestone Creek, between the headwaters of Maids Valley

Creek and Swanbrook, at the head of Horse Gully, near Sugarloaf Mountain, and at the Round Mountain and Snowy Creek near Ebor. Only pleonaste embedded in basalt was found in outcrop, but sapphire has not been found even where pleonaste is abundant in the basalt. Ilmenite has been found as xenocrysts in basalt from Round Mountain near Ebor and from the Horse Gully.

Sapphire was thought to form at some depth and occurs now as accidental xenocrysts in the basalt which acted as an intermediate source and brought the sapphire up to the surface.

According to Wellman and McDougall (1974), "The Cainozoic igneous activity in Eastern Australia is restricted almost entirely to the uplift region bordering the eastern margin of the continent... The triggering mechanism for the volcanic eruptions is thought to be related to the development of tensional stress in the lithosphere, allowing passage of magma from the upper mantle." This is another good evidence for the generation of corundum-bearing basalts at a deep level with accompanying tensional environment.

3. Scotland

a. The Island of Mull

The Island of Mull is situated on the southwestern part of Scotland. On this island, sapphire-bearing xenoliths in the composite sill are found at Mullach Glac an t'Sneacha. In general, the sills are of tholeiitic and andesitic character and penetrate the western part of Tertiary lava field (Thomas and Radley, 1922). All of the data which will be presented as follow come from the report of Thomas and Radley (1922).

They described the type example at Rudh' a' Chromain, west of Carsaig where the sill intruded the sandstone of Jurassic age. It is composed of acid and basic portions in the central part and at the margin respectively. The basic portion is in contact with the Carsaig sandstone on the west side and with an earlier intrusion of bostonite (a rock occurring in dikes and having the mineralogical and chemical composition of trachyte, except anorthoclase) which separate it from the Carsaig sandstone on the east.

The composition of the acid portion varies from rhyolite to felsite and is closely related to inninmorite (a rhyodacite having phenocrysts of highly calcic plagioclase or a glassy dike containing large phenocrysts of plagioclase and pyroxene in groundmass of sodic plagioclase, augite and glass). The composition of the basic portion is between basalt and augite-andesite or tholeiite. In general, the tholeiitic intrusions have produced little thermal alteration on the country rock.

Xenoliths occur sparingly throughout the sill, but are more abundant in basic portions. Xenoliths are mainly of sandstone which varies in size up to 15 cm. Large xenoliths of shale and sandstone which occur in the central portion have an average size of about 60 cm.

The upper basic member is divided into two zones; one is the outer zone which contains abundant cognate xenoliths of gabbroic character, the other is the inner zone which is crowded with accidental aluminous xenoliths. The lower basic member is characterized by cognate xenoliths. The size of xenoliths in all basic members varies from 2.5 cm up to 1.20 m in diameter.

The accidental xenoliths are divided into two classes as siliceous and aluminous xenoliths. Aluminous xenoliths are characterized by well-crystallized minerals such as corundum, spinel, sillimanite, cordierite, and anorthite. They occur in greater quantity than the siliceous xenoliths and have a greater average dimension.

Aluminous xenolith can be distinguished as the sillimanite- and cordierite-buchite assemblage, the anorthite-corundum-spinel assemblage, and the cordierite-sillimanite-spinel assemblage. All of these types may occur either in closely dependent association or as separated units. In some specimens, the xenoliths show an interior of sillimanite-buchite and outer zone of anorthite-corundum-spinel rock which separated the buchite from the tholeiitic magma. For details of different types of cognate xenoliths and accidental xenoliths see Thomas and Radley (1922).

Corundum always occurs as deep blue brilliant crystals of distinctly tabular habit. There are three modes of occurrences of corundum:

1. As isolated crystals in the sillimanite-buchite,

2. Associated with anorthite in the crystalline outer portions of the xenolithic masses, and
3. As well-formed crystal associated with spinel and oligolcase in a matrix of distinctly igneous nature.

Thomas and Radley interpreted from experiment and field evidence that aluminous xenoliths are formed at great depth by deep-seated metamorphism of aluminous rich rock. The metamorphism of xenoliths was completed before they were carried by the magma into their present position. The detail of texture and mineralogical relationship in xenoliths will be discussed later.

b. Aberdeenshire

Corundum-spinel xenoliths are found at an old quarry 274 m southeast of Mill of Schivas. Xenoliths are presented in the gabbro of Haddo House, Aberdeenshire (Read, 1931).

According to Read (1931), the gabbro mass has been found in the neighborhood of Haddo House, between Methlick and Ellon, 32 kms north of Aberdeen. The mass consists of two main rock-types, one as olivine-gabbro and the other as norite. The olivine gabbro is free from xenoliths of country rocks, but the norite contains such material. Siliceous, argillaceous, and calcareous types are all represented among these xenoliths.

The corundum-bearing xenolith, in general is not larger than 2.5 cm in diameter. The largest xenolith which was found is about 30 cm long, 15 cm wide, and 5 cm thick. Read classified corundum-bearing xenoliths into two groups: 1) Corundum, spinel and magnetite rock and 2) Corundum-biotite-cordierite-andesine-magnetite rock. The xenoliths are of sedimentary origin and corundum is formed by metasomatic effect of xenolith in magma.

Read also referred to some localities in which corundum-bearing xenoliths were found such as

1. Sapphire-spinel rocks which occur as xenolithic mass in hypersthene-gabbro ring dike of the Ardnamurchan Tertiary complex of west Scotland.
2. Corundum-bearing rocks found as xenoliths in the diorite of Reichelsheim in the Odenwald.
3. Corundum-spinel (which appears to show marked resemblances to the Haddo rock) occurs in diorite and norite of Klausen in South Tyrol.
4. Emery xenoliths found in the Cortlandt Series of Peekskill, New York.
5. Corundum-sillimanite rock found in norite of Bushveld.

4. Nigeria

Poor quality sapphire, zircon and green spinel are reported from Jemaa terrace gravel by Wright (1971). Sapphire and zircon are thought to be derived from Pilo-Pleistocene basalt sheet at Gimi River valley near Jemaa, southwest of Jos plateau. Spinel was not mentioned.

According to Wright (1971), the basalts are mainly alkali olivine basalt ranging from olivine and titanaugite-phyric types with basanitic affinities to relatively feldspathic varieties and carrying microphyric plagioclase. Brown glass is predominant in the groundmass of some rocks. Olivine nodules are also abundant, but the size is never greater than 2 cm in diameter. Small plagioclase grains which have a wide compositional range (An_5 to An_{50}) are also abundant.

Zircon which is thought to be derived from basalt differs from those which were derived from younger granites on the Jos plateau. The first is grey glassy prismatic crystal (4 mm in size), with W=1.93 and E=1.98, whereas the latter ranges from yellow to brown (less than 2 mm in size) and commonly turbid and rich in inclusion; with W close to 1.92 (Wright, 1971).

Wright (1972) in a more recent article concluded that corundum, spinel, zircon and olivine nodules may be derived from a source in the upper mantle. In the note added in proof, he referred to Dr. R. A. Binns who has recently reported 'fairly normal alkali olivine basalt deficient in normative diopside', carrying megacrysts of blue corundum. This evidence lead Wright (1972) to conclude firmly that the Nigerian corundum is derived from the Gimi basalt flows.

5. France, Germany, Eastern Europe and Madagascar

Corundum in these countries was mentioned by Barlow (1915) and Pirsson (1897). Unfortunately, no data in detail are available to the author. All of the occurrences of corundum in basalts and related rocks are shown in Appendix 2.

C. Summary of Geologic Occurrences

From the study in the first and the second chapter, it can now be concluded that:

1. Corundum has not been found in any kind of oceanic basalts, but has been found in continental basalts especially alkali olivine basalt.
2. Corundum has a close relationship to black spinel, sodic plagioclase, magnetite, ilmenite, zircon, clinopyroxene and pyropic garnet.
3. Spinel is the most common coarsely crystallized mineral associated with corundum deposits. Sodic plagioclase and pyropic garnet can occur in some deposits, but not all.
4. Large-grained crystals are characteristic of minerals which have been found associated with corundum in basaltic areas.
5. Corundum-bearing basalts often contain olivine nodules or dunite and pyroxenite xenoliths.
6. Corundum-bearing basalts, in general, are associated with tensional environment. Some corundum-bearing basalts in Thailand erupted in the upthrown block suggested the condition of magma generation in the deep level, probably in the mantle.

7. In general, sapphire found in basalt has better gem quality than that found in any other rock types. Basalt usually yields higher economic concentration of corundum than metamorphic rock.

IV. STRUCTURE, FABRIC AND MINERALOGICAL COMPOSITION OF CORUNDUM-BEARING BASALT AND RELATED ROCKS

A. Host Rocks

Corundum-bearing basalts in Thailand are olivine basalts or alkali olivine basalts. The rocks are holocrystalline and porphyritic. They consist mostly of olivine, augite and plagioclase phenocrysts set in a fine-grained groundmass of andesine-labradorite laths, olivine, calcic augite, magnetite and glass. Intersertal, ophitic and subophitic textures have sometimes been noted. Dunite or peridotite xenoliths are found at Phrae and Chantaburi.

In general, basalts in the areas of corundum deposits have fine- to medium-grained and glassy groundmass. The sample of basalt which contains one crystal of croundum is dark and dense. Basalts are vesicular or amygdaloidal, in general near the top of the flow. They are partly or wholly filled by calcite, chalcedony, chabazite and zeolite. The proportion of vesicles vary from place to place, for example, at Trat in the southeastern part of the country. However, corundum-bearing basalts seem to be characterized as moderately vesicular. Slaggy appearance can be noted from boulders in paydirt at Khao Ploi Waen, Chantaburi.

On the Island of Mull, corundum-bearing tholeiitic sill was reported by Thomas and Radley (1922). The rocks are dark grey and amygdaloidal with a fine texture of igneous aspect. Sapphire associated with aluminous xenoliths of all sizes is embedded in this rock. The tholeiitic sill consists of elongated irregularly-formed crystals of aluminous augite and feldspar which often show subophitic texture. The feldspar is normally zoned basic labradorite with its composition varying to oligoclase. Sub-variolitic and/or intersertal structures were also found and are abundant in the vitreous portion of the rock. The interstitial matter is devitrified and consists of sodic plagioclase and quartz. The rock contains a relatively small amount of magnetite, and abundant apatite in the form of slender needles. For the analysis of tholeiitic sill see Appendix 5. The petrographic characteristics of the xenoliths will be discussed under the heading "Xenoliths, Xenocrysts and Megacrysts."

Anakie corundum from Queensland, Australia is probably derived from Tertiary Hoy Basalt. This is composed of porphyritic olivine basalt, olivine dolerite and olivine gabbro, containing xenoliths of ultrabasic rocks, corundum and spinel. In Cooktown, Queensland, corundum is probably derived from McLean basalt, and Keyser and Lucas (1968) reported that "the basalt is generally a fine to medium-grained alkaline olivine basalt. Olivine analcitite and analcitite tuff have also been recorded, and one of the analcitites contains small crystals of nepheline. Some of the flows have a glassy groundmass containing small phenocrysts of olivine and less commonly pyroxene."

The other corundum deposits in Queensland (such as Jordan Creek, and Russel Gold Field, Huberton, and the Tully River south of Huberton etc.) are also poorly described. In the author's opinion, corundum may be derived from the four basaltic provinces there, i.e., Piebald basalt, McLean basalt, Atherton basalt and McBride basalt.

According to Keyser and Lucas (1968), basalts of the four provinces are generally porphyritic, and commonly vesicular or amygdaloidal. The amygdules are filled by calcite, chalcedony, zeolite and analcite. The rocks range from fine to coarse-grained. The most common phynocrysts are olivine and augite; plagioclase is less common. The texture ranges from holocrystalline to hypocrystalline. Intergranular texture is most common, but pilotaxitic, ophitic, subophitic, hyalo-ophitic, and intersertal texture have sometimes been noted. Xenoliths of quartz, quartzite, schist, granite, quartz-albite granulite, peridotite, amphibolite and gabbro(?) are common. Essential minerals in basalts are plagioclase (An_{60}-An_{75}), olivine, clinopyroxene, and iron oxide. Some of the basalts contain over 50 percent glass and palagonite.

According to Wilkinson (1966), the most common lava in Armidale, Glen Innes and Inverell areas, New England in New South Wales are alkali olivine basalt. The associated volcanic rocks include nepheline-basanites and olivine-nephelinites, analcime-basanites and olivine-analcimites, and ankaramitic types. Tholeiitic lavas also occur in the Inverell area. Binns and others (1970) described the rock at Glen Innes as a nepheline trachybasalt, at Guyra as olivine nephelinite. Wilkinson (1962) described the rocks at Spring Mount as analcite basalts. Basalts or related rocks of Glen Innes, Guyra and Spring Mount seem to be situated in or near the areas of corundum deposits which were indicated by McNevin (1971, 1972).

It can be summarized from reports of Wilkinson (1962, 1966), Binns (1969) and Binns and others (1970) that the rocks discussed above contain unaltered or slightly altered euhedral microphenocrysts of olivine (up to 1.0 x 0.5 mm) which are of normal composition at Guyra and Glen Innes (Fa_{13}-Fa_{20}) and less forsteritic (Fa_{30}) at Spring Mount. In general, the groundmass consists of zoned laths of plagioclase, euhedral titaniferous clinopyroxene (sometimes as phenocrysts), olivine, magnetite, nepheline, analcime and intersertal pale brown glass. Brown biotite, brown amphibole and alkaline feldspar microlites are occassionally present (e.g. at Spring Mount).

The composition of plagioclase ranges from An_{52}-An_{56} and An_{32}-An_{40} at road-cuts, 26.5 miles north of Guyra and at Spring Mount respectively.

In the United States, sapphire-bearing dikes are found in Montana. This rock may be related to basaltic rock. It is named altered analcime basalt by Pirsson (1897). It is characterized by dull-grey or greenish grey colour, fine texture with scattered flakes of dark brown biotite several mm in diameter, and has a spotted appearance due to the abundance of inclusion (Clabaugh, 1952). It should be noted that Clabaugh examined boulders and fragments of hard material discarded during mining operations.

According to Pirsson (1897), and Clabaugh (1952), this dike rock is chiefly composed of pyroxene and biotite; no feldspars are seen. Leucite(?) or analcite(?) fill the interstices between these two minerals. Pyroxene assemblages are diopside and hedenbergite or diopside, hedenbergite and aegirite, with the aegirite content higher in the marginal zones of the crystals. Most of biotite (which rarely shows crystal outlines) occurs in small grains that average 0.15 to 0.20 mm in length and 0.05 to 0.10 mm in width. Magnetite, averaging 0.05 mm in diameter, is scattered throughout the rock. Magnetite is most abundant in fine-grained mineral aggregates and interstitial material. Small crystals of apatite are common, especially as inclusions in biotite.

Pratt and Lewis (1905) and Pratt (1906) described corundum-bearing rocks from many localities in eastern United States especially in North Carolina. All of these rocks are dunite, pyroxenite, amphibole-peridotite, amphibolite and gabbro etc. For specific details of petrographic characteristics see Pratt and Lewis (1905) and Pratt (1906).

In the Lake Chatuge area in Georgia, the ultramafic, mafic, and metamafic rocks occur as a tabular unit between a garnet mica schist unit and a biotite gneiss unit. This ultramafic rock was interpreted to be a sill by Hartley (1973). According to him, the sill contains veins and/or pods of diallage and bytownite; hornblende, andesine, clinozoisite, and corundum; diallage; and hornblende. He explained that diallage-bytownite veins cut the center of the sill and show a progressive alteration into an assemblage of hornblende, andesine, clinozoisite and corundum as the margin of the sill is approached. These are mostly restricted to amphibolite, but some occur in dunite and in chlorite schist.

Corundum occurs locally as disseminated crystals. Several aggregates of corundum crystals contain a few percent of transparent mica (muscovite) between individual crystals. One crystal of corundum was found adjacent to a kyanite crystal.

It is thought (Hartley, 1973) that corundum forms from some of the alumina liberated from plagioclase during the change from bytownite to andesine during the metamorphism of diallage-bytownite veins located near the margin of the sill. He further postulated that most of the alumina probably goes into the formation of clinozoisite.

Hartley (1973) also described the corosion mantle which separates olivine from the feldspar in coronite troctolite in the Lake Chatuge area. This phenomenon is also reported by Pratt and Lewis (1905). The coronas commonly have two distinct zones. The zone adjacent to olivine is composed of orthopyroxene, while the zone adjacent to plagioclase is composed of green vermicular spinel approximately 3 to 8 microns in thickness, and pale bluish-green amphibole. Brown spinel occurs locally as anhedral crystals up to 1 mm in diameter, and locally clinopyroxene occurs between the rims.

B. Xenocrysts, Xenoliths and Megacrysts

In Thailand, it is found that corundum-bearing basalts are characterized by peridotite xenoliths and megacrysts of albite-oligoclase, black spinel, aluminous clinopyroxene, ilmenite, magnetite and zircon.

The peridotite xenoliths were noted by the author at Phrae and Chantaburi. Pothisat (personal communication, 1975) mentioned that Kanchanaburi basalt contains large grains of olivine. These are probably dunite xenoliths which are nearly identical with those of Phrae and Chantaburi basalts.

The peridotite or dunite xenoliths vary from a fraction of a cm to 5 cm in diameter. The shape of the xenoliths is angular to subrounded. A thin section from Phrae reveals that peridotite xenolith is composed dominantly of olivine (80%-90%) with a lesser amount of hypersthene and garnet(?).

Margins of peridotite xenolith show a slight reaction rim where orthopyroxene grains are in contact with the host basalt. Reaction has proceeded inward along grain boundaries converting orthopyroxene to turbid material, opaque minerals (magnetite) and small grains of olivine. Olivine was found to be the most stable mineral and shows no reaction with basalt. The reaction relationships are similar to those peridotite xenoliths in New South Wales, Australia, which are described by Wilshire and Binns (1961) and to peridotite in basalts of Minusa and Transbaikalian Region, USSR which are described by Kutolin and Frolova (1970). Thus, the Australian and USSR types of xenoliths seem to be represented in basalts of Phrae.

Corundum usually exhibits well-formed hexagonal crystals in all corundum deposits of the country and varies in size from fractions of a cm to 12 cm in diameter. The average grain size is about 3-6 mm. As known from local residents, sapphire of about 2.5-8 cm has been found in Chantaburi. Large hexagonal crystals of green-blue sapphires which are up to 9.5 cm x 6.0 cm x 5.5 cm (3,600 karats*) and 10.0 cm x 9.0 cm x 3.2 cm (2,250 karats*) in size, are found at Bang Kacha in Chantaburi and Bo Ploi in Kanchanaburi respectively. At Phrae, corundum crystals about 3-5 mm

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* 1 karat = 0.2 gram

in diameter are found; large crystals up to 1 cm are rarely found. At Trat, the third geographic or ruby zone, the shape of ruby is angular, occasionally with crystal faces. Those with grain size of about 2 mm or smaller are found in a greater quantity than those of 3-5 mm. Ruby of about 30 karat (about 1-1.5 cm in diameter) is found at Ban Tak Wang, Trat province.

Corundum embedded in basalt is rarely found. Only one sample was collected from alluvial deposit at Ban Bang Kacha in Chantaburi and is now on display in the Mineral Museum of the Department of Mineral Resources, Bangkok, Thailand. A thin section of this basalt reveals that there are phenocrysts of olivine and augite set in a dense, fine-grained groundmass of plagioclase, olivine and pyroxene.

Isolated single crystals of black spinel (2 mm-5 cm) and feldspar (1-10 cm long and 0.5-1.5 cm wide) were noted by the author at Phrae and Chantaburi and at Trat by Pothisat (1972). Well-formed octahedral crystals of black spinel and ruby spinel (rare and found only at Phrae) were found in the stream gravels. Magnetite (2-5 mm) embedded in basalts was reported from Trat by Pothisat (1972) and from Phrae by the author. Garnet embedded in basalt is found only at Ban Nong Bon in Trat (Pothisat, 1972). This garnet was shown to be pyropic garnet (see detail chemical composition under the heading "Geochemistry of Corundum-bearing Basalt.").

Large grains of minerals such as pyropic garnet, biotite, aluminous clinopyroxene, ilmenite, magnetite and black spinel are found associated with corundum in the stream or placer deposits (in or near basaltic terrains) of Thailand. They may be megacrysts, composite megacrysts or mineral assemblages of certain types of xenoliths (e.g. peridotite or eclogite) which have been eroded from the host basalt. However, large grained crystals, a vitreous appearance, and conchoidal or subconchoidal fracture, are characteristics of these minerals. These evidences support the postulate that all of these minerals are megacrysts.

Basic and ultrabasic xenoliths found in basalts in Queensland, New South Wales, are predominantly peridotites. Peridotite nodules in the four basaltic provinces in Queensland* are composed of olivine, enstatite, clinopyroxene, and some olivine to brown-green spinel. D. H. Green (in Keyser and Lucas, 1968) has identified the clinopyroxene as chrome diopside and the spinel as chromium bearing. Peridotite is thought to be derived from the upper mantle. Lucas and Keyser (1968) also mention that the effects of postcrystalline stresses are also observed in peridotite inclusions. In North Queensland, the olivine is granulated and annealed, and the pyroxene shows bending, including some kink-banding.

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* It should be noted that no available data of corundum-bearing basalts in Queensland are known to the author. He attempts to correlate these basaltic provinces with corundum deposits in the nearby areas. So, the basalts of the four provinces may or may not be the source of corundum.

Sapphire, pleonaste and ilmenite are reported as xenocrysts embedded in basalts at New England district in New South Wales by MacNevin (1971, 1972). According to him, sapphire and pleonaste have fine reaction rims with basalts and occur as discrete grains. There is no aluminum-rich halo in the basalts around them and there are no small corundum grains in the basalts in thin section.

Sapphire occurs usually as subangular crystal fragments showing some crystal faces. A few grains have been well rounded. It varies from 3 mm to over 25 mm across the prism. Sapphire specimens up to 40 karats also have been found (MacNevin, 1972).

Lherzolite inclusions, commonly 5 cm and occasionally up to 20 cm in size, occur abundantly, except at Spring Mount and Glen Innes where they are comparatively rare. Inclusions of dunite, orthopyroxenite, harzburgite, wehrlite, and gabbro, and the fragments of granite and metasedimentary basement rocks have also been observed. These inclusions are smaller than lherzolite (Binns and others, 1970).

In general, lherzolite consists of medium to coarse-grained (1-5 mm) aggregate of olivine, enstatite, chrome diopside and red-brown picotite. The composition of olivine is iron-rich. It ranges from Fa_{11} to Fa_{18} and enstatite ranges from Fs_9-Fs_{16}. The clinopyroxene are Ca-rich and contain substantial Ca-Tschermak's and jadeite components, and are nepheline normative (Binns, 1969;

Binns and others, 1970).

Binns and others (1970) reported that alkaline lavas from northeastern New South Wales contain a number of megacryst species. These include olivine, orthopyroxene, clinopyroxene, kaersutite (a black number of amphibole groups of minerals; titanium hornblende from kaersut, Greenland), titanbiotite, plagioclase, anorthoclase, spinel, titanomagnetite, and ilmenite.

According to them most megacrysts in New South Wales are single crystals, occasionally with recognizable habit but with the forms often modified by corrosion or fragmentation. A vitreous appearance and conchoidal or subconchoidal fracture are characteristic features of most megacrysts. Exsolution phenomena and deformational structure are rare. In general, megacrysts are extremely homogeneous in composition.

Binns (1969) also reported composite megacrysts from Armidale, but they are comparatively scarce. The assemblages are: 1) clinopyroxene-kaersutite-spinel-ilmenite 2) clinopyroxene-spinel-olivine 3) clinopyroxene-spinel and 4) clinopyroxene-orthopyroxene. No composite particles containing anorthoclase or zircon were recorded.

According to him, most megacrysts and composite particles show evidence of reaction with the enclosing analcime basanite or basanitoid. Clinopyroxenes have narrow marginal zones clouded by an abundance of tiny inclusions. Spinel and ilmenite are rimmed by magnetite.

Anorthoclases are surrounded by narrow zones of plagioclase. Kaersutite margins show no pronounced reaction coronas but may be clouded with tiny opaque inclusions. Their width rarely exceeds 50-100 μ.

In Rhodesia and Tanzania, corundum is found in the Eclogite association which is garnet-corundum and clinopyroxene-garnet-kyanite-corundum (Mathias and others, 1970). According to Mathias and others, the first contains corundum which shows excellent multiple twinning. The garnets are pale gold in colour and some are partially and heavily altered in different specimens. The alteration product is greenish spinel. The second contains small elongated colourless crystals of high refractive index. These were invariably present as inclusions in altered material within the kyanite crystals or in its immediate vicinity. Some of these crystals proved to be kyanite but some are corundum (Mathias and others, 1970).

In the Island of Mull, two types of xenoliths have been recognized, cognate and accidental xenoliths (Thomas and Radley, 1922). Cognate xenoliths are characterized by glomeroporphyritic bytownite and augite or bytownite and idiomorphic crystals of hypersthene. The accidental or aluminous xenoliths are characterized by well-crystallized minerals such as corundum, spinel, sillimanite, cordierite and anorthite. The aluminous xenoliths are present in three distinctive types as discussed below. All of the descriptions come from the report of Thomas and Radley (1922).

1. The sillimanite- and cordierite-buchite. These rocks are composed essentially of glass with one or more crystalline phases of sillimanite and cordierite. They are compact, vitreous, gray-blue rocks, consisting of glass in which the abundant needles of sillimanite are usually arranged in a parallel manner.

2. The anorthite-corundum-spinel assemblage. The assemblage is an almost holocrystalline mixture of these minerals.

3. The cordierite-sillimanite-spinel assemblage. This assemblage is less common than group 2.

Symmetrical xenoliths show zoned mineral assemblages. The inner zone is composed of sillimanite-buchite, while the outer zone contains scattered feldspar crystals, often skeletal in form, gradually becoming more abundant toward the outer margin to form a crystalline feldspathic zone. This zone is often several centimeters thick and rich in corundum and spinel which separates the sillimanite-buchite from the enclosing tholeiite.

Thomas and Radley (1922) also divided the feldspathic zone (the second assemblage) into two subzones. The inner subzone is rich in corundum and contains a minor amount of spinel. In contrast, the outer subzone is rich in spinel and minor amounts of corundum. In general, almost all of the xenoliths show zonal arrangement, but not always of a symmetrical character. The xenoliths usually show quite sharp contact with the surrounding tholeiite.

The anorthite-corundum-spinel assemblage resembles the corundum-spinel xenoliths in the gabbro of Haddo House rocks, Aberdeenshire (Read, 1931). According to Read, the xenoliths are classified into two groups; one as corundum-spinel-magnetite and the other as corundum-spinel-biotite-cordierite-andesine-magnetite rocks.

Thomas and Radley (1922) proposed that sillimanite formed from the metamorphosed aluminous sediments, partly a product of direct vitrification and partly as a primary phase separated from the original aluminous melt as temperature decreased. Corundum crystallized from the excess of alumina which remained after the formation of sillimanite, and was the first phase to separate from the fused aluminous melt.

Thomas and Radley suggested that the second assemblage resulted from reaction between tholeiitic melt and aluminous xenoliths. Xenoliths absorbed Ca^{++}, Fe^{++}, Mg^{++} from the tholeiite which resulted in the formation of anorthite enclosing corundum, spinel (deep green variety-hercynite-pleonaste) and sillimanite. Further action by magma lead to the crystallization of cordierite and spinel (depending on available magnesia) or cordierite and corundum and oligoclase.

Spinel in the outer zone is black, brown or dark plum colour and is in well-shaped octahedra. It formed from anorthite (which contains sillimanite inclusions) that has been resorbed by magnesium-rich magma; the excess of alumina precipitated as spinel and was accompanied by oligoclase and glass. This feldspar crystallized late, but prior to the eruption of the magma.

Corundum in Montana is found in a lamprophyric dike which also contains xenoliths. Limestone fragments are the most common xenoliths in the dike. Weed (Clabaugh, 1952) noted xenocrysts of quartz, calcite, and pyroxene which represent altered fragments of sedimentary rocks carried up in the molten mass as the dike was formed.

Clabaugh (1952) found several small xenoliths of a rock containing kyanite, quartz and calcite. Kyanite is not as abundant as quartz in granular xenoliths. Marginal grains of kyanite reacted with the lamprophyric magma to produce clots and rims of dark-green spinel. The spinel occurs as clusters of extremely small crystals joined together in moss-like, dendritic aggregates, associated with fine-grained, olivine-green biotite and an almost opaque brownish black mineral.

It will be seen that spinel crystallized from the reaction between aluminous-rich mineral (kyanite) and magma. This reaction is the same as that in the Island of Mull which show crystallization of spinel from sillimanite and might be the same case as that of the kyanite eclogite xenolith which later, forms a corundum eclogite as indicated by Mathias and others (1970).

The above data suggests the postulate that corundum can form from the excess of alumina which remains after the formation of sillimanite or kyanite and by the liberation of alumina from resorbtion of feldspar (anorthite and bytownite). This hypothesis is supported by the evidence from Mull, Montana and Georgia.

Mathias and others (1970) proposed another type of genesis of corundum, i.e. in eclogite xenoliths. Unfortunately, no eclogite is known to the author from the areas of corundum-bearing basalts. Lherzolite xenoliths from New South Wales also contain no corundum. It seems unlikely for corundum genesis in Thailand and Australia.

Another fact which should be noted is that orthopyroxene is rarely found in the areas of corundum-bearing basaltic terrains. Zircon in the stream gravel in New South Wales and Thailand are of hyacinth habit, and probably the same in Nigeria as reported by Wright (1971). Zircon of this composition was interpreted to be derived from the deep source in the upper mantle (Wright, 1971, 1972).

Garnet is found embedded in basalt in Thailand and also found associated with corundum in placer deposits. This mineral, in general, has been interpreted to form at high pressure.

Large grains of aluminous clinopyroxene, black spinel, biotite, magnetite and ilmenite etc., have been interpreted as megacrysts of high pressure origin. All of these minerals have been found associated with corundum in the deposits. This evidence combined with the evidence discussed above, leads to another postulate for the genesis of corundum: corundum crystallize as megacrysts from basaltic magma at high pressure.

V. GEOCHEMISTRY OF CORUNDUM-BEARING BASALT

Only a few chemical analyses of basalts in Thailand are available. The characteristics of corundum-bearing basalts and (unreported) corundumless basalts from 24 chemical analyses (which are shown in Appendix 3) are compared with field evidences and mineralogical composition of the rocks. The distribution of basalts in Thailand is shown in figure 10. The analyses were done by wet chemical analysis and by atomic absorption method for Na and K. The samples may or may not represent typical corundum-bearing basalts in each area.

Figure 12 shows a plot of total alkali-Al_2O_3 diagram developed by Kuno (1960) to distinguish between volcanics of the tholeiitic, high alumina and alkaline series. A plot of alkali-SiO_2 is also shown, developed by Macdonald and Katsura (1964), to distinguish between alkaline and tholeiitic series.

On the basis of this plot practically all of the corundum-bearing basalts are classified as alkaline except at Phrae province which falls into tholeiitic series. It should be noted that this is based on only one analysis of basalt from this area. From the study of textural and mineralogical composition of the rock, this basalt seems to be alkaline basalt or alkali-olivine basalt. Because the peridotite xenoliths generally are absent in tholeiite*

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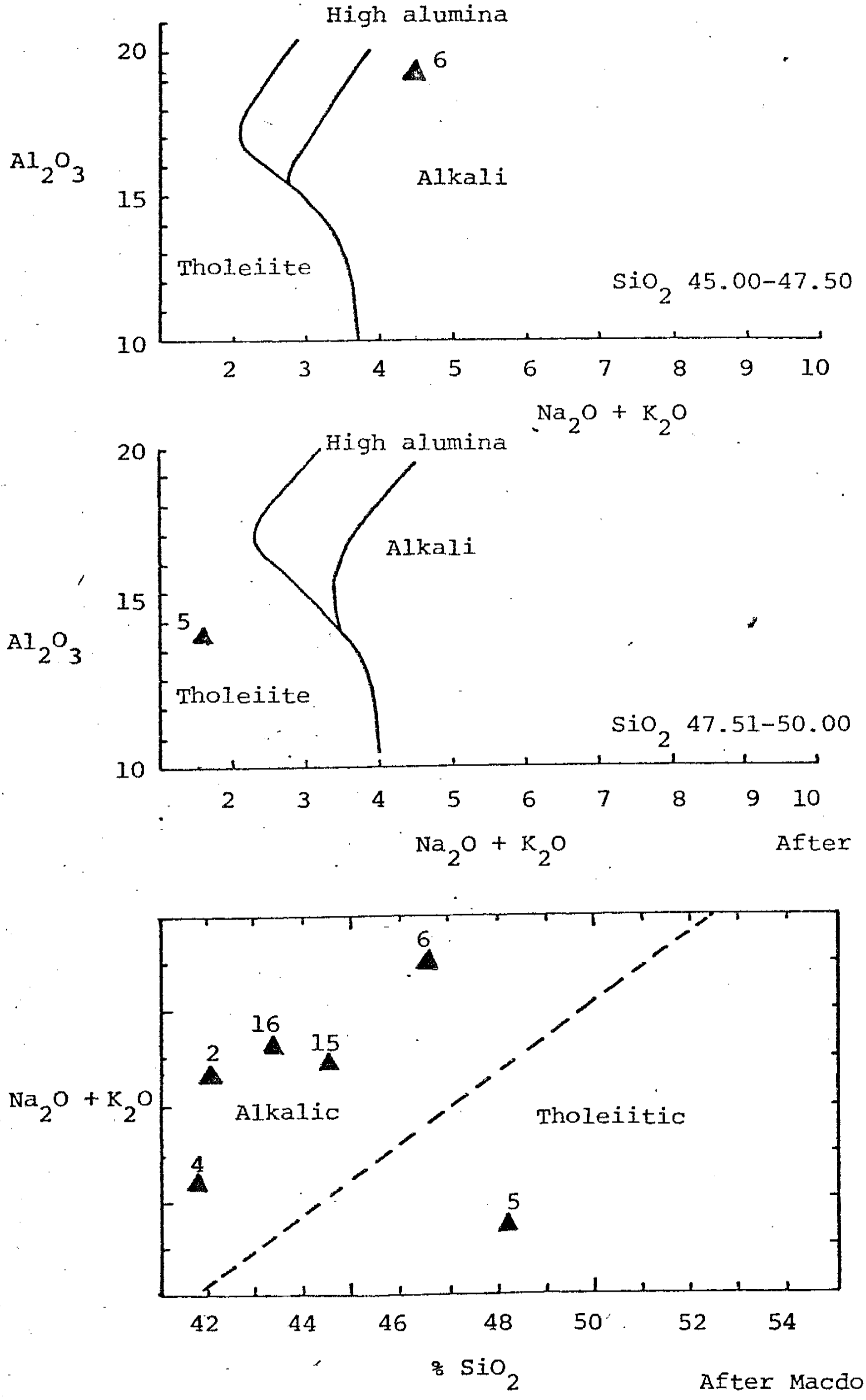
* It should be noted that lherzolite xenoliths in olivine tholeiite were recently reported from the Tasmanian Tertiary volcanic province by Sutherland (1974).



After Kuno (1960)

After Macdonald and Katsura (1964)

Figure 12

No. 2 and 4	Corundum bearing from Trat province (zone of blue and red corundum)
No. 5	Corundum bearing from Phrae province (blue and green sapphire)
No. 6	Corundum bearing from Kanchanaburi province (blue and green sapphire)
No. 15 and 16	Corundum bearing from Chantaburi province (zone of blue, green and yellow sapphire)

(Kuno, 1959) and the mafic or ultramafic xenoliths are rarely found in subalkali basaltic rocks; nepheline-barren alkali basaltic lava have gabbro, pyroxenite, spinel-peridotite and sometimes eclogite nodules (Macgregor, 1968). Thus, the Phrae basalt tends to be of alkaline type. This is also supported by textural evidence which has been discussed previously (page 71).

On the solidification index aspect (see Appendix 4) which was proposed by Kuno (1969), the SI values of corundum-bearing basalts in the southeastern part of Thailand lie between 21 to 27.2; those from Kanchanaburi and Phrae have SI values up to 34.1 and 37.7 respectively. Corundumless basalts from Loei province which have nearly the same silica range as corundum-bearing basalts (see analysis No. 7-10) show SI values lying between 24.0-35.6; the Kantaraluk basalts have SI's between 22.0-27.0; and basalts from Nakornrajasima have SI's of about 24.0

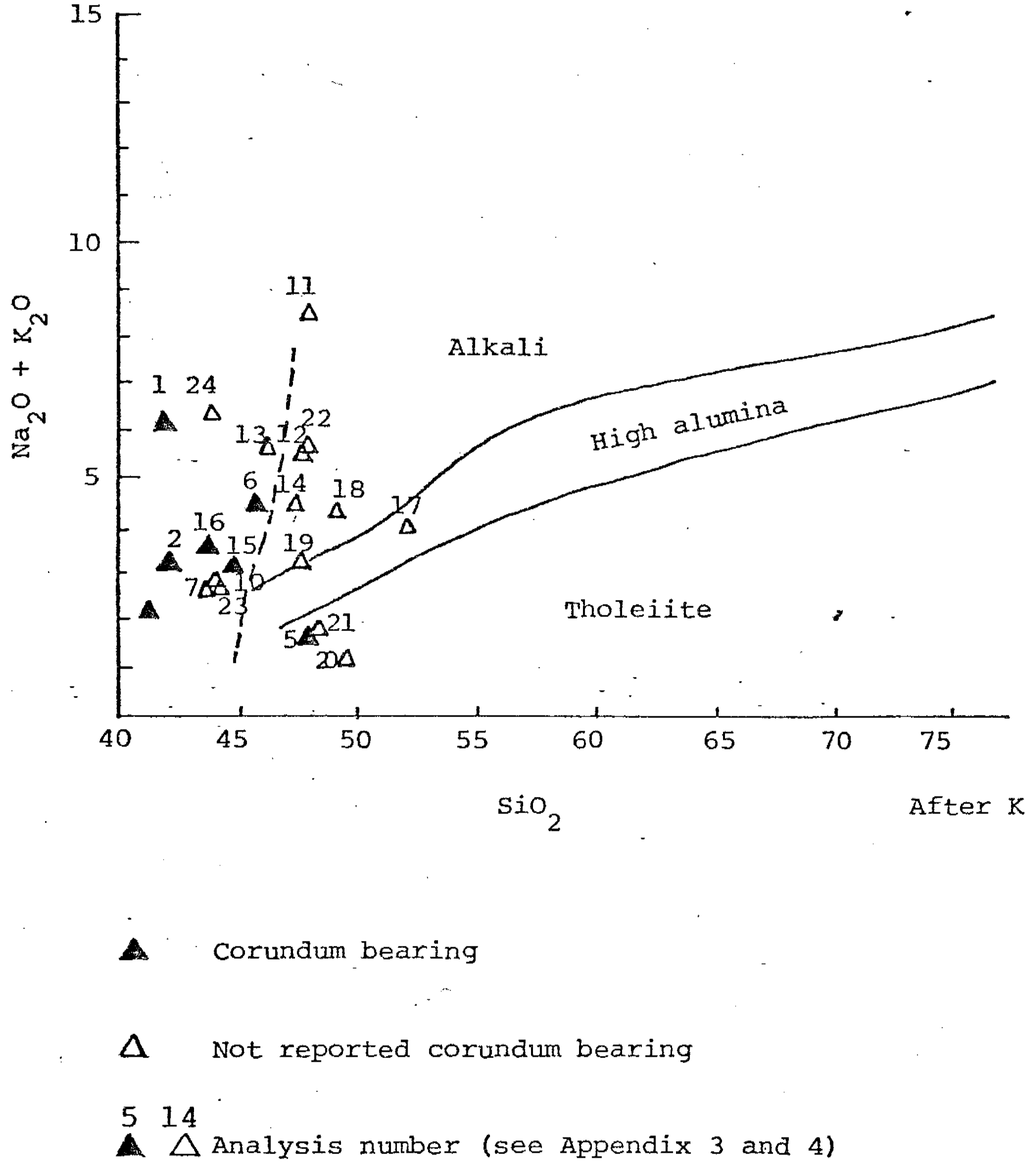
The difference in SI values of corundum-bearing basalts and corundumless basalts can not be sharply distinguished. However, corundum-bearing basalts in the southeastern part have the SI values less than 30 which differs from Phrae basalts and Kanchanaburi basalts in the northern and central part of the country respectively.

According to Kuno (1969), SI values which are less than 35, lead us to suspect that corundum-bearing basalts in the southeastern part of Thailand probably have undergone differentiation and tend toward the iron and titanium (or alkali) enrichment before erupting to the surface. Phrae and Kanchanaburi imply little or no differentiation.

The basalt at Phrae is different from the other corundum-bearing basalts which implies that the genesis of this basalt is probably also different. It should be noted that basalt at Phrae does not yield high concentrations of corundum. The grain size of corundum there is smaller than that of the other areas.

A plot of $(Na_2O+K_2O)-SiO_2$ which was proposed by Kuno (1966) is shown in Figure 13. A plot of the MFA diagram is shown in Figure 14. The plots show nicely that corundum-bearing basalts tend to group separately from corundumless basalts. Some of the latter, in which corundum has not been reported such as No. 7 and 10, 23 and 24 from Loei, Lampang (at Pa-Lad) and Sraburi provinces fall into corundum-bearing group. This implies that these basalts are favorable for corundum occurrences.

Chemical analyses in Appendix 5 and Figure 12 lead the author to conclude that corundum-bearing basalts in Thailand have low silica content; those in the southeastern part range from 42.0-44.5%; those in Kanchanaburi and Phrae are 46.5 and 48.1% respectively. The percentages of total iron (as total FeO) and TiO_2 are also high compared to corundumless basalts. The iron content of corundum-bearing basalts is greater than 10% and the TiO_2 ranges from 1.84-2.96%. Generally, in the southeastern part, basalts show high values of TiO_2 from 2.58-2.96%. But,



After Kuno (1966)

Figure 13. A plot of ($Na_2O + K_2O$) versus SiO_2 of corundum-bearing basalts and corundumless basalts from Thailand. Dash line nicely separates the field of corundum bearing from corundumless basalts.

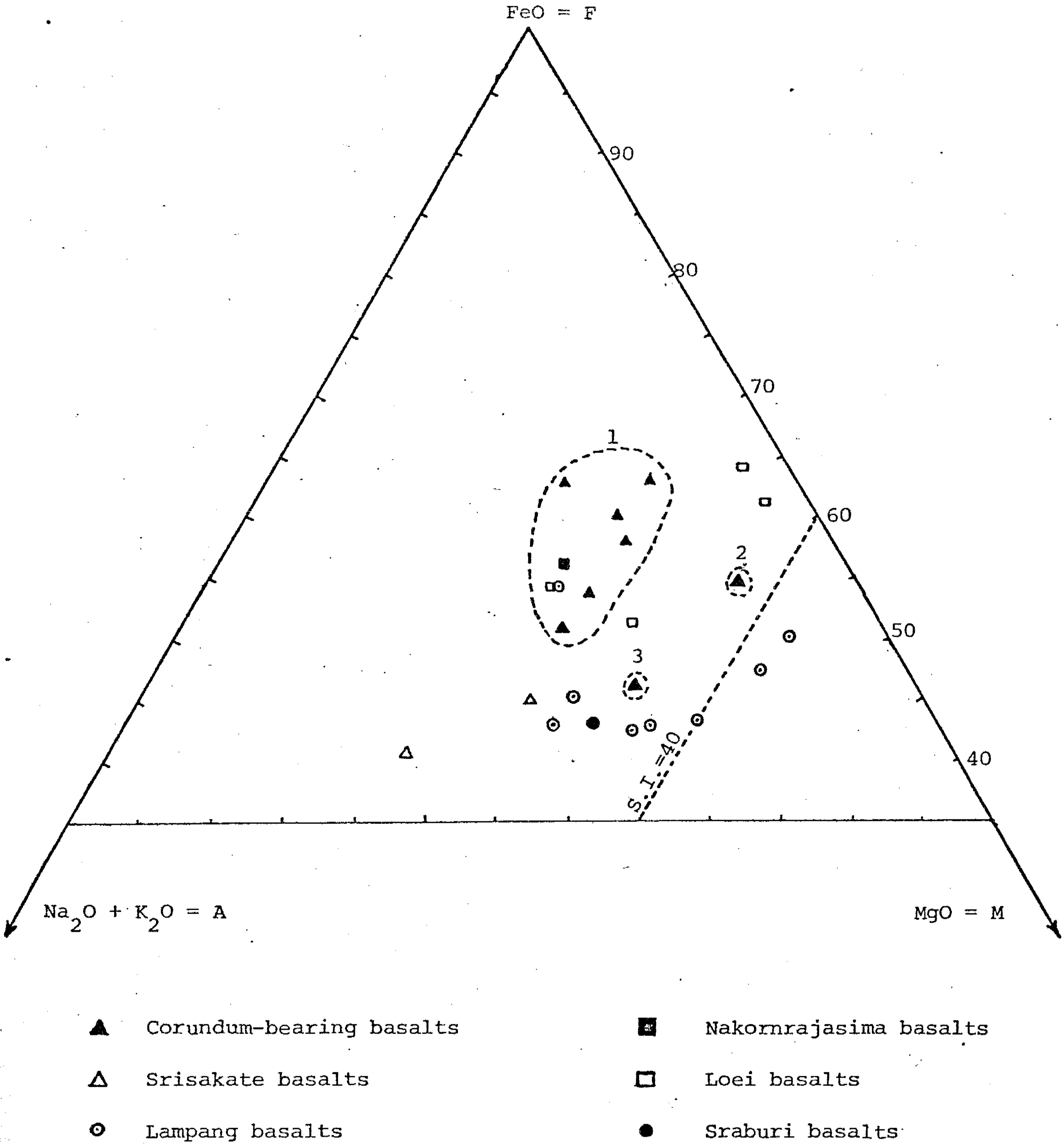


Figure 14. A plot of MFA diagram showing corundum-bearing and corundumless basaltic fields from Thailand. Dash-cricles No. 1, 2, and 3 are corundum-bearing basalts from Chantaburi and Trat, Phrae and Kanchanaburi respectively.

at Phrae they yield lower values than the above (1.84%). Basalts from other provinces for which corundum has not been reported also show high values of TiO_2 (1.87-2.05%) e.g. at Lampang and Loei provinces. High titanium concentration may be related to higher pressure of magma generation in the deep level, probably in the upper mantle (Macgregor, 1969; Renault, 1970).

Al_2O_3 cannot be compared accurately because of the difference in silica percentage. In general, percentage of Al_2O_3 in corundum-bearing basalts varies from low (12.19%) to high (19.91%) and corundumless basalts show rather high percentage of alumina (up to 20.54, see Appendix 3, analysis No. 20).

The chemical analysis of tholeiite from Mull, Scotland and analcime basalt (dike rock) from Yogo Gulch in Montana are shown in Appendix 5 (analysis No. 8 and 12). Both rocks have rather low alumina percentages: 14.65 and 11.93 respectively.

The silica content of tholeiite and lamprophyric (dike) rock is also low. Analcime basalt from Montana shows markedly high content in MgO and CaO and low in Fe_2O_3 and FeO. Tholeiite from Mull has low values of MgO and CaO and high value of K_2O (1.52%). However, the results of chemical analysis cannot precisely be interpreted as a typical composition of corundum-bearing rocks because it is only one analysis from each area.

If we compare the chemical composition of basalt from New England district, N.S.W., Australia (Appendix 5, analysis No. 1) with alkali olivine basalts from Hawaii and from Japan and Korea (Appendix 5, analyses No. 9, 10 and 11 respectively); the New England basalt does not show significant difference in chemical composition from the other two areas. This may be because either (1) the tectonic environment is different or (2) the basalt from New England is not the representative type of corundum-bearing basalt.

It should be noted that basalts and associated rocks in New South Wales generally contain residual glass. According to Wilkinson (1966), the analysis of glass from alkali olivine basalt reveals appreciable normative corundum. Two analyses from Wilkinson's article show glass containing 3.88 and 4.99% corundum in the norm. The compositions of glass from alkali olivine basalt and nepheline-basanite are alkali trachytic and phonolitic in composition respectively. The glass analyses show marked decreases in $FeO+Fe_2O_3$, MgO and CaO, and increases in SiO_2, Na_2O, Al_2O_3 and K_2O. The chemical composition of alkali olivine basalt which contains glass as indicated above is shown in Appendix 5, analysis No. 1.

Two chemical analyses of garnet are shown in Table 3. The sample G1 and G2 were analyzed by Mrs. Lynn A. Brandvold and Mr. Jospeh Taggart of the New Mexico State Bureau of Mines and Mineral Resources, Socorro, New Mexico respectively.

TABLE 3. Chemical analyses of Garnet from Thailand

	G1	G2*
SiO_2	44.74	44.42
TiO_2	0.75	-
Al_2O_3	22.62	21.58
Fe_2O_3	14.08**	-
FeO	-	9.57†
MgO	15.70	19.71
CaO	2.08	3.22
Na_2O	0.04	-
Cr_2O_3	-	0.23
MnO	0.35	1.02
Moisture	N.D.	-
L.O.I.	N.D.	-
Total	100.36	99.75

* Calculated from electron microprobe analysis by Dr. J. R. Renault

** Total iron as Fe_2O_3

† Total iron as FeO

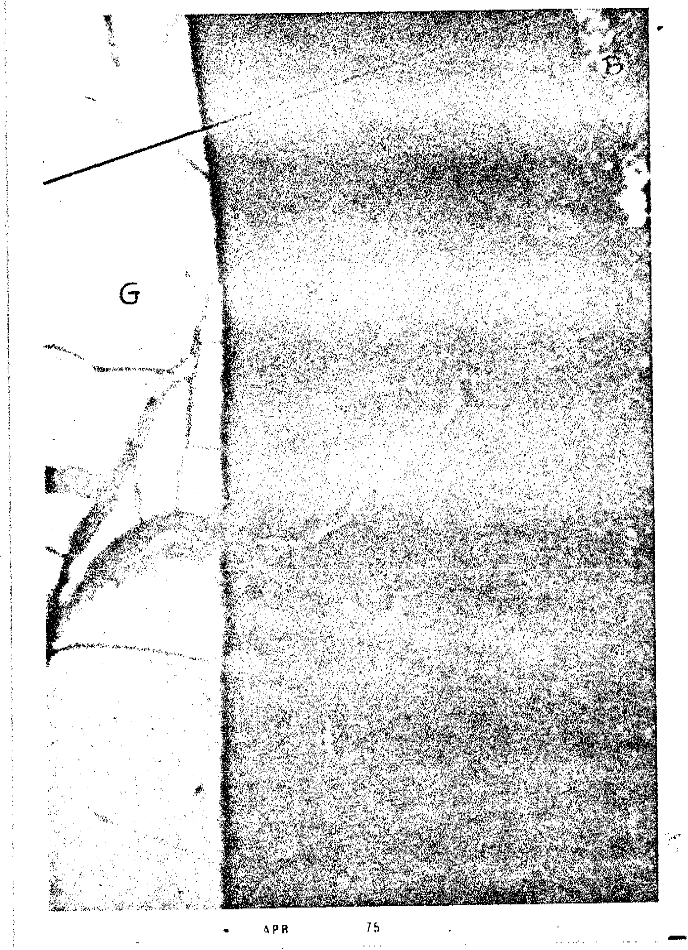


Figure 15 showing reaction rim between garnet and basalt from Ban Nong Bon, Trat province, Thailand. G = Garnet, B = Basalt, R1 = Reddish brown zone, R2 = Gray zone. The line indicates electron microprobe scan. Ordinary illumination.

Figure 16 showing reaction rim between garnet and basalt from Trat province, Thailand (the same specimen as figure 15). G = Garnet, B = Basalt, R1 = Reddish brown zone, R2 = Gray zone. Ordinary illumination.

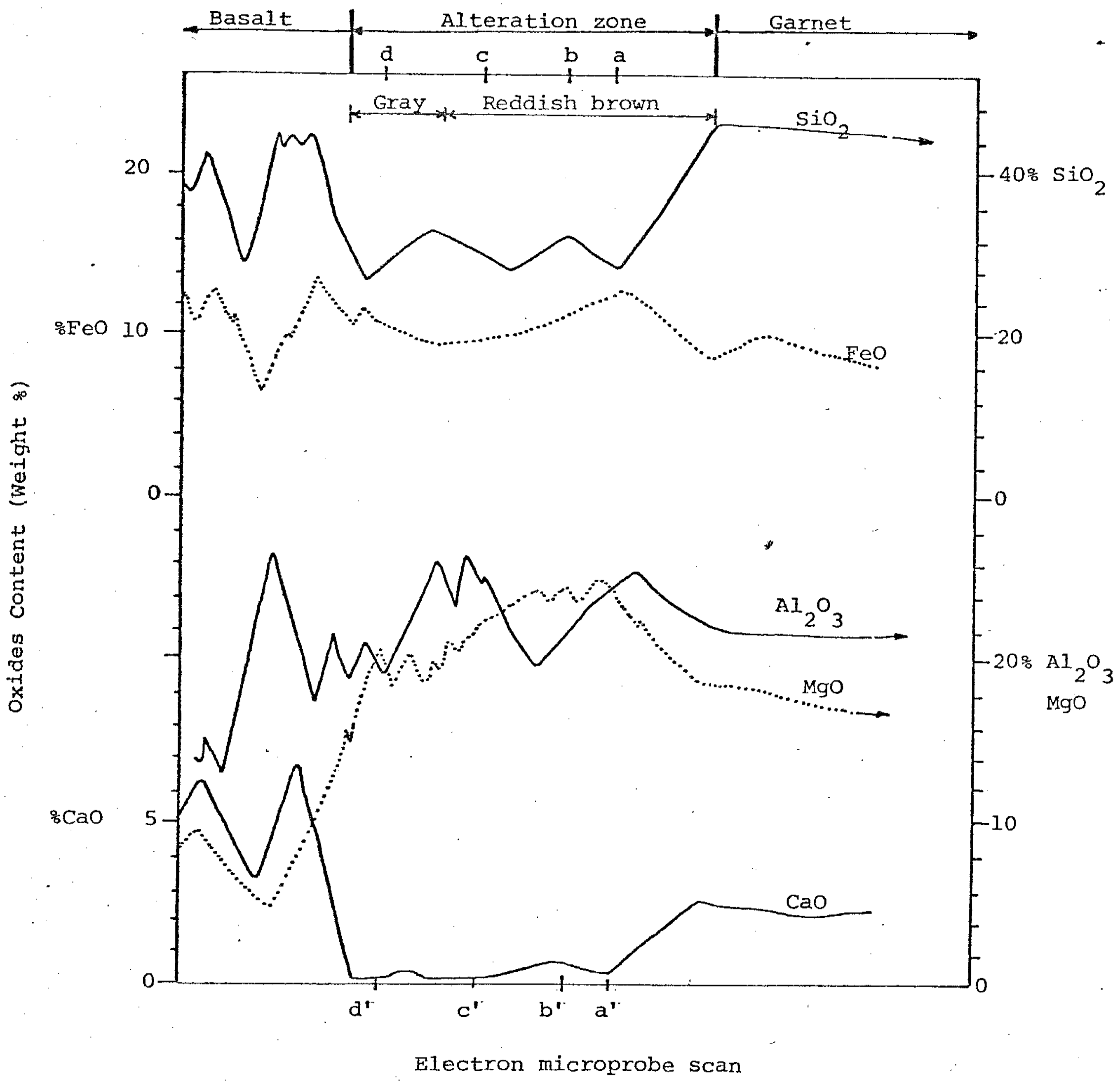


Figure 17 showing oxides content (from electron microprobe analysis) in alteration zone between pyropic garnet and basalt from Thailand. The width of alteration zone is approximately 0.8 mm.

Electron microprobe analysis (sample G2) of garnet embedded in basalt from Trat indicates nearly the same chemical composition as garnet (sample G1) recovered from residual basaltic soil in corundum area at Khao Ploi Waen, Chantaburi, Thailand. Both are pyropic garnet. It can be now firmly concluded that garnet associated with corundum in the stream or alluvial deposits or from residual basaltic soil is of igneous origin, that is, it comes from basalt. The electron microprobe analysis shows that the pyropic garnet which is embedded in basalt is zoned; the inner zone contains more iron and magnesium than the outer zone. A thin fibrous reaction rim (0.8 mm) has been noted. In this rim, there are two colour zones; the one adjacent to basalt is gray and the other adjacent to garnet is reddish brown. See figure 15 and 16. The fluctuating composition of iron, magnesium, silicon and alumina in the rim between basalt and garnet is shown in figure 17.

The reddish brown colour zone in the rim has the average composition (along the lines a-a', b-b' and c-c' in figure 17) of 30.48% SiO_2, 23.65% Al_2O_3, 11.42% FeO, 23.91% MgO and 0.35% CaO. The gray colour zone in the rim composes of 30.00% SiO_2, 19.00% Al_2O_3, 10.80% FeO, 20.89% MgO and 0.21% CaO (along the line d-d' in figure 17).

The reaction rim implies the instability of garnet in basaltic magma at low pressure. Pyropic garnet is thought by many authors (e.g. Green and Ringwood, 1967; Yoder and Tilley, 1962; Mathias and others, 1970) to be formed at great depth in the mantle. Thus, the garnet initially formed at some depths and was brought by alkali olivine basalt magma to shallower levels.

The chemical composition of clinopyroxene from Khao Ploi Waen, Chantaburi, Thailand, demonstrates that it is aluminous clinopyroxene. In comparison with other clinopyroxene megacrysts and clinopyroxene xenocrysts in ultramafic xenoliths of the other areas (see Appendix 7), clinopyroxene from Thailand has higher SiO_2, Na_2O and is lower in CaO and MgO content. It is rich in Fe and Ti which are comparatively the same as clinopyroxene from other areas. High Na in pyroxene from Thailand is reflected in high jadeite component.

Titaniferous pyroxene or Ti-Al rich pyroxene is characteristically found in undersaturated alkaline basalts. It is an indicator of the alkalic suite (Macdonald and Katsura, 1964). This fact leads the author to conclude that corundum-bearing basalts in Thailand are of the alkaline type. The interpretation of whether or not titanium-aluminous clinopyroxene from corundum-bearing basalts in Thailand is of megacryst or xenocryst origin in ultramafic xenoliths is uncertain from only one chemical analysis. However, the physical characteristics of this clinopyroxene (e.g. large grain and concohoidal fracture) imply that it is a megacryst.

Electron microprobe analysis of a sample of zoned (blue and pale blue) sapphire from Thailand reveals that there is a fluctuation change of iron content while alumina is still nearly constant across the zones of sapphire. Only a trace amount of Ti was detected.

VI. DEPTH OF ORIGIN OF ALKALINE BASALTS CONTAINING MEGACRYSTS AND MAFIC XENOLITHS

Yoder and Tilley (1962) reported from their experimental studies that alkaline basalt can be derived from olivine tholeiite magma at depths of approximately 60 km. MacGregor (1969) indicated that alkaline basalts are formed in the depth range of approximately 30 to 60 km.

According to Green and Ringwood (1967), aluminous orthopyroxene or orthopyroxene + subcalcic augite can be separated from tholeiite by fractionation at about 35 to 70 km depth (corresponding to pressures of 13.5 to 18 kilobar*). The fractionation trend yields olivine-rich, alkaline basaltic magmas. They also mentioned that a liquid of alkali olivine basalt can be produced at depth 35 to 70 km by 20 per cent partial melting of hypothetical mantle material (pyrolite) and also yields residual olivine + aluminous orthopyroxene ± aluminous clinopyroxene. More details of fractionation of alkali olivine basalt at different depth will be discussed later (page 110).

Mafic or ultramafic xenoliths, for example: spinel peridotite (MacGregor, 1974) or lherzolite (Green and others, 1968; Bacon and Carmichael, 1973) have been interpreted to represent accidental fragments of the mantle (Green and Ringwood, 1967; Green and other, 1968; Kutolin

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* For general conversion, 1 kolobar (kb) is approximately equal to 3.5 kilometers.

and Frolova, 1970; Bacon and Carmichael, 1973; MacGregor, 1974). They may have originated by partial melting of less refractory material within an inhomogeneous mantle (Binns and others, 1970).

Megacrysts, in general, are interpreted to form at high pressure, i.e. in the deep crust or upper mantle. They have been interpreted to be of cognate origin or to have crystallized from their host basalts (Binns, 1969; Binns and others, 1970). However, Irving (1974) pointed out that host basalts may not necessarily represent parental magmas of the megacrysts they contain.

Many authors (Green, 1968; Wilkinson, 1973; Bacon and Carmichael, 1973) think that megacrysts originated at great depth. The temperature and pressure of formation of lherzolite, peridotite and megacrysts are shown in Tables 4 and 5. The interpretation of formation for suites of ultramafic xenoliths from alkaline basalts and kimberlite is also shown in figure 18.

Alkaline basalt, which generally contains xenoliths and xenocrysts of high pressure origin, is rich in normative olivine. For this reason, Green (1968) concluded that it is the parental magma which is derived by partial melting of peridotitic source rocks. It probably generated in the deep crust or upper mantle. Schwarzer and Rogers (1974) also concluded from their study that alkali olivine basalt magma is generated in the upper mantle.

From the data presented above, it can be seen that

TABLE 4. Temperature and pressure of xenoliths in equilibrium with host rocks

Host Rocks	Xenoliths	Temperature °C	Pressure (kb)	Depth (km)	References
Alkaline olivine basalt	Lherzolite	1360	28.5	99.8	Bacon and Carmichael (1973)
	"	1395	31.2	109.2	"
	"	1330	27.5	96.3	"
	"	1360	30.1	105.4	"
	"	1375	29.0	101.5	"
	"	1410	31.6	110.6	"
Alkaline olivine basalt	Lherzolite	1000	Between 8-10 and 20-25	Between 28-35 and 70-87.5	Green (1968)
Trachy basalt	Spinel peridotite	1396	24.2	84.7	Nicholls and Carmichael (1972)
	Garnet peridotite	1321	22.7	79.5	
Alkaline basalt	Spinel-bearing xenoliths (wehrlite-pyroxenite-gabbro)	-	7-10	25-35	Aoki (1968)

TABLE 5. Temperature and pressure of megacrysts in equilibrium with host rocks

Host Rocks	Megacrysts	Temperature °C	Pressure (kb)	Depth (km)	References
Alkaline trachy-basalt	Clinopyroxene	1350-1450	10-23	35-81	Wilkinson (1973)
	Orthopyroxene	1350-1450	10-23	35-81	
Alkaline olivine basalt	Orthopyroxene	1200	14-16	49-56	Green and Hibberson (Nicholls and others, 1972)
Alkaline olivine basalt	Clinopyroxene	1055	10.6	37.1	Bacon and Carmichael (1973)
	Plagioclase ($Ab_{58.6}Or_{3.4}An_{37.2}$)	1055	10.6	37.1	
Alkaline basalt	Andesine	-	8-18	30-60	Aoki (1970)

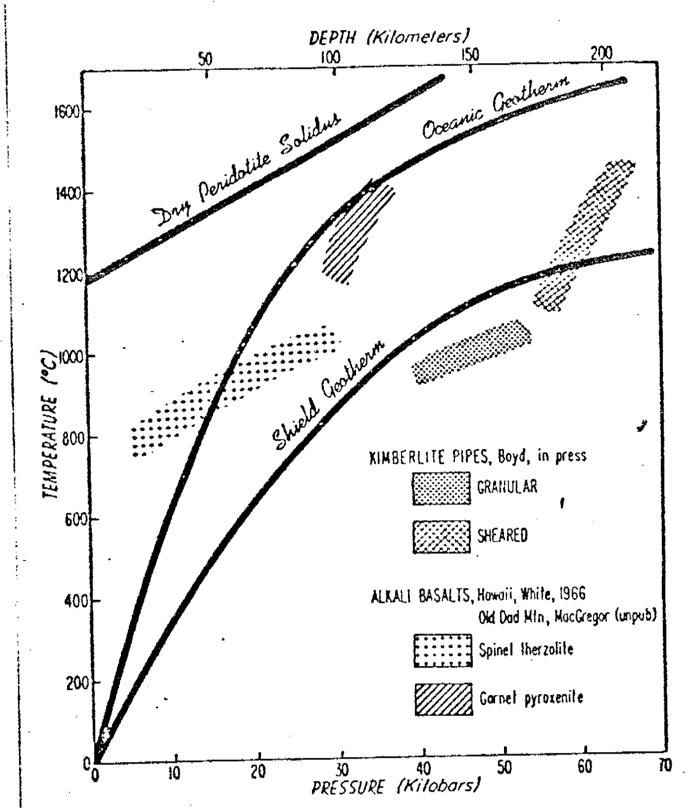

Figure 18. Interpreted conditions of formation for suites of ultramafic xenoliths from alkaline basalts and kimberlite. After MacGregor, 1974.

megacrysts and mafic or ultramafic xenoliths occur in alkaline basalt at depths greater than 25 km. Because of their association with corundum, it is deduced that corundum can be produced from basalt at these depths.

VII. ORIGIN OF CORUNDUM IN BASALT

From the available data which has been discussed in previous pages, the origin of corundum in basalt can be described in many ways. The possibility of its genesis will be discussed below.

A. Corundum in xenoliths with or without reaction with wall rock

1. The shallow environment

In this case, an example of high temperature and low pressure of formation of corundum is reported from Asama volcano in Japan (Aramaki, 1961). High temperature of formation of corundum was also reported from the Island of Mull in Scotland (Thomas and Radley, 1922) but the pressure is not known. It was mentioned only that the xenoliths are of deep-seated character.

In both deposits, corundum was found associated with sillimanite, andalusite and cordierite. The last three minerals have not been reported from corundum-bearing basalts in Thailand and Australia. Therefore, if the corundum associated with basalts there is due to assimilation of metamorphosed aluminous sediments, there is insufficient detail to prove it. It is possible, but not likely, that these minerals have been completely changed to other minerals before the eruption of basaltic magma.

If corundum is formed from the breakdown of andalusite, sillimanite and kyanite, high pressure is needed to convert these three minerals to corundum and quartz (see Table 6). All of the calculated pressures are too high for a shallow environment. Thus, it is not likely for this case.

According to Green and Ringwood (1967), the reaction between wall rock and magma at shallow depth can cause only a minimum chemical exchange during any fractionation process because of high temperature contrast between them and consequent quenching of the magma. It is possible but probably would not result in large scale crystallization of corundum to yield such deposits as are known from Thailand and Australia.

In the case of corundum already formed in some rocks (e.g. schist, gneiss and syenite) and brought up to the surface by basalt, corundum embedded in these rocks would be expected because the host basalt could not melt all pieces of such rocks. The presence of such fragments in basalt of Thailand is not known to the author. Such xenoliths might be absent because the rock has undergone much erosion and weathering; however, the mineralogical composition and texture of corundum, spinel, garnet, and pyroxene in corundum deposits are not characteristic of metamorphic rocks. Thus, this genesis also seems to be unlikely.

2. The deep environment

In this environment, wall rock is near the depth of

TABLE 6. Calculated equilibrium pressure at various temperatures

Temperature °K	Pressure (kilobar)			
		Quartz+Corundum=Andalusite	Quartz+Corundum=Silimanite	Quartz+Corundum=Kyanite
298.15	α	18.2	22.6	-12.9
400		18.4	25.0	-10.7
500		18.7	27.2	- 8.5
600		18.9	29.3	- 6.3
700		18.9	30.7	- 4.1
800		18.7	31.4	- 1.7
900	β	26.6	84.0	0.8
1000		25.1	81.1	3.0
1100		23.9	78.6	5.2
1200		22.8	76.6	7.3
1300		21.9	75.3	9.3
1400		21.1	74.9	11.2
1500		20.2	74.3	13.1
1600		19.4	74.9	14.9
1700		19.3	78.4	16.3
1800		15.7	81.2	17.8

Method of Calculation

$$\left\{ \frac{@(\Delta G)}{@P} \right\} = (\Delta V)$$

$$d(\Delta G)^{P}_{To} = (\Delta G)^{o}_{To} + \int_{1}^{P} (\Delta V)_{To} dP$$

$$(\Delta G)^{P}_{To} = (\Delta G)^{o}_{To} + 0.024(\Delta V)_{To}(P-1)$$

At equilibrium $-(\Delta G^{o})^{o}_{To} = 0.024(\Delta V)_{To}(P-1)$

$$P = \left\{ \frac{-(\Delta G)^{o}_{To}}{0.024(\Delta V)_{To}} + 1 \right\} \times 1.0133$$

$$= \text{Bar}$$

Data from Robie and Waldbaum (1968)
Only molar volume of β quartz comes from Clark, Jr. (1966)

partial melting of the mantle. The marginal border of magma will not be chilled and exchange of ions can take place. According to Green and Ringwood (1967), aluminous enstatite can be produced by reaction of mantle wall rock with tholeiite which is segregated at 35 to 70 km depth. They mentioned that as cooling continues, the liquid would trend towards alkali olivine basalt composition with slightly decreasing Mg/Fe ratio. If corundum crystallized due to mantle-wall rock reaction, the mantle-wall rock itself should be enriched in alumina. Pyrolite and garnet peridotite which were proposed for mantle material by Green and Ringwood (1967) and Yoder and Tilley (1962) respectively, are not rich in alumina. At present, it is accepted that 80-90% of possible mantle material falls within the system $MgO-Al_2O_3-SiO_2$; of these three components, Al_2O_3 content is only 4% (Schreyer and Seifert, 1969). Thus, development of corundum in mantle wall rock is possible only where there is locallized enrichment of alumina. Because of the inhomogeneity of the mantle, this origin of corundum is possible, but there are insufficient data to prove it at present.

B. Corundum-bearing ultramafic and/or mafic xenoliths

Corundum is found in eclogite xenoliths in kimberlite and in garnet-corundum-kyanite assemblages in kimberlite according to Mathias and others (1970) and Sobolev, Kuznetsova and Zyuzin (Schreyer and Seifert, 1969) respectively. Mathias and others attributed this occurrence to partial melting of garnet peridotite in the upper mantle.

Although this origin seems plausible, the facts that oppose this origin are: (1) corundum in eclogite xenoliths in kimberlite occurs only to a minor extent, (2) isolated and well formed hexagonal crystals of corundum in basalts from Thailand and Australia reveal that corundum does not occur there in a xenolith assemblage, and (3) to the author's knowledge, no ultramafic or mafic xenoliths <u>in alkali olivine basalts</u> anywhere in the world have been reported to contain corundum. From these observations, it seems to the author that this genesis is not likely to account for corundum deposits associated with basalts.

C. <u>Corundum as megacrysts in basalts</u>

The origin that seems to fit best is the crystallization of corundum from basaltic magma itself at high pressure and temperature, that is, as megacrysts or high pressure phenocrysts in basalt. The high pressure origin of corundum was mentioned by Wright (1971, 1972) and Irving (1974). The lines of evidence which tend to support this hypothesis are as follows:

1. The host basalts are of alkaline type which can be derived from the deep crust or upper mantle.

2. Low silica and high TiO_2 content indicate a deep source of magma (MacGregor, 1969; Renault, 1970; Bacon and Carmichael, 1973). These are the characteristics of corundum-bearing basalts in Thailand.

3. The mineralogical and textural characteristics of megacrysts of aluminous clinopyroxene, spinel and pyropic garnet, which are associated with corundum, indicate high pressure origin, the same as ultramafic and mafic xenoliths.

4. Isolated and well-shaped crysts of corundum as shown in the figure in the report of MacNevin (1972) reveal a direct crystallization from basaltic magma. Only a thin reaction rim has been noted by him. This indicates corundum in equilibrium with magma since the time of formation.

5. Postcrystalline stresses are observed in peridotite xenoliths of the four basaltic provinces in Queensland. If these xenoliths are sheared, they may be derived from mantle material at depths of approximately 150-170 km (Boyd, 1973).

The problem with which we have to be concerned is the depth of formation of basaltic magma in conjunction with associated minerals. The presence of sodic plagioclase, spinel, clinopyroxene, and garnet and also the type of basaltic magma tend to limit the depth interval of crystallization of corundum and associated minerals to between 25 and 70 km. The reasons are as follows:

1. Alkali olivine basalt can be produced by partial melting of mantle material at depth interval about 30 to 70 km (Yoder and Tilley, 1962; Green and Ringwood, 1967; MacGregor, 1969) if the geothermal gradient is steep enough.

2. Experimental data of Green and Ringwood (1967)

and Yoder and Tilley (1962) indicate that garnet could crystallize at depth greater than 60-70 km. The crystallization of garnet from a primitive basalt (which was derived by partial melting of eclogite) tends to produce alkaline type basaltic liquid (Yoder and Tilley, 1962).

3. Feldspar will become more sodic at high pressure for particular alkaline basaltic composition (Binns and others, 1970). Sodic feldspar (andesine) has been suggested by Aoki (1970) to crystallize at depths about 30 to 60 km.

4. Spinel and plagioclase appear on the solidus at 13.5 kb but are absent at 18 kb. Garnet appears late in the crystallization sequence at 18 kb (Green and Ringwood, 1967).

5. Aluminous clinopyroxene can be produced at depths about 35-70 km (Green and Ringwood, 1967). According to Binns and others (1970), spinel apparently accompanies clinopyroxene at all stages of megacryst precipitation at Armidale, Glen Innes and Guyra which are the areas of corundum deposits.

6. All of the above minerals occur together with corundum. Thus, they should crystallize at the same depth interval including the host alkali olivine basaltic type.

Before the genesis of corundum in basalt is proposed, the fractionation of alkali olivine basalts at different depth intervals will be discussed. The following data come from Green and Ringwood (1967) unless otherwise specified.

At 27 kb, garnet is the liquidus phase. Extraction of garnet results in an increase of SiO_2 content and particularly in a decrease of Al_2O_3 content. If there is an extraction of 10 per cent garnet, the normative nepheline and anorthite content changes from 2.2-4.0 per cent and 26.2-21.5 per cent respectively. According to Green and Ringwood, "the separation of garnet or garnet-rich mixture of garnet + clinopyroxene may produce nepheline normative liquids from the compositions rich in olivine but poor in hypersthene. Such fractionation, if significant, must be restricted in basaltic rocks as extraction of garnet with its high Al_2O_3 content leads to residual liquids inconsistent with basaltic chemistry." Because of low Al_2O_3 and high SiO_2 content in the magma, it is unlikely for corundum to crystallize at this depth range.

At about 10 to 20 kb (35-70 km), extraction of pyroxene from alkali olivine basalt tends to decrease the SiO_2 content and increase the Al_2O_3 and CaO contents. Alumina is not sufficiently concentrated for corundum to precipitate at this pressure. Clinopyroxene appears early in the fractionation sequence and it is very sub-calcic if accompanied with orthopyroxene. Both of them are aluminous. Garnet appears late in the crystallization sequence at 18 kb (63 km). Spinel and plagioclase appear near the solidus at 13.5 kb (47 km).

At about 4 to 10 kb (15 to 35 km), there is the crystallization of a relatively large proportion of olivine and pyroxene before the appearance of plagioclase and resulting in a marked increase in Al_2O_3 with relatively constant SiO_2 content (47-49 per cent). In terms of normative minerals, there is an increase in nepheline and the liquid remains undersaturated with low or moderate degree of fractionation.

More specifically, at about 9 kb (31.5 km), olivine can coexist with liquid alone down to 1230±10°C. As the temperature goes down from 1210°C to 1100°C, there is a decrease in solubility of Al_2O_3 in pyroxene with decreasing temperature. At this stage, spinel and plagioclase can occur and imply reactions:

$$\text{Olivine} + \text{Plagioclase} \rightleftharpoons \text{Aluminous pyroxene}_{(ss)}$$

$$\text{Spinel} + \text{Plagioclase} \rightleftharpoons \text{Aluminous pyroxene}_{(ss)}$$

At pressure less than occur at 15 km depth, phases crystallizing from fractionating alkali olivine basalt would result in increase in SiO_2, alkalis and Al_2O_3 in the early fractionation stage. The liquid becomes enriched in SiO_2 and because corundum and quartz are incompatible, they will combine to form other minerals. Corundum can not form. At low pressure, clinopyroxene is poor in alumina and plagioclase is poor in soda. The megacrysts which are found show the contrary.

If corundum and associated minerals result by fractionation of alkali olivine basalt alone without any contamination, the depth interval for crystallization of corundum which seems to give the best fit is from 15 to 35 km. In that interval, there is a marked increase in Al_2O_3 content if the calcic plagioclase does not precipitate.

The presence of garnet and ultramafic xenoliths at these depths poses a problem. The author has to assume that both garnet and ultramafic xenoliths were derived from the wall rock and incorporated into alkali olivine basaltic magma.

In order to define the minimum depth of partial melting of basaltic magma, the geothermal gradient should be known. Unfortunately, the data are not available for the areas of corundum-bearing basalts. Volcanic areas in the Basin and Range province of the United States have high geothermal gradient (Reiter, personal communication, 1975). This gradient is not high enough to cause partial melting at depths of approximately 15 to 35 km. Thus, it requires extremely high geothermal gradient for partial melting of alkali olivine basaltic magma. Green and Ringwood (1967) proposed that the solid (pyrolite) mantle material rises from great depth and melts at shallower depth for different kinds of basaltic magma. This idea seems to be the best explanation for corundum-bearing basalt at present. The path of magma rising is shown in figure 19.

The stages in the genesis of corundum associated with

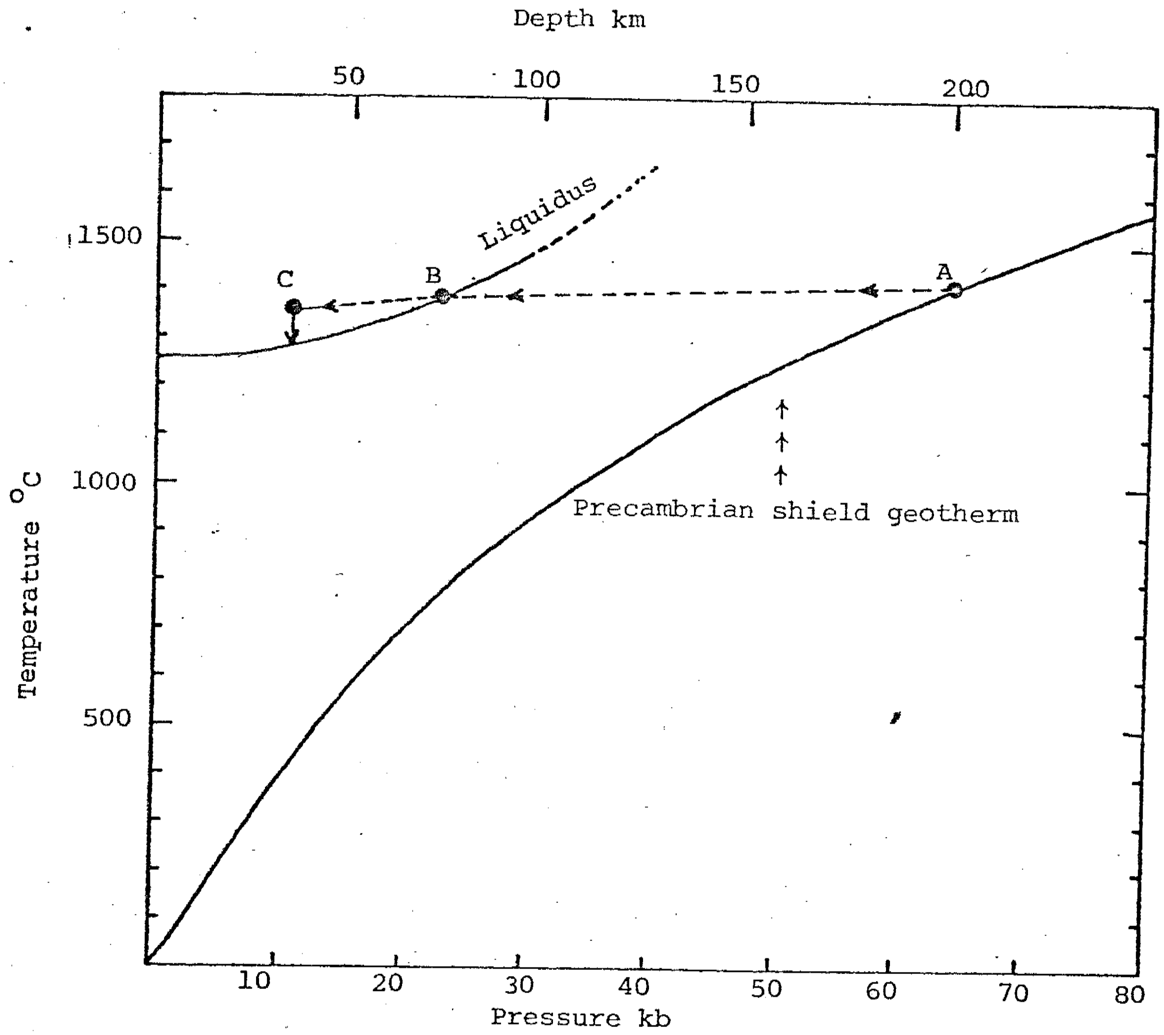

Figure 19. Diagram showing path of rising of alkali olivine basaltic magma. At point A, solid mantle material rises adiabatically and intersects the liquidus of alkali olivine basaltic magma at B. Some aluminous pyroxenes precipitate at this stage. Magma continues to rise from B to C and remains in the reservoir at approximately 25-30 km depth. As temperature decreases, corundum and associated minerals precipitate. The liquidus curve and shield geotherm are from Green and Ringwood (1967) and Ringwood (1969)

basalt are proposed to be as follows:

1. Solid mantle material rises adiabatically at great depth to shallower levels of about 45-70 km depth. Partial melting of mantle material yields alkali olivine basaltic magma and residual olivine+aluminous orthopyroxene±aluminous clinopyroxene. The residual crystals would be present as megacrysts or ultramafic xenoliths if they accumulated. According to Green and Ringwood (1967), the precipitation of aluminous orthopyroxene and/or clinopyroxene results in a decrease of SiO_2 and small increase in Al_2O_3 in the residual liquid. Some of spinel and sodic plagioclase may appear at about 13.5 kb. If the ratio of Al_2O_3/SiO_2 of pyroxene is less than that of basaltic magma, Al_2O_3 will become enriched in the residual liquid. In other words, when the removal rate of SiO_2 from basaltic magma is greater than that of Al_2O_3, then the magma will become enriched in Al_2O_3.

2. Alkali olivine basalt moves to the shallower level at about 30 km depth (9-10 kb) and also brings up garnet and peridotite or dunite xenoliths.

3. Olivine and sub-aluminous clinopyroxene precipitate resulting in a marked increase in Al_2O_3 with relatively constant SiO_2 content (47-49 per cent). Corundum may begin to precipitate at this stage. Pyroxene continues to crystallize with sodic plagioclase in the late crystallization sequence while magma still has constant SiO_2 content (see figure 20). Clinopyroxene crystallizing

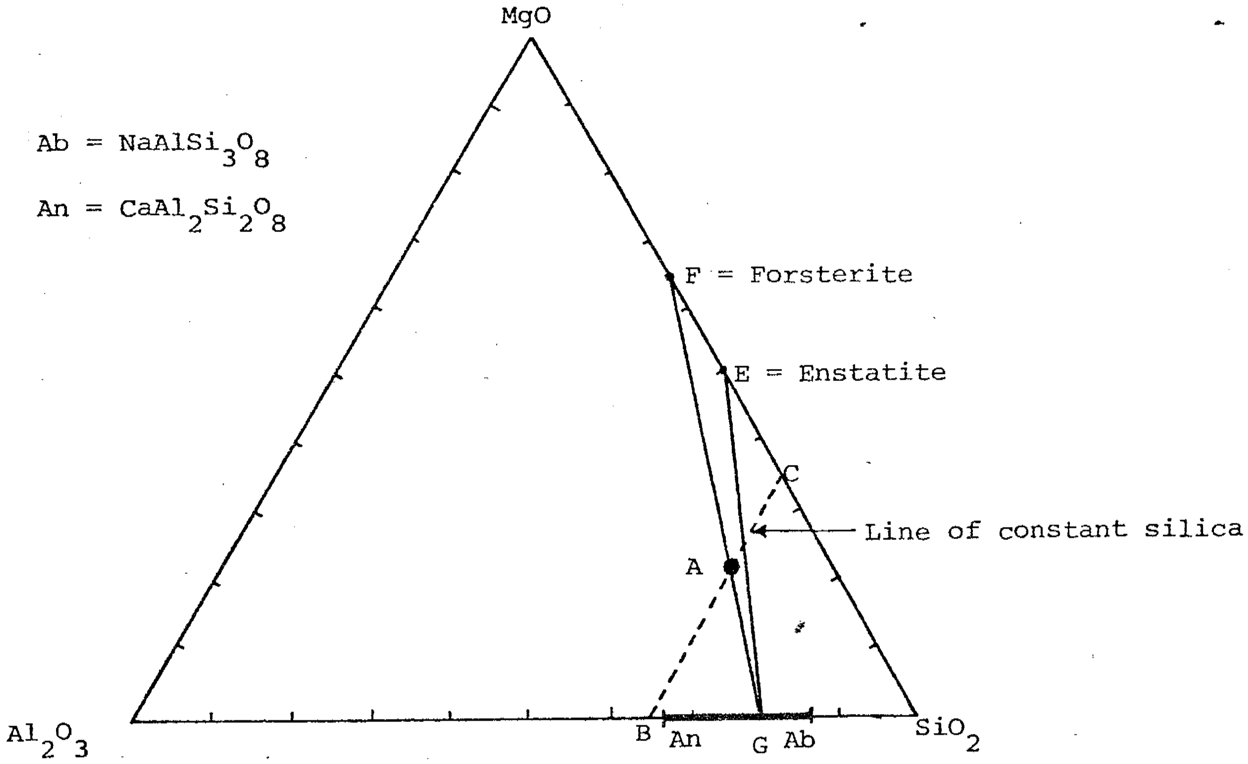

Figure 20. A plot of mole proportion of $MgO-SiO_2-Al_2O_3$ in a modal basalt system showing how basaltic magma increases in Al_2O_3 with relatively constant SiO_2 content. The liquid at point A has 65.5% SiO_2, 12.4% Al_2O_3 and 22.1% MgO, which corresponds to 45.39, 14.69, 10.37 weight percent SiO_2, Al_2O_3, and MgO. Line BC indicates constant SiO_2 content. A plagioclase of composition $Ab_{30}An_{70}$ which corresponds to the SiO_2: Al_2O_3 (mole proportion 4:1) was plotted at point G between the pure anorthite (An) and albite (Ab). If only one phase crystallizes the path of liquid composition change is directly away from the crystal. Thus, to move along the constant silica line toward B, both pyroxene and plagioclase have to crystallize together in the right proportions.

at this depth will be less aluminous and less calcic than that at 13.5-18 kb.

4. Slow cooling results in the continued growth of corundum, olivine, sodic plagioclase, spinel and/or zircon to form megacrysts. Olivine, sodic plagioclase and spinel may also be formed by break-down of aluminous pyroxene which crystallizes at 13.5-18 kb. At this stage, the time interval should be long enough to grow large crystals of corundum. Convective circulation of magma may cause corundum megacrysts to be zoned.

5. Eruption and quenching of magma brings up all minerals and xenoliths to the surface.

The alumina content in alkali olivine basaltic magma is the problem. The critical factor is whether or not the magma is saturated with alumina by the processes of the first and the third stages. If the alumina content is not enough to precipitate corundum, the other processes such as contamination must be involved.

There are other possibilities which should be taken into account:

1. Incongruent melting of pure anorthite to corundum plus liquid. This process was mentioned by Aoki (1968), Binns and others (1970) and Carmichael and others (1974) to occur at greater than 10 kb. This is unlikely because of the large amount of anorthite needed.

2. Contamination by wall rock. This could be provided by aluminous minerals of metamorphic rock which

are present at depth. One possibility is the breakdown of kyanite to corundum plus quartz. It can be seen from the figures 21 and 22 that the equilibrium curve of kyanite and corundum plus quartz intersects the melting curve of alkali olivine basalt and eclogite at about 13-15 kb. Alumina can be enriched in basalt in this way, but according to Yoder and Tilley (1962), "No kyanite or hypersthene was found in any of the basalt subjected to the high pressure and temperature." It is clearly seen that basalt itself cannot be rich in kyanite without contamination. Thus, the metamorphic rock is expected to be found in this pressure range, since regional metamorphic facies can occur at pressures up to 10 to 12 kb.

If this process is possible, the explanation for the excess silica from the reaction kyanite=corundum+quartz is that it goes into other phases, for example, diopside, enstatite, zircon or quartz. The last two minerals are found in the corundum deposits of Thailand.

3. If Precambrian anorthosite can be present at depth, alumina may be liberated from plagioclase. This seems reasonable, for sodic plagioclase is the high pressure equilibrium feldspar. This explanation is preferred to the derivation of Al from metamorphic rocks, especially for the case of corundum deposits in Thailand where sillimanite, andalusite, kyanite and cordierite have not been reported from basalts. Plagioclase might be melted by

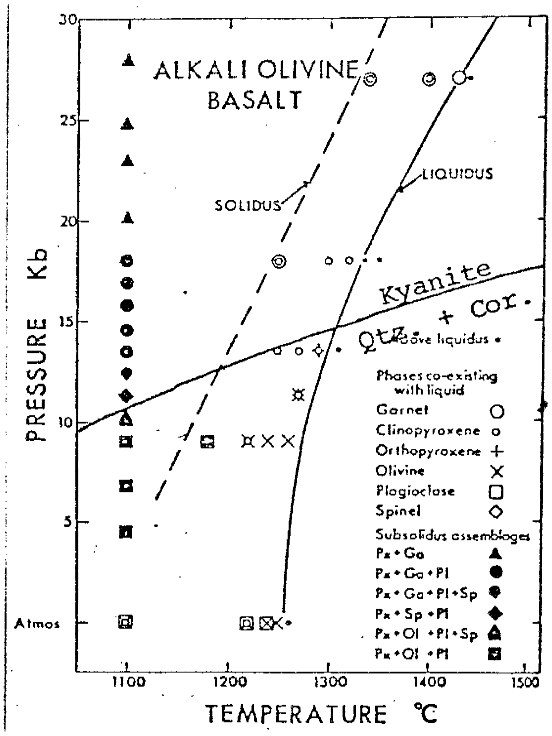

Figure 21 showing the equilibrium curve of kyanite = corundum + quartz intersects liquidus curve of alkali olivine basalt (after Green and Ringwood, 1967) at approximately 14.5 kb.

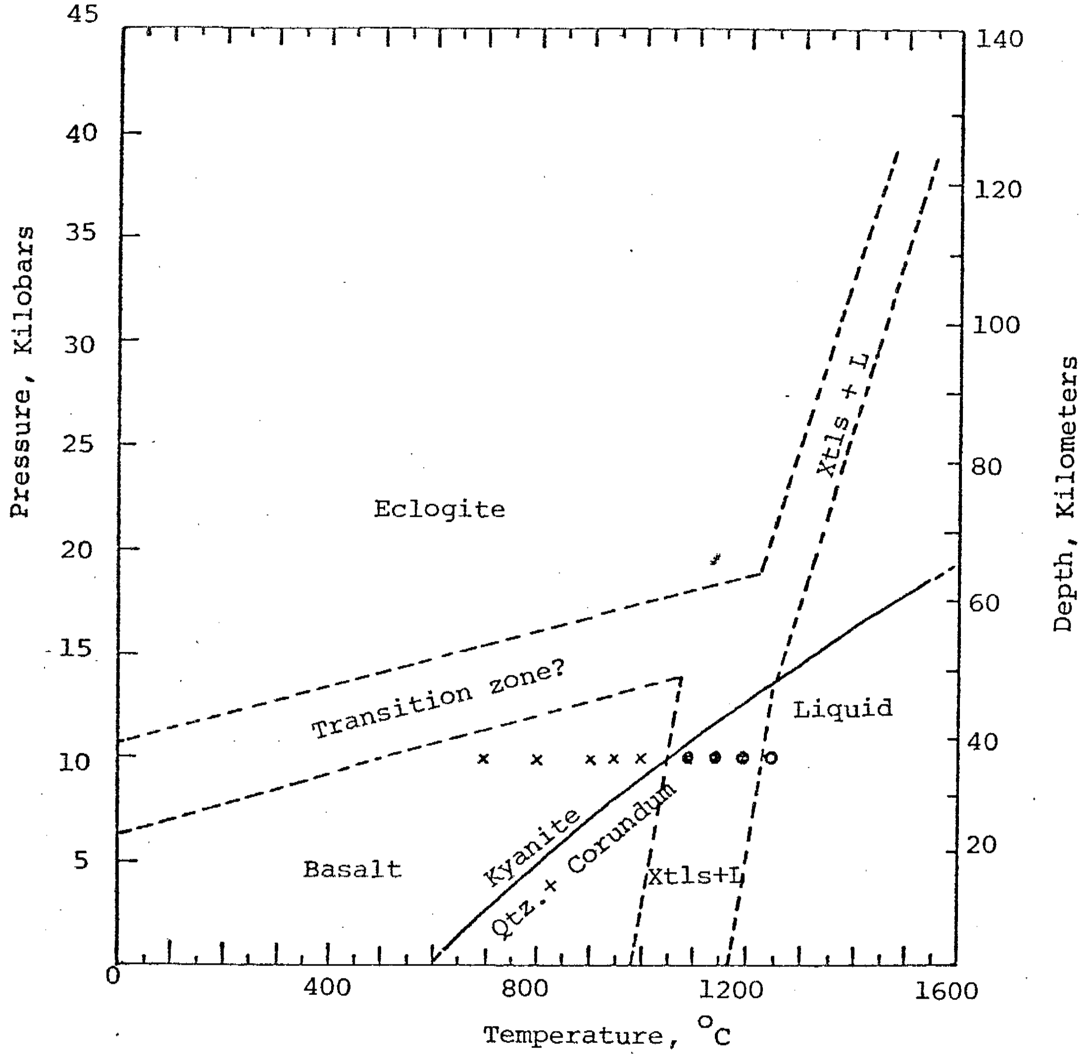

Figure 22 showing the equilibrium curve of kyanite = corundum + quartz intersects liquidus curve of eclogite (After Yoder and Tilley, 1962) at approximately 13.5 kb.

the heating from basaltic magma which moves to shallower levels than those from which it originated (around 8-10 kb). If the pressure is greater than 10 kb, anorthosite melts. Since Precambrian anorthosite has not been found(?) to date in Thailand, this poses a problem.

4. At present, there is still uncertainty as to the composition of the lower crust and upper mantle. The lower crust is thought to be composed of a mixture of granite and gabbro. If the crust contains gabbroic layers or lenses in some local areas and the rock was heated, the plagioclase in the gabbroic rock would melt and liberate alumina and then form corundum. If this is the case, the stages in the genesis of corundum in basalt are proposed to be as follows:

a. Partial melting of mantle material yields alkali olivine basaltic magma. At this stage, aluminous clinopyroxene precipitates and results in decreased SiO_2 and increased Al_2O_3 in the residual liquid.

b. Crustal extension causes fracturing and permits alkali olivine basaltic magma to move to shallower levels at about 25-30 km depth (8-10 kb) and also brings up garnet.

c. At that depth, an increase in geothermal gradient accompanied by local heating either from radioactive elements or by injection of alkali olivine basaltic magma; or combination of both processes would probably be sufficient to melt a fraction of gabbroic rocks and cause plagioclase to liberate alumina. At this stage, basaltic magma becomes saturated with alumina.

d. Slow cooling results in the crystallization of corundum, olivine, zircon and spinel. The last mineral may also form by breakdown of aluminous pyroxene which crystallizes at 13.5-18 kb. Alkali olivine basaltic magma remains in the reservoir for a long enough period of time to grow large crystals of corundum.

e. The residual gabbroic materials may be incorporated into the magma as dunite or peridotite xenoliths and sodic feldspar megacrysts. Eruption and quenching of magma brings up all minerals and xenoliths to the surface.

This model also explains the origin of corundum in basalt. It may explain all the problems which we had discussed previously except the garnet problem (we have to assume that garnet is incorporated into magma at great depth). However, it should be realized that this process must occur where there is high geothermal gradient or high concentration of radioactive elements and localized gabbroic layer in the crust.

All in all, the genesis of corundum in basalt cannot be considered definite without detailed investigation. At this time, the conclusion is that corundum crystallizes in basalt at depth somewhere around 25-30 km. Whether or not there is contamination of lower crustal or mantle material is still unknown.

VIII. ENUMERATION OF PROBLEMS IN SOLVING THE ORIGIN OF CORUNDUM IN BASALT

1. The upper mantle or deep crust origin for corundum in basalt is difficult to establish because of the inhomogeneity of the mantle and lower crust. The definite data are not known and they might be variable from place to place.

2. If corundum represents a phase crystallized from alkali olivine basalt, some processes which cause this magma to become saturated with alumina must be involved because some alkali olivine basalts which originated at the same depth contain no corundum.

3. No corundum is reported from the areas of alkaline basalts which contain sodic feldspar megacrysts described by Vitaliano and Harvey, 1965; Aoki, 1970; Bacon and Carmichael, 1973. This fact implies that either special considerations are involved in the formation of corundum; or the sodic feldspar megacrysts have no relation with corundum. If corundum and plagioclase represent phases crystallizing from alkali olivine basaltic magma and have a genetic relationship to each other, the depth of formation of corundum may be determined from the depth of formation of plagioclase. The liquidus or near-liquidus plagioclase will become more sodic at high pressure for particular alkali basaltic composition (Binns and others, 1970). At present, data seem to indicate that sodic

plagioclase megacrysts might occur at depths between 25 and 60 km.

4. The chemical composition of minerals associated with corundum is not definitely known. If the chemistry of these minerals is established, it will help to establish (a) whether or not they are of igneous or metamorphic origin and (b) their depth of formation and that of corundum.

5. There is a lack of detail in chemical characteristics and textural relationship of minerals of basalts. The first will tell, for example, whether or not alkali olivine basalt represents the host rock for corundum. This information could indicate if this basalt comes from the deep source in the deep crust or upper mantle. It could also show how much differentiation the basalt has undergone. The geographic distribution zone of corundum in Thailand might be solved. The latter will tell, for example, the paragenesis of minerals in basalt; whether or not the minerals associated with corundum are of megacrysts origin or occur as xenocrysts in ultramafic xenoliths.

6. The systematic data on trace element distribution and isotropic ratios of all megacrysts and basalts in the areas of corundum deposits are not known. These facts will lead to more understanding about the depth of formation of megacrysts and basalt and also whether or not there is contamination involved in the formation of corundum.

7. The geothermal gradient in the corundum-bearing basaltic terrains are not known. The geotherms will help to determine the minimum depth at which partial melting can occur.

8. In Thailand, basalts have undergone much erosion and weathering, and some facts which might have provided clues concerning the condition of formation of corundum may be obliterated. It might be difficult to solve the problem.

IX. SUMMARY AND CONCLUSIONS

Corundum-bearing basalt is often characterized by low silica, high iron and rather high titanium content. It generally contains dunite or peridotite and pyroxenite xenoliths. Megacrysts of sodic feldspar, spinel, garnet, aluminous clinopyroxene, olivine, ilmenite and to a minor extent biotite, are found associated with corundum in the areas of the deposits. Corundum-bearing basalts are generally dark, dense and have fine-grained or glassy groundmass. The corundum-bearing alkaline type is much more common than corundum-bearing tholeiitic type. The period of eruption usually is Tertiary. In general, basalts erupted in the areas of tensional environment. Corundum, especially sapphire from basaltic terrain is of better gem quality than corundum from any other rock type and is especially better than corundum from metamorphic rock.

The origin of corundum is not well understood because of the lack of detailed investigations. However, it can be explained in terms of a model involving megacrysts crystallizing from alkali olivine basaltic magma which originated at depth about 35-70 km. In this model, the magma moves to shallower levels of approximately 25-30 km. At this stage, magma can be saturated with alumina by combination of the processes of fractionation at depth where it initiated and at the shallower level. There is a possibility that alumina may be derived from wall rock or from a gabbroic layer in the crust, but there are insufficient data to prove it. Corundum could crystallize at this stage if the temperature decreases. Alkali olivine basalt might remain in the reservoir for a long enough period of time to allow large crystals of corundum to grow and then eruption would carry magma to the surface where it would be quenched.

X. SUGGESTIONS FOR FURTHER INVESTIGATION

1. Study the chemical composition of all minerals associated with corundum, especially feldspar, pyroxene, spinel, garnet and olivine.

2. Study the particular physical characteristics and textural relationships of each of the minerals which were found in basalts in comparison with other related rocks.

3. Study the chemical composition of the specific type of basalts which carry corundum.

4. Study the normative minerals of the glassy phase of corundum-bearing basalt. If it comes from great depth, it should contain no hypersthene in the norm.

5. Study the trace element distribution and isotropic ratio of corundum-bearing basalts, for example, Rb/Sr and Sr^{87}/Sr^{86}.

6. Study the geothermal gradient in each corundum-bearing basaltic terrain.

7. If possible, study the ratio of mineral concentration in the areas of corundum deposits and compare them with each other. This could provide some clues which might lead to more understanding about the process of formation of corundum.

8. Detailed investigation should be made in basaltic areas of Loei (at Huai E-Chin), Lampang (Pa-Lad) and Sraburi (Ban Thung Yo) provinces because the chemical

composition of the basalts there imply that they are favorable for corundum.

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APPENDIX

APPENDIX 1. Some corundum occurrences in the world exclusive of basalts

Country	Localities	Type*	Setting	Modes of Formation	Economic
Afghanistan	Near Jagdalak, thirty-two miles east of Kabul	Ruby	In micaceous crystalline limestone	Similar to the occurrence in Burma (Bauer, 1968)	It is said to have been mined in the past (Palache and others, 1946; Bauer 1968)
Austria-Hungary (Eastern Europe)	Bohemia	Ruby and sapphire	In association with kyanite and quartz (Barlow, 1915)		
	Near Kerchmislau, Moravia	Blue sapphire	In talc schist, (Barlow, 1915)		
	At Nedwieditz, Moravia	Pale blue sapphire	Disseminated in crystalline limestone (Barlow, 1915)		
Australia	Mount Painter, South Australia	Sky-blue corundum	In corundum-chlorite rocks (Oliver and Jones, 1965)	The rock probably crystallized at 500° to 700°C under 20,000 lb/in pressure. Corundum in equilibrium at the time of formation (Oliver and Jones, 1965)	
Burma	Mogok	Ruby and sapphire	Impure dolomitic marble and a feldspathic rock	Metamorphism of impurities in impure dolomitic limestone (Bauer,	Gem quality, commercial deposit

(cont)

APPENDIX 1 (continued)

Burma (cont)				1968, MacNevin, 1972)	
Canada	Craigmont and Klondike workings, Renfrew County, Ontario	Corundum	In scapolite-Andeclase-nepheline gneiss complex	It is attributed to the transformation of sediments locally rich in alumina into the corundum-bearing portions of the complex either by metasomatic replacement or by magmatic assimilation (Carlson, 1957)	Commercial deposits of the total Canadian corundum production of 24,800 tons, 84 per cent has come from the Craigmont and Klondike cuts. Average grade in these two workings was 6-7 per cent corundum (Carlson, 1957)
Ceylon	Kalupahana and Haldumulla estates on the Haputale escarpment	Violet crystals of corundum	In corundum-sillimanite rock (Wells, 1955)	Corundum is thought to form by removal of other oxides during period of lateritic weathering and being formed in a localized bauxitic deposit during regional metamorphism (Wells, 1955)	

APPENDIX 1 (continued)

Ceylon .	Small area around Non Pareil estate (66 miles east-southeast of Colombo and 38 miles south-south-east of Kandy)	Sapphire (blue and blue green hexagonal prismatic and steep pyramidal crystals of corundum). Many are over 1 cm in length	Sapphire-bearing syenite-limestone contact. Corundum formed in between the phlogopite zone (which is in between limestone and syenite) (Wells, 1955)	Corundum formed by desilication of syenite. Limestone has caused desilication to such an extent that corundum has formed (Wells, 1955)	High proportion of sapphires are clear and of good gem quality (Wells, 1955).
	Saffragam district and Ukkette near Ratnapura	Ruby and sapphire	Sapphire and garnet were originally embedded in gneiss. Ruby and spinel have been derived from marbles which are associated with gneiss (Bauer, 1968)		Commercial deposits. Sapphire is not of very good quality (Bauer, 1968)
Colombia	Muso	Emery	In black limestone (Barlow, 1915)		
England	Dartmoor near South Brent in Devonshire	Corundum	Found near the contact of felsite (granite) and clay slates	It is thought to form from an excess of alumina which is resulted from dissolving of slate in granitic magma (Barlow, 1915)	

APPENDIX 1 (continued)

Finland	In Lojo at Ammänkallio (Maila)	Corundum	In limestone (Barlow, 1915)		
France	Arignac in Ariège	Blue sapphire	In crystalline limestone interfoliated with gneiss (Barlow, 1915)		
	Puy-de-Dôme	Dark blue sapphire	In a granitic inclusion containing nephelinite (Barlow, 1915)		
Germany	Saxony	Violet corundum	In corundum granulite (Barlow, 1915)		
Greece	Island of Naxos	Emery (dark gray color, usually mottled with bluish specks or streaks)	In red soil, and crystalline limestone surrounded by micaceous schist and gneisses (Barlow, 1915)	It is thought to have originated from the influence of massive dikes of pegmatite which are related to intrusions of granite (Barlow, 1915)	It has been mined from the earliest time (Barlow, 1915)
Italy	near Mosso Santa	Corundum	In plumasite dike (Barlow, 1915)		
Japan	Asama Volcano, about 140 km NW of Tokyo	Corundum	In volcanic xenoliths which are composed of sillimanite and nt)	It is thought to form during the pyrometamorphism by the magma (cont)	

APPENDIX 1 (continued)

Japan (cont)			cordierite (Aramaki, 1961)	(Aramaki, 1961)	
Kashmir	Zanskar district	Sapphire	Pagmatite veins penetrating actinolite-tremolite rock in crystalline limestone (MacNevin, 1972)	Metamorphism of impurities in impure limestone or as a pegmatite mineral (crystals of sapphire are said to frequently enclose green tourmaline) (MacNevin, 1972)	Gem quality, commercial deposit? (Bauer, 1968)
Madagascar	Gogogo	Ruby	Matrix of green mica schist (MacNevin, 1972)	Formed as a metamorphic mineral (MacNevin, 1972)	
	Ambohitranefitra near Beforona on the Tananarive-Tamatave road	Reddish corundum	Alluvium. It has been eroded from corundum syenites and their contact zones (Kun, 1965)		It is reported to be recovered by Kun (1965)
	Ambatolampy-Ambositra area (south of the capital)	Corundum	In the zones of mica schist affected by granite (Kun, 1965)		It is reported to be recovered by Kun (1965)
	Amavoha and Vohitany NE of Ejeda and near Sakeny, NW of Ihosy	Corundum	Disseminated in hard, feldspathic pyroxenites, sakenites (plagioclasites granites)		It is reported to be recovered by Kun (1965)

APPENDIX 1 (continued)

Mozambique	Zobue, 50 miles west of Blantyre (in Malawi) and at Moatize near Canchoeira, 15 miles east of Tete	Corundum	In corundum feldspar pegmatite (Kun, 1965)		It is reported to be recovered by Kun (1965)
Southern Rhodesia	Mazoe district, between Ndiri and Talland	Corundum	In corundum granulite which forms a long, sub-vertical lens in an itabirite horizon, intersected by a dolerite dike (Kun, 1965)		
South Africa	Northern Transvaal	Corundum	In plumasite or coarse corundum plagioclasite (Kun, 1965)		
Switzerland	St. Gotthard	Red and blue corundum	In dolomite (Barlow, 1915)		
Sweden	Alnö Island	Corundum	In alvikite or calcitic carbonatite (Barlow, 1915)		
Tanzania	Matabatu Mountains, Tanganyika	Ruby	In zorsite-amphibolite rock (Game, 1954; MacNevin, 1972)	Metamorphic mineral	

APPENDIX 1 (continued)

U.S.S.R.	Kyschtym	White, grey, and light to dark blue corundum	Corundum rock (Kyschtymite) (Barlow, 1915)		
United States of America	Elk Creek, Bozeman and Bear Trap in Montana	Corundum	Occurs as lens in gneiss. A thin border zone of vermiculite-rich gneiss commonly separates the corundum-bearing rocks from the enclosing gneiss (Clabaugh, 1952)	Metamorphosed alumina-rich sedimentary rock (Clabaugh, 1952)	Abrasive corundum. The deposits yield only a few thousand tons of rock containing 10 per cent or less corundum (Clabaugh, 1952)
	Plumas County, California	Corundum	In plumasite (the rock composed of 84 per cent oligoclase and 16 per cent corundum) (Pratt, 1906)	It is believed to separate from peridotite ? (Pratt, 1906)	
	Mentasta Mountains of the eastern Alaska range, Alaska	Blue sapphire	In pegmatite dike which cut a syenite-monzonite gneiss (Richter, 1970)		

*If it is not indicated in the literature, the author described as corundum. Modified after Mac-Nevin, 1972.

APPENDIX 2. The occurrences of corundum in basalts and related rocks of the world

Country	Localities	Type	Setting	Modes of Formation	Economic
Austria-Hungary	Near Ajnacsko, Hungary	Blue corundum	In basalt		
Australia	Anakie sapphire fields, Queensland	Blue, green, and yellow sapphires	In alluvium	It is thought to be derived from the Tertiary Hoy Basalt (Olgers, 1969, 1972)	The actual value of gems is not known. In 1920, the value of production was estimated at £65,000. In 1960, it is approximately about £700,000 (Olgers, 1969) Anderson (1965) estimated the value of uncut stones from 1961-1964 about £23,246 (2422 oz.)
	Annan River Tin Field and from gullies north of Butchers Hill and the McLean Basalt, Cooktown, Queensland (Lucas and Keyser, 1965)	Blue sapphire	In alluvium	Sapphire is probably derived from Tertiary McLean Basalt (?)	

APPENDIX 2 (continued)

Australia (cont)	Inverell-Glen Innes-Glencoe area, New England district, New South Wales	Variable color sapphires (colorless, pale blue to very dark blue parti-colored blue-green, blue-yellow and occassionally green or yellow)	In alluvium and embedded in basalt (MacNevin, 1971, 1972)	It is thought to be accidental xenocrysts. Basalt acts only as an intermediate source to bring corundum up to the surface (MacNevin, 1971, 1972)	Sapphire has been mined since 1919. The production from 1919 to 1969 is about 27,414 oz (8,498,340 carats). Estimated value is about $3,121,910. The recorded production for 1969 of about $1.5 million (MacNevin, 1972) The certified production was reported by Coldham (1973) for 1971 at $2,830,000 and for 1972 at $2,694,832
Cambodia	Bo Pailin	Blue sapphire	In alluvium	Sapphire is probably derived from basalts	It is reported to be recovered but the actual value of production is not known. This deposit yields good gem quality. Blue sapphire is well-known among gemmologists for its good color.

APPENDIX 2 (continued)

France	Volcanic district of the Auvergne Mountain in the "Plateau Central"	Corundum	In trachytes, andesite and basalts (Barlow, 1915)		
	At Le Croustet and volcano Le Coupet	Bluish corundum	In basalts or enclosed within the tuff and breccias. (Barlow, 1915)		
Germany	In the basin of the Rhine, in Siebengebirge and in Eifel district	Corundum	In silicate inclusions in basalt (Barlow, 1915)		
	At Unkel on the Rhine and Steinheim near Frankfort on the Main	Blue sapphire	Enclosed in fresh basalt (Pirsson, 1897)		
Madagascar	In the vicinity of Diego-Suarez	Corundum	In basaltic tuff (Barlow, 1915)		
Nigeria	Near basaltic terrain of the Nigeria's Cenozoic volcanic province	Corundum	In alluvial deposits	It is thought to be derived from the Gimi basalt flow (Wright, 1972)	

APPENDIX 2 (continued)

Scotland	At Mullach Glac an t'Sneacha, on the shore of Carsaig Bay in the Island of Mull	Blue sapphire	It is found in aluminous xenolith which embedded in the sill of tholeiitic and andesitic character (Thomas and Radley, 1922)	Corundum crystallized from the excess of alumina which remained after the formation of sillimanite and also formed by reaction between tholeiitic melt and aluminous xenoliths (Thomas and Radley, 1922)	
	Haddo House, Aberdeenshire	Corundum	In corundum-spinel xenoliths in norite (Read, 1931)	It is thought to form by metasomatic replacement of aluminous xenoliths by magma (Read, 1931)	
South Africa and Tanzania	Lesotho, Rhodesia	Blue purple, pale pink and colourless corundum	In the Eclogite association in kimberlite. Corundum occurs in garnet-corundum and clinopyroxene-garnet-kyanite-corundum xenoliths (Mathias and others, 1970)	It is interpreted that "calcium-aluminum enrichment that operates in the lower regions results in the series Eclogite → Kyanite Eclogite→ Corundum-Eclogite as crystal cumulates from a melt formed by partial fusion (cont)	Only 13 xenolith samples which contain corundum were reported by Mathias and others (1970)

APPENDIX 2 (continued)

South Africa and Tanzania (cont)				of garnet-peridotite". Mathias and others (1970)	
Thailand	Ban Bo Khaeo, Phrae province	Blue and green sapphire	In stream gravels	It is thought to be derived from basalt (See text)	Gem quality, but in general, average grain size is never greater than 1 cm. Peridot is also reported as gem
	Bo Ploi, Kanchanaburi province	Blue and green sapphire	In eluvial or alluvial deposit	It is thought to be derived from basalt (See text)	Good gem quality
	Petchaboon, Sriakate and Ubol Ratchatanee province	Blue and green sapphire	In stream gravels	It is thought to be derived from basalt (See text)	Good gem quality
	Chantaburi and Trat provinces	Blue, green, yellow sapphire and ruby	In stream gravels, residual basaltic soil, laterite and alluvium deposits	It is thought to be derived from basalt (See text)	Good gem quality

Remark: Kanchanaburi, Chantaburi and Trat province yield remarkably high concentrations of corundum and higher than the rest. The actual value of gems is not known, but at least is equal to Australia or higher.

APPENDIX 2 (continued)

United States of America	Yogo Gulch, Montana	Sapphire	In weathered lamprophyric dike (Clabaugh, 1952; MacNevin, 1972)	Possibly formed in basaltic lamprophyre dike but may be xenocryst (MacNevin, 1972). It is thought to be a product of direct crystallization from the magma, possibly as a result of reaction between the magma and kyanite-bearing inclusions (Clabaugh, 1952).	Gem quality, commercial deposit. Before, 1929, the Yogo deposit yield sapphires at value about $2,500,000 Cut stones from the deposit probably have value of more than $25,000,000 (Clabaugh, 1952).
	In the Appalachian belt especially in North Carolina and Georgia. This belt extends from Alabama to Newfoundland for a distance of 1,800 miles	Blue, green and yellow sapphire and some ruby	In contact between peridotite, (dunite) and country rocks of gneiss and schist. In some instances are found in peridotite body (Pratt and Lewis, 1905)	It is attributed to crystallization from peridotitic magma near the contact of country rocks (Pratt and Lewis, 1905)	Gem quality is reported from Macon and Jackson counties in North Carolina. Good commercial product comes from Pine Mountain in Georgia (Pratt and Lewis, 1905; Bauer, 1968)

APPENDIX 3. Chemical composition of basalts from Thailand

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	42.00	42.07	36.80	41.71	48.09	46.55	44.15	39.54	43.80	45.25	49.52	48.58	47.53	48.17
TiO_2	2.86	2.96	2.58	3.58	1.84	-	1.58	0.82	1.97	1.87	1.82	1.65	2.05	1.83
Al_2O_3	14.14	19.91	12.19	18.92	14.49	19.31	18.41	25.68	19.00	15.35	17.65	17.05	16.03	15.79
Fe_2O_3	2.51	4.64	5.31	4.63	4.25	4.07	2.13	3.25	2.80	10.00*	7.90*	11.23*	10.15*	14.28*
FeO	11.87	9.29	12.34	9.57	7.57	6.91	4.73	9.11	6.82	-	-	-	-	-
MnO	0.19	0.16	0.20	0.30	0.16	-	0.08	0.13	0.12	0.15	0.22	0.25	0.16	0.18
MgO	7.39	4.51	8.57	5.87	7.82	7.8	2.97	6.98	4.73	5.43	4.54	5.49	6.32	5.64
CaO	9.42	9.61	9.06	8.90	9.96	8.31	9.88	4.99	10.53	10.29	7.66	9.40	9.06	8.89
Na_2O	4.89	2.92	5.25	1.94	1.19	2.88	1.82	0.34	0.10	3.55	4.84	4.17	3.10	3.68
K_2O	1.23	0.44	0.86	0.24	0.35	1.62	0.77	0.24	0.35	0.95	3.81	1.43	2.31	0.92
H_2O^+	2.74	2.50	3.24	3.24	2.46	-	4.29	6.15	3.23	-	-	-	-	-
H_2O^-	0.20	0.10	0.80	0.20	0.64	0.02	0.22	0.20	0.22	0.16	0.08	0.08	0.15	0.08
P_2O_5	0.14	0.45	0.93	0.90	0.16	-	0.41	0.20	0.37	0.71	0.50	0.19	0.29	0.94
CO_2	0.77	-	0.77	-	-	-	-	-	-	-	-	-	-	-

* Total iron calculated as Fe_2O_3.

APPENDIX 3 (continued)

	15	16	17	18	19	20	21	22	23	24
SiO_2	44.47	43.39	51.91	49.11	48.93	49.39	48.51	47.46	44.15	43.49
TiO_2	-	-	-	-	-	-	-	2.00	1.58	2.00
Al_2O_3	14.66	17.47	16.64	18.94	19.47	20.54	20.61	17.17	18.41	15.27
Fe_2O_3	7.01	6.09	2.82	3.70	1.18	1.86	1.40	4.50	2.13	6.82
FeO	8.68	8.94	6.38	5.26	7.52	6.80	7.22	6.42	4.73	5.35
MnO	-	-	-	-	-	0.12	0.12	0.12	0.08	0.11
MgO	6.52	6.76	7.61	7.20	7.82	7.26	7.53	6.94	2.97	8.70
CaO	10.50	10.20	8.86	8.66	8.05	8.12	8.15	5.39	9.88	8.20
Na_2O	2.24	2.24	1.66	2.20	1.13	0.82	1.36	2.33	1.82	3.75
K_2O	1.22	1.42	2.46	2.12	2.14	0.33	0.40	3.11	0.77	2.65
H_2O^+	-	-	-	-	-	-	-	3.73	4.29	2.59
H_2O^-	0.03	0.01	0.16	0.28	0.32	0.44	0.24	0.00	0.22	0.02
P_2O_5	-	-	-	-	-	-	-	0.81	0.41	0.76
CO_2	-	-	-	-	-	-	-	-	-	-
SO_3	-	-	-	-	-	-	-	0.02	0.04	0.03

APPENDIX 4. Calculated oxide of basalts from Thailand

Analysis No.	1	2	3	4	5	6	7	8	9	10	11	12
$Na_2O + K_2O$	6.12	3.36	6.11	2.18	1.54	4.50	2.59	0.58	0.45	2.96	8.65	5.60
MgO + CaO	16.81	14.11	17.63	14.77	17.78	16.11	12.85	11.97	15.26	15.72	12.20	14.89
$(Na_2O + K_2O)/$ (MgO + CaO)	0.36	0.24	0.35	0.15	0.09	0.28	0.20	0.05	0.03	0.19	0.71	0.38
Total Fe as FeO	14.12	13.46	17.11	13.73	11.39	10.57	6.64	12.03	9.34	9.04	7.09	9.12
MgO + FeO	19.26	13.80	20.91	15.44	15.39	14.71	7.70	16.09	11.55	-	-	-
MgO/(MgO + FeO)	0.38	0.33	0.41	0.38	0.51	0.53	0.39	0.43	0.41	-	-	-
S.I.	26.74	21.14	26.96	26.95	37.69	34.11	24.34	35.63	32.58	31.15	22.39	27.16

APPENDIX 4 (continued)

Analysis No.	13	14	15	16	17	18	19	20	21	22	23	24
$Na_2O + K_2O$	5.69	4.60	3.46	3.66	4.12	4.32	3.26	1.15	1.76	5.66	2.59	6.40
MgO + CaO	14.95	12.14	17.02	16.96	16.47	15.86	15.87	15.38	15.68	12.33	12.85	16.90
$(Na_2O + K_2O)/(MgO + CaO)$	0.38	0.38	0.20	0.22	0.25	0.27	0.21	0.07	0.11	0.46	0.20	0.38
Total Fe as FeO	9.12	13.19	14.98	14.42	8.92	8.59	8.58	8.47	8.48	10.47	6.65	11.49
MgO + FeO	-	-	21.50	21.18	16.53	15.79	16.40	15.73	16.01	17.41	9.62	20.19
MgO/(MgO + FeO)	-	-	0.30	0.32	0.43	0.46	0.48	0.46	0.47	0.40	0.31	0.43
S.I.	29.9	24.07	26.12	27.21	36.85	35.80	39.78	43.00	42.38	30.08	24.32	32.72

Localities of Basalts Related to Appendix 3 and 4

1. Bo Na Wong, Trat province (the area of ruby deposit)
2. Bo Na Wong, Trat province (the area of ruby deposit)
3. Ban Tok Phrom, Trat province (the area of ruby and sapphire [minor amount] deposit)
4. Ban Tok Phrom, Trat province (the area of ruby and sapphire [minor amount] deposit)
5. Ban Bo Khaeo, Denchai, Phrae province (the area of sapphire deposit)
6. Bo Ploi, Kanchanaburi province (the area of sapphire deposit)
7. Huai E-Chin Watershed, Loei province
8. Phu E-Mua, Loei province
9. Phu Khok, Loei province
10. Phu Khok, Loei province
11. Khao Du Fai, Kantaraluk, Srisakate province
12. Khao Phu Din, Kantaraluk, Srisakate province
13. At road-cut, 35 km from Lampang province
14. Ban Thung Yo, Khonburi, Nakornrajasima province
15. Bang Kacha, Chantaburi province
16. Bang Kacha, Chantaburi province
17. Lampang province (610/8 km from Bangkok along the road-cut)
18. Lampang province (610/12 km from Bangkok along the road-cut)
19. Lampang province (610/14 km from Bangkok along the road-cut)
20. Lampang province (610/16 km from Bangkok along the road-cut)

Localities of Basalts Related to Appendix 3 and 4 (continued)

21. Lampang province (611/4 km from Bangkok along the road-cut)
22. Lampang province (Sóp Prap)
23. Pa-Lad, Mae Ta, Lampang province (another basalt flow different from No. 13, 17-22)
24. Rim Pa-Sak, Kang Koi, Sraburi province

Analysis No. 1-9 and 15-22 were determined by wet chemical analysis method except K and Na by atomic absorption spectrophotometry. All of the samples were analyzed by chemistry section, Geological Survey Division, Department of Mineral Resources, Bangkok, Thailand. Analysis No. 10-14 were determined by Poonwiwat, T., graduate student, New Mexico Tech, Socorro, New Mexico. Total iron calculated as Fe_2O_3.

A hyphen (-) in the appendix means that it is not analyzed.

APPENDIX 5. Chemical composition of basalts from other areas of the world.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	45.60	42.63	46.31	45.20	44.48	44.29	44.94	38.54	45.54	46.46	48.11	53.97
TiO_2	2.42	2.11	1.28	1.61	2.42	2.49	2.52	1.06	2.85	3.01	1.72	1.24
Al_2O_3	15.36	13.07	15.36	15.51	13.47	13.98	14.65	11.73	17.61	14.64	15.55	14.65
Fe_2O_3	2.44	2.02	4.66	4.72	3.50	2.94	4.53	3.33	3.56	3.27	2.99	3.62
FeO	8.89	10.78	6.31	7.00	9.09	9.19	8.17	3.58	8.25	9.11	7.19	6.32
MnO	0.15	0.20	0.27	0.20	0.24	0.24	0.19	0.14	0.17	0.41	0.16	0.32
MgO	7.36	10.19	4.26	4.02	9.43	10.18	8.94	11.30	6.42	8.19	9.31	4.49
CaO	8.99	10.97	5.21	5.83	8.12	9.09	8.13	15.60	10.82	10.33	10.43	7.89
Na_2O	3.13	3.35	5.20	4.27	4.08	3.55	4.45	1.10	2.74	2.92	2.85	2.54
K_2O	1.68	0.93	3.41	3.76	2.23	1.15	1.52	2.32	0.70	0.84	1.13	1.52
H_2O^+	3.27	1.77	5.11	5.29	1.29	1.73	1.35	2.33	0.60	-	-	1.92
H_2O^-	0.38	1.22	1.91	1.96	0.38	0.28	0.03	1.34	0.10	-	-	0.94
P_2O_5	0.80	1.00	0.92	1.17	0.97	0.71	0.78	1.18	0.34	0.37	0.56	0.92
CO_2	-	-	0.34	n.d.	n.d.	n.d.	-	5.56	-	-	-	0.51
Cr_2O_3	-	-	-	-	0.09	0.11	0.02	0.10	-	-	-	-
NiO	-	-	-	-	0.04	0.03	0.06	-	-	-	-	-
BaO	-	-	-	-	-	-	-	0.41	-	-	-	0.04
Etc.	-	-	-	-	-	-	-	0.38	-	-	-	-

APPENDIX 6. Calculated oxide of basalt from other areas of the world

Analysis No.	1	2	3	4	5	6	7	8	9	10	11	12
$Na_2O + K_2O$	4.81	4.28	8.61	8.03	6.31	4.70	5.97	3.42	3.44	3.76	3.98	4.06
MgO + CaO	16.35	21.16	9.47	9.85	17.55	19.27	17.07	26.90	17.24	18.52	19.74	12.38
$(Na_2O + K_2O)/$ (MgO + CaO)	0.29	0.20	0.91	0.82	0.36	0.24	0.35	0.13	0.20	0.20	0.20	0.33
Total Fe as FeO	11.08	12.69	10.49	11.24	12.24	13.34	12.23	6.57	11.45	12.05	9.87	9.57
MgO + FeO	16.25	20.87	10.57	11.02	18.52	19.37	17.11	14.88	14.67	17.30	16.50	10.81
MgO/(MgO + FeO)	0.45	0.49	0.40	0.36	0.51	0.53	0.52	0.76	0.44	0.47	0.56	0.42
S. I.	31.66	37.52	18.24	17.26	33.70	37.40	32.94	53.07	30.13	34.12	40.20	24.77

Solidification index (SI) = MgO x 100/($Na_2O + K_2O$ + MgO + FeO)

Localities of Basalts Related to Appendix 5 and 6

1. Alkali olivine-basalt, New England Highway, 26.5 miles north of Guyra (Wilkinson, 1966, Analysis No. 1, p. 850).
2. Nepheline basanite, 7 miles west of Inverell (Wilkinson, 1966, Analysis No. 2, p. 850).
3. Analcite basalt, Spring Mount, west of Glen Innes, N.S.W. (Wilkinson, 1962, Analysis No. 1, p. 195)
4. Analcite basalt, Spring Mount, west of Glen Innes, N.S.W. (Wilkinson, 1962, Analysis No. 2, p. 195).
5. Analcite basanite from top most flow, University site, Armidale, N.S.W. (Wilshire and Binns, 1961, Analysis No. 4, Table 3, p. 190).
6. The Drogheda Trigonometrical flow, 15 miles southeast of Oberon (Wilshire and Binns, 1961, Analysis No. 5, Table 3, p. 190).
7. Basanitoid, near middle of sequence, University site, Armidale, N.S.W. (Binns, 1969, Analysis No. 2, p. 34).
8. Sapphire-bearing dike rock (altered analcite basalt?), Yogo Gulch, Montana, U.S.A. (Clabaugh, 1952, p. 13).
9. Alkalic olivine-basalt, with feldspar phenocrysts; on the road from Kamuela to Hawaii, 0.9 miles east of Puu O Kawaiwai (Macdonald and Katsura, 1964, Analysis No. C-69, Column 16, Table 3, p. 117).
10. Average alkalic basalt (mostly olivine-bearing) from Hawaii (Macdonald and Katsura, 1964, Analysis No. 4, Table 10, p. 124).
11. Average alkali olivine basalt from Japan and Korea (Kushiro and Kuno, 1963, Analysis No. 11a, Table 2, p. 77).
12. Tholeiite, basic portion of composite intrusion, Rudh 'a' Chromain, west side of Carsaig Bay (Thomas and Radley, 1922, Analysis No. 2, p. 236).

APPENDIX 7. Chemical analyses of clinopyroxene from Thailand and other areas

	P1*	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
SiO_2	54.52	48.12	48.31	49.45	48.81	48.31	47.9	48.32	48.44	49.60	51.80	47.46
TiO_2	1.80	1.95	2.04	1.25	0.85	2.37	2.0	1.14	1.14	0.13	0.22	1.67
Al_2O_3	8.84	8.76	9.66	8.70	8.46	6.39	10.3	8.71	8.72	5.17	4.12	8.19
Fe_2O_3	9.89*	2.20	2.78	1.96	2.14	0.30	-	1.32	2.82	3.51	1.53	3.14
FeO	-	6.30	6.19	4.35	5.94	8.28	8.7**	7.88	6.38	3.28	2.43	4.76
MgO	11.87	14.21	13.04	14.12	17.21	14.15	12.3	13.51	14.52	15.99	16.57	13.58
CaO	11.29	16.68	16.04	18.70	14.82	18.19	16.8	15.14	14.62	18.76	19.83	19.90
Na_2O	2.41	1.55	1.88	1.38	1.38	0.55	2.1	1.90	1.80	1.04	1.12	0.74
K_2O	-	0.05	0.00	0.01	0.04	0.25	-	0.12	0.11	0.12	0.06	0.03
MnO	0.13	0.16	0.18	0.13	0.16	0.13	0.12	0.16	0.28	0.08	0.05	0.17
Cr_2O_3	-	0.00	0.02	0.02	0.08	-	<0.04	0.22	n.d.	0.27	0.89	0.05
P_2O_5	-	-	-	-	0.03	-	-	0.06	n.d.	0.11	0.29	-
NiO	-	0.05	0.00	0.05	-	-	-	0.01	0.01	0.01	0.03	-
H_2O^+	-	-	-	-	-	-	-	0.96	0.71	1.50	0.62	} 0.21
H_2O^-	-	-	-	-	-	-	-	0.08	0.12	0.20	0.35	
TOTAL	100.75	100.03	100.14	100.12	99.92	98.92	100.2	99.53	99.67	99.77	99.91	99.90

P1	Megacryst from Khao Ploi Waen, Chantaburi, Thailand
P2	Megacryst from Armidale analcime basanite and basanitoid, N.S.W., Australia, Table 4, Analysis No. 7 (Binns and others, 1970).
P3	Megacryst from Glen Innes Trachybasalt, N.S.W., Australia, Table 4, Analysis No. 5 (Binns and others, 1970)
P4	Megacryst from Guyra nephelinite, Table 2, Analysis No. 9, N.S.W., Australia (Binns and others, 1970)
P5	Megacryst from Mount Noorat, Southeastern Australia, Table 2, Analysis No. RAB1 (Irving, 1974).
P6	Megacryst from Mount Bullengarook, Southeastern Australia, Table 2, Analysis No. E (Irving, 1974).
P7	Megacryst from Mount Franklin, Southeastern Australia, Table 2, Analysis No. C4 (Irving, 1974).
P8	Large crystal of black augite, Tergesh explosive pipe, Minusa, USSR, Table 4, Analysis No. 23/30 (Kutolin and Frolova, 1970)
P9	Large crystal of black augite, Bartoi-river basalts flow, USSR, Table 4, Analysis No. 56/51 (Kutolin and Frolova, 1970).
P10	Clinopyroxene from green spinel pyroxenite, USSR, Table 4, Analysis No. 5a (Kutolin and Frolova, 1970)
P11	Clinopyroxene from spinel lherzolite, USSR, Table 4, Analysis No. 6/40 (Kutolin and Frolova, 1970)
P12	Aluminous titanaugite from spinel-bearing inclusions, Iki Island, Japan, Table 4, Analysis No. 4c (Aoki, 1968).

* Analysis P1 was determined by atomic absorption spectrophotometry. The sample was analyzed by Lynn A. Brandvold, Chemist for the State of New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Total iron calculated as Fe_2O_3.

** Total iron calculated as FeO.