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47. Petrological conditions affecting porosity in granite, and negative effects of K- and Si-metasomatism on the trapping of oil in layered Precambrian quartz diorite-gabbro sills penetrated by the AOC Granite 7-32-89-10 drill hole near Fort McMurray, Alberta, Canada

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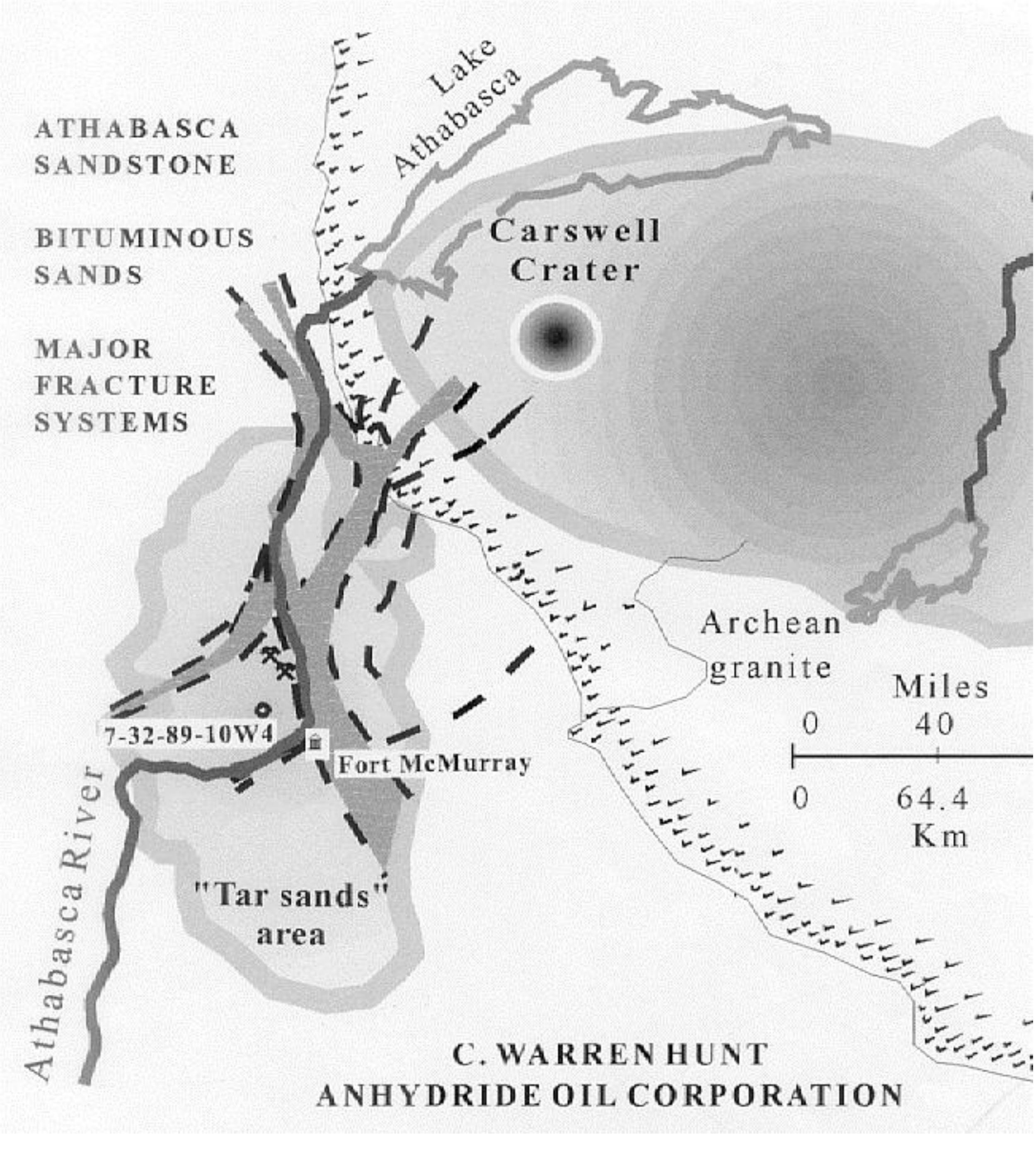
Abstract

The AOC Granite 7-32-89-10 hole, drilled to search for oil in the Precambrian basement below the Alberta bituminous (tar) sands near Fort McMurray, Canada, penetrates layered biotite-hypersthene quartz diorite-gabbro sills that occur between 543 and 2363.3 meters depth. Three episodes of fracturing and cataclasis affected these sills. The first allowed K- and Si-metasomatism to change many parts of the sills into myrmekite-bearing granite and granodiorite. Recrystallization, accompanying this metasomatism, eliminated any porosity. A second episode of fracturing, barren of oil and methane, allowed minor magnetite to fill tiny fractures, cutting both granite and quartz diorite. A third, Tertiary period of deformation caused faulting and fracturing of the sills to produce an anticlinal-shaped cataclastic zone in which oil and methane were trapped. Repeated showings of oil and methane occur throughout the 1820-meter-thick series of sills, but insufficient for production. Lessons learned from this study suggest that the search for oil in myrmekite-bearing Precambrian granitic rocks will likely be unsuccessful unless such rocks have been fractured during a time later than any fracturing that permitted the K- and Si-metasomatism. Non-myrmekite-bearing, fractured, primary granitic rocks would not have this problem.

Introduction

In 1994, C. Warren Hunt initiated exploration for oil in the Precambrian basement underlying the Alberta bituminous (tar) sands in the Cretaceous Mannville Formation by drilling the AOC Granite 7-32-89-10 hole, 5 km northwest of Fort McMurray, Alberta, Canada (Fig. 1). These tar sands represent



one of the largest single oil accumulations on earth, consisting of an estimated 209 billion m^3 of hydrocarbons, or 1.315 trillion barrels, and extend across an area of 28 thousand km^2 Fig. 1; Hunt et al., 1992). The theoretical oil reservoir to which the drill hole was directed is an anticlinal shear zone in the basement rocks. Seismic studies showed that the eastern limb of this anticline intersects a fault that extends up and through the tar sands (Fig. 1). Therefore, logically, the oil that moved into the sedimentary rocks and which eventually became tar could also have moved laterally into this anticlinal structure and be trapped there.

The hole was located so that drilling would reach the objective, a potential oil reservoir at a depth of about 2200 meters. Drilling in 1994 penetrated 543 meters of the overlying sedimentary rocks and then into basement rocks to a depth of 1650 meters. Unfortunately, drilling had to be stopped at the 1650 meter depth because the high costs of drilling in the hard igneous rocks exhausted the available funds. Thus, the targeted depth of 2200 meters was initially not achieved. However, several places in this portion of the drill hole intersected faulted rock that contained showings of oil and gas. Therefore, strong support existed for finding more oil at the targeted depth.

A new source of funds was found in the year 2002, and the drill hole was then extended to a depth of 2363.3 meters in early January, 2003, before funds again ran out. Described in this paper are the results of (a) refractive index studies of plagioclase and orthopyroxene obtained from drill cuttings in the 543-1650-meter interval, (b) thin section analysis of coarse fragments from these cuttings in the same interval, (c) analysis of the driller's log in the depths from 1650 to 2347.5 meters, and (d) petrographic studies of extra-large thin sections of core obtained from depths of 1656.80 to 1657.42 meters and of eleven extra-large thin sections of core obtained from depths of 2348.30 to 2363.30 meters. Drill cuttings between 1658 and 2347.5 meters depth have not yet been analyzed.

General observations

The results of these various studies indicate that the drill hole penetrates basement rock consisting of multiple gradational sequences of former layered quartz diorite-gabbro sills. These sills are composed principally of plagioclase, orthopyroxene (hypersthene), and quartz. Locally, biotite coexists with the orthopyroxene and less commonly, with small amounts of hornblende. Biotite is more common in the upper parts of each sill where the rock is more sodic and less abundant at the bottom where the rock is more mafic and calcic.

On the basis of refractive index studies of plagioclase and orthopyroxene (hypersthene) in drill cuttings (sampled every 3 meters) and from thin section analysis of coarse fragments obtained in the 543 to 1650 meter depth-interval, the uppermost sill was identified. The refractive index studies show that plagioclase at the top is quite sodic ($An_{17\text{-}26}$), but gradually it becomes more calcic (An_{35}). In the bottom 15 meters, the plagioclase grades downward more rapidly to An_{41} and then to An_{56-63} in gabbro. The orthopyroxene is relatively iron rich in the upper part of the sill (Fs_{69-71}), becomes progressively but irregularly less iron rich in the middle parts of the sill, and then has the lowest iron content toward and at the bottom (Fs_{41-56}); see Table 1.

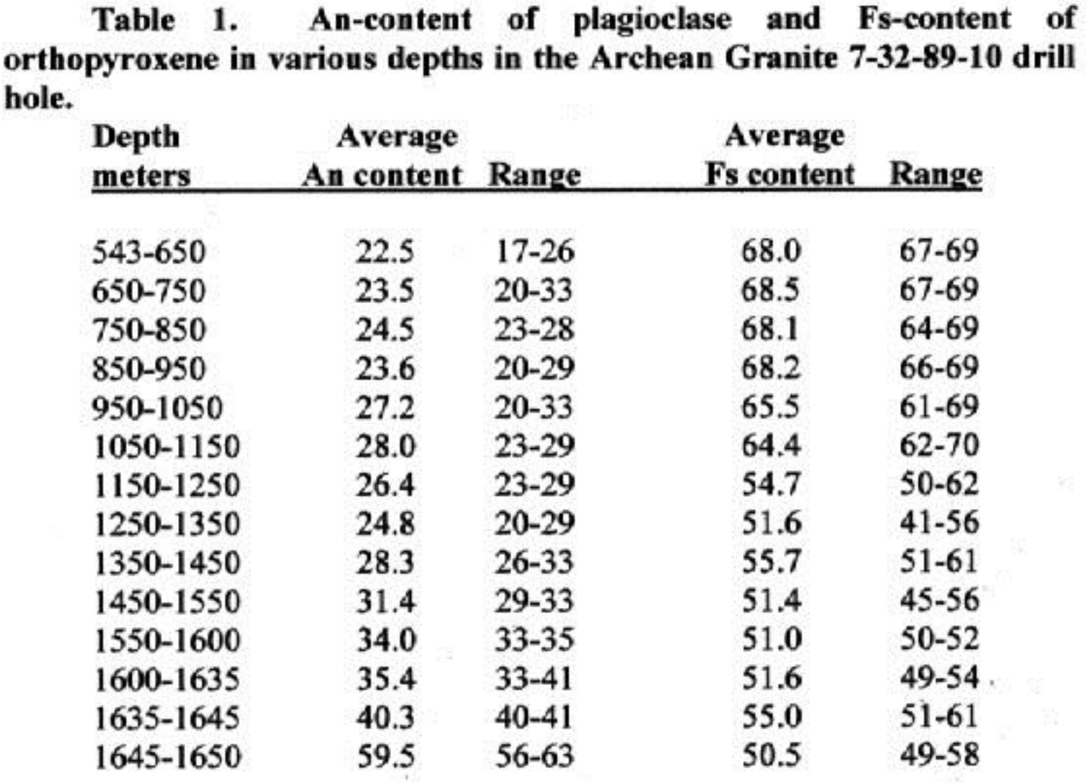


Table 1. An-content of plagioclase and Fs-content of orthopyroxene in various depths in the Archean Granite 7-32-89-10 drill hole.

Depth meters	Average An content	Range	Average Fs content	Range
543-650	22.5	17-26	68.0	67-69
650-750	23.5	20-33	68.5	67-69
750-850	24.5	23-28	68.1	64-69
850-950	23.6	20-29	68.2	66-69
950-1050	27.2	20-33	65.5	61-69
1050-1150	28.0	23-29	64.4	62-70
1150-1250	26.4	23-29	54.7	50-62
1250-1350	24.8	20-29	51.6	41-56
1350-1450	28.3	26-33	55.7	51-61
1450-1550	31.4	29-33	51.4	45-56
1550-1600	34.0	33-35	51.0	50-52
1600-1635	35.4	33-41	51.6	49-54
1635-1645	40.3	40-41	55.0	51-61
1645-1650	59.5	56-63	50.5	49-58

In localized areas throughout the sill that are relatively more calcic and iron rich, hornblende and magnetite are associated with the orthopyroxene. Both hornblende and clinopyroxene (augite) coexist with orthopyroxene in thick pyroxenite layers at and near the bottom where the plagioclase is calcic, and the rock becomes gabbroic. Olivine is likely absent because the quartz diorite is relatively iron-rich. In some places hornblende and relatively calcic plagioclase are altered to epidote. In other places late minor calcite fills fractures. Traces of apatite are common, and tiny zircon crystals occur in the biotite.

On the basis of the driller's log and thin sections of core samples, another thick sill with a sodic top begins at the 1650 meter depth of the drill hole, and this sill and others occur at deeper levels to the final 2363.3 meter depth of the drill hole. Also, on the basis of the mineralogical changes shown in the driller's log, each sill is assumed to have about the same mineralogical downward sequence as in the uppermost 543-1650-meter sill, described above and shown on Table 1.

In some places in the upper parts of each quartz diorite-gabbro sill, 2-cm thick layers, containing 10-30 vol. % *black* orthopyroxene, alternate with layers containing no orthopyroxene and only *white* to *gray* plagioclase and quartz. Thus, the rock appears banded with dark and light bands. The banding, however, is not the result of metamorphism to form gneissic layers but the result of rhythmic magmatic precipitation of crystals alternating (a) felsic and (b) mafic plus felsic minerals, typically found in layered igneous sequences (Winter, 2001).

Representative modal compositions of sodic portions of the banded quartz diorite (Qd), determined from thin sections of core, are shown in Table 2. See modes for samples 2350.20, 2356.22, and 2361.20 (sample numbers indicate depth in meters). Orthopyroxene ranges from 2.1 to 21.2 vol. %; quartz ranges from 6.6 to 20.9 vol. %; and plagioclase (An_{25-30}) ranges from 61.0 to 75.1 vol. %. Higher percentages of orthopyroxene are possible in the mafic bands. The plagioclase is commonly antiperthitic (containing uniformly-distributed tiny islands of K-feldspar; Fig. 2), but not always, as shown in sample 2350.20.

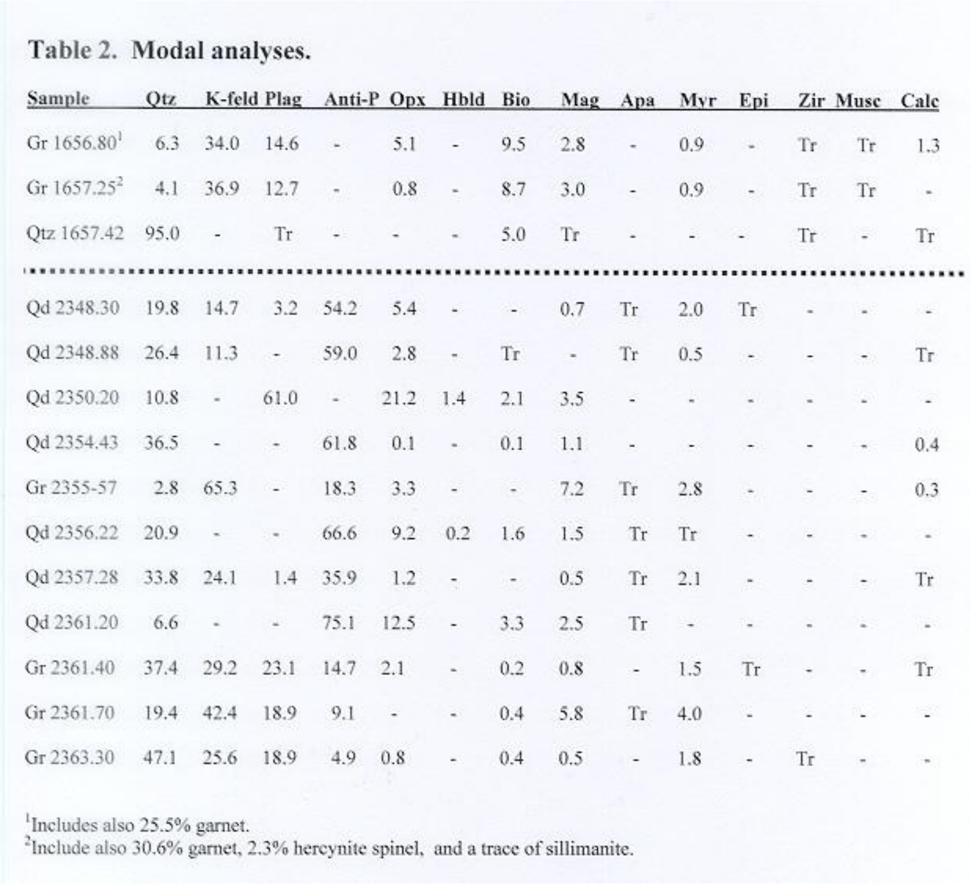


Table 2. Modal analyses.

Sample	Qtz	K-feld	Plag	Anti-P	Opx	Hbld	Bio	Mag	Apa	Myr	Epi	Zir	Musc	Calc
Gr 1656.80[1]	6.3	34.0	14.6	-	5.1	-	9.5	2.8	-	0.9	-	Tr	Tr	1.3
Gr 1657.25[2]	4.1	36.9	12.7	-	0.8	-	8.7	3.0	-	0.9	-	Tr	Tr	-
Qtz 1657.42	95.0	-	Tr	-	-	-	5.0	Tr	-	-	-	Tr	-	Tr
Qd 2348.30	19.8	14.7	3.2	54.2	5.4	-	-	0.7	Tr	2.0	Tr	-	-	-
Qd 2348.88	26.4	11.3	-	59.0	2.8	-	Tr	-	Tr	0.5	-	-	-	Tr
Qd 2350.20	10.8	-	61.0	-	21.2	1.4	2.1	3.5	-	-	-	-	-	-
Qd 2354.43	36.5	-	-	61.8	0.1	-	0.1	1.1	-	-	-	-	-	0.4
Gr 2355-57	2.8	65.3	-	18.3	3.3	-	-	7.2	Tr	2.8	-	-	-	0.3
Qd 2356.22	20.9	-	-	66.6	9.2	0.2	1.6	1.5	Tr	Tr	-	-	-	-
Qd 2357.28	33.8	24.1	1.4	35.9	1.2	-	-	0.5	Tr	2.1	-	-	-	Tr
Qd 2361.20	6.6	-	-	75.1	12.5	-	3.3	2.5	Tr	-	-	-	-	-
Gr 2361.40	37.4	29.2	23.1	14.7	2.1	-	0.2	0.8	-	1.5	Tr	-	-	Tr
Gr 2361.70	19.4	42.4	18.9	9.1	-	-	0.4	5.8	Tr	4.0	-	-	-	-
Gr 2363.30	47.1	25.6	18.9	4.9	0.8	-	0.4	0.5	-	1.8	-	Tr	-	-

[1] Includes also 25.5% garnet.

[2] Include also 30.6% garnet, 2.3% hercynite spinel, and a trace of sillimanite.

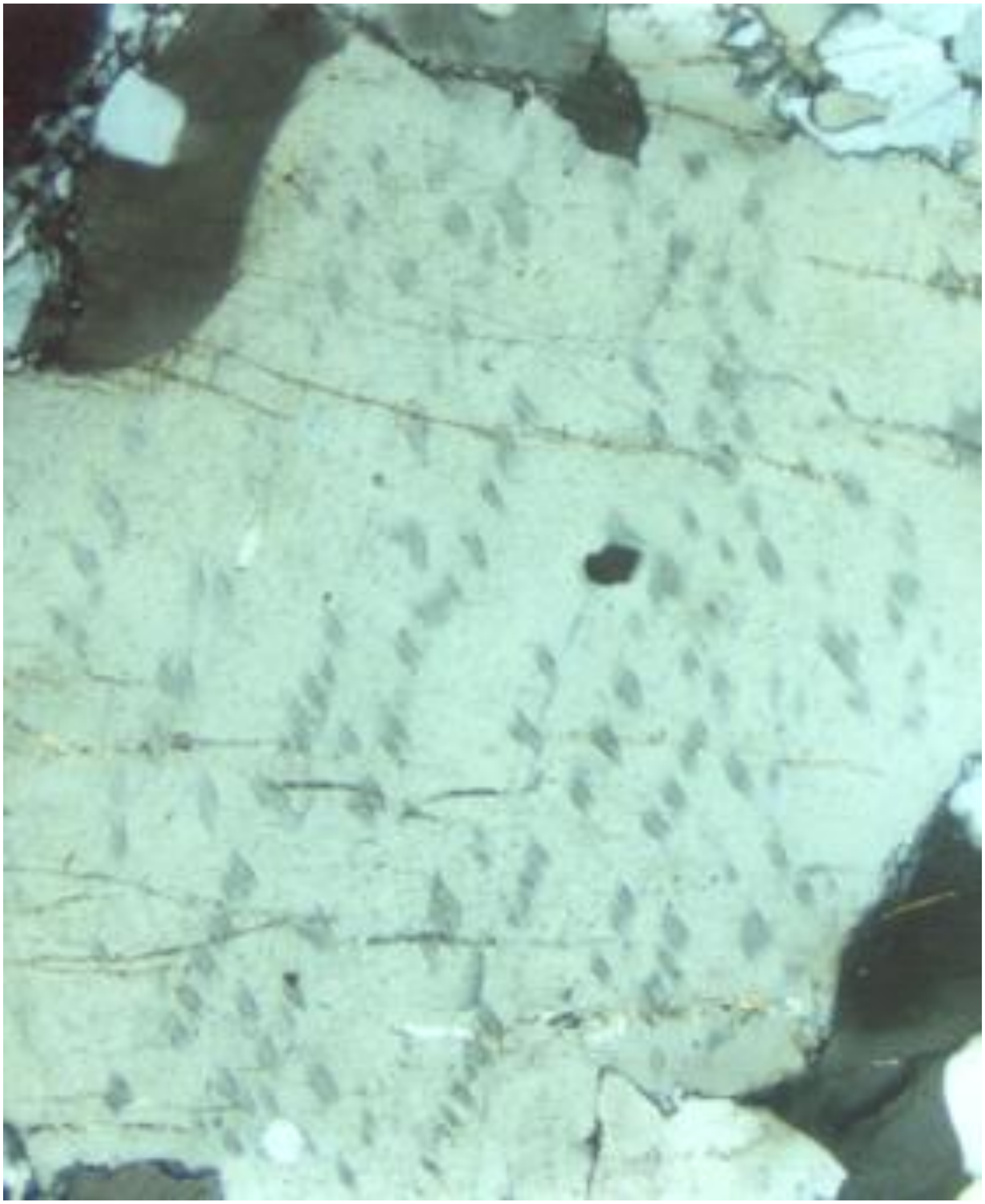


Fig. 2. Antiperthite, showing tiny uniformly distributed K-feldspar inclusions (dark gray) in plagioclase (light gray).

In some parts of the lower sills, thick sequences (a meter to tens of meters thick) consist of either (a) only fine-grained, white, albitic plagioclase or (b) plagioclase plus interstitial quartz, but little to no mafic minerals. The drill-hole logger called these places "sandstones," but they are likely thick anorthosite layers that are common in layered diorite-gabbro (Winter, 2001). Perhaps typical of some of these thick, quartz-bearing anorthosite layers is the mode shown in sample 2354.43 (A HREF="oilT2.htm">Table 2), which contains 61.8 vol. % antiperthite and 36.5 vol. % quartz and only traces of orthopyroxene (0.1 vol. %), biotite (0.1 vol. %), and magnetite (1.1 vol. %). Another example of anorthositic layers occurs on a small scale in the 2-cm-wide felsic bands in narrowly banded portions of the quartz diorite. The interlocking textures of the quartz and plagioclase crystals in these felsic rocks are typical of a primary magmatic hypidiomorphic fabric. That is, the quartz shows no evidence of being injected by Si-bearing fluids introduced from an outside source, but crystallized directly from magma.

Following the crystallization of all these sills and at much later time, deformation along planes of weakness caused the solidified rocks to be fractured and/or faulted, creating a cataclastic texture during at least three episodes of deformation.

First episode of deformation

The first episode of deformation most commonly occurred where biotite was more abundant; for example, at the felsic top of one sill and adjacent to the non-biotite-bearing mafic bottom of the overlying sill. The differences in physical strength of rocks in this place, having contrasting mineralogical compositions, would provide an easy opportunity for stresses to create breakage. Because biotite has a Moh's hardness of 3 and planar cleavage, its presence weakens the rock. Cataclasis of mineral grains opened avenues for fluids carrying both K and Si to come into the fractured rock and to cause K- and Si-metasomatism. Microfractured plagioclase was replaced by K-feldspar (perthitic microcline), and biotite and orthopyroxene were replaced by quartz (Si-metasomatism). Where incomplete K-replacement of plagioclase occurred, remnant myrmekite with tiny quartz vermicules formed between the microcline and the plagioclase (Fig. 3). Where the myrmekite occurs with coexisting plagioclase with relatively high An content near the gabbro at the bottom of the uppermost sill, the quartz vermicules are somewhat coarser (Fig. 4). See Collins (1988, 1997abc) and Collins and Collins (2002) for an explanation for the metasomatic origin of myrmekite. Recrystallization following these replacements eliminated most of the evidence for the former cataclasis.

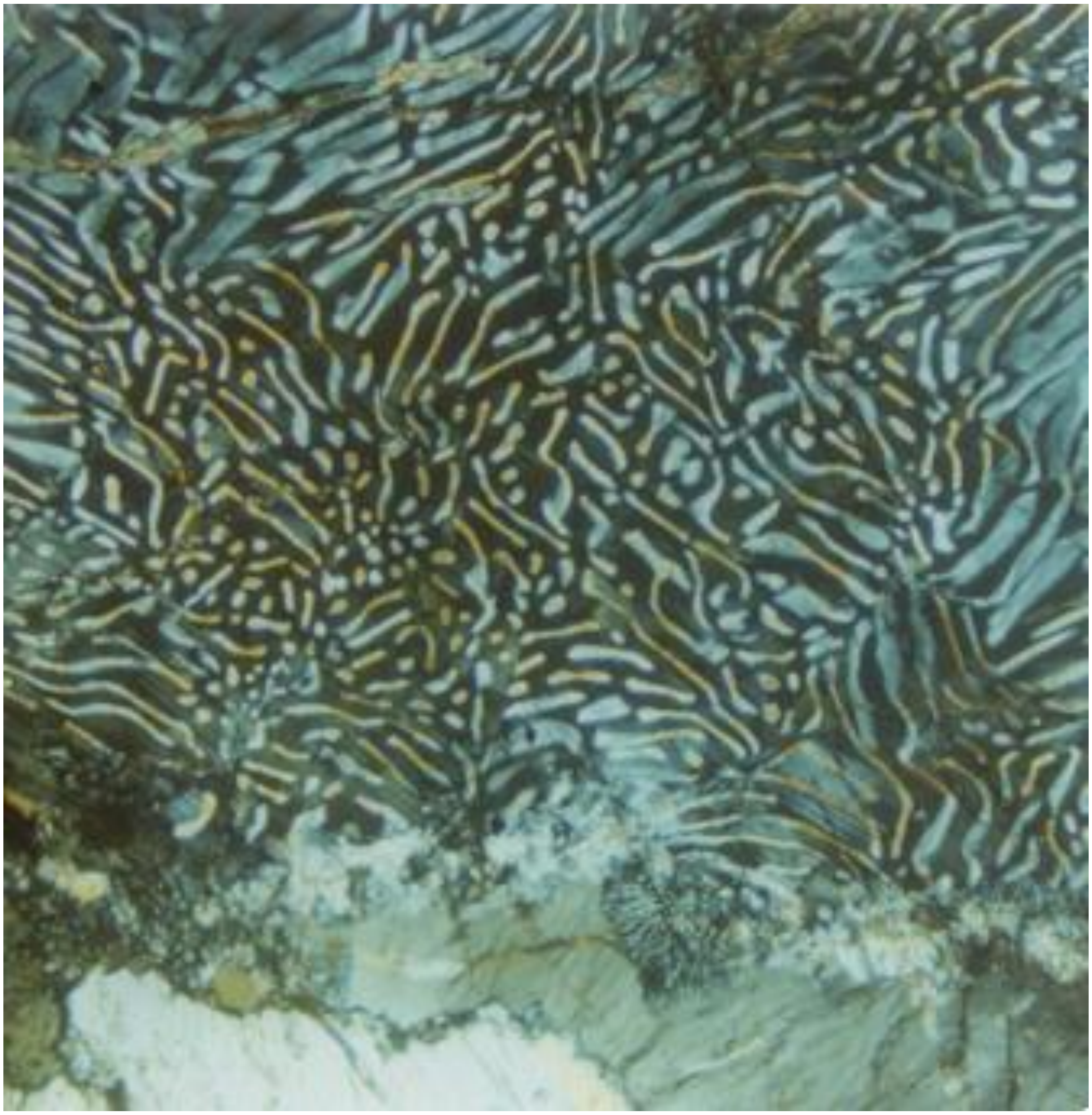


Fig. 3. Myrmekite with tiny quartz vermicules associated with sodic plagioclase and microcline. Quartz vermicules are even narrower at lower edge of myrmekite against microcline (light gray).

Fig. 4. Myrmekite in fragment collected from drill-hole cuttings, with slightly coarser quartz vermicules associated with a relatively more-calcic plagioclase. Quartz (white). Thin section is slightly too thick, and some quartz vermicules have orange and red colors. Black is glue in thin section.

In some places the plagioclase is antiperthitic, containing tiny uniformly distributed islands of K-feldspar (Fig. 2). Where the rock has been deformed and recrystallized, some plagioclase grains lack these K-feldspar islands, and such plagioclase may be secondary, recrystallized, more-sodic plagioclase. In other places, however, all plagioclase is free of K-feldspar islands and may just be primary non-antiperthitic plagioclase rather than secondary recrystallized plagioclase (sample 2350.20, Table 2).

Where cataclasis occurs, the former quartz diorite has been changed into granite (or granodiorite) because of the increased presence of microcline and quartz. The conversion to granite is particularly noted where biotite (a source of K) was once relatively abundant. For example, in samples (Gr) 1656.80 and 1657.25 (Table 2) at the top of one of the lower sills, the biotite (8.7-9.5 vol. %) was replaced by garnet (plus or minus hercynite spinel inside or outside the garnet and sillimanite inside the garnet), and most of the plagioclase was replaced by microcline (perthite) to change the rock into a garnet-bearing granite (Fig. 5). Remnants of biotite occur in the garnet. On that basis, the source of Al in the garnet, hercynite spinel ($FeAl_2O_4$), and sillimanite likely came from the breakdown of the biotite as well as perhaps from fractured and replaced aluminous calcic plagioclase in the gabbroic bottom of the overlying sill. Where extensive shearing, replacements, and recrystallization occur, thick veins of white bull quartz are common, as in sample 1657.42. Remnants of former biotite concentrations occur in this quartz mass.

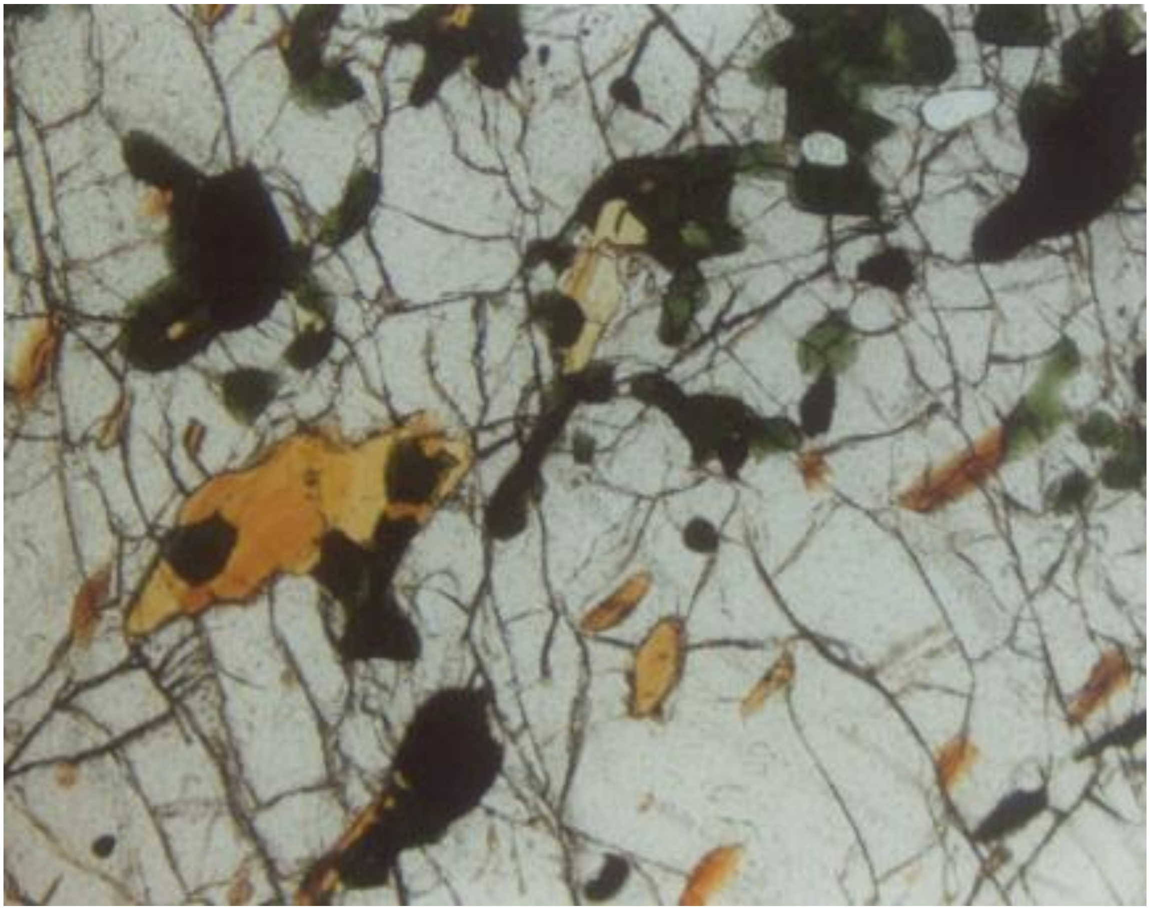


Fig. 5. Garnet (light gray) with hercynite spinel (light green and black green) and biotite (orange-brown) inclusions. Tiny sillimanite needles do not show in this view. Thin section is viewed in plane-polarized light.

Representative modal compositions of modified quartz diorite (Gr) are shown in Table 2 where the modes indicate the occurrence of K-feldspar, myrmekite, and relatively more abundant quartz and lesser amounts of orthopyroxene and biotite. See the seven samples: 2348.30, 2348.88, 2355.57, 2357.28, 2361.70, and 2363.30. In hand specimen the K-feldspar is pink in contrast to the white albitic plagioclase or the gray vitreous quartz.

The above observed changes in mineralogy of the layered quartz diorite-gabbro sills during K- and Si-metasomatism, which produced myrmekite-bearing granite (and granodiorite), are similar to the observed mineralogical changes in a layered quartz diorite which produced megacrystal quartz monzonite and granodiorite in the Wanup pluton near Sudbury, Canada (Collins, 2001).

During the K- and Si-replacement process, recrystallization of the minerals completely eliminated any openings (fractures) in the rock so that the final produce of the first episode of deformation lacked any porosity or permeability. Thus, if oil and methane were introduced and accompanied the K- and Si-metasomatism, this oil and methane would have been totally displaced.

Second episode of deformation

Because the places where cataclasis once occurred are still places exhibiting planes of weakness, renewed deformation would cause a second episode of fracturing and cataclasis. Evidence for a second period of fracturing is preserved where tiny veins of magnetite extend, not only through quartz and plagioclase Fig. 6, but also through the secondary replacement microcline and myrmekite (Fig. 7). This second period of cataclasis is noted particularly in both granite and quartz diorite (samples 2350.20, 2355.57, and 2361.70), where the magnetite content ranges from 3.5 to 7.2 vol. % (Table 2). The fluids that carried and deposited this magnetite may have been rich with carbon dioxide because of the local presence of calcite in some of the silicate mineral grain interstices.

Fig. 6. Magnetite veinlets (black), cutting albite-twinned plagioclase (light gray) and quartz (white).

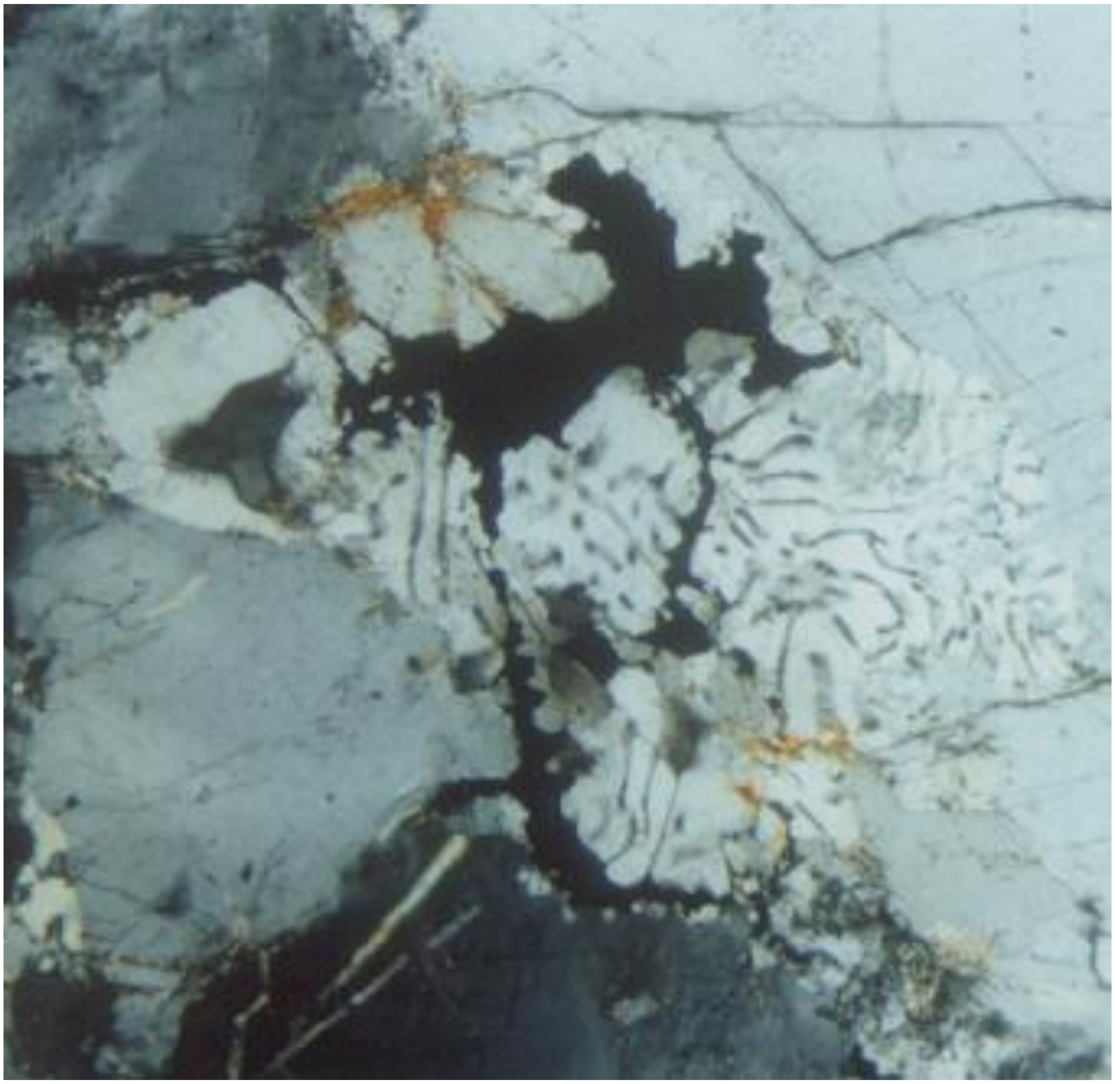


Fig. 7. Magnetite veinlets (black), cutting myrmekite with quartz vermicules (white), microcline (dark gray); left side), and plagioclase (light gray; right side).

A third period of deformation

A third period of deformation is supported by the presence of oil in fractures in the core samples at the 1656-1657 and 2348-2363 meter levels, as indicated by the yellow fluorescence and oozing of oil that was reported by the well site geologist. These fractures and others that occur in higher levels in the drill hole would be Tertiary in age because the oil is Tertiary. Although faulting of the core could be seen in hand specimen, it was not clearly defined in the thin sections. Faulting should produce granulated mineral fragments, but all open fractures observed in the thin sections had the physical appearance of fractures created by the drill bit. Some of these fractures occurred only on the margins of the core samples and did not extend entirely through the thin section. Most of them had matching walls on each side of the fracture. Even so, these fractures would represent perhaps only one percent porosity or much less. Older fractures preserving evidence of cataclasis were observed in the thin sections, but the broken crystals in these fractures were pressed together and recrystallized, eliminating all of the old openings. No openings were evidence on the basis of the absence of a first order red color when a gypsum plate was inserted.

Although no fractures were observed in the thin sections in which oil or methane might have been trapped, their absence is not necessarily evidence that such oil- or methane-filled fractures through several meters do not exist extensively in the drill hole. Likely, fractured, oil- and methane-bearing rock would have been easily chewed up by the drill bit or lost in coring, and only the more resistant, less fractured rock would have been preserved and brought up as core samples.

Repeated showings of oil and methane were found to occur throughout the 1820 meter thick series of sills, but following the swabbing of the hole to remove the drilling mud, it was found that the faulted rocks did not yet have sufficient porosity and permeability for production.

Significance of quartz

Silica (SiO_2) is generally among the first compounds to move through fractures or to low pressure sites in open hydrous systems either (a) by diffusion or flow in fluids or (b) by solid state flow and recrystallization. Silica is everywhere in silicate rocks, so it is readily available to move through an open system. Moreover, where fractured plagioclase is being replaced by K-feldspar, metallic ions are also extracted from adjacent fractured unstable biotite, hornblende, and orthopyroxene. In that process the residual silica in their altered lattices is left over to become quartz. Some of this quartz may remain in place, but some can also be further mobilized. Therefore, in many parts of the fractured and modified portions of the quartz diorite which contain secondary K-feldspar, increased amounts of residual and mobilized quartz are natural products of hydrothermal dissolution and replacement of the ferromagnesian silicate minerals.

Any quartz, whether primary or secondary, is extremely mobile and will fill any low pressure site or fracture as fluids carrying silica move through the system or as the quartz flows by solid state recrystallization. This same mobility is commonly observed in gneisses where quartz veins cut the foliation. Such quartz-filled veins rarely if ever contain euhedral quartz because repeated movements along former fracture systems would granulate any euhedral crystals and because pressure and recrystallization would eliminate any spaces in which good crystal faces could form. The highly mobile quartz would cause the quartz to move into voids and eventually close the system to any porosity and permeability and expel any oil if it had been introduced. Therefore, places containing much quartz would not likely be good places where oil and methane would be trapped or preserved. Nevertheless, subsequent breakage during the third period of deformation and at temperatures below which K- and Si-metasomatism occurred could provide openings into which oil and methane could be introduced and trapped.

Conclusion

Thin section studies of the core samples listed in Table 2 neither provide direct support for the existence of oil in the rocks nor negate its possible abundance. The rock core sawed for the thin sections, likely broke where oil-filled fractures might have been present. Therefore, the resistant, relatively unbroken parts of the rock were where the thin sections were obtained, and the fractured edges of the rocks that probably contained the oil were not included in the thin sections.

The modes in the core samples (Table 2) and the range of compositions reported in the drilling log and in Table 1 indicate the mineralogical variability of the quartz diorite and gabbro and the potential for planes of weakness which could allow strong fracturing to occur. Those levels containing the most biotite are likely where oil-bearing fractures would occur. The association of biotite with quartz diorite containing the most sodic plagioclase suggests that the tops of sills or perhaps biotite-rich zones in the thick anorthositic layers are the most probable places where fracturing would be prevalent, but, of course, strong fracturing can cut through any rock type if that is where the stress is directed.

The effects of K- and Si-metasomatism and recrystallization on the quart diorite-gabbro sills have no bearing on how the oil was formed, either by a biotic origin or by an abiotic origin. Nevertheless, exploration petroleum geologists who are considering drilling in Precambrian basement rocks need to be aware that recrystallization that accompanies K- and Si-metasomatism will eliminate any porosity and permeability that might occur in the basement rocks and prevent any entrapment of oil. Later fracturing, occurring at P-T conditions below that at which any mafic rocks in the basement are converted to myrmekite-bearing granitic rocks, would be necessary to allow oil and methane to be introduced into the granitic rocks and be trapped there. Fractured and faulted primary granitic rocks lacking myrmekite would not be affected by this problem.

Acknowledgments

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References

Collins, L. G., 1988, *Hydrothermal Differentiation And Myrmekite - A Clue To Many Geological Puzzles*: Athens, Theophrastus Publications, 387 p.

Collins, L. G., 1997a, Origin of myrmekite and metasomatic granite: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 1, http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf.

Collins, L. G., 1997b, Replacement of primary plagioclase by secondary K-feldspar and myrmekite: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 2, http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf.

Collins, L. G., 1997c, Microscopic and megascopic relationships for myrmekite-bearing granitic rocks formed by K-metasomatism: Myrmekite, ISSN 1526-5757, electronic Internet publications, no. 3, http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf.

Collins, L. G., 2001, Evolution of a layered diorite-gabbro to become a layered quartz monzonite-granodiorite in the Wanup pluton near Sudbury: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 40, http://www.csun.edu/~vcgeo005/Nr40Wanup.pdf.

Collins, L. G., and Collins, B. J., 2002, Myrmekite formation at Temecula, California, revisited: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 43, http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf.

Hunt, C. W., Collins, L. G., and Skobelin, E. A., 1992, *Expanding Geospheres, Energy And Mass Transfers From Earth's Interior*: Calgary, Polar Publishing Company, 421 p.

Winter, J. D., 2001, *An Introduction to Igneous and Metamorphic Petrology*: Upper Saddle River, Prentice Hall, 697 p.