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NOTES ON THE PETROLOGY OF NEPHELINE GNEISSES NEAR MOUNT COPELAND, BRITISH COLUMBIA

K. L. Currie

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PREFACE

The origin and development of nepheline-bearing gneisses have been petrological problems of special interest to Canadian geologists since the pioneering work of F. D. Adams and A. E. Barlow in the Bancroft region of Ontario, some 70 years ago. The occurrence at Mount Copeland is unusually well exposed, both on surface and in underground workings, and the author uses these favourable conditions to show that rocks of igneous parentage are more widespread than expected from the distribution of the syenite. The formation of this particular nepheline gneiss is shown to lead to concentration of molybdenite, forming a deposit now commercially exploited.

The formal objectives of the Geological Survey include ascertaining Canada's energy and mineral resources, facilitating their exploration and development, and promoting regional development. Studies such as those carried out by Dr. Currie contribute directly to these objectives and thus to Canada's economic well-being.

D. J. McLAREN
Director-General
Geological Survey of Canada

OTTAWA, 30 January, 1975

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NOTES ON THE PETROLOGY OF NEPHELINE GNEISSES NEAR MOUNT COPELAND, BRITISH COLUMBIA

Abstract

The rocks west and southwest of Mount Copeland comprise a metasedimentary sequence lying on the southern flank of a gneiss dome. Repeated sequences of pelitic, quartzitic, and calcareous schists overlie the core zone of migmatitic and granitoid gneisses. Alkaline, nepheline-bearing syenite gneiss occurs at a fixed stratigraphic level within this sequence, but other metamorphosed alkaline rocks, ranging in chemical composition from syenite to alkaline basalt to nephelinite, are found at various stratigraphic levels. The disposition and range in composition of the alkaline rocks suggest that they originate from an alkaline igneous complex, probably emplaced in the form of a stratified sill or series of sills and dykes. Petrochemical considerations suggest that none of the alkaline rocks are of volcanic derivation.

Sedimentary and igneous rocks were deformed together during prograde metamorphism, reaching peak conditions of 650°C and 5.7 kb. The rocks were later deformed again under lower, though unspecified, P-T conditions, and they now appear in the form of complex, mainly isoclinal and overturned, folds, with strongly attenuated limbs. Late tensional, brittle fractures are occupied by unusual alkaline ultrabasic dykes emplaced 45 m.y. ago.

The peak metamorphism led to a certain amount of anatexis melting in compositionally favourable beds, including a marginal, saturated phase of the syenite, resulting in a complex of aplitic syenite schlieren and dykes. The process of anatexis led to concentration of molybdenum in the melt and formation of a molybdenite deposit now being commercially exploited.

Résumé

Parmi les roches de l'ouest et du sud-ouest du mont Copeland se trouve une série métamorphique d'origine sédimentaire qui s'étend sur le flanc sud d'un dôme de gneiss. Des séries répétées de zones pélitiques, quartzitiques et calcaires recouvrent la zone centrale, constituée de gneiss migmatiques et granitiques. A un niveau stratigraphique précis de cette série se trouvent des gneiss syénitiques alcalins contenant de la néphéline, mais, à divers niveaux stratigraphiques, se trouvent d'autres roches alcalines métamorphiques dont la composition chimique s'étend de la syénite à la néphélinite en passant par le basalte alcalin. La répartition et l'étendue de la composition des roches alcalines laissent supposer qu'elles proviennent d'un complexe igné alcalin, qui s'est probablement installé sous forme d'un sill stratifié ou d'une série de sills et de dykes. Selon des considérations d'ordre pétrochimique, aucune de ces roches alcalines ne résulte de phénomènes volcaniques.

Les roches sédimentaires et ignées ont été déformées au même temps qu'elles ont été affectées par un métamorphisme dont les conditions ont atteint leur paroxysme à 650°C et 5,7 kb. Ces mêmes roches ont subi une déformation ultérieure à des températures et des pressions moindres, de valeur encore indéterminées, et apparaissent aujourd'hui sous forme de plis complexes, surtout isoclinaux et renversés, dont les flancs sont grandement atténués. Des fractures tardives dues à la tension sont remplies de dykes ultrabasiques alcalins qui s'y sont insérés il y a 45 millions d'années.

Le métamorphisme à son paroxysme, provoquant ainsi une fusion anatexique, a produit une certaine quantité de matériaux types localisés dans les couches dont la composition y était favorable; ces couches renfermant aussi une alternance saturée de syénite, en bordure, ce qui a concouru à former un complexe de schlieren et de dykes de syénite aplitique. La fusion anatexique a provoqué une concentration de molybdène et la formation d'un gisement de molybdénite qui fait de nos jours l'objet d'une exploitation commerciale.

INTRODUCTION

Alkaline, nepheline-bearing gneisses occur as a narrow fringe around the southern and western margins of the Frenchman's Cap gneiss dome, in the northern part of the Shuswap Metamorphic Complex (Reesor, 1970). The thickest and best exposed sequence of such gneisses is near Mount Copeland, some 21 km northwest of Revelstoke.

Mount Copeland is easily reached from Revelstoke via a good mining and lumbering road leaving the Trans-Canada Highway 5 km west of Revelstoke and running up the Jordan River valley for about 14 km to the mouth of Hiren Creek. From there a mining company road runs

another 15 km to the west along the valley of Hiren Creek to the formerly producing molybdenum mine of King Resources Ltd., lying about 2 km southwest of the peak of Mount Copeland at an elevation of 1,890 m (Fig. 1). All parts of the map-area south of the crest of the ridge west of Mount Copeland can be reached by easy climbs from this mine road. The northern flank of the ridge can be reached by climbing down from the north portal of the adit driven through the ridge by King Resources Ltd. or, with more difficulty, from a lumber road running up the Jordan River to the mouth of Copeland Creek, and thence by a poor trail up the creek valley.

Mount Copeland lies within the Gold Range of the Monashee Mountains, a terrain characterized by east-west ridges separated by steep-walled creek valleys—in the present



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FIGURE 1. Mount Copeland Mine, King Resources Ltd., showing the timbered slopes of the south face of Mount Copeland and the headwaters of Hiren Creek.

case, Copeland Creek to the north of Mount Copeland and Hiren Creek to the south. Above an altitude of about 2,000 m, the land is relatively flat or gently rolling, consisting of alpine meadows and lakes, with relatively rare rock prominences such as Mount Copeland rising as high as 2,607 m (8,472 feet). The north slopes of the ridge are rocky and precipitous, supporting little vegetation down to relatively low levels and hosting a large glacier and snowfield near the top. The south side of the ridge is much gentler in slope and is densely covered with trees, right up to the treeline. Outcrop is therefore continuous on the north side of the ridge and less complete, although still excellent, on the south side.

Previous Geological Work

Alkaline rocks in the Mount Copeland region were first identified by Wheeler (1965) in the course of regional mapping. Mount Copeland formed part of an area studied in detail by Fyles (1970), whose principal object was elucidation of a stratabound lead-zinc deposit on the north side of the ridge, just north of Mount Copeland. The field work of Fyles (1970) was completed before the construction of the road to the Mount Copeland Mine and before completion of the adit through the ridge. McMillan (1973) studied the alkaline gneisses just west of the map-area, in the Perry River district.

Scope of Present Study

The present study was undertaken to determine the origin and development of the alkaline rocks, a petrological problem of considerable economic interest because the molybdenite deposit exploited by the Mount Copeland Mine lies within them. The detailed map resulting from the work of Fyles (1970) was used as a basis for further mapping—in particular, subdivision of the igneous rocks—and sampling of the stratigraphic units proposed by Fyles. During six

weeks of field work in 1969 and 1970, about 70 km² were mapped (Fig. 14, *in pocket*) with the aid of air photographs, using foot traverses from the Mount Copeland Mine. This covered all of the map-area except the extreme northeastern corner, data for which have been taken without alteration from Fyles' (1970) map. In addition, a small amount of underground mapping was done in the workings of the mine.

The laboratory work included routine petrographic examination of 171 thin sections as well as universal stage and electron probe examination of genetically significant minerals. A total of 21 new chemical analyses and 2 new radiometric age determinations were included in the work.

Acknowledgments

This study was made possible only by the unstinting assistance of King Resources Ltd. and the staff of the Mount Copeland Mine. I wish to thank in particular Mr. J. M. Patterson, Senior Mining Geologist, and Mr. Bob Friesen, Mine Geologist. I have also benefited from correspondence with Mr. George A. Wilson, geological consultant, of Calgary. The chemical analyses were made by Geological Survey staff under the direction of J. L. Bouvier, and the electron probe analyses were made by G. R. Lachance.

The debt to the work of the British Columbia Department of Mines and Petroleum Resources is obvious. In addition to permission to use Dr. J. T. Fyles' work, previously noted, the department supplied a base map for compilation of the data. Dr. Fyles and Dr. W. J. McMillan, British Columbia Department of Mines and Petroleum Resources, read the manuscript, making substantial suggestions for improvements. Dr. J. E. Reesor, Geological Survey of Canada, provided invaluable advice and criticism on problems of 'Shuswap geology.'

DESCRIPTIONS OF THE ROCK-UNITS

The nepheline-bearing gneisses of the Mount Copeland area lie within the Shuswap Metamorphic Complex (Reesor, 1970), a belt of metamorphic rocks in the core zone of the eastern Cordilleran Fold Belt (Wheeler, 1965). Along the eastern margin of the belt there is a series of gneiss domes at 50- to 75-km intervals. They are composed of migmatitic granitoid cores mantled by intricately deformed metasedimentary rocks (Fig. 2). The northernmost, the Frenchman's Cap dome, is the only one known to contain alkaline gneisses, which lie within the mantling metasedimentary rocks. Both the derivation and the metamorphism of these mantling gneisses are clouded by controversy and uncertainty. They are thought to be derived from Paleozoic and latest Precambrian sedimentary sequences, but satisfactory identification with particular formations or groups has not been achieved in the Frenchman's Cap dome. Work by Reesor and Moore (1971) and by Froese (1971) to the south of this dome suggests that metamorphic gradients can be very steep within the Shuswap terrane, and caution must therefore be exercised in speaking of 'grade of metamorphism' when applied to large areas.

The rocks west of Mount Copeland consist mainly of

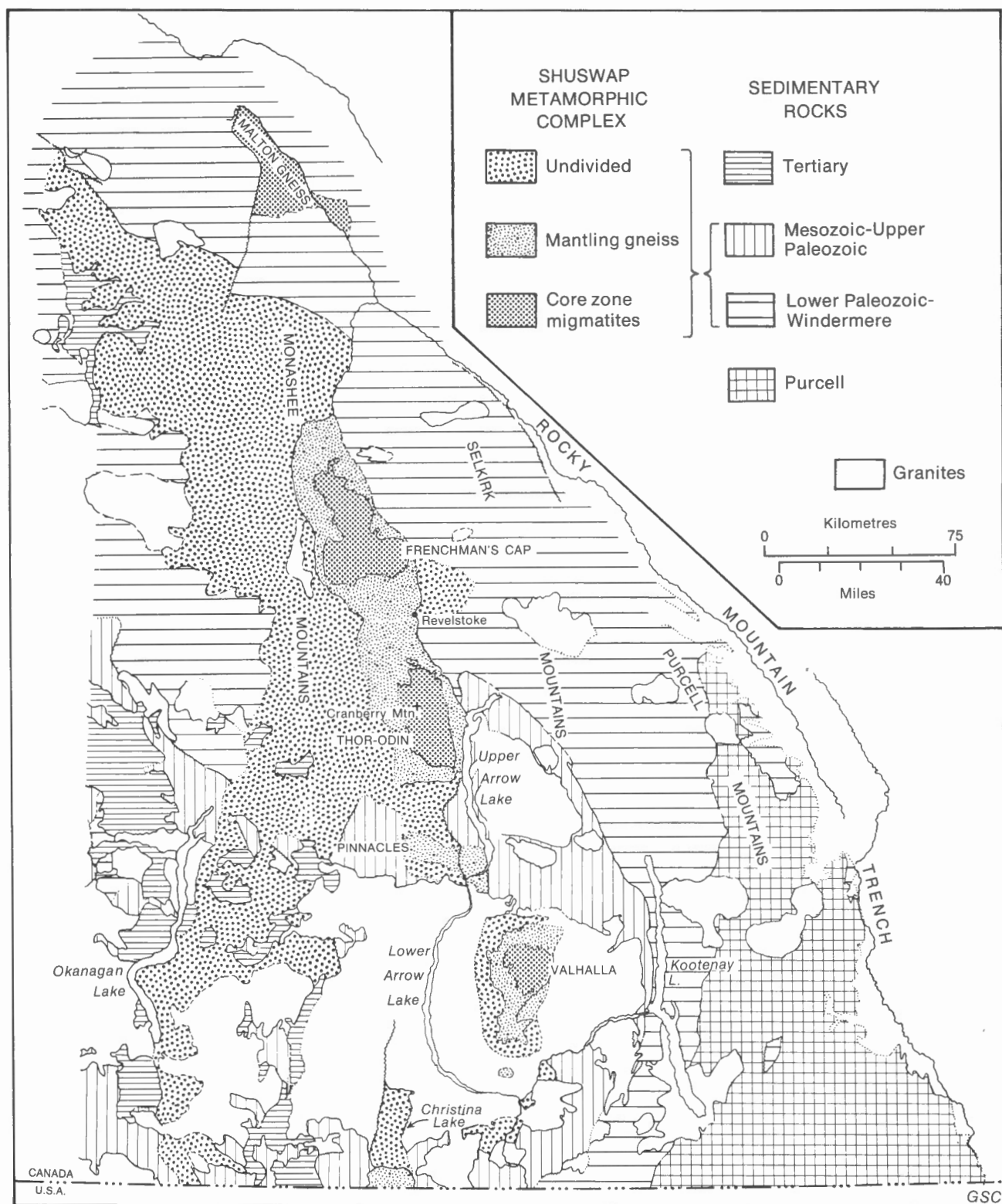


FIGURE 2. Generalized regional map, showing the location of major gneiss domes and the Shuswap Metamorphic Complex (after Reesor, 1970).

Table of Formations

Unit number Fyles 1970	Unit number	
	12	Area of little or no rock outcrop, mainly covered by talus, glacial deposits, recent stream gravels, or snow and ice accumulations
	11	unconformity Black to brownish lamprophyre dykes, ocellar in some cases intrusive contact
10	10	10a, Interlayered biotite schist and fine-grained grey biotite gneiss, with prominent augen gneiss zones; 10b, minor granitoid gneiss gradational contact
9	9	Blocky white quartzite containing biotite schist layers. Characterized by layers of massive, coarse-grained, transparent quartz gradational contact
8	8a	Finely banded bronzy mica schist, commonly containing numerous quartzite layers at top, with calc-silicates and marble at base gradational contact
8	8	Strongly banded purplish quartz-diopside-biotite gneiss, with glassy quartz layers, and a bronze sheen to the biotite, rare marble lenticles gradational contact
A	A3	Greenish grey to white syenite gneiss: A3a, calcareous syenite gneiss; A3b, white aplitic syenite commonly silica-saturated; A3c, porphyritic syenite gneiss abruptly gradational contact
	A2	Alkaline amphibolite, amphibole - biotite schist, minor carbonate lenses gradational contact
	A1	Massive to faintly gneissic, pale pink leucocratic nepheline syenite gneiss: A1a, augen syenite with nepheline augen; A1b, near massive homogeneous syenite; A1c, transitional syenite, biotite-bearing gradational contact
7	7	Finely banded biotite-muscovite quartzite with thin mica schist interfaces gradational contact
6	6	Deep green amphibole-pyroxene-biotite gneiss, with many quartz lenticles and layers. Commonly has bronzy sheen gradational contact
5	5	Mainly fine-grained micaceous quartzite and mica schist in lower part grading to calcareous schist, and capped by marble abruptly gradational contact
4	4	Biotite-sillimanite schist; rusty red, crenulated schist with minor marble lenticles relations uncertain (Bews Creek Fault)
3	3	Melanocratic biotite schist with interlayered grey biotite gneiss, and thin quartzite layers gradational contact
2	2	Platy to blocky white quartzite with layers of micaceous quartzite. Deformed quartz pebble conglomerate at base unconformity (?)
1	1	Grey biotite-feldspar gneiss, migmatite, pink granitoid gneisses (core gneisses of gneiss dome)

GSC

sequences of interbedded quartzite, pelitic gneiss, and calc-silicate gneiss, with rare, small, marble lenses. A major problem is the correct correlation of lithologically similar rocks from outcrop to outcrop. This is rendered even more difficult by abrupt changes in thickness of many of the units because of either thickening and attenuation in fold noses and limbs or relict sedimentary facies changes, or both. The sequence outlined in the Table of Formations is that established by Fyles (1970), which seems to best fit both the lithologic and the structural succession near Mount Copeland, but interdigitations and occasional reversals of units are common.

Core Gneisses (Unit 1)

The granitoid and migmatitic gneisses typical of the core of the Frenchman's Cap dome outcrop only in a small region in the extreme northeast of the map-area. There they comprise inhomogeneous, mesocratic to leucocratic migmatitic gneisses, characterized by schlieren and blocks of amphibolitic mafic rocks, and streaky, lens-like 'sweats' of pegmatoid quartz and feldspar.

The contacts with the overlying quartzite are poorly exposed within the mapped area, but the gneissosity is said by McMillan (1973) to be conformable, and the two are folded together (Fyles, 1970).

In outcrop the core gneisses have a strong but streaky gneissosity, commonly with one or two lineations, due to wrinkling of gneissosity or presence of streaks of mafic minerals. Amphibolitic blocks or boudins commonly show a peculiar 'plastic shearing' that gives an unusual wavy outline, usually emphasized by a pegmatoid salic rim. Garnet, apatite, and sphene are in places prominent constituents of the amphibolitic blocks, although biotite is the only obvious mafic in the leucocratic portions.

In thin section the leucocratic phases consist of moderately strained, amoeboid quartz, tartan-twinned microcline forming small augen, surrounded here and there by 'mortar,' granular oligoclase (An_{13-27}), some of it in myrmekitic intergrowths, and biotite with strong reddish-brown pleochroism. Accessory amounts of zircon, apatite, and magnetite are common, and one specimen contains apparently primary epidote. McMillan (1973) mentioned the presence of garnet, but it was not seen by the writer. The mafic blocks consist mainly of weakly pleochroic brown hornblende (Z_{10} , 15° ; X, yellow; Y, pale brown; Z, khaki) and saussuritized oligoclase, with lesser amounts of euhedral biotite having the same chestnut to greenish pleochroism seen in the leucocratic fraction. Severely altered augite and a pink garnet are varietal minerals. Apatite and sphene are commonly present as accessories, quartz and microcline less commonly.

The mineral assemblages of this unit are not definitive of any particular grade of metamorphism, although the presence of epidote suggests either that the grade is not particularly high or that the rocks have been subject to retrograde metamorphism. The origin of the gneisses is also uncertain. Fyles (1970) suggested tentatively that they are, in the main, highly metamorphosed granitoid intrusions, but there is no obvious reason that some of the core gneisses could not be derived from Proterozoic sedimentary sequences, as found elsewhere in the Shuswap terrane by Reesor (1970).

Quartzite and Conglomerate (Unit 2)

Quartzite and quartz-rich gneisses are present throughout the metasedimentary succession west of Mount Copeland. One of the purest and most prominent examples is near the base, overlying the core gneisses in the valley of Copeland Creek. In addition to the horizon immediately above the core gneisses, which thickens and thins in spectacular fashion, another thin but persistent layer of quartzite occurs within the overlying mica schist, roughly 50 m stratigraphically higher.

The outcrop appearance of this unit approximates that of massive white, medium-grained quartzite including varying amounts of tan-weathering, thinly layered, micaceous material. Compositional layering is often accentuated by elongation of quartz and feldspar grains, quartzofeldspathic swaths, and streaking of mafic minerals. There is a quartz-pebble conglomerate at the base of the quartzite unit. This conglomeratic layer, mostly only 2 to 3 m thick, contains rounded to subangular, mildly elongated cobbles of feldspathic muscovitic quartzite up to 10 cm in diameter in a matrix of granular quartz and biotite. The conglomerate

grades upward into gritty, micaceous, quartz-rich gneisses and feldspathic quartzites within which are melanocratic biotite schist layers. In the upper part of the unit where fine-grained quartzite is interbedded with mica schist, cross-lamination and graded bedding occur at several localities (cf. McMillan, 1973, p. 11; Fyles, 1970, p. 15), indicating that the quartzite faces away from the core gneisses and is, in general, right side up.

These top determinations are of considerable importance because they are the only clear indication of facing seen in the map-area. On the western flank of the gneiss dome, where the succession of sedimentary rocks is apparently continuous, McMillan (1973) used similar determinations to establish the facings of the entire stratigraphic section. Fyles (1970) mapped a considerable thrust fault, the Bews Creek fault, between the mica schists and quartzite of unit 3 and the other sedimentary rocks in this area, so that the top determinations cannot be applied directly to the rest of the sedimentary column.

Microscopically, the rocks are found to comprise mainly seriate, amoeboid, slightly strained quartz having intricately sutured boundaries. Biotite, either disseminated or in thin layers, shows frayed ends and chestnut pleochroism. Biotite layers may contain interleaved muscovite. Microcline-rich areas commonly contain tourmaline, a mineral characteristic of this quartzite and often recognizable in hand specimen. Apatite, zircon, and magnetite are present in many places in accessory amounts.

Mica Schist and Quartzite with Melanocratic Schist Lenticles (Unit 3)

A small area on the northern headwaters of Copeland Creek exposes a sequence of thinly layered quartzose gneisses with rare lenticles of melanocratic schist. Fyles (1970) mapped similar rocks to the east as lenses beneath the Bews Creek fault and as remnant synclinal keels in unit 2 on the Jordan River. At the head of Copeland Creek the rocks consist mainly of thinly laminated, grey, fine-grained biotite gneiss and schist with locally persistent quartzite layers, but the most notable rock is fissile brownish-black schist consisting chiefly of mica but including minor hornblende and diopside. This rock forms schlieren-like bands, notably coarser than the surroundings, which seem to cut the gneissosity at low angles locally.

The common quartzose gneisses are seen under the microscope to be composed of subequal amounts of quartz, oligoclase, microcline, and biotite, and as rather rare varietal minerals, poikiloblastic pink garnet and fibrous sillimanite. Apatite, magnetite, and zircon are there in accessory amounts, but tourmaline is not present, even in the quartzites. The schlieren of the melanocratic schist consist of biotite, a hornblende amphibole more or less replaced by actinolite, diopside (also replaced by actinolite), and varying amounts of labradoritic plagioclase. Large rounded garnets are seen here and there. The schlieren are considerably replaced by secondary analcite and coarse calcite.

The more common quartzose gneisses seem to be ordinary metasediments. The schlieren of the melanocratic schist could well be metamorphosed basic igneous rocks,

such as those found in unit 6 (*see below*). The occurrence of analcite among the alteration products suggests mildly alkaline chemistry. Unfortunately, because of weathering and secondary alteration, no suitable specimens could be obtained for chemical analysis.

Biotite-Sillimanite Schist (Unit 4)

Within the map-area, unit 4 occurs only in a small region north of Mount Copeland, but the same rocks have been observed in several other locations to the east. The rocks, which form rather distinctive rusty cliffs, have a characteristic lenticular or 'knotted' surface due to clusters of sillimanite and alkali feldspar, which also give a rather marked lineation to the rock. Although small-scale folds are common and fissility is ubiquitous, gneissosity is usually difficult to read in these rocks. This unit and unit 5 were not studied in detail by the writer, and the following description is summarized from Fyles (1970).

Compositions vary within the unit from quartz-rich varieties very similar to some parts of unit 3 to muscovite-rich varieties poor in potash feldspar. The most common mineral assemblages are quartz-biotite-sillimanite, quartz-andesine-biotite-muscovite-sillimanite, and quartz-microcline-sillimanite. Apatite and tourmaline are common accessories. Cordierite is reported to be present locally in small amounts. In addition to the sillimanite schist, there are a few marble layers up to 30 cm wide.

Lead-Zinc Sequence (Unit 5)

The rocks overlying the sillimanite schist grade from quartzitic in their lower part through calc-silicates to a capping of marble. The immediately overlying unit is a platy grey quartzite containing thin marble horizons, which in turn pass through thick-layered white, grey, and green quartzite interlayered with greyish and brownish micaceous quartzite and mica schist until the base of a calcareous sequence is reached. The latter sequence contains porphyroblastic and calcareous mica schist, thin layers of diopside and actinolite-bearing gneiss, and at least three distinct marble layers, the thickest of which caps the unit. A sulphide-rich layer, described in detail by Fyles (1970), lies a few feet above the quartzitic part of the unit and consists of calcareous schist, lime-silicate gneiss, and local marble lenses mineralized with fine-grained pyrrhotite, sphalerite, and galena. The calcareous part of the unit consistently contains quartz and calcic plagioclase (An_{56-70}) and in many places contains biotite, diopsidic pyroxene, and actinolite. Phlogopite marble is common. Potash feldspar, epidote, and garnet occur locally.

Quartz-Biotite-Pyroxene-Hornblende Gneiss (Unit 6)

This heterogeneous unit (no. 6) outcrops more or less continuously along the north side of Mount Copeland, but it is not found in Hiren Creek valley. It is composed of grey or greenish granular, banded hornblendic gneisses, with lesser amounts of fine-banded quartz-mica gneiss and schist

and some prominent quartzite layers. A diagnostic feature is the presence of coarse amphibolite lenses containing pods of pegmatitic amphibole-calcite rock. Lenticular masses of glassy quartz, characteristic of the lithologically similar unit 11, are not found in this unit.

In outcrop the rock usually weathers to pale grey or greenish shades and rather lumpy, rounded surfaces. Amphibolite layers tend to form prominent raised black knots, and mica-rich layers weather recessively to tan shades. Hand specimens tend to show pale brown faces because the rock splits on mica-rich layers, commonly displaying pronounced crenulation. The rocks are medium- to coarse-grained and inequigranular, calcite and feldspar forming prominent white megacrysts locally. Amphibolite lenses consist of alternating zones of pegmatitic, poikilitic amphibole with interstices filled with pyroxene, or more rarely with calcite, and finer grained gneissic amphibole-plagioclase rocks. At the end of the ridge running west from Mount Copeland, a homogeneous, almost massive, tan quartzite caps the unit, separating it from the overlying syenitic gneisses.

In thin section the rocks consist mainly of plagioclase, hornblende, biotite, and calcite; however, they include varying but significant amounts of diopside, quartz, and scapolite. Sphene is locally a varietal mineral, and microcline microperthite appears sporadically. Tourmaline, apatite, magnetite, and pyrrhotite are the more common accessories.

Plagioclase occurs in anhedral interstitial grains, here and there showing faint normal zoning and patchy twinning. Compositions range rather erratically from albite to as calcic as An_{48} . The amphibole that is characteristic of this unit is not a tremolite, nor does it appear to be particularly calcium-rich. It occurs in intergrown prisms with somewhat cusped boundaries and generally shows biotite along cleavage planes. Optic properties approximate those of common hornblende (2V, 82°; α_c , 16°; X, pale yellow; Y, pale brown; Z, olive). Both hornblende and plagioclase are commonly intensely poikilitic, usually with biotite and calcite. The biotite forms well-shaped euhedra, either oikocrysts or small lentils. The pleochroism is strong in shades of reddish brown and pale green, and analysis shows that the mica is indeed biotite, very likely of relatively high titanium content. Calcite is the only carbonate noted in these rocks. It is commonly a granular aggregate, very strongly twinned, with numerous deformed twins, kink bands, and strain extinction. Sphene, when present, tends to be euhedral and may form prominent clumps of water-clear, honey-yellow grains. Pyroxene is relatively rare in this unit, forming dense, subhedral grains into grain with amphibole. The z_{ac} of the pyroxene in the amphibolitic portions is perceptibly higher than that in the surrounding rocks (about 45° as compared to 38–40°), but the optic properties are similar.

Amphibolitic layers are not uncommon in metamorphosed calcareous sediments, but such layers could equally well be of igneous origin. In order to clarify this ambiguity, a specimen of typical amphibolite from the northwestern corner of the map-area was submitted for analysis. The results (Appendix 1) strongly suggest an igneous origin for the layers. According to the criteria of Leake (1964) the high Ni and Cr contents are particularly diagnostic. No sedimen-

TABLE 1 *Chemical composition of rocks, Mount Copeland and other regions*

	1	2	3	4	5	6	7	8
SiO ₂	48.81	46.77	48.07	53.47	44.18	40.25	39.72	40.26
TiO ₂	3.08	3.00	0.89	1.07	5.49	2.90	1.26	3.95
Al ₂ O ₃	11.23	14.65	18.83	15.87	7.51	11.32	13.96	15.48
Fe ₂ O ₃	1.16	3.71			8.06	4.87	2.64	6.23
FeO	10.18	7.94	6.90*	8.36*	7.20	7.69	5.17	6.56
MnO	0.15	0.15	0.00	0.86	0.37	0.22	0.14	0.23
MgO	8.37	6.82	3.56	3.48	7.76	13.28	7.45	5.29
CaO	10.07	12.42	4.96	4.06	9.68	12.99	10.22	10.28
Na ₂ O	2.24	2.59	1.17	5.39	3.69	3.14	1.62	2.52
K ₂ O	1.58	1.07	2.57	3.01	3.77	1.44	5.24	3.69
H ₂ O	2.16	0.51	10.91†	3.18	1.21	1.08	1.96	3.68
CO ₂	0.59	0.00		0.00	0.26	0.00	6.54	1.20
P ₂ O ₅	0.28	0.37		0.27	0.59	0.78	1.73	0.63

1. Pyroxene-biotite amphibolite, west end of Mount Copeland (unit 6).

2. Average alkali basalt (Nockolds, 1954).

3. Average coarse clay (Grout, 1925).

4. Average deep sea clay (Turekian and Wedepohl, 1961).

5. Melanocratic amphibolite, Mount Copeland (unit A2).

6. Average olivine nephelinite (Nockolds, 1954).

7. Average lamprophyre dyke, Mount Copeland (unit 11).

8. Average lamprophyre dyke, Callander Bay complex (Ferguson and Currie, 1971a).

* Total iron reported as FeO.

† Loss on ignition.

tary rock of this silica contact approaches the analysis at all closely, but Nockolds' (1954) average alkali basalt is an almost perfect fit (Table 1).

The presence of lava flows is not unlikely. In 1965 Wheeler reported thick flows in lower Cambrian sediments of the Hamill Group in the Selkirk Range. Those flows, however, are of tholeiitic affinity, whereas the present rocks are distinctly alkaline. Furthermore, it is quite uncertain that the amphibolites were once flows; they could equally well have been sills, or even dykes transposed into the foliation plane by tectonic deformation. The presence of alkaline igneous rocks suggests a possible connection with the syenite complex, but given the present degree of deformation and metamorphism, the only strong evidence of such a connection would be demonstration of the absence of similar alkaline amphibolites elsewhere in this region. No data are available on this point.

The number and thickness of the alkaline rock layers cannot be accurately estimated at present, because tectonic stretching and dissection have severely modified the material in shape and distribution. However, several horizons of amphibolite are certainly present.

Biotite-Muscovite Quartzite (Unit 7)

The heterogeneous unit 6 is overlain everywhere in the map-area by a pale grey, finely banded, micaceous quartzite, or quartz-rich gneiss (unit 7) whose thickness varies from less than 50 m in the northern part of the map-area to several hundred metres in the southeastern corner. Although the principal part of this unit is quartzite, much of the rock is a fine-banded, quartz-rich biotite gneiss, which, in the

upper part, becomes increasingly rich in diopside, grading to the calc-silicate rocks of unit 8. The unit is noticeably metasomatized where it is in contact with the syenites of unit A near Hiren Lake.

In outcrop this rock is pale grey to almost white, with strong regular gneissosity defined by micas but relatively little segregation banding. It is typically fine and gritty and quite homogeneous in outcrop scale. Where lenticles of other compositions are present, mainly of feldspathic types, the contacts are gradational, and there is no change in grain size save for occasional brownish knots, up to 5 mm across, on the surface.

In thin section the rocks are seen to be composed mainly of seriate, moderately strained amoeboid quartz showing diffuse deformation lamellae. Biotite is present as small, well-formed euhedra with pleochroism distinctly weaker than that in the lower units but still in reddish-brown shades. Muscovite is present in most specimens in about the same form as biotite, but it is much rarer. In feldspathic areas, both potash feldspar and plagioclase are invariably present. The former is commonly microcline, but considerable amounts of braid perthite are sometimes present. The plagioclase is always in smaller grains, commonly equant, and not twinned. It is optically positive, falling in the oligoclase range. The knots previously noted are composed of fibrous sillimanite and biotite, the latter commonly containing sillimanite along cleavage planes. Pink garnet is, in places, a varietal mineral, and apatite, zircon, graphite, and pyrite are the common accessories. Tourmaline is seen here and there but is much rarer than it is in the lower quartzite (unit 2). In the metasomatized quartzite north of Hiren Creek, the plagioclase is albite, the cryptoperthites are rimmed by

albite, and substantial amounts of a peculiar riebeckitic amphibole (Appendix 2) (-2V, 38°; z_{ac} , 44°; X, pale violet; Y, yellowish; Z, pale blue) are present as ragged poikilitic grains. Sphene occurs among the accessories.

No chemical analysis was made of the unmetasomatized quartzite. The average of six modal determinations, however, was quartz, 86.4 per cent; biotite, 3.9 per cent; muscovite, 0.5 per cent; K-spar, 7.9 per cent; An_{27} , 1.0 per cent; and opaque, 0.3 per cent. Assuming that the quartz, muscovite, K-spar, and plagioclase are pure phases and that the biotite has the composition of biotite in the overlying calc-silicates, the principal additions during metasomatism were aluminum and sodium, balancing loss of silica. The compositions of the mafic minerals (Appendix 2) in the metasomatized rock are very magnesium-rich compared to either the unmetasomatized rocks in the metasedimentary pile or the alkaline gneisses. The mica is so poor in aluminum it must contain taeniolite component, and the amphibole approaches magnesioriebeckite (cf. Deer *et al.*, 1962, v. 2, p. 366). Calculation of the effect of removal of silica on the rest of the analysis suggests that the other elements did not increase but in fact decreased slightly during metasomatism and that magnesium was removed less efficiently than iron, and of course much less efficiently than silica. These calculations raise the problem of the ultimate depository of the silica, presumably deposited as quartz in the surrounding quartzites.

Nepheline Syenite Gneiss (Unit A1)

Nepheline-rich gneisses, as distinguished from the weakly alkaline syenite of unit A3, occur in two major areas—one just south of the crest of the ridge west of Mount Copeland, running along the core of a major anticline for about 5 km in strike length, and the other lying parallel and about 2 km farther south, in the core of another anticline. In addition, a number of small occurrences of nepheline-rich rocks are found well outside the bodies of this unit, particularly on the southwestern slopes of Mount Copeland.

This unit is defined simply on the basis of nepheline content exceeding 10 per cent and is by no means homogeneous in appearance. The rocks fall into three major types, each related to its mode of occurrence. Each of the major nepheline syenite occurrences contains a central core of leucocratic granular rock, creamy or pale pink, in which the mafic components define a strong banding but the salic components have virtually massive texture (unit A1b). Surrounding this core are more or less narrow belts of finely gneissic homogeneous rock of slightly darker colour in which both mafic and salic components show a strong lineation and/or elongation (unit A1c). Finally, nepheline syenites from outlying areas, particularly lenticles in the calc-silicate rocks, tend to show a spectacular augen texture (unit A1a) with porphyroblasts of nepheline and alkali feldspar up to 2 cm across packed into a finer grained matrix of mafic minerals.

None of these varieties display sharp contacts, either with each other or with the country rocks. Even where such apparently incompatible rock types as nepheline syenite and quartzite are in contact, the contact is marked by a tran-

sitional zone of syenite of unit A3 that grades into quartzite by loss of alkali feldspar and into nepheline syenite by appearance of nepheline and alkaline mafic minerals. These transitions may take place with extreme rapidity: at the west end of the ridge west of Mount Copeland, lenticles of nepheline-bearing mafic gneiss no greater than 20 cm wide by 100 cm long are found in the quartzite. Similar lenses of nepheline-bearing mafic gneiss are common in the calc-silicate rocks to the west of the Mount Copeland Mine and, more rarely, to the east toward East Lake. Within the nepheline gneisses proper, numerous gradational transitions from one kind to another are present, so that in detail all three varieties may be present in a single outcrop. Pegmatitic varieties are very rare or absent from the major nepheline gneisses, distinguishing them from, for example, nepheline gneisses in the Bancroft district of Ontario.

In hand specimen, the nepheline augen gneisses (unit A1a) are mesocratic rocks with a faint purplish tinge dominated by cubic to subrounded crystals of nepheline as much as 2 cm across. The porphyroblasts generally weather high, creating a knobby, pitted surface. In detail the crystals are grey to white but have a distinct pinkish tinge. Trains of fine-grained biotite and feldspar wrap around them, and purple fluorite and cancrinite tend to make haloes. In thin section the porphyroblasts are found to be single crystals of nepheline, fairly fresh in appearance though narrow rims of cancrinite may be present. Other minerals are much finer grained. The most common is calcite, which tends to form chains of equant, twinned grains around the nepheline, commonly intergrown with a pale yellow biotite (pleochroic to nearly opaque), and a colourless, twinned fluorite. Alkali feldspar commonly shows patches of microcline twinning and areas of rod perthite. The twinning is usually curved, and this appears to be a growth feature rather than deformation. Zoned extinction is common. Tourmaline, apatite, and sphene are accessories in many places, generally in the neighbourhood of the mafic minerals. A small amount of pale bluish riebeckitic amphibole is commonly present in this type of rock, and more rarely, poikilitic aegirine. Where the latter is present, it may form spectacular euhedral porphyroblasts full of biotite and nepheline oikocrysts.

During microscopic examination, an exotic mineral was discovered. It occurred in stubby brownish pleochroic prisms having the following optical properties: -2V, 43°; n_b , 1.662; pleochroic scheme X, pale yellow; Y, pale brown; Z, cinnamon. X-ray powder diffraction patterns suggest that this mineral is a member of the rinkite group.

Some chemical data from this rock type are presented in Appendix 1. The chemical analyses are low in silica and relatively high in alumina. The most notable features, however, are the extreme soda and cerium contents, the latter accounted for by the presence of accessory rinkite, which presumably also carries the other rare-earth elements. The high soda content gives relatively high agpaitic indices ($Na+K/Al=0.96-0.98$) compared to the other nepheline syenite gneisses (0.69–0.80). An agpaitic tendency in the rocks is also suggested by the high total FeO/CaO ratio and the low content of lime and magnesia in a rock of this silica content. No example of a metasomatic agpaitic rock is known to the author. This chemistry thus seems to offer strong

evidence of an igneous origin for the rock. However, the field relations seem to show an origin by metasomatism, because the rock type tends to occur in rootless lenses near the margins of the nepheline syenite or in the wall rocks, commonly in association with clearly metasomatic phenomena in the wall rocks, such as growth of nepheline crystals in the calc-silicates or biotite schists. These phenomena can be reconciled by supposing the nepheline-rich syenites to be metamorphosed pegmatite dykes or schlieren. Such dykes and schlieren are almost invariably present in alkaline plutonic complexes and even in alkaline volcanics. They commonly are substantially more agpaite than the bulk rocks are (compare for example the pegmatites of the Ice River complex [Currie, 1976]). The present disposition might be explained by assuming transposition of attitude by tectonic deformation combined with a certain loss of sodium to metasomatize the wall rocks.

The core parts of the nepheline syenite (unit A1b), while much more homogeneous and less coarse-grained than the nepheline augen gneiss, also show significant variation. The inner core consists of a near-massive, pale pink leucocratic rock that weathers to a pale creamy shade in outcrop. The gneissosity is defined only by local nebulous marginal segregations of fine-grained black mafic minerals on felsic schlieren (Fig. 3). In the medium- to coarse-grained, homogeneous matrix, the only dark mineral is specularite, commonly in prominent euhedra up to 5 mm across.



FIGURE 3. Homogeneous nepheline syenite gneiss, west end of ridge west of Mount Copeland. Note mafic edges on felsic schlieren.

In thin section, the rocks consist of a xenomorphic, granular aggregate of nepheline, potash feldspar, and albite. The nepheline tends to be roughly equant, with lobate margins. The grains show a faint reddish dust but are in general virtually unaltered. An alternation of nepheline-rich layers and feldspar-rich layers gives the rock a distinct gneissosity in thin section. The potash feldspar is extremely variable in appearance. The grains are mostly rounded, approaching augen shapes, and quite large, occasionally with poikilitic edges containing nepheline and potash feldspar of a second generation. The feldspar is always rather

dusty, and it varies from very fine braid perthite through patch perthite to microcline in the same grain. Patches displaying fine albite twinning are also common. Albite also occurs in the form of small anhedral interstitial grains displaying excellent albite twinning. Extinction measurements suggest a composition near An₁₀. The principal mafic mineral is an aegirine of brownish-green pleochroism (2V, 85°; λ_{calc} , 85°) occurring in very irregular scalloped prisms, strongly aligned along the gneissosity and, in many places, partially rimmed by finely granular yellow sphene. Among the accessory minerals, the most persistent is calcite, present in tiny grains along narrow seams. To a lesser extent, fluorite, garnet, and zircon are found in similar seams. A little brown biotite, possibly developed during secondary alteration, is usually present in the aegirine, and muscovite, along with cancrinite, occurs in some places on the margins of the nepheline. Rinkite was seen in only one specimen of this variety, and that only as two grains. Trace amounts of a severely altered yellowish mineral, believed to be relict diopside, are associated here and there with the garnet.

Some chemical data on this type of nepheline syenite are presented in Appendix 1. The rocks are substantially higher in SiO₂ than are the augen type previously described, and they have much lower sodium content but marginally higher potash content. The trace element assemblage is much poorer than that in the augen rocks, particularly in the rare-earth elements. Upon examining the individual minerals (Appendix 2), it may be seen that there is a substantial difference in the pyroxene in the two rocks—that in the homogeneous gneiss being poorer in sodium but much richer in aluminum and iron, approaching a ferroaugite. The nephelines both approximate to the Burger-Morozewicz composition, but the alkali feldspar in the homogeneous gneiss contains substantially more sodium than that in the augen unit. In bulk composition the rocks approach rather closely the average nepheline syenite of Nockolds (1954), and this may be taken as weak evidence of an igneous origin.

Yet a third type of nepheline syenite is present (A1c). It may be transitional to the alkaline (but nepheline-free) syenites of unit A3. This gneiss (unit A1) is generally pale buff to creamy, is finely gneissic, is commonly on a millimetre scale, and contains biotite. The biotite is usually prominent on parting faces of the rock, where it glitters in the light, but inconspicuous and rare in the interior. These rocks are the most pronouncedly gneissic of the nepheline-bearing group and may show complexly contorted structure on outcrop scale, often interbanded with thin bands of mafic calcareous rocks (unit 8a) (Figs. 6, 7).

In thin section the rocks are dominated by large, rounded, slightly amoeboid grains of alkali feldspar showing a patchy extinction, which is resolved locally into microcline grid twinning. Vague patches of braid perthite, small areas of which show albite twins, are present. Nepheline occurs as somewhat smaller grains, commonly distinctly dusty and showing substantial replacement by cancrinite and thomsonite. This is the only nepheline that shows a significant 2V, reaching 15° in some places. Mica, the type mafic mineral in this variety, rarely is present in amounts greater than 5 per cent by point count, but it is prominent in thin section because of an unusual pale yellow to opaque pleochroism (and

excellent alignment, defining a good microgneissosity). Electron probe analysis shows that the mica is in fact a phlogopite rather than a biotite (Appendix 2).

Biotite-bearing nepheline gneisses almost always contain aegirine in addition to biotite, and they may also contain a deep green amphibole approaching hastingsite (Appendix 2). The aegirine has a brownish to green pleochroism (2V, 85°; λc , 78°) and a rather extreme birefringence, and it occurs as poikilitic scalloped crystals or as rounded, small, dense granules. There is a noticeable alignment of aegirine. Amphibole is a relatively rare mineral in these rocks, but where present, it forms near-euhedral dense grains pleochroic from pale yellow to brownish green. It is usually associated with sphene and aegirine in a fashion suggesting that they grew at its expense. Among the accessories, the most common are sphene, always found associated with the mafic minerals, apatite, calcite, and specularite.

Some chemical data from these rocks are presented in Appendix 1. They contain the most silica of any of the alkaline gneisses (and consequently the least nepheline), but the striking feature is the high to extreme K_2O/Na_2O ratios, expressed modally by the dominance of potash feldspar. Among the trace elements, Zr is notably high, three to four times the value in the other types of nepheline gneiss, whereas the rest of the assemblage is rather impoverished, as are the homogeneous nepheline gneisses. Among the minerals, the aegirine is the closest to acmite found in the Mount Copeland rocks, although the content of diopside-hedenbergite still amounts to nearly 30 per cent. The mica, as noted, is phlogopite, and the amphibole has a rather unusual iron-rich composition, probably best referred to as ferrohastingsite. The alternative would be to refer to it as an amphibole of the barkevikite type, but this fits neither the paragenesis nor the optical properties, whereas amphiboles of the hastingsitic type are a well-known component of nepheline gneisses (Tilley, 1957).

The biotite-nepheline syenite gneisses display an unusual composition, rich in iron and potassium, which seems unlikely to have arisen by normal magmatic differentiation processes. They lack the rinkite and fluorite believed to be relict magmatic minerals in the other alkaline gneisses. They are interbedded with clearly nonsyenitic rocks of unit 8a. If metasomatic alkaline gneisses are present on Mount Copeland, these rocks seem to be the strongest candidates. None of the nepheline gneisses show any signs of strain or brecciation in the salic minerals (nepheline and feldspars), although such symptoms are common in the subalkaline gneisses. This, together with the obvious common folding of the alkaline gneisses and their surroundings, strongly suggests that, whatever their ultimate origin, the present mineralogy of the alkaline gneisses is a result of their deformation, recrystallization, and metamorphism.

Alkaline Amphibolite (Unit A2)

One of the most characteristic features of the Mount Copeland alkaline gneisses is the presence within them of a persistent amphibolite screen. On the ridge west of Mount Copeland this mafic lense was traced for more than 10 km, and in the smaller occurrence north of Hiren Lake it was

traced for an additional 3 km. The disappearance of this layer appears to be due entirely to tectonic thinning rather than to lensing out, because sheared lenticles of the unit can be found along strike as much as a kilometre to the southeast of the end of its mappable extent. Although the unit is shown on the map as a single band, it appears to form several parallel lenses, perhaps as many as 10, occurring over a width of up to 200 m and separated by syenite screens.

In outcrop the rocks are medium- to coarse-grained and mesocratic to melanocratic. They are almost always strongly gneissic and fissile, but they vary from relatively homogeneous in gross aspect to spectacularly banded. Lineation, small-scale crumpling of foliation, slickensiding, and an attenuation of the gneissosity resembling boudinage are almost universal. The rocks tend to have a black, lustrous aspect because of an abundance of biotite. Their situation in pale syenites produces a striking colour contrast.

In hand specimen, the rocks look rather like sheared amphibolite. They are fine-grained, have prominent biotitic parting planes, and contain finely granular white to pale pink salic minerals. A greenish-black, prismatic mineral readily mistaken for amphibole forms aligned prisms. In thin section, however, this mineral is seen to be an aegirine (−2V, 83°; λc , 77°) showing a pale brown to greenish pleochroism. The habit is prismatic to rounded, the larger grains showing better crystal form. Biotite displays a pale yellow to deep greenish-brown pleochroism and forms in prominently aligned grains that may display considerable kinking. Some biotite grains appear corroded and cusped against the feldspathic constituents. Sphene is a major constituent, forming distinct seams of granular rounded grains that display a perceptible pleochroism in pale brown. Calcite is present in minor amounts that form chains of strongly twinned, minute granules.

Feldspathic constituents are relatively rare, and potash feldspar is always the dominant salic phase, commonly in the form of small lenticles of anhedral, amoeboid grains showing either poorly developed braid perthite or a kind of shimmering extinction suggestive of submicroscopic perthitic structure. Plagioclase is rare, but it occurs here and there on the margins of the potash feldspar lenses in the form of poikilitic grains containing biotite and sphene. Weak reverse zoning from about An_{33} to An_{45} may be present, but most of the grains are a sodic andesine. Plagioclase, where relatively abundant, may be replaced by scapolite. Quartz, in the form of minute interstitial grains, occurs in trace amounts in the most feldspathic specimen examined. Apatite is in minute, well-formed prisms enclosed in biotite.

Some chemical data for these rocks are given in Appendix 1. The chemical analysis was made on a composite sample of six specimens from the rocks on the southern side of Mount Copeland. The analysis reveals a remarkable composition: the content of soda and potash is vastly higher than that of any normal igneous rock of comparable silica and alumina content, but no plausible sedimentary parent can be pointed out. The composition strongly suggests the intervention of metasomatism. The only rocks that approach it are certain basic to ultrabasic alkaline rocks such as nephelinites. Given such an original composition, the analysis could be reached by removing a little alumina and lime and adding soda and

potash, and possibly some silica. Such changes are normal during the fenitization of mafic rocks (Currie and Ferguson, 1972). Further, the high Ni, Cr, and Co content seems to distinguish a basic igneous rock as the ultimate source of the mafic screens, and the rare-earth and Nb content could be ascribed to fenitization.

The mineral composition of the mafic rocks (Appendix 2) is typical of that in the alkaline gneisses—phlogopitic mica coexisting with an iron-rich aegirine. The aegirine, however, is much closer to the sodium-rich varieties of the transitional nepheline syenite than it is to the complex pyroxenes of the core syenites. This iron- and soda-rich composition seems fairly consistently to indicate metasomatic formation of pyroxene in the complex.

While the chemical data strongly indicate an igneous origin, they do not indicate whether this rock was intrusive or extrusive. A survey of ultrabasic alkaline igneous rocks suggests that intrusive varieties are somewhat richer in titanium and poorer in aluminum than their extrusive equivalents (Currie, in press), suggesting that an intrusive origin for the Mount Copeland rocks is more probable.

Grey Syenitic Gneiss (Unit A3)

The strongly alkaline rocks of units A1 and A2 are surrounded by a thick shell of less alkaline rocks, collectively grouped as unit A3, although no conclusive age relations have been discovered between these three units and none is implied by the choice of numbers. The syenitic gneisses are particularly well exposed along higher parts of the ridge west of Mount Copeland, and to the southeast down to the edge of outcrop in Hiren Creek valley. Good exposures are also found along the upper part of Hiren Creek. Outside these large areas, smaller lenticles are distributed within the calc-silicate rocks and, less commonly, within the biotite gneisses of unit 8a.

In outcrop the syenitic gneisses are characterized by a pale grey colour, generally with a greenish tinge, and are of medium- to fine-grain size. Within these restrictions they are quite heterogeneous, although three principal types can be discerned. Near the surrounding calc-silicate rocks the syenite is fine-grained and quite homogeneous, and it has nebulous, slightly darker gneissic banding (unit A3a). This rock, which can easily be confused with the more feldspathic varieties of calc-silicate rocks, grades by increase of grain size and by lightening of colour into a white, aplitic leucosyenite (unit A3b), characteristically found around the central nepheline syenite, particularly on the northern slope of the ridge west of Mount Copeland. In some occurrences this rock contains analcite and/or thomsonite and is clearly transitional to the undersaturated nepheline syenites. The third phase of the rock is a buff to pale pink variety, characterized by twinned alkali feldspar tablets up to 5 mm across and containing as a mafic mineral one of those seen in the biotite gneisses and schists (unit A3c)—biotite, a diopsidic pyroxene, or a hornblende amphibole.

The fine-grained syenites gradational to calcareous gneisses are particularly abundant in the region of the Mount Copeland Mine. In outcrop the rocks have a rather mesocratic appearance, weathering pale grey with a buff tint.

Gneissosity is commonly present but inconspicuous and is lenticular because of the pinching out, or gradational disappearance, of the mafic-rich layers that define the foliation. The rocks are fine-grained but commonly have a glittering appearance in bright light owing to the reflection from small calcite crystals. Unlike the calc-silicates the mafic minerals appear as minute black prisms rather than the greenish minerals typical of the calc-silicates, but some specimens contain fine flakes of the bronzy brownish mica typical of the calc-silicate units.

In thin section the rocks are dominated by feldspar. The earliest seems to be plagioclase (about An₃₅) in which the twinning appears and disappears in an irregular, patchy fashion. This material commonly shows a slight normal zoning towards more sodic rims, but this tendency is strongly overprinted by wholesale replacement by albite along cracks and rims. The twins on the plagioclase are strongly deformed and crinkled, but this deformation is not shown by the later alkali feldspar. Potash feldspar forms fairly large grains, many being augen-shaped but having amoeboid edges containing opaque dust and biotite inclusions. The smaller grains are commonly fine rod perthites in a grid-twinning microcline matrix. The coarser grains, however, do not show grid twinning and extinguish rather evenly. Some give 2V as low as -50° , suggesting a relatively disordered potash feldspar. Quartz is, very rarely, found in this unit as fine interstitial grains among the alkali feldspar. The most prominent mafic mineral is a biotite having a pale yellow or orange to deep green pleochroism, preponderantly in near-euhedral forms confined to narrow zones, where it forms a reticulate network. A colourless diopsidic pyroxene (+2V, 58° ; χ_{AC} , 36°) appears in many places as chains of rounded granules associated with sphene and large irregular grains of magnetite. Calcite is also common, in minor amounts, in these calcareous zones. The characteristic grey-green shade is imparted by a variable content of finely granular epidote of small positive 2V, distinct pink to greenish pleochroism, and extreme red-greater-than-violet absorption. Accessory amounts of apatite, muscovite, and zeolite, generally analcite or thomsonite, may also be present.

A chemical analysis of this material (Appendix 1) shows an unusual composition suggesting a mildly alkaline trachybasalt, rather than a rock believed to be syenitic, perhaps contaminated with calcareous sediments. In addition to the low silica and high titanium, the relatively high contents of Na, Cr, and Co suggest an igneous provenance. The mineral analyses (Appendix 2) show that the pyroxene is indeed in the diopside-hedenbergite line, and not sodic, and the biotite contains substantially more magnesia than that in the gneisses remote from the alkaline rocks and is perhaps transitional to the phlogopitic micas of the nepheline-bearing rocks.

The aplitic leucosyenites (unit A3b) are particularly common on the higher parts of the ridge above the mine adit and are abundantly represented in the rocks penetrated by the adit. In outcrop the rocks are virtually white, although many have a faint green tint, and can easily be mistaken for marble. Complex intrusive relations are commonly found within this unit, some parts of which seem to consist almost entirely of lenticular to tabular intrusive masses. The contacts of these

bodies are not marked by any chilled margins, but rather by differences in texture of the various components and here and there by concentration of mafic minerals in one or the other phase. In hand specimen the rocks have a granular, sugary texture best described as aplitic. Some specimens are almost monomineralic feldspar but include rare grains of mafic minerals of habit similar to that of the salic material; others are more mesocratic and may show a faint gneissosity owing to alignment of streaks of a greenish mafic mineral. There are comparatively rapid local transitions from this type of rock to the calcareous syenite just described. This is because of the coarsening in grain size of the latter and the disappearance of mafics.

In thin section the aplitic rocks are seen to be composed of an albitic plagioclase, which from optical data seems to contain almost no anorthite component. The texture is xenomorphic-granular, having good but rather faint albite twinning. A potash feldspar is present in similar form but much lesser amount, displaying only local grid twinning and marginal flame perthite. The 2V, however, is consistently large, suggesting a high triclinicity. Muscovite exists in large, nearly equant grains with lobate edges, and the contacts with potash feldspar are in some places complexly intergrown. Either calcite or diopside may be present, but they appear to be mutually exclusive. Both occur in small disseminated granules. Biotite, zircon, apatite, pyrite, and molybdenite are mainly in trace amounts. This rock is the host of the Mount Copeland molybdenite deposit, in the vicinity of which molybdenite is more abundant and epidote is present. Although usually only in traces, molybdenite is found in this rock throughout the mapped area.

The chemical composition of the aplitic syenite reflects the modal peculiarities (Appendix 1), being very high in soda, of extreme Na/K ratio, and very low in ferric iron and magnesium. The relatively high content of CaO is almost entirely present in calcite, as can be seen from the content of CO₂. The rock is generally very low in trace element content, except for Sr, which is undoubtedly contained in the carbonate fraction. Among the minerals, the biotite is sufficiently rich in magnesia to approach the phlogopite common to the alkaline rocks in this district (Appendix 2), but the diopsidic pyroxene contains practically no soda. The feldspars approach the pure end members for soda and potassium feldspars.

The origin of this rock and its relations to the other alkaline gneisses remain obscure. The observed outcrop occurrences of complex cross-cutting relations suggest that most or all of it was at one time fluid. The persistent presence of calcareous seams and schlieren suggests, however, contamination or hybridization with the country rocks. The existence of intermixed carbonate and syenite is not uncommon in carbonatite complexes (Ferguson and Currie, 1971b), but such syenites are usually very rich in potash. The very low trace element content in the aplitic leucosyenite also suggests a derivation varying from that of the nepheline syenites and alkaline amphibolites. This problem is discussed in the final section.

The third group of syenites (unit A3c) in the Mount Copeland area forms a 'garbage can' for syenitic rocks not fitting elsewhere. In general these rocks are buff to pink and

leucocratic to mesocratic, exhibiting pronounced gneissosity due to mafic alignment and occurrence of lenticles of mafic minerals. Potash feldspar is commonly nearly euhedral and may form prominent augen. Such rocks are in three settings. Most commonly, they are found in the thin extensions of syenite, such as those northwest of Mount Copeland and south of Hiren Creek, where all the units of the syenite are presumably transformed into this type of material. However, very similar rocks are also found in the main mass of syenite on the western end of the ridge west of Mount Copeland, where the syenites are in direct contact with the biotite gneisses of unit 9 rather than with calc-silicate rocks. Finally, small amounts of syenites of this type, usually rather melanocratic, are found where the syenites are in contact with the mafic gneisses of unit 7.

In hand specimen the rocks range from yellowish grey to various shades of pale buff or pink, those in the latter category tending to be richest in mafic minerals. The grain size varies from medium- to coarse-grained, and large porphyroblasts are common. Mafic minerals form marked poikilitic, lenticular streaks, commonly showing some contortion.

In thin section the rocks are dominated by large amoeboid grains of potash feldspar, within which the textures are remarkably variable. Within the same grain, both positive and negative optic signs can be found, and the appearance varies from homogeneous, one-phase material through fine flame perthite to microcline with coarse rod perthite. The feldspar tends to be quite dusty and displays curving marginal cracks. The plagioclase tends to be close to albite in composition, but where calcite is present, it may show reverse zoning out to margins of An₂₅. The mineral is commonly found in finely twinned intergrowths with potash feldspar, but it is also present as larger grains surrounded by fine mosaic albite, a texture reminiscent of mortar texture but possibly due to recrystallization of an originally larger albite grain. Some hand specimens of this rock contain a pale yellow-green mineral in amoeboid patches; it is a fine-grained aggregate of analcite and cancrinite, plus a little very fine-grained biotite (gieseckite). This aggregate is presumably secondary after nepheline, and these rocks are transitional to the nepheline syenites.

The mafic minerals in these rocks show no consistency from one specimen to another. Biotite, aegirine, and a hastingsitic amphibole are the species seen, but they may occur either in virtually any combination or separately. The biotite has the usual pale yellow to almost opaque pleochroism and tends to be in reticulate networks of spears, not uncommonly intergrown with the amphibole. The amphibole, pleochroic in shades of bluish green, has an unusually small -2V of 48-53° and a high α_c of 29-32°. Aegirine, always optically positive, is commonly found as the lone mafic in the long fingers of syenite extending away from the main masses. The mineral is in dense, well-formed prisms showing moderately strong alignment. Among the accessories, zircon, magnetite, and apatite are the most common, but tourmaline occurs erratically and fluorite was found in two specimens.

Because of the heterogeneous character of this unit, it is not possible to determine its chemical composition by a single analysis. However, in Appendix 1, an analysis of the

syenite found in contact with the biotite gneisses is presented. This is believed to be representative of most of the material forming the long trailing arms of syenite. Note the highly oxidized character of the analysis and the predominance of potash over soda, in contrast to the albite syenite. Note also the substantial content of rare-earths.

Quartz-Diopside-Biotite Gneiss (Unit 8)

The syenitic gneisses of unit A3 are almost always found in contact with a greenish quartz-rich rock containing abundant diopside. This (unit 8) is found on both sides of the ridge above the mine, forming part of the steep face beneath the north portal of the mine, as well as in a tightly folded area to the northwest. It appears on the south side of the ridge as a narrow but persistent layer outlining the folds in the syenite. According to Fyles (1970) and McMillan (1973) it is particularly characteristic of the Mount Copeland area, as it persists only a few hundred metres east of the mapped area and its equivalent does not occur on the west flank of the gneiss dome.

The most typical exposures of these rocks are found on the northwest side of Mount Copeland near the exit of the mine adit, where the rocks show a strong, but very lenticular, gneissosity because of alternating bands of dense, jade green mafic minerals and glassy, coarse quartz. Such rocks are comparatively limited in extent, grading by increase of biotite and feldspar into greenish or greyish-green schists and gneisses, commonly possessing a marked augen structure in the feldspar, and containing lenticular zones rich in biotite.

These rocks range from mesocratic to melanocratic but invariably contain white or pale buff lenses, up to a metre across, of granular marble, or calcite plus white calcium silicates. A bronzy mica with purplish tinge is characteristic of the whole unit, but it is particularly obvious in these light-coloured bands.

The upper unit of diopside-bearing rocks grades by increase in feldspar and development of granular texture into the calcareous syenites of unit A3 (Figs. 4, 5) and by increase in biotite and decrease in calc-silicates into the gneisses of unit 10. Lenses of these units are found within the calc-silicates, some of the largest occurring in noses of apparent phase 1 folds. Quartzite lenses occur throughout both the calc-silicates and the overlying unit 10, but the contacts with quartzite are commonly discordant and folds within the surrounding thin-bedded rocks disharmonic, suggesting that the quartzite 'slid' on the more incompetent bedded rocks.

In thin section the rocks are seen to be composed mainly of diopside, tremolitic amphibole, plagioclase of varying anorthite content, biotite, and lesser amounts of potash feldspar and quartz. Diopside forms large, poikilitic grains, usually full of feldspar and biotite. In some sections these grains seem partially recrystallized to aggregates of small, dense granules. In these sections the grains are often surrounded by feathery tremolite. In general, however, the diopside is relatively fresh, but it is by no means uniform in colour, displaying a patchy greenish colouration irregularly spread over the grain. Tremolite is common only in the palest rocks, including the marble bands, but a related pleochroic amphibole, presumably actinolite, occurs in some of the more mesocratic rocks. The tremolite is in complexly intergrown sheaves of prisms, which



FIGURE 4. Contact of transitional syenite (left) with upper calc-silicates on mine road east of Hiren Lake. Note apparent conformity.

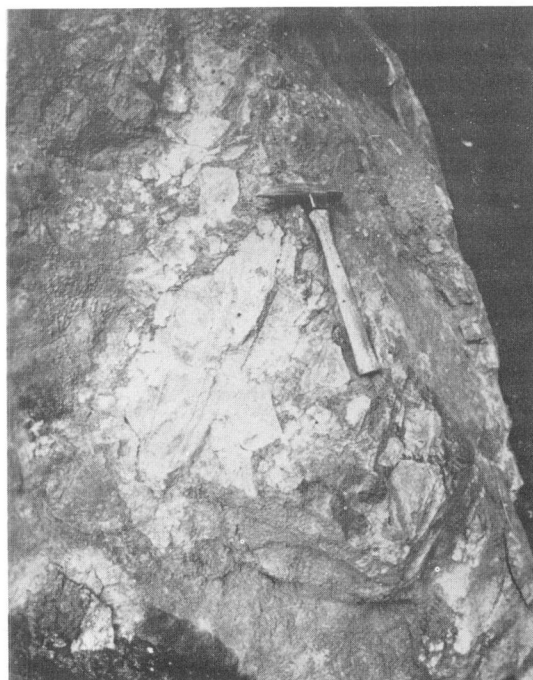


FIGURE 5. Contact of transitional syenite (left) with upper calc-silicates near Mount Copeland Mine. Note brecciation of syenite.

overall display marked alignment. The actinolitic amphibole shows a pale yellow to pale brownish-green pleochroism and substantially smaller extinction angle than the tremolite, but both share a strong red-greater-than-violet absorption. The biotite varies considerably in pleochroism between various specimens, but it always has very pale colour in the X direction and tends to reddish shades in the Y-Z directions. Biotite is generally in sharply bounded zones, where it may be intergrown with diopsidic pyroxene and/or amphibole. Plagioclase occurs in mosaic aggregates of small grains, commonly forming lenticles in the rock. Albite twinning is generally good but may be patchy and discontinuous, particularly on grains that show cracking and clouding. Plagioclase compositions, as measured from twinning orientation, is extremely variable, ranging from pure albite (rare) to labradorite or bytownite. Most of the determinations, however, fall in the range An_{30} to An_{40} , and both normal and reverse zoning are common.

Garnet close to grossular in composition (a , 11.82 Å; n , 1.735; density, 3.07) is an important varietal mineral, appearing in clumps of yellow granules. Quartz may be in the albite mosaics or form large, highly strained, single grains, but it is absent from many specimens. Potash feldspar, though rare, is present in the form of small interstitial grains that may display microcline twinning but commonly show only a peculiar extinction indicative of submicroscopic twinning. Sphene is an important accessory mineral, in some places reaching varietal status in these rocks; generally, it is in masses of small grains, possibly recrystallized megacrysts. Calcite is common in the marble bands, but is only in trace amounts elsewhere. Scapolite, apatite, zircon, and vesuvianite are less common accessories, but in a few places they are in large amounts. Tourmaline and rinkite were seen in one specimen each. An unusual amphibole appears in one specimen that is transitional to the biotite gneiss of unit 10. A colourless mineral ($2V$, 78° ; $z\alpha c$, 27°), it seems to be close to edenite.

The heterogeneity of the calc-silicate unit makes it difficult to select samples for chemical analysis. The rocks below the north portal of the mine adit appear to be the most characteristic, and a composite sample of these was analyzed; the results are given in Appendix 1. They show an extremely high ratio of calcium and magnesium to iron, which combined with the high silica content definitely indicates an origin from siliceous carbonate rocks. The relatively high potash content and the high potash-to-soda ratio could be explained by a high initial content of clays in the sediment. The trace element assemblage is virtually devoid of rare-earths and niobium, suggesting that at least in the sampled locality the rocks have not been subjected to appreciable metasomatism.

Among the minerals, the diopside approaches the end member, being virtually free of alumina and containing only a little iron. The green colour is therefore not due to either iron or soda admixture, but it may be due to incipient chlorite alteration, which can be detected in a few specimens. The biotite approaches phlogopite, and the amphibole is an actinolite with a surprising amount of soda. Presumably there is a transition from this to the edenitic amphibole previously described.

Bronzy Mica Schist (Unit 8a)

The calc-silicate unit is heterogeneous enough to include considerable amounts of quartzite and brownish mica schist. Overlying this material, however, is a more homogeneous, though still strongly calcareous, mica schist. This unit is best exposed around Heart Lake and southeast of East Lake, but similar rocks occur in a thin but persistent layer passing around the anticline-syncline pair in upper Hiren Creek valley. Although the most persistent band lies above the rocks of unit 8, separating them from the quartzite of unit 9, petrographically identical rocks occur west of Mount Copeland mine in direct contact with the syenites and below unit 8. Moderately large amounts of similar material are also found intercalated with unit 8.

The rocks are mesocratic mica schists and gneisses with a characteristic bronzy tinge imparted by the lustre of the mica. Seen from a distance they have a lustrous brownish shade; in outcrop lenticular brown and white patches are seen. Although the rocks split readily on crenulated, mica-rich planes, compositional layering is not pronounced, the rocks tending to a knotted, lenticular type of compositional segregation. Quartz lenses and thin platy quartzite horizons are common toward the top of the unit, where the rocks pass gradationally into the quartzites of unit 9 (Fig. 6), and calc-silicate-rich horizons are more common toward the base, where the unit grades into the calc-silicate rocks of unit 8.

In hand specimen the rocks give a mesocratic impression dominated by coarse bronzy mica and knots of grey-green feldspar, which locally contain visible, intergrown sillimanite needles. Some specimens from the base of the unit contain sillimanite-rich knots up to 5 cm in diameter. Virtually all

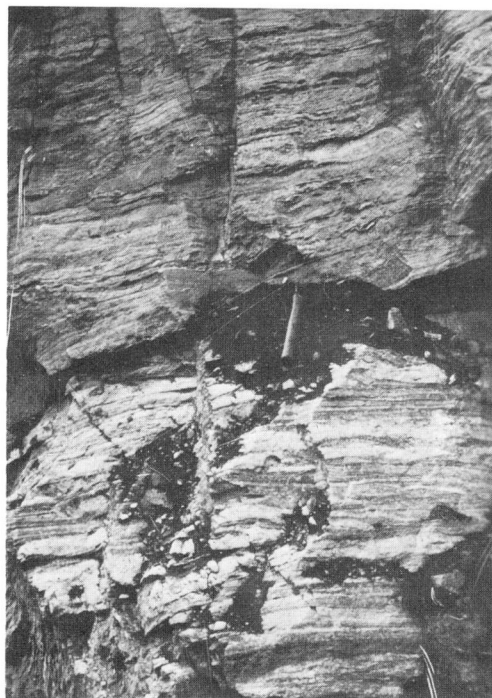


FIGURE 6. Transition from calcareous gneiss (above) to quartzitic gneiss (below), west of Hiren Lake.

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hand specimens contain visible small folds, and where this is particularly strong, the rocks tend toward pinkish shades and contain prominent porphyroblastic feldspar.

In thin section the texture is porphyroblastic and seriate; its gneissosity is feeble. The porphyroblasts, sometimes recrystallized but little strained, have quartz lentils, myrmekitically intergrown here and there with oligoclase (An_{28}), on the margins. Plagioclase more commonly occurs in small scalloped grains showing good twinning, moderately to severely sericitized. Alkali feldspar is always present in the form of fine bleb microcline perthite. The size and freshness of the grains is directly proportional to the amount, the most contorted rocks containing up to 25 per cent by volume in fresh porphyroblastic grains. The mica characteristic of this unit is in euhedral flakes, faintly scalloped by the salic constituents, sometimes forming radiating clusters. The pleochroism is rather strong, from pale yellow to almost opaque chestnut brown, but from the chemical analysis (Appendix 1), it seems probable that the mica is relatively rich in magnesium. An amphibole feebly pleochroic from yellow to brownish green is always present, with a characteristically large $2\alpha c$ ($24-27^\circ$). The optic sign varies from positive to negative in different specimens. The large optic angle and positive sign, although not diagnostic, indicate a magnesian amphibole, possibly of edenitic or pargasitic type. The amphibole forms large poikilitic masses that, as they replace diopside and include potash feldspar porphyroblasts, are probably late. The colour of the amphibole may be quite patchy and irregular owing to replacement by chlorite plus opaque matter. Diopside occurs in a similar habit in a few rocks. Sillimanite, seen in about half the specimens examined (mainly from the lower half of the unit), occurs as clusters of well-formed, radiating prisms commonly associated with biotite or, less commonly, as mats of fine-grained fibres in, or with, potash feldspar. The accessory minerals are not prominent in this unit. The most common are apatite, forming rounded grains with sphene, and zircon. Calcite is erratically present in varying amounts. It may be disseminated as small rounded grains, but usually it forms seams of mosaic calcite.

Appendix 1 presents a chemical analysis of a typical specimen of this unit, that is, one containing neither calc-silicate nor quartzite interbeds. Compared with the calc-silicate unit, which it overlies, this unit is surprisingly rich in iron, titanium, and the associated trace elements Ni, Cr, and Co. The rock also contains substantial amounts of rare-earth elements, comparable to those in some of the syenites. Because calc-silicate and quartzite layers are found intimately intermingled within the unit and the general aspect is mesocratic to leucocratic, it is doubtful that this can be ascribed directly to igneous activity such as intercalated lava flows or sills. These elements might have been derived from clastic debris contributed to the sedimentary rocks by igneous rocks comparable in composition to those of units 6 and 3. Some of the material might also have been added by metasomatism, but this seems unlikely for major elements such as iron and titanium. If the source really is a clastic component from mafic igneous rock, this implies that moderately unweathered igneous material was supplied to the sedimentary basin, and the sedimentary sequence must have

included rocks of a greywacke type. The alternative would be to assume a tuff component or else a large number of thin sills.

Quartzite (Unit 9)

A prominent white quartzite just west of the Mount Copeland Mine underlies a knoll some 250 m high and extends westward beyond the limits of the map-area. A similar, but thinner, quartzite in a comparable stratigraphic position occurs east of the mine, running southeast along the shores of East Lake; even farther to the east a narrow band of similar material crosses the crest of the west spur of Mount Copeland. In all these localities, the quartzite separates the bronzy mica schists from a distinctive unit of augen gneiss grading to granite gneiss. Comparable quartzites are found slightly lower in the succession, forming thin layers within the mica schists (Fig. 6); for convenience of delineation, these have been shown in the same colour on the map.

In outcrop the quartzite is commonly a white and massive rock with prominent, fine, grey colour bands. On close inspection various lentils and interbeds of brownish biotite schist, similar to the underlying mica schist, are visible, particularly near the base of the unit. Both portions usually show a strong lineation due to rods of quartz or feldspar, probably deformed porphyroblasts but possibly remnants of pebbles. The lineation may mark the intersection of earlier cleavage and bedding. The contact of the quartzite with the overlying augen gneiss seems to be quite sharp, although there are a few thin quartzite beds in the augen gneiss. On the whole, the quartzite is the cleanest and most homogeneous unit seen in the map-area.

In outcrop the quartzite is composed mainly of white to pale grey vitreous quartz in which the outlines of individual grains can rarely be seen. The biotite-bearing interlayers are always fine-grained and compact; they do not show the easy fissility characteristic of the underlying mica schists.

The mineralogy of the quartzites is simple, as might be expected, consisting of quartz, biotite, muscovite, and some sillimanite, plus accessory zircon, magnetite, and apatite. Quartz always forms more than 65 per cent of the rock, even in the apparently mesocratic biotite-bearing varieties. The texture is variable, ranging from xenomorphic-granular with strong strain to mosaic with no strain, presumably because of recrystallization. Many of the rocks display amoeboid interlocking textures that could not have been penetratively deformed. Biotite is present in small euhedral grains, often contained within large quartz grains. Extreme preferred orientation is common, so that in many thin sections all the grains have essentially the same orientation. The pleochroism is relatively strong in shades of reddish brown in the western part of the area, but this becomes weaker to the east. In many places, muscovite is much subordinate in amount to biotite and forms thin haloes or crusts around it. Sillimanite exists mainly in the lower and upper edges of the unit as bundles of fine fibres projecting into all the other minerals. Apatite and zircon are sparsely present as rounded, clastic-looking grains.

A chemical analysis of one of the biotite-rich interbeds (transitional to the augen gneiss of unit 10) is given in

Appendix 1. It shows that the mica is still moderately rich in phlogopite component. The trace element assemblage is impoverished, as might be expected in a relatively clean, clastic rock, but the high magnesia content and the persistent presence of nickel and chromium suggest that some of the debris must have come from mafic igneous rocks, either directly or by recycling from the rocks of the biotite schists (unit 8a). The comparatively high potash content and extreme K/Na ratio can presumably be explained by assuming a substantial clay component in the original sediment, which would also explain the presence of sillimanite.

Augen Gneiss and Granite Gneiss (Unit 10)

The youngest unit of the metamorphic complex observed in this area is a heterogeneous brown-weathering schist and gneiss (unit 10a) containing and grading to various types of granitoid gneisses (unit 10b). Such rocks are exposed more or less continuously along the southern and southwestern margins of the map-area, as isolated remnants east and west of East Lake, and in the tight syncline north of Mount Copeland.

In outcrop the rocks of the gneiss complex exhibit a strong, even gneissosity, defined by prominent mafic lenticles or by interfaces. The salic minerals are present in blobby, or schlieren-like, masses up to 10 or 15 cm long and 2 to 5 cm wide (Fig. 7). Depending on the number and size of the salic schlieren, the rock varies from a whitish, mesocratic gneiss to a pale pink, almost homogeneous, granitoid one.

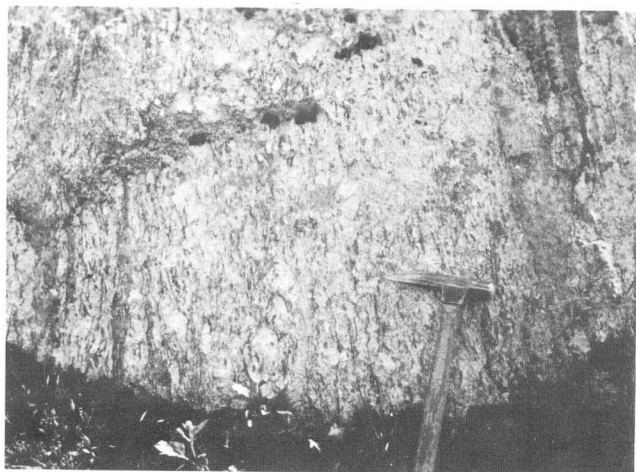


FIGURE 7. Typical texture of the augen gneisses, showing dark mafic seams and pale felsic blotches.

In hand specimen the rocks consist of alternating lenticles of mafic and salic material. The mafic minerals sometimes seem to form continuous sheets, but when the specimen is cut at the appropriate angle, these always turn out to be rather sigmoid lenticles or, more rarely, two sets of sigmoid lenticles cross-cutting each other at a low angle, possibly reflecting earlier cleavages. Along the elongation, a wavy crenulation also is common. Mafic layers are always darkest around the nose of the salic lenticles, and along the sides of these lenticles they contain abundant small salic grains,

locally to such an extent that the differentiation of the mafic and salic fractions becomes difficult. The salic layers usually have a squarish to oval cross-sectional outline, in places lobate, as though several individual lenticles have aggregated. Along their length, they tend to boudin-like form, but with a distinct waviness. Some are monomineralic feldspar, but most are granular quartz-feldspar aggregates. Despite the augen appearance of the rock, none appear to be single crystals of feldspar.

In thin section the felsic portions are seen to consist of amoeboid strained quartz, well-twinned andesine (An_{32-35}), and large grains of alkalic feldspar locally replacing both. The alkalic feldspar rarely shows good development of perthitic twinning but rather a peculiar sort of moiré extinction, with strong red-greater-than-violet absorption, probably caused by submicroscopic exsolution. Biotite, pleochroic in shades of olive, is the principal mafic mineral, generally in the form of sheaves of radiating grains, but hornblende (X, pale olive; Y, pale green; Z, deep green; z_{AC} , 28° ; $-2V$, 43°) is common in large poikilitic grains, including plagioclase, biotite, apatite, and sphene. In a given section, all the amphiboles show identical or very similar orientations. A few specimens contain pale pink garnets as blobby, dense grains in the mafic layers. Such rocks usually also contain small amounts of muscovite and sillimanite intergrown with each other and growing on the sides of biotite clusters. The predominant accessory minerals are apatite, zircon, and magnetite, all generally found in the cleavages of the biotite.

Two chemical analyses of the augen gneiss complex are presented in Appendix 1 and analysis of some of the minerals in Appendix 2. Although the analyses were chosen to represent the two apparent extremes of the complex in terms of mafic content and potash feldspar content, they are very similar, suggesting that despite small-scale heterogeneity, the composition of this unit is relatively constant. The composition of the rock is not diagnostic of its origin, but the intercalated bands of quartzite suggest a sedimentary origin, in part at least, and the analysis is compatible with origin as a shale or a greywacke. The poverty in rare-earth elements is comparable to that of the underlying quartzite.

Lamprophyre Dykes (Unit 11)

The highly deformed metamorphic rocks of the ridge west of Mount Copeland are cut by a number of fresh, undeformed lamprophyre dykes up to 3 m wide. These dykes all have a generally north-northeast trend and seem to occupy joint or shear planes in the rock. Most of the occurrences were in a belt about 1,000 m wide extending from the upper Hiren Creek valley to the crest of the ridge west of Mount Copeland, including the adit of the Mount Copeland Mine. However, they were also seen on the west end of the ridge, and the apparent concentration may be due to accidents of exposure, particularly the presence of blasted road cuts in favourable locations. More than 20 exposures of this rock were seen, which allowing for the repeated exposure of the same dyke, appears to represent at least a dozen dykes.

The dykes weather recessively, leaving brownish trenches. On exposed surfaces they are either brown or

black, the brown varieties displaying abundant euhedral biotite crystals moderately aligned in a finely granular brownish matrix, the black containing prominent nodular spots of carbonate (ocelli) in a fine-grained black matrix, in some cases containing small phenocrysts of mica. The dykes commonly contain rounded inclusions up to several centimetres across and some appear rubbly—a mass of fragments both cognate and exotic.

In thin section the rocks are dominated by a colourless or very pale yellow pyroxene in large stubby prisms variously corroded at the edges. This pyroxene (+2V, 62°; ZAC, 39–43°) is apparently diopsidic, with little soda. A small amount of kaersutitic brown amphibole may be present, but the other main mafic mineral is a deep brown biotite showing very feeble pleochroism, in most places forming euhedral blades of varying sizes. The matrix is composed of a mixture of a low-index, low-birefringence mineral in large, distinctly zoned grains, presumed to be analcite, and frondlike masses of natrolite, the whole heavily laced with apatite needles. X-ray determinations revealed patterns for only analcite and thomsonite, although a little alkali feldspar was thought to be present in thin-section examination. Calcite occurs either in the form of sharply bounded, coarse-grained, monomineralic masses rimmed with chlorite and opaques or as chains of tiny granules crossing parts of the thin section. Magnetite is scattered irregularly through the thin sections but is not abundant.

The dykes contain a variety of inclusions and xenocrysts, particularly from the nepheline syenite. The inclusions appear very little altered, except for a thin film of chlorite or muscovite, or both, around the margin. Even xenocrystic plagioclase seems little affected where it is distributed in the matrix.

Chemical analysis of the dykes revealed their unusual character (Appendix 1). The differences in colour are purely superficial because the two types give essentially identical analyses. They are not the ordinary lamprophyres associated with granitic terranes, which have dioritic or granodioritic compositions, but rather alkaline ultrabasic rocks of a peculiar type usually found associated with carbonatite and syenite in alkaline igneous complexes (Table 1) (Ferguson and Currie, 1971a). The composition of the minerals (Appendix 2) reveals close links with the kaersutite lamprophyres of the Callander Bay complex, which yielded a syenitic fraction by immiscibility.

The presence of such unusual alkaline rocks in the vicinity of alkaline gneiss of uncertain origin leads to speculation on a connection between the two types. However, the tectonic setting of the two poses a severe barrier to such correlation. The nepheline syenite gneiss shows clearly the effects of all the deformational episodes that affected the country rocks, whereas the dykes show no deformation except for a little marginal shearing of negligible importance. Their emplacement must thus be separated by the time required for deformation of the country rocks, presumably by several millions or tens of millions of years. If a connection between the two exists, it must be on the level of a mechanism persistently generating alkaline rocks in this region rather than on a direct genetic connection between them.

Biotite was concentrated from a lamprophyre dyke that

crosses the mine road just north of Hiren Lake, and the sample was submitted for age determination by the K/Ar method. The concentrate contained 6.15 per cent K and 67 per cent radiogenic argon. According to the standards of Engels (1972), the results must thus be treated with some reserve, because a certain amount of either contamination or alteration seems probable. The result was 44 ± 3 m.y., compatible with other ages from young basic dykes in this region and presumed to date a period of tensional fracturing post-dating the penetrative determinations of the metamorphic complex by millions of years.

STRUCTURE OF THE NEPHELINE GNEISSES

The nepheline gneisses near Mount Copeland lie on the southern flank of the Frenchman's Cap gneiss dome, a major structure dominating the regional disposition of the Shuswap Metamorphic Complex for more than a hundred kilometres northwest of Revelstoke. In the small area studied, however, the effects of this regional structure are only indirectly apparent, because complex multiple folds dominate the patterns seen on scales that vary from a single outcrop to that of the whole map-area.

These patterns have been studied in considerable detail by Fyles (1970), and his results are summarized in this section (Fig. 8). However, detailed mapping shows that the

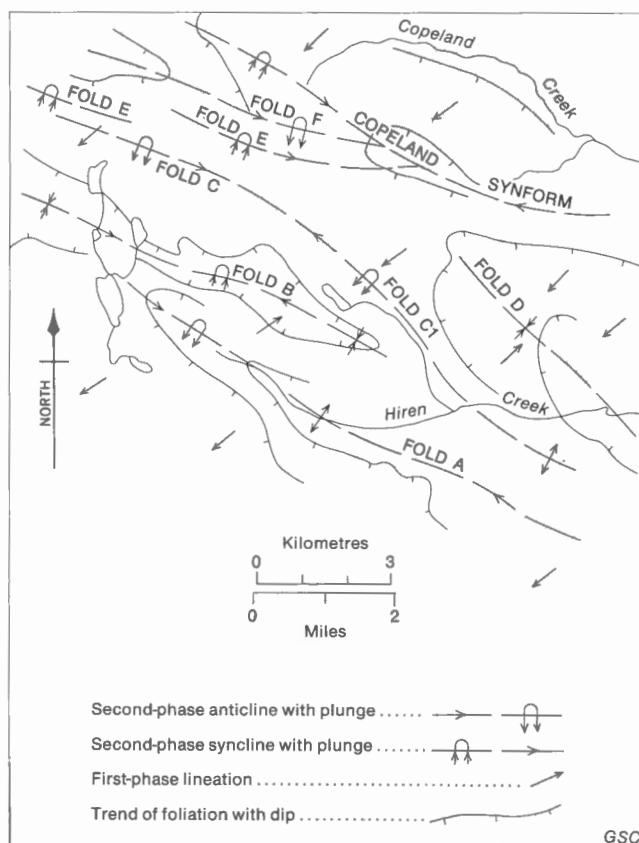


FIGURE 8. Generalized sketch of the Mount Copeland area, showing the disposition of the major structures (after Fyles, 1970).

syenites of Mount Copeland lie in an antiform not recognized by him. This prompts some revision of his structural synthesis, but the modifications are of minor character, so that the general structure is identical to his, which in turn is reasonably concordant with that of McMillan (1973), derived from rocks a few kilometres west of the mapped area.

Two major phases of folding are recognized. Phase 1 encompasses recumbent isoclinal folds with warped axial surfaces and attenuated limbs. Although only minor folds of this phase have been clearly delineated, major ones control the overall outcrop pattern in the map-area. Those in phase 2 are upright to overturned, their axial surfaces dipping moderately to the southwest and south. Both these fold episodes were accompanied by flowage and plastic deformation.

Fyles (1970) distinguished a third period of folding, which resulted from the flexing of the rocks around the Frenchman's Cap dome, and McMillan (1973) distinguished two additional periods of folding said to be related to the uprise of the dome. Fracturing, mainly of extensional character, appears to have been the latest episode of deformation in this area, producing the planes later occupied by the lamprophyre dykes.

The rocks display an abundance of minor structures, which ordinarily help in the interpretation of the larger structures, although their very abundance is confusing in some cases (Fig. 9). Layering, usually the result of pronounced compositional differences, presumably reflects original bedding, variously modified. Cleavage, or schistosity, rarely crosses layering, except in the axial zones of folds. A strong lineation is commonly defined by parallelism or by



FIGURE 9. Two phases of small folding exposed in boulder on shore of Hiren Lake.

rodding of the mafic minerals or, less commonly, of the feldspar porphyroblasts. This mineral lineation is almost invariably parallel to the axes of the phase 1 folds. In micaeous rocks a prominent wrinkling of the cleavage is quite common, defining a lineation. The lineation is in most instances parallel to the axes of the phase 2 folds. In a few rocks, both lineations are present, yielding rather spectacular interference patterns (Fig. 10).



FIGURE 10. Calc-silicate gneiss in which leucocratic beds have been reduced to contorted lenticles by intersecting S surfaces.

Folds

The phase 2 folds dominate the structure and map pattern of the area, controlling the distribution of the map-units, in distinction to the phase 1 folds, which are obscure.

The axial traces of four major phase 2 folds are shown on Figure 8 together with their associated parasitic folds. From north to south these folds comprise a complex synform along the northern slopes of the ridge west of Mount Copeland termed the Copeland synform, an antiform following the upper part of the ridge (fold C), a synform whose axis passes just north of the upper course of Hiren Creek (fold B), and an antiform that follows the upper course of Hiren Creek, passing to the south at its eastern end (fold A). With the exception of the Copeland synform, these folds vary from isoclinal to open and, in style, from concentric to similar, and they show strong thickening in hinge zones and attenuated limbs.

The prominent synform on the northern slopes of Mount Copeland has been explored by extensive drilling on the King Fissure property north of Mount Copeland (Fyles, 1970). Although the outcrop of units 4 and 5 display a well-defined, nearly isoclinal synform, the stratigraphy adopted suggests that this synform could be an anticlinal nose, because the units may become older toward its centre.

On the King Fissure property the trend of the Copeland synform is disturbed by the presence of two cross-folds termed folds E and F by Fyles (1970). The anticline, fold F, can be traced westward to the boundary of the area, passing from a "small broad concentric warp" (Fyles, 1970) on the King Fissure property to an isoclinal fold with an apparently cross-cutting syenite core on the west edge of the map-area. The synform E is a large concentric fold north of Mount Copeland. According to Fyles (1970) it can also be traced continuously to the west edge of the area, into a well-defined isoclinal syncline in the calcareous gneisses of unit 11.

An anticline (fold C) passes just south of the crest of the ridge west of Mount Copeland as far as the mine adit and thence southeast to the east of East Lake. Fyles (1970)

recognized only the southeastern part of this fold, although his structure sections B-B' and D-D' imply the presence of an anticline on the western part of the ridge. Mapping of the syenite complex both on surface and underground revealed many small structures consistently indicating the presence of an overturned isoclinal anticline. Fyles (pers. comm., 1974) has pointed out that the structure might be a series of small folds on a monoclinical limb, but the net effect is the same as that of a larger anticline.

The limbs of fold C are strongly attenuated on the end of the ridge west of Mount Copeland, where the distinctive syenite units can be traced across several structures. For example on the western end of the ridge, the syenites thin from roughly 400 m in the nose of the major anticline to less than 100 m on the limb of the minor syncline to the north. Boudinage and development of schlieren from the syenite are abundant on the limbs of the fold. The plunge of the major anticline is very gently west near the Mount Copeland Mine, but near East Lake the plunge reverses to easterly and locally becomes moderate to steep, reaching 50 degrees in some localities. There the fold is relatively open and upright, the limbs dipping about 50 degrees. To the southeast the dips and plunge both decrease, and the fold may disappear beneath Hiren Creek valley.

A complex synformal basin occurs east of fold C in the Hiren Creek valley (fold D of Fyles, 1970). The axis of this structure trends south-southeast in the mapped area, but according to Fyles it curves to a more easterly trend farther east. In general aspect the fold appears to be a reasonably symmetrical open synform having limbs dipping about 60 to 70 degrees inward. The plunge is 30 to 40 degrees to the south at the north end and about 15 to the northwest at the eastern edge of the mapped area. Despite the apparent simplicity, there are areas within the synform displaying north-east-plunging small structures, anomalous for any of the known major structures, so there are some unresolved complexities in this structure.

Another syncline appears southwest of East Lake, on the opposite side of the broad anticline in the syenites previously described (fold B of Fyles, 1970). Although this fold is basically an isoclinal overturned syncline, reversals in dip of foliation can be found along the axis, and the fold appears to become more open towards the east, where it probably disappears beneath the overburden in Hiren Creek valley. The plunge of the fold is moderately westward in its eastern part, but there is a reversal near the mine road, where the fold plunges 10 to 15 degrees eastward. Another reversal occurs near Heart Lake, and at the western boundary of the map-area the fold plunges 10 to 15 degrees westward. The dip of the axial surface is nearly vertical at the east end of the fold, but the southward dip gradually decreases westward as the fold becomes tighter, reaching about 75 degrees at the western margin of the map-area.

One of the most prominent second-phase folds in the map-area has an axial trace almost coincident with the upper course of Hiren Creek (fold A of Fyles, 1970). The fold is beautifully outlined by the quartzite, calc-silicate, and syenite units, all of which display strong thinning along the limbs of the fold. In the southeastern part of the area it is an overturned, nearly isoclinal anticline trending easterly, the axial

surface dipping about 65 degrees to the south. To the westward the axial trace turns in a more northwesterly direction and the fold becomes open and upright. The plunge remains relatively constant throughout the length of the fold at 20 to 25 degrees west-northwest, but at the extreme western end it seems to flatten and the fold disappears. The exact nature of this disappearance is not entirely clear because flattening of the limbs, reversal of plunge, and faulting are all apparently involved.

Phase 1 folds are most difficult to map satisfactorily. In general, where strongly lenticular bulging and thinning of map-units occur, phase 1 folding is strong and obvious. Small phase 1 folds can be seen on many outcrops, but large ones are obscure, though the axes are defined by pronounced penetrative mineral lineation and rodding. Because the phase 1 folds are mainly isoclinal and have axial planes essentially parallel to the layering, the plunge of this axial lineation reverses across open phase 2 folds. Excellent examples of this characteristic can be seen in fold B and at the western end of fold A. In the main, however, the phase 2 folds are nearly isoclinal and of relatively constant trend. The lineation associated with the phase 1 folds is therefore of fairly constant attitude, averaging 240 degrees in azimuth and 50 degrees in plunge.

The syenites can be clearly seen to be involved in phase 1 folds in the southeastern corner of the map-area. The syenites are greatly thickened in the nose of a phase 1 fold and appear to terminate on its flank, presumably by tectonic thinning. Several similar, though smaller, examples can be seen west of Mount Copeland, where the syenites are involved in phase 1 folds, showing radical changes in thickness from the nose to the limbs of relatively small folds (Fig. 11). A particularly spectacular example in the quartzite occurs about 0.7 km west of the Mount Copeland Mine, where the quartzite on the north side of a phase 2 syncline is almost of negligible thickness, but on the south side, in the nose of a phase 1 antiform, it forms a prominent knoll several scores of metres high.

Despite these clear examples, it was not possible to



FIGURE 11. Small-scale, rootless, phase 1 folds in syenite west of Mount Copeland. Note rapid attenuation of limbs.

consistently integrate the effects of phase 1 folding into the fold pattern. The most prominent effect that was generally recognized is drastic thickening and attenuation of units, locally to the point of causing units to disappear, only to reappear elsewhere as pod-like masses.

Faults

Fyles (1970) distinguished two stages of faulting as early- and late-stage faults. The most prominent early fault, the Bews Creek Fault, is marked by a lineament, shearing, and a rusty zone. This fault, which truncates lithologic units and significant structures throughout the map-area, originated at the time of phase 1 folding and seems to have been folded during phase 2. The displacement on the fault appears to be considerable, although comparison with the stratigraphic column of McMillan (1973), compiled on the west side of the Frenchman's Cap dome where no fault is present, suggests that any stratigraphic gap must be small, because reasonably good correlation seems possible between all units up to unit 5 on the present map (Table 2). On the interpretation of folding adopted in this report, the fault truncates both phase 1 and phase 2 folds (as suggested by Fyles), and the extremely sinuous outcrop trace suggests that it was folded by later folds. Despite the assumed substantial displacement, the surface expression of the fault is not impressive. Small-scale shearing is present near the fault trace, but it is also found in virtually all biotite-rich rocks in the map-area. The lineament and rusty zone seem to be mainly products of the different hardnesses of the quartzite and the overlying gneisses rather than direct products of tectonic disturbance.

Late faults of relatively minor offset are common and, together with related joints, form a network of north- and north-northeast-trending lineaments in the map-area. On many prominent lineaments, no offset of formations could be detected. Where they were detected, they were rarely greater than a few tens of metres and appeared to be mainly west side down. The only fault that could be traced with any continuity was that bounding the west end of the ridge west of Mount Copeland and running south to Heart Lake and beyond the map-area.

Several of the faults are filled by lamprophyre dykes, which in a few cases show some slight marginal shearing. Others contain coarse, purple fluorite and/or a few sulphides, mainly in fracture fillings but also disseminated in the country rocks, both presumably related to nearby lamprophyres.

Regional Significance

The possible correlation of stratigraphic units in the Mount Copeland region with formations elsewhere was considered at some length by Fyles (1970) and by McMillan (1973). Both concluded that no satisfactory detailed correlation could be made, although possible correlations all turn on the Upper Proterozoic Horsethief Creek Group and the Lower Cambrian Hamill Group. Wheeler (1965) concluded from regional considerations that rocks of these groups must be present on the Frenchman's Cap dome, but both Fyles (1970) and McMillan (1973) found it impossible to make a

satisfactory detailed correlation of the observed stratigraphic sequence with the stratigraphy of these groups as observed elsewhere.

Fyles (1970) pointed out that the phase 1 folds extend considerably beyond the Frenchman's Cap dome to the east of the Columbia River. They are apparently part of a regional system not related to formation of the dome. The other folds, however, seem to be limited to the region of the dome and presumably are related to its formation. In a general way, the folds become more open and upright with distance from the core gneisses. This would be the result if the central part of the dome (core gneisses) were diapirically intruded. McMillan (1973) presented evidence that the core gneisses were more ductile than their surroundings.

PETROGENESIS OF THE NEPHELINE GNEISSES

In considering the origin of the nepheline gneisses, four hypotheses must be examined: (1) the alkaline rocks could be metasomatic, derived from a subalkaline protolith; (2) they could have derived from an intrusive complex tectonically deformed into apparent conformity with their surroundings; (3) they could be metavolcanic, originally intercalated into the sedimentary pile and hence deformed and metamorphosed with it; and (4) they could be sills intruded into the sedimentary pile after consolidation but before metamorphism. The discrimination between these possibilities rests on what may be broadly termed stratigraphic and chemical considerations. According to possibilities 1 and 3, the alkaline rocks should tend to be bound to very specific horizons, but possibilities 2 and 4 suggest repetition at several horizons or crossing of the stratigraphy by the alkaline rocks. Similarly, possibilities 1 and 3 require chemistry different from that of 2 and 4, and presumably that of 1 should be unique.

Stratigraphy

The alkaline syenitic rocks commonly occur in a well-defined stratigraphic interval within the lower part of the quartz-diopside-biotite gneiss (unit 8) or between this unit and the quartzitic gneiss (unit 7). In some instances, however, they contact other units. West-northwest of the Mount Copeland Mine, the syenite complex touches brownish biotite schist of unit 8a. Fyles (1970) mapped an occurrence of nepheline syenite just beyond the northeast corner of the map-area, emplaced in the lower part of the quartz-biotite-pyroxene-hornblende gneiss of unit 6. In general, however, the syenites are in a limited stratigraphic interval and do not appear randomly throughout the section.

No clear-cut example of syenite cutting a sedimentary unit was found on outcrop scale. Given the degree of deformation, it might be expected that most, or all, cross-cutting bodies have been rotated into the foliation, and cross-cutting relationships would be extremely rare. However, some medium-scale features of the syenites suggest that a few relict cross-cutting features may be present. In the north-west corner of the map-area, syenite seems to pierce dia-

TABLE 2 *Stratigraphy, Mount Copeland and Perry River area*

Mount Copeland	Perry River†
Lamprophyre dykes (11)*	None
Augen gneiss with pegmatite lenses and granite gneiss (10a)	Metasedimentary rocks laced with pegmatite (5)
Quartzite '3' (9)	Quartzite with biotite schist, biotite-sillimanite schist, and biotite-quartz gneiss layers (4d)
Bronzy mica schist (8a)	
Quartz-diopside-biotite gneiss (8)	
(Syenite and nepheline syenite gneiss [A1-A2-A3])	
Quartzitic gneiss and quartzite '2' (7)	Quartz-biotite gneiss with calc-silicate gneiss and a quartzite layer (upper 4c)
Quartz-amphibole-biotite gneiss with quartzite and calc-silicate layers (6)	
Quartzite at base grading to calc-silicate gneiss and capped by marble (5)	Biotite schist, biotite-quartz gneiss marble (middle 4c)
Biotite sillimanite schist (4) with marble layers	Carbonatite
— Bews Creek Fault —	Biotite sillimanite schist with quartzite, calc-silicate gneiss, and some marble layers (lower 4c)
Biotite schist and gneiss with quartzite and calcareous layers (3)	Biotite schist and gneiss with quartzite and calc-silicate layers (lower 4c)
	(Nepheline syenite gneiss and carbonatite [4b])
Quartzite '1', with basal conglomerate (2)	Quartzite, some conglomerate (4a)
Heterogeneous gneisses (1)	Migmatite and agmatitic migmatite (2, 3)

* Numbers in parentheses in this column refer to map-unit numbers.

† Stratigraphy after McMillan, 1973. Numbers in parentheses refer to his map-unit numbers.

pirically the quartzite in the core of a tight anticline (fold F, Fig. 8). It could be argued that this relationship is due to mobilization during deformation and thus not indicative of original cross-cutting relations. Southwest and west of Hiren Lake, the syenite appears to truncate successively the quartzitic gneiss (unit 7) and the quartz-diopside-biotite gneiss (unit 8) to come in contact with the mica schists of unit 8a. No major structural complications were seen to obscure the relationships at this point. The number of small lenticles of alkaline gneiss (Fig. 12) scattered through the subalkaline rocks surrounding the syenite suggest the presence of former dykes or veins. Such bodies are far too small (measured in centimetres) to be sills or flows, yet their chemistry (Table 1) suggests igneous derivation. If they are boudins derived from larger bodies, they should be in a reasonably constant stratigraphic position, which was not observed.

Although nearby bodies of alkaline rocks are not necessarily of the same origin, some striking similarities in petrography and structure of the other alkaline gneisses fringing the Frenchman's Cap dome suggest similarities in origin. In the

Perry River area, a few kilometres west of Mount Copeland, McMillan (1973) mapped nepheline-bearing gneisses and carbonatite at an horizon that correlates fairly reliably with the contact between units 2 and 3. Carbonatite is also found at a higher horizon, tentatively correlated with the boundary between units 4 and 5 (Table 2). McMillan (1973) argued on the bases of rare relict igneous textures and of chemical compositions that the syenitic rocks are mainly of igneous derivation, and he suggested, because of their form, that they were emplaced as concordant bodies. The carbonatites he considered, tentatively, to have resulted from volcanic action, either as tuffs or as exhalatory deposits.

McMillan's (1973) arguments for concordant emplacement do not convince me. Repeated intense deformation, such as that undergone by the gneisses around Frenchman's Cap dome, tend to make all lithologies appear concordant. The appearance of alkaline rocks at a similar stratigraphic horizon for 10 miles (15 km), as described by him, is impressive, but in the Ice River alkaline complex 100 km to the east, alkaline rocks appear at the same stratigraphic horizon



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FIGURE 12. Boudin of syenite in mica schist on north face of Mount Copeland. This may represent a dyke translated into the gneissosity plane.

over 18 km of arc length (Currie, 1976), even though the degree of deformation is far less than that at Frenchman's Cap, and the internal structures of the pluton are completely preserved, showing it to have been originally layered, elliptical, and cross-cutting. The evidence for volcanic origin of the upper carbonatite seems even more tenuous. If one makes the reasonable assumptions that the alkaline rocks of the Perry River district and the Mount Copeland district are genetically related and of approximately identical ages, McMillan's (1973) hypothesis cannot be correct, because the syenite complex at Mount Copeland is intruded into rocks that are substantially stratigraphically higher than the strata hosting alkaline rocks at Perry River.

Nepheline-bearing gneisses are also found on the northeast flank of the Frenchman's Cap dome at Trident Mountain (Wheeler, 1965) and a few miles farther northeast at Kinbasket Lake. These occurrences are less strongly gneissic than the Mount Copeland and Perry River nepheline gneisses and are thought to be in rocks of the Upper Proterozoic Horsethief Creek Group and the Lower Cambrian Hamill Group, respectively. Hence nepheline gneisses are present in a broad stratigraphic range throughout the whole of the dome.

If all the possibly igneous rocks on Mount Copeland are considered, alkaline rocks exist in units 6 through 9 and range from nephelinitic through alkali basaltic to syenitic. They occur through a broad range of stratigraphy and composition. These considerations weigh heavily against the alkaline rocks' being metasomatic. The range in stratigraphic occurrence and comparison of stratigraphic level also argue, although less strongly, against a volcanic origin for most of the rocks.

Chemistry

Could the alkaline rocks indeed be metasomatic? There are two variations of the hypothesis. First, if the metasomatism is of regional extent, stemming from an unspecified source outside the map-area, the undersaturated alkaline rocks could be ascribed to original compositions particularly favourable for formation of syenites by metasomatism. However, in such a case, all other rocks in the mapped area should also show some signs of metasomatism, and its intensity should not depend on their propinquity to the syenites. This proposition is clearly false. In general, the less alkaline rocks surround the nepheline-rich varieties in a series of concentric shells, and in particular, a study of fenitization in the quartzite of unit 7 showed clearly that the development of alkaline amphibole in this rock depended on its distance from the syenites. This hypothesis can therefore be discarded and the second considered—that one, or a few, beds are the source of the undersaturated, sodic character of the alkaline rocks and that this character has, so to speak, diffused from this source into the surroundings. Given the location of the syenite rocks within a generally calcareous sedimentary sequence, it seems clear that the only possible source of such an undersaturated, sodic character would be salt beds. Even leaving to one side the probability of formation of salt within a quartzite–greywacke–shale–dirty carbonate sequence, such an hypothesis is unacceptable on chemical grounds because of the high niobium and rare-earth content of the syenites. These elements are extremely low in salt deposits, and this, together with the high Ni and Cr content of the syenites and related rocks, seems to demonstrate an igneous origin.

The problem is therefore twofold: to define the range of igneous activity and to decide between an intrusive and an extrusive manner of emplacement. Finally, the significance of metasomatism around the igneous bodies will be investigated.

In Table 3 the major-element analyses of possibly igneous rocks have been arranged in order of ascending stratigraphic level and named according to the chemical classification scheme of Irvine and Baragar (1971). From this compilation it can be seen that the observed rocks cover the range from nephelinite through alkaline basalt to phonolite and trachyte. This range, however, is not complete; but it falls into two well-marked parts: the nephelinitic to alkalic basaltic and the generally syenitic. Both the range of compositions and the division into well-marked fields may be duplicated in numerous well-studied alkaline igneous complexes, both volcanic and plutonic. The mainly volcanic igneous rocks of Otago in New Zealand (Coombs and Wilkinson, 1969), for example, cover a roughly similar range, and among plutonic rocks the composite igneous plutons of the Montereian Hills, such as the Brome Complex (Valiquette and Archambault, 1968), also show a similar range. The pronounced division between salic and mafic components is a well-known feature of igneous rocks, having a long history of petrologic comment going back to Daly (1914) and beyond. The range of chemical composition thus seems appropriate to an alkaline igneous complex, and there is no obvious reason to suppose that large-scale metasomatism must have been involved in the formation of the major units of alkaline rocks.

TABLE 3

Possibly igneous compositions from Mount Copeland

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	48.81	47.23	48.78	54.92	52.00	55.05	54.11	44.18	49.09	54.79	57.97
TiO ₂	3.08	0.28	0.73	0.55	0.32	0.50	0.49	5.49	2.53	0.62	0.47
Al ₂ O ₃	11.23	26.06	25.22	23.01	25.91	21.63	21.69	7.51	18.48	21.82	18.08
Fe ₂ O ₃	1.16	3.64	3.46	2.57	0.89	1.07	2.48	8.06	0.22	3.81	0.04
FeO	10.18	1.59	0.23	2.62	0.21	5.16	0.62	7.20	7.17	0.49	0.51
MnO	0.15	0.28	0.12	0.22	0.05	0.28	0.11	0.37	0.05	0.12	0.23
MgO	8.37	0.31	0.32	0.67	0.23	1.07	0.19	7.76	2.81	0.29	0.11
CaO	10.07	1.52	3.08	1.53	1.32	0.29	3.01	9.68	11.57	2.51	6.53
Na ₂ O	2.24	12.61	9.89	6.06	5.40	2.31	5.85	3.69	2.63	4.33	9.32
K ₂ O	1.58	4.62	7.21	7.47	7.53	11.29	9.37	3.77	3.20	7.62	0.91
H ₂ O ⁺	2.16	0.88	0.30	0.49	4.72	1.11	1.26	1.21	0.82	2.29	0.18
CO ₂	0.59	0.80	0.12	0.23	1.11	0.10	0.24	0.26	0.88	0.28	5.22
P ₂ O ₅	0.28	0.03	0.01	0.02	0.02	0.03	0.01	0.59	0.49	0.01	0.14

1. Pyroxene-biotite amphibolite (unit 6), west end of Mount Copeland.

2, 3. Augen type of nepheline syenite (unit A1a).

4, 5. Homogeneous nepheline syenite (unit A1b).

6, 7. Biotite nepheline syenite (unit A1c).

8. Pyroxene amphibolite (unit A2).

9. Calcareous syenite (unit A3a).

10. Marginal syenite (unit A3c).

11. Albite syenite (aplite), unit A3b.

The question of whether this complex was entirely intrusive or mainly extrusive is much more difficult. Many petrologic works deny, either implicitly or explicitly, that such a distinction can be made on chemical grounds, analyses of lavas and intrusive phases being used indifferently in computing the descent of the residual liquids. For alkaline rocks, however, intrusive rocks do seem to show a number of peculiarities not seen in extrusive equivalents, particularly where carbonatitic rocks are involved. Although no carbonatites have been discovered in the present map-area, McMillan (1973) made a strong case for the existence of carbonatites associated with the syenites a few kilometres to the west. It may be assumed, therefore, that the igneous rocks of the Mount Copeland area either derive from magmas that also produced carbonatite or were closely related to such magmas. In alkaline complexes containing both a salic and a mafic fraction, the salic fraction is generally very poorly represented among the extrusive rocks. King (1965) documented this very well for eastern Uganda. Similar observations may be made at many points in the Cordillera, for example at Goosly Lake (Church, 1970a), where syenitic rocks are relatively abundant among the plutonic types but virtually absent among the extrusives. The abundance of syenite among the Mount Copeland rocks thus suggests a plutonic origin. Of course phonolites are not rare volcanic types, but they are rarely found intercalated with mafic rocks, as are the alkaline rocks of Mount Copeland. The alkaline rocks of the Otago province in New Zealand form an exception to both these rules (Coombs and Wilkinson, 1969), but such exceptions seem to be rare. Furthermore, carbonatites appear to be extremely rare as extrusive rocks but relatively common as intrusive rocks. The known examples of extrusive or pyroclastic carbonatite in East Africa (Dawson, 1964) are apparently more petrological curiosities than indicators of the possible significance of volcanic carbonatitic rocks.

The association of carbonatite with the syenite may therefore be taken as additional weak evidence of the intrusive character of the alkaline rocks.

King (1965) showed in a study of volcanic and plutonic alkaline rocks from eastern Uganda that there are perceptible differences between the chemistry of the intrusive rocks and that of the volcanic rocks, principally related to variations in the alkali/alumina ratio and the absolute contents of alkalis and alumina. Both the ratio and the absolute contents tend to be higher in plutonic rocks than in otherwise equivalent volcanic rocks. King (1965) deduced that rocks in which $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{Al}_2\text{O}_3$ form greater than 40 mol per cent of the rocks are exclusively plutonic. This criterion is met by all the syenites of Mount Copeland with the exception of the aplitic rocks (unit A3), for which the percentage is 35.8. It may be argued that, in the first place, the criterion is valid for only the rocks of eastern Uganda, and in the second place, account has not been taken of the metamorphism of the Mount Copeland rocks. Although it could be shown only by exhaustive compilation whether the criterion is universally valid, it is certainly obeyed by numerous other phonolitic rocks of East Africa, such as those of Mount Suswa in Kenya (Nash *et al.*, 1969), and by phonolitic rocks from the southern Cordillera (Church, 1970b). Conversely, most of the plutonic syenites from the Ice River and Callander Bay complexes (Currie, 1976; Ferguson and Currie, 1971a, b), both of which contain coexisting mafic and salic alkaline rocks, have molecular percentages of $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$ exceeding 40. So as a rough guide, the rule seems to have considerable merit. If the high values in the case of the Mount Copeland rocks are the result of metamorphism and/or metasomatism, the implication is that alkalis and/or aluminum must have been transported into the alkaline rocks. This hypothesis as it relates to sources outside the map-area has already been rejected. If the sources were

inside the map-area, the source rocks would be correspondingly depleted in alkalis and/or alumina. Hence metasomatism cannot explain all the high values, although it may explain a few of them. Finally, we note that the highest values of $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$ occur in the augen nepheline syenites for which the chemical evidence of igneous origin seems strongest (p. 8 above).

The evidence gleaned from stratigraphic and chemical considerations can be summarized as follows. The alkaline rocks are now locally found in a relatively fixed stratigraphic position, and they are commonly, though not invariably, present at this position. However, the stratigraphic position at which they are found varies from area to area. The range in chemical composition lies within that found in other alkaline igneous complexes, particularly those associated with carbonatites, and there seems no necessity to appeal to large-scale metasomatism to explain considerable parts of the igneous rocks, although metasomatism has undoubtedly been operative in the surroundings of the igneous rocks and possibly within them. The geometric relations, relative importance of rock types, and chemical composition all suggest that the alkaline rocks arose entirely, or principally, as the result of intrusion of alkaline igneous rocks rather than partly by intrusion and partly by extrusion of lavas, as supposed by McMillan (1973).

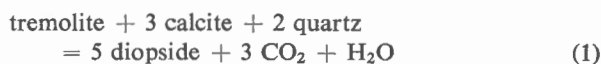
The emplacement of alkaline rocks in the form of nearly concordant masses or as series of sills and dykes is not rare, and may indeed be taken as almost normal, although cross-cutting dykes are ubiquitous around such complexes. Among well-known examples are the Ice River complex (Allan, 1914; Currie, 1976), only 100 km east of Mount Copeland, and the Shonkin Sag body in Montana (Nash and Wilkinson, 1969), some 500 km to the southeast, both of which show a range in composition at least equal to that of the Mount Copeland rocks. Some other examples that display multiple dyke and sill-like masses of varying composition are the Callander Bay complex (Ferguson and Currie, 1971a, b) and the minor intrusions of the Monteregian petrographic province northwest of Montreal (Philpotts and Hodgson, 1968). The model offered for the origin of the Mount Copeland igneous rocks therefore seems quite credible.

Conditions of Metamorphism

Petrographic evidence suggests that the Mount Copeland rocks underwent metamorphism approximately contemporaneously with phase 1 deformation, and further metamorphism during a second period of deformation did not reach a significantly higher grade. The evidence is based on the alignment of metamorphic minerals on phase 1 structures, both foliation and lineation, and the deformation of both single minerals and aggregates of minerals defining lineation and foliation during the phase 2 deformation.

Definition of the grade of metamorphism must be attempted with caution because of the possibility of rapid changes in metamorphic grade, even over the relatively small map-area (cf. Reesor and Moore, 1971), and a slight overprint by regressive metamorphism. However, the maximum P-T conditions can be estimated from mineral assemblage data. Throughout the map-area, sillimanite is encountered to the

exclusion of the other aluminosilicate polymorphs, although McMillan (1973) observed all three polymorphs a few miles to the west in apparently correlative rocks. Muscovite coexists, apparently stably, with sillimanite in units 4 and 10, and no instances of its breakdown to sillimanite, such as those reported by McMillan (1973), were observed. The most distinctive mineral assemblages appear in the calc-silicate gneiss of unit 8, where the assemblage grossularite-diopside-tremolite-calcic plagioclase-quartz-calcite is relatively widespread. Assuming on textural grounds that all these minerals form during prograde metamorphism, some experimental data can be applied. Skippen (1971) investigated the reaction



for which the free energy change is

$$-12486/T + 27.96 + 0.515/T(P-2000) \\ = \log (f_3^{\text{CO}_2} \cdot f_{\text{H}_2\text{O}})$$

T is the temperature, P the pressure, and f_i the fugacity of gaseous species i . This equation may be arranged with the help of the general relation

$$f_i = a_i P_i \quad (2)$$

where a_i is the fugacity coefficient and P_i the partial pressure of species i , to give

$$3 \log P_{\text{CO}_2} + \log P_{\text{H}_2\text{O}} = -12486/T + 27.96 \\ + (0.515/T)(P-2000) - 3 \log a_{\text{CO}_2} \\ - \log a_{\text{H}_2\text{O}} \quad (3)$$

If it is assumed that $P_{\text{H}_2\text{O}} + P_{\text{CO}_2} = P_{\text{total}}$, a condition commonly true for prograde metamorphism of siliceous carbonates and more generally correct when f_{O_2} is relatively high, then Equation 3 gives a limiting upper bound for the coexistence of tremolite, calcite, quartz, and diopside, for a given total pressure, P. This upper temperature has been calculated using the fugacity coefficients for water as given by Burnham *et al.* (1969) and the fugacity coefficient for CO_2 taken from the charts of Hougén *et al.* (1947). The boundary curve is plotted on Figure 13 and labelled 1.

The work of Gordon and Greenwood (1971) on the stability of grossularite shows that the assemblage grossularite-quartz-anorthite-calcite has a lower temperature bound, controlled by the disappearance of zoisite. As determined by them, this lower bound is independent of fluid composition and ranges from 525°C at 2 kb to 650°C at 6 kb. The lower bound for the stability of grossularite without zoisite is shown on Figure 13 as curve 2. In order for the six-phase assemblage grossularite-diopside-tremolite-plagioclase-quartz-calcite to be stable, the temperatures and pressures must fall between curves 1 and 2. We have added the aluminosilicate stability relations after Richardson *et al.* (1969) and the curve for breakdown of muscovite after Kerrick (1972). A small field exists in which the observed six-phase assemblage would be stable if associated with

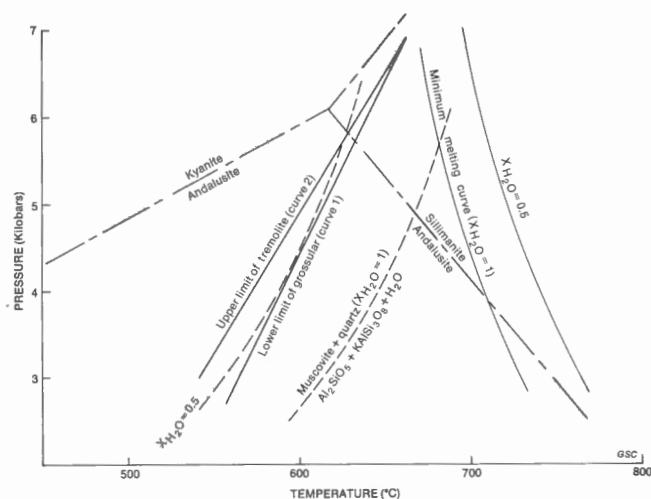


FIGURE 13. Experimental data bearing on the conditions of metamorphism in the rocks near Mount Copeland. The possible range of conditions lies along the curve marking coexistence of grossular, calcite, diopside, tremolite, and plagioclase in the sillimanite field between the kyanite boundary and the upper stability of muscovite.

muscovite and sillimanite in rocks of appropriate composition. The assemblage containing grossularite can *not* be stable at the same fluid composition as that containing tremolite, because the former requires low $\text{CO}_2/\text{H}_2\text{O}$ ratios but the maximum stability of tremolite requires relatively high ratios. This ratio must therefore have varied from place to place in the rock, if all the minerals are in equilibrium. Hence the rocks were not 'open' to CO_2 and H_2O , and the ratios of these components were established by local conditions. Possibly solid solution in the minerals observed may reduce the gap in apparent $\text{H}_2\text{O}/\text{CO}_2$ ratios by expanding the field in which the six phases could coexist.

According to Boettcher (1970), the postulated conditions are above the stability of zoisite in quartz-bearing rocks but not in quartz-free rocks, hence the epidote observed in the syenites. Because the postulated conditions lie close to both the aluminosilicate triple point and the minimum melting curve, McMillan's observations (1973) of muscovite breakdown and local presence of three aluminosilicate polymorphs are easily explained, and the observed development of migmatite seems reasonable. With the calculated P - T - H_2O conditions, the oxygen fugacity can be estimated from Equation 6 of Wones and Eugster (1965) using the assemblage quartz-biotite-magnetite-K-spar. The phlogopite from the calc-silicates (Appendix 2) containing 32.5 mol per cent annite gives an f_{O_2} of $10^{-11.37}$, and the biotite of the mica schist (Appendix 2) at 37.5 mol per cent annite gives a slightly lower f_{O_2} , near $10^{-11.98}$. These values are surprisingly high, lying above the hematite-magnetite buffer (10-12). The biotite of the syenite (50.1 mol per cent annite, Appendix 2) indicates a lower f_{O_2} , $10^{-13.66}$, well below the HM buffer, indicating that fluid phase compositions varied but that oxygen fugacity was generally high, thus supporting the assumption that $P = P_{\text{H}_2\text{O}} + P_{\text{CO}_2}$. Variation in $\text{CO}_2/\text{H}_2\text{O}$ can explain part of the f_{O_2} variation.

We have concluded that the temperature and pressure conditions lay very close to, but just under, the minimum melting curves for the quartz-feldspathic gneisses. Given that the minimum melting temperatures for alkaline compositions tend to lie at slightly higher temperatures than those for the corresponding saturated compositions (Morse, 1969), it follows that the bulk of the syenitic rocks were unaffected by anatexis. However, the aplitic syenite found around the margins of the alkaline rocks, particularly near the Mount Copeland Mine, is almost entirely composed of alkali feldspar. Its normative composition (Appendix 1) consists of over 90 per cent orthoclase-albite-quartz. Abundant experimental data for this system (Luth *et al.*, 1964) show that such a composition would in fact melt at conditions of 650°C and 5.7 kb, even allowing for some dilution of the fluid phase by carbon dioxide. The aplites are not, however, the product expected from such a partial melt; they are too rich in soda and too poor in silica to fall near the minimum melting composition. Morse (1969) pointed out that empirical observations as well as inconclusive experimental evidence suggest that syenitic liquids more potassic than the minimum compositions, and lying along the feldspar join in the quartz-nepheline-kalsilite projection, can be generated from feldspar-pyroxene or feldspar-amphibole parents. The aplitic syenites are tentatively assumed to represent such melts, and their unusual chemistry and texture, as well as the observed cross-cutting relations, are ascribed to this secondary remobilization, which probably took place during phase 1 metamorphism but perhaps partly during phase 2 metamorphism.

Relation to Mineralization

The molybdenite ore of the Mount Copeland Mine being associated principally with the aplitic phase, the conclusion that the aplitic syenites are secondarily melted suggests significant economic implications. Khitarov and co-workers (Khitarov, Arutyunyan, and Lebedev, 1967; Khitarov, Arutyunyan, and Malinin, 1967) examined the partition of molybdenum between coexisting aqueous phase and melts and also the efficiency of collection of molybdenum by aqueous phases. They concluded that molybdenum is efficiently transported in a fluid medium at temperatures above 200°C but is strongly fractionated into the melt when melt appears. Because according to standard thermodynamic theory the initial melt must be saturated in water, and succeeding melts become gradually undersaturated as the temperature rises, a chemical potential exists around developing anatectic melts, driving the water toward the melt. Such melts therefore serve as collectors of materials preferentially dissolved from the rocks, including molybdenum in this case. During solidification, the molybdenum is held in the melt until a late stage, but it may also be transported in the hydrothermal fluids in significant amounts. The operation of these mechanisms appears to explain satisfactorily the localization of the molybdenite in the aplitic syenite and its persistent appearance with this rock type.

Such a mechanism does not preclude a genetic connection between the syenites and the lead-zinc mineralization northeast of Mount Copeland (cf. Fyles, 1970, p. 45-57)

if it is assumed that lead and zinc are strongly fractionated into the aqueous phase from the melt phase and hence tend to escape from the vicinity of the magma. No definite evidence on the origin of the lead-zinc mineralization was seen by the writer except the observation that galena is very commonly associated with lamprophyre dykes. Because these dykes are clearly postdeformation, whereas the principal lead-zinc mineralization is predeformation, there is a suggestion that the lead, at least, is very mobile and its ultimate origin correspondingly difficult to ascertain.

Comparison to Other Nepheline Gneisses

Nepheline gneisses are not particularly rare rocks. In Canada they are known in the vicinity of the Frenchman's Cap dome, forming a discontinuous girdle for nearly 100 km. They occur in a belt some 300 km long from Bancroft, Ontario, to Ste-Véronique, Québec, and as isolated occurrences farther east in Québec, in southern Baffin Island, and near the northeast corner of Georgian Bay. On other continents they are known from eastern Africa (Derkainle region of Somali Republic [Gellatly and Hornung, 1968]) and from Ghana (Holm, 1971), and they exist in Norway (Heier, 1961). The type miaskites of the Ural region of Russia appear to be nepheline gneisses (Ronenson, 1971). Because they are not easy to identify in the field, it is probable that there are many other examples. They may, in fact, be typical of orogenic belts. Occurrences show certain striking similarities as well as a number of significant differences.

In geometric form, the gneisses are all in elongate belts, more or less exactly concordant with the surrounding gneisses, although within the various belts there may be almost continuous gradation between clearly igneous complexes, more or less deformed, and clearly metasomatic rocks. Wherever the structural sequence has been worked out the gneisses were emplaced before the major period of deformation. In general they occur in recognizably meta-sedimentary terranes, although there are exceptions, such as the Bigwood-Rutter district of Ontario (Hewitt, 1960). Extremely coarse nepheline-rich pegmatites are almost always present, commonly showing evidence of development by metasomatism. The principal mafic minerals are biotite, aegirine, and a characteristic hastingsitic amphibole, usually in that order of importance. Most of the belts show a considerable range in composition of nepheline-bearing rocks, comparable to that seen in many alkaline complexes. Virtually all of the belts, however, contain either rocks whose origin is debatable or rocks for which there is strong evidence of metasomatic origin. Perhaps the clearest description is that of Appleyard (1967), dealing with nepheline-bearing calc-silicate rocks of southeastern Ontario. All of the nepheline gneisses examined by the writer contain molybdenite, commonly concentrated in the pegmatitic or aplitic schlieren. The molybdenite crystals are typically deformed, showing that they formed before the latest deformation.

The general picture offered by nepheline gneiss is thus one of emplacement of alkaline rocks before deformation, followed by more or less intense polyphase deformation during which the alkaline rocks 'leaked' alkalis, creating metasomatic alkine rocks, particularly in formations rela-

tively low in silica in the first place. The conventional opinion that alkaline complexes containing nephelinitic and carbonatitic components are emplaced only in reasonably stable crust, generally under tensional conditions (Bass, 1970), implies that the rocks involved in nepheline gneiss belts have undergone a complex history of development from stable crust to orogenic belt.

Summary and Conclusions

The alkaline gneisses of Mount Copeland are due to metamorphism of a series of dykes and/or sills ranging in composition from alkaline basalt through nephelinite to syenite, but with nepheline syenite dominant. The igneous rocks were emplaced into a sequence of sedimentary rocks displaying repetitive sequences of quartzitic, pelitic, and carbonate beds. Sedimentary and igneous rocks were deformed together during metamorphism, reaching peak conditions of about 650°C and 5.7 kb, and were later deformed again under lower but unspecified P-T conditions. The peak metamorphism led to a certain amount of anatexis melting in compositionally favourable beds, including a marginal, saturated phase of the syenite, resulting in a complex of aplitic syenite schlieren and dykes. The process of anatexis led to concentration of molybdenum in this phase and to formation of the commercially exploited deposit.

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APPENDICES

APPENDIX 1

Modes and Chemical Analyses of Selected Rocks from Mount Copeland

All modes based on count of 2,000 points at 0.3-mm intervals. One thin section used if grain size less than 0.5 mm, otherwise two sections. Sample locations given in text under relevant unit numbers.

(tr. = present in trace amount)

Unit	7	6		A1a		A1b		A1c		A2		A3a	
	Modes												
Specimen No.	70274	69323	70203	69338	70309	70294	70210	70265	70249	69341	70212	69329	69335
quartz	19.1	8.3	2.1										
nepheline	} 50.1			39.6	48.1	14.7	18.9	0.5	tr.		4.9		
K-feldspar			4.3							1.8			
perthite				27.3	37.8	55.8	65.3	63.0	56.3		30.6	34.3	64.2
plagioclase		18.7	10.9	2.1		2.2	12.4	1.4	7.8	22.7	0.6	12.1	31.7
An	6	22-30	28-42		3	8	6	5		30	33	35	23
calcite			31.6	16.1		1.1	1.3			4.7	5.1	0.3	1.6
biotite	5.6	18.6	1.8	11.1				27.2		40.6	31.2	7.0	tr.
hornblende		48.2	48.3										
Na-amphibole	6.5			5.7									3.9
diopside		6.7	1.9									20.7	
aegirine					6.4	13.9	10.4		16.2	40.9	11.1		
tremolite													
opaque	tr.	2.6	4.1			0.3	1.3					3.9	
sphene	tr.	4.2	3.1	tr.	0.4	1.0	1.4	1.1		11.0	5.0	0.7	
rinkite				0.2	3.7								
apatite	tr.	0.5	0.8		tr.	0.1	tr.	0.6		0.3	tr.		
zircon	tr.	tr.	tr.			tr.	tr.	0.1			tr.		
fluorite				2.8	tr.				4.8				
garnet					1.4							tr.	7.3
muscovite						0.1						0.5	
epidote												0.9	0.7
sillimanite	tr.												
alteration and matrix			tr.	0.4		0.5	1.4	0.2		0.1			0.6

	Chemical Analyses												
Specimen No.	70274	69323	70203	69338	70309	70294	70210	70265	70249	69341	70212	69329	69335
SiO ₂	72.22		48.81	48.78	47.23	54.92	52.00	55.05	54.11	44.18		49.09	
TiO ₂	0.28		3.08	0.73	0.28	0.55	0.32	0.50	0.49	5.49		2.53	
Al ₂ O ₃	12.02		11.23	25.22	26.06	23.01	25.91	21.63	21.69	7.51		18.48	
Fe ₂ O ₃	1.27		1.16	3.46	3.64	2.57	0.89	1.07	2.48	8.06		0.22	
FeO	0.98		10.18	0.23	1.59	2.62	0.21	5.16	0.62	7.20		7.17	
MnO	0.06		0.15	0.12	0.28	0.22	0.05	0.28	0.11	0.37		0.05	
MgO	2.83		8.37	0.32	0.31	0.67	0.23	1.07	0.19	7.76		2.81	
NaO	0.59		10.07	3.08	1.52	1.53	1.32	0.29	3.01	9.68		11.57	
Ca ₂ O	5.18		2.24	9.89	12.61	6.06	5.40	2.31	5.85	3.69		2.63	
K ₂ O	3.42		1.58	7.21	4.62	7.47	7.53	11.39	9.37	3.77		3.20	
H ₂ O	0.39		2.16	0.30	0.88	0.49	4.72	1.11	1.26	1.21		0.82	
CO ₂	0.10		0.59	0.12	0.80	0.23	1.11	0.10	0.24	0.26		0.88	
P ₂ O ₅	0.05		0.28	0.01	0.03	0.02	0.02	0.03	0.01	0.59		0.49	
Sr	0.28		0.023	0.19	0.14	0.022	0.18	0.19	0.18	0.094		0.12	
Ba	0.034		0.0027	0.013	0.0059	0.036	0.012	0.12	0.032	0.028		0.10	
Cr	nil		0.0040	nil	nil	<0.001	nil	nil	nil	0.024		0.00043	
Co	nil		0.0051	nil	nil	nil	nil	nil	nil	0.0057		0.0024	
Ni	0.009		0.017	0.002	<0.001	nil	0.0033	0.0080	0.0064	0.022		0.0098	
Zr	0.24		0.022	0.19	0.058	0.027	0.092	0.22	0.16	0.060		0.24	
Nb	0.027		nil	0.051	0.014	nil	0.047	0.026	0.034	0.020		0.030	
La	0.009		nil	0.059	0.071	0.011	0.036	nil	0.0044	0.027		0.0034	
Ce	nil		nil	0.0099	0.13	nil	<0.050	nil	0.078	0.051		0.054	
Nd	nil		nil	0.042	0.031	nil	<0.020	nil	0.033	0.055		0.063	
Y	0.003		0.003	0.023	0.0041	0.0039	0.010	nil	0.00058	0.00068		0.00095	
Yb	<0.0004		<0.0004	0.00027	0.00071	<0.0004	0.00089	<0.0002	0.00071	0.0072		0.0011	
Sc	nil		0.0035	0.00072	0.00073	0.00076	0.00056	nil	0.00078	0.0031		0.0012	
Total	99.99		99.98	100.05	100.30	100.46	100.16	100.53	99.95	100.18		100.56	

Descriptions and Locations of Specimens

70274 Fine-grained tan quartzite, north portal of Mount Copeland Mine.

69323 Black pyroxene amphibolite, Mount Copeland Mine.

70203 Pyroxene-biotite amphibolite, west end of Mount Copeland.

69338 Nepheline augen gneiss layer in calc-silicates, 1.7 km northwest of south portal of mine.

70309 Leucocratic augen syenite, mine road 1.6 km south of portal.

70294 Nepheline syenite gneiss, mine road 0.8 km south of mill.

70210 Pink nepheline syenite gneiss, west end of Mount Copeland.

Analyses by Rapid Methods Group, Geological Survey of Canada.

70265 Pink biotite-nepheline syenite, west end of Mount Copeland.

70249 Grey biotite syenite, mine road at tailings pond.

69341 Black amphibolite, 2.6 km northeast of mine portal.

70212 Porphyroblastic amphibolite, west end of Mount Copeland.

69329 Grey granular syenite, north portal of mine adit.

69335 Muscovite leucosyenite, mine adit 0.8 km from north portal.

70218 Aplitic syenite, 200 m above north portal of mine adit.

69332 Grey syenite, 2.1 km northwest of south portal of mine adit.

70225 Greenish granular syenite, 0.9 km northeast of south portal.

70215 Greenish-grey granular syenite, north portal of mine.

(Appendix 1 continued)

A3b		A3c		8		8a		9		10		11	
Modes													
70218	69332	70225	70215	70228	69322	70198	70324	69346	70235	70230	70231	69336	70320
				0.6	19.1	8.9	11.5	91.8	62.9	17.9	10.5		
						62.3		0.9				8.2	
19.8	55.1	48.2	39.7	52.4	3.8		8.9			55.5	52.3		
66.7	36.4	4.3	7.6	5.1	5.2	14.7	21.1			14.6	17.9	18.1	12.6
28	31	3	3	25	28	35	28			26	24	29	33
	0.3		0.4		4.7	1.3	tr.	0.3				8.3	5.0
1.3	4.1		1.0	3.8	15.3	4.9	31.3	5.7	25.0	7.4	6.8	13.7	12.6
	2.8						26.4			4.6	5.8		4.6
				30.1	14.9	3.1						14.6	7.2
		7.2	35.9										
				8.0	35.1	4.2							
1.2	0.9				0.3							2.3	
		tr.	3.2	tr.	0.3	0.3	0.2			tr.	tr.		
		tr.			0.1	tr.	0.3			tr.	tr.		
	tr.	tr.		tr.		tr.	tr.			tr.	tr.		
		4.7			0.5	tr.							
11.0				tr.	tr.	1.3		1.3	3.5				
0.2	tr.								8.7	tr.	6.8		
	0.1	35.6	13.2				0.3					34.8	51.2
		(zeolites)										(matrix)	

Chemical Analyses													
70218	69332	70225	70215	70228	69322	70198	70324	69346	70235	70230	70231	69336	70320
	57.97	54.79			60.12		53.58		71.42	65.21	63.50	39.73	39.71
	0.47	0.62			0.20		1.63		0.55	0.57	0.51	1.24	1.28
	18.08	21.82			13.26		15.39		14.01	16.49	17.82	14.44	13.49
	0.04	3.81			0.11		2.57		0.42	1.39	1.41	2.71	2.56
	0.51	0.49			1.51		6.06		2.88	2.29	2.32	4.92	5.43
	0.23	0.12			0.06		0.16		0.03	0.07	0.05	0.14	0.14
	0.11	0.29			7.51		6.01		3.53	1.79	1.72	7.34	7.56
	6.53	2.51			8.48		4.78		0.37	2.81	2.40	9.41	11.03
	9.32	4.33			2.10		2.51		0.41	3.12	3.55	1.32	1.91
	0.91	7.62			5.81		5.09		4.48	4.78	5.11	6.20	4.28
	0.18	2.29			0.38		1.64		1.61	0.60	0.82	2.03	1.90
	5.22	0.28			0.08		0.11		nil	nil	nil	7.09	6.01
	0.14	0.01			0.06		0.37		0.06	0.36	0.30	1.77	1.68
	0.31	0.34			0.014		0.045		0.0081	0.11	0.11	0.42	0.34
	0.0033	0.013			0.064		0.063		0.031	0.20	0.18	0.95	0.98
	nil	nil			nil		0.022		0.0034	0.0027	0.018	0.016	0.025
	nil	nil			nil		0.0028		nil	nil	nil	0.0031	0.0036
	nil	0.01			nil		0.013		0.0039	nil	0.0018	0.0089	0.0090
	0.029	0.27			0.015		0.034		0.010	0.030	0.0022	0.036	0.022
	nil	0.047			nil		0.0095		nil	nil	nil	0.0086	0.010
	0.0083	0.050			0.0058		0.011		nil	0.009	0.013	0.028	0.029
	nil	0.082			nil		0.0042		nil	nil	<0.05	<0.05	<0.05
	nil	0.027			nil		nil		nil	nil	<0.02	0.041	0.051
	nil	0.0015			0.0047		0.0042		nil	<0.0004	<0.0004	0.0027	0.0026
	0.00065	0.015			0.00052		0.0032		0.00013	<0.002	<0.002	<0.0004	<0.0004
	<0.0004	0.00068			nil		0.00021		<0.0004	nil	0.0011	0.0026	0.0031
	100.06	99.83			99.78		100.11		99.83	99.83	99.90	99.90	98.50

70228 Glassy, green and white gneiss, 0.8 km west of mill.
69322 Green and white gneiss, north portal of mine adit.
70198 Bronzy mica schist, 0.9 km northwest of mine adit.
70324 Melanocratic mica schist, 0.9 km northwest of mine adit.
69346 Bronzy quartzite, mine road near Hiren Lake.
70235 Pale grey quartzite, knoll 1 km west of mine adit.
70230 Augen gneiss, 1 km northwest of Hiren Lake.
70231 Augen gneiss, 0.3 km west of East Lake.
69336 Ocellar lamprophyre dyke, south portal of mine adit.
70320 Biotite-rich lamprophyre dyke, mine road near tailings pond.

Electron Microprobe Analyses of Selected Minerals from Mount Copeland

Unit	7					Ala			Alb			Alc		A2			A3		10			11			Unit	
Spec. No.	70274					69338			70294			70265		69341			69329		70230			70320			Spec. No.	
Mineral	1	2	3	4	5	2	4	5	1	3	1	2	3	1	5	1	2	5	1	2	5	1	2	3	6	Mineral
SiO ₂	48.8	56.5	50.8	42.9	65.3	39.4	42.2	65.1	39.8	52.7	38.5	43.0	51.5	40.1	64.4	37.3	41.0	64.6	34.5	39.7	47.6	0.0				SiO ₂
TiO ₂	1.4	0.5	0.0	0.0	0.0	1.2	0.0	0.0	1.9	0.0	3.6	1.3	0.1	1.8	0.0	3.0	0.9	0.0	6.4	4.5	1.2	0.0				TiO ₂
Al ₂ O ₃	7.1	0.8	2.8	33.9	18.5	11.3	34.1	18.7	13.0	1.2	14.4	9.8	0.8	13.2	18.2	14.2	12.2	18.3	16.4	14.7	5.6	0.0				Al ₂ O ₃
FeO*	5.2	11.8	22.7	0.4	0.1	30.3	0.1	0.1	10.9	25.8	19.6	16.9	10.8	11.9	0.1	18.7	19.9	0.2	12.7	10.9	9.5	2.5				FeO*
MnO	0.03	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.1	0.3	0.2	0.2	0.1	0.1	0.0	0.2	0.2	0.0	0.1	0.1	0.1	0.08				MnO
MgO	21.8	16.2	3.2	0.0	0.0	2.5	0.0	0.0	19.9	2.2	12.3	10.9	12.1	17.5	0.0	14.5	9.3	0.0	18.6	12.2	11.8	18.2				MgO
CaO	0.0	3.0	12.8	0.2	0.0	7.1	0.1	0.0	0.0	7.8	0.0	11.9	24.3	0.0	0.0	0.0	12.5	0.1	0.1	11.9	21.2	32.5				CaO
Na ₂ O	0.1	7.0	6.5	16.3	1.6	4.9	16.1	2.1	0.4	9.5	0.1	1.5	0.2	0.1	1.6	0.0	1.5	1.8	0.0	2.8	1.0	0.1				Na ₂ O
K ₂ O	10.9	1.3	0.0	6.4	14.7	2.1	7.0	14.5	10.5	0.0	9.6	1.1	0.0	10.7	15.8	9.5	1.6	15.0	8.3	2.2	0.2	0.0				K ₂ O
Total	95.3	97.2	98.9	100.1	100.3	99.1	99.6	100.5	96.5	99.5	98.3	96.6	99.9	95.4	100.1	97.4	99.1	100.0	97.1	99.0	98.2	53.38				Total

Mineral Analyses Computed as Standard Cells

Si	3.44	8.01	1.93	1.03	3.00	5.98	1.02	2.99	2.89	2.10	2.85	1.96	2.96	2.99	2.78	6.22	2.99	2.56	5.84	1.83	0.00	Si
Al ^{IV}	0.56	0.00	0.07	0.96	1.00	2.02	0.97	1.01	1.11	0.00	1.15	1.46	1.04	0.99	1.22	1.78	0.99	1.44	2.16	0.17	0.00	Al ^{IV}
Al ^{VI}	0.31	0.14	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.10	0.30	0.01	0.00	0.02	0.30	0.00	0.00	0.39	0.08	0.00	Al ^{VI}
Ti	0.07	0.03	0.00	0.00	0.00	0.13	0.00	0.00	0.10	0.00	0.20	0.15	0.003	0.10	0.17	0.10	0.00	0.35	0.50	0.035	0.00	Ti
Fe	0.31	1.40	0.73	0.008	0.008	3.85	0.002	0.004	0.66	0.86	1.21	2.15	0.34	0.73	1.16	2.53	0.008	0.78	1.34	0.30	0.07	Fe
Mn	0.01	0.01	0.003	0.00	0.00	0.04	0.00	0.00	0.006	0.01	0.01	0.026	0.003	0.006	0.012	0.03	0.00	0.006	0.012	0.003	0.002	Mn
Mg	2.33	3.42	0.19	0.00	0.00	0.57	0.00	0.00	2.15	0.13	1.36	2.47	0.67	1.92	1.61	2.10	0.00	2.05	2.67	0.66	0.85	Mg
Ca	0.00	0.45	0.52	0.005	0.00	1.15	0.003	0.00	0.00	0.32	0.00	1.94	0.99	0.00	0.00	2.03	0.005	0.007	1.87	0.88	1.08	Ca
Na	0.01	1.92	0.48	0.76	0.14	1.44	0.76	0.19	0.06	0.73	0.01	0.44	0.01	0.01	0.00	0.44	0.15	0.00	0.80	0.07	0.006	Na
K	0.98	0.23	0.00	0.20	0.86	0.41	0.22	0.83	0.96	0.00	0.91	0.21	0.00	1.00	0.91	0.31	0.87	0.79	0.41	0.01	0.00	K

1. Mica analyses; standard cell computed to 22 charges.

2. Amphibole analyses; standard cell computed to 46 charges.

6. Carbonate analysis; standard cell computed to 12 charges.

v. Carotide analyse, standarda con computer to 12 canale;

*Total iron reported as FeO.

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