

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

GEOCHEMISTRY OF MESOZOIC DOLERITES  
"  
FROM LIBERIA, AFRICA AND SPITSBERGEN

A thesis submitted in partial satisfaction of the  
requirements for the degree of Master of Science in

Geology

by

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DEDICATION

To my parents and sisters  
Zip, Angie, Debbie and Charlene

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## TABLE OF CONTENTS

<u>Title</u>	<u>Page</u>
ACKNOWLEDGEMENT	iv
ABSTRACT	x
INTRODUCTION	1
PURPOSE	2
GEOLOGIC SETTING AND PREVIOUS WORK	4
Liberia	6
Spitsbergen	8
PETROGRAPHY	14
MODAL ANALYSIS PROCEDURES	14
LIBERIA	19
SPITSBERGEN	24
DISCUSSION	27
GEOCHEMISTRY	31
ANALYTICAL METHODS	31
RESULTS	34
Liberia	34
Spitsbergen	49
CLASSIFICATION	50
AFM DIAGRAM	55

DISCUSSION	57
QUALITATIVE COMPARISON	57
Spitsbergen	57
Liberian dolerites	65
ENA dolerites	67
CRYSTAL FRACTIONATION MODELS	71
SPECULATIVE HYPOTHESES	87
CONCLUSIONS	91
REFERENCES CITED	94
APPENDIX I	100
APPENDIX II	102
APPENDIX III	103
APPENDIX IV	104
APPENDIX V	105

## LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1. Distribution of Triassic-Jurassic diabase dikes throughout eastern North America, West Africa and northeastern South America	3
2. Geologic map of part of western Liberia showing sample locations	7
3. Vicinity map showing relative locations of Svalbard and Franz Joseph Land	9
4. Vicinity map showing distribution of Mesozoic dolerites on Spitsbergen	11
5. Weight percent $\text{SiO}_2$ versus weight percent MgO	38
6. Weight percent $\text{TiO}_2$ versus weight percent MgO	39
7. Weight percent $\text{Al}_2\text{O}_3$ versus weight percent MgO	40
8. Weight percent $\text{FeO}_T$ versus weight percent MgO	41
9. Weight percent MnO versus weight percent MgO	42
10. Weight percent CaO versus weight percent MgO	43
11. Weight percent $\text{Na}_2\text{O}$ versus weight percent MgO	44
12. Weight percent $\text{K}_2\text{O}$ versus weight percent MgO	45
13. Weight percent $\text{P}_2\text{O}_5$ versus weight percent MgO	46
14. Weight percent $\text{TiO}_2$ versus volume percent opaque minerals	48
15. Plot of normative mineralogy on a diopside-hypersthene-olivine-nepheline-quartz diagram	53
16. Alkali-silica diagram	54
17. AFM diagram	56
18. Weight percent $\text{SiO}_2$ versus weight percent MgO for major Mesozoic basalt provinces	58

<u>Figure</u>	<u>Page</u>
19. Weight percent $TiO_2$ versus weight percent MgO for major Mesozoic basalt provinces	59
20. Weight percent $Al_2O_3$ versus weight percent MgO for major Mesozoic basalt provinces	60
21. Weight percent $FeO_T$ versus weight percent MgO for major Mesozoic basalt provinces	61
22. Weight percent CaO versus weight percent MgO for major Mesozoic basalt provinces	62
23. Weight percent $Na_2O$ versus weight percent MgO for major Mesozoic basalt provinces	63
24. Weight percent $K_2O$ versus weight percent MgO for major Mesozoic basalt provinces	64
25. Plot of mafix index versus weight percent $TiO_2$	69
26. Weight percent $SiO_2$ versus weight percent MgO showing mineral compositions and control lines	74
27. Weight percent $TiO_2$ versus weight percent MgO showing mineral compositions and control lines	75
28. Weight percent $Al_2O_3$ versus weight percent MgO showing mineral compositions and control lines	76
29. Weight percent $FeO_T$ versus weight percent MgO showing mineral compositions and control lines	77
30. Weight percent CaO versus weight percent MgO showing mineral compositions and control lines	78
31. Weight percent $Na_2O$ versus weight percent MgO showing mineral compositions and control lines	79
32. Weight percent $K_2O$ versus weight percent MgO showing mineral compositions and control lines	80
33. Weight percent $Al_2O_3$ versus weight percent $SiO_2$ showing mineral compositions and control lines	81
34. Weight percent CaO versus weight percent $SiO_2$ showing mineral compositions and control lines	82

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
1a.	Modal analysis of Liberian dolerites	15
1b.	Modal analysis of Spitsbergen dolerites	17
2.	Analytical precision	32
3a.	Major element analyses of dolerites from Liberia	35
3b.	Major element analysis of dolerites from Spitsbergen	37
4.	Calculated parental magma compositions for successive 10% crystallization intervals	86

## APPENDICES

APPENDIX I	Sample location of Mesozoic Liberian dikes	100
APPENDIX II	Instrumental parameters for atomic absorption spectrometric analyses	102
APPENDIX III	Dissolving procedure for atomic absorption analysis	103
APPENDIX IV	Instrumental parameters for analysis by x-ray spectrometry	104
APPENDIX V	Normative mineralogy (CIPW) for the Liberian and Spitsbergen dolerites	105

ABSTRACT

GEOCHEMISTRY OF MESOZOIC DOLERITES  
FROM LIBERIA, AFRICA AND SPITSBERGEN

by

Stephen Michael Testa

Master of Science in Geology

Mesozoic tholeiitic dolerite dikes that trend northwest-southeast intrude three geologic provinces of contrasting age, lithology and structure throughout northwestern Liberia. Major- and minor-element analyses of thirty-one representative samples show the dolerites to be predominantly quartz-normative tholeiitic basalts. Distinct geochemical differences are found to exist between the doleritic intrusions and the geologic province which they intrude. Dolerite dikes that intrude the Paynesville Sandstone exhibit moderately smooth variation trends. These dikes differ from dikes that intrude Precambrian basement rock by being less mafic in character, having higher  $\text{SiO}_2$  contents, and relatively lower percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$ . Dikes intruding the Pan-African province tend to be more uniform in composition and contain generally higher percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ , and generally lower percentages of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ . A rela-

tively large degree of scatter is evident for those dikes that intrude the Liberian province. Chemical composition of those dikes that intrude the northern Liberian province appear to be fairly restricted compared to their southern counterparts. Calculations based on assumed parent and daughter compositions suggest that the chemical variability of the Liberian dolerites may be explained primarily by about 60% crystal accumulation of clinopyroxene. Minor differences in chemistry might be explained by some degree of crustal contamination or wall rock reaction during magma ascent.

Nine-major- and minor-element analyses of dolerites representative of Mesozoic sills which intrude Spitsbergen and the nearby island of Wilhelmöya were also made. These dolerites are quartz-normative tholeiites consisting primarily of plagioclase, titanite, pigeonite and opaque minerals. The most striking aspect about the Spitsbergen dolerites studies is the general chemical uniformity of these rocks.

Generally, the Liberian dolerites compare well with other Mesozoic basalt provinces, but minor differences are evident and distinguish them as a distinct geochemical province. The Liberian dolerites do not compare well with more primitive eastern North American olivine-normative tholeiites. In comparison to the quartz-normative tholeiites of eastern North America, the Liberian dolerites

exhibit a greater degree of differentiation and Fe-enrichment. These differences indicate that the evolutionary course of the eastern North American and Liberian doleritic magmas were different during the time of their emplacement.

## INTRODUCTION

During the Mesozoic, a state of tension existed in the Southern Hemisphere and in localized areas in the Northern Hemisphere. The tectonic environment during the early Mesozoic was characterized by a single great landmass known as Pangaea. This irregular-shaped landmass was surrounded by the universal ocean of Panthalassa (the ancestral Pacific) and the Tethyan Sea (the ancestral Mediterranean), which formed a large bay separating Africa and Eurasia (Bullard et al., 1965; Dietz et al., 1970). The immediate prelude to the breakup of Pangaea were large outpourings of basaltic rock along the continental margins which were associated with the rifting apart of the Americas, Eurasia and Africa.

During Late Triassic and Early Jurassic time, extensive basaltic volcanism and intrusion occurred in Australia and Tasmania, South and West Africa, eastern South America, eastern North America, and in localized areas in the North Atlantic including the eastern border of Greenland and the Svalbard region. Associated with the flows and intrusions on either side of the Atlantic Ocean are somewhat parallel sets of doleritic dikes which exhibit a systematic pattern. When the continents are restored to their relative position in the Triassic, the pattern produced by the dikes is roughly convergent on the Blake plateau, the Bahama plat-

form and the western Senegal basin (Fig. 1). The pattern is interpreted as being in response to the crustal stresses accompanying the breakup of Pangaea, and the dikes themselves have been intruded along the fringes of the continental margins (May, 1971). According to May (1971), where dolerites have not undergone differentiation as in thick sills and dikes, their chemical range falls within that of the oceanic basalts. Ragland et al. (1968), also noted closer compositional similarities between dolerites of Northern Carolina and oceanic or oceanic margin tholeiites than to continental tholeiites.

In summary, Mesozoic tholeiitic dolerites emplaced as dike and sill complexes appear extensively along the continental margins bordering the Atlantic and Arctic Ocean. These doleritic intrusions are widely distributed and are tectonically related to the initiation of mid-Atlantic rifting, and their age is considered to coincide with the estimated time of the breakup of Pangaea (Behrendt and Wotorsen, 1970; Dalrymple et al., 1975; May, 1971; Sheridan et al., 1969).

#### PURPOSE

The purpose of this investigation is twofold. The first is to define the main petrographic and chemical types of Mesozoic dolerites from Liberia (West Africa)

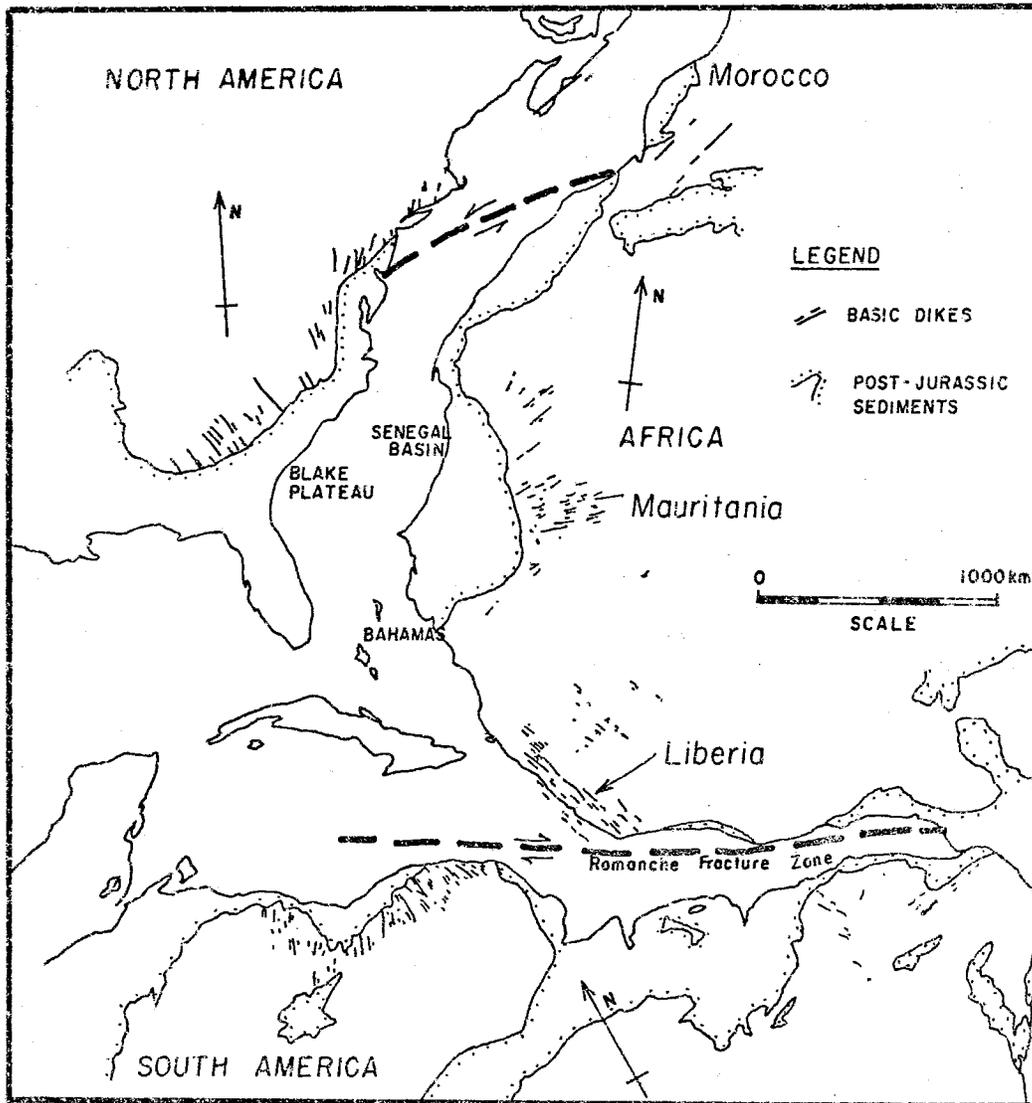


Figure 1. Triassic-Jurassic diabase dikes in eastern North America, West Africa, and northeastern South America, with the continents restored to their relative position in the Triassic. North arrows indicate present geographical direction on each continent. Heavy dashed lines are possible shear faults (Modified after May, 1971).

and Spitsbergen (North Atlantic region) and their relationship to other Mesozoic doleritic complexes, to determine the spatial distribution of these types, and to investigate the origin and evolution of the doleritic magmas and their relationship to the tectonic environment.

Secondly, it is of special interest to compare the chemical composition of eastern North American (ENA) dolerites with those of Liberia. Both doleritic complexes are of similar age, but were intruded on opposing sides of the mid-Atlantic ridge. Weigand and Ragland (1970) reported three main types of ENA Mesozoic dolerites; olivine-normative, high-TiO<sub>2</sub> quartz-normative, and low-TiO<sub>2</sub> quartz-normative. An attempt will be made to chemically correlate the ENA dolerites with those that intrude northwestern Liberia.

GEOLOGIC SETTING AND PREVIOUS WORK

In the United States, diabase is an intrusive igneous rock whose main components are labradorite and pyroxene, and is characterized by ophitic texture. In British and French usage, the term dolerite is preferred and is defined as an intrusive rock of the composition of diabase as defined in the United States. The term dolerite will be used in this report.

The most voluminous continental lavas are basalts of which tholeiitic basalts are by far the most extensive. In the strict sense of the word, tholeiite as a rock type has either the essential mineral augite or a subcalcic augite, plagioclase (near  $An_{50}$ ), and various iron oxides (Yoder and Tilley, 1962). Olivine is present in subordinate amounts and may even be absent. The critical feature in this definition is the nature of the pyroxenes. Yoder and Tilley (1962) state that these pyroxenes may consist of zoned augite to subcalcic augite with pigeonite or hypersthene or both. Therefore, tholeiitic basalts can be further subdivided into the following three types: saturated, oversaturated (normative quartz), and undersaturated (normative olivine). Normative hypersthene is essential in all three types of tholeiitic basalts.

Numerous petrological and geochemical studies have been made on various large Mesozoic tholeiitic complexes. These tholeiitic complexes include the Karro basalts of southern Africa (Compston et al., 1968; Cox et al., 1967; Walker et al., 1949), the Ferrar dolerites of Victoria Land, Antarctica (Gunn, 1962, 1965, 1966; Hamilton, 1965), the Tasmanian dolerites (McDougall, 1962; Heier et al., 1965), and the dolerite dikes of eastern North America (Hermes, 1964; Smith et al., 1975; Walker, 1940; Walker, 1969; Weigand and Ragland, 1970).

Liberia Tholeiitic dolerite dikes intrude three provinces of contrasting age, lithology and structure throughout northwestern Liberia (White and Leo, 1970). These provinces are west to east, the Liberian province, the Pan-African province, and the Paynesville Sandstone (Fig. 2). Based on reliable K/Ar ages, the doleritic intrusions of Liberia are contemporaneous and were intruded within the range 173 to 192 m.y. (Dalrymple et al., 1975).

According to Dalrymple et al. (1975), the Liberian province is essentially made up of Precambrian granitic gneisses ranging in composition from granite to quartz diorite with northeast-trending belts of sedimentary rocks folded into the gneiss and metamorphosed to the amphibolite facies.

The Pan-African province consist of metasedimentary and mafic-rich igneous rocks that have been refoliated and metamorphosed to the granulite and amphibolite facies. Along the coast of western Liberia, overlying the Precambrian crystalline basement rocks, are unmetamorphosed sedimentary rocks considered to be early or middle Paleozoic in age and are referred to as the Paynesville Sandstone. The thickness of this unit is not known, but geologic and geophysical evidence suggest a maximum of about 1 km. onshore (Behrendt and Wotorsen, 1972). The Paynesville Sandstone unit lies unconformably under the Cretaceous Farmington River formation, which has not been intruded by the

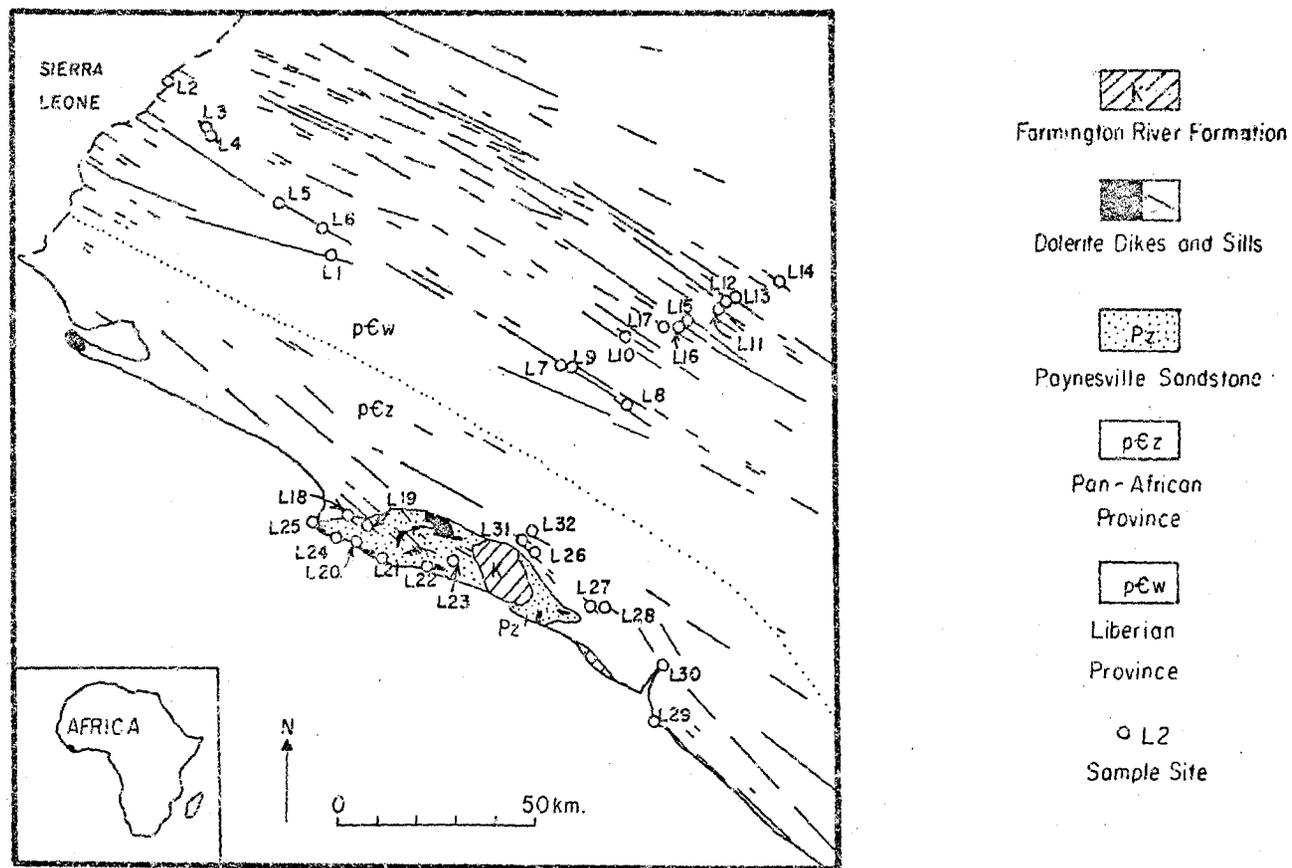


Figure 2. Geologic map of part of western Liberia showing sample locations, modified from Dalrymple et al. (1975). Dotted line is approximate boundary between Pan-African province (ca. 550 m. y.) and Liberian province (ca. 2,700 m. y.) of Hurley et al. (1971).

dolerites. Based on magnetic data (Behrendt and Wotorsen, 1972), doleritic dikes or their extrusive equivalents are traceable beneath the younger sedimentary rocks in the sedimentary basins on the continental shelf to the edge of the continental slope.

Paleomagnetic investigations have been made on the doleritic intrusions of northwestern Liberia (Behrendt and Wotorsen, 1970; Dalrymple et al., 1975). To date, no systematic petrographic study has been made, and only four samples have been chemically analyzed. Two analyses were reported by White (1972), and samples from two other localities were analyzed, although the data have not been published (Dalrymple et al., 1975). These analyses indicate that the dolerite is tholeiitic.

Spitsbergen Spitsbergen is located west of northern Greenland bordering the Arctic Ocean (Fig. 3). It is the main island group that together with Bear Island, Hope Island, and Kong Karls Land, forms the larger archipelago and political area termed "Svalbard" (Harland, 1969). Spitsbergen and its three large adjacent islands comprise more than 99.0% of the total land area of Svalbard and is the better known name. Mesozoic rocks exist on most of the major islands of Svalbard and together with the late Paleozoic strata form a single sedimentary complex of platform strata which overlies a basement of Devonian

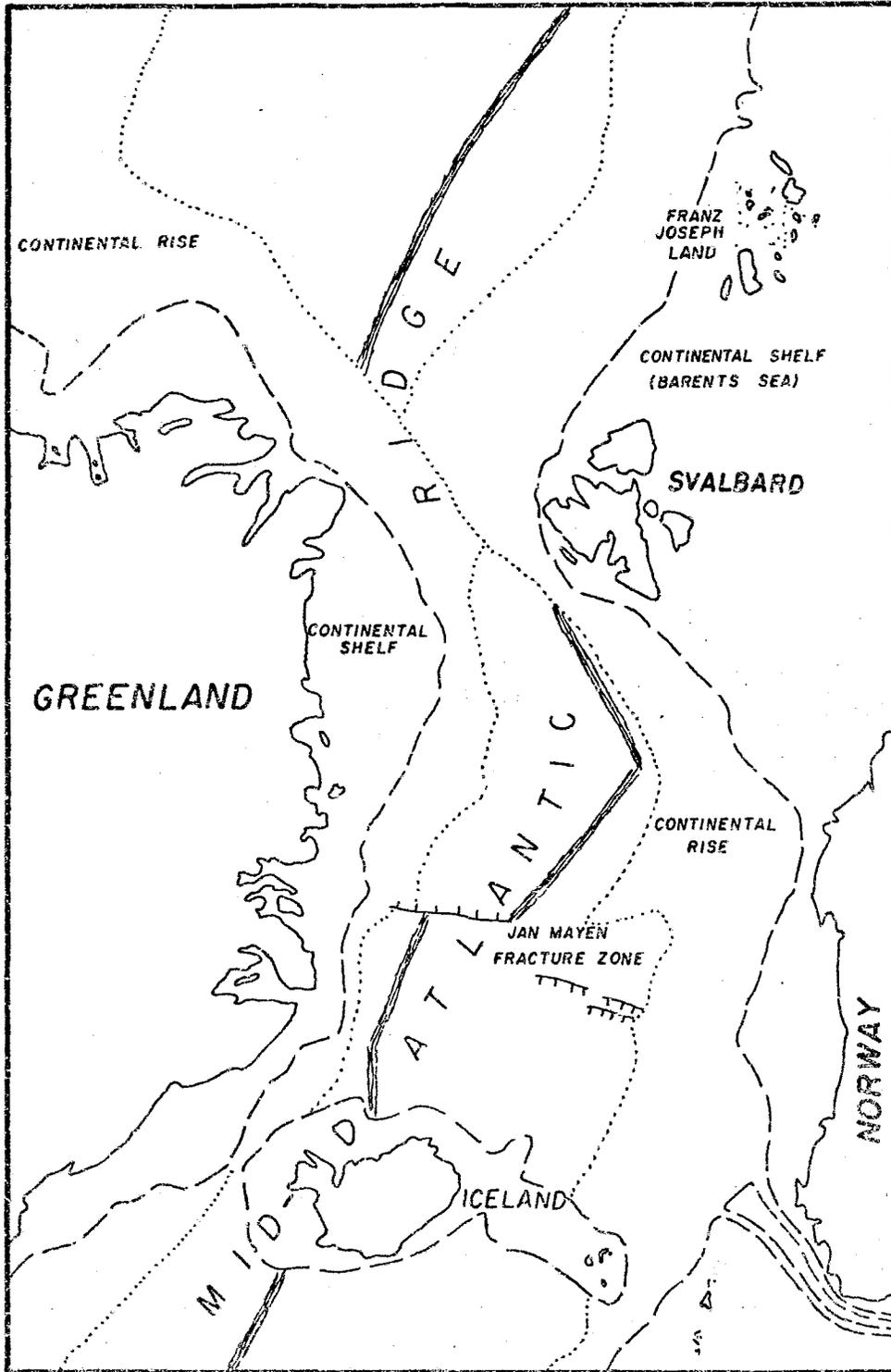


Figure 3. Vicinity map showing relative location of Svalbard and Franz Joseph Land in respect to the mid-oceanic ridge (Modified after Johnson et al., 1969).

and Caledonian tectonized rocks. Tertiary strata unconformably overlies the Mesozoic rocks (Harland, 1973).

The main phase of magmatic activity occurred during the Cretaceous. Magmatic events occurred at a time of renewed continental drift in the Arctic region, but preceded the formation of the neighboring oceanic basins (Harland, 1973). Numerous Mesozoic sills and dikes intruded into upper Jurassic to lower Cretaceous strata are found distributed throughout the Hinlopen Strait area of northeast Spitsbergen (Fig. 4). In the Hinlopen Strait, Triassic sedimentary rocks and rocks mainly Permo-Carboniferous in age are intruded. On the island of Wilhelmöya in the Hinlopen Strait, the Triassic sequence is overlain by Jurassic strata which are also intruded by doleritic sills. These basaltic lavas are overlain by unbaked lower Cretaceous sediments (Parker, 1966). Doleritic rocks also exist on the islands comprising Franz Joseph Land northeast of Spitsbergen (Harland, 1973; Fig. 3) and may correlate with the Spitsbergen dolerites.

It was first suggested by Gayer et al. (1966), based on K/Ar ages, that the dolerite intrusions of Spitsbergen were of late Jurassic age (149±11 m.y.). Parker (1966, 1967) conclusively demonstrated that at least part, and probably most of the doleritic rocks were intruded between the deposition of the Agardhfjellet formation and the

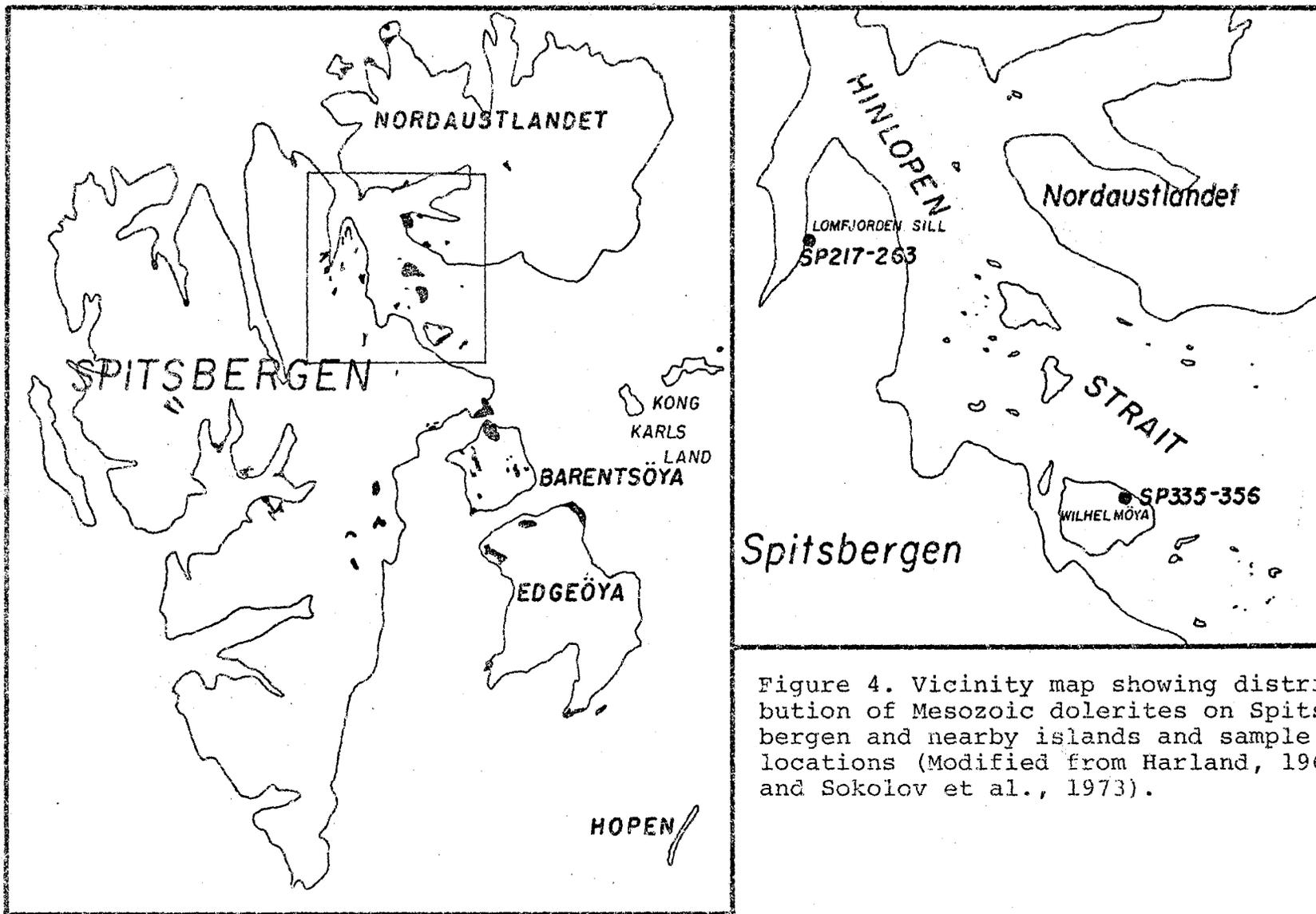


Figure 4. Vicinity map showing distribution of Mesozoic dolerites on Spitsbergen and nearby islands and sample locations (Modified from Harland, 1969 and Sokolov et al., 1973).

Rurifjellet formation (middle Jurassic to lower Cretaceous). In summary, the doleritic intrusions of Svalbard may have spanned a long period of time, but it appears that all the evidence is consistent with a middle Jurassic to lower Cretaceous age.

The dolerite intrusions exposed on Spitsbergen are intruded as sills and occasionally as dikes (Halvorsen, 1973). Thickness varies from a few decimeters to nearly 100 meters, although most are about 10 to 30 meters thick, and in some cases the intrusions can be followed for long distances. Based on magnetic susceptibility anisotropy measurements, the Lomfjorden sill and the nearby doleritic islands in the Hinlopen Strait have been shown to be relics of one or more sills, and are believed to be of the same age (Halvorsen, 1971).

Tyrrell and Sandford (1933) made the first systematic petrologic study of the intrusive doleritic dike and sill complexes from Spitsbergen and grouped them into four main classes:

- 1) Normal, medium- to fine-grained rocks which constitute the greater part of all intrusions.
- 2) Coarse gabbroidal and pegmatitic types which occur in the interior parts of the larger sills and massive intrusions.
- 3) Dense, slightly porphyritic, basaltoid, contact rocks.

- 4) "White-traps", endomorphic modifications due to intrusions into carbonaceous and calcareous rocks.

Tyrrell and Sandford (1933) also summarized what little chemical data that existed at the time. No recent geochemical analysis on the intrusive rocks of Spitsbergen are known to the author. Later petrologic studies were made by Russian investigators. Gayer et al. (1966) discussed rather inconclusive isotopic determinations and Parker (1966, 1967) gave the first conclusive stratigraphic evidence for the age of the doleritic intrusions. Numerous paleomagnetic investigations have been reported (Halvorsen, 1973; Krumsiek et al., 1968; Spall, 1968). During the past decade, much emphasis has been placed on the structural geology and tectonic elements in the Svalbard region due to the increasing search for petroleum prospects in the Arctic (Harland, 1969, 1973).

## PETROGRAPHY

MODAL ANALYSIS PROCEDURES

Oriented cores 2.50 cm. in diameter representing dolerites from northwestern Liberia were collected using portable equipment from 31 sample localities (Appendix I) for a paleomagnetic study reported by Dalrymple et al., (1975). Core samples were obtained by Dr. Peter W. Weigand from Mr. Richard W. White of the U. S. Geological Survey, Denver, Colorado. Modal analysis of thin sections from 21 of these cores were made using a point spacing of 1.0 mm. and 1000 counted points.

From each sample locality shown in Figure 2, two core samples were available. Thin sections from both core samples were studied for sample localities L7, L17 and L28 to see if there was an appreciable amount of mineralogical variability that would require analysis of both core samples for each sample locality. Modal analysis showed little mineralogical variability to exist within one sample locality, therefore, only one core sample was studied per each locality (Table 1a). An-contents of the plagioclase feldspars were determined by the Michel-Levy method.

TABLE 1a. MODAL ANALYSIS OF LIBERIAN DOLERITES

sample	Plag	An- Content	Augite	Pig	Hyp	Ol	Opaque Mins	Hbl	Biot	Geologic Province
L 1	66.1	54	29.5	0.6	-	-	1.7	2.1	-	
L 2	56.6	58	34.6	0.3	-	1.7	5.4	1.4	tr	
L 3	53.2	54	38.9	tr	-	-	6.5	1.4	tr	
L 4	52.7	58	38.7	1.1	-	-	7.5	tr	tr	
L 5	47.8	55	45.6	-	-	0.8	5.8	-	-	
L 6	57.5	61	37.6	tr	-	3.3	1.6	tr	-	
L 7a	47.7	53	46.9	2.0	-	-	2.7	0.5	0.2	
L 7b	46.9	55	47.3	1.7	-	-	3.1	0.6	0.2	Liberian
L 9	49.0	63	47.0	-	-	-	4.0	tr	-	
L10	50.7	63	37.7	0.2	-	2.0	8.0	0.6	0.8	Province
L11	67.4	56	26.5	0.4	-	-	2.3	3.4	tr	
L12	56.8	63	31.7	0.4	-	-	8.9	1.9	tr	
L13	56.4	64	30.3	0.9	-	0.1	11.6	0.7	-	
L14	58.3	65	33.1	0.7	-	0.6	5.8	1.5	-	
L15	52.9	54	34.7	tr	-	-	12.2	0.2	tr	
L16	58.0	56	37.3	tr	-	0.9	2.8	2.7	0.7	
L17a	50.2	55	34.6	0.9	-	3.0	10.3	0.7	0.3	
L17b	49.1	58	35.8	0.5	-	2.6	11.3	0.5	0.2	
L19	57.9	63	37.9	1.0	-	0.6	2.6	tr	tr	
L20	55.8	55	41.9	0.1	-	0.2	2.4	3.6	-	Paynesville
L21	36.0	52	34.5	-	14.4	4.5	3.4	tr	-	
L22	53.6	59	38.4	0.8	-	0.7	3.3	2.8	-	
L23	63.1	66	27.0	1.5	1.4	0.4	3.0	3.6	-	Sandstone
L25	46.1	58	33.2	1.8	16.2	-	2.7	tr	-	

TABLE 1a (Continued).

sample	Plag	An- Content	Augite	Fig	Hyp	Ol	Opaque Mins	Hbl	Biot	Geologic Province
L18	53.0	54	30.6	-	-	1.9	11.8	1.7	1.0	
L26	59.2	62	28.5	0.4	-	0.7	7.3	1.3	2.6	
L27	42.2	61	34.5	0.3	-	0.5	21.3	0.9	-	Pan-African
L28a	34.4	63	38.3	1.1	2.2	1.7	20.6	0.5	0.7	
L28b	36.8	60	37.0	1.5	1.8	1.0	19.7	1.3	0.9	Province
L29	72.7	52	18.3	-	-	-	5.7	3.3	-	
L30	54.6	58	35.9	0.9	-	-	8.0	0.4	0.2	
L31	52.7	59	37.5	1.6	-	1.8	5.3	0.5	0.6	
L32	50.9	59	40.9	0.3	1.4	-	4.6	1.6	0.3	

TABLE 1b. MODAL ANALYSIS OF SPITSBERGEN DOLERITES

sample	Plag	An- Content	Augite	Pig	Hyp	Ol	Opaque	Glass	Hbl	Biot	Geologic
217	57.3	61	31.4	2.4	-	-	8.9	-	-	tr.	
223	54.3	58	35.8	1.5	-	-	8.6	-	-	tr.	
257	49.1	60	40.1	0.5	-	-	10.3	-	-	tr.	Lomfjorden Sill
260	52.5	63	34.0	2.9	-	-	10.6	-	-	tr.	
263	53.7	62	39.5	0.5	-	-	6.3	-	-	tr.	
335	48.5	64	36.6	0.3	-	-	11.6	-	-	3.0	
346	42.4	60	43.4	tr.	-	-	10.9	1.8	-	1.5	Wilhelmöya
354	38.9	61	28.5	tr.	-	-	12.1	16.5	-	4.0	
356	56.9	60	32.0	tr.	-	-	8.9	-	-	2.2	
ave. 200 series	53.4	61	36.1	1.6			8.9	-	-	tr.	
ave. 300 series	46.7	61	35.1	0.1			10.9	4.6	-	2.7	

The petrologic description for the Liberian dolerites includes samples collected from the Liberian province, Pan-African province and the Paynesville Sandstone (Fig. 2). The samples studied are assumed to be representative of the doleritic intrusions throughout northwestern Liberia.

Modal analysis were also made of nine samples from the Hinlopen area of Spitsbergen (Table 1b). Samples SP217, 223, 257, 260 and 263 were collected from the Lomfjorden Sill, and samples SP335, 346, 354 and 356 were collected from the island of Wilhelmöya in the Hinlopen Strait (Figure 4). Rock samples were obtained by Dr. Peter W. Weigand from Dr. Erik Halvorsen who collected the samples for a magnetic anisotropic study (Halvorsen, 1974).

All the samples studied are from within 1-3 meters of a contact zone (Halvorsen, personal communication). This is intended to eliminate any effects of differentiation due to crystal settling upon the chemistry or mineralogy. According to Dr. Erik Halvorsen (personal communication), width of the sill or sills from which the samples were obtained is about 12-16 meters. Whether the samples from Spitsbergen represent one or more sills is not known.

LIBERIA

Modal analysis of 33 thin sections from Liberia are presented in Table 1a. The doleritic rocks are gray, medium- to fine-grained granular rocks. In thin section, ophitic to subophitic texture predominates. This is characteristic of doleritic rocks in which large euhedral to subhedral plagioclase crystals are partially to completely enclosed in randomly distributed augite crystals. A less common texture occurs in samples L7, L9, 10 and 27 which are holocrystalline, fine-grained rocks that exhibit intergranular textures with fairly large glomerocrysts of lath-like plagioclase crystals. Some of the plagioclase crystals exhibit concentric zoning. The opaque minerals are represented by skeletal crystals which are randomly dispersed throughout the slides. Alkali feldspar and quartz are commonly associated and exhibit a micrographic texture.

Many workers (i.e. Justus, 1966; Ragland et al., 1968) have been aware of variations in textural zonation from the contact of a dike toward its center. Fine-grained, intergranular texture is common near a contact, grading into a coarser-grained, ophitic texture toward the center of the dike. It is probable that samples L7, 10 and 27 were collected from relatively thin dikes or from near the contacts of thicker dikes.

Plagioclase, augite and the opaque minerals are the main constituents comprising the doleritic intrusions with plagioclase and augite being the most dominant. Minor constituents include hypersthene, pigeonite and olivine. Trace minerals consist of apatite, biotite, chlorite, hornblende, sericite and uralite.

Plagioclase is usually more abundant than augite (34-72% compared to 18-47%: Table 1). Plagioclase ranges from  $An_{53}$  to  $An_{66}$ , falling within the range of babradorite. Plagioclase is lath-like and commonly corroded and altered to sericite yielding turbid laths. Albite and Carlsbad twins are frequently combined. Glomerocrysts of plagioclase are common in the finer-grained rocks.

Clinopyroxene is the most common pyroxene found in the Liberian dolerites. Augite crystals are normally subhedral and randomly distributed in all the thin sections studied. Oval-shaped pyroxene crystals embedded within plagioclase sometimes show radial oriented fractures which may be due to differential cooling between the plagioclase and the pyroxene. Zoned and occasional twinned augite crystals occur. Extreme chemical zonation of the pyroxene is evident by birefringence variations from center to edge of some grains.

The amount of pigeonite is variable and difficult to identify. It commonly occurs enveloped within cores of augite with isolated grains present but rare. Pigeonite was distinguished from augite by its lack of: optical continuity with augite, its lower birefringence and by its extremely low optic axial angle.

Hypersthene was identified in some of the Liberian samples. Where present, it forms euhedral to subhedral crystals and is commonly enveloped within clinopyroxene grains. Based on its larger size relative to augite, hypersthene appears to have crystallized before augite. No hypersthene was noted in samples obtained from the Liberian province, whereas within the Paynesville Sandstone, L25 shows as much as 16% hypersthene (Table 1).

Olivine makes up only a minor constituent in the Liberian dolerites ranging up to approximately 3.0% in abundance. Olivine was most frequently observed as randomly distributed, subhedral to anhedral grains. It is commonly enclosed within pyroxene and in some cases is highly fractured. Alteration of olivine grains is infrequent and appears to commence along grain boundaries or fractures and proceed inwards.

Primary crystals of opaque minerals occur in all thin sections and range from about 2-12% in total volume with two samples, L22 and 28, having opaque contents of 20.6 and 21.3%, respectively. These two samples may represent cumulates. Specks of opaque minerals were observed within some augite grains suggesting secondary opaque minerals due to alteration of the pyroxene. The opaque minerals generally form equant, subhedral to anhedral crystals which are randomly dispersed. According to Dalrymple et al. (1975), magnetite and ilmenite are the predominate opaque minerals in these dikes. The opaques commonly form skeletal aggregates, but also appear as long rods or stringlets which penetrates nearby crystals. Dikes which intrude the Paynesville Sandstone are characterized by having relatively low abundances of opaque minerals (2.4 to 3.3%).

Accessory minerals consist of apatite, biotite, chlorite, hornblende, sericite and uralite. Biotite flakes appear to be in close association with the opaque minerals. Hornblende forms subhedral to anhedral grains and is pleochroic (yellowish-green to brown). The presence of hornblende is inferred to be due to the alteration of pyroxene.

Uralite, a fibrous, light blue-green amphibole, with the habit of a pyroxene but the structure of an amphibole, is present in trace amounts and is also probably due to the alteration of the pyroxenes. In some cases uralite occurs as single crystals or as an aggregate of small prismatic crystals. The formation of uralite is due to either the action of hydrothermal solutions which could be associated with late-stage differentiation and crystallization in these rocks, or to post-consolidation processes unrelated to igneous activity from which the rocks were derived (Deer et al., 1975).

Alkali feldspar and quartz are commonly associated and exhibit a micrographic texture. Micrographic texture appear to be more abundant in the coarser-grained rocks. Interstitial quartz is present but rare. Apatite, although not included in the modal analysis due to its small abundance, is present in trace amounts. Apatite is present as small acicular crystals randomly dispersed throughout the slides.

Sample L29 is strikingly different in comparison to other samples from dikes which intrude the Paynesville Sandstone. Whether or not the poorly exposed outcrop from which L29 was obtained is a sill or dike could not be determined in the field (Gromme', personal communication).

In thin section, the gabbro is a hollocrystalline coarse-grained rock which is more felsic in comparison to other Liberian dolerites. Plagioclase is abundant (72.7%) and appears as highly fractured tabular crystals which have been highly sericitized. Augite is the only pyroxene present and occurs as subhedral, semi-tabular crystals that have been highly altered to hornblende, uralite and biotite.

#### SPITSBERGEN

The dolerites from Spitsbergen are gray, medium- to fine-grained, granular rocks. Holocrystalline subophitic texture predominates in most of the thin sections studied but subintersertal and intergranular textures are also present. Sample SP354 is unusual in that it consists of a dark mesotaxis containing glass and tiny crystals of thin acicular opaque minerals. This texture is probably due to quenching at the marginal portion of the intrusion. Sample SP223 has a subintersertal texture in which a groundmass of fine-grained, partly altered crystalline material other than augite occupies the interstices between the unoriented feldspar laths. This groundmass forms a relatively small proportion of the rock.

Plagioclase and augite are the predominate minerals, and plagioclase is usually greater in abundance than augite. Plagioclase ranges from 42 to 57% with An-contents ranging from An<sub>58</sub> to An<sub>64</sub> that falling within the range of labradorite (Table 1). Augite ranges from 31 to 43% in total volume. The opaque minerals range from 6 to 12% in abundance. Accessory minerals include biotite, chlorite, sericite and glass.

Augite is the most common pyroxene present, and is characterized by violet-purple pleochroism. Although TiO<sub>2</sub> content of the clinopyroxene grains was not determined, the strong pleochroism noted is suggestive of titanaugite and will be referred to as such. Titanaugite forms subhedral to anhedral, irregular, pale brownish-purple grains that are randomly dispersed throughout the slides. Suboval shaped grains of augite commonly enclose pigeonite, which is distinguished from augite by its relatively higher birefringence, higher relief and clearer nature in plane light. The crystallization of augite and pigeonite, both becoming progressively richer in iron, is typical of middle levels of most sills (Charmichael et al., 1974).

Samples SP217, 223 and 257 show irregular grains of augite surrounded by relatively smaller grains of opaque

minerals. Augite is commonly altered to chlorite and biotite around the rims of grains and along cleavage traces. The variations in birefringence from the center an an augite grain to its edge implies chemical zonation and Fe-enrichment.

The abundance of pigeonite is variable from slide to slide and well-defined grain boundaries are noted in the Spitsbergen dolerites. In some cases, as in sample SP335, augite grains enveloping the pigeonite are relatively acicular in shape. Pigeonite is most pronounced in sample SP260 where it makes up as much as 3.0% in total volume. Pigeonite is relatively more abundant in those samples from the Lomfjorden sill vicinity than those samples from the island of Wilhelmöya (Table 1b).

The abundance of opaque minerals in the Spitsbergen dolerites are uniformly high ranging from about 3.0 to 6.0% in total volume. In all the slides investigated, the opaque minerals form unoriented skeletal acicular rods which penetrate nearby crystals. Where glass is present, small acicular grains of opaque minerals are dispersed throughout the glass.

Neither hypersthene nor olivine were noted in the samples studied. The identification of olivine is

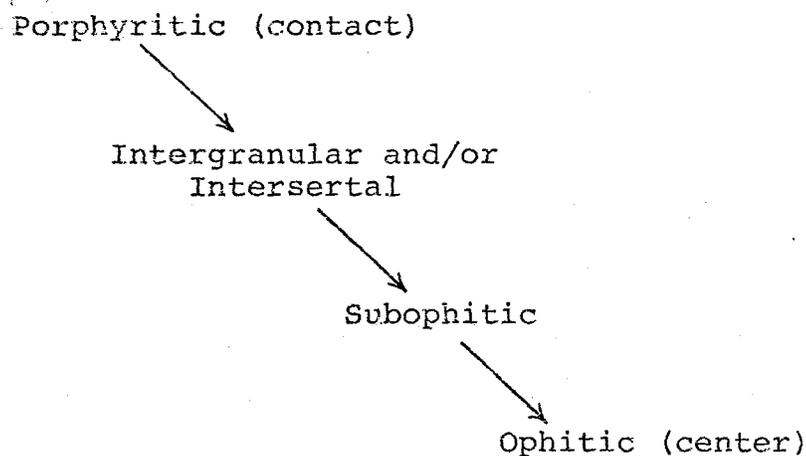
questionable due to the extreme alteration of some grains suspected of being olivine.

Irregular patches of reddish-orange biotite ranging up to about 4.0% are found randomly dispersed throughout most of the thin sections studied. Biotite is more abundant in samples from the island of Wilhelmöya.

#### DISCUSSION

The main minerals which comprise the dolerite rocks studied are plagioclase, augite (titanaugite?), hypersthene, olivine and the opaque minerals. With the exception to hypersthene and olivine, these minerals make up approximately 95% total volume and their proportions vary from sample to sample. Mineralogical criteria consistent of tholeiitic character as reported by Yoder and Tilley (1962) is the presence of augite or a subcalcic augite, plagioclase (near  $An_{50}$ ) and various iron oxides. According to Yoder and Tilley (1962), pyroxenes may consist of zoned augite to subcalcic augite in association with pigeonite or hypersthene or both. Olivine is present in subordinate amounts and may even be absent. On the basis of mineralogy, the dolerites from Liberia and Spitsbergen are characteristic of tholeiitic criteria.

Subophitic texture predominates but intersertal, intergranular and ophitic textures are also present. Justus (1966) described progressive textural variations across many North Carolina dolerite dikes regardless of the thickness. A moderately simplified version of this progression is presented below:



In regards to the Liberian dolerites, it is noted that coarser-grained rocks have the character of thicker dikes as suggested by Justus (1966) and have crystallized toward the central portion of a dike. Likewise, fine-grained rocks have the character of rocks that crystallized nearer toward the margins or crystallized in relatively thin dikes. Other mineralogical variations progressing from the contacts of a dike toward its center noted by Justus (1966) include a decrease in An-content, a decrease in normative plagioclase, elongation and widening of

plagioclase laths and a slight increase in the concentration of opaque minerals. Usually more than one textural type is present in one thin section and there is a wide variety in grain size. Since grain size is consistent with texture, these two factors can be used to determine the relative place within the dike from which the Liberian samples were obtained.

Subophitic texture predominates and may be explained by the modal plagioclase/pyroxene ratio which exceeds 1.0 in most of the Liberian and Spitsbergen samples. Chalcraft (1972) showed that the plagioclase/pyroxene ratio has an effect on the development of subophitic texture. Subophitic texture is usually dominant when the modal plagioclase/pyroxene ratio exceeds 1.0. When the plagioclase/pyroxene ratio is less than 1.0, subophitic texture is rarely dominant. According to Chalcraft (1972), the reduction of nucleation sites for pyroxene growth seems to retard the crystallization of pyroxene therefore producing the prominence of plagioclase over pyroxene.

The Liberian and Spitsbergen dolerites can be compared with other major doleritic complexes which contain two pyroxene phases, a calcium-rich pyroxene (augite) and a calcium-poor pyroxene (hypersthene or pigeonite, or both), suggesting similarities in magma types. These

complexes include the ENA dolerites (Ragland et al., 1968; Weigand and Ragland, 1970; Steele, 1971; Chalcraft, 1972), the Ferrar dolerites of Victoria Land, Antarctica (Gunn, 1966), the Karroo basalts of South Africa (Cox et al., 1967) and the Red Hill dike, Tasmania (McDougall, 1962).

## GEOCHEMISTRY

### ANALYTICAL METHODS

The Liberian and Spitsbergen dolerites were analyzed in the Department of Geoscience, California State University, Northridge. Concentrations of Al, Mg, Mn, Fe and Na were determined using an Instrumentation Laboratory Model 151/251 atomic absorption unit on 200ppm solutions prepared by normal HF dissolving procedures. Acetylene was used as the fuel with nitrous oxide as the oxident for Al, and air as an oxident for the other elements. Additional information concerning instrumental parameters and dissolving procedures is given in Appendices II and III. Concentrations of Si, Ti, Ca and K were determined on pressed-powder samples with a Norelco Universal Vacuum-Path X-ray Spectrograph equipped with a Cr tube and a PET or LIF analyzing crystal. Instrumental parameters for X-ray spectrometric analyses are given in Appendix IV. The P analyses, modified after Shapiro (1975), were made using a Bausch and Lomb Spectronic 20 spectrophotometer. Information regarding analytical precision is given in Table 2. Duplicate samples for P were not analyzed, therefore, analytical precision was not determined for this element.

Table 2. Analytical precision. Duplicate pellets and solutions were prepared for each sample, and each was analyzed at least twice for each element. Precision was calculated as relative standard deviation ( $RSD = 100s/\bar{x}$ ) where  $s$  is one standard deviation and  $\bar{x}$  is arithmetic mean of the weight percentage of each element.

Oxide	RSD	Method
$SiO_2$	.45	XRF
$Al_2O_3$	.92	AA
$TiO_2$	1.51	XRF
$FeO_T$	1.81	AA
MgO	2.50	AA
MnO	2.72	AA
CaO	1.08	XRF
$Na_2O$	3.68	AA
$K_2O$	.25	XRF

Calibration curves were drawn for each element using standard rocks selected from the following list: Geologic Survey standard rocks, AGV1, BCRI, GSP1 and W1; Japanese Geological Survey basalt standard JB1; Centre de Recherches Petrographiques basalt standard BR; Queen Mary College basalt standard QMC-I3; and University of North Carolina dolerite standard BD1.

## RESULTS

The major-element analyses, expressed as oxides, are given in Table 3. Magnesia variation diagrams (Figs. 5 to 13) were prepared for comparative purposes and to evaluate compositional variations within and between the different dolerite groups.

Liberia The dolerite dikes from the three geological provinces of Liberia exhibit dissimilar compositional characteristics. Dolerite dikes intruding the Pan-African province tend to be fairly uniform in composition. These dolerites contain generally higher percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ , and generally lower percentages of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  than the other Liberian dolerites. A relatively large degree of scatter is evident for dikes that intrude the Liberian province. Dikes that intrude the northern part of the Liberian province exhibit a smaller range in  $\text{MgO}$  compared to those from the southern part (5.9-7.2% versus 3.9-8.8%). Dolerite dikes that intrude the Paynesville Sandstone exhibit moderately smooth variation trends. These dolerites differ from Liberian dolerites which intrude Precambrian basement rocks by a higher percentage of  $\text{SiO}_2$  and lower percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$ .

TABLE 3a. Major element analyses of dolerites from Liberia.

sample number	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sub>T</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	total	
L 1	51.88	.73	14.06	11.14	.19	5.89	10.29	2.19	.74	.12	97.23	
L 2	49.82	.66	14.39	9.78	.16	7.24	11.74	1.80	.41	.08	96.08	northern
L 3	49.69	2.22	12.59	13.51	.21	6.08	10.31	2.37	.43	.23	97.64	Liberian
L 4	47.12	1.43	12.46	13.47	.19	6.78	9.74	2.43	.37	.12	94.11	province
L 5	50.49	.75	13.87	10.81	.19	7.14	11.52	1.90	.46	.08	97.21	
L 6	49.25	1.80	13.26	13.28	.21	6.71	10.65	2.27	.31	.00	97.74	
L 7	49.83	1.73	13.47	12.84	.20	6.52	10.85	2.24	.29	.10	98.12	
L 9	50.10	.69	13.99	11.20	.18	7.41	11.69	1.83	.39	.04	97.52	
L10	51.28	2.42	12.94	12.39	.20	5.48	9.71	2.40	.78	.33	97.93	
L11	50.50	2.63	12.06	16.23	.23	4.30	8.62	2.36	1.05	.33	98.31	southern
L12	49.44	3.51	12.14	14.61	.21	5.73	9.50	2.29	.93	.37	98.73	Liberian
L13	50.78	3.36	12.80	13.54	.20	3.92	8.77	2.55	1.09	.47	97.48	province
L14	50.21	1.25	13.22	12.62	.21	5.84	11.11	2.02	.40	.10	96.98	
L15	51.41	3.49	12.37	14.37	.21	4.36	8.43	2.48	1.22	.53	98.87	
L16	49.80	1.56	11.13	12.91	.21	8.75	8.79	1.92	.81	.21	96.09	
L17	50.13	2.15	12.97	14.35	.21	6.34	10.28	2.39	.43	.17	99.42	

TABLE 3a. (Continued)

sample number	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sub>T</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	total	
L19	54.52	2.02	12.24	12.13	.18	3.40	7.10	2.26	1.51	.25	95.61	
L20	51.27	1.47	13.26	9.50	.17	7.09	9.94	2.14	.95	.17	95.96	
L21	50.20	.96	12.10	10.45	.16	9.15	9.80	1.64	.67	.10	95.23	Paynesville Sandstone
L22	50.86	1.11	12.57	9.45	.16	8.62	10.37	1.61	.68	.17	95.60	
L23	52.06	1.04	14.96	8.30	.14	6.32	10.70	2.18	.78	.08	96.56	
L24	52.80	1.16	13.65	10.23	.17	5.42	9.92	2.26	.90	.23	96.74	
L25	51.15	.82	13.87	8.34	.15	8.15	11.41	1.82	.59	.12	96.42	
L18	49.02	3.59	12.62	14.53	.22	5.07	8.98	2.56	1.09	.45	98.13	
L26	48.51	4.04	11.70	15.58	.24	5.44	9.26	2.27	1.16	.79	98.99	
L27	48.16	5.29	11.72	14.48	.23	5.15	9.37	2.41	1.07	.47	98.35	Pan-African province
L28	48.49	3.70	12.34	15.13	.22	5.69	9.47	2.25	1.02	.61	98.92	
L29	51.06	2.75	14.78	13.78	.19	2.15	8.17	3.22	1.08	.69	97.87	
L30	48.51	3.59	13.07	14.59	.21	5.41	9.53	2.39	1.01	.63	98.94	
L31	50.24	2.33	12.43	13.25	.20	5.37	9.90	2.39	.84	.29	97.24	
L32	50.09	3.91	12.08	14.68	.22	4.66	9.17	2.47	.98	.47	98.73	

TABLE 3b. Major element analyses of dolerites from Spitsbergen

sample number	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sub>T</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	total	
217	49.65	3.51	12.78	13.12	.20	5.59	9.70	2.32	.81	.29	98.97	
223	50.30	3.55	12.67	13.05	.20	5.64	9.78	2.47	.63	.26	98.55	
257	50.11	3.49	12.85	13.12	.19	5.50	10.00	2.40	.57	.35	98.58	Lomfjorden Sill
260	50.00	3.42	12.49	12.93	.19	5.30	10.14	2.26	.55	.33	97.61	
263	49.09	3.34	12.13	12.69	.19	5.20	10.20	2.28	.54	.31	96.77	
335	49.72	3.50	12.65	12.45	.16	5.06	9.10	1.97	.78	.36	95.75	
346	50.31	3.30	12.84	13.08	.20	5.77	9.21	2.28	.83	.27	98.09	Wilhelmöya
354	50.21	3.41	12.61	12.58	.18	5.19	9.47	2.15	.73	.33	96.86	
356	50.39	3.39	12.77	12.87	.20	5.23	9.54	2.08	.79	.35	97.61	
ave. 200 series	49.99	3.46	12.58	12.98	.19	5.45	9.96	2.35	.62	.31		
ave. 300 series	50.16	3.45	12.72	12.75	.19	5.31	9.33	2.12	.78	.33		

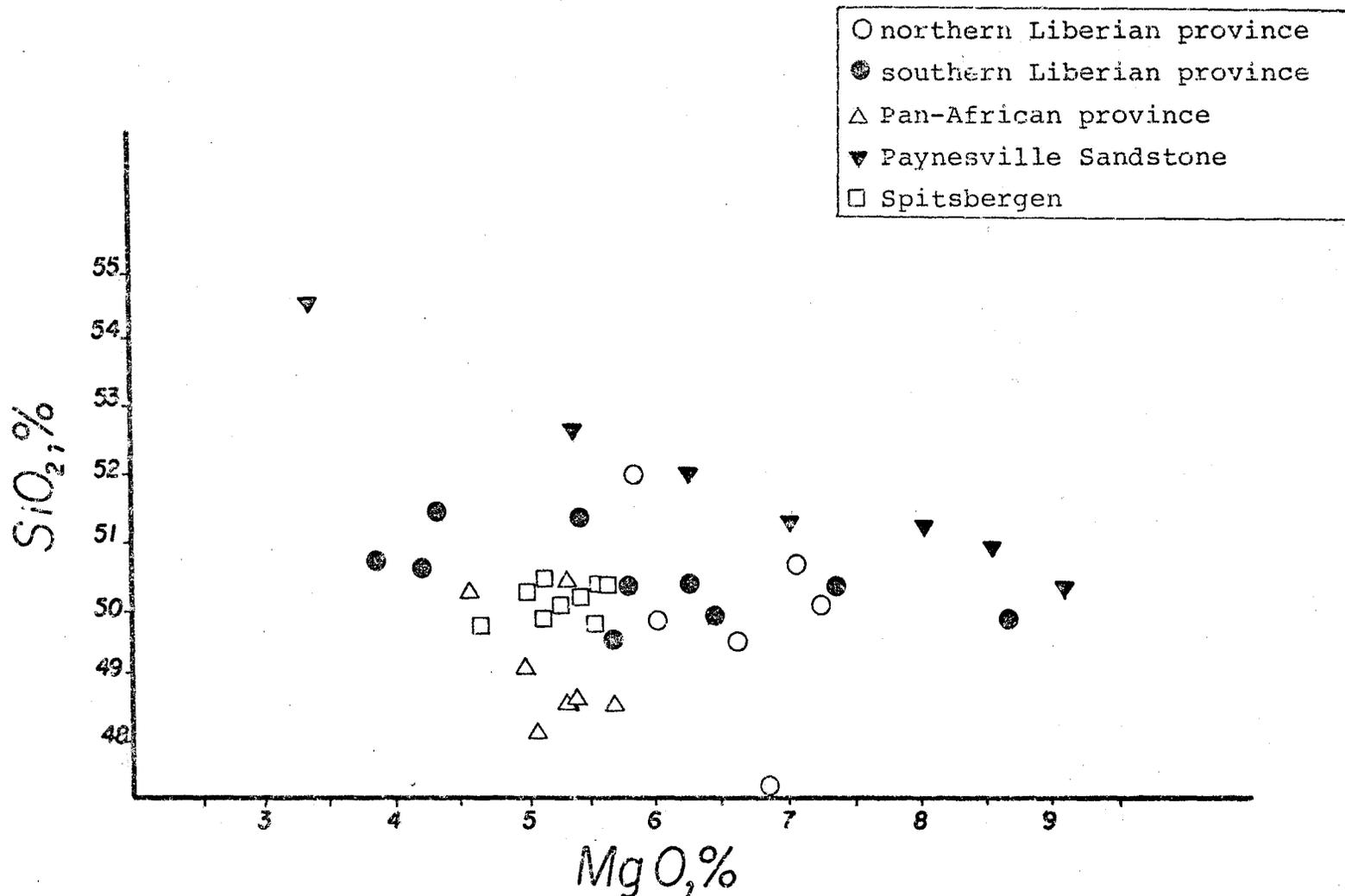


Figure 5. Weight percent SiO<sub>2</sub> versus weight percent MgO.

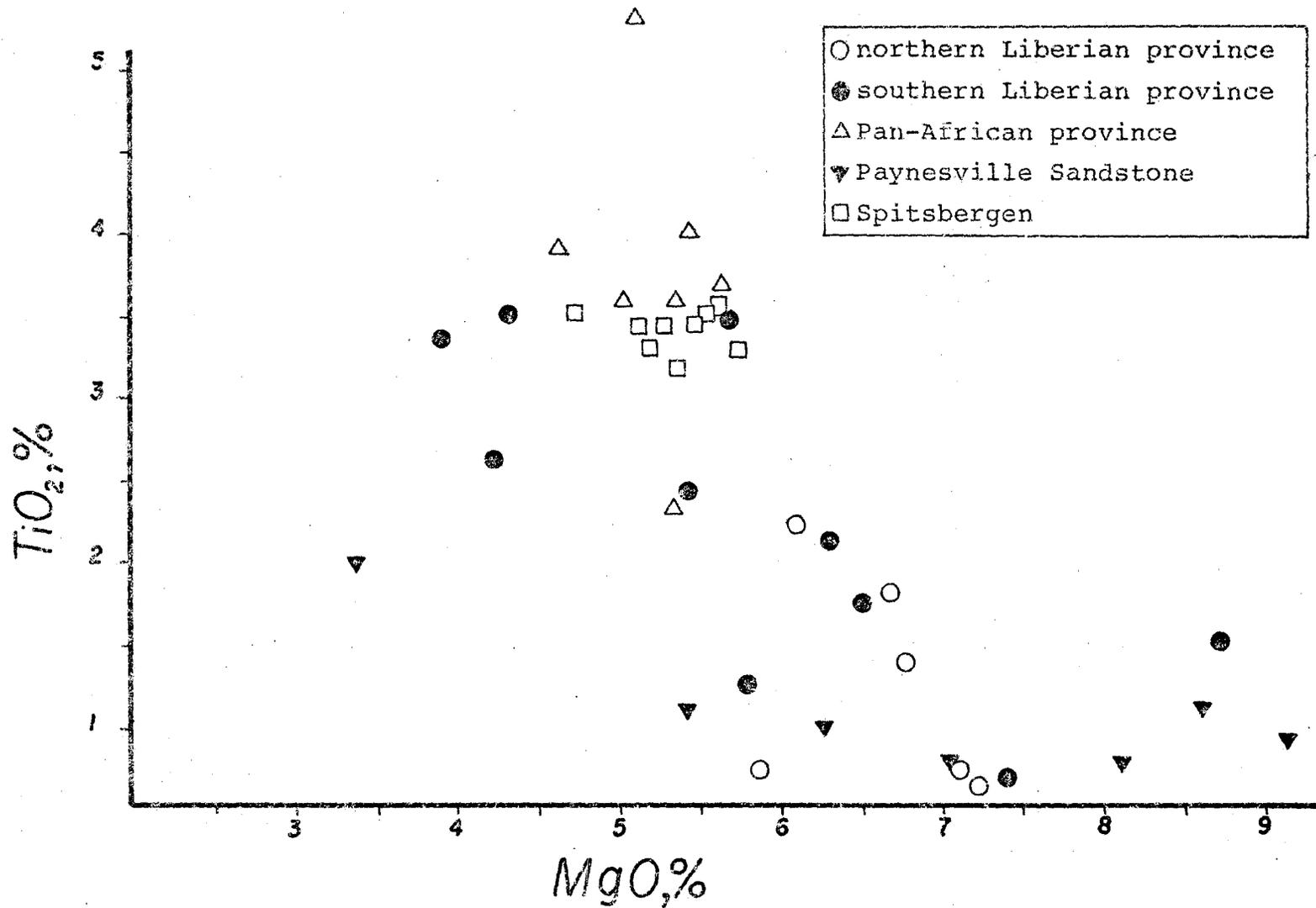


Figure 6. Weight percent  $TiO_2$  versus weight percent  $MgO$ .

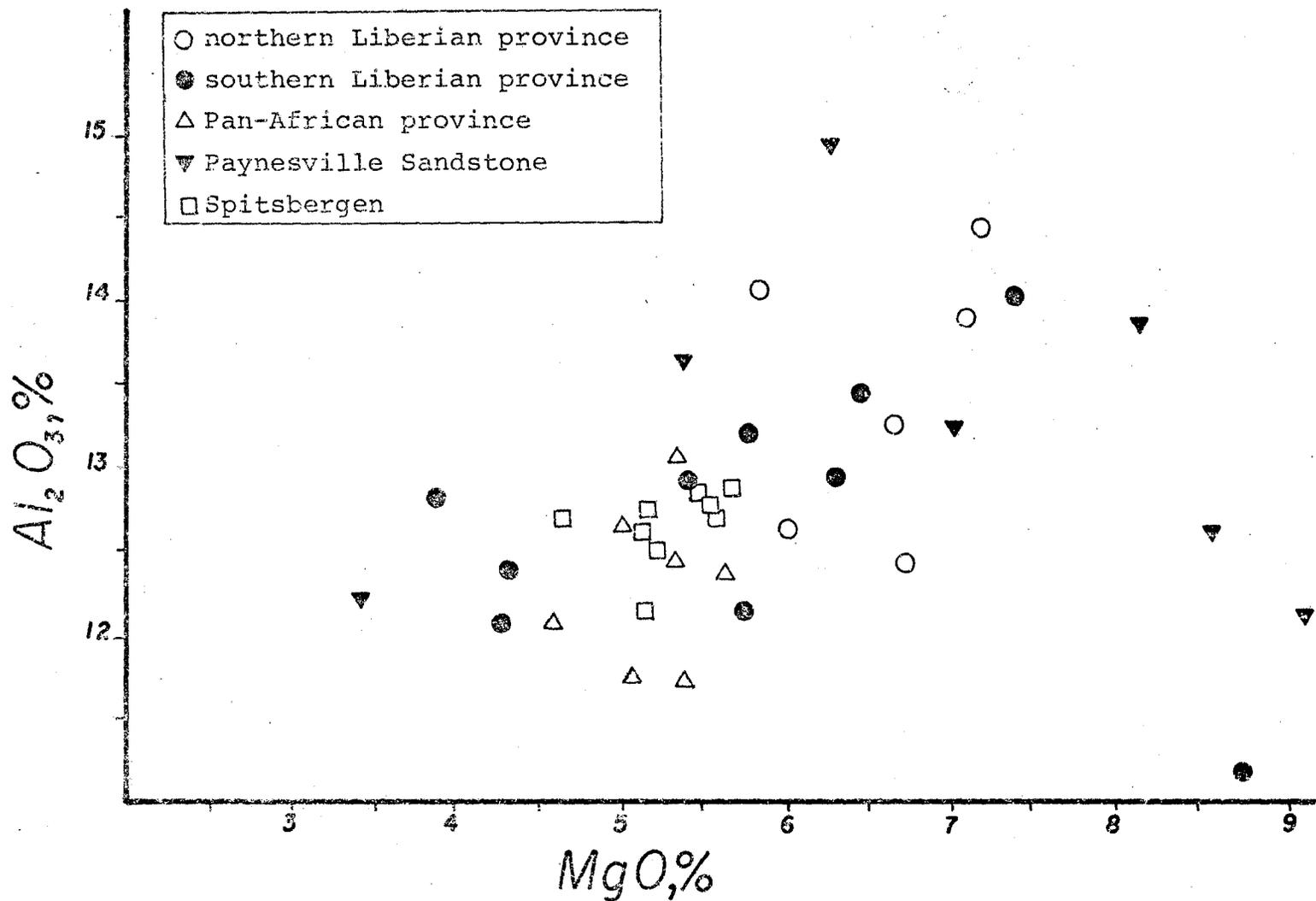


Figure 7. Weight percent Al<sub>2</sub>O<sub>3</sub> versus weight percent MgO.

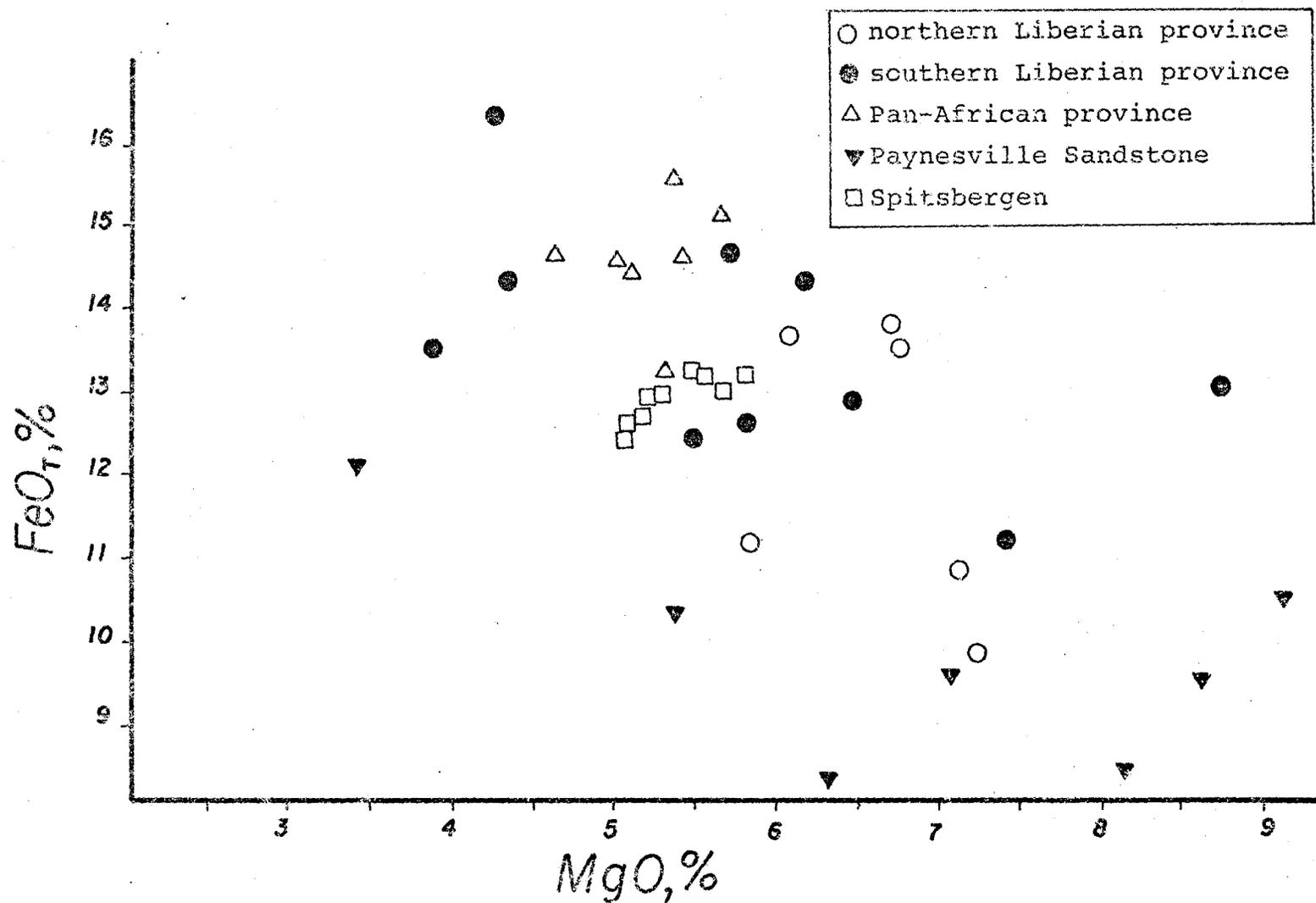


Figure 8. Weight percent FeO<sub>T</sub> versus weight percent MgO.

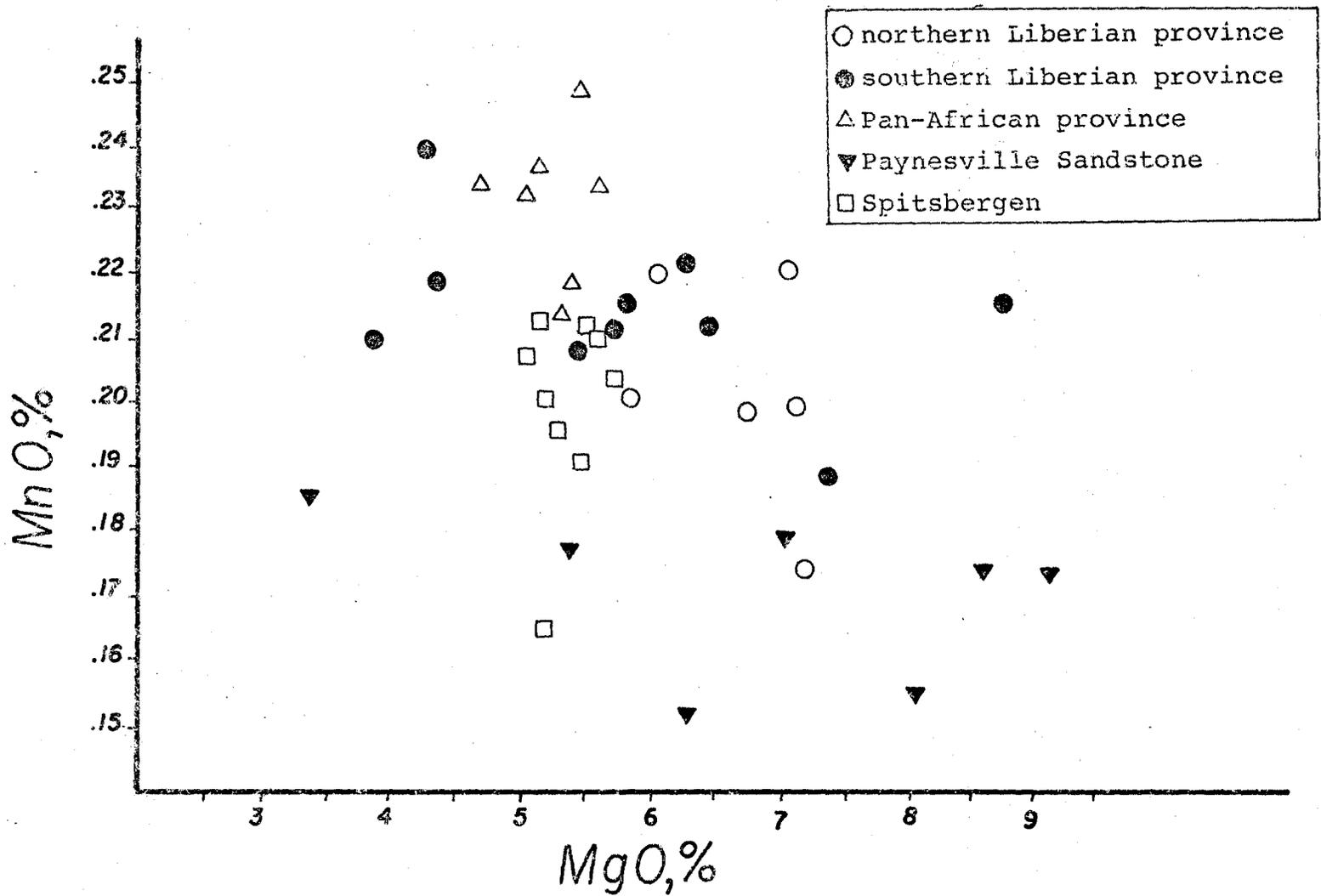


Figure 9. Weight percent MnO versus weight percent MgO.

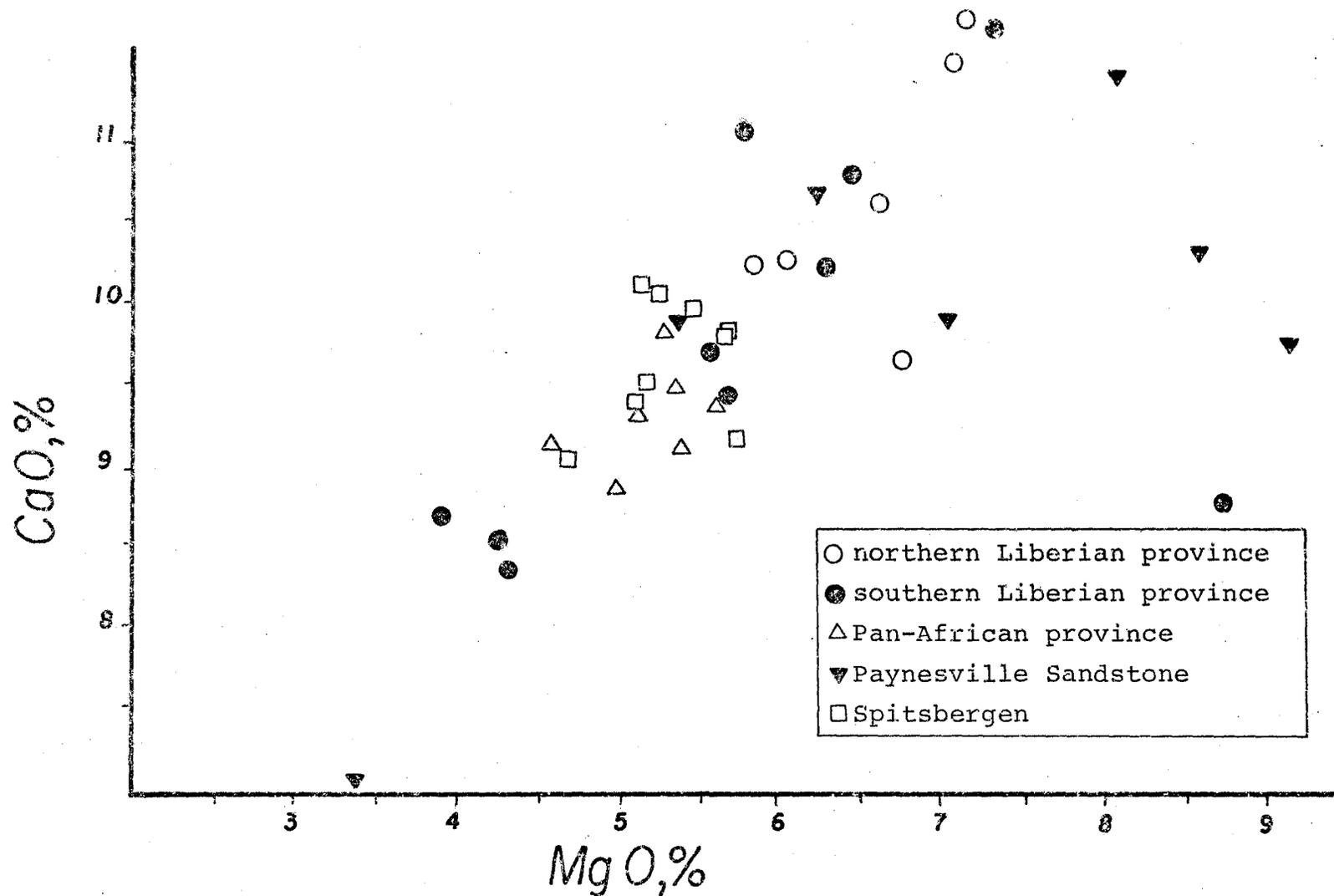


Figure 10. Weight percent CaO versus weight percent MgO.

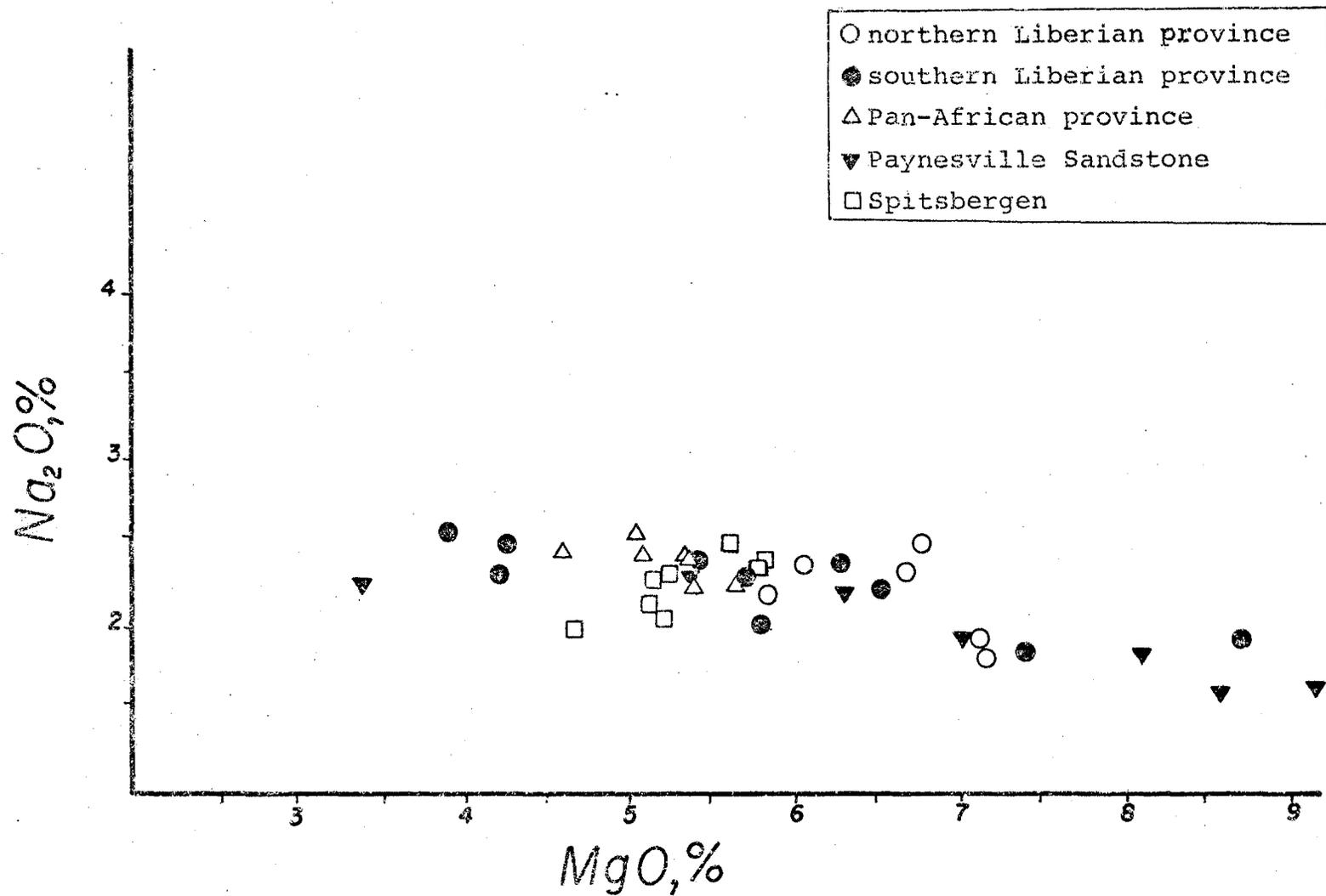


Figure 11. Weight percent  $\text{Na}_2\text{O}$  versus weight percent  $\text{MgO}$ .

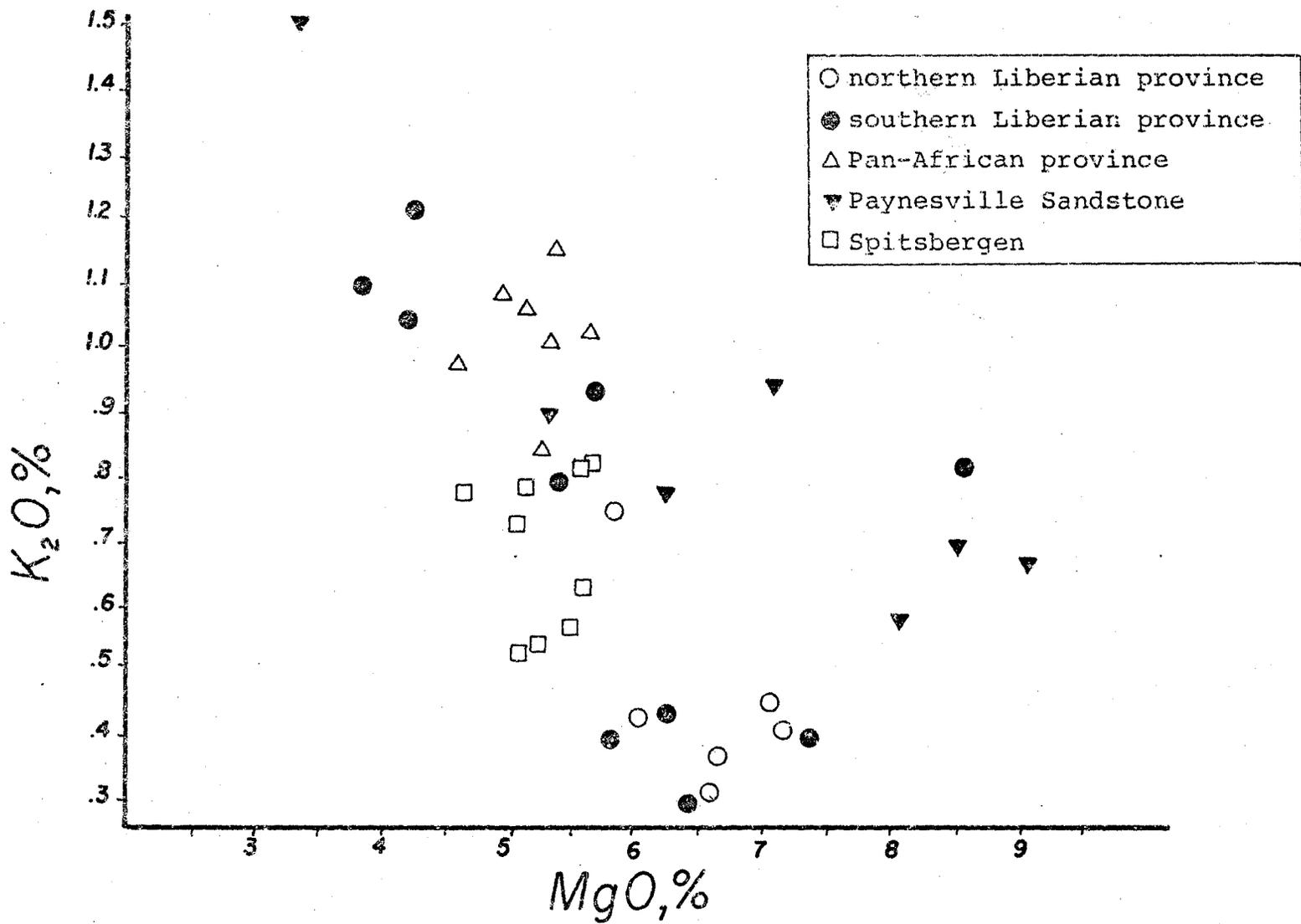


Figure 12. Weight percent K<sub>2</sub>O versus weight percent MgO.

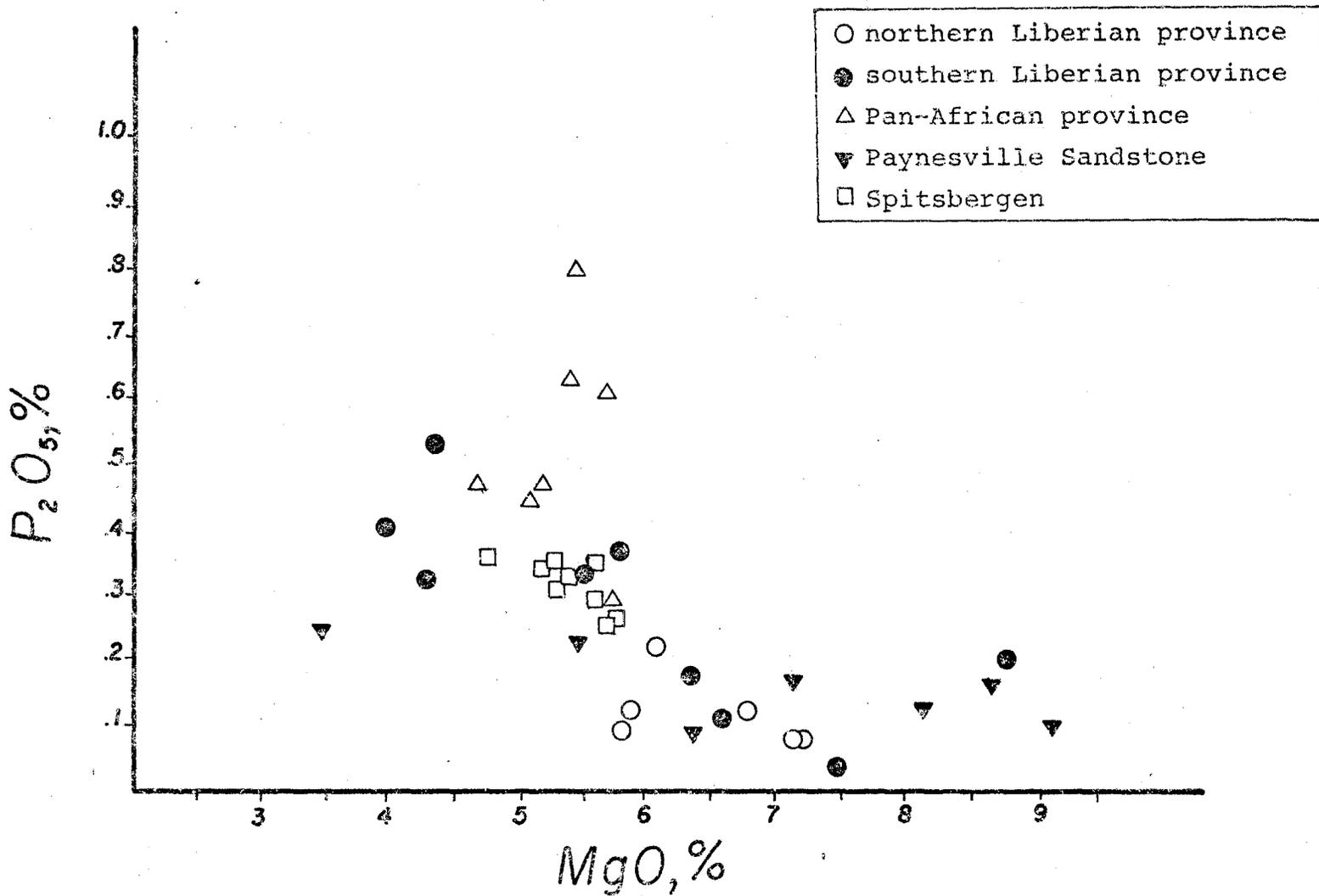


Figure 13. Weight percent P<sub>2</sub>O<sub>5</sub> versus weight percent MgO.

In discussing the petrogenetic relationship among the dolerite suite of rocks being studied, MgO was chosen as an index of differentiation. Differentiation trends can be distinguished based on the assumption that MgO is the one major oxide that decreases continuously during fractional crystallization for most mafic liquids regardless of the starting composition and pressure (Wright, 1975). According to Wright (1975), MgO also does not have an overlapping range of values in each fractionating mineral phase. In the suite of rocks being studied, MgO has a reasonably wide range of values which also makes it a likely choice as an index of differentiation. The following observations can be made by the trends exhibited by the Liberian dolerites on the magnesia variation diagrams:

- (1)  $\text{SiO}_2$  illustrates a progressive increase with increasing differentiation. The trend shown by the dolerites from the Paynesville Sandstone is especially noteworthy.
- (2)  $\text{TiO}_2$  increases with differentiation. Variation in  $\text{TiO}_2$  is strongly reflected in the modal percentage of the opaque minerals, most likely ilmenite. Not all the  $\text{TiO}_2$  is attained within the opaque minerals. Samples that fall above the dashed line in Figure 14 suggest that some  $\text{TiO}_2$  occurs in a non-opaque phase, almost certainly clinopyroxene. Sample L27 stands out because of its abnormally high  $\text{TiO}_2$  content (5.29%) and its high concentration of

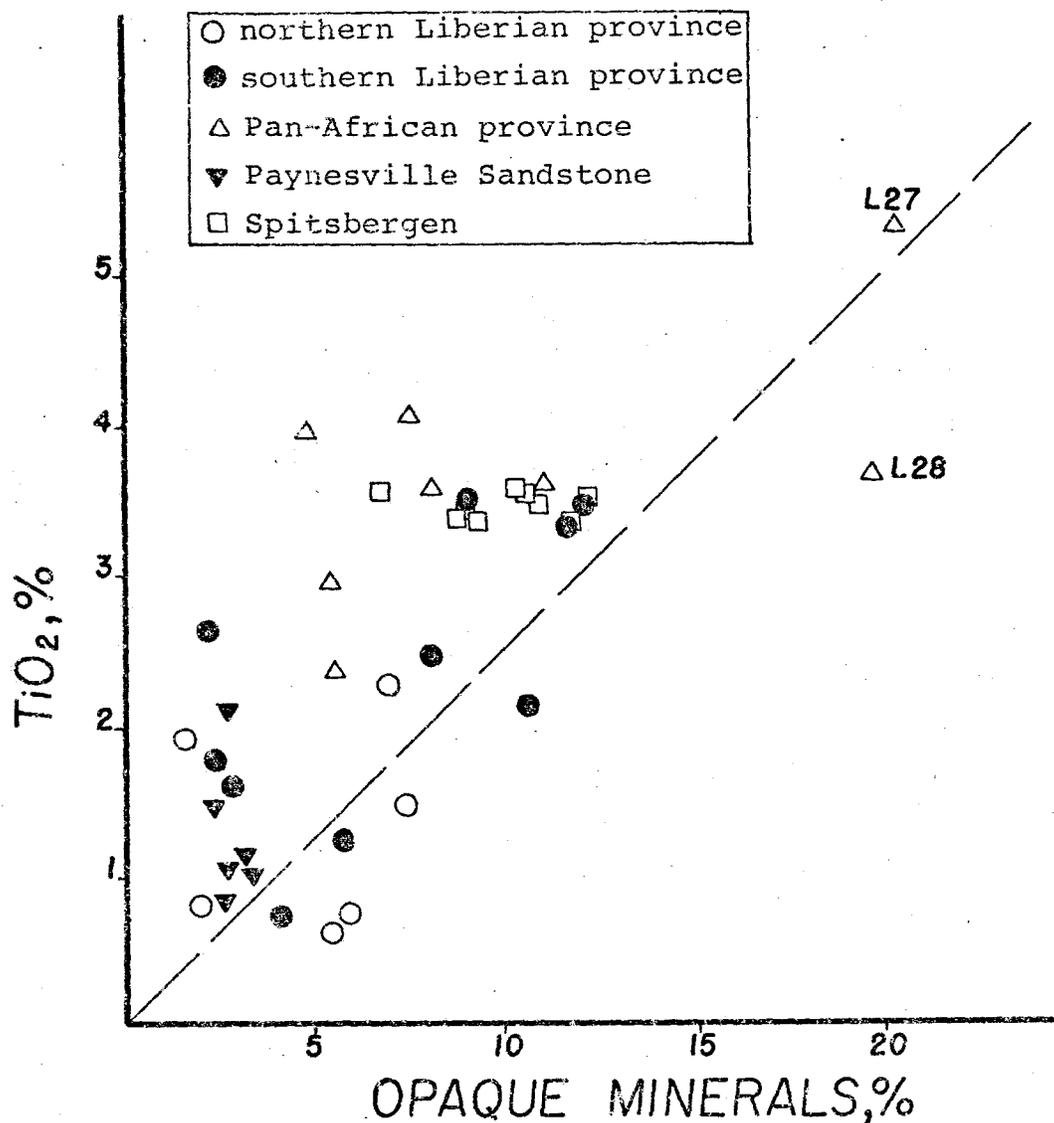


Figure 14. Weight percent  $\text{TiO}_2$  versus volume percent opaque minerals. If  $\text{TiO}_2$  were entirely contained in stoichiometric ilmenite, points would fall along the dashed line. Points that fall above the line suggest that some  $\text{TiO}_2$  occurs in a non-opaque phase (clinopyroxene). Points that fall below the dashed line suggest that some of the opaque minerals are not ilmenite (magnetite).

opaque minerals (21.3%). This sample was collected from a composite dike (Gromme, personal communication), but the reason for its unusual composition is not known.

- (3)  $\text{FeO}_T$  and MnO show differences but overall increases with differentiation. The low abundance of opaque minerals in the dolerites that intrude the Paynesville Sandstone is probably attributed to the low percentages of  $\text{FeO}_T$  and  $\text{TiO}_2$ .
- (4) MgO decreases with increasing differentiation and its percent variation is attributed to olivine and pyroxene fractionation at low pressures during magma ascent. The high contents of MgO in the dolerites that intrude the Paynesville Sandstone is probably reflected in the crystallization of hypersthene as well as olivine. Samples from each geologic province of Liberia are highly differentiated for basalts which is reflected in their low MgO contents (less than 5.0%).
- (5)  $\text{Al}_2\text{O}_3$  and possibly CaO shows an initial increase to about 7.0% MgO, then a decrease. This suggests that differentiation was controlled by non- $\text{Al}_2\text{O}_3$  bearing phases until the magmas reached a composition of 7.0% MgO, after which plagioclase begins to affect the  $\text{Al}_2\text{O}_3$  content.
- (6)  $\text{Na}_2\text{O}$  exhibit an overall smooth increase with differentiation for all the Liberian samples.

- (7)  $K_2O$  has much scatter, but shows a general overall increase with differentiation.
- (8) Except for a few samples,  $P_2O_5$  shows a smooth increase with differentiation for the Liberian samples.

Even though there is some overlap in chemical fields exhibited by the dolerites and the geologic province which they intrude, it is suggested by their respective variation trends that differences between them do exist. Whether these are real differences or are a result of the small number of samples is not known.

Spitsbergen The most striking aspect about the Spitsbergen dolerites is the general chemical uniformity of these rocks. Potash shows more variation than other oxides, with the samples from Wilhelmöya having generally higher  $K_2O$ , and lower  $CaO$  and  $Na_2O$  contents, than those from the main island of Spitsbergen. The higher  $CaO$  and  $Na_2O$  contents in samples from the Lomfjorden sill may be reflected in the higher modal plagioclase, whereas the higher  $K_2O$  in the samples from Wilhelmöya may be reflected in the high  $TiO_2$  contents ranging from approximately 3.3 to 3.5%. This is strongly reflected in the high modal amounts of opaque minerals, as well as the occurrence of brownish-purple augite, which is interpreted to be titaniferous.

This is consistent with the Spitsbergen samples falling above the dashed line in Figure 14.

Because of the chemical uniformity, few strong variation trends can be distinguished. With decreasing MgO content,  $P_2O_5$  increases slightly, while  $FeO_T$  and  $Na_2O$  decrease slightly. The Spitsbergen dolerites are generally similar in major and minor chemistry to the Liberian dolerites and especially to the Pan-African dolerites.

#### CLASSIFICATION

Besides mineralogical criteria, these are chemical criteria that can be used to classify basaltic rocks. One method is based on CIPW normative mineralogy. One drawback of this method is that iron was determined in this study as total Fe expressed as  $FeO_T$ . In order to calculate normative mineralogy,  $FeO/FeO_T$  was averaged from 65 available analyses of samples across several tholeiitic dikes from North Carolina (Ragland et al., 1968) which were presumed to be similar to the samples of this study. This ratio (0.31) was then used to calculate  $FeO$  and  $Fe_2O_3$ , and CIPW norms were calculated using a computer program modified after Bingler et al., (1976). These norms are tabulated in Appendix V .

Small variations in the  $\text{Fe}^{2+}/\text{Fe}^{3+}$  ratio leads to small variations in normative mineralogy. The main effect of increasing this ratio is to increase normative olivine content and decrease normative quartz and magnetite contents.

Figure 15 graphically illustrates a plot of the normative mineralogy for the Liberian and Spitsbergen dolerites on a diopside-hypersthene-olivine-nepheline-quartz diagram introduced by Yoder and Tilley (1962) to classify basalt type. This diagram is a projection from plagioclase in the Di-Qz-Ol-Plag tetrahedron (Yoder and Tilley, 1962). All samples of this study but one are classified as quartz tholeiites. The exception, sample L4, contains 0.5% normative olivine. This is probably due to the low amount of  $\text{SiO}_2$  (47.12%) which is lower than any other sample in this study. That this figure is possibly in error is supported by the low total (94.33%).

The tholeiitic nature of the dolerites studied is confirmed on an alkali-silica diagram (Figure 16). This diagram was used by Tilley (1950) to distinguish alkalic from tholeiitic basalts from Hawaii, and all but one of the samples from Spitsbergen and Liberia fall in the tholeiitic field.

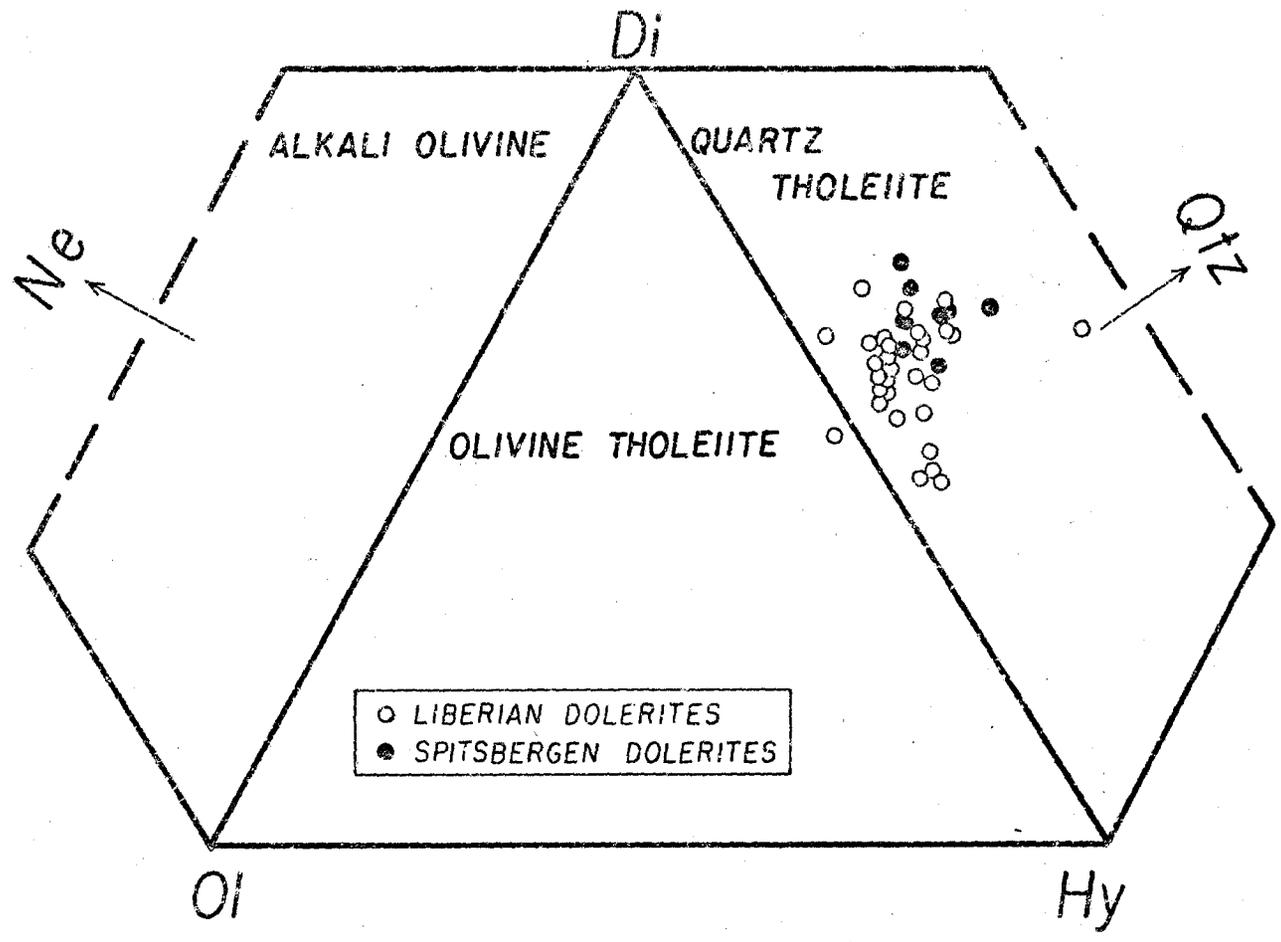


Figure 15. Plot of normative mineralogy on a diopside-hypersthene-olivine-nepheline-quartz diagram.

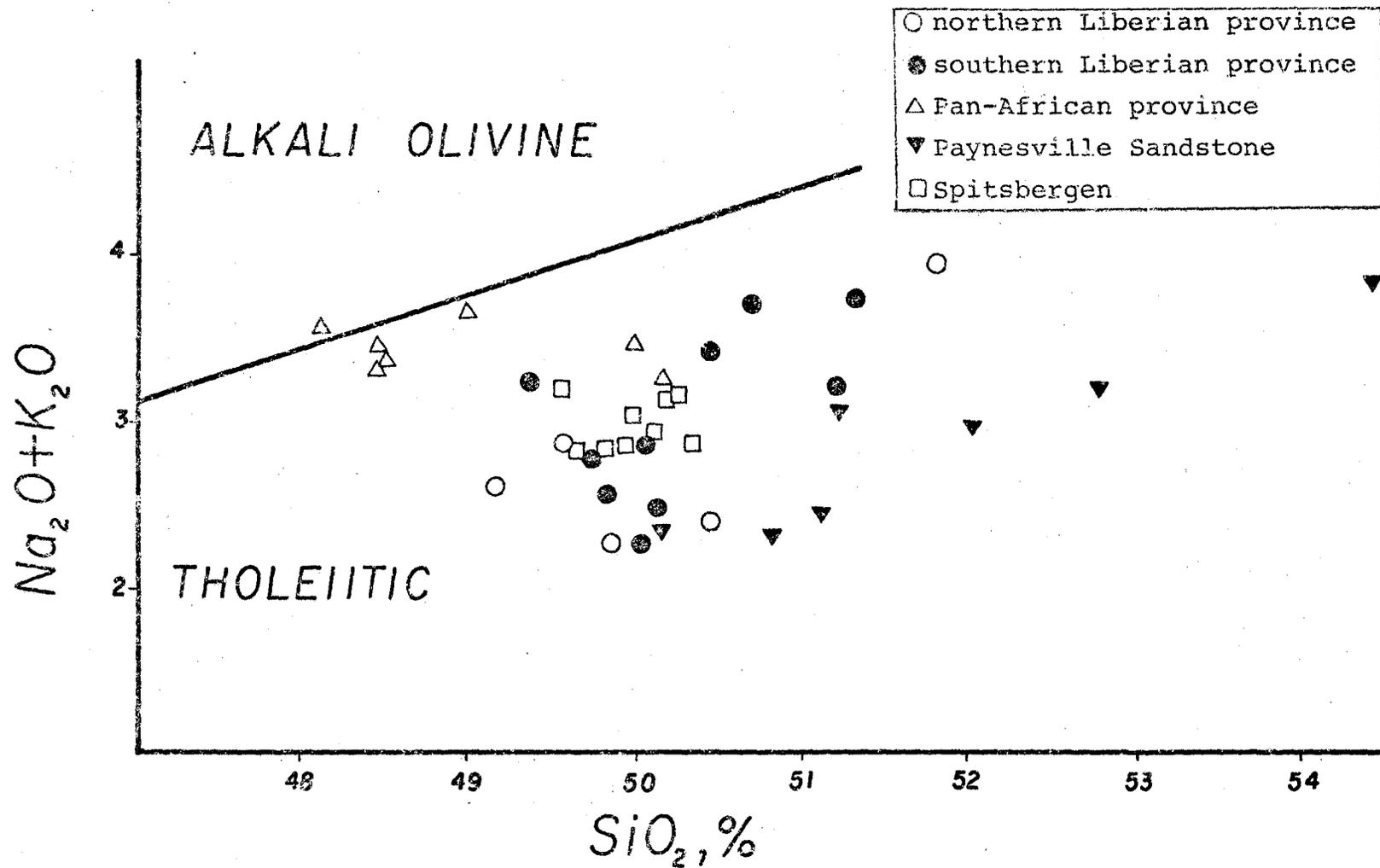


Figure 16. Alkali-silica diagram. Alkali and tholeiitic basalts are distinguish by the diagonal line (Tilley, 1950).

AFM DIAGRAM

The standard AFM diagram (Fig. 17) indicates that as a group, the Liberian dolerites have undergone Fe-enrichment. The trend coincides with the normal differentiation trend of Fe-enrichment commonly found in tholeiitic basalts. The marked Fe-enrichment trend for the Liberian and Spitsbergen dolerites overlaps at least a portion of fields occupied by other basaltic provinces shown. A more extreme Fe-enrichment trend is indicated for the Liberian dolerites in comparison with the eastern North American dolerites, Tasmanian dolerites and the Karroo basalts.

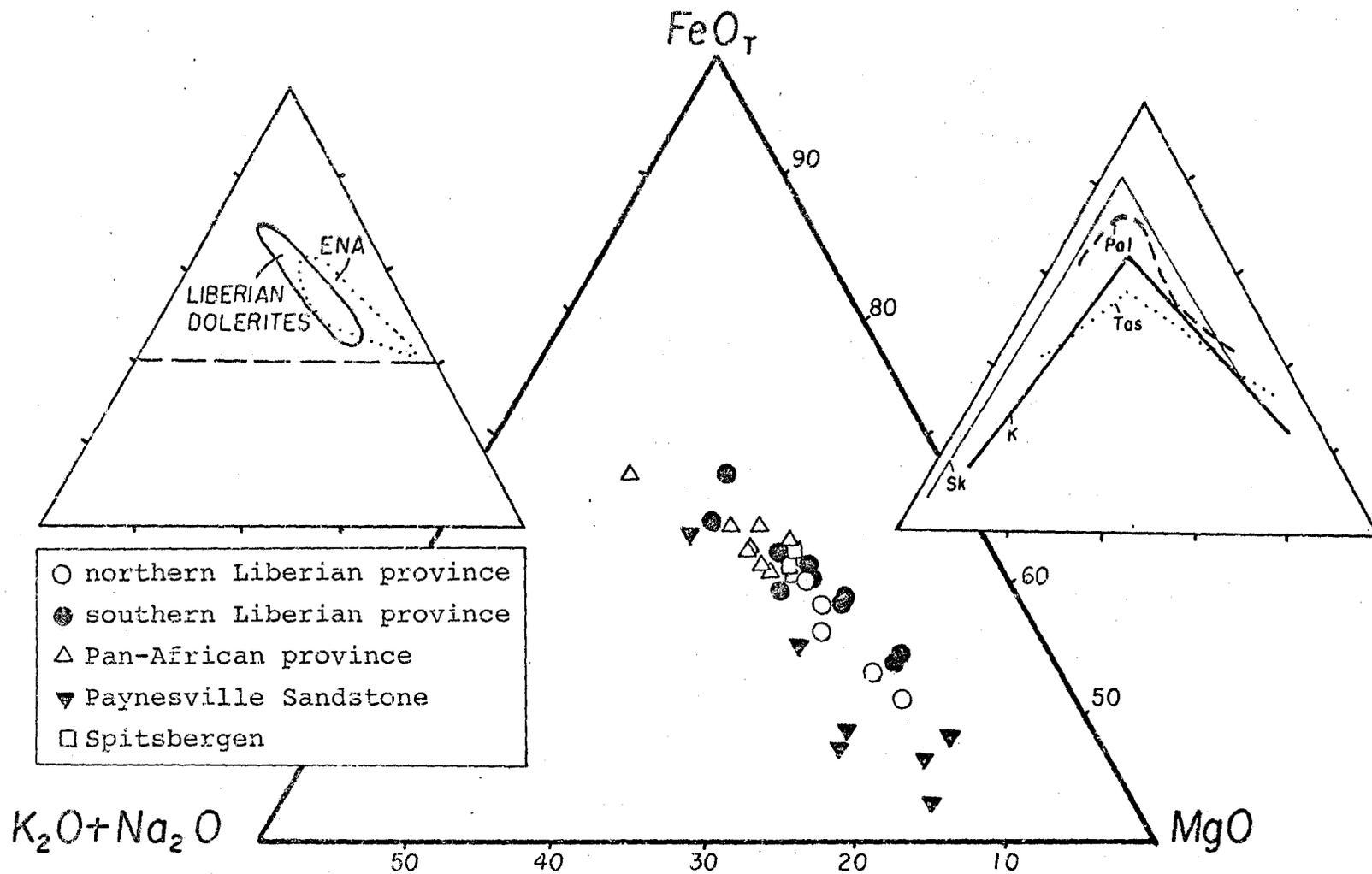


Figure 17. AFM diagram. Trends for dolerites from eastern North America (ENA), Palisades sill (Pal), Karroo basalts (K), Tasmanian dolerites (Tas), and the Skaergaard intrusion (Sk) are shown for comparison. Larger triangle is a blow-up of a portion of the upper left triangle.

## DISCUSSION

### QUALITATIVE COMPARISON

Dolerite dikes indicate crustal tension and it is of special interest to relate them to other basalt provinces and geologic features of similar age. This comparison also aids in the understanding of the origin of doleritic magmas. Figures 18 thru 24 consist of magnesia variation diagrams that compare the compositional differences which exist between Liberian and Spitsbergen dolerites and the following Mesozoic basaltic provinces:

1. ENA dolerites (Weigand and Ragland, 1970, Table 1)
2. Ferrar dolerites (Gunn, 1966, Table 2)
3. Karroo basalts (Cox et al., 1967, Table 3)
4. Tasmanian dolerites (McDougall, 1962, Table 7)

### Spitsbergen

As previously noted, the composition of the Spitsbergen dolerites generally compare favorably with the Liberian dolerites. More striking similarities exist between the Spitsbergen dolerites and the dolerites that intrude the Pan-African province. In detail, the Spitsbergen dolerites contain slightly lower percentages

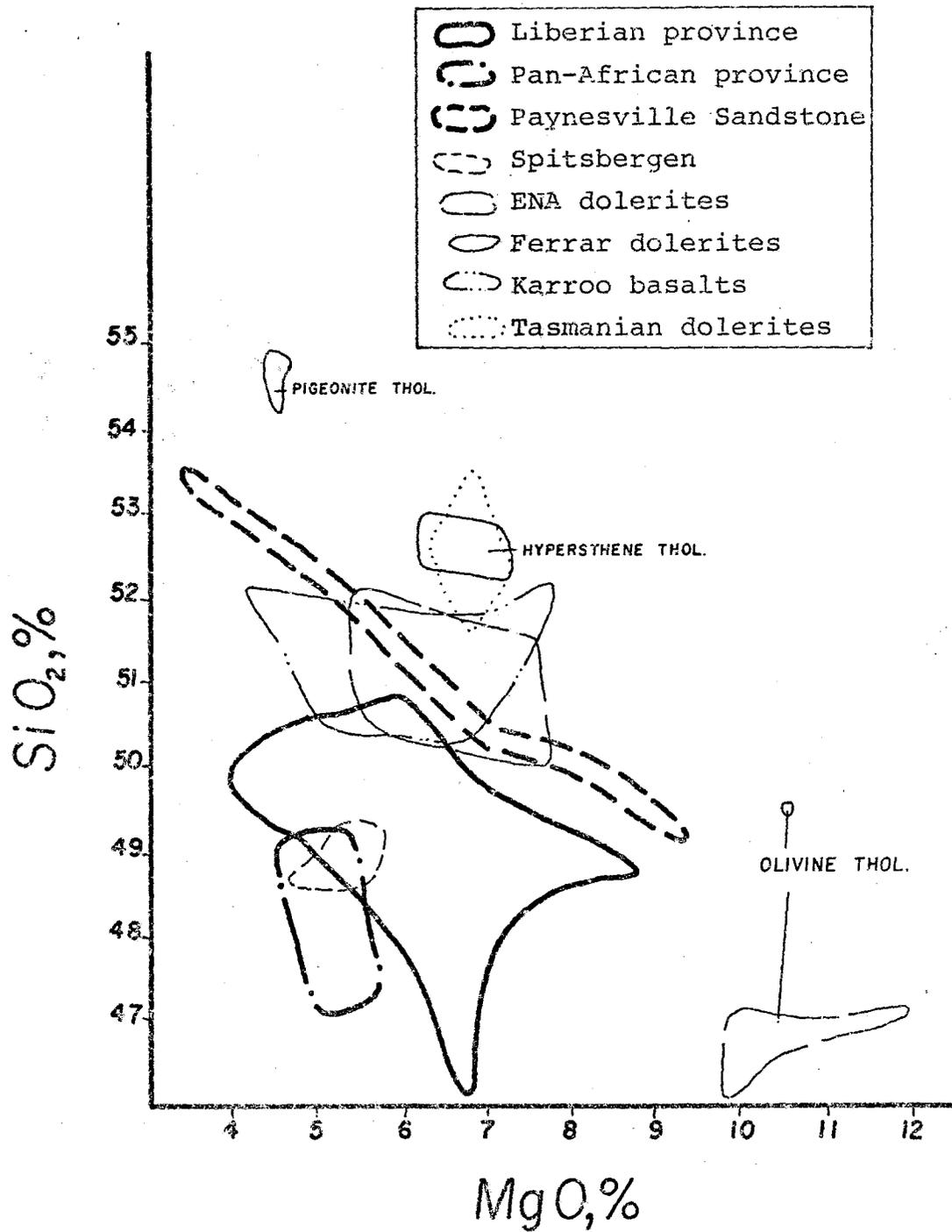


Figure 18. Weight percent  $\text{SiO}_2$  versus weight percent  $\text{MgO}$  variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic basalt provinces.

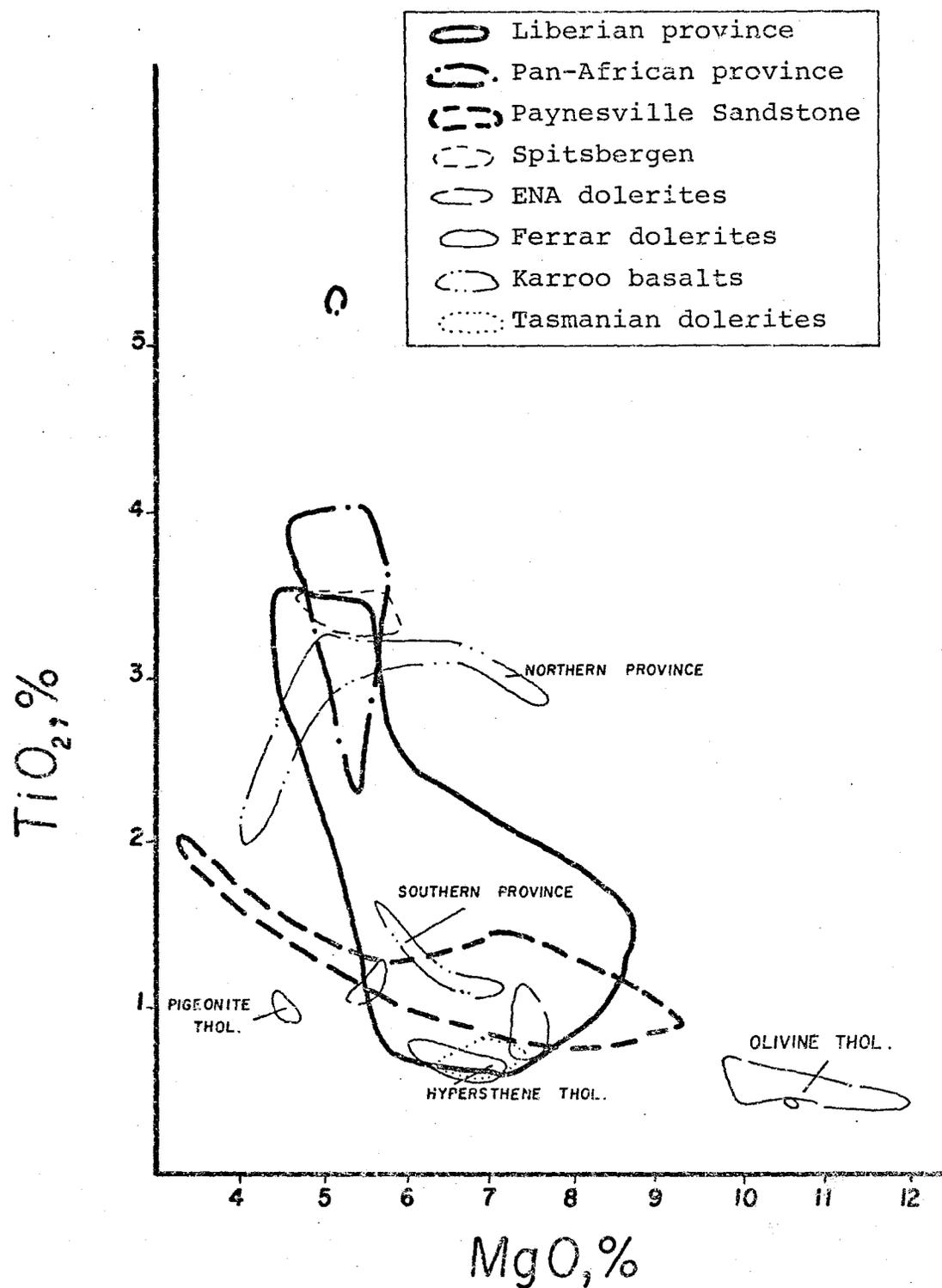


Figure 19. Weight percent  $\text{TiO}_2$  versus weight percent  $\text{MgO}$  variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic basalt provinces.

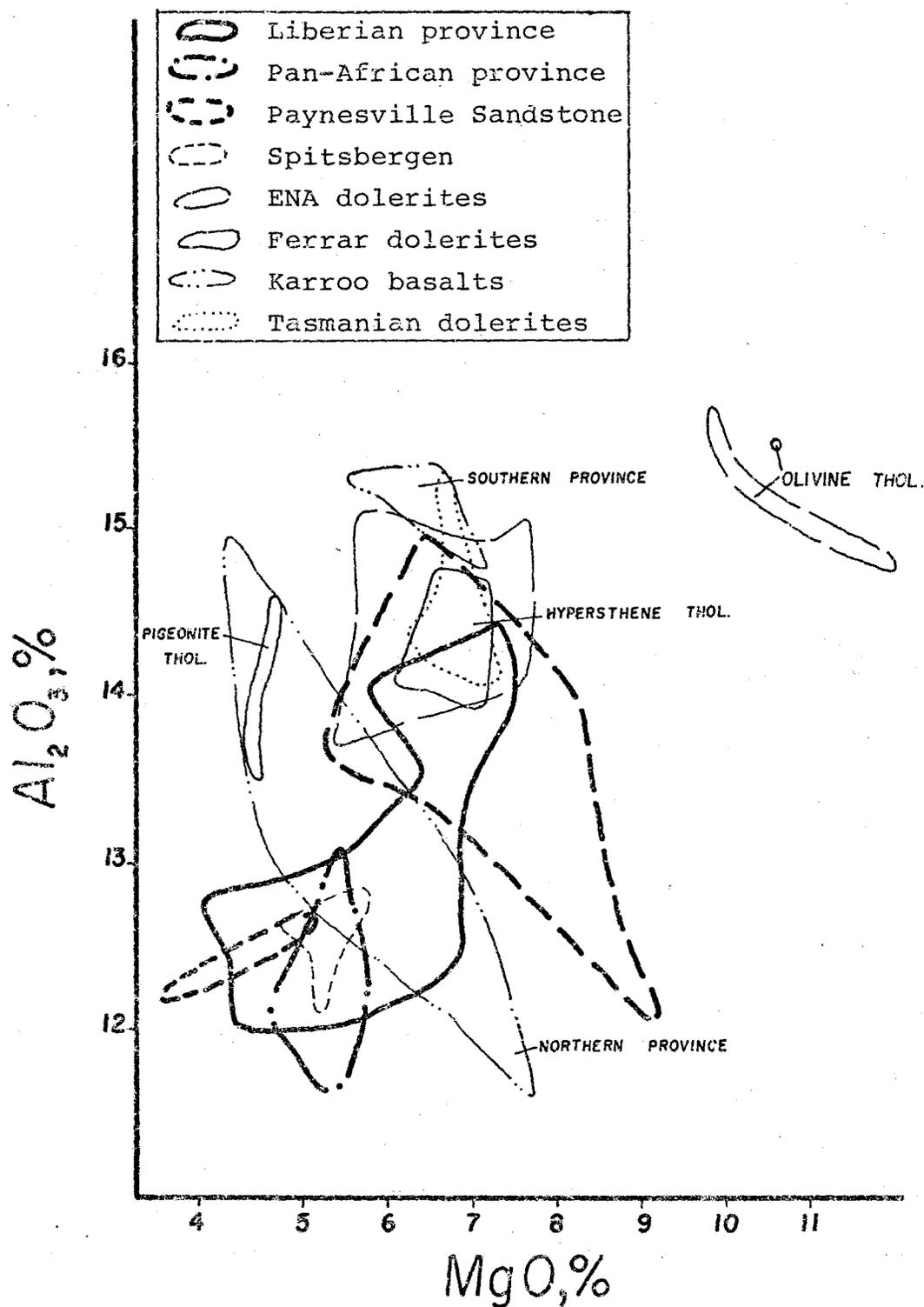


Figure 20. Weight percent  $\text{Al}_2\text{O}_3$  versus weight percent  $\text{MgO}$  variation diagram comparing Liberian and Spitsbergen dolerites with other major mesozoic basalt provinces.

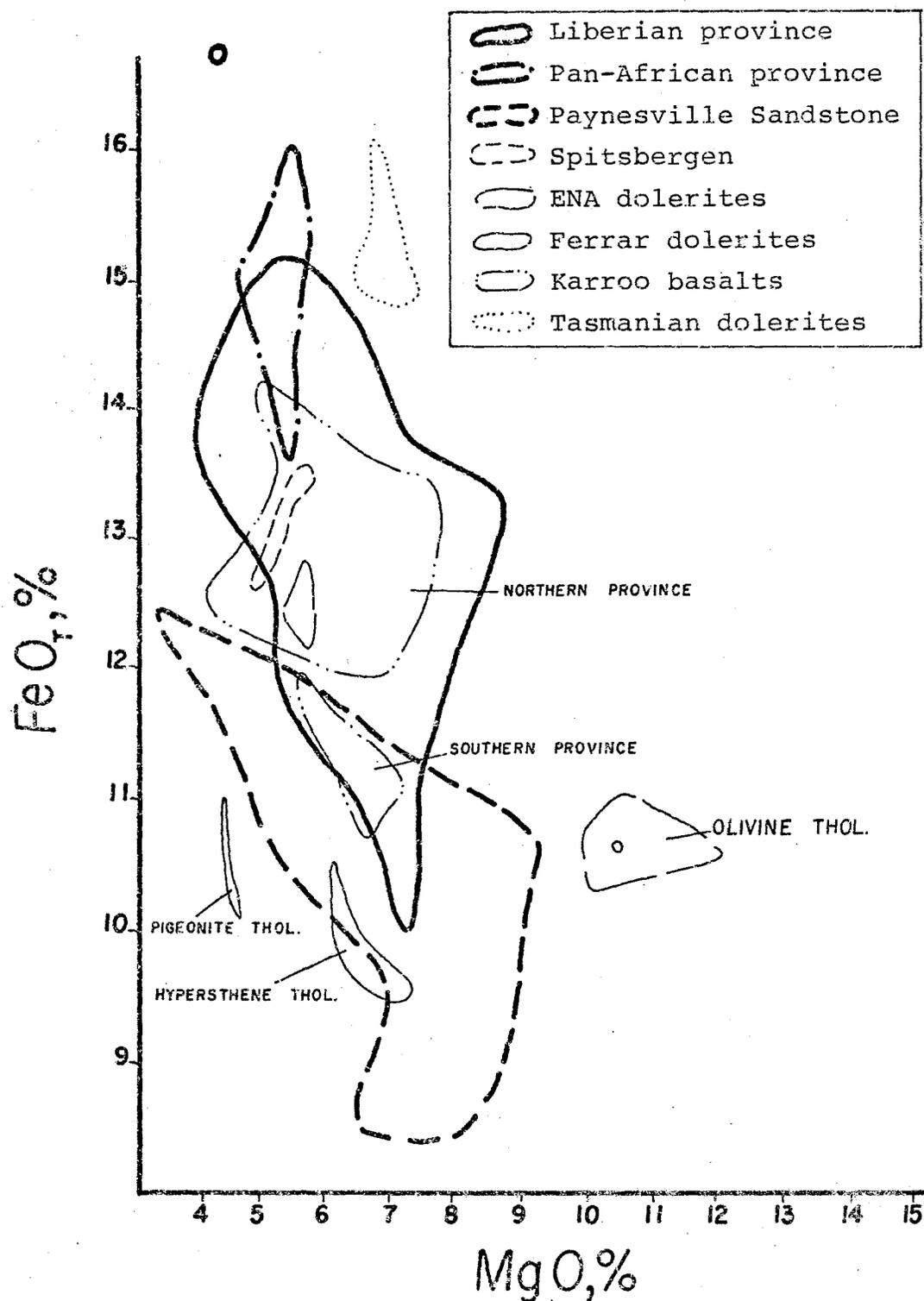


Figure 21. Weight percent  $\text{FeO}_T$  versus weight percent  $\text{MgO}$  variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic basalt provinces.

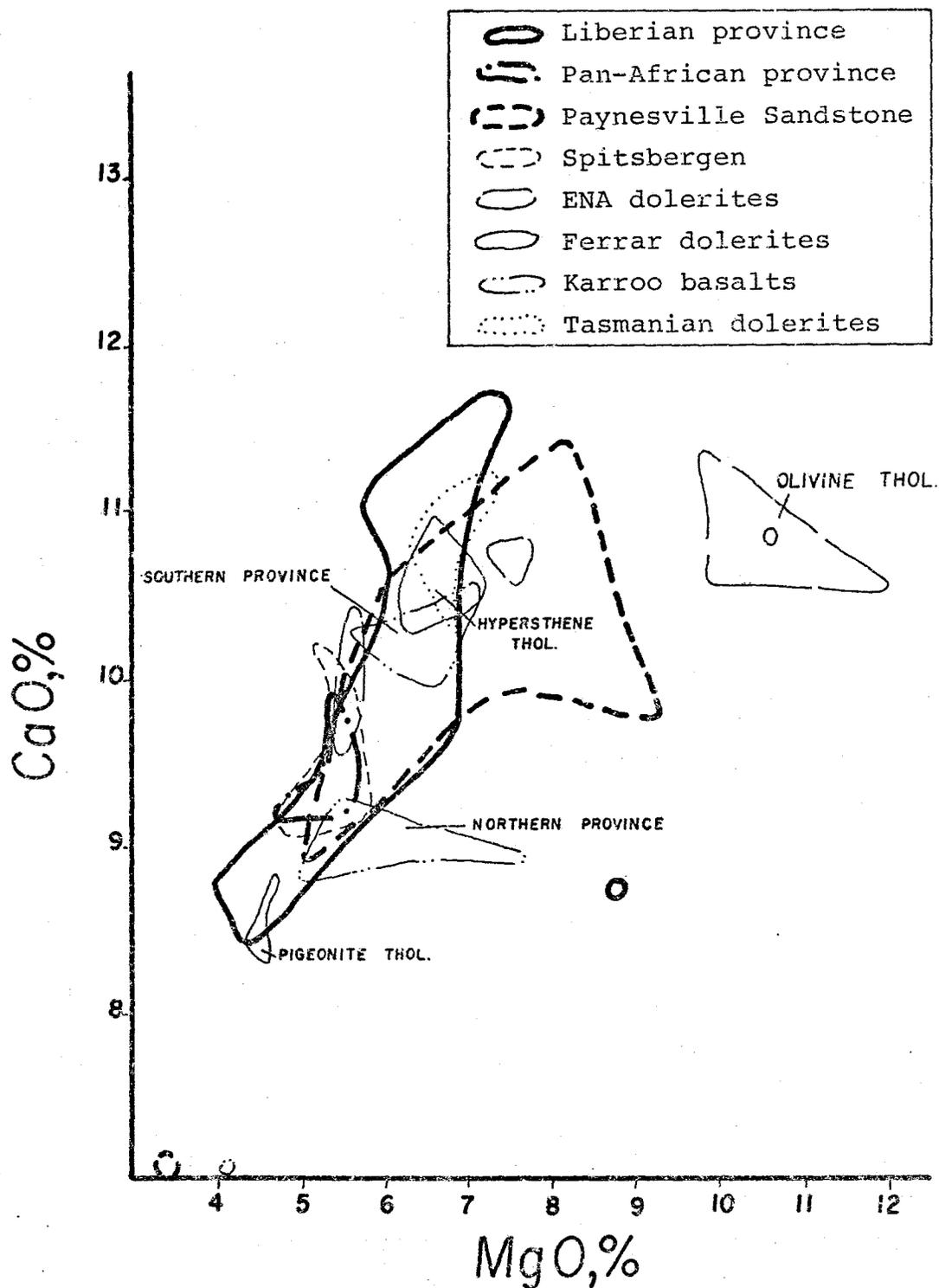


Figure 22. Weight percent CaO versus weight percent MgO variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic basalt provinces.

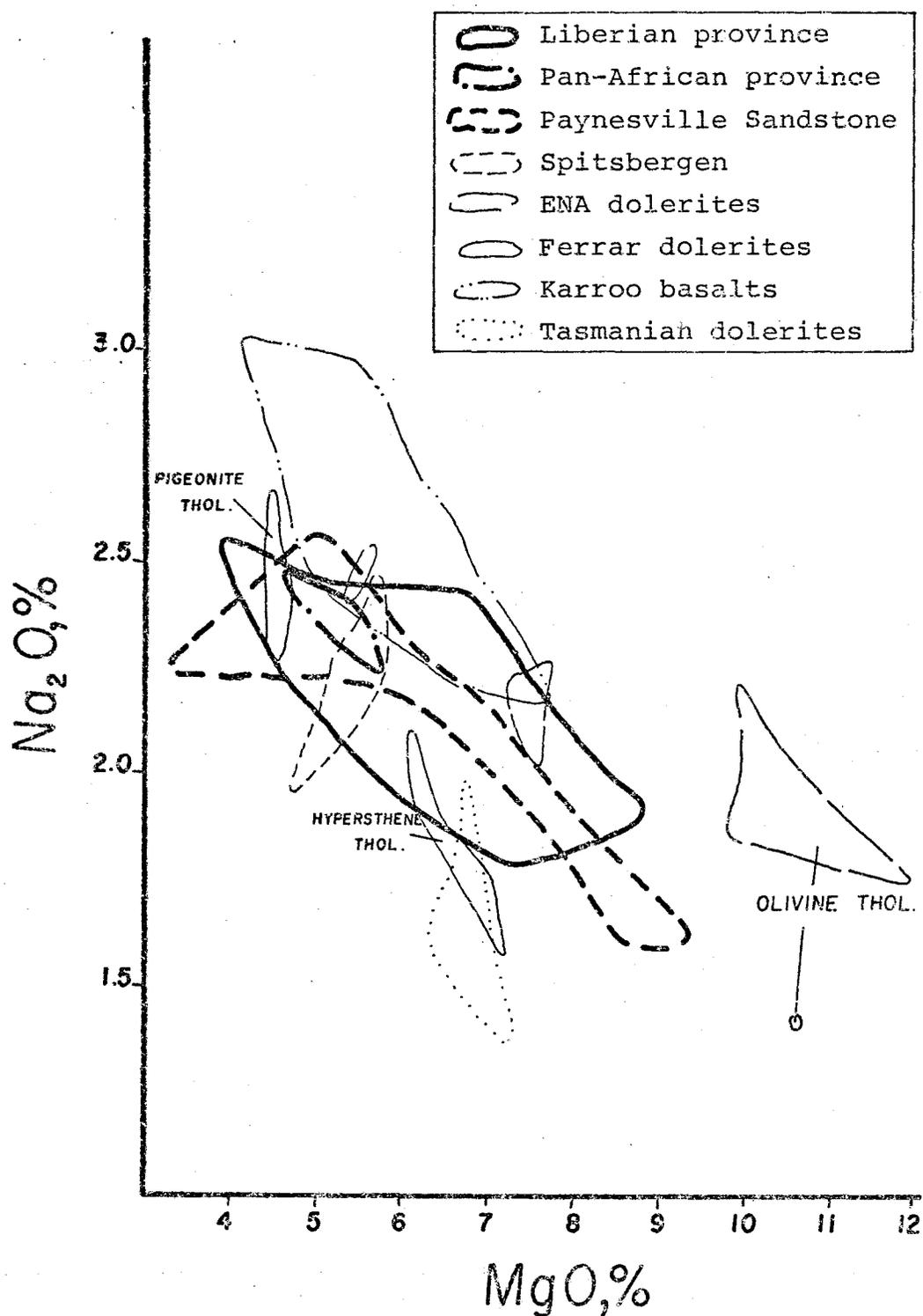


Figure 23. Weight percent  $\text{Na}_2\text{O}$  versus weight percent  $\text{MgO}$  variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic provinces.

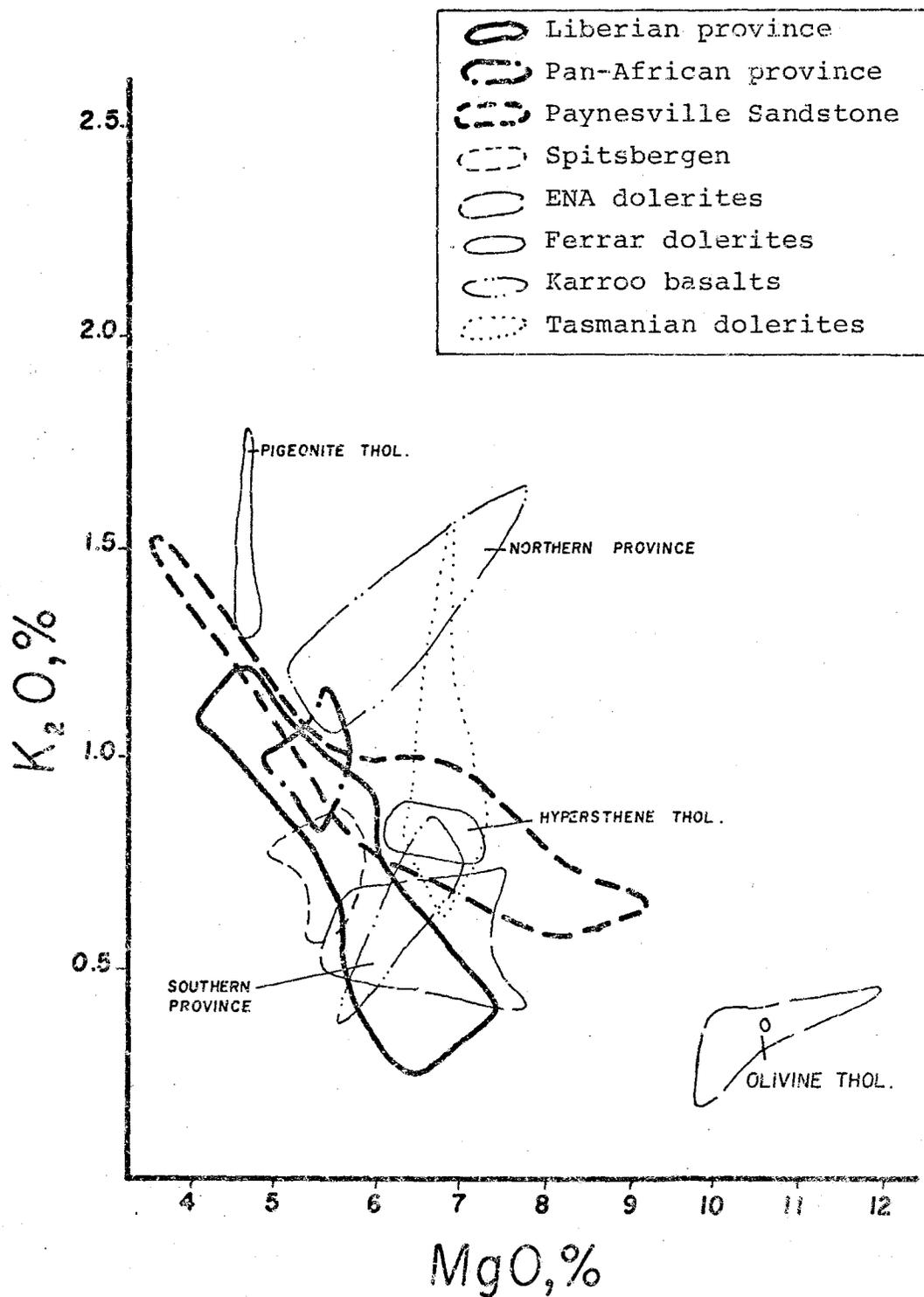


Figure 24. Weight percent  $K_2O$  versus weight percent  $MgO$  variation diagram comparing Liberian and Spitsbergen dolerites with other major Mesozoic basalt provinces.

of  $\text{FeO}_T$ ,  $\text{MnO}$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ . Mineralogical differences are also evident. The doleritic magmas of Spitsbergen crystallized Ti-rich augite as well as pigeonite. Pigeonite found in the Spitsbergen samples exhibit well defined grain boundaries that exist between the pigeonite and the enveloping augite. Olivine was not noted in the Spitsbergen samples studied, but has been recorded in some of the nearby doleritic sills (Tyrrell and Sandford, 1933). These intrusions that contain olivine are thought to be characteristic of more recent intrusions (Harland, 1973).

#### Liberian dolerites

The dolerites that intrude the Liberian province show a wide compositional range which overlaps almost all fields exhibited by other basaltic provinces with respect to  $\text{TiO}_2$ ,  $\text{MgO}$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$ . Chemical similarities with exception to one element is noted in comparison to the Karroo basalts ( $\text{K}_2\text{O}$ ), Tasmanian dolerites ( $\text{SiO}_2$ ) and the ENA quartz-normative dolerites ( $\text{SiO}_2$ ). Mineralogically, the Tasmanian dolerites do not compare well due to a higher percentage of pyroxene, lower percentage of opaque minerals, presence of quartz and the absence of olivine.

The hypersthene tholeiitic variety of Ferrar

dolerites, described by Gunn (1966), best compares to the Liberian dolerites, especially to those dolerites that intrude the Liberian province. The higher abundance of micrographic quartz and the lower abundance of opaque minerals in the Ferrar hypersthene tholeiites is attributed to a higher percentage of  $\text{SiO}_2$  and lower percentages of  $\text{TiO}_2$  and  $\text{FeO}_T$ .

Dolerites that intrude the Pan-African province are fairly restricted in chemistry and the low  $\text{SiO}_2$  content distinguishes them from other basaltic provinces. Their close similarities in comparison to the Spitsbergen dolerites have already been discussed.

The Pan-African dolerites also compare favorably to the Karroo northern province basalts. Chemical fields for both basalt provinces overlap with the exception to  $\text{SiO}_2$ . Slightly higher percentages of  $\text{Al}_2\text{O}_3$ ,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  along with slightly lower percentages of  $\text{FeO}_T$  and  $\text{CaO}$  are exhibited by the Karroo northern province basalts. Two chemically distinct provinces have been distinguished for the Karroo basalts (Cox et al., 1967). According to Cox et al., (1967), a different order of crystallization is evident for the two basalt provinces. The more aluminous southern province reflects the appearance of plagioclase as a phenocryst phase before pyroxene. In

the less aluminous northern province, pyroxene appears before plagioclase.

The dolerites that intrude the Paynesville Sandstone are similar to other basaltic provinces due to the large range in chemistry exhibited by these rocks. These dolerites overlap and compare favorably to the Karroo southern province basalts and the ENA quartz-normative tholeiites. The Karroo southern province basalts generally have a higher percentage of  $Al_2O_3$  and slightly lower percentage of  $K_2O$ . The ENA quartz-normative tholeiites also have a slightly lower percentage of  $K_2O$ .

#### ENA dolerites

Dolerite dikes that intrude the Paynesville Sandstone and to a lesser degree the Liberian province compare favorably to the quartz-normative type dolerites described by Weigand and Ragland (1970). The Pan-African dolerites differ from the ENA quartz-normative type dolerites by higher percentages of  $FeO_T$  and  $TiO_2$ , and relatively lower percentages of  $SiO_2$ ,  $Al_2O_3$ ,  $CaO$  and  $Na_2O$ . The Liberian dolerites do not compare well with the more primitive olivine-normative ENA tholeiites.

Mineralogical differences are also evident between the Liberian dolerites and the ENA dolerites. ENA dolerites generally contain only minor amounts of opaque minerals on the order of 1.0 to 4.0%, rarely exceeding approximately 10.0% in abundance (Roberts, 1928; Lester and Allen, 1950; Ragland et al., 1968, Chalcraft, 1972). Average dolerite in the Deep River Triassic basin in North Carolina normally contains 15.0 to 20.0% olivine (Hermes, 1964). ENA dolerites also contain higher percentages of modal olivine (olivine-normative tholeiite) and micrographic quartz (quartz-normative tholeiite).

In view of Figures 18 thru 24, it is obvious that the Liberian dolerites have undergone a greater degree of differentiation in comparison to the ENA dolerites. On the basis of  $TiO_2$  versus mafix index ( $MI = FeO_T / (FeO_T + MgO)$ ), the ENA quartz-normative tholeiites can be subdivided into either a high- $TiO_2$ , low- $TiO_2$  or high  $Pe_2O_3$  type basalt (Weigand and Ragland, 1970). The trace elements Cu, Rb, Sr and Zr reaffirms the existence of the high- $TiO_2$  and low- $TiO_2$  basalt types.

Figure 25 is a plot of mafix index ( $MI = FeO_T / (FeO_T + MgO)$ ) versus  $TiO_2$  illustrating the three quartz-normative type basalts noted by Weigand and Ragland (1970). Also illustrated for comparison are the Liberian and Spitsbergen

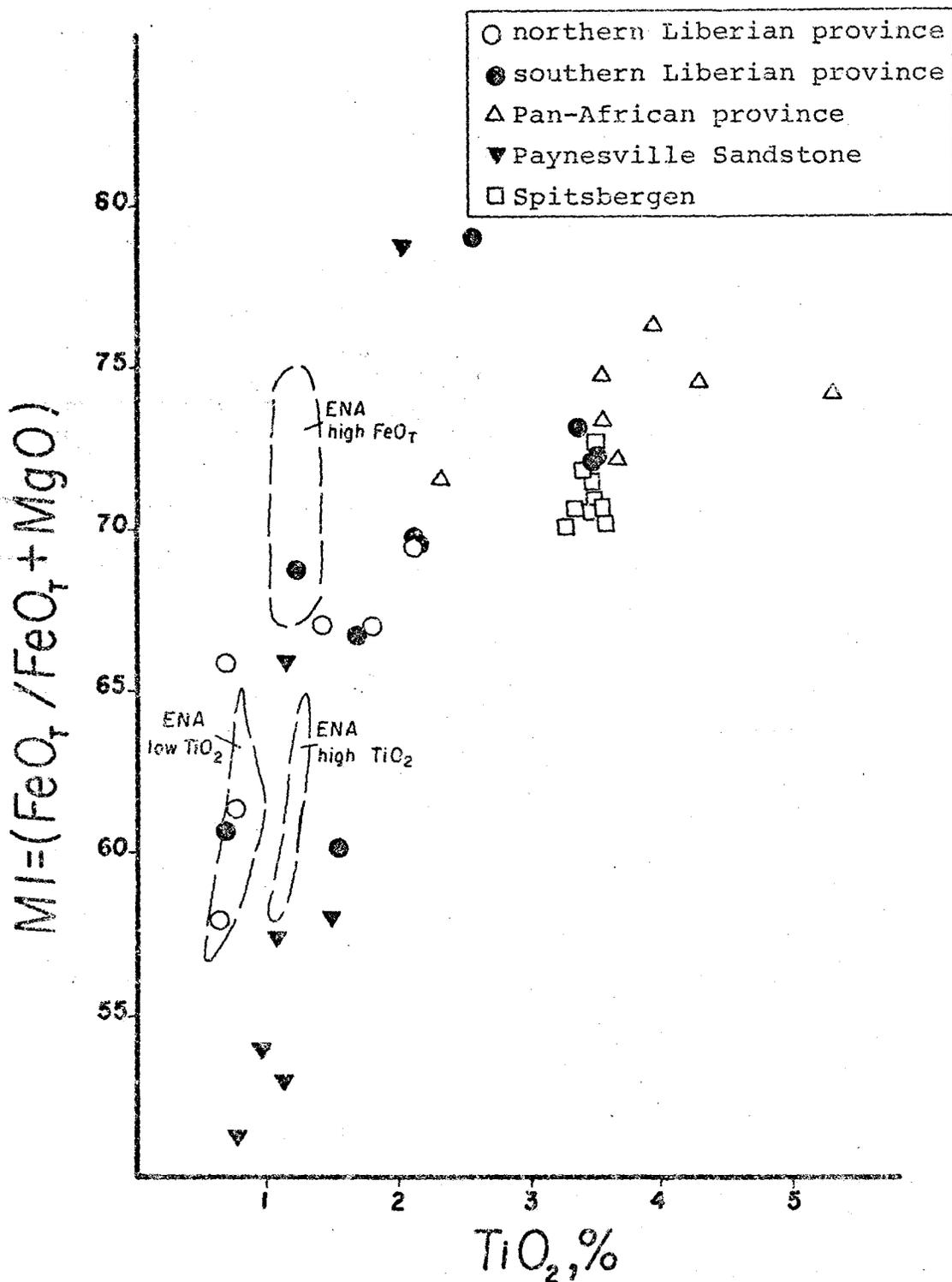


Figure 25. Plot of mafic index (MI) versus weight percent  $TiO_2$ . Liberian, Spitsbergen and ENA dolerites are represented.

dolerites. The Liberian dolerites may possibly indicate a continuum of increasing  $TiO_2$  with respect to the mafix index. It is again noted that a greater degree of differentiation affected the Liberian dolerites moreso than the ENA dolerites. The high values denoting the mafix index for the Liberian dolerites is in part due to their low MgO contents.

In summary, the Liberian dolerites as well as those from Spitsbergen are, in general terms, not unlike other Mesozoic basaltic provinces. Minor differences do exist and distinguish the Liberian and Spitsbergen dolerites from other basaltic provinces. It is also suggested that doleritic magmas which intruded continental crust on opposite sides of the mid-Atlantic ridge are similar but distinct differences also exist. When the Liberian dolerites are compared to the three ENA quartz-normative type basalts on the basis of  $TiO_2$  content versus mafix index, the disimilarities that exist reaffirm and distinguish the Liberian dolerites as a distinct geochemical basalt province.

### CRYSTAL FRACTIONATION MODELS

One of the striking features shown on the magnesia variation diagrams is the strong distinguishable trends exhibited by the Liberian dolerites that intrude the Paynesville Sandstone. That these smooth trends represent differentiation trends due to the result of the crystallization and removal of a single mineral phase can be tested by a simple crystal fractionation model.

It has been well documented by a number of studies on Hawaiian basalts (Murata and Richter, 1966a, b; Wright and Fiske, 1971; Wright, 1971) while studying Hawaiian basalts, that it is possible to determine if a single mineral phase is controlling the chemical variation displayed by a particular suite of rocks. If this process has operated, the resulting variation trend will extrapolate to the composition of that mineral whose composition is plotted on the same oxide versus oxide diagram. The line which is extrapolated from, and defined by, the variation trend of a particular suite of rocks is termed a control line. If the control line for all oxide versus oxide diagrams extrapolate to the compositional range of a single mineral, the addition or subtraction of that one mineral can be said to act as the

control of the chemical variation observed (Wright, 1971).

Two other conditions which could exist are: (1) the mineral phase controlling the variance in chemistry is of variable composition or (2) that there is more than one mineral which controls the chemical variance. If the mineral attributing to the variance is of variable composition, then the control lines will be curvilinear. More commonly though, the situation arises in which a combination of mineral phases is involved. According to Wright (1971), it is rarely possible to define quantitatively a multi-mineral control. However, additional mineral phases accounting for the variation in chemistry of a suite of rocks can be indicated by the sense of deviation which occurs from lines that define a single mineral control.

Dolerites from the Liberian province and Paynesville Sandstone exhibit the most obvious variation trends on the magnesia variation diagrams and least square lines were calculated for these two sets of rocks. With the exception of  $\text{Al}_2\text{O}_3$ , and possibly  $\text{CaO}$ , all of the control lines for the oxide versus  $\text{MgO}$  variations diagrams appear to be linear. Alumina and calcium contents

appear to have increased during the initial stages of differentiation, and later stages decreased.

Since microprobe analyses of minerals from the Liberian rocks were not made, representative analyses of phases likely to be liquidus phases were compiled from Deer et al (1963, Volume 2, Table 17, columns 6, 7, 8, 10, 11, 14 and 16; Table 2, columns 10, 11, 12 and 13), Walker et al (1973, Tables DB1 and DB4) and Wright (1971, Figure 1, Table 15). Compositional fields of these phases and the least squares lines (light lines) are shown on magnesia variation diagrams (Figs. 26 to 32). The extrapolation of the least squares lines intersect or nearly intersect the clinopyroxene composition field, suggesting that the crystallization of this phase was a dominant process accounting for the variation in composition observed for the dolerites that intrude the Liberian province and Paynesville Sandstone.

Since plagioclase contains little MgO, magnesia variation diagrams are not particularly useful in indicating whether addition or removal of plagioclase has an affect on the observed chemical variation. Variation diagrams of CaO and  $Al_2O_3$  versus  $SiO_2$  were plotted (Figs. 33 and 34) to see if plagioclase would

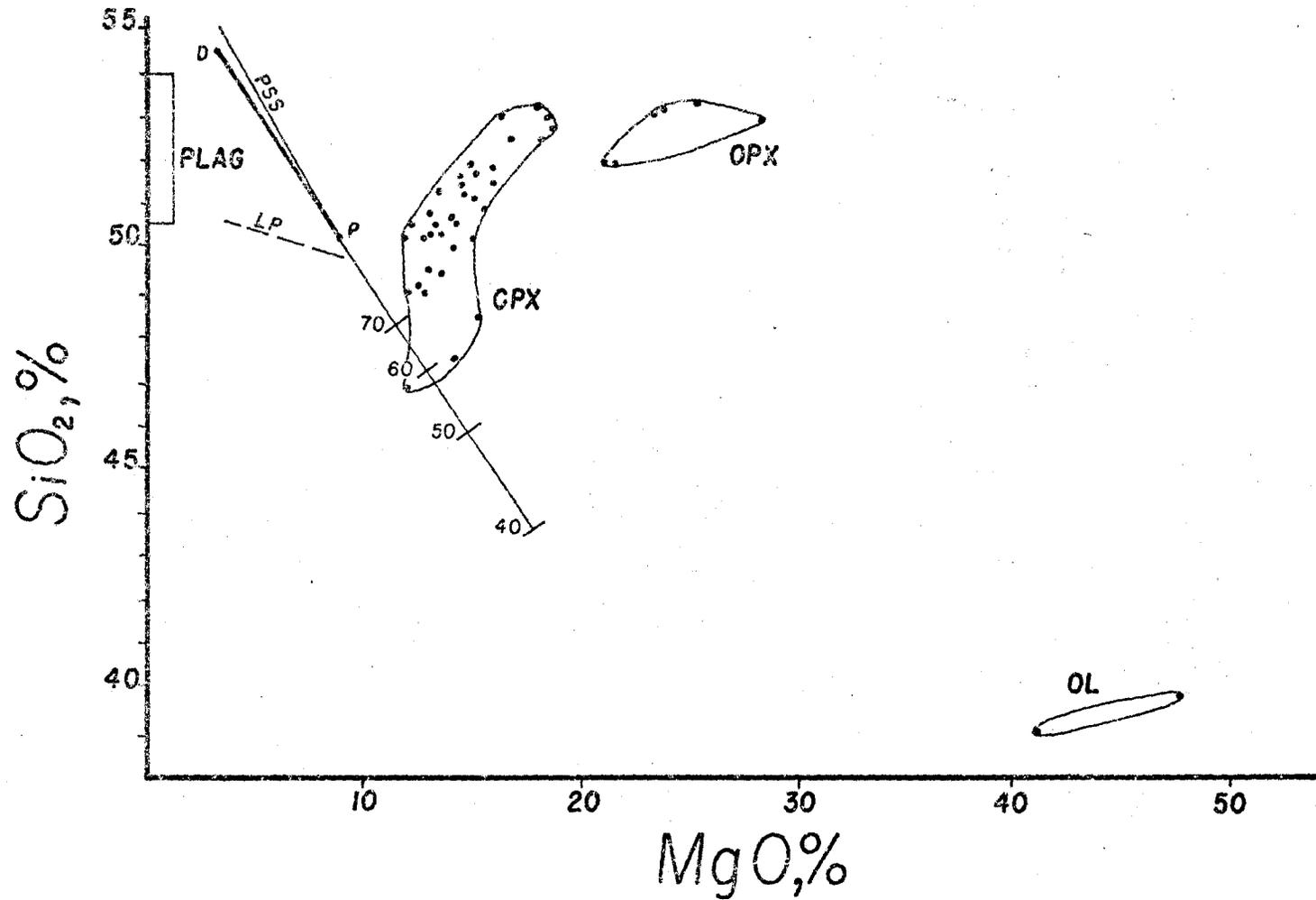


Figure 26. Weight percent  $\text{SiO}_2$  versus weight percent  $\text{MgO}$  variation diagram showing the various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

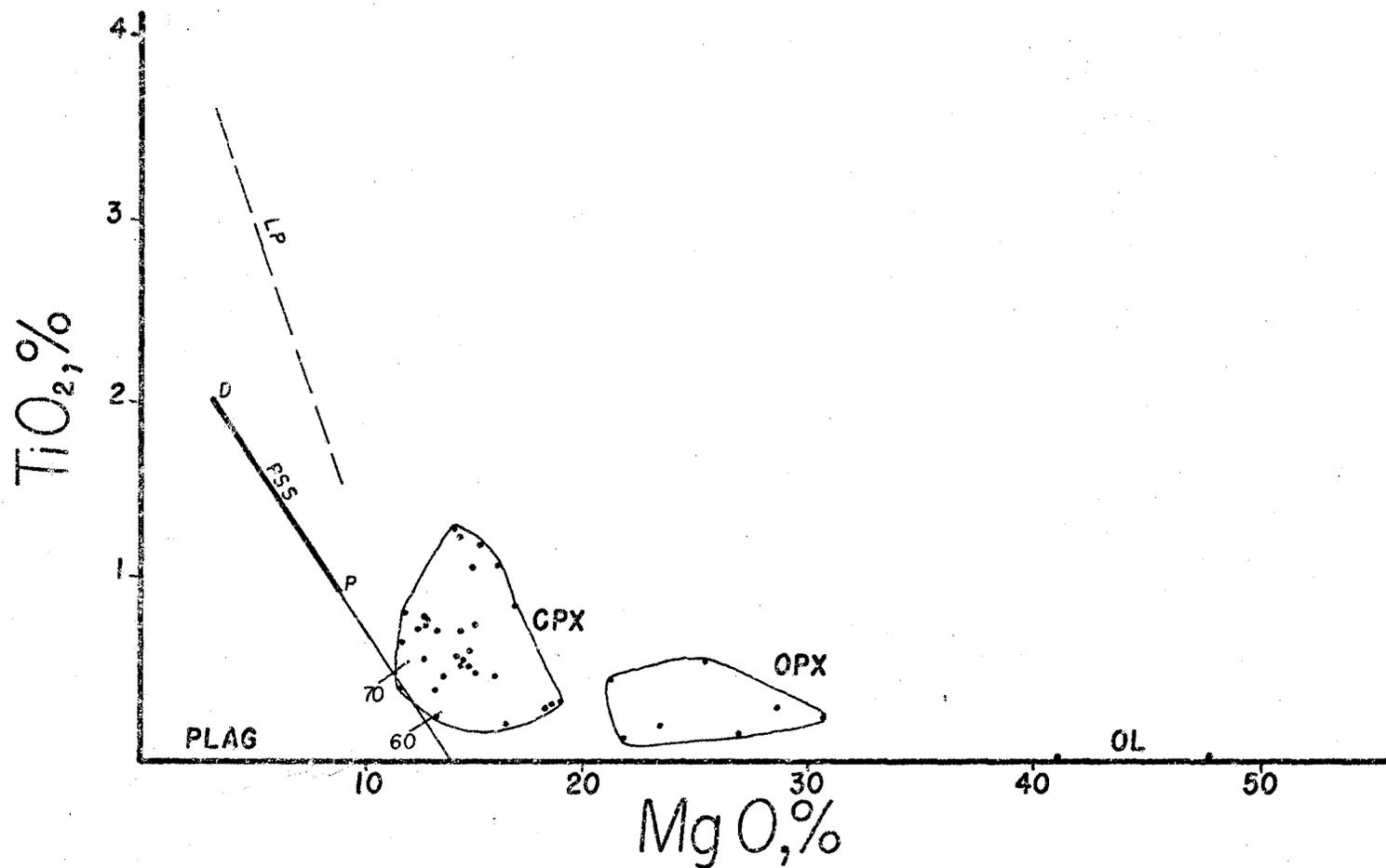


Figure 27. Weight percent  $\text{TiO}_2$  versus weight percent  $\text{MgO}$  variation diagram showing various control lines, individual mineral compositions and crystal accumulation at 10% intervals.

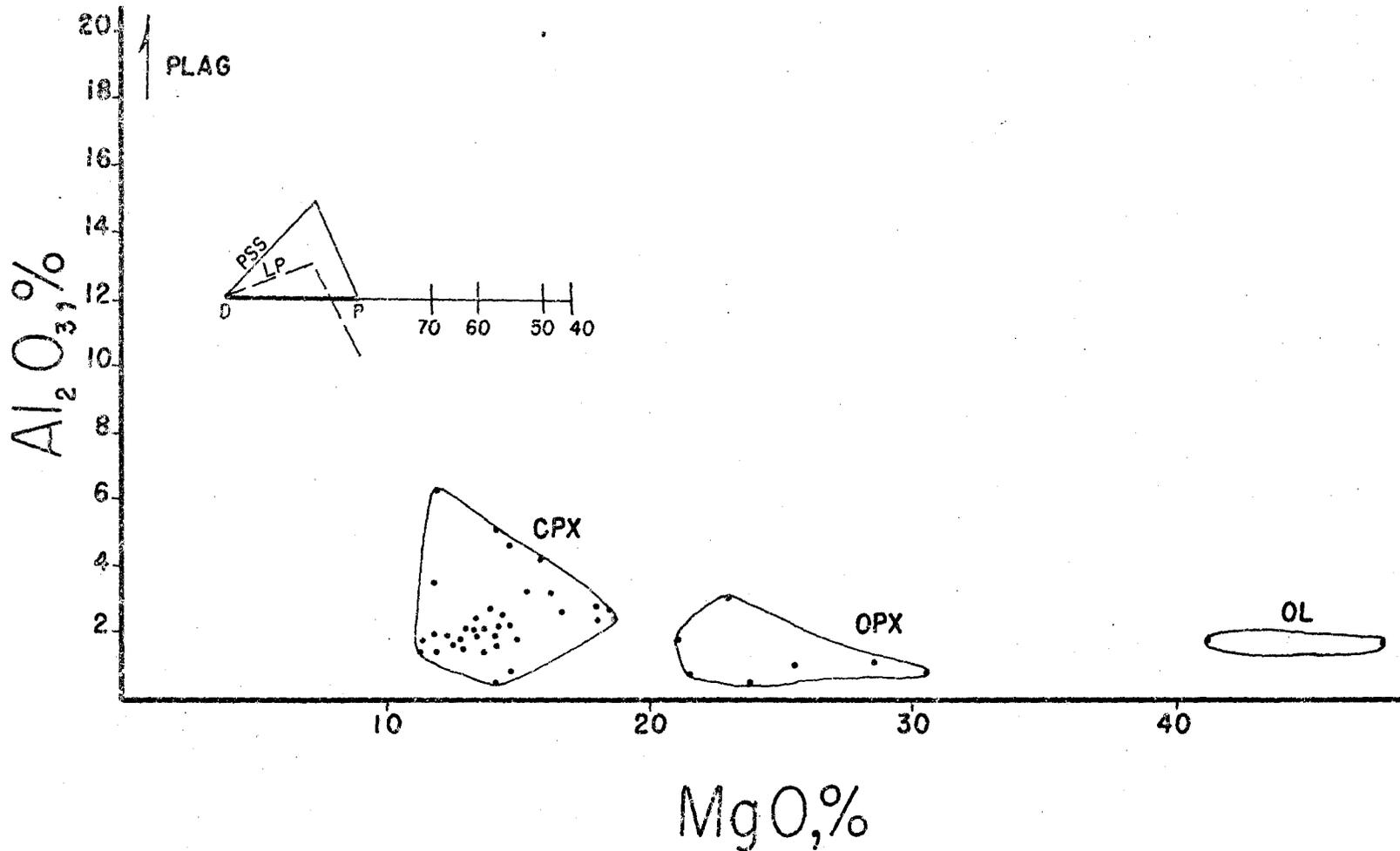


Figure 28. Weight percent  $Al_2O_3$  versus weight percent  $MgO$  variation diagram showing the various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

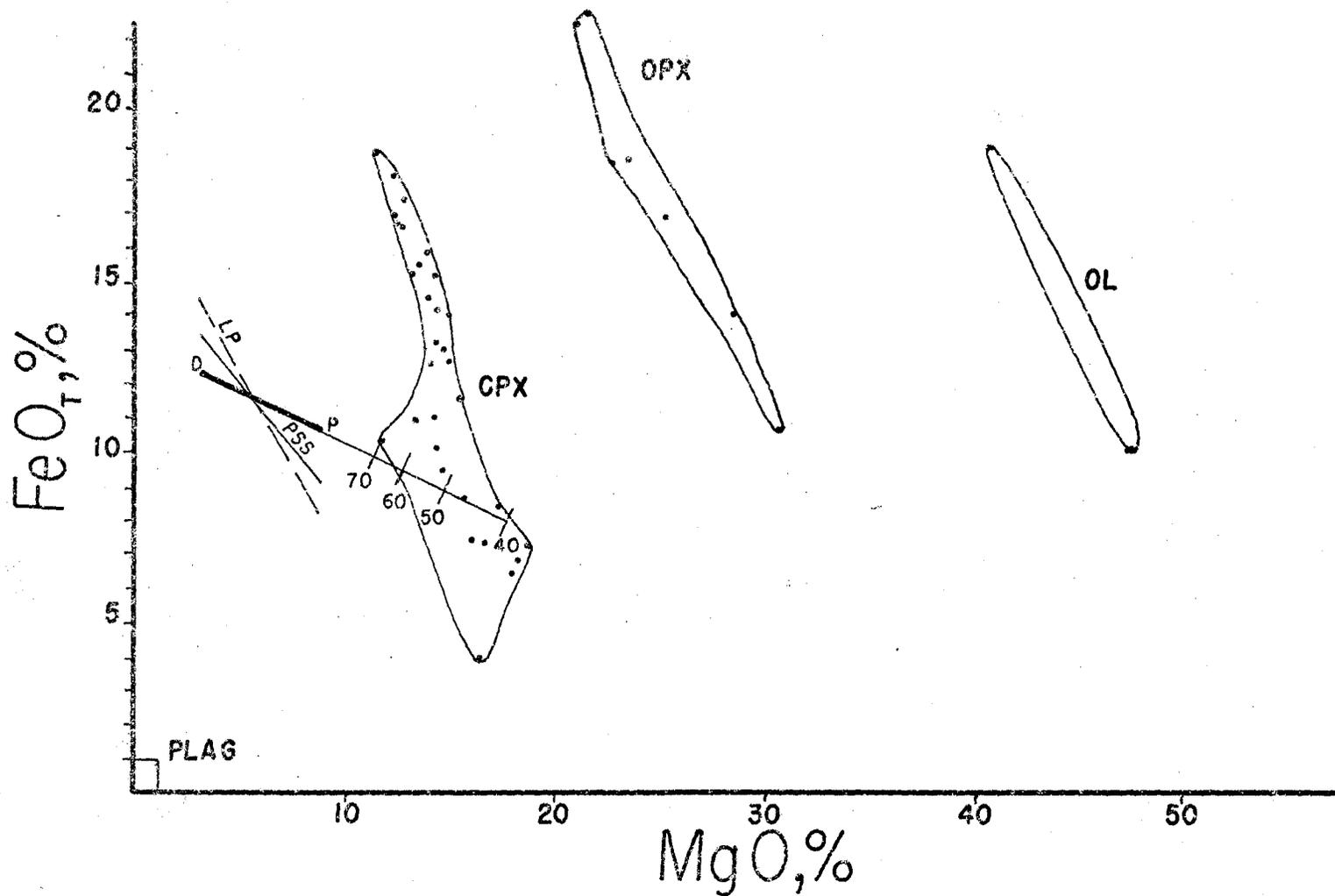


Figure 29. Weight percent  $\text{FeO}_T$  versus weight percent  $\text{MgO}$  variation diagram showing the various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

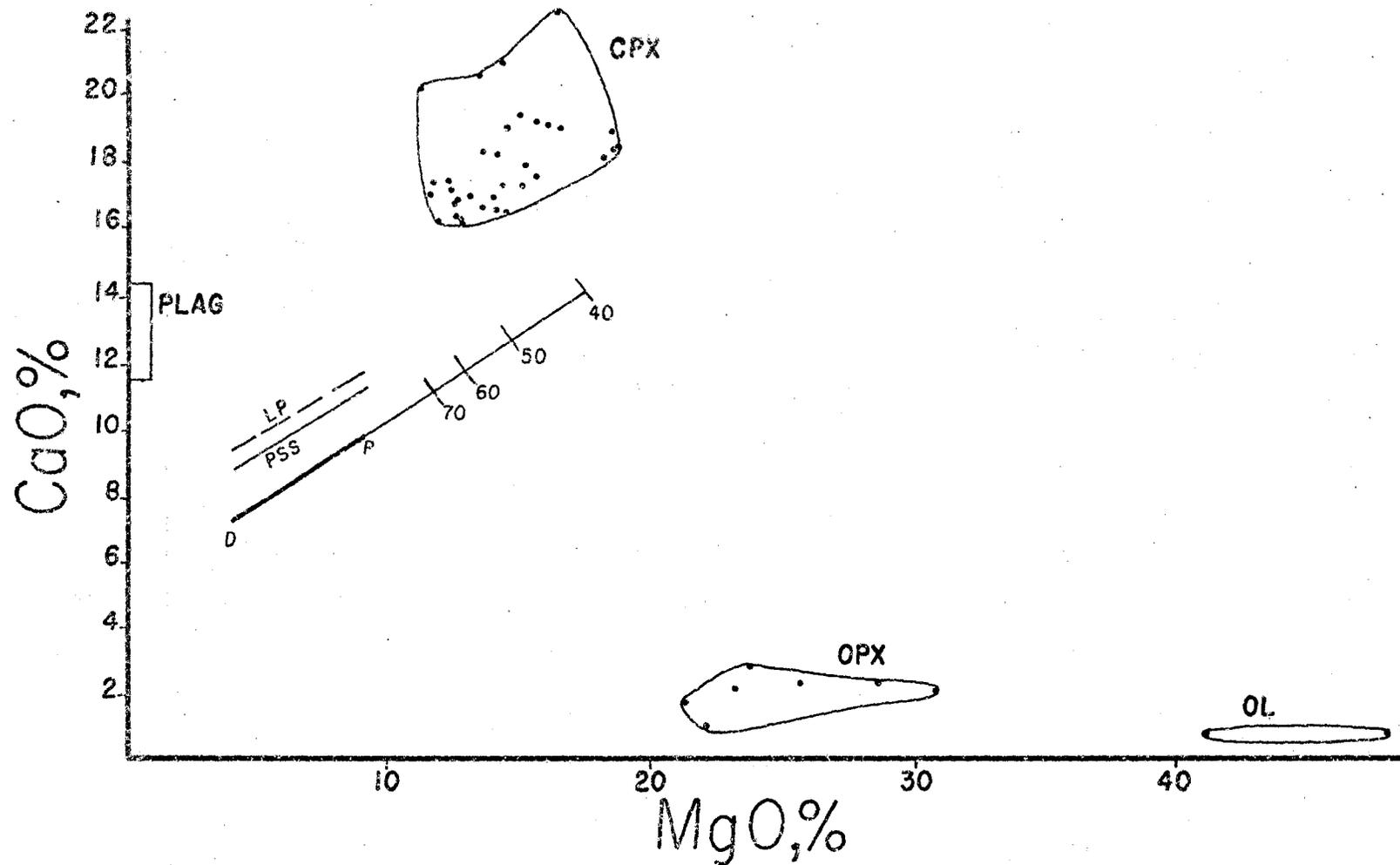


Figure 30. Weight percent CaO versus weight percent MgO variation diagram showing the various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

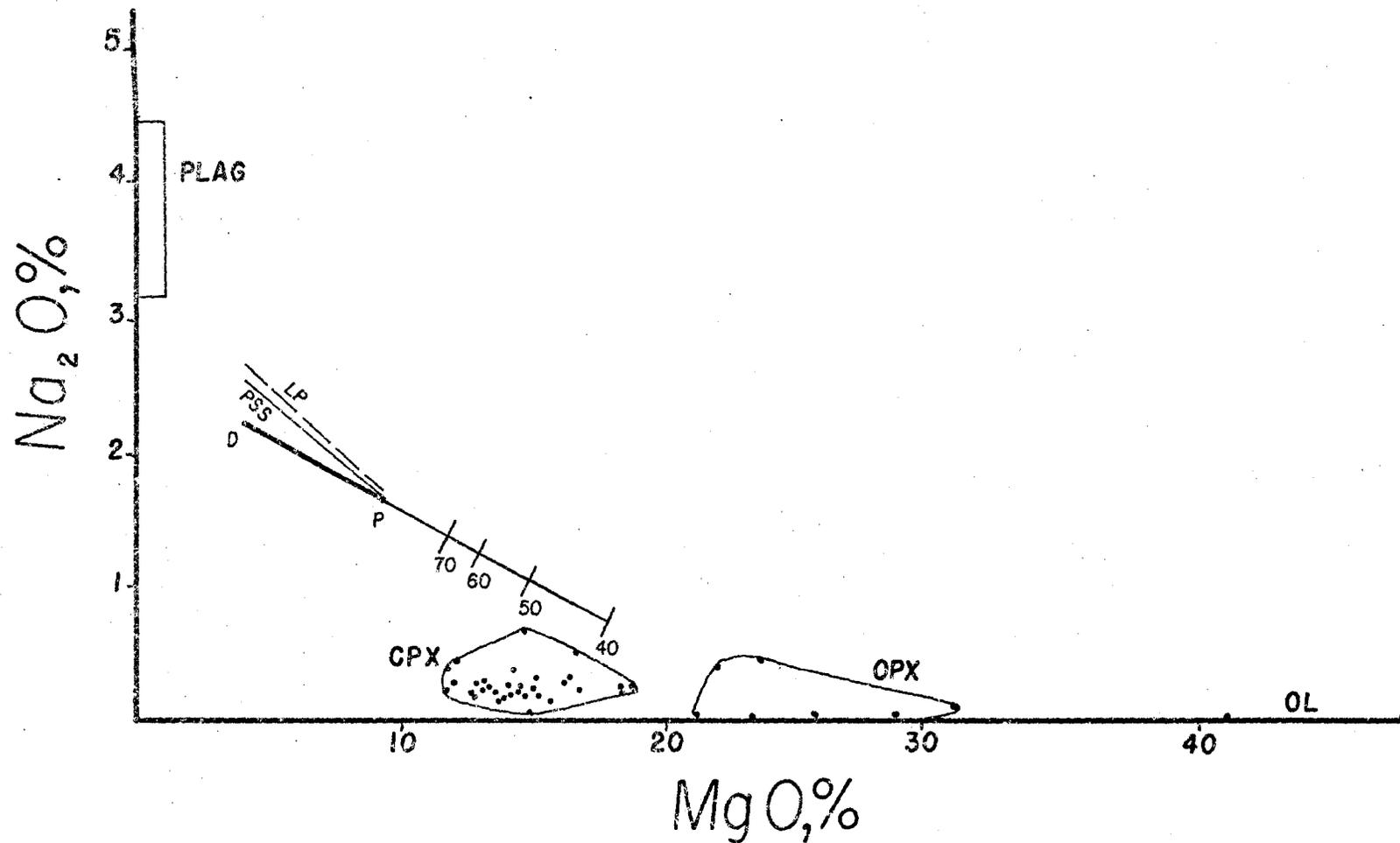


Figure 31. Weight percent  $\text{Na}_2\text{O}$  versus weight percent  $\text{MgO}$  variation diagram showing the various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

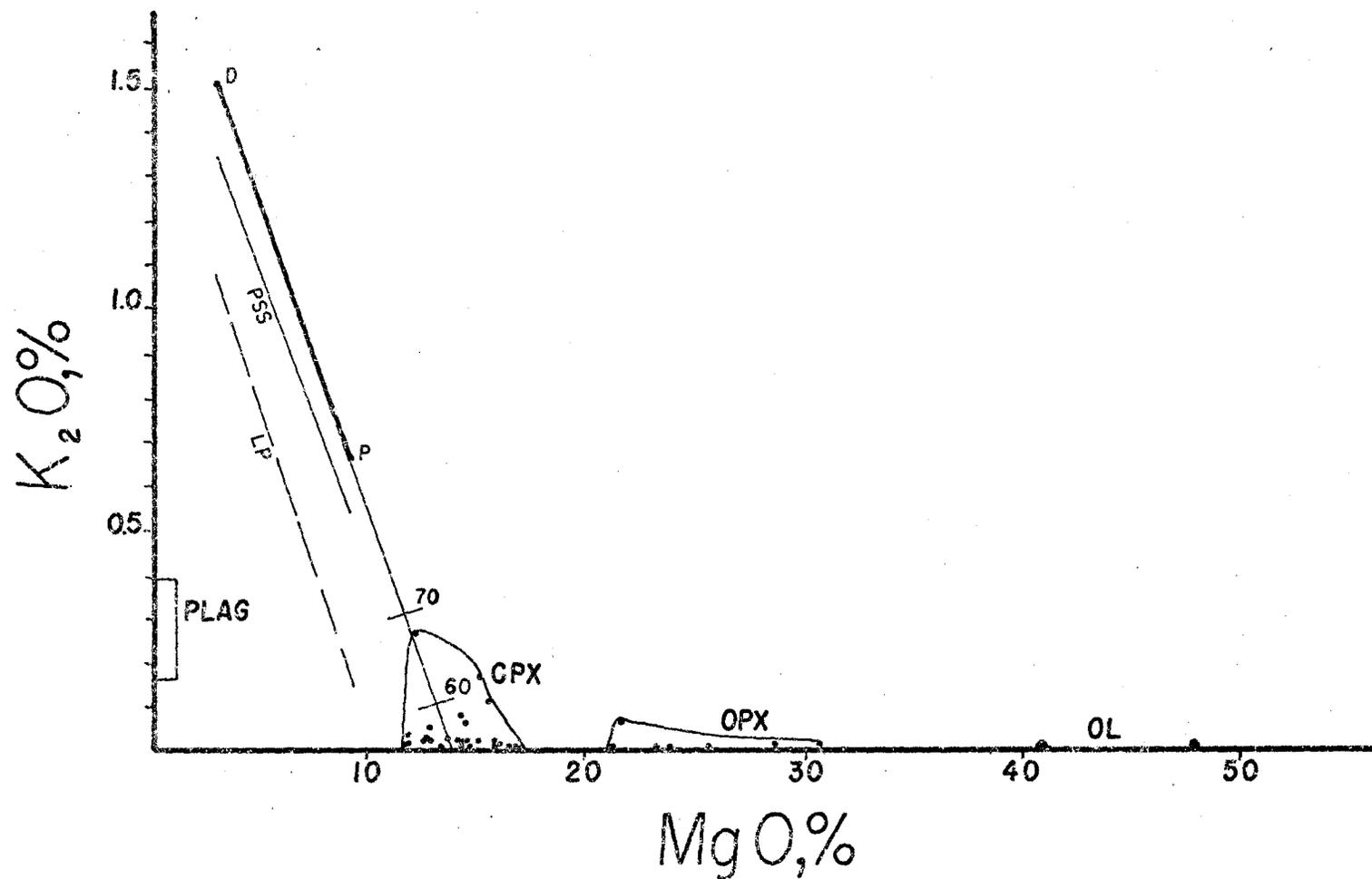


Figure 32. Weight percent  $K_2O$  versus weight percent  $MgO$  variation diagram showing various control lines, individual mineral compositions and percent crystal accumulation at 10% intervals.

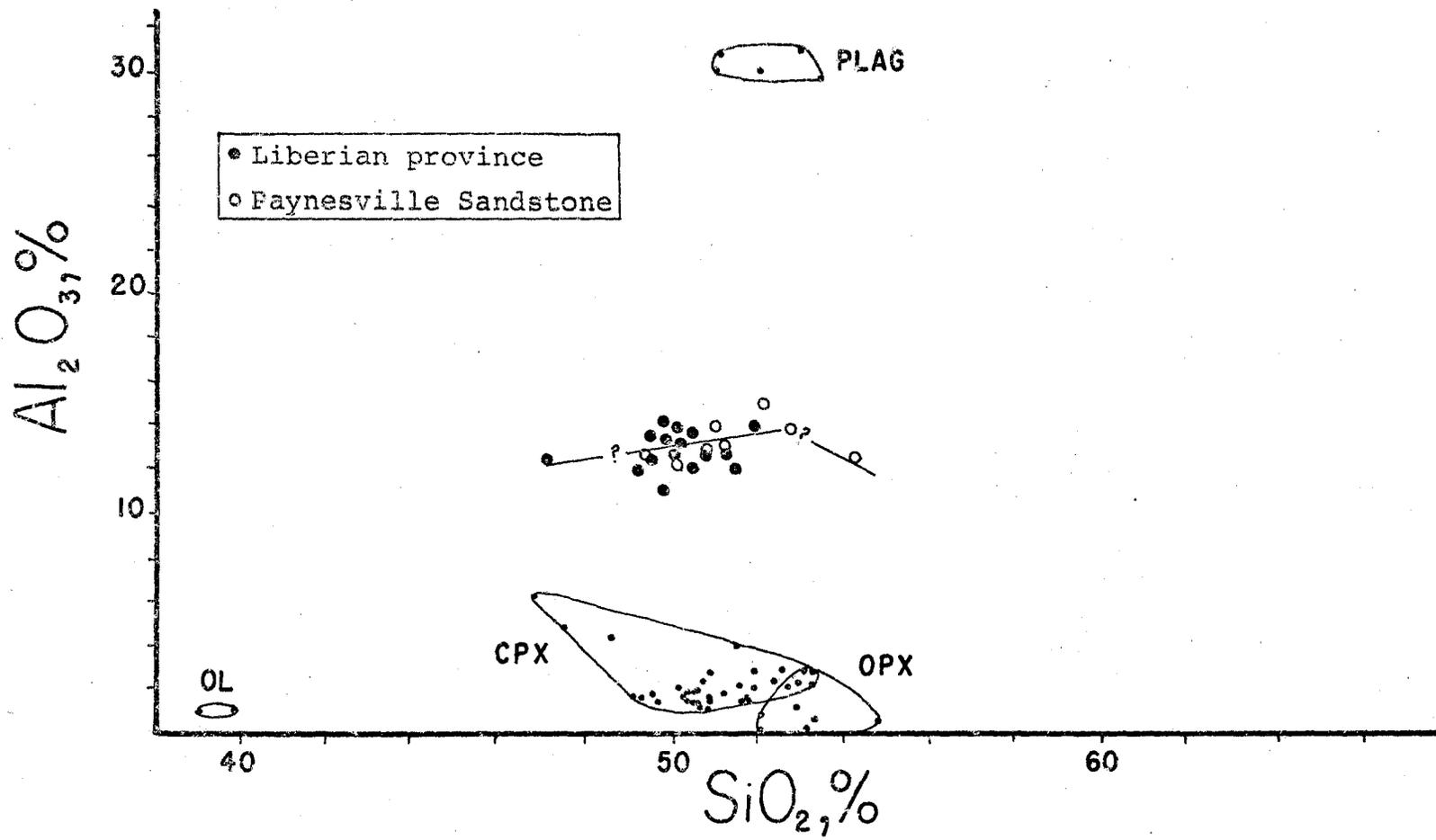


Figure 33. Weight percent  $Al_2O_3$  versus weight percent  $SiO_2$  variation diagram showing possible control lines and the composition of the Liberian dolerites and individual minerals.

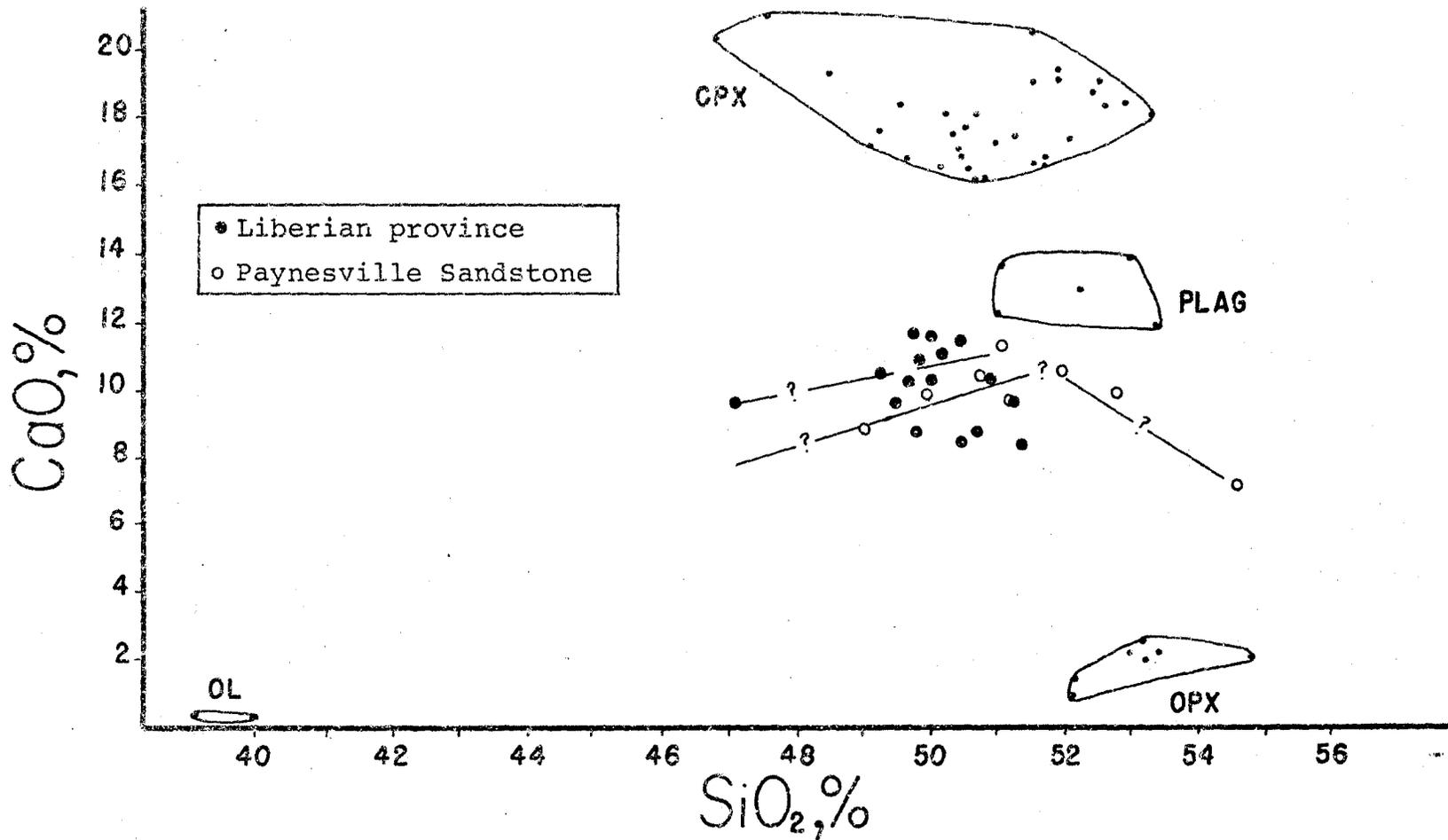


Figure 34. Weight percent CaO versus weight percent SiO<sub>2</sub> variation diagram showing possible control lines and the composition of the Liberian dolerites and individual minerals.

show any indication of its influence on the chemistry. In spite of the small range in  $\text{SiO}_2$  and the lack of well pronounced differentiation trends, these plots indicate that settling of plagioclase was not an important influence.

Olivine can represent accumulate phases in the tholeiitic magma series (Wright, 1971; Yoder and Tilley, 1962). However, olivine does not appear to influence the chemistry of the doleritic magmas of Liberia. This is evident in the lack of correlation in respect to  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{CaO}$  and  $\text{K}_2\text{O}$  (Figs. 27, 29, 30 and 32). Combinations of clinopyroxene  $\pm$  orthopyroxene  $\pm$  plagioclase  $\pm$  olivine also show a lack of correlation which is evident on the  $\text{CaO}$  versus  $\text{MgO}$  variation diagram (Fig. 30). One exception to this is the combination of clinopyroxene  $\pm$  olivine, but this combination lacks correlation on the  $\text{FeO}_T$  versus  $\text{MgO}$  variation diagram (Fig. 29).

In an attempt to quantify this model, calculations were made to determine the absolute amount of differentiation necessary to produce the observed variation trends. The relationship between the three compositions - parental magma, residual magma (daughter), and accumulating crystals - can be described by the following algebraic expression

$$X = \frac{100P - 100D + nD}{n}$$

where P = parental magma, D = residual liquid, X = accumulating crystals, and n = percent accumulation.

Dolerites from the Paynesville Sandstone were chosen for these calculations because they exhibit the strong-east variation trends. The sample with the highest MgO content (L21) was chosen as the parent (P) and the sample with the lowest MgO content (L19) was chosen as the daughter (D) or residual liquid. It is assumed here that the parent can yield the daughter through the process of fractional crystallization. With P and D defined, the composition of the extracted mineral (X) can be calculated for different amounts of accumulation (n). Table 4 shows the results obtained from 40, 50, 60, and 70% accumulation. The compositions of D and P (heavy lines), and the subtracted material at these 4 values of n are shown on Figs. 26 through 32.

These calculations show that the variation of 5 elements ( $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{FeO}_T$ , MgO and  $\text{K}_2\text{O}$ ) can be explained by the subtraction of about 60% of material that falls in the compositional range of clinopyroxene. This remarkable consistency argues strongly for the previous quantitative conclusion that the removal of augite is responsible for

Table 4. Calculated parental magma compositions for successive 10% crystallization intervals. Parent composition is based on highest MgO content. Daughter composition is based on lowest MgO content.

Oxide	Parent	Daughter	% accumulation			
			40	50	60	70
SiO <sub>2</sub>	50.20	54.52	43.70	45.90	47.30	48.30
TiO <sub>2</sub>	0.96	2.02	-0.63	-0.10	0.25	0.51
Al <sub>2</sub> O <sub>3</sub>	12.10	12.24	11.89	11.96	12.01	12.04
FeO <sub>T</sub>	10.71	12.43	8.13	8.99	9.56	9.97
MnO	0.16	0.18	0.13	0.14	0.15	0.15
MgO	9.15	3.40	17.80	14.90	13.00	11.60
CaO	9.80	7.10	13.85	12.50	11.60	10.96
Na <sub>2</sub> O	1.64	2.26	0.71	1.02	1.23	1.37
K <sub>2</sub> O	0.67	1.51	-0.59	-0.17	0.11	0.31
P <sub>2</sub> O <sub>5</sub>	0.10	0.25	-0.13	-0.05	0.00	0.04

the variation observed for the dolerites from the Liberian province and the Paynesville Sandstone. On the other hand, the three elements that are not consistent ( $\text{Al}_2\text{O}_3$ , CaO and  $\text{Na}_2\text{O}$ ) are all important components of plagioclase, and argues against the simple model of augite fractionation.

### SPECULATIVE HYPOTHESES

The southern coast of West Africa has been suggested to correspond to a line of tension which existed during the early Mesozoic (May, 1971). Between the Ivory Coast and Nigeria, the continental margin tend to subparallel a direction of shear which is probably related to the Romanche fracture zone of the mid-Atlantic Ocean (Fig. 1). With the onset of rifting the tensional fractures could have been coupled with a shear component due to the development of the Romanche fracture zone. The common occurrence of quartz-normative tholeiites throughout Liberia may be a result of fracture zones less conducive to magma ascension. This would allow time for differentiation of the doleritic magmas to proceed, resulting in highly differentiated quartz-normative tholeiites. Weigand and Ragland (1970) suggest a similar situation for the origin of quartz-normative tholeiites in Connecticut and Pennsylvania. Therefore, the fracture pattern into which the dolerites have been intruded could possibly be a major factor contributing to the presence of quartz-normative tholeiites throughout Liberia.

Crystal fractionation is the dominant influence attributing to the variation in chemistry that is observed. Out of the many factors which may have caused the minor chemical differences in the Liberian dolerites and the geologic province which they intrude, the following bear further discussion.

- (1) assimilation, wall rock reaction
- (2) crustal contamination
- (3) different rates of ascent, ponding
- (4) slightly different conditions of crystal fractionation
- (5) different parental magmas
- (6) different erosional levels exposed

No field evidence suggesting assimilation, such as the presence of xenoliths, was evident, possibly due in part to poorly exposed outcrops (Sherman Gromme', personal communication). However, chemical analyses indicates the possibility that some reaction between the country rock and the intruding magma may have taken place. The Paynesville Sandstone is predominately an arenitic sandstone, dolerites intruding this province differ in chemistry from other Liberian dolerites. The less mafic character, high  $\text{SiO}_2$  contents, and relatively lower percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$  suggest the

possibility of some wall rock reaction. Likewise, the higher abundance of opaque minerals and higher percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$  in dikes that intrude the Precambrian basement rocks further east could be attributed in part to wall rock reaction or crustal contamination. Whether different parental magma sources are required to explain these differences is difficult to determine with the available data.

Whether or not different rates of magmatic ascent attributes to the chemical variance observed is only speculative. Surely different rates of magma ascent may be responsible for some of the chemical variance. The pronounced differentiation trends noted for dolerites that intrude the Paynesville Sandstone could possibly be due to a slower rate of magmatic ascent or ponding, allowing the residual liquids more time to differentiate.

Berhendt and Wotorsen (1972) showed that even though some of the dolerite intrusions have the surface appearance of sills, aeromagnetic and gravity data indicated that the intrusions must be of substantial vertical extent and more structurally complex at depth than simple sills cropping out at the surface. This data also indicates that some of the dikes that intrude the Pan-African province are of greater width at

depth, such as a combination of several dikes in a narrow zone, with only one of which is exposed at the surface. Again, this could influence the rate of magmatic ascent and ponding which may account for the mafic character and higher percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$  in these dikes.

The mafic character of those dikes that intrude Precambrian basement rocks could be a result of erosion exposing relatively lower portions of the intrusions. Vertical settling of olivine or/and pyroxene would then attribute to the increase in the mafic characteristics of these dikes, but field relationships and the higher elevation of exposure does not support this possibility.

## CONCLUSIONS

The Mesozoic dolerite dike swarm of Liberia was intruded into fractures resulting from the rifting of North America and South America from Africa and Eurasia. These intrusive rocks are predominately quartz-normative tholeiites consisting primarily of plagioclase, clinopyroxene and opaque minerals. Subophitic texture is dominant but intersertal, intergranular and ophitic textures are also present. Petrologic and chemical differences exist between dolerite dikes that intrude different geologic provinces. Most notable are the differences between the dolerite dikes that intrude Precambrian basement rocks and those that intrude the Paynesville Sandstone. Dikes that intrude the Paynesville Sandstone are less mafic, have higher  $\text{SiO}_2$  contents, and relatively lower percentages of  $\text{TiO}_2$ ,  $\text{FeO}_T$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$ .

Crystal fractionation appears to be a dominant influence attributing to the variation in chemistry in the doleritic magmas. Crystal fractionation models suggest that the chemical variance observed is due to crystal settling of clinopyroxene. Calculations based on assumed parental and daughter compositions suggest

that about 60% accumulation of clinopyroxene would have to had settled in order to account for most of the chemical variance observed. The conclusions drawn from these models are tentative but appear to be consistent with the available data.

The dolerites that intrude Spitsbergen and the nearby island of Wilhelmsøya consist primarily of plagioclase, Ti-rich augite, pigeonite and opaque minerals. Pigeonite is commonly enveloped within augite. Plagioclase is more abundant in those samples from the Lomfjorden sill. Pigeonite and biotite are relatively more abundant in those samples that intrude the island of Wilhelmsøya. Hypersthene and olivine were not noted in these intrusions. The most striking aspect of the Spitsbergen dolerites is their chemical uniformity. Few strong differentiation trends can be distinguished. The Spitsbergen dolerites compare most closely with those dikes that intrude the Pan-African province of Liberia.

The Liberian dolerites, in general terms, compare well with other Mesozoic basalt provinces. Minor differences do exist which distinguish the Liberian dolerites from other basalt provinces. The Liberian dolerites do not compare well with the more primitive ENA olivine-normative tholeiites, but compare favorably

with the ENA quartz-normative tholeiites. In comparison, the Liberian dolerites exhibit a greater degree of differentiation and Fe-enrichment. Disimilarities also exist when the Liberian dolerites are compared to the ENA quartz-normative tholeiites on the basis of  $TiO_2$  content versus mafic index ( $MI = FeOT/FeOT + MgO$ ). These differences reaffirm and distinguish the Liberian dolerites as a distinct geochemical basaltic province.

In comparing the Liberian dolerites to those of eastern North America, it becomes evident that the evolutionary course of these two basalt provinces are different. The problem in understanding the intrusive episodes preceding the breakup of Pangaea and the initial stages of ocean formation will be clearer when petrologic and chemical data becomes available from the dolerite intrusions of Sierra Leone, Mauritania and Morocco, West Africa.

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APPENDICES

APPENDIX I. Sample location of Mesozoic Liberian dikes. (Dalrymple et al., 1975).

<u>Site</u>	<u>North Latitude</u>	<u>South Longitude</u>	<u>Locality Descriptions</u>
L1	6.94	349.24	Mano River, bridge 0.3 miles east of Yoma
L2	7.34	348.86	Mano River at Mano Mine pumphouse
L3	7.24	348.95	Mano Mine Road 11.7 miles SE of Noway Camp
L4	7.23	348.97	Mano Mine Road 13.4 miles SE of Noway Camp
L5	7.07	349.12	Lofa River $\frac{1}{4}$ mile east SE of Waasua Village
L6	7.01	349.22	1.1 miles NE of Gbama on road to Zuo
L7	6.69	349.77	Gibi Dike. Kakata-Totota Road, 14.4 miles NE of Kakata, in quarry
L9	6.69	349.78	0.3 miles SW of Wiala, 0.3 miles N of Gibi dike
L10	6.76	349.91	2.0 miles E of Salala. Copper-bearing dike
L11	6.83	350.13	5.5 miles NE of Totota
L12	6.84	350.15	6.7 miles NE of Totota
L13	6.85	350.16	7.9 miles NE of Totota
L14	6.88	350.27	2.1 miles E of Ziensu
L15	6.79	350.05	1.2 miles S of Totota
L16	6.78	350.05	3.0 miles S of Totota
L17	6.78	350.01	5.1 miles SW of Totota, 1.2 miles S of CooCoo Nest

## APPENDIX I. (Continued)

<u>Site</u>	<u>North Latitude</u>	<u>South Longitude</u>	<u>Locality Descriptions</u>
L18	6.34	349.27	Monrovia Refining Co., N side of refinery
L19	6.31	349.31	White Plains-Monrovia pipeline 1.05 miles from Tubman Boulevard
L20	6.27	349.28	Quarry on hill 2000 feet SW of Elwa turnoff Tubman Blvd. Sill overlying sandstone
L21	6.23	349.38	Quarry on hill 0.8 miles west NW of Duazon
L22	6.20	349.45	0.35 miles E of entrance to Camp Schieffelin
L23	6.23	349.50	1.5 miles E of bridge at Scieffelin on new Roberts Field Road
L24	6.28	349.23	Bernard's Bench
L25	6.32	349.18	Quarry below Ducor Hotel
L26	6.25	349.69	3.2 miles E of bridge on Farmington River on road to Buchanan
L27	6.12	349.82	1.5 miles W of Vahn. Composite dike in quarry
L28	6.12	349.87	200 yards W of Lloydsville Church
L29	5.86	349.95	Gabbro $\frac{1}{2}$ miles S of Lamco docks at Buchanan
L30	5.99	349.98	At bridge on St. John River on Buchanan Road
L31	6.28	349.67	200 yard N of bridge on Farmington River
L32	6.30	349.68	SE end of intake dam for Firestone power house on Farmington River

APPENDIX II. Instrumental parameters for atomic absorption spectrometric analyses

	Al <sub>2</sub> O <sub>3</sub>	FeO <sub>T</sub>	MnO	MgO	Na <sub>2</sub> O
slit width	160	320	80	320	160
wavelength	309.2	248.2	279.5	285.2	588.7
current (H.C.)	10	10	10	5	—
volts (H.V.)	460	620	620	530	530
integration (secs)	4	4	4	4	4
curve correct	0	0	0	0	0
burner height	6.5	4.5	4.8	5.6	5.2
oxidizer	N <sub>2</sub> O	air	air	air	air
standards	AGV	AGV	AGV	AGV	AGV
	BCR	BCR	BCR	BCR	BCR
	JB	JB	JB	JB	JB
	QMC	WI	QMC	QMC	QMC
	WI		WI	WI	WI

APPENDIX III. Dissolving procedure for atomic absorption analysis.

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1. Prepare the following solutions:
  - A. 1:3 HCL:HF (50 ml/sample)
  - B. 1:1:8 HCl:HNO<sub>3</sub>:H<sub>2</sub>O (50 ml/sample)
2. Weigh 0.500 gm powdered sample into teflon baker.
3. Measure 50 ml of solution A Into plastic graduated cylinder. Add 10 ml to sample, swirl to insure wetting, then add rest.
4. Cover with teflon watchglass and heat for 12 hours with hotplate on a setting of 325.
5. Remove watchglass, increase heat to just below boiling point, and remove beaker from heat after sample evaporated to dryness (2-4 hours). Caution is to be taken not to burn sample.
6. Measure 50 ml of solution B into graduated cylinder. Add 10 ml to dried sample, wetting well, and break up sample with teflon rod. Add remaining solution while rinsing rod.
7. Replace beaker on hotplate and evaporate to 35 ml (approximately 1 hour).
8. Let cool, then transfer to 50 ml volumetric flask. Rinse beaker twice with deionized water, adding rinse to flask.
9. Dilute to 50 ml with deionized water, mix well, and store solution in plastic bottles.
10. Run a blank (add all reagents but no sample) with each set of samples.
11. Full strength, 1% by weight, rock solutions used for trace-element analyses.
12. Solutions diluted by 50 times (2 ml diluted to 10 ml) used for major-element analyses.
13. All determinations must be corrected for weight by dividing by the factor  $\frac{\text{sample wt.}}{0.5000}$ .

APPENDIX IV. Instrumental parameters for analysis by x-ray spectrometry

	SiO <sub>2</sub>	TiO <sub>2</sub>	CaO	K <sub>2</sub> O
kv	45	22	25	44
ma	25	12	16	35
PHA	base	46	47	18
	window	165	200	262
peak	79.27	6.70	15.24	20.73
gain	1x256	1x128	1x128	1x128
detector voltage	1450	1480	1450	1450
detector position	2	2	2	2
detector	FLOW	FLOW	FLOW	FLOW
crystal	PET	PET	PET	PET
vacuum	yes	yes	yes	yes
standards	AGV, BCR, BD	AGV, BGR, BD	AGV, BCR, JB	BCR, BD, BR
	GSP, JB, QMC	BR, GSP, JB	QMC, W1	JB, QMC, W1
	W1	QMC, W1		

APPENDIX V. Normative mineralogy (CIPW) for the Liberian and Spitsbergen dolerites.

		Liberian	Province (north)				
		L1	L2	L3	L4	L5	L6
	Qtz	5.26	3.04	3.62	-	3.10	1.80
	Or	4.49	2.52	2.59	2.31	2.97	1.87
	Al	19.01	15.81	20.47	21.77	16.49	19.59
	An	27.02	31.12	22.91	23.29	28.58	25.57
	Wo	10.24	12.03	11.59	11.29	12.31	11.82
Di	En	5.31	7.05	6.00	5.89	6.95	6.28
	Fs	4.65	4.40	5.29	5.08	4.85	5.17
Hy	En	9.74	11.67	9.46	11.58	11.29	10.79
	Fs	8.53	7.28	8.34	9.99	7.87	8.86
Cl	Fo	-	-	-	.29	-	-
	Fa	-	-	-	.28	-	-
	Mg	4.05	3.60	4.88	5.05	3.94	4.81
	Il	1.42	1.30	4.30	2.88	1.46	3.48
	AP	.29	.29	.56	.30	.19	-
	An- content	58.71	66.31	52.81	51.69	63.42	56.63

## APPENDIX V. (Continued)

		Liberian Province (south)					
		L7	L9	L10	L11	L12	L13
	Qtz	2.93	2.36	6.25	6.19	4.33	8.06
	Or	1.74	2.36	4.69	6.29	5.55	6.05
	Al	19.26	15.84	20.67	20.23	19.56	22.08
	An	26.26	29.46	22.63	19.46	20.28	21.01
Di	Wo	11.59	12.35	10.11	9.05	10.37	8.51
	En	6.17	6.95	5.30	3.65	5.37	3.88
	Fs	5.06	4.89	4.51	5.48	4.73	4.56
Hy	En	10.33	11.92	8.59	7.19	9.04	6.11
	Fs	8.48	8.39	7.31	10.79	7.97	7.19
Ol	Fo	-	-	-	-	-	-
	Fa	-	-	-	-	-	-
	Mg	4.61	4.05	4.47	5.83	5.22	4.91
	Il	3.34	1.34	4.68	5.06	6.73	6.53
	Ap	.24	.10	.80	.79	.88	1.14
	An-Content	57.69	65.04	52.26	49.03	50.91	48.75

## APPENDIX V. (Continued)

		Liberian Province (south)			
		L14	L15	L16	L17
	Qtz	4.71	7.87	3.06	2.71
	Or	2.43	7.27	4.97	2.55
	Al	17.57	21.15	16.85	20.27
	An	26.54	19.17	20.08	23.46
Di	Wo	12.29	8.14	9.91	11.09
	En	6.16	3.78	5.79	5.64
	Fs	5.86	4.28	3.64	5.17
Hy	En	8.79	6.68	16.81	10.19
	Fs	8.37	8.13	10.57	9.35
Ol	Fo	-	-	-	-
	Fa	-	-	-	-
	Mg	4.61	5.13	4.75	5.10
	Il	2.44	6.68	3.07	4.09
	Ap	.24	1.27	.52	.40
	An- Content	60.17	47.54	54.37	53.63

## APPENDIX V. (Continued)

		Paynesville Sandstone			
		L18	L19	L20	L21
	Qtz	3.58	14.37	4.90	3.89
	Or	6.54	9.31	5.84	4.15
	Al	21.99	19.94	18.82	14.53
	An	20.03	19.59	24.71	24.79
Di	Wo	9.28	6.44	10.61	10.62
	En	4.60	2.69	6.49	6.62
	Fs	4.50	3.78	3.52	3.36
Hy	En	8.22	6.14	11.87	17.25
	Fs	8.04	8.64	6.44	8.75
Ol	Fo	-	-	-	-
	Fa	-	-	-	-
	Mg	5.24	4.49	3.50	3.89
	Il	6.92	4.00	2.90	1.91
	Ap	1.08	.62	.42	.25
	An- Content	47.66	49.56	56.76	63.05

## APPENDIX V. (Continued)

Paynesville Sandstone					
	L22	L23	L24	L25	
Qtz	5.39	5.61	7.77	4.01	
Or	4.19	4.76	5.48	3.61	
Al	14.22	19.06	19.72	15.94	
An	26.15	29.69	25.20	28.91	
Di	Wo	11.01	10.28	10.02	12.05
	En	7.01	6.25	5.35	7.74
	Fs	3.29	3.47	4.35	3.51
Hy	En	15.40	10.02	8.57	13.27
	Fs	7.23	5.57	6.98	6.01
Ol	Fo	-	-	-	-
	Fa	-	-	-	-
Mg	3.50	3.04	3.74	3.05	
Il	2.20	2.04	2.27	1.61	
Ap	.42	.20	.56	.29	
An- Content	64.79	60.90	56.10	64.46	

## APPENDIX V. (Continued)

		Pan-African Province						
		L26	L27	L28	L29	L30	L31	L32
	Qtz	4.12	4.84	3.43	6.61	2.98	4.71	6.35
	Or	6.90	6.41	6.07	6.50	6.01	5.09	5.85
	Al	19.33	20.66	19.17	27.74	20.37	20.73	21.09
	An	18.42	18.24	20.71	23.70	22.11	21.22	19.15
Di	Wo	9.44	10.75	9.44	5.67	8.92	11.35	9.88
	En	4.73	5.94	4.82	1.74	4.53	5.67	4.78
	Fs	4.51	4.40	4.39	4.15	4.17	5.44	4.94
Hy	En	8.91	7.05	9.46	3.71	9.04	8.04	6.94
	Fs	8.51	5.22	8.62	8.85	8.32	7.72	7.18
Ol	Fo	-	-	-	-	-	-	-
	Fa	-	-	-	-	-	-	-
	Mg	5.56	5.21	5.40	4.98	5.21	4.80	5.25
	Il	7.72	10.18	7.08	5.32	6.87	4.54	7.49
	Ap	1.88	1.13	1.46	1.66	1.50	.70	1.12
	An- Content	48.80	46.89	51.92	45.43	52.05	50.59	47.59

## APPENDIX V. (Continued)

		Spitsbergen				
		217	223	257	260	263
	Qtz	4.95	5.58	5.84	6.93	7.17
	Or	5.29	3.77	3.41	3.32	3.29
	Al	19.96	21.14	20.53	19.53	19.87
	An	22.22	21.87	22.86	22.78	21.91
Di	Wo	10.35	10.64	10.44	11.02	11.75
	En	5.64	5.85	5.65	5.90	6.29
	Fs	4.34	4.40	4.42	4.75	5.08
Hy	En	8.52	8.36	8.20	7.58	7.05
	Fs	6.55	6.29	6.42	6.10	5.69
Ol	Fo	-	-	-	-	-
	Fa	-	-	-	-	-
	Mg	4.73	4.68	4.71	4.68	4.63
	Il	6.78	6.82	6.70	6.63	6.53
	Ap	.70	.62	.84	.80	.75
	An- content	52.68	50.85	52.68	53.85	52.44

## APPENDIX V. (Continued)

		Spitsbergen			
		335	346	354	356
	Qtz	9.99	6.04	8.21	8.07
	Or	4.82	4.98	4.44	4.77
	Al	17.45	19.60	18.72	17.97
	An	24.46	22.71	23.76	23.66
	Wo	8.49	9.16	9.55	9.32
Di	En	4.52	5.00	5.16	4.98
	Fs	3.70	3.83	4.06	4.05
Hy	En	7.81	9.61	8.14	8.33
	Fs	6.38	7.36	6.41	6.78
Ol	Pc	-	-	-	-
	Fa	-	-	-	-
	Mg	4.55	4.71	4.60	4.66
	Il	6.96	6.37	6.67	6.57
	Ap	.89	.65	.80	.85
	An- content	58.37	53.67	55.40	56.84