Studies of the Geology and Mineral Resources of the Southern Antarctic Peninsula and Eastern Ellsworth Land, Antarctica

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PETER D. ROWLEY *and* WALTER R. VENNUM, Editors

A. Geology of the Southern Black Coast, Antarctic Peninsula

By PETER D. ROWLEY, KARL S. KELLOGG, WALTER R. VENNUM, RICHARD B. WAITT, *and* STEPHEN J. BOYER

B. Igneous Petrology of the Merrick Mountains, Eastern Ellsworth Land, Antarctica

By WALTER R. VENNUM *and* THOMAS S. LAUDON

C. Porphyry-type Copper Deposits and Potassium-Argon Ages of Plutonic Rocks of the Orville Coast and Eastern Ellsworth Land, Antarctica

By PETER D. ROWLEY, EDWARD FARRAR, PAUL E. CARRARA, WALTER R. VENNUM, *and* KARL S. KELLOGG

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Description of the bedrock geology of an area in the Andean belt of West Antarctica

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GEOLOGY OF THE SOUTHERN BLACK COAST, ANTARCTIC PENINSULA

By PETER D. ROWLEY[1], KARL S. KELLOGG[1], WALTER R. VENNUM[2], RICHARD B. WAITT,[1], and STEPHEN J. BOYER[3]

ABSTRACT

The southern Black Coast, in the southeastern Antarctic Peninsula, includes the Wegener Range, Carey Range, and northern Dana Mountains. The geology of the area is similar to that of the Lassiter Coast, Orville Coast, English Coast, and eastern Ellsworth Land, all of which lie farther south in the peninsula. All these areas are part of the Andean magmatic and deformational belt. Except for some late Paleozoic or Triassic sedimentary rocks in the English Coast, the oldest rocks in the southern Antarctic Peninsula are Middle and Upper Jurassic fine-grained volcaniclastic sedimentary rocks of the Latady Formation and interlayered silicic- to intermediate-composition rocks of the Mount Poster Formation. Siltstone, slate, and fine-grained sandstone dominate in the Latady Formation; ash-flow tuff, lava flows, and dikes dominate in the Mount Poster Formation. The Mount Poster Formation was deposited as a magmatic arc, southeast of which a shallow marine back-arc basin accumulated sediment that formed the Latady Formation. The magmatic arc, which now underlies the axis of the southern Antarctic Peninsula, resulted from southeastward subduction of the southern Pacific oceanic lithosphere beneath the Antarctic Peninsula.

The Jurassic sedimentary and volcanic rocks were tightly folded along north- to north-northeast-trending axes as subduction continued. Late during deformation, in Early Cretaceous time, plutons and dikes were emplaced into the rocks of the Jurassic arc and back-arc basin. The intrusive rocks define either another magmatic arc that formed during continued subduction or a late phase of the Jurassic magmatic arc; any volcanic material that may have accompanied the Early Cretaceous intrusive activity, however, has not been identified in the southern Antarctic Peninsula. In the southern Black Coast area, exposed plutons consist of the west Wegener Range batholith, the east Wegener Range batholith, and the Werner batholith. Granite and granodiorite are the most abundant rock types in these plutons, but each pluton has a thin border facies of mafic rocks. The Jurassic sedimentary and volcanic wall rocks are contact metamorphosed over wider zones than farther south in the Antarctic Peninsula, where plutons are less abundant. Altered and mineralized plutonic rocks are widely scattered in the area—but do not appear to be of economic value. Slightly mineralized, sheared phyllic-argillic zones, similar to those in the Lassiter Coast copper deposit to the south, occur in the western Carey Range.

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INTRODUCTION

The southern Black Coast, which lies along the Weddell Sea on the eastern flank of the southern Antarctic Peninsula (figs. 1, 2), includes the Wegener Range, Carey Range, and northern Dana Mountains. The area was first visited and geologically mapped in reconnaissance during the 1972–73 austral summer by a U.S. Geological Survey field party that included the authors. The northern Lassiter Coast, to the south, also was mapped at this time (Rowley, 1973). The Antarctic Peninsula is part of the Andean magmatic and deformational belt of Early Jurassic to late Tertiary age, which extends from the Andes of South America southward through the Scotia arc and Antarctic Peninsula, and from there westward through Ellsworth Land, Marie Byrd Land, and the western rim of the Pacific Ocean (Craddock, 1969, 1982; Herron and Tucholke, 1976; Craddock and Hollister, 1976; LeMasurier and Wade, 1976; LeMasurier and Rex, 1982; Cooper and others, 1982; Rowley, 1983).

The geology of the southern Black Coast (Rowley, 1973; Kamenev, 1975; Rowley and Williams, 1982) is similar to that of the Lassiter Coast, Orville Coast, English Coast, and eastern Ellsworth Land, which lie successively farther south and west (Williams and others, 1972; Laudon and others, 1964, 1969; Laudon, 1972; Rowley, 1978; Thomson and others, 1978; Rowley, Vennum, and others, 1983; Rowley and others, 1985). Except for some late Paleozoic or Triassic sedimentary rocks in the English Coast (Laudon and others, 1985), the oldest rocks of this overall region are Middle and Upper Jurassic volcaniclastic sedimentary rocks of the Latady Formation and intertonguing silicic- to intermediate-composition volcanic rocks of the Mount Poster Formation of the Antarctic Peninsula Volcanic Group. These rocks were tightly folded and later intruded by Lower Cretaceous plutons and dikes. The areal proportions of plutonic rocks progressively increases northward through the southern Antarctic Peninsula;

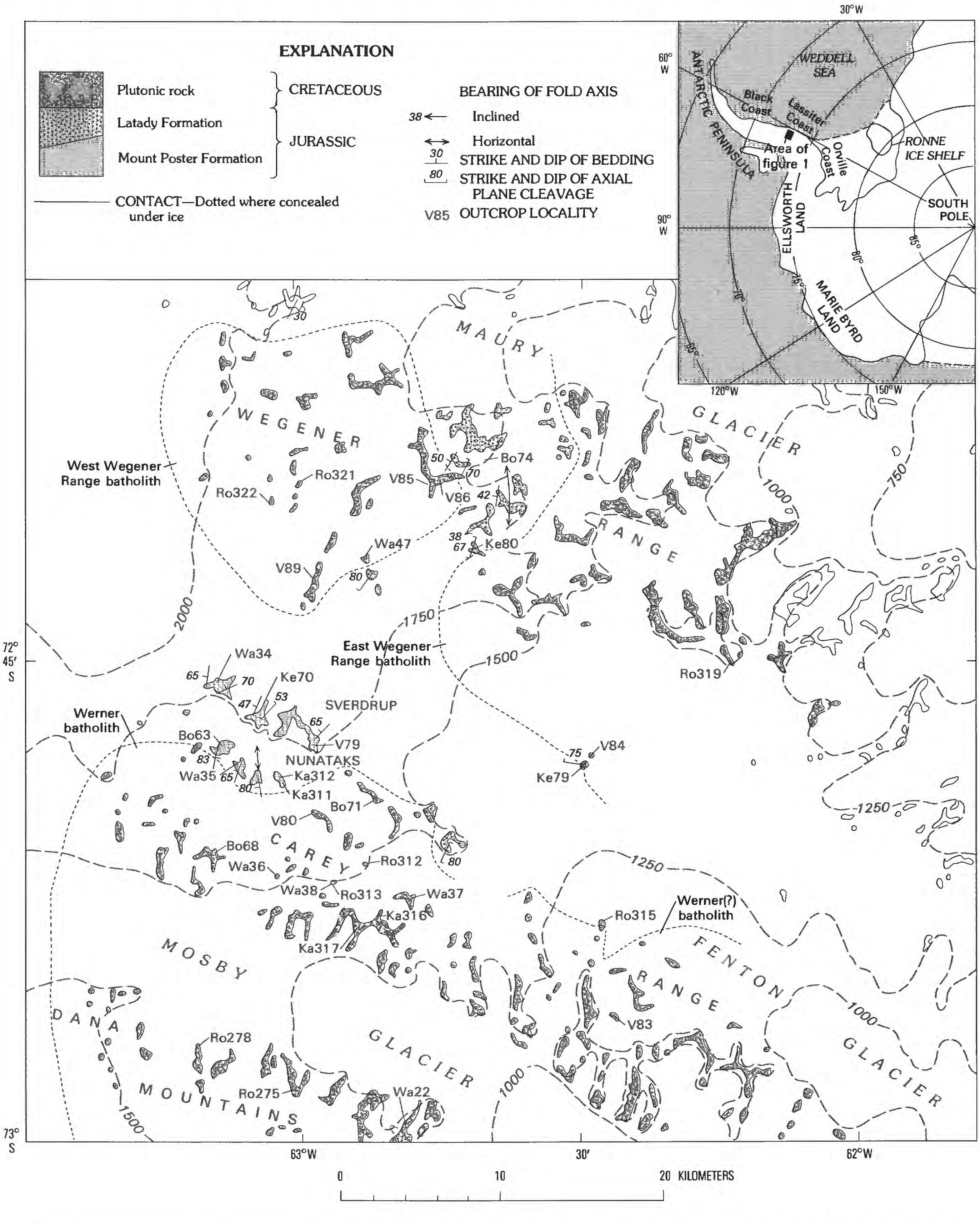

FIGURE 1.—Reconnaissance geologic map of the southern Black Coast, Antarctica. Large areas of rock outcrop are shown by patterns; unvisited outcrops are outlined but left blank. Dotted where concealed under ice. Contours in meters. Base map from British Antarctic Survey, by permission.

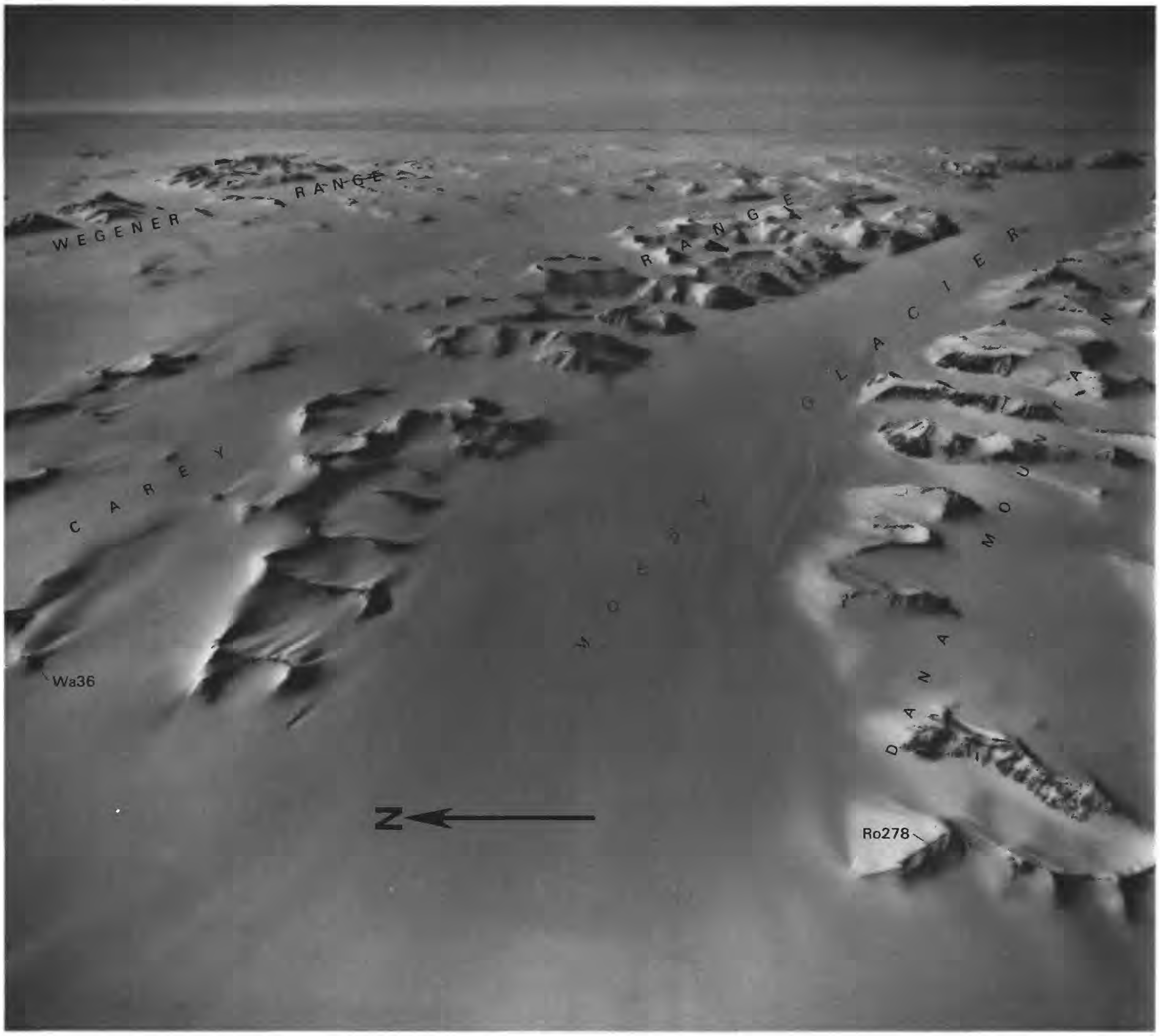

FIGURE 2.—U.S. Navy oblique aerial photograph (TMA 1745 16, F31) of part of the southern Black Coast, Antarctica. Two outcrop nunataks are shown, whose localities are marked in figure 1. View is eastward, toward the ice-covered Weddell Sea.

thus, Jurassic rocks are progressively less abundant and display more widespread contact-metamorphic effects northward. In the southern Antarctic Peninsula, rocks of the Mount Poster Formation are most abundant near the present axis of the peninsula, which probably was near the axis of a subduction-generated magmatic arc that formed no later than Middle(?) and Late Jurassic time and which has dominated the geologic setting since then (Rowley and Williams, 1982; Rowley, Vennum, and others, 1983). The Latady Formation represents deposition in a back-arc marine basin on the southeastern side of the contemporaneous magmatic arc (Suárez, 1976; Rowley, 1978; Thomson and others, 1978; Rowley and Williams, 1982; Laudon and others, 1983; Rowley, Vennum, and others, 1983).

The central Black Coast, about 110 km north of the study area, is the only other part of the Black Coast that has been visited or geologically mapped. Singleton (1980a, b) mapped a so-called gneissic and schistose high-grade (amphibolite facies) metamorphic complex, overlain by a unit of fine-grained clastic sedimentary rocks and interbedded volcanic rocks (Mount Hill Formation) that he tentatively correlated with the Latady Formation. These rocks are overlain by sparse outcrops of tuff, lava flows, and clastic sedimentary rocks, all of which may be correlative with the Mount Poster Formation. All these rocks are intruded by Lower Cretaceous plutons and dikes. Hence, the main geologic difference between the central and southern Black Coasts is the presence in the north of a very tentative high-grade metamorphic complex; more probably, however, these metamorphic rocks represent contact phases of the Lower Cretaceous plutons (Meneilly, 1983, Pankhurst, 1983).

The only other nearby areas to the north that have been geologically mapped are the Seward Mountains near the axis of the Antarctic Peninsula 90 km west-northwest of the Wegener Range, the Journal Peaks about 50 km west of the Wegener Range, and the Gutenko Mountains about 80 km northwest of the Wegener Range. The Seward Mountains are dominated by rocks of the Antarctic Peninsula Volcanic Group, which are intruded by probable Jurassic or Cretaceous plutons and, in turn, by an upper(?) Tertiary intrusive mass of olivine basalt (Singleton, 1980c). The Journal Peaks are underlain by rocks of the Antarctic Peninsula Volcanic Group (British Antarctic Survey, 1982). The Gutenko Mountains contain rocks of the possible high-grade metamorphic complex that are overlain by the Antarctic Peninsula Volcanic Group, all of which are intruded by plutons (British Antarctic Survey, 1982).

The British Antarctic Survey recently compiled a geologic map of the central Antarctic Peninsula as far south as latitude 73° South, including the southern Black Coast (British Antarctic Survey, 1982). We contributed the information for the southern Black Coast to this map; the present report gives the supporting data.

Outcrop numbers given in the text refer to rock nunataks or parts of nunataks that were studied. Each outcrop may have rock types of differing lithology or origin. When rocks were sampled they were assigned the same whole number as the outcrop; letters and even subscripts appended to the outcrop numbers refer to individual samples. Outcrops referred to here are shown in figure 1.

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LATADY FORMATION

The oldest exposed rock unit in the southern Black Coast consists of black and gray, fine-grained marine volcaniclastic sedimentary rocks that were named the Latady Formation by Williams and others (1972). Where the rocks are less metamorphosed in the Lassiter Coast to the south, they locally are rich in Late Jurassic shallow-water temperate-marine invertebrate fossils (Imlay and Kauffman, in press). In the Orville Coast and eastern Ellsworth Land, most rocks of the Latady Formation also appear to be Late Jurassic (Stevens, 1967; Quilty, 1970, 1977, 1982, 1983; Thomson, 1980, 1983; Crame, 1981; Mutterlose, 1986), but in eastern Ellsworth Land and perhaps parts of the Orville Coast, faunas as old as Middle Jurassic also were found (Quilty, 1970, 1972, 1982, 1983; Thomson, 1983; Stanek and Wormbs, 1985). On the basis of poorly preserved fossil pelecypods, pollen, and spores from the northern Lassiter Coast, Kamenev and Orlenko (1982) suggested that parts of the Latady Formation may be Early or Late Cretaceous; Kauffman and Imlay (in press) and Thomson (1983) have disagreed with this interpretation. We consider the Latady Formation in the southern Black Coast to be Middle and Late Jurassic.

Metamorphism is too great in the southern Black Coast for fossils to be preserved. Because of the absense of fossils, Kamenev (1975) suggested that the rocks here belong not to the Latady Formation but to the Triassic (Thomson, 1975a, 1982; Edwards, 1982) Trinity Peninsula Formation ("Trinity Peninsula Series" of Adie, 1957; redefined by Thomson, 1982), which occurs in the northern Antarctic Peninsula. Rowley and Williams (1982) disagreed with this interpretation, and Kamenev and Orlenko (1982) later referred all sedimentary rocks to the Latady Formation.

Contact metamorphism is minimal in the Orville Coast, and therefore evidence for environments of deposition of the Latady Formation is preserved. Here, depositional environments progress southeastward from (1) continental just east of a magmatic arc where the sedimentary rocks intertongue with the volcanic rocks of the Mount Poster Formation through (2) shallow-marine deltaic to (3) open-marine shallow water farthest southeast (Rowley, 1978; Thomson and others, 1978; Laudon and others, 1983; Rowley, Vennum, and others, 1983). The clastic material of the Latady Formation was largely derived from contemporaneous volcanic rocks of the magmatic arc and was deposited rapidly.

The largest exposed area of Latady Formation in the southern Black Coast occurs in the western Wegener Range (fig. 1). The rocks here are medium-gray to black, moderately resistant, fine- to medium-bedded siltstone and slate (fig. 3) and subordinate medium-gray and tan, fine-grained sandstone. Similar rocks are exposed in small areas in the Carey Range. Slate and other rocks locally are coated with thin crusts of evaporation or oxidation products (Vennum, 1979, 1980). A dark-gray porphyritic ash-flow(?) tuff in the Wegener Range (locality Ke80) and lava flows in the northern Carey Range (locality Ro315) are interbedded with the sedimentary rocks. The thickness of the exposed part of the Latady Formation in the southern Black Coast is uncertain because folding of monotonous beds repeats the section and because cleavage obscures bedding. The Latady Formation probably is thicker than several kilometers.

Contact metamorphism converted most sedimentary rocks in the field area to hornfels. Other evidence of penetrative deformation also locally accompanied metamorphism. Thus, original depositional structures and bedding have been obscured. In most places the metamorphic grade is albite-epidote hornfels, but within about 1 km of pluton contacts, andalusite crystals are as long as 3 cm and the metamorphic grade is hornblende hornfels. The metamorphic grades and the mineral assemblages are similar to those in the southern Lassiter Coast (Plummer, 1974) and central Black Coast (Singleton, 1980a). Unlike the areas farther south, however, all Jurassic rocks in the Black Coast are extensively affected by contact metamorphism (Rowley and Williams, 1982).

The widespread metamorphism in the southern Black Coast and northern Lassiter Coast led Kamenev (1975) and Kamenev and Orlenko (1982) to propose (1) that these areas exhibit zonal regional metamorphism on which contact metamorphism is superimposed and (2) that the zonal regional metamorphism is related to the folding, not to Early Cretaceous plutonism. We contend, on the contrary, that most metamorphic effects in the southern Black Coast are due to contact metamorphism

FIGURE 3.—Typical outcrop of slate of the Latady Formation. Outcrop Bo74, Wegener Range, Antarctica.

that is extensive because of the more abundant plutonic rocks, some of which may underlie the exposed Jurassic rocks. We agree, however, that a regional zeolite-grade or greenschist-grade metamorphism was imposed prior to Early Cretaceous plutonism on the Jurassic and older rocks of the southern Antarctic Peninsula and eastern Ellsworth Land during burial and (or) during development of folds and slaty cleavage. The effects of this metamorphism are best seen where plutonic rocks are sparse, in the southern Lassiter Coast, the Orville Coast, the English Coast, and eastern Ellsworth Land.

Dark-gray fine-grained micaceous schist is in contact with plutonic rocks at a small outcrop between the Wegener Range and the Carey Range (locality Ke79). The schist is considered to be a contact phase of the pluton, but it resembles descriptions of the possible high-grade metamorphic complex of Singleton (1980a) in the central Black Coast.

MOUNT POSTER FORMATION

Folded Jurassic volcanic rocks, previously called the "Upper Jurassic Volcanic Group" (Adie, 1972), occur throughout the Antarctic Peninsula. Thomson (1982) redefined them as the Antarctic Peninsula Volcanic Group; Thomson and Pankhurst (1983) suggested that they range in age from at least Early Jurassic to Tertiary.

As used by Thomson, the group consists of numerous different types of volcanic rocks from widely scattered localities deposited in different environments of a magmatic arc. No regional study has described these different facies or their significance to the plate-tectonic development of the arc they define. To encourage regional facies studies, formation-rank stratigraphic names within the Antarctic Peninsula Volcanic Group are needed in local areas containing volanic rocks of the same general rock type and stratigraphic setting. Those rocks of the group in the southern Antarctic Peninsula consist of several subaerial calc-alkaline volcanic fields that interfinger with the Latady Formation. Accordingly, Rowley, Schmidt, and Williams (1982) defined these rocks as the Mount Poster Formation after a mountain in the western Lassiter Coast that contains a well-exposed volcanic section, summarized by Williams and others (1972). All rocks of the Antarctic Peninsula Volcanic Group in the southern Antarctic Peninsula appear to belong to the Mount Poster Formation.

The rocks of the Mount Poster Formation occupy axial parts of the southern Antarctic Peninsula. They have been mapped at Mount Poster in the western Lassiter Coast (Williams and others, 1972), in the northwestern Orville Coast (Rowley, Vennum, and others, 1983), in the northern part of eastern Ellsworth Land (Laudon and others, 1969; Laudon, 1972; Rowley, 1978), in the western part of the central Black Coast (Singleton, 1980a, c), in the Gutenko Mountains (British Antarctic Survey, 1982), and in the western part of the southern Black Coast. The volcanic fields that comprise the formation thin to the east or southeast, away from the axis, where they intertongue with the Latady Formation, and farther east they pinch out in the Latady Formation. The mutual intertonguing indicates that the rocks of the Mount Poster Formation must be of the same age (Late Jurassic and in some places also Middle Jurassic) as the Latady Formation. At Mount Poster (Williams and others, 1972) and in the central Black Coast (Singleton, 1980a), however, the main volcanic mass apparently overlies the western featheredge of the Latady. The correlation of volcanic rocks in the English Coast with the Mount Poster Formation is less certain than in other parts of the southern Antarctic Peninsula because recent fieldwork suggests that some sedimentary rocks here are older, perhaps late Paleozoic or Triassic (Laudon and others, 1985; Rowley and others, 1985).

The Mount Poster Formation is well exposed in the Sverdrup Nunataks of the southern Black Coast, where the volcanic rocks are folded and steeply dipping. The sequence is at least 300 m thick and probably several times thicker than this amount; individual volcanic units are 1–20 m thick. The main volcanic rock type is a medium-greenish-gray to black, sparsely porphyritic, rhyolitic to dacitic, moderately welded to densely welded ash-flow tuff. Abundant lenticules of collapsed pumice, characteristic of ash-flow cooling units, have been erroneously interpreted to be mylonite zones or shear planes (Kamenev and Orlenko, 1982). Dark-green to black, dacitic to andesitic lava flows (and perhaps sills), generally containing amygdaloidal cavities flattened by folding, also are common. Tan to light-gray beds of airfall tuff or slightly welded ash-flow tuff are uncommon. Dark-greenish-gray andesitic dikes were intruded into and folded with the volcanic rocks. The volcanic rocks are interbedded with thin (perhaps 10 percent by volume) Latady-type volcaniclastic fine-grained sandstone, shale, and intraformational conglomerate. All rocks of the formation have undergone metamorphism of albite-epidote hornfels or greenschist facies.

In thin section (Ka311, Ka312–2, Ka312–4, Ke70b, V79a, V79e; table 1), ash-flow cooling units contain 5–20 percent phenocrysts of plagioclase (mostly calcic oligoclase), subordinate biotite and sanidine, and minor "beta" quartz and Fe-Ti oxides[4]. The lava flows (Bo63a, V79f, Wa34, Wa35a; table 1) and dikes are generally aphanitic or contain sparse phenocrysts of pyroxene, subordinate hornblende and plagioclase, and minor biotite and Fe-Ti oxides. The aphanitic groundmass (Wa34; table 1) consists mostly of flow-foliated microlites of pyroxene, hornblende, and plagioclase, and minor biotite, Fe-Ti oxides, and sphene. Chemical analyses (table 2) show an ash-flow tuff (Ka311) to be rhyolitic and a lava flow (Bo63a) to be andesitic.

[4]Opaque minerals, consisting of magnetite, ilmenite, pyrite, and related minerals, which contain iron and (or) titanium.

TABLE 1.—*Modes, in volume percent, of igneous rocks from the southern Black Coast, Antarctica*

[Five hundred points counted in thin sections and stained rock slabs. Sample localities shown in figure 1. Tr., trace; n.d., not determined; (---) leaders, not present; An determinations by Michel-Lévy method using universal stage and either low-temperature or high-temperature curves of Slemmons (1962, table 3)]

Sample No.	Phenocrysts														Groundmass	Vesicles
	Plagioclase		K-feldspar	Quartz	Biotite	Hornblende	Pyroxene	Olivine	Fe-Ti oxides	Sphene	Apatite	Chlorite	Epidote	Sericite		
	Volume percent	Anorthite content														
Mount Poster Formation																
Bo63a	---	---	---	---	---	---	---	---	---	---	---	---	---	---	87.2	12.8
Ka311	9.2	18-22	0.6	0.6	0.8	---	---	---	0.8	---	---	Tr.	0.4	Tr.	90.0	---
Ka312-2	2.0	26	.4	.4	2.6	---	---	---	.2	---	---	Tr.	---	Tr.	94.4	---
Ka312-4	.4	19-21	5.2	---	---	---	---	---	.2	Tr.	---	Tr.	Tr.	Tr.	94.2	---
Ke70b	8.0	17-31	.8	---	9.0	---	---	---	.8	---	---	Tr.	Tr.	Tr.	81.4	---
V79a	13.0	18-26	1.0	.4	8.6	---	---	---	.2	---	---	Tr.	Tr.	Tr.	76.8	---
V79e	13.6	19-26	.2	.2	4.6	Tr.	---	---	1.0	---	---	Tr.	Tr.	---	81.4	---
V79f	---	---	---	---	---	---	---	---	---	---	---	---	---	---	74.6	25.4
Wa34	10.2	n.d.	---	---	1.2	16.4	36.2	---	.2	---	---	Tr.	Tr.	---	35.8	---
Wa35a	---	---	---	---	---	---	---	---	---	---	---	---	---	---	83.0	17.0
Granite of west Wegener Range																
Ro322a	33.6	30-33	24.0	33.6	3.6	1.8	---	---	.6	.4	---	.2	---	---	---	---
V85	30.4	26	37.4	26.6	6.2	.4	---	---	.6	---	---	.8	---	---	---	---
V86a	63.2	15-30	5.2	13.8	3.6	9.2	---	---	1.8	.2	Tr.	Tr.	Tr.	---	---	---
Granite of east Wegener Range																
Ro319a	35.8	20-21	10.0	22.6	11.2	11.2	---	---	.2	.2	Tr.	.4	Tr.	---	---	---
Ro319c	36.6	14-30	38.8	14.8	3.4	3.8	---	---	1.2	.4	Tr.	2.8	Tr.	---	--	---
V84b	58.4	37-46	.4	.2	---	40.2	---	---	.2	---	.2	Tr.	Tr.	---	---	---
V84c	60.2	29-47	.4	4.4	9.0	19.8	---	---	.4	---	.4	---	---	---	---	---
Werner batholith from west Carey Range and north Dana Mountains																
Bo68a	55.4	25-36	13.8	24.6	2.8	2.0	---	---	.8	Tr.	Tr.	Tr.	Tr.	---	---	---
Ro275a	42.6	24-34	18.8	31.0	5.4	.6	---	---	1.0	.4	Tr.	.6	Tr.	---	---	---
Ro312b	41.0	31-38	24.0	20.4	10.6	4.2	---	---	1.0	.4	Tr.	.4	Tr.	---	---	---
Ro313a	63.8	25-30	5.2	20.8	1.8	---	---	---	.8	Tr.	Tr.	5.8	---	.4	---	---
V80c	38.0	28-41	4.4	6.0	2.0	41.0	---	---	2.6	.4	.2	6.4	1.4	Tr.	---	---
Wa38b	62.0	25-50	12.8	8.2	4.4	11.0	---	---	1.4	.4	.2	.2	Tr.	---	---	---
Werner(?) batholith from east Carey Range																
V83	40.0	26-34	17.4	28.6	9.0	2.6	---	---	.2	.2	Tr.	2.0	Tr.	Tr.	---	---
Cretaceous dike																
Ka317	34.0	14-34	---	5.0	6.0	5.8	---	---	1.2	Tr.	Tr.	---	---	---	52.2	---
Ro315d	22.0	15-32	---	.8	---	11.8	---	---	.6	Tr.	Tr.	.8	Tr.	Tr.	62.2	---
V89b	31.6	27-36	2.2	5.2	1.0	.6	---	---	1.4	.4	Tr.	3.2	.8	---	57.4	---
Tertiary(?) dike																
Ro321a	---	---	---	---	---	.2	2.4	5.8	---	---	---	---	---	Tr.	76.0	3.0

TABLE 2.—*Chemical analyses and CIPW norms of fresh igneous rocks from the southern Black Coast, Antarctica*

[Sample locations shown in figure 1. Symbols for rock units given in table 1. Rapid rock chemical analyses by Hezekiah Smith. Semiquantitative spectrographic analyses by J. L. Harris. Less than lower limit of detection: Ag, As, Au, B, Bi, Cd, Cs, Cr, Ge, Hf, Hg, In, Ir, Li, Lu, Nd, Os, Pd, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Tl, Tm, V, and W. L, less than limit of detection, (---) leaders, not present]

Rock unit	Mount Poster Formation		Granite of west Wegener Range		Granite of east Wegener Range				Werner batholith: W. Carey Range and N. Dana Mtns.		Werner batholith: E. Carey Range
Sample No.	Bo63a	Ka311	Ro322a	V86a	Ro319a	Ro319c	V84b	V84c	Bo68a	Ro275a	V83
Chemical analyses (weight percent)											
SiO_2	53.00	71.30	68.90	60.10	60.10	68.00	45.90	53.40	69.20	68.50	69.30
Al_2O_3	13.70	12.10	15.40	18.50	15.40	15.40	20.30	18.60	15.90	16.20	16.20
Fe_2O_3	4.20	1.90	1.90	3.10	2.30	2.00	3.50	2.30	1.40	1.70	1.40
FeO	10.40	3.20	1.50	3.20	4.10	1.40	7.60	6.80	1.40	1.20	1.20
MgO	3.60	.77	.83	1.50	3.70	.80	4.10	3.30	.68	.41	.55
CaO	9.20	1.80	3.60	7.50	7.00	4.20	13.10	8.90	3.80	3.60	4.00
Na_2O	3.30	2.70	3.50	3.60	3.00	3.60	2.80	3.50	3.50	3.90	3.60
K_2O	.60	4.10	3.70	1.40	2.60	3.20	.43	.94	3.50	3.10	3.00
H_2O (total)	.91	.63	.38	.40	.75	.77	1.00	.86	.41	.41	.47
TiO_2	1.50	.70	.29	.59	.60	.51	1.20	.62	.26	.18	.16
P_2O_5	.31	.25	.21	.36	.46	.26	.72	.48	.19	.18	.12
MnO	.18	.03	.04	.13	.10	.05	.21	.19	.03	.01	.03
CO_2	.12	.04	.05	.02	.01	.03	.05	.02	.03	.03	.02
Total	101.02	99.52	100.30	100.40	100.12	100.22	100.91	99.91	100.30	99.42	100.05
Semiquantitative spectrographic analyses (ppm)											
Ba	109	770	654	345	442	481	72	178	1030	549	453
Be	1	2	1	L	2	2	L	L	L	2	2
Ce	L	75	35	73	62	55	L	85	55	48	38
Co	29	6	3	10	14	3	11	14	3	3	2
Cr	15	8	4	2	135	6	L	2	8	10	3
Cu	81	8	2	6	67	11	19	16	L	37	3
Dy	6	9	4	5	L	6	L	L	5	L	4
Eu	L	1	L	1	1	1	1	1	1	1	L
Ga	6	5	8	8	9	6	7	8	11	11	8
Gd	4	4	L	L	L	4	L	3	L	L	L
Ho	L	L	2	L	L	L	L	L	2	L	L

La	L	31	16	16	15	29	L	20	28	26	16
Mn	1880	580	679	1640	1360	718	2360	2200	623	598	619
Mo	3	L	L	1	2	L	3	2	L	1	L
Nb	L	4	3	L	L	L	L	L	3	5	L
Ni	14	3	2	L	19	1	1	2	2	5	1
Pb	6	24	12	5	7	9	3	2	12	4	10
Pr	L	7	4	5	5	7	7	L	4	6	6
Sc	57	13	6	11	18	5	11	12	6	3	5
Sn	4	4	L	L	L	L	L	L	L	4	L
Sr	159	144	335	434	613	474	852	585	499	446	382
Th	L	L	L	L	L	28	L	L	L	L	L
V	286	30	28	56	94	42	97	106	26	26	29
Y	28	30	16	16	21	30	11	14	12	17	15
Yb	5	4	2	3	3	5	1	2	2	3	2
Zn	112	51	24	55	52	24	76	65	34	25	22
Zr	118	219	69	65	13	165	15	59	49	117	60
CIPW norms (weight percent)											
Q	6.191	34.420	25.897	16.306	13.626	25.851		4.214	26.374	26.131	27.486
C		.642								.386	.092
Or	3.510	24.345	21.799	8.240	15.346	18.868	2.518	5.560	20.621	18.426	17.719
Ab	27.642	22.957	29.527	30.341	25.355	30.395	20.973	29.643	29.527	33.193	30.447
An	20.587	7.078	15.336	30.064	20.850	16.374	41.177	32.294	17.285	16.590	18.924
Ne							1.358				
Wo	9.118		.329	1.890	4.497	1.057	7.621	3.605	.035		
En	8.875	1.927	2.061	3.721	9.204	1.988	3.861	8.226	1.688	1.027	1.369
Fs	13.349	3.222	.778	2.572	4.818	.169	3.582	9.925	1.038	.523	.838
Fo							4.386				
Fa							4.484				
Mt	6.028	2.768	2.747	4.477	3.331	2.893	5.029	3.338	2.024	2.479	2.029
Il	2.820	1.336	.549	1.116	1.138	.966	2.259	1.179	.492	.344	.304
Ap	.727	.595	.496	.849	1.088	.614	1.690	1.138	.449	.429	.284
Cc	.270	.091	.113	.045	.023	.068	.133	.046	.068	.069	.045
Total	99.117	99.380	99.632	99.622	99.276	99.246	99.048	99.166	99.601	99.597	99.667

PLUTONIC ROCKS

Calc-alkaline plutonic rocks are the most abundant rock type in the Antarctic Peninsula. Most of these plutonic rocks post-date the volcanic rocks now assigned to the Antarctic Peninsula Volcanic Group, and they were named the "Andean intrusive suite" (Adie, 1955). Isotopic age dating has subsequently shown that the plutonic rocks occupy several magmatic pulses within a broad time range (Rex, 1976; Pankhurst, 1982). Many of these dated plutons have Late Cretaceous and early Tertiary isotopic ages, as Adie (1955) suggested they would. But the rest range in isotopic age from Late Triassic to late Tertiary (Rex, 1976; Pankhurst, 1982) and locally may be even as old as late Paleozoic (Smellie, 1981). Despite their diverse ages, however, all plutons are one-mica upper crustal (Hamilton, 1981) rocks that appear to be chemically similar to each other and to rocks of the Antarctic Peninsula Volcanic Group (Adie, 1964; Saunders and others, 1980, 1982); all rocks probably reflect a similar long-lived subduction geometry.

Because of the wide range of ages of these plutonic rocks, the present use of "Andean" has become confused. Some workers have restricted it to only a latest Cretaceous to early Tertiary period of plutonism. Others have coined the name "Andean orogeny" for deformation and plutonism along the Pacific margin of West Antarctica of either this same age or a broader time span, and they have contrasted this "orogeny" with the Gondwanide "orogeny" of Late Triassic to Early Jurassic age. But in West Antarctica, the Pacific margin is characterized primarily by long-lived subduction-related igneous activity. Deformation in the belt is generally local and of diverse ages. The belt thus did not form in one or more "orogenies" of the classical sense. Thus, Rowley, Vennum, and others (1983) and Rowley (1983) suggested that "Andean" be retained as a general term for the Pacific-margin belt of subduction-related structures and calc-alkaline igneous rocks of Early Jurassic to late Tertiary age. Gondwanide and pre-Gondwanide structures and rocks in Pacific-margin parts of West Antarctica may also be the products of Andean-type subduction.

As isotopic ages become more abundant, recognition and definition of specific intrusive suites within the broad Andean belt will focus attention on differences in local genesis of various parts of the Antarctic Peninsula. The plutons in the Black Coast, Lassiter Coast, Orville Coast, and eastern Ellsworth Land occupy the same tectonic setting along the eastern side of the southern Antarctic Peninsula, and they appear to have a restricted age range of about 130–95 m.y. (million years). Following usage proposed by the North American Commission on Stratigraphic Nomenclature (Henderson and others, 1980) as applied in the Sierra Nevada (Stern and others, 1981), Rowley, Vennum, and others (1983) proposed the name Lassiter Coast Intrusive Suite of Early Cretaceous age for all plutons in the southern Antarctic Peninsula known to be of this age. The plutons are best exposed and dated in the Lassiter Coast (Williams and others, 1972; Rowley and Williams, 1974, 1982; Farrar and others, 1982).

In the southern Antarctic Peninsula, plutonism probably accompanied the volcanism that resulted in the volcanic rocks of Mount Poster. Such an older intrusive suite has been recognized in more northern parts of the Antarctic Peninsula (Rex, 1976; Pankhurst, 1982), but we have not yet identified any exposed plutons of this age in the southern Antarctic Peninsula. Because the volcanic rocks of Mount Poster thicken toward the present axis of the southern Antarctic Peninsula, it is likely that the first plutons of this age to be recognized in the southern Antarctic Peninsula will be found near the axis.

About 70 stocks and batholiths have been mapped in the southern Antarctic Peninsula and eastern Ellsworth Land, where they intrude folded rocks of the Latady and Mount Poster Formations. Compositions range from gabbro to granite, with the most abundant rock type being granodiorite (IUGS classification; see fig. 4). Isotopic dating indicates that the most silicic plutons are generally the youngest (Farrar and others, 1982). Most plutons contain sharp, chilled intrusive contacts and apophyses extending into wall rocks; they were emplaced by both forcible and passive means. Stoped wall-rock blocks locally occur along the intrusive contacts, and mafic inclusions are locally abundant within the plutonic rocks. Most plutons are zoned concentrically by composition: thin mafic margins grade abruptly into or are intruded by the main mass of silicic rock. Most plutons and, locally, adjacent country rocks are cut by late-stage pegmatite and aplite bodies, which are in turn cut by mafic dikes of various compositions and textures. Hydrothermal alteration and copper mineralization took place locally during the terminal stages of magma emplacement.

Plutons in the southern Antarctic Peninsula that have been isotopically dated (Halpern, 1967; Mehnert and others, 1975; Farrar and Rowley, 1980; Farrar and others, 1982) have K-Ar and Rb-Sr ages of 123–98 m.y.—Early Cretaceous (ages corrected according to new constants of Steiger and Jäger, 1977). Several plutons in the central Black Coast have K-Ar ages of from 127 to 107 m.y. (Pankhurst, 1980; ages corrected according to Steiger and Jäger, 1977). Sample Bo68a from the Werner batholith in the western Carey Range has a K-Ar age of 103.1 m.y. (Farrar and others, 1982; age corrected according to Steiger and Jäger, 1977).

Silicic to mafic, mostly porphyritic dikes, containing the same minerals as the plutonic rocks, commonly cut the plutonic rocks. The isotopic dates of two dikes suggest that dike emplacement immediately followed plutonism. Thus, a Rb-Sr age of 101 m.y. for a dike in the Behrendt Mountains of eastern Ellsworth Land is similar to ages of 101 and 100 m.y. for two nearby plutons (Halpern, 1967). A dike in the Copper Nunataks of the Lassiter Coast has a KAr age of 98.0 m.y., identical (within analytical uncertainty) to the pluton that it cuts (Farrar and others, 1982). All plutons and dikes that have been paleomagnetically analyzed have normal polarity, which suggests emplacement during the same Early Cretaceous Epoch of mostly normal polarity (van Hinte, 1976; Kellogg and Reynolds, 1978; Kellogg, 1980).

Three plutons are exposed in the southern Black Coast (fig. 1). One in the western Wegener Range is here named the west Wegener Range batholith, and another in the eastern and central Wegener Range is named the east Wegener Range batholith. The northern part of the Werner batholith, named by Vennum (1978) for exposures in the Werner Mountains of the northern Lassiter Coast, occurs in the northern Dana Mountains and western Carey Range. Plutonic rocks in the eastern Carey Range also probably belong to this pluton. The Werner batholith and probably the other two undated plutons belong to the Lassiter Coast Intrusive Suite.

WEST WEGENER RANGE BATHOLITH

The west Wegener Range batholith (fig. 1) extends about 19 km in long dimension (north-south). The main part of the pluton consists of pink to light-gray granite (fig. 4), but a locally foliated, chilled border facies, generally less than several hundred meters wide, of medium- to light-gray tonalite and granodiorite occurs along most contacts. Stoped blocks of metamorphosed Latady Formation, some at least 10 m long, occur along the southeastern contact (Wa47; fig. 5). At outcrop V86, foliated granite and pegmatite containing blocks of border-facies rock suggest slightly younger movement of the silicic main part of the pluton along this part of the contact. The granite is medium grained (1–5 mm) to very coarse grained (more than 3 cm), and commonly porphyritic; poikilitic phenocrysts of K-feldspar are as long as 4 cm. The border-facies rocks are fine grained (less than 1 mm) or medium grained. Mafic inclusions, as long as 20 cm, are sparse (rarely more than one inclusion per square meter of rock outcrop) in the pluton; locally, however, clusters of inclusions are present. Pegmatite, aplite, and mafic dikes (thin section V89b; table 1) are exposed in many outcrops. Probably nearly all dikes were emplaced shortly after the main period of plutonism during Early Cretaceous time. One possible exception to this conclusion is a dike at outcrop Ro321 (table 1) that approaches basalt in composition, a distinctive chemistry that suggests that it correlates with Tertiary basalt dikes and volcanic rocks scattered about West Antarctica.

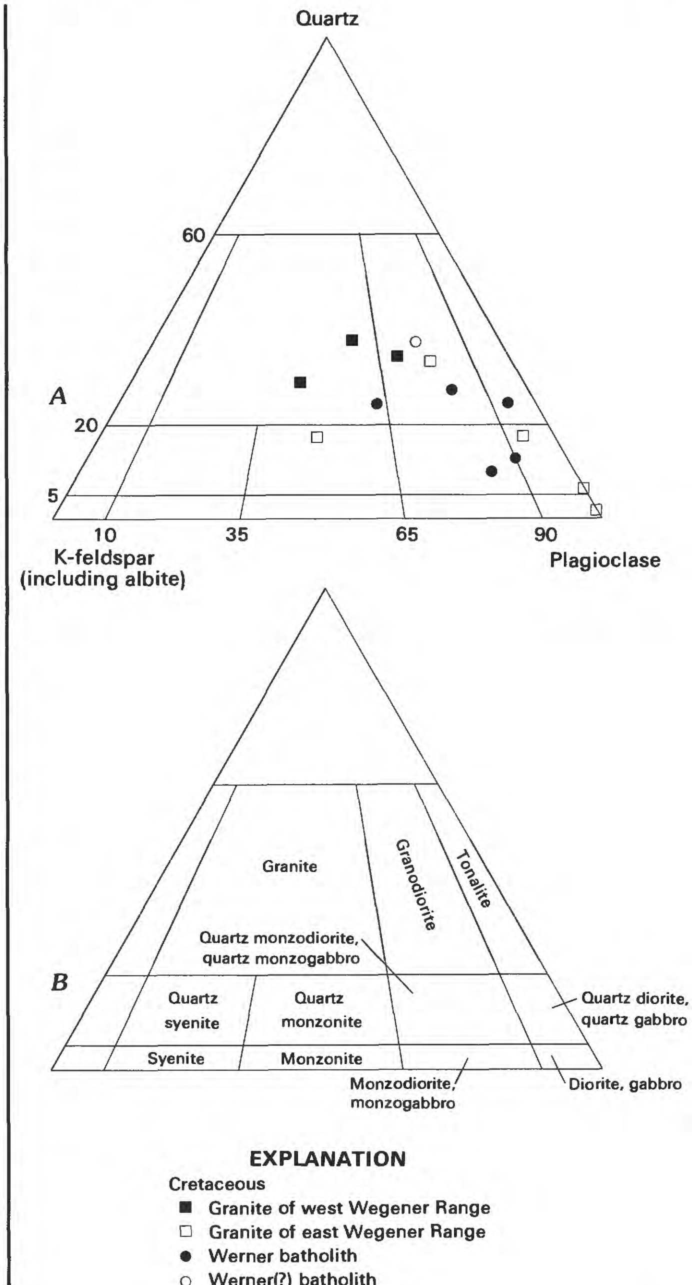

FIGURE 4.—*A*, Ternary plot of modal quartz, K-feldspar, and plagioclase in igneous rocks, southern Black Coast, Antarctica. Calculated from data in table 1. *B*, Igneous classification used, from International Union of Geological Sciences (Streckeisen, 1976).

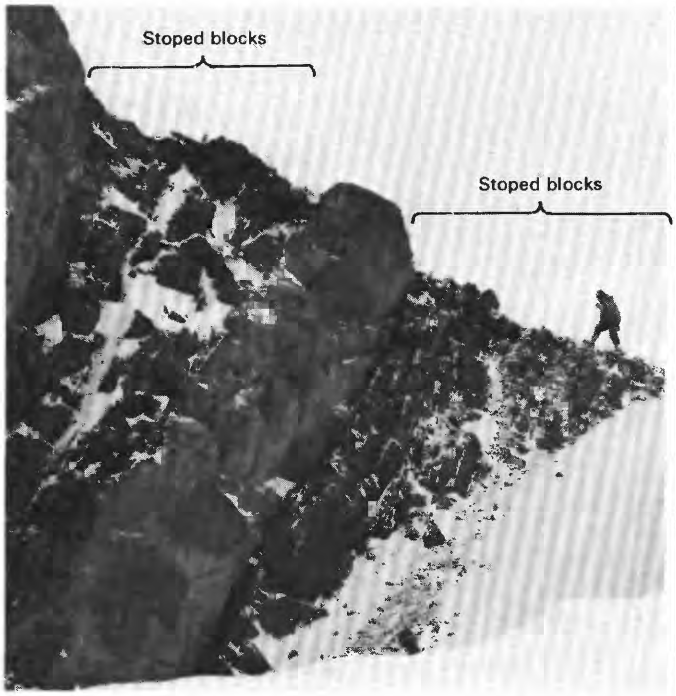

FIGURE 5.—Two stoped-block masses (topographically lower areas, on one of which the man is standing) within plutonic rock just inside the contact of the west Wegener Range batholith. Outcrop Wa47, Wegener Range, Antarctica.

In thin section (table 1), both the main silicic part (Ro322a, V85) and the mafic border facies (V86a) of the west Wegener Range batholith have hypidiomorphic-granular textures. As is typical for other plutons in the Antarctic Peninsula, plagioclase in the west Wegener Range batholith is normally zoned; most crystals are calcic oligoclase to sodic andesine, but rims may be as sodic as sodic oligoclase. K-feldspar lacks grid twinning and is poikilitic—petrographic features that are typical of plutonic rocks in the southern Antarctic Peninsula. Sphene is a common accessory mineral here and in many other plutonic rocks of the southern Antarctic Peninsula.

Chemical analyses and CIPW norms (table 2) show that the west Wegener Range batholith and other plutons in the southern Black Coast are similar to other Mesozoic and Cenozoic plutons in the southern Antarctic Peninsula (Laudon and others, 1969; Williams and others, 1972; Laudon, 1972, 1982; Rowley and others, 1977; Vennum, 1978; Rowley and Williams, 1982) and in the northern Antarctic Peninsula (Adie, 1955; Saunders and others, 1980, 1982). Major-element oxide trends for plutons in the southern Black Coast (table 2), as elsewhere in the peninsula, define typical differentiated calc-alkaline magma bodies: with progressively higher SiO_2 in the rocks, CaO, MgO, and total iron oxides are progressively lower; whereas, K_2O, and in some cases Na_2O, are progressively higher. Alumina values are variable but generally are progressively lower with progressively higher silica. Cobalt exceeds nickel in most rocks of the southern Black Coast (table 1), as in rocks elsewhere in the peninsula (Adie, 1955; Vennum, 1978; Laudon, 1982; Vennum and Laudon, 1983). Ternary plots of selected oxides and normative minerals (fig. 6) show some differences between trends for the west Wegener Range batholith (table 2), the east Wegener Range batholith (table 2), and northern and central Werner batholith (table 2; Vennum, 1978; unpub. data, 1981).

Trace elements show systematic variations in plutons of the southern Black Coast. Rocks containing higher SiO_2 contain lower values of TiO_2, Co, Cu, Mn, Sc, Sr, V, and Zn, but higher values of Ba and Pb. The alkali-lime index of the plutons in the southern Black Coast is 63, somewhat higher than the average (61) for all plutons in the Lassiter Coast and southern Black Coast (Rowley and Williams, 1982).

EAST WEGENER RANGE BATHOLITH

The east Wegener Range batholith is at least 24 km in long dimension. The main part of the pluton is composed of pink and light-gray, coarse to very coarse grained granite, but near the contact this facies grades abruptly into a thin, light- to dark-gray and pink, fine- to medium-grained, locally foliated, chilled border facies of granodiorite, tonalite, and diorite. Both facies are locally porphyritic; in the main facies, poikilitic phenocrysts of K-feldspar attain lengths of 5 cm. As shown at outcrop Ro319 (fig. 7), the more silicic main part of the pluton (thin section Ro319c; table 1) locally intrudes and incorporates masses of the more mafic border facies (thin section Ro319a; table 1). Thus, at least in places, the mafic border facies is somewhat older than the main facies. Mafic inclusions as large as 15 cm are sparse in the pluton, but pegmatitic, aplitic, and mafic dikes are common.

A few thin sections (table 1; fig. 5), mostly of the border-facies rocks (Ro319a, V84b, V84c), suggest that the east Wegener Range batholith is petrologically similar to the west Wegener Range batholith. The most common minerals are (1) normally zoned plagioclase and (2) porphyritic to poikilitic K-feldspar that lacks grid twinning and is locally perthitic. The texture is hypidiomorphic-granular. In the silicic part, plagioclase is calcic oligoclase; in the border facies it ranges from calcic oligoclase to calcic andesine. As in other plutons in the southern Black Coast, plagioclase rims may have about 10 percent less anorthite than cores.

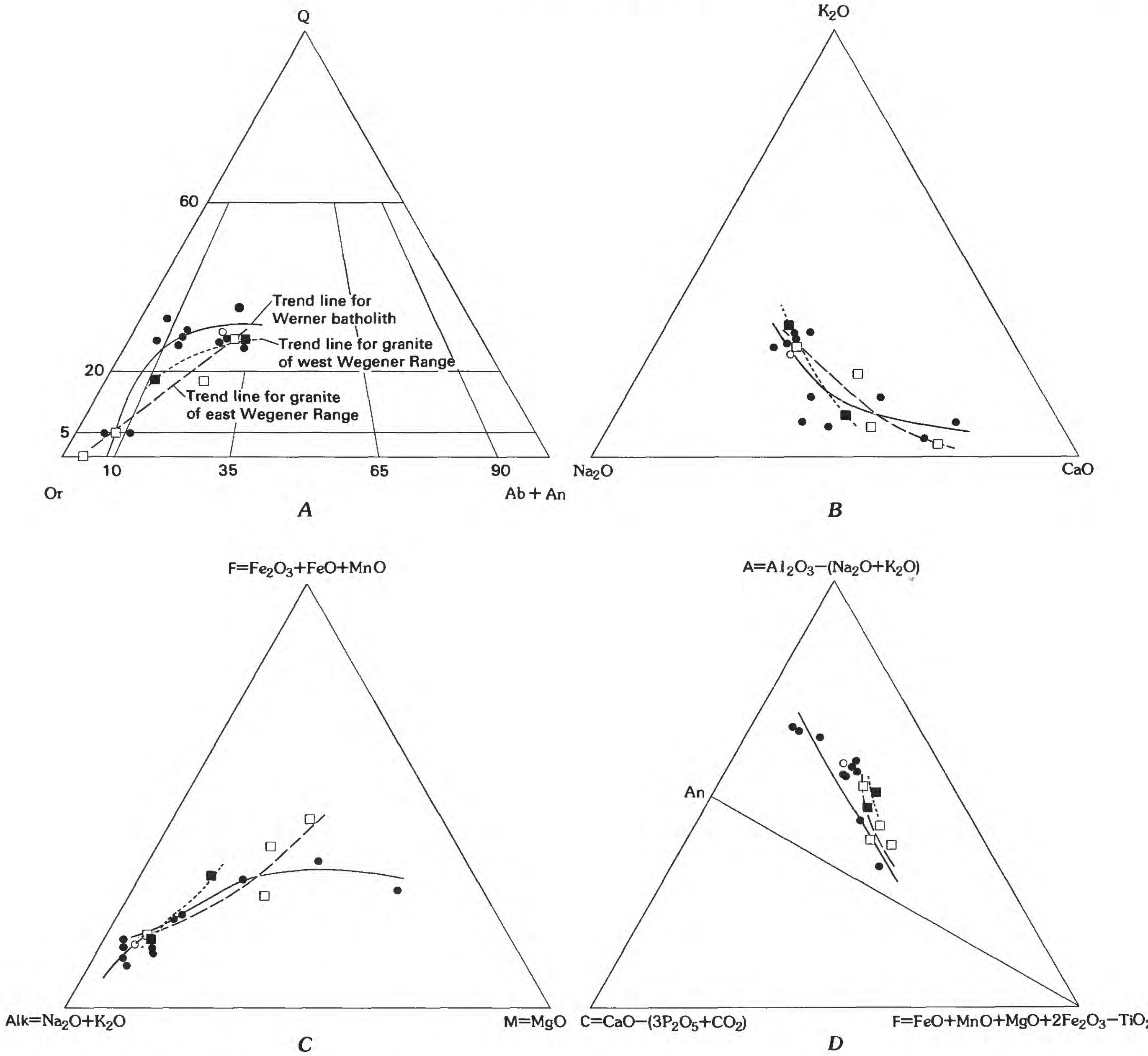

FIGURE 6.—Ternary plots of selected oxides and normative minerals from plutonic rocks of the southern Black Coast and northern Lassiter Coast, Antarctica. Data are from table 2, Vennum (1978, table 4), and unpublished analyses. Explanation of rock units is the same as that of figure 4. *A*, Normative quartz, orthoclase, and plagioclase (weight percent). Boundaries are from igneous classification defined in figure 4*B*. *B*, Na_2O-K_2O-CaO (weight percent), *C*, A-F-M (weight percent), *D*, A-C-F (weight percent).

The rocks of the east Wegener Range batholith are chemically similar to those of the west Wegener Range batholith (table 2; fig. 6). Rocks that are progressively higher in SiO_2 are progressively lower in TiO_2, Cu, Mn, Sr, V, Zn, and perhaps Co, but they are progressively higher in Ba, Pb, Y, and perhaps Zr. The alkali-lime index of the east Wegener Range batholith is about 64.

WERNER BATHOLITH

The Werner batholith is the largest known pluton in the southern Antarctic Peninsula; it is exposed over a north-south length of more than 140 km (Vennum, 1978; Rowley and Williams, 1982). At the northern end of the batholith in the western Carey Range and northern Dana Mountains, it is at least 24 km wide (east-west),

FIGURE 7.—Lighter colored main-facies granite containing dark masses of border-facies granodiorite. Outcrop Ro319, Wegener Range, Antarctica. Compass for scale.

and it is 40 km wide if the plutonic rocks in the eastern Carey Range are included. Field relations and K-Ar ages (Farrar and others, 1982) indicate that the batholith is composite: it contains a mafic border facies dated at about 115 m.y. and a main silicic part dated as young as 100 m.y. The 103 m.y. age of the previously mentioned sample (Bo68a) from the western Carey Range is one of several samples dated from the main silicic part. The central part of the batholith, south of the mapped area of figure 1, contains extensive roof pendants and shows evidence of plutonic assimilation (Vennum, 1978; Vennum and Meyer, 1979).

In the western Carey Range and northern Dana Mountains, the batholith consists of a main part of light-gray and pink, medium- to coarse-grained granodiorite and subordinate tonalite and granite. This main part grades into a thin (generally less than 100 m), chilled border facies of light- to dark-gray, fine- to medium-grained tonalite and diorite (fig. 4). Near the northern contact (V80), pendants as long as 100 m of fine- to medium-grained diorite (thin section V80c; table 1) occur within granodiorite. The contacts between the older diorite blocks and the younger granodiorite are sharp to gradational. Similar features occur in the central Werner batholith (Vennum, 1978); in both places the relations indicate forcible intrusion of the main facies rocks into partly consolidated, slightly older border-facies rocks. Small mafic inclusions are abundant at outcrop V80, but elsewhere they are sparse and smaller than 20 cm. Pegmatite and aplite bodies and slightly younger mafic dikes (thin section Ka317) occur in many places.

The plutonic rocks in the eastern Carey Range are lithologically similar to those in the western Carey Range and northern Dana Mountains. In the eastern Carey Range, they consist of light-gray and pink, medium- to coarse-grained granodiorite and—near the contacts of the pluton—a thin border facies of light- to medium-gray, fine- to medium-grained tonalite and diorite. Mafic inclusions, as long as 30 cm, are uncommon. Pegmatite, aplite, and mafic dikes (thin section Ro315d) are common.

Thin sections (table 1) of rocks from the main silicic part (Bo68a, Ro275a, Ro312b, Ro313a, Wa38b; table 1) and from a small block of mafic border-facies rock (V80c) from the northern Dana Mountains and western Carey Range reveal a hypidiomorphic-granular texture consisting in large part of normally zoned plagioclase and poikilitic K-feldspar. Plagioclase compositions range from calcic oligoclase to sodic andesine; rims of zoned crystals are as sodic as calcic oligoclase. K-feldspar in some rocks (Ro275a, Ro312b, V83; table 1) is locally grid twinned, the only known occurrence of this petrographic feature in the southern Antarctic Peninsula. Grid-twinned K-feldspar also occurs in the largest pluton in the central Black Coast, a granodiorite (Singleton, 1980a).

The rocks of the northern (table 2) and central (Vennum, 1978; P. D. Rowley, unpub. data, 1981) Werner batholith are petrologically and chemically similar to the plutons in the Wegener Range, but trend lines on ternary plots are somewhat different (fig. 6). Rocks from the northern part of the Werner batholith containing progressively greater SiO_2 are progressively lower in TiO_2, Co, Cu, Mn, Ni, Sc, V, and Zn but are progressively higher in Ba and Pb. Vennum (1978) noted similar relations for the central Werner batholith. The alkali-lime index of the northern and central Werner batholith is about 66, somewhat lower than the value of 69 for the central Werner batholith alone (Vennum, 1978) but well above the average (61) for plutons in the Lassiter Coast (Rowley and Williams, 1982).

One thin section (V83; table 1) examined from plutonic rocks in the eastern Carey Range is like those in the western Carey Range and northern Dana Mountains except for an absense of grid twinning in K-feldspar crystals. Chemical analyses (table 2) of rocks from the eastern Carey Range, western Carey Range, and northern Dana Mountains are similar, which further suggests that the plutonic rocks in the eastern Carey Range belong to the Werner batholith. These rocks also are chemically similar to those from the central Werner batholith (Vennum, 1978, table 4).

STRUCTURAL GEOLOGY

The Latady Formation and Mount Poster Formation were tightly folded along north- to north-northeast-trending axes prior to plutonism of the Lassiter Coast Intrusive Suite. Folds range from open to isoclinal, but most are asymmetrical or overturned. Wavelengths of folds range from less than a centimeter to about a kilometer; most are betweeen 100 and 300 m. Well-developed axial-plane cleavage formed during folding. Cleavage and axial planes of most folds dip west-northwest. Fold axes are horizontal to gently plunging. Some fold axes plunge steeply within 0.5 km of intrusive contacts where regional folds have been refolded during forcible intrusion of plutons.

Thrust faults, strike-slip faults, and high-angle dip-slip faults, such as occur in the Orville Coast and eastern Ellsworth Land (Kellogg, 1979), were not recognized in the southern Black Coast. They may be present in the Black Coast, but if so, they are covered by ice or are obscured by the greater metamorphism and the poorer exposures.

PLATE-TECTONIC SETTING

The rocks now exposed in the southern Black Coast were deposited and deformed during almost continuous southeastward subduction of the southern Pacific plate under the area of the present Antarctic Peninsula (Dalziel and Elliot, 1973; Herron and Tucholke, 1976; Craddock and Hollister, 1976; Rowley and Williams, 1982; Rowley, Vennum, and others, 1983; Rowley, 1983). The subduction probably varied in speed, geometry, and perhaps direction so that different rocks and structures were produced at different times (for example, Cross and Pilger, 1982). Discussion of the essential details of the plate-tectonic setting of the Antarctic Peninsula and Scotia arc was given first by I. W. D. Dalziel and D. H. Elliot in their 1973 publication and in subsequent papers with coworkers. Suárez (1976) and Smellie (1981) borrowed from their ideas and published useful summaries of magmatic arcs in the Antarctic Peninsula of, respectively, Middle Jurassic to Early Cretaceous age and pre-Early Jurassic age.

Information on rocks that underlie those of the Black Coast is sketchy and is based on sparse exposures in the central Black Coast (Singleton, 1980a) and farther north. From these exposures, it appears possible that a middle-crustal, high-grade, schist-and-gneiss complex underlies the Latady Formation. The complex may represent pre-Jurassic continental lithosphere, or it may represent the root zone of a deeply eroded pre-Jurassic magmatic arc (Dalziel, 1975; Smellie and Clarkson, 1975; de Wit, 1977; Smellie, 1981; Dalziel and others, 1981; Dalziel, 1982). Sedimentary rocks of the Trinity Peninsula Formation and related units, apparently all of mostly Triassic age (Thomson, 1975a, b, 1982; Edwards, 1982), have been attributed to an outer-arc basin adjacent to a magmatic arc (Barker and others, 1976) that was either roughly axial to (Dalziel and others, 1981), or on the eastern flank of (Smellie, 1981), what is now the Antarctic Peninsula. The arc resulted from subduction of the Pacific lithosphere under the area of the present Antarctic Peninsula. On the basis of sparse information (Barker and others, 1976; Smellie, 1981) on the petrologic maturity of the igneous rocks (that is, how evolved they are; Hamilton, 1981) of the magmatic arc, the arc may have formed on continental lithosphere. The arc was deformed during the Late Triassic to Early Jurassic Gondwanide deformation, which coincided with a minor intrusive suite of calc-alkaline plutons (Rex, 1976); on the basis of $^{87}Sr/^{86}Sr$ ratios and petrologic maturity of the rocks (Pankhurst, 1982), we conclude that continental lithosphere was present at least by this time in the Antarctic Peninsula area.

The tectonic setting of the oldest exposed rocks in the Black Coast is that of a Middle and Upper Jurassic continental-margin magmatic arc (Hamilton, 1981), whose axis was near or west of the topographic axis of the southern Antarctic Peninsula (Suárez, 1976). The Mount Poster Formation was extruded during calc-alkaline igneous activity above the subduction zone; corresponding plutons, however, have not been identified. The petrologic maturity, including the silicic nature of many of the volcanic rocks, of the arc indicates that continental lithosphere underlay the arc. The eastern shoreline of the arc trended parallel to the long axis of the present peninsula and through its eastern flank. A back-arc marine basin formed east of the arc, on the craton side, during subduction. The Latady Formation was deposited in large part in this basin but in part also on the eastern flank of the arc, where continental sedimentary rocks intertongue with mostly subaerially deposited volcanic rocks.

The Jurassic rocks were folded during continuing east to southeastward subduction. North-northwest-dipping axial planes and cleavage (that is, structures showing east-southeast vergence) indicate that the rocks yielded toward the east-southeast. East-southeast thrusting accompanied folding in the Orville Coast (Kellogg, 1979; Rowley, Vennum, and others, 1983), but the rocks in the Black Coast are too poorly exposed to prove thrusting. This episode of crustal shortening of Late Jurassic to Early Cretaceous age may be due to east-southeastward gravitational spreading in response either to isostatic uplift caused by crustal thickening during subduction or to uplift and shouldering aside by emplacement of the underlying batholith that was the source of the Mount Poster Formation. Alternatively, the crustal shortening may be due to collision of the present area of the southern Antarctic Peninsula and eastern Ellsworth Land with the craton of West Gondwanaland, or it may be due to either an increase in motion of the converging plates or a decrease in the angle of the subduction zone.

Development of the Middle and Upper Jurassic magmatic arc mostly preceded the start of the opening of the South Atlantic Ocean in Early Cretaceous time (Sclater and others, 1977). The continent was faulted near the western edge of the continent of Gondwanaland, thereby leaving a sliver of continental lithosphere that now deeply underlies the Antarctic Peninsula. At about this time, activity along the arc or a separate younger overlapping magmatic arc developed on continental lithosphere during Early Cretaceous plutonism of the Lassiter Coast Intrusive Suite. This magmatic pulse apparently occurred between 130 and 95 m.y. ago according to the available isotopic ages. Calc-alkaline plutons are the sole evidence for this Lower Cretaceous magmatic arc, for no corresponding volcanic ejecta have been identified in the southern Antarctic Peninsula. The trend of the axis of the Cretaceous arc, as for the older arc, appears to follow the trend of the present Antarctic Peninsula, but the location of the axis in the Black Coast area is uncertain because east-west differences in volume of plutonic rocks have not been identified. Either the arc was broader than the Jurassic arc or the axis of the Lower Cretaceous arc was farther east, because Cretaceous plutons occur well east of known concentrations of the Jurassic Mount Poster Formation. In the Orville Coast (Rowley, Vennum, and others, 1983), most plutons occur on the southeastern flank of the peninsula, southeast of the main part of the Mount Poster Formation but inland from the coastline itself, so here the margins of the magmatic arc can be inferred; the axis here seems to be east of the apparent axis of the Jurassic arc.

Subduction of Pacific oceanic lithosphere beneath West Antarctica ceased in Late Cretaceous time in Marie Byrd Land and western Ellsworth Land (LeMasurier and Wade, 1976; LeMasurier and Rex, 1982) and in Tertiary time in the northern and central Antarctic Peninsula (Herron and Tucholke, 1976). A new tectonic regime involving extensional block faulting and alkalic volcanism began no later than early Tertiary time in Marie Byrd Land and western Ellsworth Land (LeMasurier and Wade, 1976; LeMasurier and Rex, 1982). A small volume of 6-m.y.-old lava flows and breccia of alkalic basalt (basanite) in eastern Ellsworth Land (Laudon and others, 1969; Laudon, 1972; chap. B, this volume) and the English Coast (O'Neill and Thomson, 1985) reflects a late stage of this regime. Fault-block topography also extended as far east as eastern Ellsworth Land, as indicated here by seismic-reflection and gravity data (Behrendt, 1964) that reveal rough subice topography, including valleys nearly 2,000 m below sea level (Laudon, 1982). A small intrusive mass of olivine basalt in the Seward Mountains (Singleton, 1980c) and the dike at outcrop Ro321 within the west Wegener Range batholith are the only evidence that the extensional regime may have exerted an influence in the Black Coast area.

ALTERED AND MINERALIZED ROCKS

Small parts of plutonic rocks and dike rocks have been hydrothermally altered and mineralized in the southern Black Coast. Analytical data and a summary of localities containing metallic minerals are given by Rowley and others (1977); some localities are shown by the British Antarctic Survey (1982). No occurrences in the southern Black Coast appear to contain metal concentrations of economic significance.

Most altered or mineralized rocks are in the Carey Range, where at several places we found sheared phyllic-argillic zones similar to those of the Lassiter Coast copper deposit (Rowley and others, 1977) of the Copper Nunataks. Similar zones and associated evidence of low-grade copper mineralization also occur in stocks in the SkyHi Nunataks and Merrick Mountains of eastern Ellsworth Land (Rowley, 1978, 1979; Rowley and Pride, 1982; chap. C, this volume; Rowley, Williams, and Pride, 1983; Rowley, Ford, and others, 1983). All these mineralized sites are interpreted to be the roots of porphyry-type mineral deposits. In the Lassiter Coast copper deposit, hydrothermally altered phyllic and argillic rocks occur in subvertical, closely spaced, subparallel, linear sheared zones, each of which is less than 20 m wide. The intensely altered rocks are softer than adjacent propylitic grade rocks and thus weather into trenches that are locally filled with snow and ice. The shear zones in the southern Black Coast are similar to those in the Lassiter Coast copper deposit, but they are less than 5 m wide and underlie smaller areas (generally less than 30 m wide). The shear zones of the Lassiter Coast copper deposit strike west-northwest to north-northwest, the extension direction that persisted during and since folding (folds axes trend northeast). The shear zones in the Carey Range trend west to west-northwest, the extension direction in that area, where folds trend almost north. Sparsely mineralized rocks of the Lassiter Coast copper deposit generally are in altered rocks adjacent to the shear zone rather than within the zones. In the Carey Range, the shear zones and their adjacent altered rocks are barren of megascopic metallic minerals other than pyrite and, locally, chalcopyrite, both of which are mostly oxidized. Semiquantitative spectroscopic analyses of altered rocks of the Lassiter Coast copper deposit (Rowley and others, 1977) show only low to moderate (40–100 ppm (parts per million)) metal contents, as do those at localities Bo68 (Pb), Bo71 (Cu, Zn), Ka316 (Cu, Zn), Ro313 (Cu, Pb, Zn), and Wa37 (Cu) in the southern Black Coast (Rowley and others, 1977).

The only other types of hydrothermally altered and sparsely mineralized rocks in the southern Black Coast are at plutonic contacts. In the northern Carey Range (locality Ro315), quartz veins contain pyrite, chalcopyrite, and oxidized sulfides; semiquantitative spectroscopic analyses of two of the veins revealed copper contents of 70–100 ppm, molybdenum contents of as much as 300 ppm, and zinc contents of as much as 70 ppm. Rocks at the contact of the east Wegener Range batholith (locality Ke80) are locally altered and stained by oxidized iron sulfide.

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Igneous Petrology of the Merrick Mountains, Eastern Ellsworth Land, Antarctica

By WALTER R. VENNUM *and* THOMAS S. LAUDON

STUDIES OF THE GEOLOGY AND MINERAL RESOURCES OF THE SOUTHERN ANTARCTIC PENINSULA AND EASTERN ELLSWORTH LAND, ANTARCTICA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1351-B

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Petrology of Lower Cretaceous plutonic rocks and related dikes as well as Tertiary basanite lava flows

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IGNEOUS PETROLOGY OF THE MERRICK MOUNTAINS, EASTERN ELLSWORTH LAND, ANTARCTICA

By WALTER R. VENNUM[1] and THOMAS S. LAUDON[2]

ABSTRACT

A Lower Cretaceous composite stock of mafic to felsic composition, at least 10 km in largest exposed diameter, crops out in the Merrick Mountains of West Antarctica. This pluton, here named the Merrick Mountains stock and belonging to the Lassiter Coast Intrusive Suite, intrudes a folded Middle to Upper Jurassic sequence of clastic marine sedimentary rocks known as the Latady Formation and interbedded lava flows of intermediate to felsic composition. The pluton consists of two facies: (1) an older mafic quartz diorite that forms a thin (100–200-m-wide) border facies of the stock; and (2) a younger felsic quartz diorite that comprises the bulk of the stock and intrudes the older quartz diorite. The younger felsic quartz diorite appears to grade inward into quartz monzodiorite and locally into granodiorite. Dikes of diverse composition, ranging from olivine-rich wehrlite to rhyodacite porphyry, were emplaced after both the older and younger plutonic events. Quartz veins and numerous aplite, alaskite, and pegmatite dikes of uncertain age intrude both facies of the stock. Igneous activity recurred in Miocene(?) time when a basanite lava flow and associated hyaloclastite were deposited in the southwestern Merrick Mountains. These volcanic rocks appear to represent a subglacial eruption.

INTRODUCTION

The Merrick Mountains were discovered in 1935 by Lincoln Ellsworth and Herbert Kenyon during the first Antarctic transcontinental flight (Ellsworth, 1936). Trimetrogon aerial photographs of the range were taken in 1947 by the Ronne Antarctic Research Expedition (Ronne, 1949) and in 1965 and 1966 by the U.S. Navy. The Ellsworth Land oversnow traverse (Antarctic Peninsula Traverse) passed just north and southeast of the Merrick Mountains during the 1961–62 austral summer. Although brief stops were made to collect bedrock samples at nine nearby nunataks, the Merrick Mountains were not entered at this time (Behrendt and Parks, 1962). Geological mapping of the Merricks and several other adjacent ranges and nunataks (figs. 1, 2) was conducted in November and December of 1965 by a University of Wisconsin field party led by the junior author (Laudon and others, 1969; Laudon, 1972). At this time the pluton described in this report, the Merrick Mountains stock, was discovered and mapped. During the 1977–78 field season, a U.S. Geological Survey field party completed reconnaissance geological mapping of the Merrick Mountains (Rowley, 1978; Thomson and others, 1978).

Numerous geologists have reported hybrid plutonic rocks (summary in Vennum, 1978) and low grade sulphide mineralized rocks (Rowley and Pride, 1982) in more northerly portions of the Antarctic Peninsula. Therefore, reports of hybrid plutonic rocks and abundant occurrences of copper efflorescences and copper and iron sulphides in the Merrick Mountains (Laudon and others, 1969) aroused our interest in this range. Consequently, several days in late January 1978, were devoted to detailed mapping in the Merrick Mountains. The composite nature of the stock proved to be noteworthy for the southern Antarctic Peninsula, and the mineralized rocks were found to be similar to, although lower in grade than, the noneconomic porphyry-type copper deposit which crops out in the Copper Nunataks (fig. 1) of the Lassiter Coast (Rowley and others, 1975, 1977). This report summarizes field data on the igneous petrology of the Merrick Mountains resulting from approximately 35 man-days of work and draws heavily on the field notes and reports of the 11 men privileged to have worked in this small, remote, yet highly interesting range of mountains just 1,500 km from the South Pole. The metallic minerals of the Merrick Mountains stock are discussed in chapter C (this report).

Outcrop numbers given in the text refer to rock nunataks or parts of nunataks that were studied. Each outcrop may have rock types of differing lithology or origin. When rocks were sampled they were assigned the same whole number as the outcrop; letters and even subscripts appended to the outcrop number refer to individual samples.

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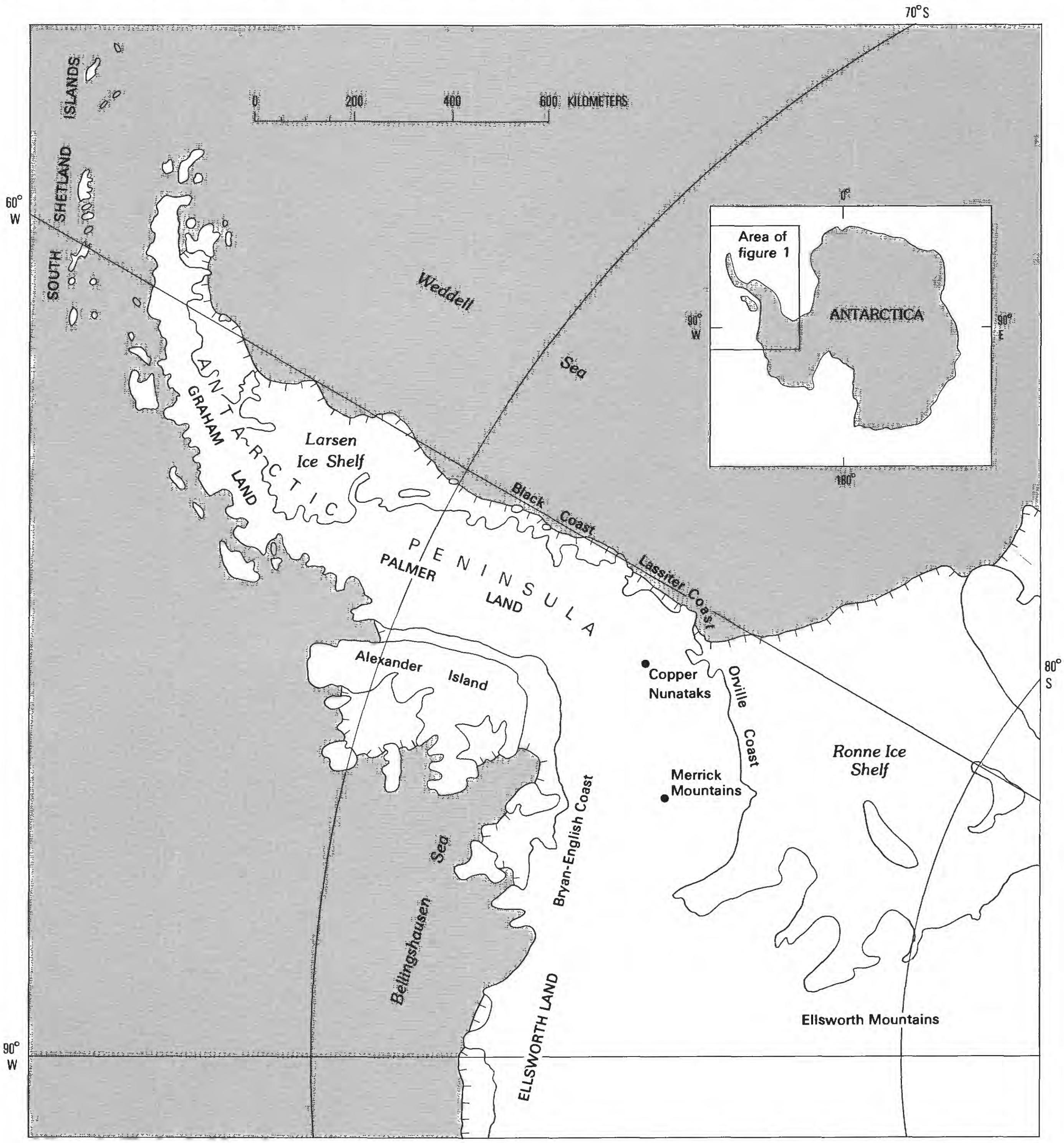

FIGURE 1.—West Antarctica showing location of the Merrick Mountains. Modified from Rowley, Williams, and Pride (1983), using the suggestions of Swithinbank and others (1976). Hachures indicate edge of shelf ice.

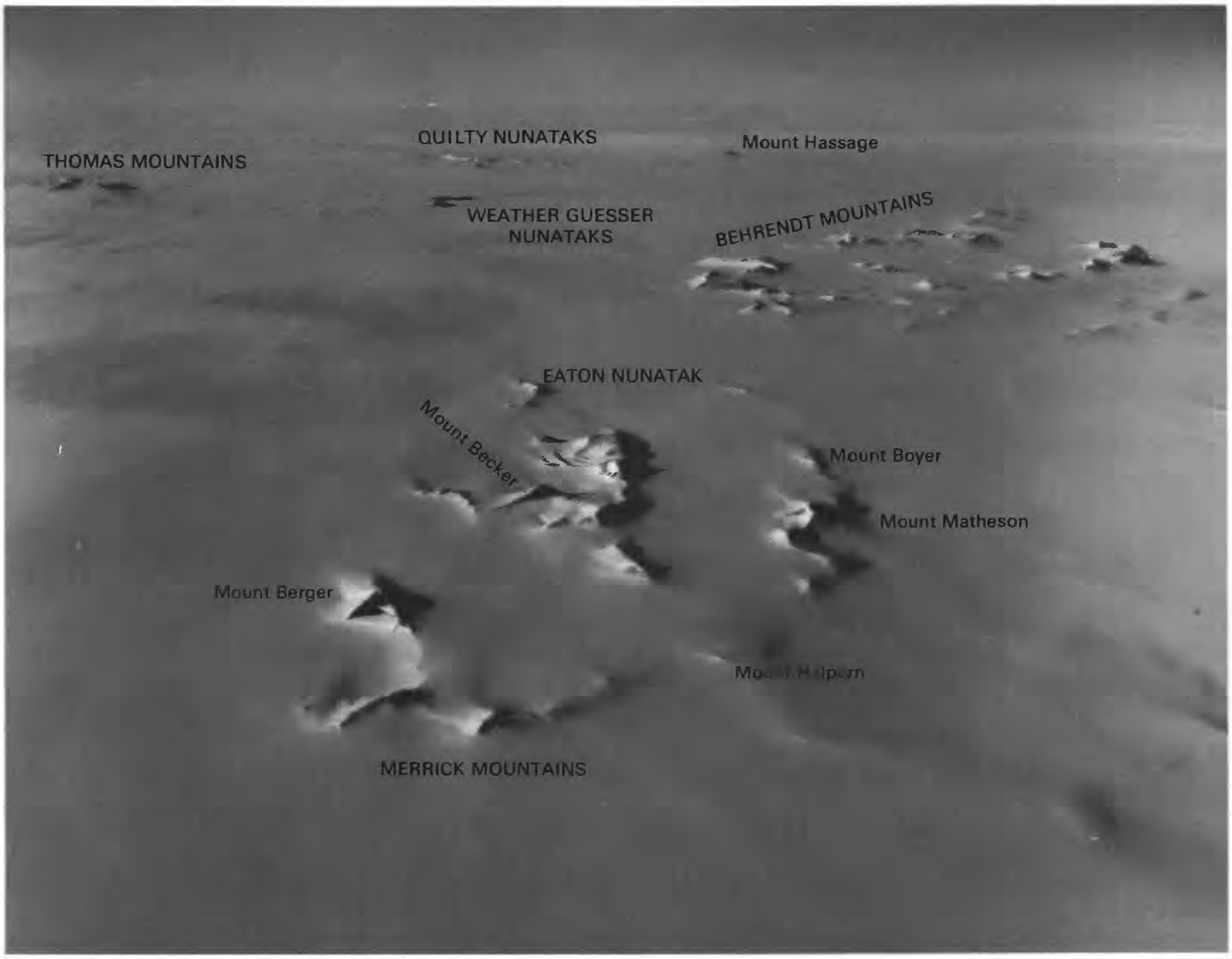

FIGURE 2.—Physiographic setting of the Merrick Mountains. U.S. Navy high altitude oblique aerial photograph TMA 1645 135 F33. View looking south from 7600 m, February 1965.

ACKNOWLEDGMENTS

We thank the other members of the 1965–66 field party (L. L. Lackey, P. G. Quilty, P. M. Otway, and P. J. Wasilewski) and the 1977–78 field party (J. M. Boyles, P. E. Carrara, K. S. Kellogg, P. D. Rowley, and M. R. A. Thomson) for their help with the fieldwork and for the use of their field notes and reports. P. D. Rowley did some of the modal analyses. This study was financed by National Science Foundation grants DPP76-12557 and DPP78-24214. Logistical support was provided by the U.S. Antarctic Research Program of the National Science Foundation and by U.S. Navy squadron VXE-6. A previous version of this report was reviewed by P. D. Rowley and J. M. O'Neill; these reviews greatly improved the manuscript.

GEOLOGIC SETTING

The oldest exposed rock unit in the Merrick Mountains, as in most other parts of the southern Antarctic Peninsula, is a thick sequence of Middle to Upper Jurassic clastic marine sediments named the Latady

Formation after exposures in the northern Latady Mountains of the southern Lassiter Coast (Williams and others, 1972). The formation is composed of black to gray slate, siltstone, subordinate sandstone that contains abundant volcaniclastic detritus, and minor lenses of coal, conglomerate, and limestone. Plant and invertebrate fossils are locally abundant. Most of the clastic material appears to have been deposited in a temperate nearshore enviroment. Structural complexity, metamorphism, and lack of continuous exposures and of mappable key beds negate the possibility of accurately estimating a total thickness; the sequence does, however, appear to be several thousand meters thick (Rowley, 1978; Thomson and others, 1978; Rowley and Williams, 1982).

Silicic calc-alkaline ash-flow tuff, andesitic to dacitic lava flows, and minor amounts of airfall tuff intertongue with and may in part overlie the Latady Formation. On the basis of age and lithology, these volcanic rocks are correlated with the Middle and Upper Jurassic Mount Poster Formation, named for exposures at Mount Poster, in the western Lassiter Coast (Rowley, Schmidt, and Williams, 1982). The Mount Poster Formation is part of the Antarctic Peninsula Volcanic Group (Thomson, 1982), which is exposed throughout the Antarctic Peninsula; the Mount Poster Formation is the only formation of the Antarctic Peninsula Volcanic Group in this area.

The Latady and Mount Poster Formations were folded about west-northwest-to east-northeast-trending axes that roughly parallel the trend of the Antarctic Peninsula. Lower Cretaceous stocks, batholiths, and associated mafic to intermediate dikes (Farrar and others, 1982) intruded these rocks. The stratigraphic unit to which all known plutons in the southern Antarctic Peninsula belong is termed (Rowley, Vennum, and others, 1983) the Lassiter Coast Intrusive Suite of Early Cretaceous (130–95 m.y. (million years)) age. The plutonic rocks range in composition from gabbro to granite; granite, granodiorite, and tonalite are the most common rock types. Field relations, petrography, and chemical analyses (Laudon and others, 1969; Laudon, 1972, 1982; Rowley and Williams, 1974, 1982) indicate that the plutonic rocks are similar to Mesozoic and Cenozoic calc-alkaline intrusive rocks exposed extensively throughout the Antarctic Peninsula and the Chilean and Patagonian Andes (Adie, 1955).

Contact metamorphic aureoles extend 1–2 km outward from intrusive contacts and attain a hornblende-hornfels facies (Plummer, 1974). Scattered, local, porphyry-type copper and molybdenum mineralization, which are related to shear zones, was a late stage product of the igneous activity (Rowley and others, 1975, 1977; Rowley and Pride, 1982). A Miocene(?) olivine-basanite lava flow and associated hyaloclastite crop out at a single small nunatak in the southwestern Merrick Mountains; these rocks are lithologically similar to rocks of probable Tertiary age in the English Coast of northeastern Ellsworth Land (O'Neill and Thomson, 1985).

JURASSIC SEDIMENTARY AND VOLCANIC ROCKS

The Latady Formation crops out in the Merrick Mountains and is also exposed at several scattered nunataks both north and south of the main mass of the Merrick Mountains (fig. 3). The rocks consist of dark-gray to black carbonaceous slate and siltstone interbedded with fine- to medium-grained tan to gray sandstone. Axial-plane cleavage is locally strongly developed in the finer grained rocks, and the sandstone is laminated, bioturbated, and locally crossbedded in many places. An extensive fossil collection from Eaton Nunatak includes abundant tube worms (*Rotularia* sp.) and bivalves (mainly *Inoceramus* sp.), but the assemblage also contains belemnites, plant fragments, and rarely, some ammonites. Fossils collected from other Latady Formation outcrops in the Orville Coast and eastern Ellsworth Land are Middle and Late Jurassic in age (Quilty, 1970, 1972; Thomson, 1980; Crame, 1981). Dark-gray plagioclase-porphyritic lava flows of intermediate to felsic composition are interbedded with Latady Formation at all nearby outcrops except in the Eaton Nunataks. These volcanic rocks correlate with the Mount Poster Formation of the Antarctic Peninsula Volcanic Group, and they comprise about 5 percent of the exposed section.

Contact-metamorphic effects produced in the Latady Formation by intrusion of the Merrick Mountains stock are similar to those described by Vennum (1978) and Plummer (1974) from contact aureoles in the northern and southern Lassiter Coasts, respectively. Most of the contact metamorphic rocks in the Merrick Mountains area are fine-grained subarkosic sandstone (Dott, 1964). In thin section these rocks are seen to contain various amounts of plagioclase (mainly oligoclase) and argillaceous material, minor amounts of slightly perthitic potassium feldspar, and sparse, opaque grains and subrounded zircons. Quartz makes up at least 80 percent of all samples examined.

Quartz in most places shows signs of recrystallization, and feldspar, especially plagioclase, is generally partly sericitized. The most commonly developed metamorphic groundmass minerals are sericite, pale-green, very weakly birefringent chlorite, red-brown biotite, and graphite dust. Porphyroblasts are not evident in any of the hand samples and are relatively small and uncommon in thin section. Numerous minute reddish-brown biotite grains locally occur in clots of 0.3–0.4 mm diameter. Andalusite

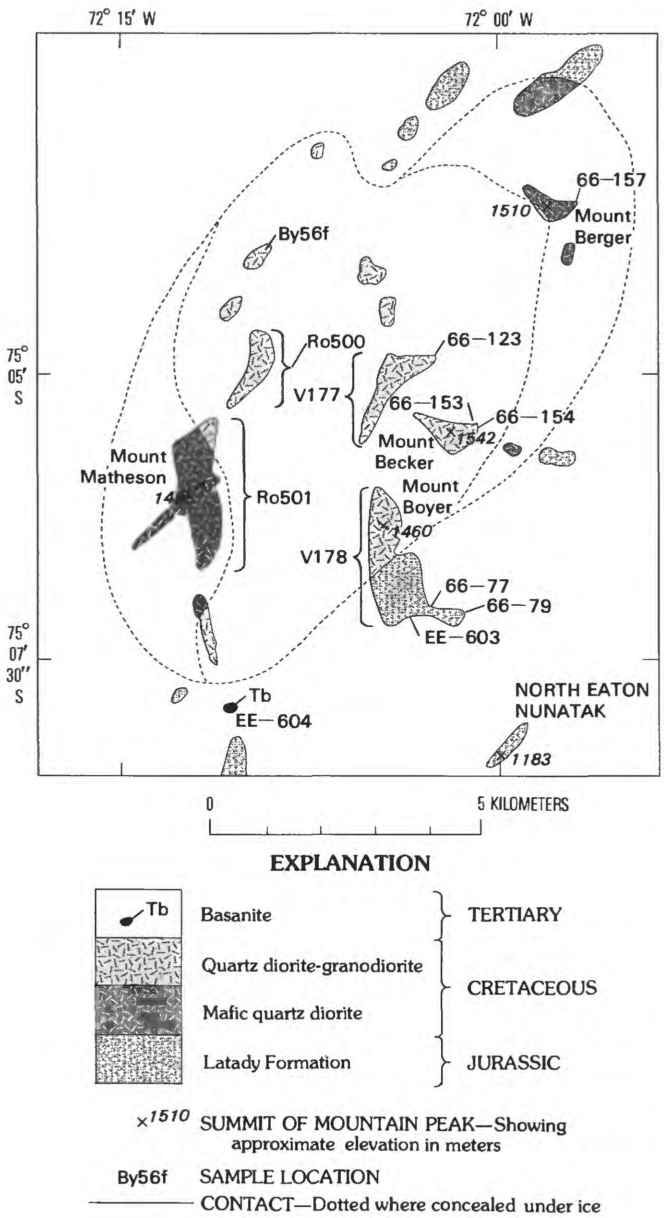

FIGURE 3.—Geologic map of the Merrick Mountains. Geology by J. M. Boyles, P. E. Carrara, K. S. Kellogg, L. L. Lackey, T. S. Laudon, P. M. Otway, P. G. Quilty, P. D. Rowley, M. R. A. Thomson, and W. R. Vennum. Outlines show nunataks and mountains that are surrounded by snow and ice.

is present both as anhedral to subhedral granules and as euhedral prismatic porphyroblasts 0.5 mm long. Minor cordierite locally occurs as spongy indistinct porphyroblasts 0.3–0.4 mm long and is crowded with sericite inclusions. Garnet, metamorphic hornblende, and tourmaline—which are present in other contact aureoles developed in the Latady Formation throughout the southern Antarctic Peninsula—are not present in metamorphic rocks of the Merrick Mountains. Although rare parallel lenses and streaks of graphite and sericite are present, the metamorphic minerals in most samples do not show preferred orientation, which indicates that their growth took place under static conditions. Retrograde effects include the development of epidote along biotite cleavage planes, thin rims of sericite on the euhedral andalusite porphyroblasts, and thin rims of hematite on magnetite. Contact metamorphism in the Merrick Mountains corresponds to Turner's (1968) hornblende-hornfels facies.

PLUTONIC ROCKS

The northern and northeastern two-thirds of the Merrick Mountains are underlain by a composite, concentrically-zoned(?) stock that is largely quartz diorite in composition, but which also includes quartz monzodiorite and, locally, granodiorite (fig. 3). Magnetometer surveys indicate that the snow-covered central portion of the Merrick Mountains is also underlain by plutonic rock (Laudon, 1982). The composite pluton, containing numerous lithologies, is here named the Merrick Mountains stock; it belongs to the Lassiter Coast Intrusive Suite. The pluton is best exposed at Mount Matheson, especially along a north-south ridge of almost continuous outcrop (fig. 3, outcrops Ro500, Ro501) extending from both flanks to the summit of the mountain. Here, the composite nature of the stock is best demonstrated, for much of the outcrop shows complex intrusive relations between a darker older plutonic facies and a lighter-colored younger plutonic facies. The northern part of the ridge is underlain mostly by the lighter plutonic facies; whereas, the southern part is underlain mostly by the darker plutonic facies. The major intrusive contact between the two is at the summit of Mount Matheson.

The older plutonic event of the Merrick Mountains stock formed a mafic border facies of irregular width (fig. 3). The main rock type is dark-gray to black, medium-grained (1–5 mm) quartz diorite (color index of 40–45). The border facies extends around the pluton margin from the southern slope of Mount Matheson clockwise to the northern slope of Mount Boyer. No outcrops of dark quartz diorite were seen along the southern and southeastern one-third of the intrusive contact with the Latady Formation (fig. 3). Outcrops in this area, however, are strongly frost shattered, and it is possible that dark quartz diorite is hidden beneath extensive talus accumulations of younger plutonic rocks.

Wherever exposed, the dark quartz diorite is intruded by light- to medium-gray, medium-grained quartz diorite (color index of 20–25) of the younger plutonic event, which makes up the bulk of the stock. Wherever the mafic border facies and the main interior facies of the stock are observed in contact with each other, irregular pods, veinlets, and dikes of light quartz diorite are intimately intermixed with dark quartz diorite. This zone of hybrid or mixed rock is as much as several hundred meters wide. Agmatitic contact breccia composed of angular inclusions of dark quartz diorite in light quartz diorite occur at Mount Matheson and at Mount Becker. Although outcrops are limited, the light quartz diorite appears to grade inward into quartz monzodiorite and locally into granodiorite. It is possible that the interior, snow-covered portions of the pluton are more felsic than the exposed rocks. Concentrically zoned plutons with mafic border facies similar to the Merrick Mountains stock have been reported at numerous other localities in the southern Antarctic Peninsula (Rowley and others, 1976, 1977; Vennum, 1978; Farrar and others, 1982; Rowley and Williams, 1982). Quartz veins and numerous aplite, alaskite, and pegmatite dikes intrude both the light and dark quartz diorite facies of the stock and were accompanied by shearing (crackling), hydrothermal alteration, and porphyry-type copper mineralization that are best exposed at Mount Matheson. Although the quartz veins and aplite, alaskite, and pegmatite dikes cut both facies of the pluton, field mapping rarely conclusively indicates whether any of these rocks were emplaced before the younger plutonic event. The mineralized rock is of noneconomic grade (chap. C, this report) and bears many similarities to that described by Rowley and others (1975, 1977) in the Copper Nunataks area of the Lassiter Coast.

Chemical and semiquantitative spectrographic analyses, CIPW norms, and modes of analyzed samples are listed in table 1. Modes of analyzed samples are also plotted in a ternary diagram (fig. 4), using the International Union of Geological Sciences (IUGS) classification of Streckeisen (1976). Sample locations are marked in figure 3. A biotite whole-rock Rb-Sr isochron obtained from biotite "diorite" collected at Mount Berger yielded a radiometric age of 107 m.y. (Halpern, 1967; age corrected for new decay constants of Steiger and Jäger, 1977), which is the age of the dark quartz diorite of the older plutonic event of the Merrick Mountains stock. The age is generally similar to the ages of other plutons dated in the southern Antarctic Peninsula and eastern Ellsworth Land. All these plutons have been assigned to the Lassiter Coast Intrusive Suite (Rowley, Vennum, and others, 1983).

In thin sections from the Merrick Mountains stock, plagioclase occurs in conspicuously zoned subhedral to euhedral tablets. Individual crystals in the dark quartz diorite range in composition from calcic labradorite to sodic andesine, those in the light quartz diorite and quartz monzodiorite range from sodic labradorite or calcic andesine to calcic oligoclase, and those in the granodiorite range from calcic andesine to sodic oligoclase.

Clinopyroxene ($2V_\alpha$ =55°, $z \wedge c$=41°, δ =0.025) is the most abundant mafic mineral in the dark quartz diorite and is present in lesser amounts in the light quartz diorite and quartz monzodiorite. In some places clinopyroxene forms poikilitic crystals that enclose plagioclase and, locally, biotite. Trace amounts of olivine, rimmed with hypersthene and clinopyroxene, occur in dark quartz dioritic rocks from the southern tip of Mount Matheson and from Mount Berger.

Euhedral and subhedral prisms of twinned hornblende ($2V_\alpha$ =70°, $z \wedge c$=16°, δ =0.020, z and y = olive brown, x = very pale yellow to colorless, $z = y > x$) occur in both the light and dark quartz diorite, but the prisms of hornblende are much more abundant in the more felsic rocks. In the dark quartz diorite this mineral is largely secondary after clinopyroxene, but in the more felsic rocks it is pyrogenetic in origin. The hornblende locally occurs as large (5–7 mm long) platelike crystals that poikolitically enclose groundmass grains. Biotite ($2V_\alpha$ =10°, z=y=red brown, x=straw yellow, z=y>x) is generally less abundant than hornblende, although the ratio of the amounts of these two minerals is variable.

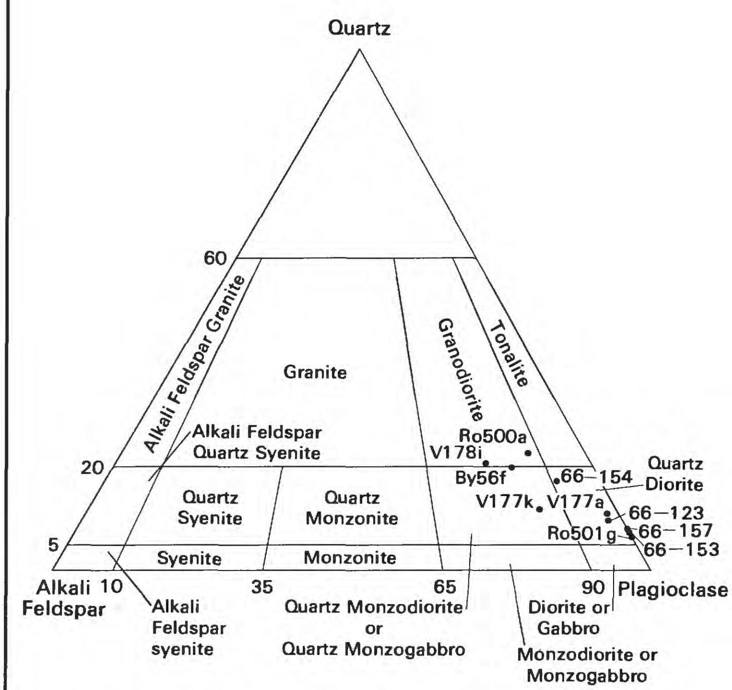

FIGURE 4.—Ternary plot of modal quartz, alkali feldspar, and plagioclase from chemically analyzed samples of plutonic rocks and one dike rock from the Merrick Mountains. Classification is from Streckeisen (1976). Calculated from data in table 1.

All mafic minerals tend to occur in clots, rather than distributed in a homogeneous fashion throughout the rock. Where present, quartz and potassium feldspar are generally interstitial. In the more felsic samples, however, potassium feldspar locally occurs as indistinct, slightly perthitic, poikilitic phenocrysts that have a maximum length of 10–15 mm. Accessory minerals in approximate order of abundance include opaques, apatite, sphene, and zircon.

ULTRAMAFIC, MAFIC, AND INTERMEDIATE DIKES

Virtually every outcrop of plutonic and sedimentary rock in the Merrick Mountains is cut by members of a mineralogically diverse series of dikes that are largely mafic in composition. The majority of these dikes appear to have been emplaced after the younger plutonic event; however, some were intruded after the older plutonic event, but prior to the intrusion of the light quartz diorite (younger event). For example, on the eastern ridge of Mount Boyer, a mafic dike that cuts Latady Formation is truncated by light-colored quartz diorite (Laudon, 1982).

Individual dikes are from a few centimeters to greater than 10 meters wide; some can be traced along strike for several hundred meters. Dikes of similar composition are associated with Lower Cretaceous plutonic rocks throughout the southern Antarctic Peninsula (Williams and others, 1972; Rowley and Williams, 1974, 1982; Laudon and others, 1969; Laudon, 1972; Rowley and others, 1977; Vennum, 1978). Farrar and others (1982) concluded that plutonism in the southern Antarctic Peninsula, including emplacement of most or all of the mafic dikes, occurred during a relatively short period of Early Cretaceous time. On the basis of field relations and chemistry of the dikes, we feel that this conclusion can be extended to eastern Ellsworth Land. Chemical and semiquantitative analyses and CIPW norms of analyzed samples are listed in table 1 and the normative mineralogy is plotted in figure 5.

Many of the dikes are porphyritic, but some are also equigranular and (or) aphanitic. Common phenocryst assemblages include clinopyroxene-plagioclase, hornblende-plagioclase, and plagioclase. Some of the hornblende-plagioclase porphyritic dikes contain scattered phenocrysts of biotite and partly resorbed "beta" quartz. Clinopyroxene and hornblende phenocrysts are mutally exclusive; none of the dikes are lamprophyres in the sense of containing only mafic phenocrysts.

Both clinopyroxene ($2V_\alpha = 55°$, $z\wedge c=42°$, $\delta=0.030$) and plagioclase phenocrysts in the clinopyroxene-

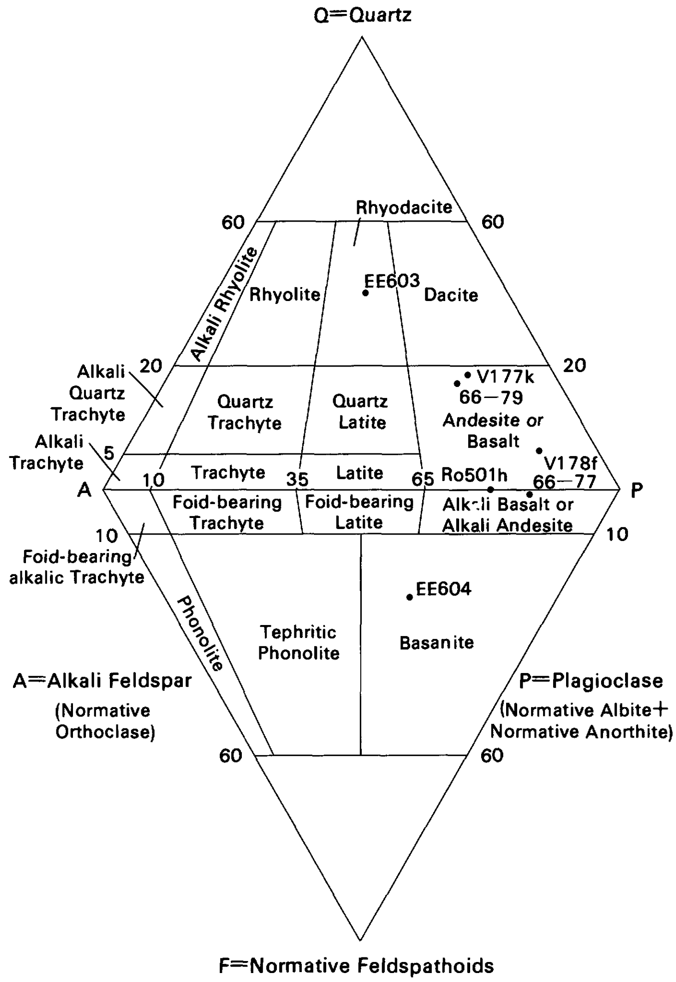

FIGURE 5.—Quaternary plot of normative quartz, orthoclase, plagioclase, and feldspathoids from chemically analyzed samples of dikes and lava flows from the Merrick Mountains. Classification is from Streckeisen (1979). Calculated from data in table 1.

plagioclase porphyritic dikes are strongly zoned, with the plagioclase ranging in composition from calcic labradorite to calcic andesine. Plagioclase phenocrysts are commonly partly sericitized, and the clinopyroxene phenocrysts are usually altered to epidote on their margins. Groundmass minerals in these dikes include plagioclase, clinopyroxene, opaques, apatite, sphene, minor hornblende (z=pale olive green, y=pale red brown, x=colorless to very pale yellow; $z>y>x$), and scarce quartz.

Both hornblende ($2V_\alpha=70°$, $z\wedge c=21°$, $\delta=0.024$; same pleochroic and absorption scheme as mentioned previously) and plagioclase phenocrysts in the hornblende-plagioclase porphyritic dikes are strongly zoned, with the plagioclase ranging in composition from sodic labradorite to sodic andesine. The plagioclase phenocrysts are usually partly altered to sericite±

TABLE 1.—*Chemical and modal data of igneous rocks from the Merrick Mountains*

[Rapid rock chemical analyses of samples Ro501g, V177a, Ro500a, By56f, V178i, Ro501h, V178f, and V177k by J. Riviello. Methods used are described in Shapiro and Brannock (1962) and are supplemented by atomic absorption. Analyses 66-157, 66-154, EE603, and EE604 from Laudon (1972); analyses 66-123, 66-153, 66-77, and 66-79 from Laudon (1982). Six-step semiquantitative spectrographic analyses by J. C. Hamilton. N, not detected or at limit of detections; L, detected, but below limit of determination; dash, not looked for. Not detected or at limit of detection for all samples: Ag, As, Au, B, Be, Bi, Cd, Ce, Ge, Hf, In, La, Li, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W]

Sample No.	Plutonic rocks									Dikes						Basanite
	Ro501g	66-157	V177a	66-123	66-153	66-154	Ro500a	By56f	V178i	Ro501h	66-77	V178f	66-79	V177k	EE603	EE604
Chemical analyses, in weight percent																
SiO_2	47.06	51.32	53.22	53.30	53.40	54.96	59.15	60.64	68.17	45.97	46.62	50.76	58.48	58.77	72.81	44.64
Al_2O_3	18.61	18.32	18.41	18.85	19.07	17.42	16.88	16.89	15.85	13.18	16.52	17.71	16.90	17.91	13.83	15.11
Fe_2O_3	5.10	1.41	4.01	3.63	3.23	3.17	3.39	3.21	0.56	2.72	2.10	2.28	2.00	3.83	0.41	2.84
FeO	6.19	6.57	4.47	5.65	5.79	4.74	3.47	2.87	2.15	13.86	10.07	7.40	6.12	2.66	0.34	7.49
MgO	5.04	5.38	4.55	3.36	3.22	3.70	2.88	2.73	1.00	7.03	6.88	5.12	2.47	2.42	0.17	8.13
CaO	9.94	9.92	9.24	8.29	8.19	7.57	5.92	5.99	2.14	9.29	10.26	10.11	4.34	5.46	1.25	8.13
Na_2O	2.68	2.48	3.16	3.34	3.67	3.16	2.78	2.68	3.23	1.79	2.27	1.90	3.45	3.63	2.66	4.24
K_2O	2.08	1.15	0.62	1.30	1.13	2.29	2.87	2.59	5.29	2.02	1.84	1.27	2.70	2.50	4.36	2.54
H_2O^+	1.27	0	1.03	0	0	0	0.90	1.03	1.01	1.81	0	2.16	0	1.26	0	0
H_2O^-	0.06	0	0.08	0	0	0	0.06	0.03	0.06	0.03	0	0.07	0	0.08	0	0
Total H_2O	0	2.70	0	1.78	1.80	1.67	0	0	0	0	2.75	0	3.45	0	1.47	3.54
TiO_2	1.26	0.67	0.66	0.85	0.84	0.80	0.61	0.54	0.29	0.86	1.13	0.76	0.42	0.74	0.06	2.24
P_2O_5	0.47	0.15	0.16	0.33	0.32	0.27	0.18	0.13	0.09	0.16	0.19	0.17	0.14	0.30	0.15	0.79
MnO	0.19	0.16	0.14	0.13	0.13	0.14	0.14	0.12	0.07	0.19	0.14	0.17	0.08	0.14	0.14	0.15
Co_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.65	0
Total	99.95	100.23	99.75	100.81	100.79	99.89	99.23	99.45	99.81	98.91	100.77	99.87	100.56	99.70	100.30	99.84
Semiquantitative spectrographic analyses, in parts per million																
Ba	500	--	300	--	--	--	1,000	1,000	700	100	--	300	--	1,000	--	--
Co	20	--	20	--	--	--	20	15	7	30	--	30	--	15	--	--
Cr	7	--	20	--	--	--	7	7	L	70	--	20	--	N	--	--
Cu	150	--	100	--	--	--	100	70	7	1.5	--	150	--	30	--	--
Ga	30	--	15	--	--	--	20	20	15	15	--	15	--	30	--	--
Mo	N	--	N	--	--	--	N	N	30	N	--	N	--	N	--	--
Nb	10	--	N	--	--	--	L	10	N	N	--	N	--	N	--	--
Ni	7	--	10	--	--	--	7	7	N	30	--	20	--	N	--	--
Pb	N	--	N	--	--	--	N	N	15	N	--	N	--	N	--	--
Sc	30	--	50	--	--	--	30	20	7	30	--	30	--	20	--	--
Sr	1,000	--	500	--	--	--	700	700	500	500	--	700	--	1,000	--	--

V	200	--	300	--	--	--	200	150	30	150	--	200	--	150	--	--
Y	30	--	30	--	--	--	30	30	30	15	--	15	--	30	--	--
Yb	3	--	3	--	--	--	3	3	3	1.5	--	3	--	3	--	--
Zr	50	--	30	--	--	--	50	70	100	30	--	30	--	100	--	--
CIPW Norms, in weight percent																
Quartz	0	1.82	6.79	5.56	4.51	6.25	15.02	18.32	21.91	0	0	3.94	11.31	13.32	38.35	0
Corundum	0	0	0	0	0	0	0	0	1.14	0	0	0	0.74	0.02	2.83	0
Orthoclase	12.30	6.78	3.67	7.62	6.62	13.55	17.09	15.39	31.29	12.07	10.79	7.51	15.87	14.82	26.07	15.03
Albite	22.69	20.94	26.81	28.03	30.81	26.77	23.71	22.80	27.36	15.31	15.88	16.10	29.03	30.81	22.77	12.76
Anorthite	32.62	35.38	34.30	32.34	31.97	26.61	25.30	26.55	10.04	22.20	29.23	36.09	20.50	25.20	5.35	14.72
Nepheline	0	0	0	0	0	0	0	0	0	0	1.73	0	0	0	0	12.55
Wollastonite	5.70	5.29	4.43	2.64	2.62	4.20	1.30	1.03	0	9.74	8.37	5.44	0	0	0	8.56
Enstatite	3.75	13.37	11.36	8.30	7.96	9.23	7.23	6.84	2.49	5.30	4.33	12.77	6.12	6.05	0.43	5.69
Ferrosilite	1.62	10.05	4.08	6.16	6.77	5.27	2.85	1.96	3.14	6.70	3.83	10.78	8.99	0.76	0.47	2.25
Forsterite	6.17	0	0	0	0	0	0	0	0	8.69	8.89	0	0	0	0	10.22
Fayalite	2.94	0	0	0	0	0	0	0	0	12.11	8.66	0	0	0	0	4.45
Magnetite	7.40	2.04	5.83	5.22	4.65	4.60	4.95	4.68	0.81	3.99	3.02	3.31	2.88	5.57	0.60	4.12
Ilmenite	2.39	1.27	1.26	1.60	1.58	1.52	1.17	1.03	0.55	1.65	2.13	1.45	0.79	1.41	0.11	4.26
Apatite	1.11	0.38	0.38	0.78	0.75	0.33	0.43	0.31	0.21	0.38	0.45	0.40	0.33	0.71	0.34	1.87
Total----------	98.69	97.32	98.91	98.25	98.24	98.33	99.05	98.94	98.94	98.14	97.31	97.79	96.56	98.67	97.32	96.48
Modes, in volume percent																
Plagioclase	46.1	58.8	62.0	65.4	66.4	53.5	47.9	51.4	53.0	0	--	34.4	--	62.6	--	--
K-feldspar	0	0	1.3	2.1	0	5.5	7.0	11.1	15.3	0	--	0	--	11.0	--	--
Quartz	3.2	5.6	8.1	7.4	5.5	12.2	16.2	15.5	18.1	0	--	0	--	10.0	--	--
Pyroxene	18.7	18.0	4.1	4.7	3.3	0.6	0.9	0	0	7.4	--	9.0	--	3.2	--	--
Amphibole	5.2	5.4	19.1	5.4	9.8	13.0	20.1	15.7	9.7	0	--	0	--	0	--	--
Biotite	19.0	2.4	0.3	10.9	11.0	11.4	1.9	1.7	2.1	26.0	--	0	--	8.6	--	--
Apatite	0.1	0	0	0	0	0	0.1	0.1	0	0	--	0	--	0	--	--
Zircon	0.1	0	0	0	0	0	0	0.1	0	0	--	0	--	0	--	--
Sphene	0	0	0.1	0	0	0	0.1	0	0	0	--	0.8	--	0	--	--
Opaques	4.8	0.1	3.9	3.7	3.1	1.8	5.6	4.4	1.8	0	--	1.0	--	2.2	--	--
Chlorite	1.8	9.6	1.0	0.3	0.9	0	0.1	0	0	0	--	2.8	--	2.4	--	--
Epidote	1.0	0.1	0.1	0.1	0	2.0	0.1	0	0	0	--	0	--	0	--	--
Groundmass	0	0	0	0	0	0	0	0	0	66.6	--	52.0	--	0	--	--

carbonate, and the hornblende phenocrysts are altered along their margins to chlorite and epidote. Groundmass minerals in the hornblende-plagioclase porphyritic dikes and in the plagioclase porphyritic dikes include plagioclase, hornblende, red-brown biotite, opaques, quartz, apatite, and sphene.

The most unusual mineral assemblage occurs in a dike located on the northern ridge of Mount Becker; phenocrysts of hypersthene (locally rimmed with clinopyroxene), chloritized biotite, labradorite, and sparse anhedral poikolitic potassium feldspar are set in a groundmass of plagioclase, opaques, sphene, clinopyroxene, quartz, and scarce hornblende. Two olivine-rich wehrlite dikes that approach dunite in composition crop out on the northern and southern ridges of Mount Berger. Olivine occurs both as separate grains and as inclusions in poikilitic clinopyroxene grains. The clinopyroxene is relatively fresh, but olivine in the northern dike is altered to serpentine and magnetite. The southern dike is richer in olivine, most of which is totally serpentinized.

All dikes in the Merrick Mountains have undergone at least light to moderate hydrothermal alteration. A dike on Mount Matheson has been subjected to potassium hydrothermal alteration, so that all biotite reported in the mode (table 1, sample Ro501h) is fine-grained hydrothermal biotite. (See chap. C, this report.) In addition to the altered phenocrysts mentioned previously, the groundmass of these rocks contains variable amounts of secondary chlorite, epidote, sericite, carbonate, hematite, and leucoxene.

RHYODACITE PORPHYRY DIKES

Cream-colored rhyodacite porphyry dikes, as wide as 10 m, crop out at several localities (By56, C58, Ro500, V178) on and near Mount Boyer and Mount Matheson. Much of this rock occurs as frost-shattered rubble; its contacts, although apparently sharp and chilled, are not well exposed. On Mount Matheson the dikes intrude the Merrick Mountains stock and apparently crosscut mafic dikes; their age relative to the quartz veins and aplite, alaskite, and pegmatite dikes that cut the Merrick Mountains stock is not known. Some bodies that are lithologically similar and thus perhaps correlative occur in sedimentary rocks of the Latady Formation at Eaton Nunatak, at locality L58 about 4 km west of Eaton Nunatak, and at the southern end of locality V178. Some of these bodies are dikes or small irregularly shaped hypabyssal intrusions, but others appear to be sills.

The rhyodacite contains as much as 15 percent phenocrysts that attain a maximum size of 4 mm and are set in an aphanitic groundmass. Approximately 75 percent of the phenocrysts are "beta" quartz, most of which show strong resorption in which embayments are filled with groundmass material. Many quartz phenocrysts are also fractured or cracked. The remaining phenocrysts or glomerocrysts are oligoclase accompanied by minor potassium feldspar and by much smaller and less numerous microphenocrysts of muscovite and pyrite. Plagioclase is generally very strongly sausseritized; potassium feldspar, however, is much less altered. Pale-green to colorless chlorite and radial aggregates of clinozoisite are common pseudomorphs after muscovite microphenocrysts. The groundmass of most of these dikes is massive mosaic-textured quartz containing minor amounts of plagioclase, pyrite, and apatite, and variable amounts of sericite. The groundmass quartz most likely represents devitrified glass. Miarolitic cavities are locally abundant in a dike from the southern slope of Mount Boyer. X-ray and optical examination of tabular to blocky crystals projecting into these cavities indicate that the crystals are sericitized ($2M_1$ polymorph) plagioclase. A single chemical analysis and its CIPW norm are listed in table 1.

MIOCENE(?) BASANITE

Miocene(?) nepheline-normative olivine-porphyritic basanite (an alkalic basalt) and basanitic breccia are the only rock types that crop out on a small (100 m long), low (30 m high) nunatak approximately 2.1 km south-southwest of Mount Matheson. Halpern (1971) obtained a K-Ar whole rock date of 6 m.y. from this rock; the true age of this rock, however, is considered tentative because Halpern did not publish analytical data for the age. Although most of the outcrop consists of frost-shattered rubble, interpretation of the small amount of rock that is in place suggests that a single subaerial lava flow stratigraphically overlies a more voluminous basanitic breccia and suggests that the exposed section is no more than 10–12 m thick.

The breccia consists of subrounded to subangular clasts (as much as 5 cm long) of black highly vesicular aphanitic to olivine-porphyritic basanite set in a brown slightly palagonitized matrix of ash to lapilli-sized fragments of basanitic glass. The overlying flow has a highly vesicular to scoriaceous surface and is lithologically identical to the breccia clasts.

Petrographically, the flow consists of fresh olivine microphenocrysts (maximum size 0.75 mm, average size 0.3–0.5 mm), which show only slight resorption, set in a pilotaxitic groundmass of plagioclase laths, granular opaque minerals, pale-brown glass, and minor olivine. Universal-stage measurement of $2V$ angles indicate a composition of Fo_{85} for the olivine (Deer and others, 1966). If the plagioclase laths are assumed to be elongated on the a crystallographic axis, then extinction angles measured parallel to elongation yield a maximum anorthite composition of An_{55} (Burri and others, 1967). The breccia matrix is vitrophyric and highly vesicular. Olivine microphenocrysts (0.1–0.5 mm) and randomly oriented plagioclase microlites, many of which are twinned on the Carlsbad law, are set in a dark-reddish-black, almost opaque, glassy groundmass. Plagioclase laths have the same composition as in the flow, but the olivine is higher in magnesium (Fo_{95}). Around the margins of vesicles, the glass can be seen to be crowded with a myriad of minute opaque granules and prismatic crystallites. Some of the prismatic crystallites are apatite, but others have a 30°-40° extinction angle and might be clinopyroxene. A few of the vesicles are lined with pale-yellow palagonite and (or) filled with an unidentified zeolite (slow elongation; parallel extinction; *RI* estimated at 1.50, δ=0.007). The single chemical analysis and accompanying normative mineralogy (table 1; fig. 5) indicate that the analyzed sample is a basanite (Yoder and Tilley, 1962) that is very similar in composition to Miocene and Pliocene "basalt" from both the Hudson Mountains in western Ellsworth Land, 800 km west of the Merrick Mountains (Laudon, 1982), and from Marie Byrd Land (LeMasurier and Rex, 1982). The basanite is lithologically similar to hyaloclastite and basaltic lava flows recently discovered in the English Coast (fig. 1), 250 km northwest of the Merrick Mountains (O'Neill and Thomson, 1985).

LeMasurier and Rex (1982) presented convincing arguments that rocks of similar chemistry, age, and field relations (vitric clasts with lenses of holocrystalline lava) that are widespread throughout Marie Byrd Land and western Ellsworth Land are hyaloclastites that formed by eruption beneath a continental ice sheet. In spite of the vast distance separating these two areas, we suggest that based on a similar geologic setting the Merrick Mountains basanite is also a subglacial hyaloclastite.

GEOCHEMISTRY

Major element-oxide analyses, trace-element abundances, CIPW norms, and modes of nine plutonic rocks, six dikes, and the basanite lava flow are presented in table 1. Of the samples of plutonic rocks, two represent the older plutonic event (Ro500g, V178i). Samples V177a and 66-123, collected from the same area (fig. 3), probably represent the younger plutonic event. Compositions of rocks of both events locally appear to be chemically similar. Of the samples of dikes, sample Ro501h is from a dike related to, and cutting, plutonic rocks of the older plutonic event. Sample EE603 is from a rhyodacite porphyry dike. The locations of analyzed samples are shown in figure 3.

Examination of a Harker silica-variation diagram (fig. 6) reveals a calc-alkaline differentiation trend similar to that found in igneous rocks throughout the northern (Adie, 1955, 1964) and southern (Laudon, 1982; Rowley and Williams, 1974, 1982) Antarctic Peninsula: as SiO_2 increases, MgO and total iron oxides decrease, while K_2O and total alkalies increase; Al_2O_3 and CaO, however, initially increase before beginning a slow decrease with increasing silica; sodium also increases slightly before becoming essentially constant, which is a relatively common feature in calc-alkaline rocks containing 55–75 percent SiO_2.

The more mafic dikes of the Merrick Mountains are richer in MgO and total iron oxides and lower in Al_2O_3 than plutonic rocks with comparable SiO_2 percentages. Otherwise, there are no appreciable chemical differences between the dikes and the plutonic rocks. Although corundum-normative igneous rocks are relatively uncommon in the Andean belt (Vennum, 1978), the Merrick Mountains rocks become corundum-normative at approximately 58.5 percent SiO_2. Laudon (1982) also reported a strong tendency for corundum-normative rocks to evolve with increasing differentiation throughout most of eastern Ellsworth Land. Cawthorn and Brown (1976) have shown that a crystallization trend from diopside-normative to corundum-normative rocks in differentiated calc-alkaline series can result from the fractional crystallization of hornblende from a diopside-normative magma. One of the dikes (66-77) is also nepheline-normative, a rare but not a unique chemical feature in igneous rocks from the southern Antarctic Peninsula (Laudon, 1982).

When the analyses of table 1 are plotted on an alkali-magnesium-iron±manganese ternary diagram (fig. 7), they show the typical calc-alkaline trend (Nockolds and Allen, 1953) of late-stage alkali enrichment. If the analyses of the rhyodacite porphyry dike (EE603) and one of the granodiorites (V178i) are ignored, however, the overall intermediate composition of the Merrick Mountains rocks is emphasized by only a moderate increase in alkali elements with differentiation. The alkali-lime (Peacock) index of the Merrick Mountains stock is approximately 58 (fig. 6), close to that (59) for intrusive rocks of eastern Ellsworth Land (Laudon, 1982) and comparable to that (61) for intrusive rocks of the Lassiter Coast (Rowley and Williams, 1974). Relative abundance of CaO, K_2O, and Na_2O are shown in a ternary diagram (fig. 8), which also indicates a typical calc-alkaline trend. If the rhyodacite porphyry and granodiorite analyses are again ignored, the analyzed samples form a relatively small cluster near the CaO corner of the diagram and show only a moderate increase in K_2O with increasing differentiation.

Ytterbium is the only trace or minor element whose

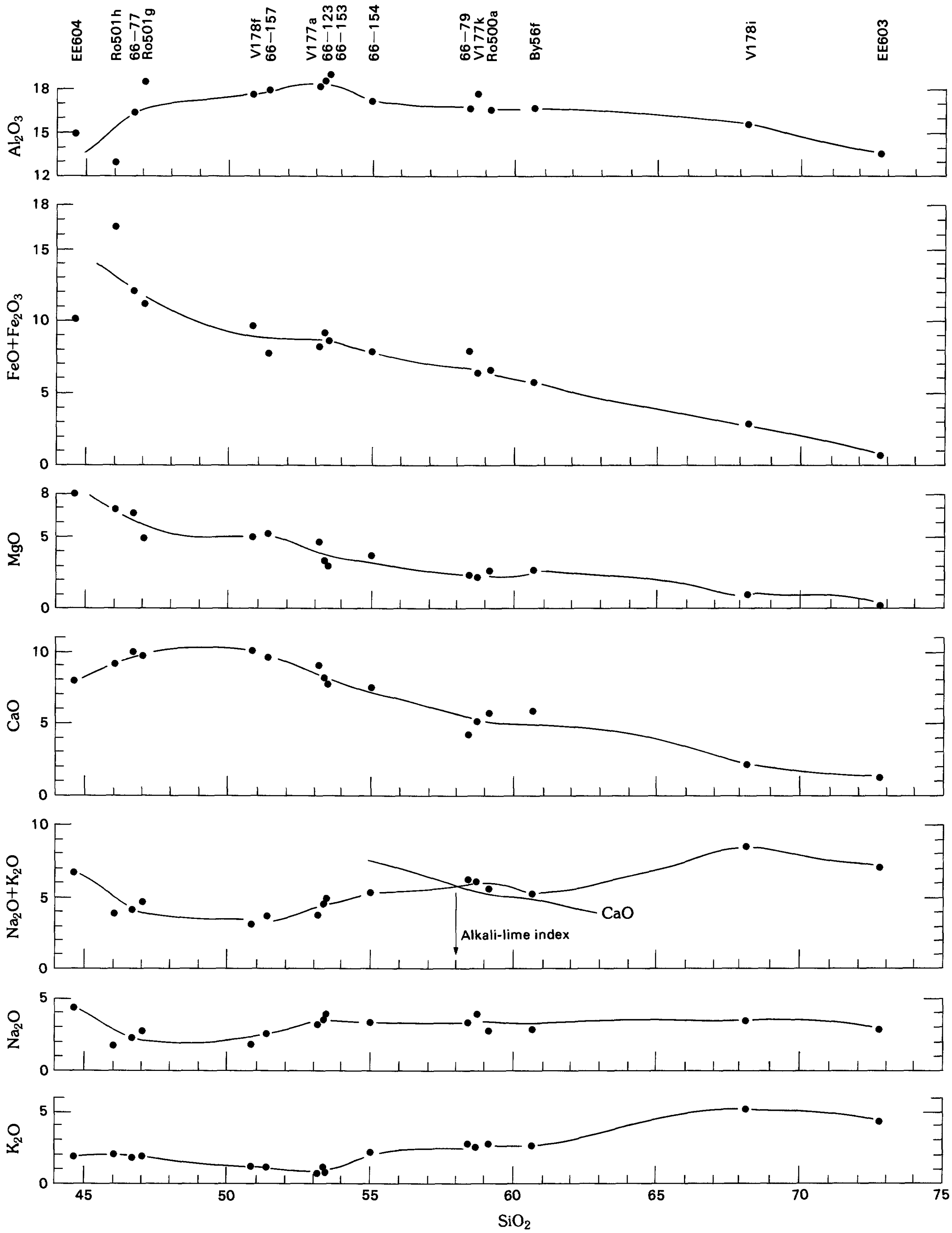

FIGURE 6.—Harker silica-variation diagram for analyzed samples of igneous rocks from the Merrick Mountains.

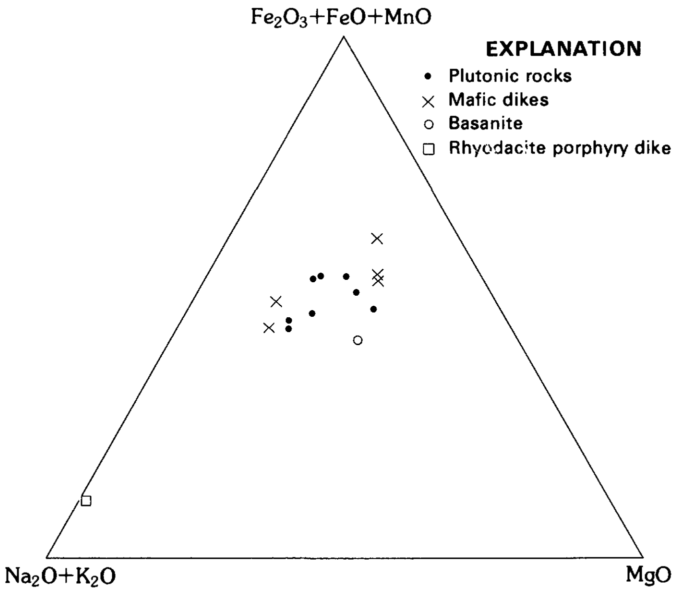

FIGURE 7.—Ternary plot of total alkalies and magnesium, iron, and manganese expressed as oxides in igneous rocks of the Merrick Mountains.

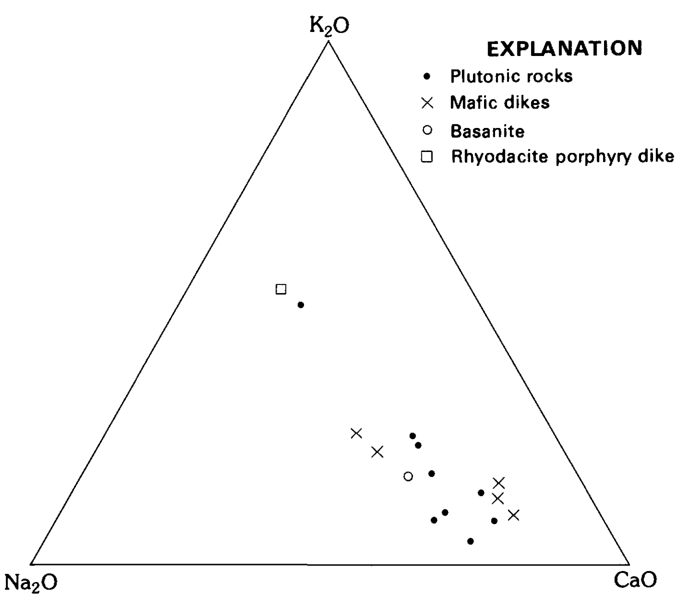

FIGURE 8.—Ternary plot of sodium, calcium, and potassium expressed as oxides in igneous rocks of the Merrick Mountains.

concentration remains relatively constant. Cobalt, chromium, nickel, and manganese oxide all steadily decrease as SiO_2 increases. These elements are all concentrated in mafic silicates and (or) oxides, and their decrease is obviously related to the corresponding decrease in these minerals with increasing differentiation. Copper also generally decreases with increasing SiO_2, although two of the analyzed samples are almost devoid of this element. Titania, however, remains relatively constant and does not begin to noticeably decrease in abundance until the more felsic end of the suite has evolved. Cobalt in excess of nickel, as in the Merrick Mountains rocks, is unusual in most calc-alkaline suites; Adie (1955) and Vennum (1978) have, however, previously noted this feature in plutonic rocks of the Antarctic Peninsula. Scandium, vanadium, and P_2O_5 increase to maximum concentrations at about 54 percent SiO_2, then slowly decrease in more felsic samples. The behavior of vanadium and P_2O_5 is believed attributable to fractional crystallization of opaque minerals and apatite, respectively. Molybdenum and lead were detected in only the most felsic samples analyzed.

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Porphyry-type Copper Deposits and Potassium-Argon Ages of Plutonic Rocks of the Orville Coast and Eastern Ellsworth Land, Antarctica

By PETER D. ROWLEY, EDWARD FARRAR, PAUL E. CARRARA,
WALTER R. VENNUM, *and* KARL S. KELLOGG

STUDIES OF THE GEOLOGY AND MINERAL RESOURCES OF THE SOUTHERN ANTARCTIC PENINSULA AND EASTERN ELLSWORTH LAND, ANTARCTICA

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the National Science Foundation

Description of two newly discovered Andean mineral deposits,
which have affinities to the porphyry copper class
but have no economic potential

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PORPHYRY-TYPE COPPER DEPOSITS AND POTASSIUM-ARGON AGES OF PLUTONIC ROCKS OF THE ORVILLE COAST AND EASTERN ELLSWORTH LAND, ANTARCTICA

By PETER D. ROWLEY[1], EDWARD FARRAR[2], PAUL E. CARRARA[1],
WALTER R. VENNUM[3], and KARL S. KELLOGG[1]

ABSTRACT

Two weakly mineralized and hydrothermally altered, Lower Cretaceous hypidiomorphic-granular (granitoid) plutons occur in the Orville Coast and eastern Ellsworth Land, Antarctica. The first, the Sky-Hi stock, and its crosscutting dacite porphyry dikes contain disseminated pyrite, magnetite, chalcopyrite, and related secondary minerals, and the same minerals are concentrated in associated quartz veins; average metal additions, however, probably do not exceed 200 ppm (parts per million) copper and 50 ppm zinc. Most plutonic rocks are propylitically altered and are transected by abundant sheared zones that consist of phyllic and subordinate argillic and sparse potassic rocks. The second pluton, the Merrick Mountains stock, partly consists of a mafic quartz diorite containing related crosscutting mafic dikes. These intrusive rocks were transected by numerous randomly oriented shear planes and then intruded by a concentrically zoned quartz diorite and granodiorite and related crosscutting rhyodacite porphyry dikes. Added metallic minerals are like those in the Sky-Hi stock; average metal additions probably do not exceed 100 ppm copper. Large areas of the stock are propylitically altered, and parts are potassically altered; some rocks are transected by sparse sheared zones altered to phyllic and subordinate argillic rocks.

The Sky-Hi and Merrick Mountains copper deposits resemble the Lassiter Coast copper deposit, located 150 km northeast of the Orville Coast. All three deposits appear to represent deeply eroded noneconomic "plutonic" porphyry copper deposits. Isotopic ages show that these plutons and most of the other plutons in the southern Antarctic Peninsula and eastern Ellsworth Land belong to the Lassiter Coast Intrusive Suite, dated at 130–95 million years. Copper mineralization may be a local characteristic of upper parts of plutons of this suite. The plutons of the suite that are most likely to contain copper deposits are in more axial parts of the Antarctic Peninsula, where erosion has not cut down to as great a depth as it has in coastal areas.

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INTRODUCTION

The Orville Coast and parts of eastern Ellsworth Land of Antarctica were mapped geologically in reconnaissance during the 1977–78 field season. The area is underlain by Middle and Upper Jurassic sedimentary rocks of the Latady Formation that intertongue with calc-alkaline volcanic rocks of the Mount Poster Formation, all of which were folded and then intruded by Lower Cretaceous calc-alkaline hypidiomorphic-granular (granitoid) plutons (Rowley, Vennum, and others, 1983). During the field studies, two of these plutons, one in the Sky-Hi Nunataks and the other in the Merrick Mountains (fig. 1), were found to be hydrothermally altered and weakly mineralized. These plutons were given greater attention during the fieldwork and subsequent laboratory studies, and they were dated by K-Ar (potassium-argon) techniques. Preliminary results of the studies were discussed by Rowley, Farrar, and others (1982, 1983).

The geology and the alteration-mineralization assemblages and patterns in the two plutons in the field area are nearly identical to those of the Lassiter Coast copper deposit (Rowley and others, 1975; Rowley and others, 1977) located in the Copper Nunataks about 150 km northeast of the Orville Coast (fig. 1). The Lassiter Coast copper deposit formed during two pulses of Early Cretaceous plutonism (Farrar and others, 1982). The older pulse involved emplacement of hypidiomorphic-granular granodiorite followed by intrusion of mafic dikes and then by "crackling" (that is, facturing along numerous criss-crossing shear planes of small

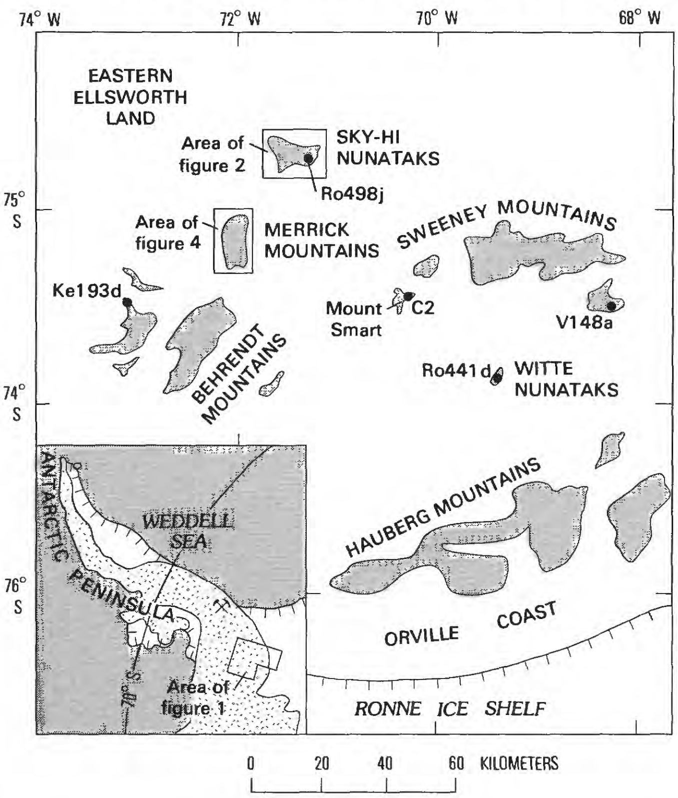

FIGURE 1.—Orville Coast and eastern Ellsworth Land, Antarctica, showing major rock exposures (stippled) and sample number and locality (dots) of rocks whose ages are reported in table 1. Also shows locations of areas of figures 2 and 4. On the insert index map that shows the area of figure 1, location of the Lassiter Coast copper deposit is shown by a mine symbol, and edges of ice shelves are shown by hachured lines. See Rowley, Vennum, and others (1983, fig. 2) for the geologic map of the area.

displacement) and pyritization along randomly oriented shear planes. The younger pulse involved emplacement of hypidiomorphic-granular granite followed by intrusion of dacite porphyry dikes and then by shearing and related phyllic-argillic alteration and porphyry copper mineralization. Dikes, sheared zones, and extension joints in both plutons of the Lassiter Coast deposit strike northwest, parallel to extension joints in the folded Latady Formation, which strikes northeast. Pyrite, chalcopyrite, magnetite, molybdenite, and related minerals were introduced by hydrothermal solutions during the mineralization; average metal additions (that is, additions in content of metallic elements to the rocks) in the most mineralized nunatak, however, do not appear to average more than 200 ppm (parts per million) copper, 100 ppm lead, and 50 ppm molybdenum. The effects of potassic alteration were only recently recognized in thin section by the presence of scattered fine-grained subhedral aggregates of hydrothermal biotite replacing primary hornblende. The potassic alteration as well as apparently attendant propylitic alteration occurred during two periods: (1) when relatively coarse-grained hydrothermal brown and light-brown biotite and associated minor rutile formed after intrusion of the granodiorite pluton and its mafic dikes and perhaps prior to "crackling;" and (2) when sparse fine-grained hydrothermal brown and light-brown biotite and associated minor rutile formed after intrusion of the younger porphyry dikes and perhaps prior to phyllic-argillic alteration. The Lassiter Coast deposit and the two deposits discovered during the 1977–78 field season are of too low grade to be economic, even if they were located in a climate favorable for development.

K-Ar ages were determined for the pluton in the Sky-Hi Nunataks and for barren plutonic rocks elsewhere in the Orville Coast and eastern Ellsworth Land in order to determine regional relationships of plutonic rocks. The K-Ar analyses were done by Edward Farrar from samples collected during the 1977–78 season; the analyses were reported in preliminary form by Farrar and Rowley (1980). This present report gives the final analytical data (table 1) for the K-Ar ages, and describes the Sky-Hi and Merrick Mountains copper deposits.

Outcrop numbers given in the text refer to rock nunataks or parts of nunataks that were studied. Each outcrop may have rock types of differing lithology or origin. When rocks were sampled they were assigned the same whole number as the outcrop; letters and even subscripts appended to the outcrop number refer to different samples.

ACKNOWLEDGMENTS

J. M. Boyles, T. S. Laudon, and M. R. A. Thomson, as members of the 1977–78 field party, greatly contributed to the geologic mapping and study of the Sky-Hi Nunataks and Merrick Mountains. We are deeply grateful to them for their help in field and other aspects of the study. Conversations with D. P. Cox were extremely valuable in clarifying concepts about porphyry deposits. M. D. Turner played a key role in logistical matters that allowed field and laboratory studies to be done. Logistical support by other members of the U.S. Antarctic Research Program of the National Science Foundation, and by U.S. Navy Operation Deep Freeze is also acknowledged. Many samples used in this study were recovered by divers of the U.S. Navy after some rock boxes were dropped overboard during offloading cargo ships in California; without the help of these divers, as well as of M. D. Turner, C.H. Nordhill, and Sam Feola,

TABLE 1.—*Potassium-argon ages of plutons in the Orville Coast and eastern Ellsworth Land, Antarctica*
[Locations and rock types given in table 2. Constants used: $\lambda_e = 0.581 \times 10^{-10}yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10}yr^{-1}$, $^{40}K = 0.01167$ atomic %]

Sample No.	Mineral analyzed	Potassium (weight percent)	^{40}Ar (radiogenic) cm^3 NTP/g x10^{-5}	^{40}Ar (radiogenic) Percent total	[1]Age ± 2σ (Ma)
C2	Biotite	5.145	21.27	82.7	103.4±1.5
	Biotite	5.145	22.85	81.4	110.8±1.5
Ke193d	Hornblende	0.584	2.548	60.1	108.9±1.6
	Biotite	6.530	27.29	85.9	104.5±1.5
Ro441d	Hornblende	0.643	2.835	82.6	110.0±1.6
	Hornblende	0.643	2.895	82.0	112.3±1.6
	Biotite	6.789	29.59	90.2	108.8±1.6
Ro498j	Hornblende	0.459	2.222	70.3	120.5±1.7
	Hornblende	0.459	2.273	71.0	123.1±1.8
V148a	Hornblende	0.957	4.321	89.1	112.6±1.6
	Hornblende	0.957	4.010	87.3	104.7±1.5
	Biotite	6.400	29.80	90.0	116.0±1.6

[1] σ= Standard deviation.

the study could not have been completed. K-Ar analyses were performed by Edward Farrar in the laboratory of the Institute of Nuclear Science, Department of Scientific and Industrial Research, Lower Hutt, New Zealand; he thanks C. J. Adams and J. E. Gabites for use of the laboratory and for many types of assistance during the work. We appreciate the aid of D. L. Schmidt, C. H. Thorman, and D. P. Cox for technical reviews of the report; of C. G. Cunningham for assistance with microscope work on fluid inclusions; and of A. M. Kaplan for petrographic studies of some plutonic rocks. K-Ar studies were supported by a grant to Farrar from the National Science and Engineering Research Council of Canada; the rest of the field and laboratory work was supported by National Science Foundation grants DPP76-12557, DPP78-24214, and DPP80-07388 to the Geological Survey.

POTASSIUM-ARGON AGES OF PLUTONIC ROCKS

Plutonic rocks of gabbro to granite composition are widespread in the southern Antarctic Peninsula and eastern Ellsworth Land. All plutons that have been dated range from 130 to 95 m.y. (million years), Early Cretaceous (Halpern, 1967; Mehnert and others, 1975; Pankhurst, 1980; Farrar and others, 1982). The products of this single broad period of calc-alkaline plutonism were named the Lassiter Coast Intrusive Suite by Rowley, Vennum, and others (1983).

Fresh plutonic rocks underlying both the Lassiter Coast and Merrick Mountains copper deposits previously have been isotopically dated. The K-Ar ages of igneous rocks of the Lassiter Coast copper deposit are 108 m.y. for the granodiorite pluton, and 97 m.y. for both the granite that cuts the granodiorite and the dacite porphyry dike that cuts the granite (Farrar and others, 1982; corrected for new constants, Steiger and Jäger, 1977). The older of two plutonic bodies that make up the Merrick Mountains stock yielded a Rb-Sr isochron, from rocks at Mount Berger, of 107 m.y. (Halpern, 1967; corrected for new constants, Steiger and Jäger, 1977).

Plutonic rocks from the Orville Coast and eastern Ellsworth Land that have been dated also belong to the Lassiter Coast Intrusive Suite. The geology of the dated plutons was summarized by Farrar and Rowley (1980). Sample locations are shown in figure 1. Petrographic information and location descriptions of dated rocks are given in table 2; rock names are from Streckeisen (1976). Of the five dated plutons, the Sky-Hi stock (sample Ro498j) is 122 m.y.—based on the average of two concordant ages on hornblende splits. Younger porphyritic dikes, altered rocks, and mineralized rocks probably formed during late phases of this plutonism. Mineralization in the Sky-Hi stock thus is older than that of the Lassiter Coast and Merrick Mountains copper deposits.

The next oldest pluton in the field area is the Haggerty Peak pluton, which is exposed over a 5 km by 3 km area in the southeastern Sweeney Mountains. Only its eastern contact is exposed; at the outcrop the rock is a fine- to medium-grained monzodiorite and quartz monzodiorite. The pluton appears to be compositionally zoned with a more silicic interior, for it grades in a short distance westward through medium-grained (crystals of 15 mm long) granodiorite into medium-grained granite and granodiorite. Sample V148a has an age of about 114 m.y. based on the average of two concordant ages on hornblende and biotite (table 1). We do not know the reason for an age of 105 m.y. on hornblende, which we reject.

The Witte pluton occurs over an area of about 1 km in diameter in the Witte Nunataks, but only its southeastern contact is exposed. Most of the rock is medium-grained granodiorite, but at the contact it consists of fine- to medium-grained diorite and quartz diorite. Sample Ro441d has an age of about 110 m.y. based on the average of three concordant ages on hornblende and biotite (table 1).

TABLE 2.—*Modal analyses and locations of dated samples, Orville Coast and eastern Ellsworth Land, Antarctica*

[Modal analyses given in volume percent; 500 points counted on thin sections and stained rock slabs. All rocks contain poikilitic K-feldspar crystals that lack grid twinning and plagioclase crystals that are mostly zoned. Chlorite replaces biotite in all rocks. Locations from British Antarctic Survey 1:500,000 map of Orville Coast (Sheet SS17-20/SE), Tr., trace]

Sample No.	C2	Ke193d	Ro441d	Ro498j	V148a
Plagioclase	33.6	42.8	50.3	50.6	39.4
K-feldspar	33.6	12.8	12.2	19.5	25.0
Quartz	18.2	31.2	23.7	17.3	23.2
Biotite	8.0	9.2	3.4	1.4	4.8
Hornblende	6.0	3.0	9.2	7.0	6.2
Chlorite	0.6	0.6	0.2	1.8	0.4
Fe-Ti Oxides	Tr.	0.4	0.8	2.2	1.0
Sphene	Tr.	Tr.	Tr.	Tr.	Tr.
Apatite	Tr.	Tr.	Tr.	Tr.	Tr.
Zircon	0	0	0	Tr.	0
Epidote	0	0	0	Tr.	0

SAMPLE DESCRIPTION AND LOCALITY

C2. Medium-grained hypidiomorphic-granular granite of the Mount Smart pluton. Sample from south flank of Mount Smart, lat 75° 17' S., long 70° 14' W., southwest Sweeney Mountains.

Ke193d. Medium-grained hypidiomorphic-granular granodiorite of the Stanton batholith. Sample from the Stanton Hills, west of the Behrendt Mountains, 19 km N. 74° W. from Mount Chandler, lat 75° 14' S., long 73° 13' W.

Ro441d. Medium-grained hypidiomorphic-granular granodiorite of the Witte pluton. Sample from lat 75° 28' S., long 69° 22' W., north Witte Nunataks.

Ro498j. Medium-grained hypidiomorphic-granular quartz monzodiorite of the Sky-Hi stock. Sample from lat 74° 55' S., long 71° 19' W., southeast Sky-Hi Nunataks.

V148a. Medium-grained hypidiomorphic-granular granite from the Haggerty Peak pluton. Sample from south flank of Haggerty Peak, lat 75° 18' S., long 68° 12' W., southeast Sweeney Mountains.

The Stanton batholith is exposed in the Stanton Hills[4], about 10 km west of the Behrendt Mountains, where it underlies an area about 12 km (north-south) by 7 km (east-west) in size; the western contact of the pluton is not exposed. In most places the pluton consists of medium- to coarse-grained granodiorite, but at its contact it consists generally of somewhat more mafic granodiorite or quartz diorite. Sample Ke193d has an age of 109–105 m.y. based on somewhat discordant ages on hornblende and biotite, respectively, from a sample collected from a slightly more mafic margin of the compositionally zoned body (table 1). The margin of the pluton probably crystallized before the interior of the body, and the biotite age may represent resetting of the "atomic clock" during the continued crystallization of the interior or during younger crystallization of biotite due to lower temperature retention; the older age for the pluton is preferable.

The Mount Smart pluton is exposed over a 3 km by 2 km area in the southwestern Sweeney Mountains. Only its western contact is exposed; at the exposure the rock is a medium- to coarse-grained diorite and quartz diorite, but most of the body east of the contact appears to consist of medium- to coarse-grained granite. Sample C2 has an age of 111–103 m.y. based on two discordant ages on biotite from the same sample (table 1). The discordance probably is due to inhomogeneity in the biotite split (Farrar and Rowley, 1980).

SKY-HI NUNATAKS COPPER DEPOSIT

The study of the Sky-Hi Nunataks began during the 1961–62 Antarctic Peninsula Traverse, when one nunatak was visited and later briefly described (Laudon and others, 1964). The rest of the nunataks were first mapped during the 1977–78 field season (Rowley, 1978; Rowley, Vennum, and others, 1983). They consist mostly of folded volcanic rocks of the Mount Poster Formation, into which plutonic rocks were emplaced (fig. 2). Intertongued sandstone and siltstone of the Latady Formation, locally containing marine fossils, underlie several small outcrops in the southwestern part of the nunataks. In this area, the main rock type of the Mount Poster Formation is a resistant, thick, dark-green, generally massive rhyodacite that in most places contains abundant large phenocrysts of feldspar and "beta" quartz. This rock type is widespread in eastern Ellsworth Land (Laudon, 1972) and the Orville Coast and seems to be one or more ash-flow tuff sheets (Rowley, Vennum, and others, 1983). The strike of the stratified rocks in the Sky-Hi Nunataks appears to be northwest or west-northwest.

The Sky-Hi copper occurrence, discovered by Carrara and Kellogg during the 1977–78 season, has been mentioned in previous reports (Rowley, 1978, 1979; Rowley and Pride, 1982; Rowley, Williams, and Pride, 1983, in press; Rowley, Ford, and others, 1983). This deposit is exposed along a narrow, partly snow-covered ridge, about 1.5 km long and with relief of about 15 m, in the southeastern part of the Sky-Hi Nunataks. This ridge is underlain by plutonic rocks, defined here the Sky-Hi stock, that belong to the Lassiter Coast Intrusive Suite. No intrusive contact with the older volcanic rocks is exposed. Modal analyses and chemical analyses of fresh igneous rocks from the ridge are given in tables 3 and 4, and figure 3, and semiquantitative spectrographic analyses of fresh, altered, and mineralized rocks are given in table 5.

Rocks that are hydrothermally altered to propylitic facies make up most of the narrow, snow-covered ridge; the rocks are cut by numerous sheared phyllic-argillic zones and have been mineralized by iron and copper sulfides and oxides. The sheared phyllic-argillic zones are as wide as 15 m, but generally are less than 3 m, and are

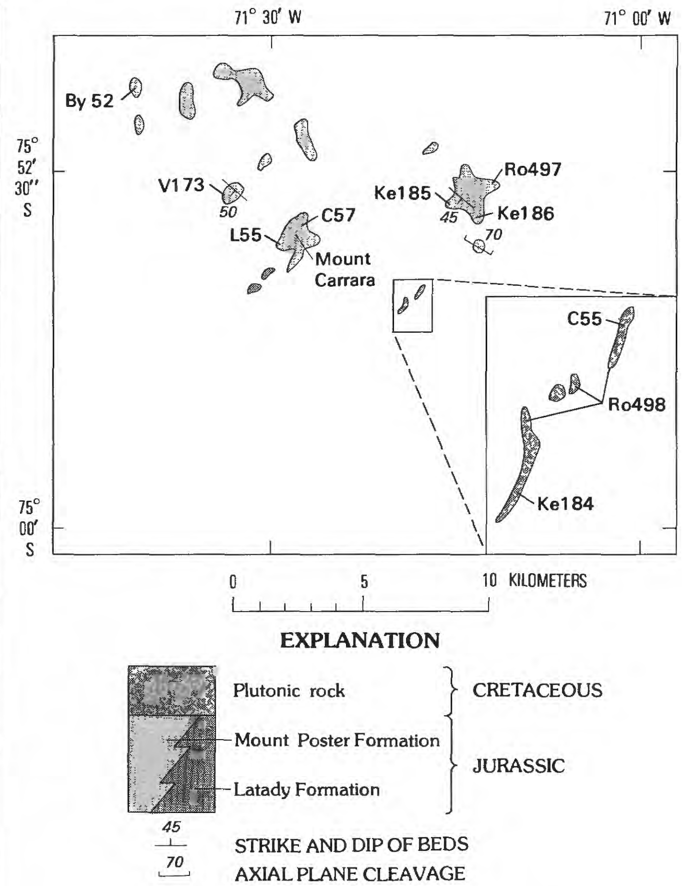

FIGURE 2.—Geologic map of the Sky-Hi Nunataks, showing numbered outcrops referred to in the text. The area in the lower right corner is expanded (dashed lines) to show details of the Ski-Hi porphyry copper deposit. Geology by J. M. Boyles, P. E. Carrara, K. S. Kellogg, T. S. Laudon, P. D. Rowley, M. R. A. Thomson, and W. R. Vennum.

[4]Name proposed in 1985 to the U.S. Board on Geographic Names.

TABLE 3.—*Modal analyses of fresh igneous rocks from the Sky-Hi Nunataks copper deposit, Antarctica*

[Modal analyses given in volume percent; 500 points counted on thin sections and stained rock slabs. Modal analysis of sample Ro498j given in table 2, Tr., trace]

Rock unit------	Granodiorite pluton			Mafic dike	Porphyritic dacite dike			
Sample No.-----	Ro498b	$Ro498d_2$	Ro498m	Ke184c	C55c	Ke184a	Ro498g	Ro498h
Plagioclase----	55.8	53.9	48.0	0	15.8	13.0	9.2	9.0
K-feldspar-----	15.0	10.9	18.2	0	0.2	0	0	0
Quartz---------	15.8	23.0	20.7	0	0.6	0	1.5	0.4
Biotite--------	1.6	2.6	0.8	0	0	0	0	0
Hornblende-----	10.4	2.2	10.2	0	7.4	16.4	12.2	9.6
Chlorite-------	0.4	6.4	0.8	0	Tr.	Tr.	Tr.	0.2
Fe-Ti oxides---	0.8	1.2	1.2	0	0.4	1.2	0.6	0.4
Sphene---------	Tr.	Tr.	Tr.	0	Tr.	0.8	Tr.	Tr.
Apatite--------	0.2	Tr.	Tr.	0	Tr.	Tr.	Tr.	Tr.
Zircon---------	0	0	Tr.	0	0	0	Tr.	0
Epidote--------	0	0	0	0	0	0.6	0	0
Pyrite---------	0	Tr.	0	0	0.2	0.2	0.2	0.8
Leucoxene------	0	Tr.	0	0	Tr.	0.4	Tr.	Tr.
Groundmass------	0	0	0	100.0	75.4	67.4	76.2	79.6

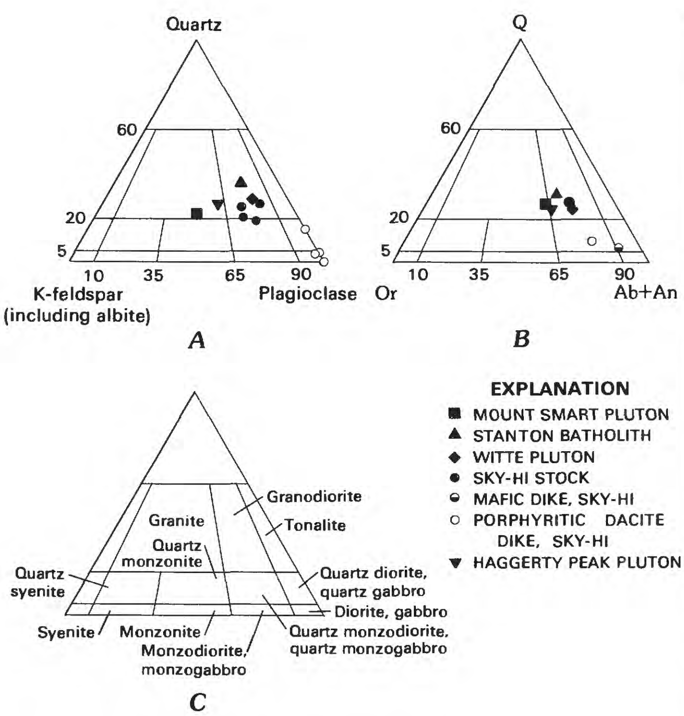

FIGURE 3.—Ternary plots of selected modal and normative minerals from dated igneous units, Orville Coast and eastern Ellsworth Land, Antarctica. Calculated from data in tables 2, 3, and 4, and from unpublished data of P. D. Rowley. Boundaries shown in *A* and *B* follow igneous classification of International Union of Geological Sciences (Streckeisen, 1976) which is shown in *C*. *A*, Modal quartz, K-feldspar, and plagioclase in fresh igneous rocks. Mafic dike of the Sky-Hi stock not plotted. *B*, Normative quartz (Q), orthoclase (Or), and plagioclase (Ab+An) in fresh igneous rocks.

distributed about every 10–20 m or less along the ridge. The zones are identical to zones in the Lassiter Coast copper deposit (Rowley and others, 1977). Most strike north-northeast, perpendicular to the regional strike of the folded rocks (west-northwest) and parallel to extension joints in both plutonic rocks and folded Jurassic rocks. They contain sparse to locally abundant fault planes generally less than a centimeter wide and along which the rock is broken and sheared by relative movement. In most other places in the sheared phyllic-argillic zones, however, the rock is not foliated or does not show any evidence of faulting. The sheared phyllic-argillic zones are recognized by their alteration, consisting mostly of tan to brown crumbly phyllically and subordinate argillically altered rock that weathers to form shallow rounded erosional trenches as deep as 0.5 m. The altered rock in the erosional trenches grades within several centimeters into almost ubiquitous propylitically altered rock. Two alteration events seem to have taken place in the sheared phyllic-argillic zones. The older event was potassic alteration, which may have the same age as the propylitically altered rock that is widespread outside the zones. The younger event was the phyllic-argillic alteration that characterizes most zones; it locally chloritized and sericitized the crystals of presumed potassic hydrothermal biotite.

Mineralized quartz veins, generally less than 1 cm wide, occur sparsely (rarely more than one vein every 5 or 10 m of rock outcrop) and randomly distributed along the ridge. The veins generally strike north-northeast and do not appear to have envelopes of altered rocks. Where quartz veins occur within sheared

TABLE 4.—*Chemical data of selected fresh rocks from the Sky-Hi Nunataks copper deposit, Antarctica*

[Sample localities shown in figures 2 and 4. Kg, granodiorite pluton; Kd, mafic dike; Kp, porphyritic dacite dike; (---) leaders, not present. Analyses of samples Ro498j and Ke184c by D. Hopping and J. Riviello; analysis of sample Ro498g by S. Kramer. Semiquantitative spectrographic analyses of these samples given in table 5]

Rock unit------	Kg	Kd	Kp
Sample no.-----	Ro498j	Ke184c	Ro498g
Chemical analyses (weight percent)			
SiO_2	63.33	50.55	54.23
Al_2O_3	16.41	18.32	18.10
Fe_2O_3	2.66	4.16	4.05
FeO	2.25	6.00	3.93
MgO	1.94	4.85	4.20
CaO	5.48	6.47	8.15
Na_2O	2.85	3.22	2.87
K_2O	2.58	1.07	2.21
H_2O-	.07	.23	.11
H_2O+	.80	3.69	.94
TiO_2	.47	.95	.66
P_2O_5	.17	.09	.19
MnO	.10	.07	.17
Total	99.11	99.67	99.81
CIPW Norms (weight percent)			
Q	22.686	4.102	6.482
C		.318	
Or	15.384	6.344	13.084
Ab	24.335	27.337	24.331
An	24.585	31.614	30.035
Wo	.721		3.854
En	4.875	12.119	10.480
Fs	1.356	6.163	3.103
Mt	3.892	6.052	5.883
Il	.901	1.810	1.256
Ap	.406	.214	.451
Total	99.142	96.073	98.960

TABLE 5.—*Semiquantitative spectrographic analyses of fresh, altered, and mineralized rocks from the Sky-Hi Nunataks*

[Analyses listed by rock units, arranged in the order they are discussed in the text. Sample localities shown in figures 2 and 4. FA, fresh to propylitically altered aplite of younger pluton; FG, fresh to propylitically altered granodiorite; FM, fresh to propylitically altered mafic dike; FO, fresh to propylically altered older mafic pluton; FP, fresh to propylitically altered porphyry dike; FY, fresh to propylitically altered younger silicic pluton; PF, peripheral fresh or slightly mineralized rock; PS, peripheral sheared phyllic-argillic zone; PV, peripheral vein; S, silicified area or quartz vein; SPA, sheared phyllic-argillic zone. Analysis of sample Ro498g by L. Mei; of C57c, C57d, Ro498c, $Ro498d_2$, $Ro498e_2$, $Ro498f_2$, Ro498h, Ro498i, Ro498l, V173f, and V173g by J. L. Harris; and of the rest by J. C. Hamilton. Value of Ce for V173g: 110 ppm; value of Gd for V173g: 21 ppm; value of Li for C57a: 97 ppm; value of Li for C57d: 130 ppm; value of Sn for By52a: 15 ppm; value of Sn for Ro498f: 5 ppm. For all other samples, As, Au, Cd, Ce, Ge, Hf, In, Li, Pd, Pt,

Rock unit	Sample No.	Weight percent								Parts per million										
		Si	Al	Fe	Mg	Ca	Na	K	Ti	Ag	B	Ba	Be	Bi	Co	Cr	Cu	Ga	La	Mn
										Sky-Hi Nunataks										
SPA	Ke184b	G	10	3	.5	5	2	1.5	.2	N	N	300	1.5	N	N	3	30	15	L	2,000
SPA	Ke184d	G	10	2	.7	3	2	3	.2	N	N	500	N	N	N	3	50	20	L	500
SPA	Ro498e	G	10	3	1	5	3	3	.3	1	20	200	1.5	N	10	5	150	20	N	1,000
SPA	$Ro498e_2$	23	7.9	3.5	1.3	3.7	.9	3	.15	<.1	27	410	2	<10	12	3	68	15	19	1,700
SPA	Ro498f	G	10	3	.7	7	5	3	.15	N	L	150	N	N	15	5	150	20	L	1,500
SPA	$Ro498f_2$	20	6.5	3.4	.9	3.4	3.3	1.6	.13	.3	22	140	1	<10	9	2	100	13	19	2,500
SPA	Ro498i	29	7.6	4.1	1.0	2.1	2.8	2.1	.13	.6	<5	270	1	<10	11	4	530	22	17	1,700
SPA	Ro498l	28	7.9	3.9	.6	5.0	2.8	1.3	.13	<.1	<5	370	<1	<10	7	13	210	17	19	1,100
SPA	Ro498n	G	10	2	1	3	3	5	.3	N	N	1,000	N	N	10	5	100	15	N	500
S	Ro498c	29	7.5	3.4	1.0	3.2	2.8	1.8	.17	<.1	7	520	1	<10	11	4	270	16	19	640
S	Ro498d	G	10	3	.7	2	5	2	.2	1.5	N	300	N	N	7	3	700	15	N	500
S	$Ro498d_2$	23	8.8	5.2	.7	2.9	>7	1.5	.15	4	6	290	<1	<10	14	4	800	16	<10	1,000
S	Ro498o	G	10	2	.7	2	2	3	.2	N	N	500	N	N	7	3	150	15	N	300
FM	Ke184c	G	G	10	3	7	5	1.5	3	N	N	700	N	N	50	10	200	30	N	700
FG	Ro498j	G	G	5	1	7	3	3	3	N	N	500	1.5	N	15	7	50	15	N	700
FG	Ro498m	G	10	3	1	5	3	3	.3	N	N	1,000	N	N	15	3	300	15	N	500
FP	Ro498g	24	7.9	6.2	2.4	3.9	1.6	1.8	4	<.1	<10	360	1	<15	18	9	23	17	29	2,200
FP	Ro498h	22	8.6	6.3	2.3	6.7	3.9	1.5	.21	<.1	<7	270	<1	<10	24	10	90	23	17	1,900
PF	V173g	33	7.1	4.1	.8	1.8	2.1	3.9	.35	<.1	<5	870	2	<10	9	33	44	16	48	650
PS	C57c	>34	1.3	.8	.1	.03	.01	.3	.04	7.4	<5	70	1	<10	<1	2	46	3	<10	120
PS	C57d	>34	6.1	2.7	.3	.26	.4	5.2	.19	38	6	680	1	26	6	43	440	12	39	1,500
PV	By52a	G	5	10	1	5	.5	.7	.3	10	N	70	1.5	30	30	15	7,000	15	70	2,000
PV	L55a	G	7	2	.5	3	.7	5	.2	N	N	1,000	N	N	L	15	15	15	L	700
PV	L55b	G	7	5	.7	1	.5	2	.2	5	L	200	1.5	10	20	15	3,000	15	L	700
PV	V173f	>34	1.3	1.9	.2	.6	.1	.1	.04	24	<5	50	<1	24	6	2	2,600	3	<10	330
										Merrick Mountains										
SPA	Ro500c	G	7	7	2	7	3	2	.1	N	N	200	N	N	20	7	70	15	N	1,500
SPA	Ro500k	G	5	3	1.5	1.5	1	1	.2	N	100	150	N	N	15	3	50	15	N	1,000
S	By56d	G	.5	3	.07	.01	N	N	.01	50	N	150	N	700	100	L	500	N	N	70
S	V177c	G	10	5	2	3	.7	3	.3	1.5	30	150	N	N	30	10	10,000	15	N	2,000
S	V178h	G	.5	G	.02	.05	N	.7	.07	1.5	N	20	N	50	L	L	3,000	--	N	300
FO	Ro500h	10	3	G	2	3	.5	.7	1.5	1	N	150	N	N	70	3	1,500	--	N	1,000
FO	Ro501g	G	10	7	2	7	3	3	.5	N	N	500	N	N	20	7	150	30	N	1,000
FO	Ro501h	G	7	7	3	7	2	3	.2	N	N	100	N	N	30	70	2	15	N	1,000
FY	By56f	G	G	7	1.5	5	3	3	.3	N	N	1,000	N	N	15	7	70	20	N	700
FY	Ro500a	G	G	7	1.5	5	3	3	.5	N	N	1,000	N	N	20	7	100	20	N	700
FY	V177a	G	G	10	1.5	7	3	.7	.3	N	N	300	N	N	20	20	100	15	N	700
FY	V178i	G	10	3	.3	1.5	5	5	.15	N	N	700	N	N	7	L	7	15	N	300
FY	V178f	G	10	7	2	7	2	1.5	.3	N	N	300	N	N	30	20	150	15	N	700
FA	V177k	G	10	7	1.5	5	3	3	.3	N	N	1,000	N	N	15	N	30	30	N	700

Merrick Mountains, Antarctica

Re, Sb, Sn, Sr, Ta, Te, Th, Tl, U, and W were not detected or were at limit of detection. For the samples analyzed by Mei and Harris, Dy, Er, Eu, Gd, Ho, Ir, Lu, Nd, Os, Pr, Ru, Sm, Tb, and Tn were less than the limit of detection. G, greater than 10 percent; N, not detected or at limit of detection; L, detected but below limit of detection; leaders (---), not looked for; <, less than; >, more than]

Parts per million										
Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr
Sky-Hi Nunataks--Continued										
3	N	N	15	7	1,000	70	30	3	700	150
7	N	N	10	10	1,000	100	30	3	N	150
N	N	5	30	15	500	100	30	3	N	150
<1	5	5	12	9	280	80	9	2	84	53
N	N	5	20	15	500	70	30	3	N	70
<1	6	4	32	8	450	64	11	2	55	59
10	4	6	12	8	470	76	9	1	69	37
<1	4	4	14	9	830	100	9	1	33	71
3	N	5	N	15	700	100	30	3	N	70
<1	9	5	13	10	640	92	13	2	25	98
N	N	5	30	10	500	70	20	3	N	70
<1	5	6	81	8	320	49	6	1	110	58
30	N	5	N	7	500	70	15	1.5	N	70
N	N	20	N	30	500	300	15	2	N	50
N	N	7	N	15	1,000	150	20	3	N	70
5	N	5	N	15	1,000	100	30	3	N	100
<2	8	17	<7	24	840	230	20	3	48	62
<1	6	12	16	20	750	160	9	2	60	48
<1	11	12	16	19	210	74	37	5	35	230
110	<3	<2	70	2	45	45	6	1	16	45
<1	6	21	1,900	9	140	51	16	2	280	84
N	N	15	200	15	200	50	70	7	700	150
30	10	10	30	15	150	50	30	3	N	150
10	10	15	150	15	100	50	70	5	1,500	150
<1	<3	<2	500	2	97	13	12	1	71	82
Merrick Mountains--Continued										
N	N	7	10	15	200	100	20	3	N	70
N	N	5	50	15	150	70	15	1.5	N	100
N	N	L	200	L	N	7	N	N	N	N
N	N	7	200	30	200	150	30	3	300	50
N	N	L	300	7	N	70	N	--	700	20
N	N	20	10	30	150	500	30	--	500	30
N	10	7	N	30	1,000	200	30	3	N	50
N	N	30	N	30	500	150	15	1.5	N	30
N	10	7	N	20	700	150	30	3	N	70
N	L	7	N	30	700	200	30	3	N	50
N	N	10	N	50	500	300	30	3	N	30
30	N	N	15	7	500	30	30	3	N	100
N	N	20	N	30	700	200	15	3	N	30
N	N	N	N	20	1,000	150	30	3	N	100

phyllic-argillic zones, they are younger than the shearing in the phyllic-argillic zones; their age with respect to the alteration, however, could not be determined. Small irregularly shaped masses of silicified rock locally occur in or adjacent to the sheared phyllic-argillic zones.

Oxidation of the primary sulfide minerals leaves the rocks locally stained by yellow and orange secondary iron minerals and green secondary copper minerals; the yellow and orange stains look like limonite or hematite in hand specimen, and the green stains look like malachite. X-ray studies, however, indicate that here and in other parts of West Antarctica, these all are complex minerals typical of very dry climates (Vennum, 1980; Vennum and Nishi, 1981). The yellow and orange minerals are iron sulphates, mainly minerals of the jarosite group, with or without gypsum. The green minerals are copper sulfates and copper chlorides.

The best exposures of the Sky-Hi stock are on the northern part of the narrow ridge. The rock is a resistant homogeneous light- to medium-gray, medium-grained (1–5 mm) hypidiomorphic-granular granodiorite. It contains subhedral plagioclase, subordinate K-feldspar, quartz, and hornblende, minor biotite and Fe-Ti oxides[5], and traces of sphene, apatite, and zircon (tables 2, 3). Both quartz and K-feldspar crystals are poikilitic. Most plagioclase crystals are zoned. Chlorite is common in fresh to propylitically altered rocks, where it replaces biotite; leucoxene replaces sparse sphene in some rocks. Fine-grained diorite inclusions as long as 5 cm and sparse aplite dikes rarely wider than 5 cm are scattered through the granodiorite. The rocks are cut by subvertical shear joints that strike northwest and subvertical extension joints that generally strike north-northeast; the latter are coated with epidote and chlorite.

Two resistant light- to medium-greenish-gray dikes of dacite porphyry cut the plutonic rocks. One on the northeastern end of the ridge is about 0.5 m wide and strikes north-northeast (sample Ro498g; tables 3, 4); the other crops out as a small exposure at the southwestern end of the ridge where the thickness and strike are indeterminate. Both may represent porphyry intrusions typically associated with porphyry-type mineralization, as in the Lassiter Coast copper deposit. The dike rock consists of sparse to moderately abundant phenocrysts of hornblende and plagioclase, and minor "beta" quartz and Fe-Ti oxides in an aphanitic groundmass of plagioclase, K-feldspar, quartz, hornblende, and Fe-Ti oxides (table 3). Both dikes are locally altered and mineralized. A third dike consists of aphanitic, somewhat more mafic rock (sample Ke184c; tables 3, 4), is as much as 6 m wide, and strikes northwest.

Pyrite is disseminated throughout the intrusive rocks of the ridge. Pyrite, as well as magnetite and chalcopyrite

[5]Opaque minerals, consisting of magnetite, ilmenite, pyrite, and related minerals, which contain iron and (or) titanium.

in many places, also occurs in quartz veins. Despite the presence of primary and secondary metallic minerals in the Sky-Hi stock, average metal additions to the intrusive rocks are low. Semiquantitative spectrographic analyses (table 5) show only small additions in copper and, in places, zinc, lead, molybdenum, and silver whether the samples were collected from sheared phyllic-argillic zones (9 samples: 30–530 ppm Cu, 15–700 ppm Zn, 7–30 ppm Pb, 1-10 ppm Mo, 0.1-1 ppm Ag), silicified areas and quartz veins (4 samples: 150–800 ppm Cu, 15–110 ppm Zn, 7–80 ppm Pb, 1–30 ppm Mo, 0.1–4 ppm Ag), fresh to propylitically altered granodiorite or mafic dikes (3 samples: 50–300 ppm Cu, 1–5 ppm Mo, 15–50 ppm Co), or fresh to propylitically altered porphyry dikes (2 samples: 20–90 ppm Cu, 50–60 ppm Zn, 7–16 ppm Pb). On the basis of these analyses from outcrops C55, Ke184, and Ro498 on the ridge, it is doubtful that the average metal additions to the rocks of the ridge exceed 200 ppm Cu and 50 ppm Zn.

Higher metal additions occur in peripheral hydrothermal quartz veins that cut volcanic country rocks elsewhere in the Sky-Hi Nunataks. These veins are most abundant in nunataks close to, and northwest of, the Sky-Hi stock (table 5). At outcrop C57 (Mount Carrara[6]), abundant north-northeast-striking sheared phyllic-argillic zones as much as 3 m wide and locally overlapping north-northeast-striking quartz veins contain pyrite and magnetite. One sample from a sheared phyllic-argillic zone at this outcrop has moderate amounts of molybdenum (110 ppm) and silver (7 ppm), and low amounts of lead (70 ppm) and copper (50 ppm); whereas, another sample from another nearby zone has moderate amounts of silver (40 ppm), lead (1,900 ppm), zinc (260 ppm), and copper (440 ppm). At outcrop L55 (Mount Carrara), north-northeast-striking locally brecciated quartz veins and mineralized sheared phyllic-argillic zones as much as 7 m wide contain pyrite, secondary iron minerals, and secondary copper minerals. In one of these zones, moderate concentrations of copper (3,000 ppm), zinc (1,500 ppm), lead (150 ppm), and silver (5 ppm) occur in a rock containing magnetite, chalcocite(?), and secondary copper minerals. In a quartz vein containing secondary copper minerals in another sheared phyllic-argillic zone at this outcrop, low values of molybdenum (10 ppm) and lead (30 ppm) were noted.

At outcrop V173 farther west, a 1-m-wide, west-northwest-striking sheared phyllic-argillic zone contains secondary copper minerals. A nearby float sample of a quartz vein containing magnetite, pyrite, chalcopyrite, and secondary copper minerals contains moderate values of copper (2,600 ppm), lead (500 ppm), and silver (24 ppm), and low values of zinc (70 ppm). A bedrock sample of porphyritic rhyodacite containing pyrite cubes, from elsewhere on the nunatak, however, is essentially barren of added base and precious metals. Two other sheared zones, one striking east and the other north, are as wide as 7 m but have no visible metallic minerals and were not sampled. Still farther northwest (By52), east-striking copper-stained quartz veins in porphyritic rhyodacite have moderate concentrations of copper (7,000 ppm), zinc (700 ppm), lead (200 ppm), and silver (10 ppm). Other quartz veins at this outcrop, not analyzed, strike north-northeast but have no recognizable metallic minerals. North of the Sky-Hi stock, at outcrops Ke185 and Ro497, quartz veins in porphyritic rhyodacite are barren, and at Ke186, a locally silicified sheared phyllic-argillic zone, 0.5 m wide and striking north-northwest, contains oxidation products of iron oxides and sulfides.

Microscopic study shows that most rock in the sheared phyllic-argillic zones is of the phyllic alteration facies. In other words, the rocks have been almost totally sericitized. Hornblende and biotite have been converted to sericite and subordinate chlorite and pyrite. Quartz generally is the only remaining primary mineral, and locally it grew during alteration. Most primary Fe-Ti oxide minerals have been altered to pyrite. Pyrite also was introduced along joints in or near phyllic-argillic zones. Sheared and foliated recrystallized rock is seen in some thin sections from the zones; in most places this sheared rock is of argillic facies. Most argillically altered rock occurs, however, at the edges of phyllic-argillic zones. In argillically altered rock, plagioclase is generally converted to montmorillonite and kaolinite, K-feldspar is partly converted to sericite, hornblende, and biotite are partly converted to chlorite and subordinate epidote, and Fe-Ti oxides are partly converted to pyrite and leucoxene.

Microscopic study shows that the propylitically altered rocks contain small amounts of the same alteration products as argillically altered rocks. Epidote and chlorite are especially noticeable in rocks of this alteration facies. Potassic alteration, which form the highest temperature facies of alteration in many porphyry mineral deposits, is weakly developed in the Sky-Hi Nunataks. It is recognized only by the presence, as seen in thin section, of very fine grained subhedral sucrose aggregates of hydrothermal light-brown biotite, perhaps locally associated with tiny masses of rutile, replacing primary hornblende.

MERRICK MOUNTAINS COPPER DEPOSIT

The Merrick Mountains area was first mapped during the 1965–66 field season (Laudon and others, 1969; Laudon, 1972). It was mapped in greater detail during the 1977–78 season, at which time evidence of alteration and copper mineralization was recognized. The area is underlain mostly by the Merrick Mountains stock of the Lassiter Coast Intrusive Suite (fig. 4). Vennum and

[6]Name proposed in 1985 to the U.S. Board on Geographic Names.

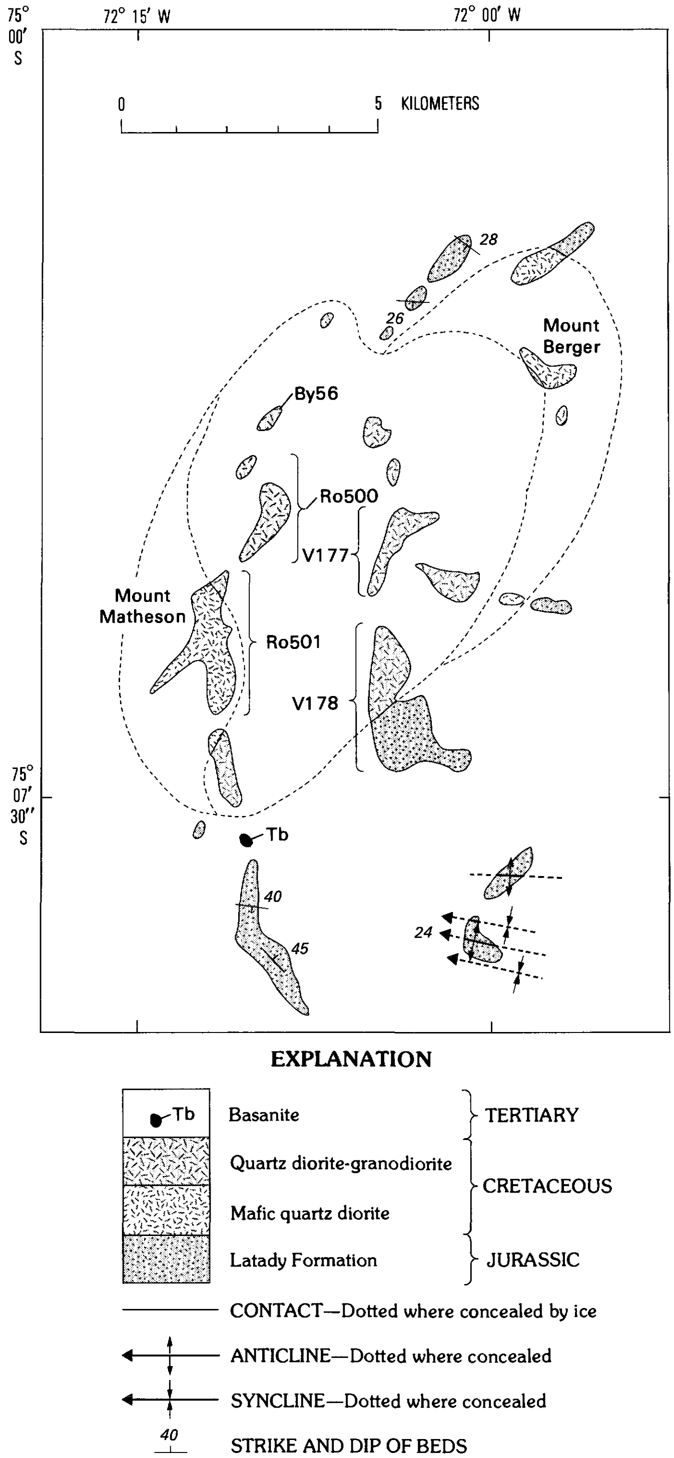

FIGURE 4.—Geologic map of the Merrick Mountains showing numbered outcrops referred to in the text.

Laudon (chap. B, this volume) discuss the petrology and chemistry of the stock; table 5 presents semiquantitative spectrographic analyses of fresh, altered, and mineralized rocks of the stock. The stock was emplaced into folded sedimentary rocks of the Latady Formation that strike west-northwest. The Latady Formation, which locally contains marine invertebrate fossils, is interbedded with lava flows and is intruded by sill-like masses. A Miocene(?) hyaloclastite basanite (that is, an alkaline basalt) lava flow underlies a small nunatak in the southwestern part of the range.

The Merrick Mountains stock was named by Vennum and Laudon (chap. B, this volume) for plutonic rock exposures in the central part of the range. As in many other places in the southern Antarctic Peninsula, including the Lassiter Coast copper deposit, the pluton is composite. It consists of an older semiconcentric outer body of black mafic quartz diorite intruded by a younger, gray, concentrically zoned quartz diorite to granodiorite body in which the most silicic rocks are near the center. Both plutonic bodies are hypidiomorphic-granular in texture and contain mafic inclusions. The younger body, and perhaps also the older body, are intruded by aplite and pegmatite dikes. Dark mafic dikes were emplaced at the close of both periods of plutonism; most strike northwest. Tan rhyodacite porphyry dikes, as wide as 10 m and mostly striking northerly, were emplaced after the mafic dikes of the younger plutonic body (chap. B, this volume). The porphyry dikes contain sparse to moderately abundant phenocrysts of "beta" quartz and subordinate plagioclase and K-feldspar in a fine-grained silicic groundmass (chap. B, this volume). Joints appear to be randomly oriented in the Merrick Mountains stock.

On the summit and southern flank of Mount Matheson (outcrop Ro501), the older mafic plutonic body is "crackled" by numerous (locally as abundant as one shear plane about every 10 cm) randomly oriented, black or gray, narrow (generally less than 2 cm wide) shear planes of minor displacement. Shearing appears to predate the younger plutonic body. No metallic minerals were found associated with the shear planes, in contrast to lithologically similar black and gray shear fractures containing pyrite in the Lassiter Coast copper deposit.

Magnetite, pyrite, and chalcopyrite, as well as secondary iron and copper minerals, are scattered throughout both intrusive bodies in both disseminated form and in widely scattered quartz veins (table 5). The wall rock surrounding the quartz veins apparently is not highly altered. Small amounts of copper and lead were noted in sheared phyllic-argillic zones (2 samples: 50–70 ppm Cu, 10–50 ppm Pb) from the southern flank of Mount Matheson (outcrop Ro501). Moderate to high amounts of copper, lead, silver, zinc, bismuth, and cobalt occur in quartz veins containing chalcopyrite from outcrops By56 and V178 and in quartz veins containing secondary copper minerals from outcrop V177 (3 samples: 500–10,000 ppm Cu, 200–300 ppm Pb, 2–50 ppm Ag, 15-700 ppm Zn, 10-700 ppm Bi, and 1-100 ppm Co). Low to moderate amounts of copper, zinc, cobalt, and chromium were noted in fresh to propylitically altered rocks of the older mafic body from outcrops Ro500 and Ro501 (3 samples: 2-1,500 ppm Cu, 15-500 ppm Zn, 20-70 ppm Co, 3-70 ppm Cr). Low amounts of copper or molybdenum occur in fresh to propylitically altered rocks of the younger plutonic body, including an aplite, at outcrops By56, Ro500, V177, and V178 (6 samples: 7-150 ppm Cu, 1-30 ppm Mo). It is doubtful whether the average grade of metal values in the stock exceeds 100 ppm copper.

Sheared phyllic-argillic zones, as wide as 20 m, occur scattered through rocks in the western and southern parts of the Merrick Mountains stock. On parts of the summit and northern flank of Mount Matheson, the zones are almost as abundant (one every 20 m or less of rock exposure) as they are in the Sky-Hi copper occurrence, but elsewhere they are not abundant. Mineralized and hydrothermally altered rocks also are most abundant in the Mount Matheson area. The sheared zones appear to postdate all plutonic rocks and all dikes. Most zones strike north to northeast, parallel to extension joints, and they consist largely of phyllically altered rock. They are similar in field and petrographic appearances to those in the Sky-Hi and Lassiter Coast copper deposits. Silicified areas in which fine grained to coarsely crystalline quartz replace plutonic rock are visible locally within the zones.

Potassic alteration resulted in very fine grained, brown and light-brown, hydrothermal biotite, locally associated with tiny masses of apparent rutile, replacing hornblende in crackled older mafic plutonic rocks and in some dikes (chap. B, this volume, table 1, sample Ro501h) on the southern flank of Mount Matheson. Propylitic alteration, perhaps related in age to the potassic alteration, affected most parts of the Merrick Mountains stock. In some places, the older mafic quartz diorite is argillically or phyllically altered even where sheared phyllic-argillic zones are absent. Similarly, rhyodacite porphyry dikes may be almost entirely altered to argillic, or less commonly, to phyllic facies even where adjacent plutonic rock is of propylitic facies.

DISCUSSION

The Lassiter Coast, Sky-Hi, and Merrick Mountains copper deposits contain the most significantly hydrothermally altered and mineralized rocks recognized in the southern Antarctic Peninsula and eastern Ellsworth Land. None of them, however, are economically important. K-Ar dating indicates that these mineral deposits span the age of the Lassiter Coast Intrusive Suite; thus, copper mineralization probably developed in upper parts of many other plutons of this suite. In contrast to these three moderately mineralized plutons, however, most other plutons of the Lassiter Coast Intrusive Suite are fresh or contain only widely scattered sheared phyllic-argillic zones and very small amounts of pyrite, magnetite, chalcopyrite, and molybdenite crystals or small clusters of crystals, as well as related secondary minerals (Rowley and others, 1977; Rowley and Pride, 1982; Rowley, Ford, and others, 1983). These other mostly barren plutons may have been eroded to deeper structural levels than the three copper-bearing plutons, or they were never mineralized as much as the three copper-bearing plutons.

The host rocks of the three copper deposits are hypidiomorphic-granular plutonic rocks ranging from a concentrically zoned body of mostly granite (Lassiter Coast deposit) through granodiorite (Sky-Hi deposit) to a concentrically zoned body of mostly quartz diorite (Merrick Mountains deposit). All plutons appear to be partly syntectonic, due perhaps to intrusion in a residual stress field. This conclusion is made because orientation of extension joints, porphyry dikes, and shear zones are more or less parallel to extension joints in the folded Jurassic wall rocks. The plutons of all three deposits are cut by silicic porphyry dikes emplaced during the latest stages of the intrusive activity that predates hydrothermal alteration and mineralization. These dikes may represent the igneous material from which hydrothermal solutions were derived that altered and mineralized the rocks, or the dikes may have provided the heat by which meteoric solutions altered and mineralized the rocks. The plutonic events that led to the main mineralization and alteration were preceded in the Copper Nunataks and Merrick Mountains by a plutonic event of more mafic material that terminated in dike intrusion and in breaking (crackling) the mafic rocks along closely spaced and randomly oriented fractures.

Alteration and mineralization patterns and metallic mineral contents are remarkably similar in all three deposits. Most mineralized rocks apparently occur in quartz veins and disseminations. The major added primary minerals are pyrite, magnetite, chalcopyrite, and molybdenite. The main metal additions were iron, copper, lead, molybdenum, zinc, and silver. Regional minor potassic alteration, indicated only by sparse development of hydrothermal biotite—and possibly related regional propylitic alteration—probably predated the development of sheared phyllic-argillic zones, which are oriented parallel to regional extension joints. These sheared zones are conspicuous features that are either widely scattered or densely distributed. Phyllically altered rock dominates in the zones; silicified rocks occur in localized patches within the zones, as are to be expected in areas of sericitic alteration.

Altered and mineralized rocks of the Lassiter Coast, Sky-Hi, and Merrick Mountains deposits bear resemblances to the classical porphyry copper system (Lowell and Guilbert, 1970) in geologic setting, in primary disseminated or quartz-vein ore minerals, in principal metal additions, and in associated potassic, phyllic, argillic, and propylitic alteration facies. None of our three mineral deposits, however, appears to have the grade or areal extent of commercial porphyry ore deposits. Nor are fractures or quartz veins as closely spaced as in commercial ore bodies. Fluid inclusions in quartz grains from fresh and altered rocks of all plutonic bodies and porphyry dikes of the three mineral deposits do not contain evidence (cubic crystals) of the high salinity typical of porphyry copper deposits (for example, Nash, 1976); inclusions are small (generally less than 5 microns) and relatively sparse; they consist of either a vapor phase or a vapor plus liquid phase.

Whereas some of the differences between our three deposits and commercial porphyry deposits may be attributable to lack of exposures due to snow and ice covers, certain differences cannot be explained by such lack of exposures. One of the most significant of these differences is the fact that the host rocks of all three deposits are plutonic rocks of hypidiomorphic-granular texture—not the shallow silicic plutons consisting of phenocrysts set in a fine-grained groundmass that normally are the hosts for, and provide the name to, porphyry copper deposits. Probably the three deposits formed at a deeper level than those normally associated with classical porphyry deposits. In fact, no trace of any volcanic cover that probably overlay plutons of the Lassiter Coast Intrusive Suite has been recognized in the southern Antarctic Peninsula and eastern Ellsworth Land. Furthermore, only the "crackle" net in the older, more mafic intrusive bodies of the Lassiter Coast and Merrick Mountains deposits resembles the fine-scale fracturing characteristic of classical porphyry deposits. Perhaps the older, more mafic bodies did not intrude to as shallow a level in the crust as did the younger, more silicic bodies; if so, the present level of erosion has exposed features in the upper part of the more mafic bodies and features in the lower parts of the younger silicic ones.

The roots of porphyry ore deposits have not been well studied, although Lowell and Guilbert (1970) and Sillitoe (1973) have presented models that suggest that as one passes downward through the porphyritic cupola into its related hypidiomorphic-granular stock, the most likely alteration grade is potassic and propylitic, quartz veins become more important relative to disseminated sulfides, magnetite becomes more abundant than pyrite, and shatter nets are less likely. Below porphyry deposits, rocks are probably hypidiomorphic-granular, unaltered, and unmineralized (Sillitoe, 1973), as in most exposed barren plutons. Cox and others (1981) were the first to describe a possible root zone, in which quartz grains in the hypidiomorphic-granular plutonic rocks contain fluid inclusions typical of porphyry deposits, but the rocks are low in copper. Hydrothermal biotite is absent in hypidiomorphic-granular plutonic rocks, indicating that the potassic alteration zone dies out at depth (Cox and others, 1981).

Another way to look at porphyry-type deposits that formed at greater depths in hypidiomorphic-granular plutonic host rocks is the "plutonic porphyry" model of Sutherland Brown (1969, 1976) and Sutherland Brown and others (1971). Several such deposits occur in the Canadian cordillera, as in the Highland Valley, Brenda, Gibraltar, and Endako areas (Field and others, 1974; Drummond and others, 1976; Kimura and others, 1976; McMillan, 1976; Nielsen, 1976; Soregaroli and Whitford, 1976; Sutherland Brown, 1976). Others occur at Butte, Montana (Miller, 1973; Brimhall, 1979); Glacier Peak, Washington (Grant, 1969); Papua New Guinea (Grant and Nielsen, 1975); the Philippines (Bryner, 1969), and other areas (Nielsen, 1976). With the "plutonic porphyry" model, ore deposits commonly occur in concentrically zoned plutons that have undergone complex multiple intrusive activity. Younger dikes or small bodies of silicic porphyry commonly are genetically linked with the mineralization and alteration. The mineral deposits commonly are controlled by faults, fractures, or porphyry dikes. Pyritic areas are generally sparsely mineralized. In the plutonic porphyry model, mineralization and alteration lack the obvious concentric patterns of high-level classical porphyry deposits; instead, they are largely confined to a regular parallel or conjugate vein set. Alteration, especially of potassic grade, tends to be weakly developed in plutonic porphyry deposits; potassic alteration may be represented almost entirely by the introduction of hydrothermal biotite. Phyllic alteration may be confined to fracture zones or veins. Most of these characteristics are similar to those of the three deposits in the southern Antarctic Peninsula.

In Antarctica, minor copper deposits have been recognized within Mesozoic and Cenozoic hypidiomorphic-granular plutonic rocks on Livingston Island, Anvers Island, Adelaide Island, and the Argentine Islands, all off the western coast of the northern Antarctic Peninsula (Rowley and Pride, 1982; Rowley, Williams, and Pride, 1983, in press; Rowley, Ford, and others, 1983). All these may be of the plutonic porphyry type. Of these, the one on Anvers Island includes "dike-like bodies of recrystallised mylonite" affected by high-grade alteration (Hooper, 1962) that resemble the sheared phyllic-argillic zones we mapped. Of the deposits, a mineralized but noneconomic deposit in the Argentine Islands has been described in greatest detail (Hawkes and Littlefair, 1981); its northern part contains quartz-magnetite veins and sparse quartz-molybdenite-chalcopyrite and quartz-pyrite veinlets as well as potassically and propylitically altered rocks in plutonic rocks of 57-56 m.y. and within Upper Jurassic or Lower Cretaceous volcanic rocks intruded by the plutonic rocks. Hawkes and Littlefair (1981) considered the deposit to represent the root zone of a porphyry copper system. An adjacent area of propylitic-altered volcanic wall rocks contains linear sheared phyllic zones like the sheared phyllic-argillic zones we describe previously. Hawkes and Littlefair (1981) have suggested that the area of propylitic alteration and sheared phyllic zones is an upper peripheral part of the deposit that has been dropped down along a fault. On the basis of the geologic similarity of the Argentine Islands with the three deposits in the southern Antarctic Peninsula, it seems equally possible that this area of propylitic- and phyllic-altered rocks underwent no displacement or could even have been upthrown.

CONCLUSIONS

Ericksen (1976), Rowley and Pride (1982), and Rowley, Ford, and others (1983) have noted that the southern Andes of South America and the Antarctic Peninsula are nowhere near as rich in metal deposits as the northern and central Andes. Rowley and Pride (1982) suggested that the break between the metal-rich and metal-poor parts occurs where the Chile Ridge is subducted beneath southern Chile, at about 45° S. lat. The difference in mineralization may be related to different subduction histories north and south of the Chile Ridge during Cenozoic and perhaps also late Mesozoic time. Compared to the oceanic plate north of the Chile Ridge, the oceanic plate to the south experienced a complex subduction history (Herron and Tucholke, 1976) and may have been warmer, thinner, softer, lighter, and younger (Forsyth, 1975; DeLong and Fox, 1977; Rowley, 1983). Relative to the northern and central Andes, plutons in the Antarctic Peninsula—including the three we discuss in this report—may have been less rich in metals or availability of meteoric water, may have had less favorable heat-volatiles-pressure conditions, may have been emplaced at different crustal levels, may have been generally older, or may have been more deeply eroded following emplacement.

The Lassiter Coast, Sky-Hi, and Merrick Mountains copper deposits resemble deeply eroded porphyry (that is, plutonic porphyry) deposits. We cannot answer with certainty whether the mineral occurrences we have mapped get richer at depth or whether they pass into unaltered and unmineralized plutonic rock. We suspect the latter, however, because the host plutons are among the most westerly of all plutons mapped in the area. In other words, the plutons are close to the topographic axis of the Antarctic Peninsula and are not as deeply eroded as those exposed farther east, at lower altitudes closer to the coast. The lower altitude, eastern plutons are generally fresh. Plutonic rocks that are exposed even closer to the topographic axis than those described here are even more likely to contain mineralized and altered rocks, for they may not be as deeply eroded.

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