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Fe–Ti–P-RICH ROCKS AND MASSIF ANORTHOSITE: PROBLEMS OF INTERPRETATION ILLUSTRATED FROM THE LABRIEVILLE AND ST-URBAIN PLUTONS, QUEBEC

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ABSTRACT

Rocks containing high concentrations of iron, titanium and phosphorus, known by a variety of names such as jotunite, ferrodiorite, monzonorite, *etc.*, are associated spatially and temporally with massif anorthosites worldwide. We report new results on the geology, mineralogy and chemistry of a distinctive group of such FTP rocks, which we term *oxide–apatite gabbronorite* (OAGN), found with the Labrieville (LBV) and St-Urbain (STU) anorthosites, Quebec. OAGNs occur at the margins of both massifs, and also within country rock adjacent to the LBV body. These three occurrences of OAGN are similar in many respects, but each has unique properties that complicate any generalized model for their petrogenesis. OAGNs vary from porphyritic varieties consisting of cm-sized plagioclase grains or aggregates ($\sim An_{34}$ at LBV, $\sim An_{44}$ at STU), set in an anastomosing, finer-grained matrix of ortho- and clinopyroxene, ilmenite, magnetite, apatite and minor plagioclase, to types with more homogeneous textures. Significant amounts of K-feldspar and quartz also occur in many samples. Bulk compositions vary widely (*e.g.*, SiO_2 ~27–42 wt%, total iron expressed as Fe_2O_3 ~19–42 wt%, TiO_2 ~4–10 wt%, P_2O_5 ~3–6 wt%, Sc ~20–40 ppm, Sr ~160–1000 ppm, Ba ~10–860 ppm), but for the most part vary systematically with Al_2O_3, primarily reflecting variations in plagioclase content. Chondrite-normalized *REE* patterns are broadly similar for all occurrences, being enriched and fractionated (La_N = 70–260×, Lu_N = 7–24×), with negligible to small negative Eu-anomalies. OAGNs lack structures that could be ascribed to cumulus processes, and appear to have intruded their host rocks in a highly fluid state, as evidenced by gross discordances, presence of apophyses and schlieren-like textures, and disaggregated xenolithic blocks of anorthosite, leuconorite and country-rock gneiss. We interpret the overall structure and composition of OAGNs to reflect the emplacement of Fe-, Ti- and P-enriched (FTP) magmas into anorthosite or country rock. The source of the postulated FTP magmas is uncertain. Although links to anorthosite are plausible, derivation from an alternative source, such as mangerite, is easier to reconcile with most aspects of the field relations, mineralogy and chemical compositions. In either case, OAGNs are not related to ilmenite ore deposits that are found in both massifs, as revealed by differences in mineral assemblage and mineral composition. The presence of two different types of Fe–Ti oxide-rich rocks at both LBV and STU provides further support for a separate source for the OAGNs.

Keywords: Fe–Ti oxides, apatite, jotunite, anorthosite, mangerite, ore deposits, immiscibility, Labrieville, St-Urbain, Quebec.

SOMMAIRE

Les roches à teneurs élevées de Fe, Ti et P, traitées jusqu'ici de jotunite, ferrodiorite, monzonorite, *etc.*, font preuve d'une association dans l'espace et dans le temps avec les massifs anorthositiques à travers le monde. Nous présentons des données nouvelles sur la géologie, la minéralogie et la composition chimique d'un groupe distinctif de telles roches, que nous appelons gabbronorite à oxydes et apatite, associé aux massifs anorthositiques de Labrieville (LBV) et St-Urbain (STU), au Québec. On trouve de telles gabbronorites dans la bordure des deux massifs, ainsi que dans les roches encaissantes du massif de LBV. Ces trois groupes d'affleurements se ressemblent à plusieurs égards, mais possèdent en même temps des caractères distinctifs qui compliquent la formulation d'un modèle pétrogénétique généralisé. Ces gabbronorites à oxydes et apatite peuvent adopter une texture porphyrique, avec des grains de plagioclase centimétrique ou des agrégats de tels grains ($\sim An_{34}$ à LBV, $\sim An_{44}$ à STU) dans une pâte contenant orthopyroxène, clinopyroxène, ilménite, magnétite, apatite et plagioclase accessoire, ou bien une texture plutôt homogène. Une proportion importante de feldspath potassique et de quartz est présente dans plusieurs cas. Les compositions globales de ces roches montrent une grande variabilité (*e.g.*, SiO_2 ~27–42% par poids, Fe_2O_3 (fer total) ~19–42%, TiO_2 ~4–10%, P_2O_5 ~3–6%, Sc ~20–40 ppm, Sr ~160–1000 ppm, Ba ~10–860 ppm), mais en général elles montrent une variation systématique avec Al_2O_3, qui dépend directement des variations dans la proportion du plagioclase. Les teneurs en terres rares, normalisées à une chondrite, se ressemblent dans tous les cas: elles sont élevées, et montrent un fractionnement (La_N entre 70 et 260×, Lu_N entre 7 et 24×), avec une anomalie négative en Eu légère ou négligeable. Ces roches ne possèdent pas de structures que l'on pourrait qualifier de cumulatives, et semblent avoir recoupé leurs roches hôtes dans un état de fluidité très élevé, comme le montrent les discordances grossières, la présence d'apophyses et de structures en schlieren, et des blocs xénolithiques désagrégés d'anorthosite, de leuconorite et de roches encaissantes. Nous croyons que la structure grossière et la composition de ces gabbronorites à oxydes et apatite reflètent la mise en place d'un magma enrichi en Fe, Ti et P dans l'anorthosite et ses roches encaissantes. La source d'un tel magma n'est pas évidente. Malgré la possibilité d'un lien avec le cortège anorthositique, une dérivation à partir d'une source alternative, comme la mangérite, est plus facilement réconciliable avec la plupart des données sur les relations de terrain, la minéralogie et les compositions chimiques. De toute façon, ces gabbronorites ne seraient pas liées aux gisements d'ilménite des deux massifs, comme le révèlent les différences dans les assemblages des minéraux et dans leur composition. Le fait que les deux complexes, LBV et STU, contiennent une différente sorte de roches enrichies en oxydes de Fe et Ti tend à confirmer notre hypothèse.

(Traduit par la Rédaction)

Mots-clés: oxydes de Fe–Ti, apatite, jotunite, anorthosite, mangérite, gîtes minéraux, immiscibilité, Labrieville, St-Urbain, Québec.

INTRODUCTION

Mafic rocks of broadly gabbroic to noritic composition that contain substantial amounts of Fe, Ti and P (hereafter, FTP rocks) are found with virtually every occurrence of massif anorthosite throughout the world (*e.g.*, Hargraves 1962, Philpotts 1981, Ashwal 1982, Duchesne 1984, Goldberg 1984). Although volumetrically minor, FTP rocks are of considerable significance in the context of anorthosite petrogenesis, for they may provide crucial information on the line-of-descent of liquids in these plutons, and represent potential links to Fe–Ti oxide ore deposits or to associated felsic plutons of the mangerite–adamellite–charnockite suite.

Despite the widespread occurrence of FTP rocks and broad overall similarities among them, there is a great range of conflicting, and mutually exclusive, hypotheses regarding their very nature. For example, allegedly similar lithologies have been interpreted as representing: [1] parental magmas of the anorthosite suite (Duchesne *et al.* 1974, Demaiffe & Hertogen 1981, Hill 1988); [2] late-stage, residual liquids following anorthosite crystallization (Ashwal & Seifert 1980, Ashwal 1982, Wiebe 1990); [3] transitional rocks in the differentiation from anorthosite to mangerite resulting from fractional crystallization (Anderson 1966, de Waard & Romey 1969, de Waard 1974) or from an episode of melt immiscibility (Philpotts 1981); [4] dense cumulates from mangeritic magmas (Emslie 1975); [5] early-formed immiscible segregations from mangeritic magma (Powell *et al.* 1982a); [6] products of combined immiscibility and crystal accumulation from ferrodiorite plutons (Herz & Force 1987); or [7] late intrusive bodies coeval with anorthosites, but having no direct comagmatic relationship to them (Emslie 1978, 1985, Duchesne *et al.* 1989, Duchesne 1990). It is clear that the problem of FTP rocks warrants further investigation.

Accordingly, the purposes of this paper are: [1] to point out, and attempt to clarify, what we consider to be certain confusing aspects of FTP rocks in the literature on massif anorthosites; [2] to evaluate possible origins of a distinctive class of FTP rocks associated with the Labrieville and St-Urbain massifs, both in Quebec, utilizing new information reported herein on their field relations, mineralogy and chemical compositions; and [3] to evaluate the hypothesis that these FTP rocks are genetically related to oxide ore deposits in both massifs.

THE NATURE OF FTP ROCKS

The rocks under consideration here have been called by a variety of terms, including ferrogabbro, melaferrogabbro, ferrodiorite, ferrogranodiorite, monzodiorite, monzonorite, jotunite, or denoted by a modifier such as "oxide-rich" (*e.g.* oxide-rich norite). This problematic nomenclature has hindered progress in understanding the petrogenesis of FTP rocks, because, in our opinion, similar rocks appear to have been called by different names by different researchers. More serious is the problem of very different rocks being included for convenience into a single category, as apparently done in the review papers of Morse (1982), Duchesne (1984) and Emslie (1978, 1985).

Another problem regarding the petrogenesis of FTP rocks concerns their uncertain position in the differentiation sequences of anorthosite and associated felsic rocks. Two opposing ideas will illustrate this situation. The "traditional" interpretation, advocated by Buddington (1972) and Ashwal (1982) among others, holds that FTP rocks formed from residual liquids following extensive crystallization of plagioclase and pyroxene from a gabbroic anorthosite parental magma. Associated felsic rocks, on the other hand, developed from a different parental magma, giving rise to a separate and distinct differentiation sequence from "jotunite" through "charnockite". To quote Buddington (1972, p. 477–478): "The term anorthositic series will be here used to include anorthosite, leucogabbro and leuconorite (gabbroic anorthosites), related gabbro and norite, and late-stage ferrogabbros, melaferrogabbros, and Fe–Ti oxide mineral-rich rocks; the quartz mangerite series includes jotunite, mangerite, quartz mangerite (farsundite), and charnockite." In contrast, FTP rocks are considered to occupy an intermediate position in the sequence anorthosite–jotunite–charnockite by those who have argued for a single trend of differentiation among these lithologies (by fractional crystallization or liquid immiscibility or both; *e.g.*, de Waard 1970, 1974, de Waard & Romey 1968, 1969, Philpotts 1981).

As we see it, part of the disagreement with regard to these opposing viewpoints stems especially from usage of the term "jotunite". As originally conceived by Hødal (1945), "jotunite" is broadly defined as a pyroxene-, hornblende-, or biotite-bearing (quartz) monzodiorite, and the rock must therefore contain some K-feldspar (33 and 16% in the samples studied by her). The need to determine modal proportions of the two feldspars consequently renders "jotunite" a very difficult term to apply in the field, as noted by several investigators (*e.g.*, Schrijver 1975, Carter 1982).

However, it is evident from numerous descriptions that many rocks called "jotunite" also contain substantial amounts of Fe–Ti oxides and apatite. Accordingly, "jotunite" has evolved into a term clearly connoting such enrichment in oxide and apatite. For example, in their work on the Morin anorthosite complex, Martignole & Schrijver (1970, p. 175) give the following description: "A narrow jotunite zone is commonly present around the Mass. The contact zone between anorthosite and jotunite is occupied by an oxide-clinopyroxene-rich gabbroic layer, a few meters thick. ... The jotunite is a dark, heavy rock, rich in iron–titanium oxides and apatite." Philpotts (1981, p. 234) characterized the border zones of anorthosite massifs in the following way: "A rather rapid increase in the content of apatite and ferromagnesian minerals, in particular magnetite and ilmenite, brings about a transition from leuconorite to a *ferrodioritic rock named jotunite*" (emphasis added). To complicate the issue further, McLelland & Chiarenzelli (1990, p. 31) stated that Adirondack "... jotunitic rocks are known to grade into high-Fe,Ti metagabbros." The relationship of these metagabbros to the various gabbros of Buddington (1972) or to the mafic "cumulate" layers studied by Ashwal (1982) and Ashwal & Seifert (1980) is unclear.

Obviously, then, "jotunitic" rocks constitute one of the most important, yet poorly characterized and understood lithologies in the evolution of massif anorthosites. Whereas it may in fact be true that there are a variety of FTP rock types in any one massif, as well as among massifs, the above quotations make it clear that one person's oxide-rich late-stage gabbro could well be another's oxide-rich transitional jotunite, and *vice versa*; similarly, ferrodiorite (or ferrogabbro) and jotunite are in some cases synonyms, and in others not. Only through careful field and petrographic descriptions, and consistent use of terms, can we hope to advance our understanding of these FTP rocks, and their overall role in the anorthosite problem.

SCOPE OF THE PRESENT STUDY

In previous preliminary accounts, we have variously referred to the FTP rocks at St-Urbain and Labrieville as oxide–apatite norite (OAN: Powell *et al.* 1982a), oxide–apatite diorite (OAD: Powell *et al.* 1982b), and oxide-rich gabbro (ORG: Owens & Dymek 1989), which regrettably contributes to the confusion noted above. Hereafter, we will term these FTP rocks *oxide-apatite gabbronorite* (OAGN), which we believe more accurately conveys their distinctive character as follows. The modifiers oxide- and apatite- indicate the exceptionally high concentrations of these minerals. The designation "gabbronorite" has been chosen over "norite" or "gabbro" owing to the ubiquitous presence of two pyroxenes, and this usage is consistent with the IUGS classification scheme (Streckeisen 1976). Finally, even though the plagioclase composition is generally below An_{50}, we consider the use of "diorite" to be rather misleading for pyroxene-rich, hornblende-free rocks of such high color index (up to 90). Although some investigators might prefer to call OAGNs "jotunite" (and they do typically contain quartz and K-feldspar), we consider this a problematic name, for reasons cited above, and one which inadequately conveys the fundamental properties of these rocks. Furthermore, OAGNs are considerably more enriched in Fe, Ti and P than most rocks designated jotunite (or ferrodiorite, monzodiorite, *etc.*) in other areas (see later discussion).

Despite this distinction, the Labrieville and St-Urbain OAGNs are not unique. Close analogues are represented by "oxide-rich norites" from the Allard Lake anorthosite, which contain an average of ~9 modal % apatite (Hargraves 1962); "ultramafic jotunites" from the San Gabriel, California, anorthosite (Carter 1982); "impure nelsonites" (pyroxene–plagioclase–ilmenite–apatite rocks) in ferrodiorites associated with the Roseland, Virginia, anorthosite (Herz & Force 1987); "ferrodiorite" associated with the Lac Gouin, Quebec, mangerite just to the northwest of Labrieville (Hocq 1977); "oxide-rich pyroxenite cumulates" in the Adirondack anorthosite (Ashwal & Seifert 1980); and "magnetite–ilmenite rich rock", which constitutes the Desgrosbois ore deposit in the Morin anorthosite (Lister 1966).

Some of these analogous rocks, along with many jotunites or ferrodiorites from other localities, have been modified by postmagmatic growth of garnet or other metamorphic phases. In contrast, the

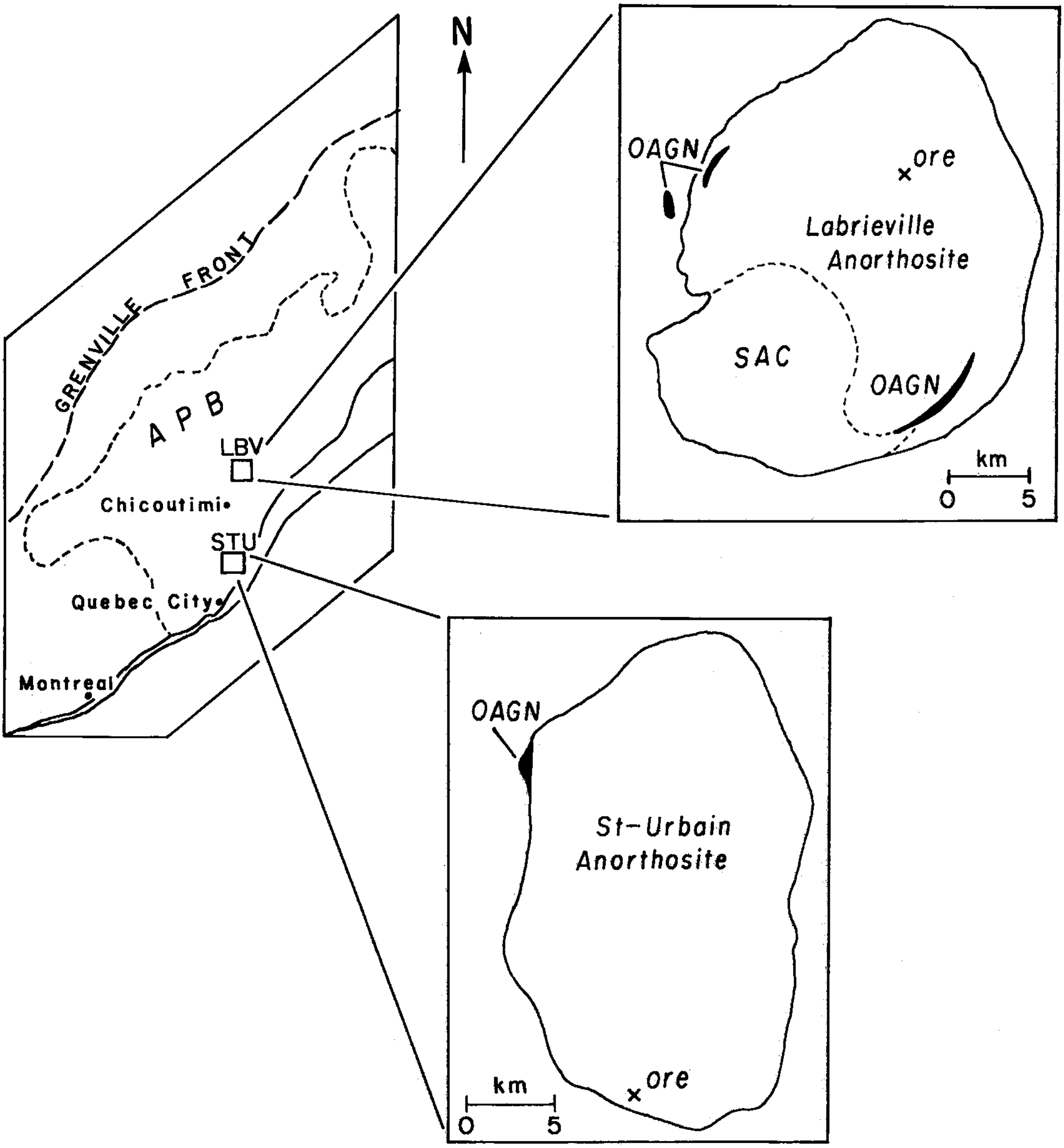

FIG. 1. Sketch map showing the locations of the Labrieville and St-Urbain anorthosite massifs within the Grenville Province of Quebec. The occurrences of OAGNs asssociated with each massif also are shown, but their size is somewhat exaggerated for purposes of illustration. APB: Allochthonous Polycyclic Belt of Rivers *et al.* (1989). SAC: Sault-aux-Cochons Complex. The Lac-des-Martres batholith (quartz monzodiorite) lies immediately to the west of the St-Urbain anorthosite.

OAGNs at Labrieville and St-Urbain bear no evidence of a metamorphic overprint. Therefore, we have been able to investigate in detail key aspects of their modal mineralogy and mineral compositions, in addition to their whole-rock chemical compositions.

GEOLOGICAL SETTINGS

Labrieville

The Labrieville massif is located about 325 km N-NE of Quebec City (Fig. 1), and lies within the

Grenville Central Granulite Terrain (Wynne-Edwards 1972), or the newly designated Allochthonous Polycyclic Belt (Rivers *et al.* 1989). Previous descriptions of Labrieville geology were provided by Morin (1956a,b, 1969) and Anderson (1962, 1963b, 1966); the following overview is based on their work as well as our own field observations. The massif is crudely circular in plan view, with a diameter of about 18 km, and structurally represents an eroded dome consisting of three principal units. These include a core zone of foliated andesine anorthosite, which is slightly more massive and mafic near its border, several lenses of OAGN, and a small ilmenite orebody. [We note that the ilmenite at Labrieville, and at St-Urbain (see below), is an exsolution intergrowth of hematite in ilmenite.] Foliation in the anorthosite is defined by discontinuous layers or lens-shaped aggregates of mafic minerals, typically orthopyroxene, and in certain areas, biotite. This foliation, which defines the domal shape of the intrusive body, may have originated as magmatic layering that was subsequently accentuated due to diapiric rise of the massif. However, features of typical cumulates such as rhythmic layering, graded bedding, *etc.*, are noticeably lacking, although crude banding in more pyroxene-rich areas may be of cumulus origin. The massif displays no evidence of a metamorphic overprint, a feature it shares with the St-Urbain pluton, and therefore the Labrieville anorthosite probably represents a late- to post-Grenville intrusion.

Abutting the anorthosite dome to the southwest is the smaller, circular-shaped Sault-aux-Cochons complex (SAC, Fig. 1). The SAC ranges in composition from gabbroic anorthosite to quartz monzonite, and is noteworthy for the presence of OAGN lenses (which have yet to be investigated). Anderson (1966) interpreted the SAC as comagmatic with the Labrieville massif, but we consider it equally likely that it represents a separate intrusive body. Several other "quartz mangerite" plutons, which also contain layers and lenses of OAGN-like lithologies, occur in the vicinity of Labrieville. These include the Lac-Gouin complex to the northwest (Hocq 1977) and several small plutons in the vicinity of Lac Riverin to the west (Anderson 1963a, Laurin & Sharma 1975).

Older country rock in this area consists predominantly of green, pyroxene-bearing quartzofeldspathic ("charnockitic") gneisses of unknown, but presumably Proterozoic age. These gneisses commonly contain fragments of deformed and metamorphosed mafic dikes, and are in part migmatitic. In many respects they resemble gneisses found further to the south in the Chicoutimi area (Woussen *et al.* 1986), and could represent the same lithostratigraphic unit.

St-Urbain

The St-Urbain massif (Fig. 1) is located about 120 km NE of Quebec City, also within the Allochthonous Polycyclic Belt. It is a relatively small, oval body (~15 × 30 km) composed almost exclusively of anorthositic rocks, dominantly andesine anorthosite of several textural types, with minor leuconorite and a few small ilmenite ± rutile ore deposits (Mawdsley 1927, Roy *et al.* 1972, Rondot 1979). Available petrological and geochemical data indicate a comagmatic relationship for these lithologies (Gromet & Dymek 1981). In addition, as much as 15% of the massif is underlain by relatively older labradorite anorthosite that is apparently not directly related to the andesine anorthosite (Dymek & Gromet, in prep.).

In general, the massif lacks penetrative deformation, corona structures, and other evidence for significant postmagmatic modification, although the border zones (approximately 1 km wide) are commonly foliated (aligned layers or lenses of orthopyroxene and biotite), a feature that is probably related to emplacement of the anorthosite to its present level in the crust (Roy *et al.* 1972, *cf.* Martignole & Schrijver 1970). Two quartz mangerite intrusive bodies (pyroxene-bearing quartz monzodiorites) also are present in this area, one of which, the Lac-des-Martres batholith (Roy 1978), is in contact with anorthosite for about 10 km along the western border of the massif.

The country rock in this area consists of white to pink granitic gneisses, a supracrustal sequence of quartzites, pelites and amphibolites, and various green quartzofeldspathic gneisses of "charnockitic" affinity. Some of the latter contain fragments of mafic dikes and may be part of the same basement gneiss complex found at Labrieville and Chicoutimi.

FIELD RELATIONS

Labrieville

OAGNs occur within anorthosite as relatively thin (≤200 m wide) elongate lenses of rusty-weathering melanocratic rock near the southern and western margins of the massif (Fig. 1). In addition, a number of small OAGN outcrops occur along the southwestern margin of the intrusive body near the contact with the Sault-aux-Cochons complex. The trend of these "inner" OAGN lenses is broadly parallel to the foliation in the anorthosite, but some discordance has been noted locally (Anderson 1963b, Morin 1969). OAGN lenses themselves also are commonly foliated, the foliation being defined by parallel alignment of plagioclase *megacrysts* (typically 0.5–2.0 cm in

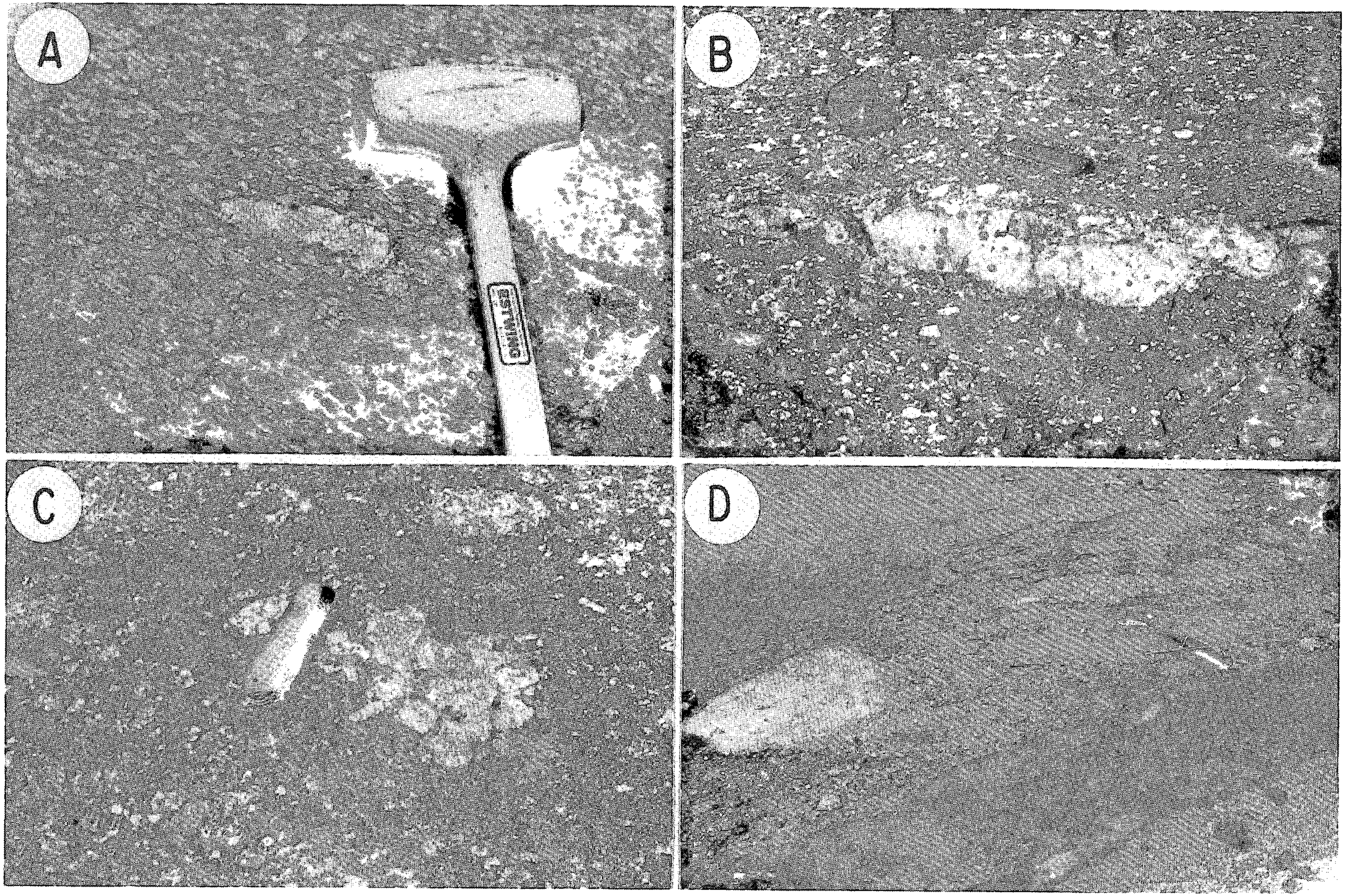

FIG. 2. Outcrop photos of Labrieville OAGN: [A] typical OAGN consisting of abundant cm-sized plagioclase grains in fine-grained dark matrix, and a single larger plagioclase megacryst; [B] anorthosite xenolith; [C] cluster of plagioclase megacrysts; [D] lenses of relatively pure OAGN matrix material within more typical OAGN; light-colored area at left of photo is an anorthosite xenolith.

length, rarely up to 15 cm), in a finer-grained anastomosing *matrix* of Fe–Ti oxides, pyroxenes, apatite and minor plagioclase (Fig. 2a). Color index ranges typically from 40 to 70, depending on the amount of plagioclase present. More leucocratic varieties consist of plagioclase megacrysts or discrete zones of smaller plagioclase grains set in a network of matrix material. Minor but conspicuous amounts of biotite and sulfide also are visible in hand sample.

The inner OAGNs display a high degree of textural complexity and heterogeneity. For example, anorthosite inclusions up to a meter across occur in several areas which, in a number of cases, have been invaded and partially disaggregated by the mafic matrix (Fig. 2b). Clusters of randomly oriented subhedral plagioclase megacrysts within the mafic groundmass are reminiscent of a glomeroporphyritic texture (Fig. 2c). In one area, two approximately 0.5-m-wide melanocratic (C.I. ≈90) layers, which are devoid of plagioclase megacrysts, occur within more typical OAGN (Fig. 2d). Thin (several cm wide) veins of OAGN invade anorthosite at another locality. Also present in the western exposure of the inner OAGN are numerous, commonly elongate, gray-green, fine-grained "leuconoritic" inclusions. These are mineralogically similar to OAGN, and may represent disaggregated synplutonic dikes, xenoliths from an unknown lithology, or even a type of autolith.

At least one other occurrence of OAGN lies entirely within country-rock gneiss to the west of the massif. This "outer" OAGN has a somewhat more homogeneous, equigranular texture compared to inner OAGN, and is not as obviously composed of plagioclase megacrysts and mafic matrix. A small (several tens of meters across), apparently intrusive body of monzodiorite also occurs within the outer OAGN, and is a light gray-green rock containing abundant K-feldspar and quartz, in addition to plagioclase, pyroxenes, oxides and apatite.

St-Urbain

OAGNs have been recognized at the NW margin of the massif (Fig. 1), where anorthosite, quartz mangerite and country-rock gneisses meet at a rather complicated "triple junction". OAGNs are exposed for about 100 m along a stream bed at the contact with anorthosite, and also can be traced further west into the country rock for about 0.5 km in roadcut and outcrop exposures.

The most common type of OAGN at St-Urbain consists of plagioclase megacrysts and aggregates in a finer-grained mafic matrix, with color index ranging approximately from 20 to 60. A second variety has an overall more equigranular, fine-grained texture, and is foliated, with isolated grains of plagioclase occurring in thin, discontinuous bands. There appears to be complete gradation and complex variation between the two textural types, such that outcrops of OAGN may be extremely heterogeneous. Erratic variation in grain size is manifested locally by "swirls" of coarser-grained within finer-grained material, and *vice versa*. Much of this complexity is associated with the breakup and dispersal of anorthosite or leuconorite inclusions, which assume a schlieren-like or nebulitic texture in several outcrops. On the other hand, sharply bounded inclusions of anorthosite and leuconorite, as well as country-rock xenoliths of amphibolite, rare granite and quartzite (one each observed), also occur. Also present are a number of fine-grained, gray-green, "leuconoritic" inclusions that resemble those found at Labrieville. Accessory biotite is a prominent feature of all exposures.

Petrography and Mineral Compositions

Table 1 lists modes of Labrieville and St-Urbain OAGNs, determined by point counting single or multiple thin sections of individual samples in both transmitted and reflected light. OAGNs from both localities contain high but variable amounts of pyroxene (24–52%), Fe–Ti oxide (12–32%) and apatite (5–14%). Orthopyroxene predominates over clinopyroxene, and ilmenite over magnetite. The amount of plagioclase varies widely (3–58%), which is a function of the proportion of plagioclase megacrysts present. Labrieville sample 087 (Table 1, #6) consists solely of matrix material (Fig. 2d), and thus is devoid of plagioclase megacrysts. K-feldspar and quartz are common only in the outer OAGN at Labrieville, but occur in all OAGN samples at St-Urbain.

TABLE 1. MODAL MINERALOGY OF LABRIEVILLE & ST–URBAIN OAGNs

Volume %	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Plagioclase	57.5	32.5	29.7	3.2	51.4	38.0	48.3	34.4	22.4	28.7
Clinopyroxene	8.6	11.6	17.9	19.2	2.4	3.0	1.6	4.2	14.5	4.6
Orthopyroxene	15.8	25.9	22.9	33.2	22.5	22.0	23.1	31.0	24.3	31.4
Apatite	5.4	9.7	8.2	12.0	7.6	10.8	9.5	10.7	13.6	11.9
Ilmenite	8.2	13.4	14.1	19.4	7.4	7.8	7.2	11.7	16.2	14.7
Magnetite	3.9	6.3	5.8	12.7	6.2	6.2	6.2	3.7	4.8	4.0
Sulfide	0.2	0.6	1.3	0.4	0.1	0.2	1.2	0.9	0.9	0.6
Total Opaques	(12.3)	(20.3)	(21.2)	(22.5)	(13.7)	(14.2)	(14.6)	(16.3)	(21.9)	(19.3)
Quartz	0.3	tr	-	-	0.7	3.3	0.8	0.7	1.2	0.5
K-feldspar	-	-	-	-	1.3	7.2	1.0	2.5	1.1	tr
Biotite	tr	-	tr	-	0.4	1.6	1.1	0.1	0.9	3.5
Zircon	-	-	-	-	tr	-	tr	tr	tr	0.1

Labrieville Inner OAGN. [1] LV88-142 (east). [2] LV88-133 (east). [3] LV88-071 (west). [4] LV88-087 (matrix, west). *Labrieville Outer OAGN.* [5] LV88-066. [6] LV88-065. *St-Urbain OAGN.* [7] CHV80-72b. [8] CHV80-205. [9] CHV80-202. [10] CHV80-203.
tr = observed but not counted - = not observed

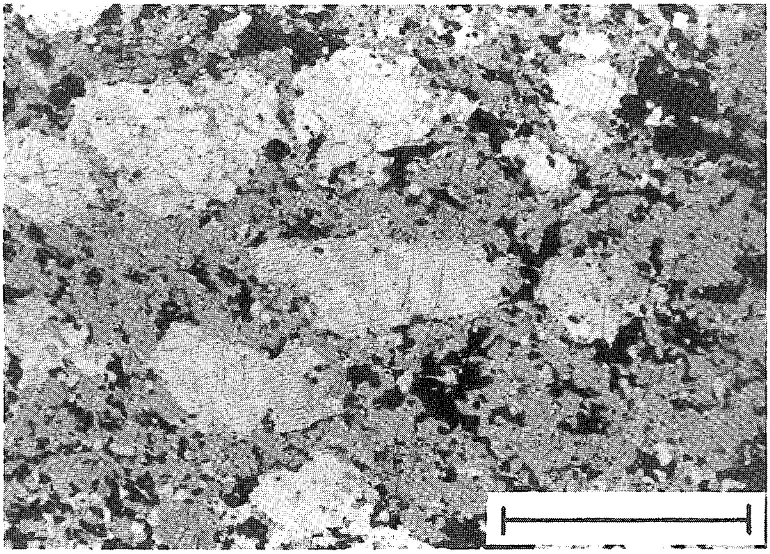

FIG. 3. Photomicrograph of Labrieville sample 071 illustrating typical OAGN texture, consisting of larger plagioclase grains or aggregates (colorless areas) set in a finer-grained matrix of pyroxene, oxide, apatite and minor plagioclase (plane-polarized light, scale bar = 1 cm).

Labrieville

The *plagioclase* megacrysts in the inner OAGN comprise cm-sized single crystals, or lens-shaped aggregates of several smaller grains (Fig. 3). Most plagioclase grains are antiperthitic, and many also contain scattered inclusions of clinopyroxene and ilmenite. Bent twin lamellae, undulose extinction and development of subgrain boundaries provide evidence of some deformation, but there is no indication that dynamic recrystallization has taken place.

In many cases, a distinction can be made between the plagioclase megacrysts and smaller ($\leq$0.5 mm) grains found within the oxide–pyroxene–apatite matrix. Some of these matrix plagioclase grains are subequant, with straight boundaries and 120° triple junctions, whereas others have almost a poikilitic habit, with irregular shapes filling interstices between other phases. Grains of matrix plagioclase typically show strong optical and reverse chemical zoning (see below), and are not antiperthitic.

Plagioclase in the outer OAGN also is antiperthitic, but many grains contain additional, irregularly shaped perthitic patches (up to 1.0 mm across), probably of exsolution origin. Discrete grains of perthitic K-feldspar (up to 2.0 mm across) also occur (only the latter were counted as K-feldspar in modal analyses), and myrmekite is commonly developed at K-feldspar - plagioclase boundaries. Such features have not been observed in the inner OAGN.

Plagioclase compositions are shown in histogram form in Figure 4, and results of selected analyses appear in Table 2. Megacrysts from the inner OAGN range from An_{33} to An_{42}, with a maximum at An_{35}. This range encompasses that of an anorthosite inclusion from the inner OAGN, and is the same compositional range as in the main body of the Labrieville anorthosite (Anderson 1966, Owens, unpubl. data). Compositions of matrix plagioclase tend to be more calcic than megacrysts in the same thin section, with a maximum at An_{39}. Interstitial grains in samples consisting solely of matrix material are the most calcic of all (up to An_{52}), with a maximum at An_{43-44}. The composition of plagioclase from a fine-grained leuconorite inclusion ($\sim An_{43}$) is similar to that in OAGN matrix. Plagioclase in the outer OAGN is slightly more sodic than in the inner OAGN, with a maximum at An_{33-34}. Interstitial grains with more calcic compositions have not been recognized in the outer OAGN.

Orthopyroxene and *clinopyroxene* occur mostly as subequant grains up to 1 mm across, and form a polygonal mosaic within the mafic matrix. This polygonal texture is probably due to static annealing of the original grains, in addition to recrystallization of larger pyroxene megacrysts (see below). Many orthopyroxene grains contain very

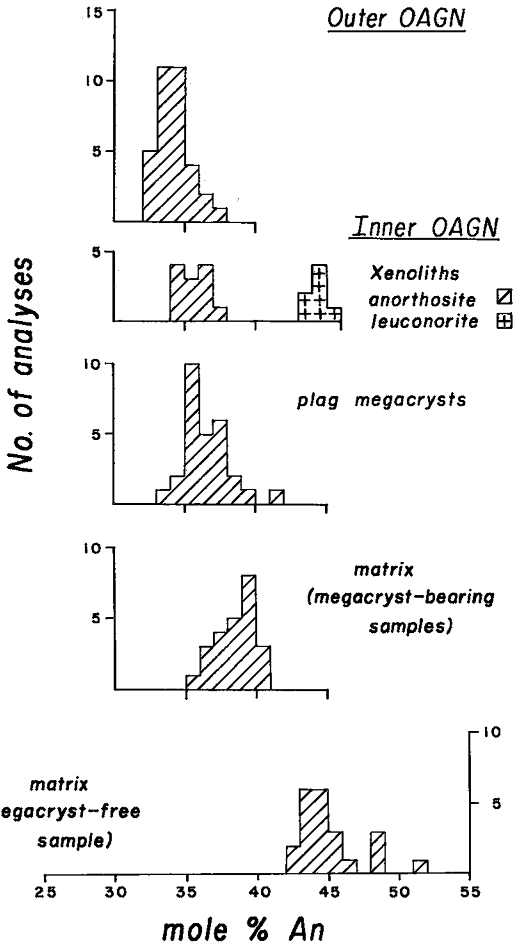

FIG. 4. Compositions of plagioclase in OAGNs and xenoliths at Labrieville.

fine (100) exsolution lamellae of clinopyroxene. Exsolution of orthopyroxene in clinopyroxene includes very fine, regular (100) lamellae, as well as local irregular patches or blebs. Considerably larger (up to 1 cm long), anhedral megacrysts of both pyroxenes occur, mainly in samples consisting solely of OAGN matrix; these grains tend to be highly exsolved and display elaborate kink-bands. Euhedral inclusions of apatite, as well as oxide, pyroxene and plagioclase, are common in these megacrysts. Rare plagioclase lamellae (~An_{42}), perhaps of exsolution origin, occur in a few megacrysts.

Pyroxene compositions are shown in quadrilateral form in Figure 5, and results of representative analyses are listed in Table 3. Individual crystals show slight variation in Mg/Fe, with the total range in measured composition being $Ca_{47}Mg_{39}Fe_{14}$ to $Ca_{43}Mg_{36}Fe_{21}$ (clinopyroxene) and En_{61} to En_{55} (orthopyroxene). The pyroxenes contain similar (and relatively low) amounts of minor elements, although grains in matrix-rich samples can be distinguished from the others on a plot of Al_2O_3 *versus* TiO_2 (Fig. 6).

Fe-Ti oxides up to several mm across typically occur as amoeboid grains that partly or completely surround all other phases. The predominant oxide is ilmenite (approximately $Ilm_{75}Hem_{25}$, with about 4 mole% $MgTiO_3$ in the ilmenite host; Fig. 7). Near grain boundaries with magnetite, ilmenite is noticeably depleted in hematite lamellae. Magnetite is nearly pure Fe_3O_4 and typically homogeneous, although a few grains not in contact with ilmenite contain sparse lamellae of ilmenite, probably of oxidation-exsolution origin.

Apatite occurs primarily as subhedral grains in the 0.2–0.5 mm range, and typically contains abundant fluid inclusions. Small euhedral grains are locally present as inclusions within pyroxene, particularly in outer OAGN.

Quartz is present in small amounts in many OAGN samples but is much more common in the outer OAGN, where it occurs typically as small interstitial grains or larger anhedral grains up to 1.5 mm across. It also forms distinctive, discontinuous "moats" (~50–100 μm wide) between oxide grains and most other phases. Reddish brown *biotite* is a common accessory, particularly in the outer OAGN. It forms large plates (up to 1.0 mm in the longest dimension), and typically is associated with Fe-Ti oxides. *Sulfides*, predominantly pyrite with minor chalcopyrite and pyrrhotite, are ubiquitous in all OAGN samples, occurring in common association with Fe-Ti oxide grains. *Zircon* occurs only in trace amounts, typically as a thin partial rim on Fe-Ti oxide grains. It is more common in the outer OAGN, where a few larger grains up to 0.3 mm across have been observed.

St-Urbain

Plagioclase compositions (Table 2) show a broad peak between An_{40} and An_{45}, but attain An_{51} (Fig. 8). Compositions of plagioclase in the xenoliths of anorthosite and leuconorite fall within this same range (Fig. 8). These compositions are consistently more calcic than typical plagioclase from the main body of the massif, which is close to An_{40} (Dymek & Schiffries 1987), although andesine anorthosites having An_{45} plagioclase are known to occur (Dymek, unpubl. data); a further distinction is the tendency of OAGN plagioclase to be much less antiperthitic than typical plagioclase from the massif.

In contrast to Labrieville, there are no obvious

TABLE 2. COMPOSITIONS OF PLAGIOCLASE FROM LABRIEVILLE & ST-URBAIN OAGNs AND XENOLITHS

wt. %	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
SiO_2	59.31	58.07	58.96	58.87	57.14	55.01	59.93	59.88	56.81	57.20	57.41	57.13
Al_2O_3	25.53	26.68	26.10	26.37	27.69	29.03	25.68	25.77	27.71	27.04	26.37	27.06
FeO	0.04	0.10	0.13	0.13	0.07	0.38	0.07	0.09	0.05	0.06	0.13	0.15
CaO	7.11	7.48	7.49	7.28	8.90	10.38	6.69	6.69	9.00	9.07	8.70	9.27
Na_2O	7.18	6.82	7.18	7.00	6.27	5.44	7.28	7.54	6.07	6.39	6.22	6.15
K_2O	0.43	0.52	0.32	0.49	0.33	0.25	0.63	0.46	0.49	0.26	0.47	0.34
BaO	0.02	0.01	0.02	0.01	0.05	0.09	0.01	0.00	0.02	0.05	0.00	0.00
Total	99.62	99.68	100.20	100.15	100.45	100.58	100.29	100.43	100.15	100.07	100.31	100.10
Formula Proportions Based on 8 Oxygen Atoms												
Si	2.656	2.605	2.630	2.626	2.552	2.469	2.664	2.659	2.546	2.566	2.607	2.563
Al	1.347	1.410	1.372	1.386	1.458	1.535	1.346	1.349	1.464	1.429	1.387	1.430
Fe	0.001	0.004	0.005	0.005	0.003	0.014	0.003	0.003	0.002	0.002	0.005	0.006
Ca	0.341	0.359	0.358	0.348	0.426	0.499	0.319	0.318	0.432	0.436	0.416	0.445
Na	0.623	0.593	0.621	0.605	0.543	0.473	0.628	0.649	0.527	0.555	0.538	0.535
K	0.025	0.030	0.018	0.028	0.019	0.014	0.036	0.026	0.028	0.015	0.027	0.019
Ba	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.000
Sum	4.993	5.001	5.004	4.998	5.002	5.006	4.996	5.004	4.999	5.005	4.981	4.999
End-Members in Mole %												
An	34.5	36.6	35.9	35.5	43.1	50.6	32.5	32.0	43.7	43.3	42.4	44.6
Ab	63.0	60.4	62.3	61.7	55.0	48.0	63.9	65.4	53.4	55.2	54.9	53.5
Or	2.5	3.0	1.8	2.8	1.9	1.4	3.6	2.6	2.8	1.5	2.7	2.0

Labrieville. [1] LV88-142 (inner, east). [2] LV88-133 (inner, east). [3] LV88-071 (inner, west). [4] LV88-085 (xenolith of anorthosite, west). [5] LV88-087 (core; matrix - inner, west). [6] [5] LV88-087 (rim; matrix - inner, west). [7] LV88-066 (outer). [8] LV88-065 (outer). [9] LV89-251 (xenolith of leuconorite, west).

St-Urbain. [10] CHV80-205. [11] CHV80-72a (anorthosite xenolith). [12] CHV80-72c (leuconorite xenolith).

compositional distinctions between large and small plagioclase grains, nor is there any apparent textural–compositional correlation with the observed variation in An-content. Overall, plagioclase compositions in St-Urbain OAGN are distinctly more calcic than plagioclase megacrysts and aggregates at Labrieville, but are similar to Labrieville matrix plagioclase.

Compositional ranges of *orthopyroxene* (En_{61} to En_{55}) and *clinopyroxene* ($Ca_{47}Mg_{39}Fe_{14}$ to $Ca_{45}Mg_{36}Fe_{19}$) are restricted and virtually identical to those at Labrieville (Fig. 5, Table 3). There is

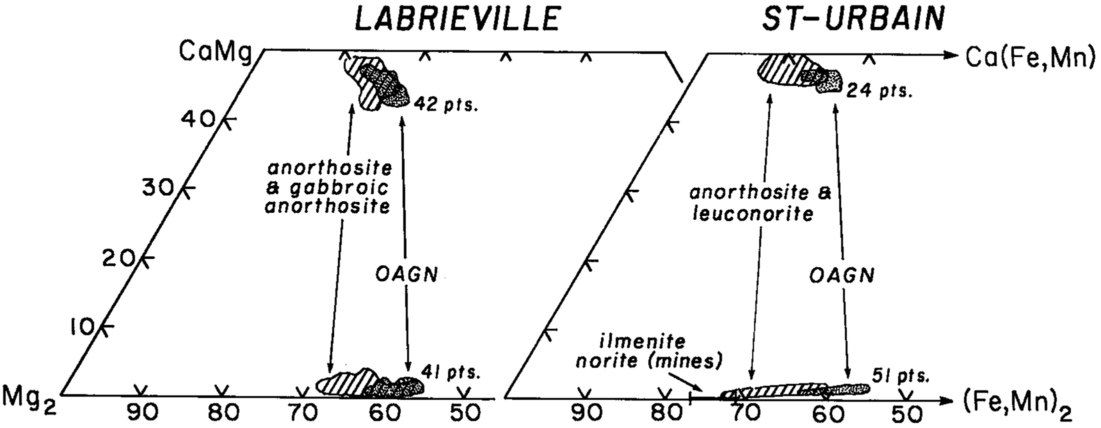

FIG. 5. Compositions of pyroxenes in OAGNs at Labrieville and St-Urbain compared with compositions elsewhere in both massifs. Compositional range of orthopyroxene (Dymek, unpubl. data) in ilmenite norites from St-Urbain ore deposits also is shown for comparison.

TABLE 3. COMPOSITIONS OF PYROXENES FROM LABRIEVILLE & ST-URBAIN OAGNs

wt. %	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	51.43	51.16	51.29	51.54	51.69	51.36	51.18	50.42	51.47	51.71
Al_2O_3	1.66	2.79	1.77	2.43	1.29	2.04	1.52	2.67	1.22	2.28
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	0.10	0.37	0.10	0.27	0.11	0.23	0.10	0.46	0.10	0.32
FeO	24.55	11.22	24.92	9.15	25.04	11.55	25.59	12.59	26.85	11.42
MgO	20.85	12.46	20.58	13.35	20.63	13.04	20.02	12.41	19.39	12.36
MnO	0.73	0.38	0.70	0.27	0.78	0.40	0.75	0.37	0.64	0.27
CaO	0.65	20.87	0.55	22.65	0.61	20.92	0.75	20.18	0.60	21.41
Na_2O	0.02	0.62	0.02	0.47	0.00	0.60	0.02	0.54	0.00	0.54
Total	99.99	99.87	99.93	100.13	100.15	100.14	99.93	99.65	100.27	100.31
Formula Proportions Based On 4 Cations & 6 Oxygen Atoms										
Si	1.933	1.920	1.932	1.917	1.945	1.921	1.936	1.904	1.951	1.936
Al	0.067	0.080	0.068	0.083	0.055	0.079	0.064	0.096	0.049	0.064
Al	0.007	0.043	0.011	0.023	0.002	0.011	0.004	0.023	0.006	0.036
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{3+}	0.056	0.060	0.053	0.079	0.046	0.099	0.057	0.086	0.038	0.048
Ti	0.003	0.010	0.003	0.008	0.003	0.006	0.003	0.013	0.003	0.009
Fe^{2+}	0.715	0.292	0.732	0.205	0.742	0.262	0.753	0.311	0.813	0.309
Mg	1.168	0.697	1.155	0.740	1.157	0.727	1.129	0.698	1.096	0.690
Mn	0.023	0.012	0.022	0.009	0.025	0.013	0.024	0.012	0.021	0.009
Ca	0.026	0.839	0.022	0.902	0.025	0.838	0.030	0.816	0.024	0.859
Na	0.001	0.045	0.001	0.034	0.000	0.044	0.001	0.040	0.000	0.039
X_{Mg}*	0.602	0.664	0.595	0.723	0.595	0.668	0.582	0.637	0.574	0.659
Normalized End-Member Proportions in Mole %										
Wo	1.3	44.1	1.1	46.6	1.2	43.2	1.5	42.4	1.2	44.9
En	58.7	36.7	58.2	38.2	58.0	37.5	56.7	36.3	55.0	36.0
Fs	40.0	19.2	40.7	15.2	40.8	19.3	41.8	21.3	43.8	19.1

Labrieville. [1] Opx, LV88-071 (inner, west). [2] Cpx, LV88-071 (inner, west). [3] Opx matrix, LV88-087 (inner, west). [4] Cpx matrix, LV88-087 (inner, west). [5] Opx, LV88-066 (outer, west). [6] Cpx, LV88-066 (outer, west). [7] Opx, LV88-133 (inner, east). [8] Cpx, LV88-133 (inner, east).
St-Urbain. [9] Opx, CHV80-205. [10] Cpx, CHV80-205. * $Mg/(Mg+Fe_T)$

also strong overlap in terms of Al and Ti contents (Fig. 6). Exsolution features are rare, and no pyroxene megacrysts were recognized.

Ilmenite is the dominant oxide phase. Compared to the Labrieville ilmenite, it has a similar amount of geikielite (~4 mole% $MgTiO_3$; Fig. 7) but fewer and narrower hematite exsolution lamellae. *Biotite* is somewhat more abundant in St-Urbain OAGN than at Labrieville, and locally occurs in large masses up to 2.0 mm across. *Quartz* occurs in every St-Urbain OAGN sample, both as discrete interstitial grains and as distinctive "moats" around Fe-Ti oxides. *Zircon* occurs as rare large grains up to 0.5 mm long in some thin sections, and also forms a thin partial rim on oxide grains. In most other respects, St-Urbain OAGNs are similar petrographically to those from Labrieville, and further discussion is not warranted.

CHEMICAL COMPOSITIONS

Initially, six OAGN samples from Labrieville and four from St-Urbain were analyzed for their major-element compositions by X-ray fluorescence methods, and for selected trace elements by a combination of X-ray fluorescence and neutron-activation methods (see the Appendix for a description of analytical methods). Two leuconorite xenoliths (one each from St-Urbain and Labrieville) also were analyzed for major and trace elements. Results are listed in Table 4, where the data are grouped by locality. Subsequently, five additional samples of Labrieville OAGN matrix were analyzed for major elements, and those data (together with mineral modes) are presented in Table 5. Note that Table 5 also includes results on two OAGN-like rocks from the Adirondacks and one from the Morin Complex (#6–8, see later discussion).

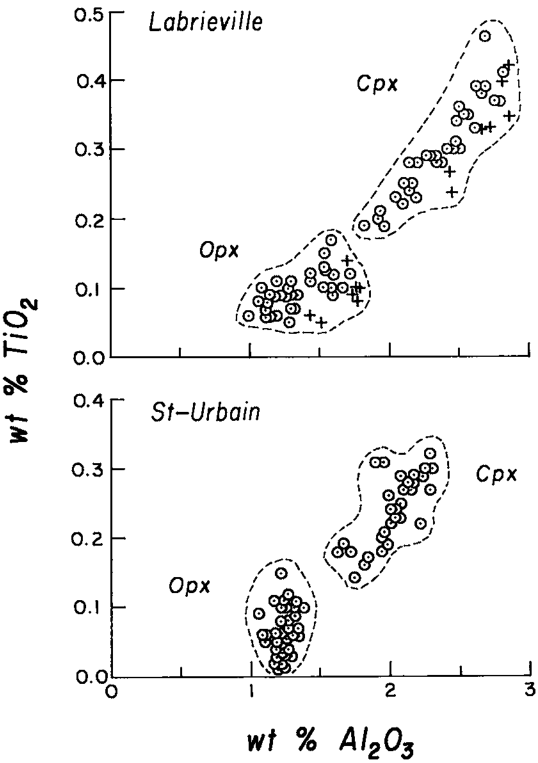

FIG. 6. Plot of wt% Al_2O_3 *versus* wt% TiO_2 in OAGN pyroxenes. Crosses: pyroxenes in relatively pure OAGN matrix at Labrieville (sample 087).

The additional analyses of Labrieville OAGN matrix were obtained because the measured P_2O_5 content of the original analysis (2.72 wt.%: Table 4, #4) seemed at variance with the high modal amount of apatite in that sample (12 vol.%: Table 1, #4). Consequently, a second split of this sample was analyzed, and this composition (Table 5, #1) can be shown to agree almost perfectly with that calculated from the mode. As such, we suspect that the original analysis was not representative (with respect to the mineral mode of a facing thin section), although multiple analyses of OAGN matrix (Table 5) confirm that this material is slightly heterogeneous on a hand-specimen scale,

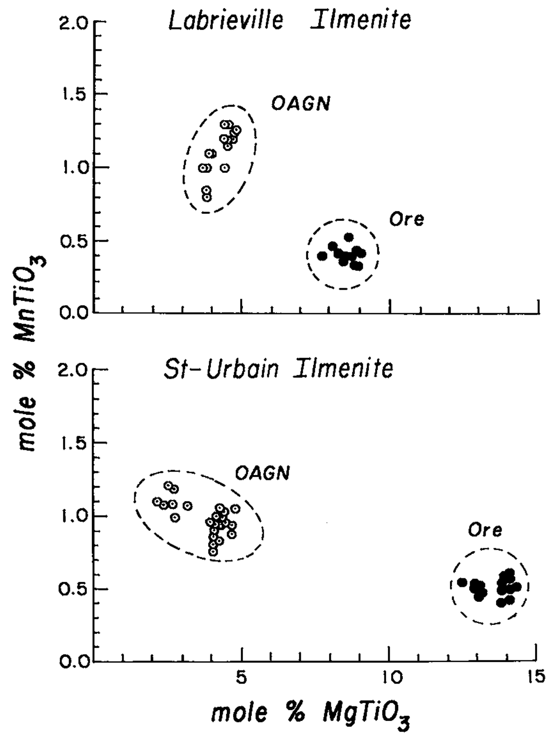

FIG. 7. A plot of mole % $MnTiO_3$ *versus* $MgTiO_3$ in ilmenite from the Labrieville and St-Urbain OAGNs. Also shown for purposes of comparison are the compositions of ilmenite from ore deposits at both localities.

with the largest (significant) relative variations shown by CaO and P_2O_5.

Major elements

As a group, the analyzed OAGNs contain high concentrations of Fe_2O_3 (19–44 wt%; note that all Fe is expressed as Fe_2O_3), TiO_2 (4–10 wt%) and P_2O_5 (2.0–5.7 wt%). The compositions of the four St-Urbain samples are similar (Table 4, #7–10), whereas those from Labrieville span a wide range reflecting, primarily, their plagioclase content, as indicated by wide variations in Al_2O_3 (1.6 to 12.4 wt%). Concentrations of CaO (8–11 wt%) and MgO (5–10 wt%) are low relative to Fe_2O_3. SiO_2 is typically low but variable (23–42 wt%), as are Na_2O (0.2–2.9 wt%) and K_2O (<0.1–1.1 wt%). The leuconorite xenoliths from both localities have similar compositions (Table 4, #11, 12), although the St-Urbain inclusion contains higher TiO_2 and Fe_2O_3, indicating a greater amount of ilmenite and magnetite.

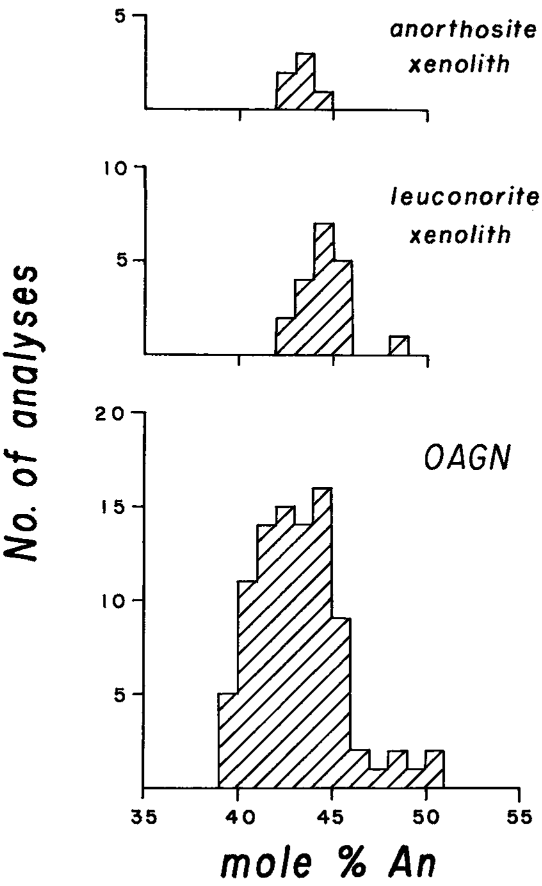

FIG. 8. Compositions of plagioclase in OAGNs and xenoliths at St-Urbain.

OAGN compositions are illustrated on an alumina variation diagram (Fig. 9), where linear arrays for SiO_2, TiO_2, MgO, Fe_2O_3, Na_2O and K_2O confirm the importance of plagioclase mixing. [For purposes of later discussion, each oxide plot shows a reference line connecting the composition of average Labrieville inner OAGN matrix to a stippled field corresponding to Labrieville anorthosites.] On the K_2O plot, data points for the outer OAGN of Labrieville lie above the array for the other samples, reflecting higher content of modal K-feldspar (Table 1). Plots for P_2O_5 and CaO yield broad clusters rather than arrays, which is due to slight variations in proportions of modal apatite/clinopyroxene (Tables 1, 5). Note that such variations in modal mineralogy are confirmed by the multiple analyses of the OAGN matrix, which form subvertical trends on Figure 9, independent of Al_2O_3.

TABLE 4. CHEMICAL COMPOSITIONS OF LABRIEVILLE & ST-URBAIN OAGNs

wt. %	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
SiO_2	42.38	35.12	33.11	26.89	41.42	39.74	33.12	33.02	31.65	33.51	54.10	49.50
TiO_2	4.59	6.78	7.70	10.37	4.44	5.02	7.71	7.63	8.45	4.88	0.87	4.27
Al_2O_3	12.43	7.76	6.40	1.58	11.56	9.97	6.97	6.99	5.87	6.30	19.62	19.07
Fe_2O_3-T	19.72	27.37	30.95	41.63	21.65	23.05	27.35	28.47	29.28	30.41	7.80	10.54
MnO	0.25	0.32	0.32	0.43	0.24	0.25	0.29	0.30	0.32	0.37	0.12	0.08
MgO	4.86	6.37	7.34	9.38	5.02	5.21	6.80	6.74	7.16	7.93	4.56	4.67
CaO	9.40	10.48	9.61	8.17	8.70	9.22	10.28	9.91	10.13	9.42	7.88	7.43
Na_2O	2.91	1.80	1.50	0.33	2.94	2.66	1.58	1.42	1.37	1.39	4.53	3.92
K_2O	0.78	0.31	0.31	<0.10	1.03	1.10	0.44	0.40	0.36	0.26	0.54	0.81
P_2O_5	2.84	4.11	3.33	2.72	3.86	4.45	5.10	4.96	5.42	5.45	0.24	0.50
LOI	-0.36	-0.57	-0.56	-1.27	-0.23	-0.39	-0.43	-0.44	-0.80	-0.07	-0.09	-0.37
Total	99.80	99.85	100.01	100.23	100.63	100.28	99.21	99.40	99.21	99.85	100.17	100.42
Sc	21.4	30.2	31.0	40.4	17.1	21.3	31.2	31.0	32.2		16.8	9.0
V	216	355	490	590	370	294	410	373	417	307	106	170
Cr	3.9	4.9	10.0	16.5	4.0	2.8	6.1	10.2	9.7	19	80	153
Co	47.7	61.6	91.5	68.3	59.9	39.1	74.8	78.3	79.3		27.7	48.0
Ni	<13	<12	32	<20	10	<14	33	28	22	28	27	121
Cu	<12	13	45	<26	53	22	32		17		<8	
Zn	195	238	303	482	248	265	356	399	352	545	84	92
Ga	22.1	21.9	21.7	21.4	26.5	25.9	24.0	22.7	21.7	22.2	25.2	22.7
As	+	<2	<3	<2	<2	<2	<0.7	+	+		<0.3	<0.3
Se	+	+	<1	+	+	+	<1.0	<0.8	<0.8		<0.5	<0.9
Br	<1.2	<0.6	<0.9	<0.5	0.4	<0.9	<0.4	+	+		<0.3	0.4
Rb	4.0	<7	<4	<5	8.9	11.0	3.7	2.5	4.0	<3	3.2	5.8
Sr	1035	667	520	164	861	744	424	463	350	333	1115	833
Y	32.9	55.2	41.9	50.7	47.5	60.7	90.1	96.1	90.0	96.3	4.2	7.5
Zr	66	95	128	93	152	336	360	32	328	67	26	85
Nb	5.4	11.7	9.7	10.8	9.9	19.0	16.3	24.4	24.4	22.4	<2.1	6.7
Sb	+	+	+	+	+	<0.06	<0.06	<0.09	<0.06		<0.08	<0.01
Cs	<0.08	0.12	<0.14	<0.3	<0.3	<0.3	<0.3	0.10	<0.2		<0.13	0.09
Ba	520	159	222	<32	861	798	308	350	269	189	535	321
La	22.2	32.7	23.9	28.7	49.1	67.3	72.6	83.9	79.6		5.66	9.41
Ce	58.9	88.5	65.1	79.6	119	163	181.	211.	198.		10.9	21.7
Nd	52	83	56	76	82	110	149	148	149		9	14
Sm	12.1	18.4	13.8	17.5	17.7	23.6	30.0	32.7	32.1		1.39	3.09
Eu	3.67	4.88	3.86	4.60	4.82	6.00	6.50	7.11	6.77		1.04	1.30
Tb	1.36	2.25	1.65	2.16	1.92	2.51	3.63	3.87	3.91		0.181	0.327
Yb	1.77	3.30	2.27	2.92	2.96	4.04	5.31	6.13	5.65		0.44	0.52
Lu	0.240	0.435	0.316	0.379	0.398	0.547	0.74	0.80	0.79		0.070	0.070
Hf	2.01	2.74	3.48	3.33	4.14	8.93	8.62	2.14	9.6		0.85	2.28
Ta	0.40	0.67	0.64	0.74	0.65	1.00	1.22	x	1.49		0.11	x
W	<3	<2	<9	+	<2	<2	<0.5	x	<1.8		<0.4	x
Pb	<7	<12	<12	<14	10	<12	<12	9	<12	<10	<12	<7
Th	0.07	0.51	0.13	0.15	0.58	0.64	1.45	1.52	1.61		0.07	0.08
U	<0.2	0.52	<0.4	<0.2	0.19	0.18	0.52	0.48	0.64		<0.3	<0.12

Labrieville Inner OAGN. [1] LV88-142 (east). [2] LV88-133 (east). [3] LV88-071 (west). [4] LV88-087 (matrix, west). *Labrieville Outer OAGN.* [5] LV88-066. [6] LV88-065. *St-Urbain OAGN.* [7] CHV80-203. [8] CHV80-205. [9] CHV80-202. [10] CHV80-72b. *Leuconorite Xenoliths.* [11] LV89-251. [12] CHV80-73.

+ = not detected   x = contaminated by grinding in WC.

Trace elements

Rb, Sr, Ba. Concentrations of Rb (<3-11 ppm) are low in all samples. Sr (164–980 ppm) and Ba (<10–760 ppm) are highly variable and correlate positively with Al_2O_3 (Fig. 10). The highest values of Ba (and Rb) are found in the outer OAGN, as is the case for K. Leuconorite xenoliths have high concentrations of both Sr (1115, 833 ppm) and Ba (535, 321 ppm).

Sc, V, Cr, Co, Ni. Concentrations of Sc (17–40 ppm), V (216–590 ppm), Cr (3–17 ppm), Co (39–92 ppm) and Ni (10–33 ppm) are variable in the OAGNs, but correlate fairly well with Fe_2O_3 and TiO_2 (not plotted). This suggests that the concentrations of the "ferromagnesian" trace elements are controlled largely by ilmenite and magnetite. However, plagioclase mixing also has an important influence on the concentrations of these elements, as shown, for example, by the good negative correlation between Sc and Al_2O_3 (Fig. 10). Compared to the OAGNs, the leuconorite xenoliths are noteworthy for high concentrations of Cr (80, 153 ppm), but lower Sc and V.

Cu, Zn. Zn values are exceptionally high (195–482 ppm), and also correlate with Fe_2O_3 (not plotted). Concentrations of Cu vary erratically and are relatively low (13–53 ppm).

TABLE 5. COMPOSITIONS AND MODAL MINERALOGY* OF LABRIEVILLE OAGN MATRIX AND OTHER OAGN-LIKE SAMPLES

wt. %	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	25.33	24.52	25.14	23.38	32.98	34.80	27.16	22.00
TiO_2	9.57	10.32	9.12	9.93	9.12	8.03	12.70	8.76
Al_2O_3	1.89	1.86	1.93	2.20	4.92	6.39	2.49	7.85
Fe_2O_3-T	41.61	44.27	41.91	43.67	32.63	28.55	40.95	42.85
MnO	0.37	0.29	0.34	0.35	0.29	0.36	0.30	0.27
MgO	8.41	7.60	8.54	8.09	8.32	6.97	7.50	3.65
CaO	9.74	8.72	9.65	9.04	8.83	10.67	7.40	9.76
Na_2O	0.26	0.33	0.15	0.29	1.05	1.07	0.19	1.19
K_2O	0.00	0.01	0.00	0.00	0.21	0.29	0.05	0.28
P_2O_5	4.07	3.18	3.92	3.76	2.05	3.66	2.01	4.06
LOI	-1.38	-1.05	-0.56	-0.79	-0.32	-0.78	-1.16	-0.63
TOTAL	99.87	100.05	100.14	99.92	100.08	100.00	99.59	100.01
volume %								
Plagioclase	3.2	1.2	7.6	4.5	9.3	1.3	0.5	31.4
Clinopyroxene	19.2	27.6	21.2	18.6	28.6	46.8	47.4	12.7
Orthopyroxene	33.1	27.3	30.8	30.4	34.7	2.1	3.1	9.3
Apatite	12.0	9.4	11.0	11.1	7.9	11.6	10.3	11.2
Ilmenite	19.4	21.1	17.4	20.7	17.0	x	x	10.5
Magnetite	12.7	13.0	10.2	13.2	1.6	x	x	21.5
Sulfide	0.4	0.4	1.5	1.5	0.7	x	x	1.8
Total Opaques	(32.5)	(34.5)	(29.1)	(35.4)	(19.3)	32.9	36.2	(33.8)
Biotite	-	-	0.3	-	0.2	0.4	x	1.2

Labrieville (OAGN matrix). [1] LV88-087 (hand specimen, 2nd split of original sample). [2] LV89-249 (hand specimen, from diffuse area of matrix). [3] LV89-253 (drill core, "sill" of pure matrix). [4] LV89-254 (drill core, "sill" of pure matrix). [5] LV89-255 (drill core, matrix-rich material).
Adirondacks (oxide-rich pyroxenite). [6] AA-121 (includes 0.4 % Quartz, 2.0 % Hornblende and 2.5% Garnet). [7] AA-122 (includes 2.5 % Hornblende). *Morin (ore from Desgrosbois Pit).* [8] MOR 89-731.
- = not present x = not reported * = Adirondack modes from Ashwal & Seifert (1980)

Ga. Concentrations of Ga in the OAGNs span a small range (from ~21 to 27 ppm), with similar values found in the two leuconorites. Ga/Al ratios (average = 7.6 × 10^{-4}) are considerably higher than in typical crustal materials (2.1 × 10^{-4}, Taylor & McLennan 1985). Furthermore, Ga does not correlate with Al_2O_3, a feature that appears to characterize all rocks of the massif anorthosite suite (Dymek 1990).

Y, Zr, Nb, Hf, Ta. Concentrations of Y are uniformly high in the OAGNs (33–97 ppm), with the highest values found in the St-Urbain samples (Table 4, #7–10). In the leuconorites, Y concentrations are markedly lower (#11–12, ~5 ppm). For the entire set of samples, Y faithfully follows variations in concentrations of the heavy rare earths, and also correlates well with Nb (see below).

Concentrations of Zr (32–360 ppm) and Hf (2–9 ppm) vary widely but are well correlated for the most part, yielding a mean Zr/Hf ratio of 35.3 ± 4.0, similar to average crust (= 32.8, Taylor & McLennan 1985). St-Urbain sample 205, however, contains an inexplicably low content of Zr (32 ppm: Table 4, #8) and a correspondingly anomalous Zr/Hf ratio of 15. Nb (5–25 ppm) and Ta (0.4–1.5 ppm) also correlate well, with a mean Nb/Ta ratio of 15.6 ±1.9, close to average crust (= 12.5, Taylor & McLennan 1985). None of these elements correlates well with TiO_2 or Fe_2O_3, suggesting that they are not harbored primarily in ilmenite or magnetite.

Rare-earth elements (REE). Measured *REE* concentrations vary by almost a factor of four (Table 4) but show coherent "group" behavior, increasing in the sequence: Labrieville inner OAGN → Labrieville outer OAGN → St-Urbain OAGN (Figs. 11, 12). There is also a good correlation between *REE* abundances and concentrations of P_2O_5 (not plotted), suggesting that apatite is the predominant reservoir for these elements.

Chondrite-normalized *REE* patterns are similar for all OAGN samples, being enriched and fractionated (La_N ~70–260×, Lu_N ~7–24×) with an overall concave-down shape, although there are some differences in detail. For example, the St-Urbain OAGNs (Fig. 12) display a small negative Eu-anomaly, whereas all Labrieville OAGNs (Fig. 11) have essentially none. The Labrieville inner OAGNs (including OAGN matrix) show a prominent downturn at La and Ce, which is lacking not only in the St-Urbain OAGN but also in the Labrieville outer OAGN. OAGNs from Labrieville were analyzed in the same reactor-run, so that these differences in light *REE* cannot be attributed to (otherwise unrecognized) errors in standardization

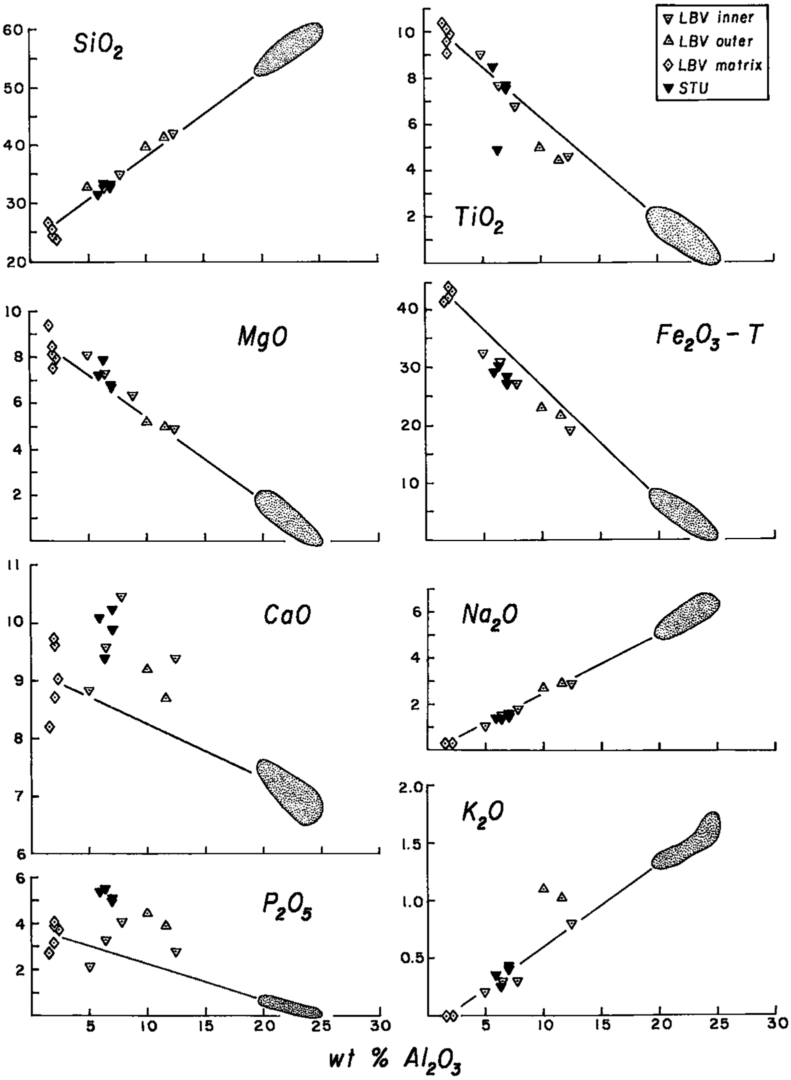

FIG. 9. A plot of major element concentrations *versus* Al_2O_3 (all in wt % oxide) in OAGNs from Labrieville and St-Urbain. The stippled field corresponds to compositions of anorthositic rocks from Labrieville (Owens, unpubl. data). The lines are drawn from this field to the average composition of inner OAGN matrix at Labrieville (see text for discussion).

or to a specific error in the determination of Nd. Furthermore, this downturn in light *REE* is manifest in samples from two separate OAGN localities (eastern and western margins of the pluton), and hence must be a fundamental property of this lithology. This difference also appears on a plot of La *versus* Al_2O_3 (Fig. 10), where the St-Urbain and Labrieville outer OAGNs are enriched compared to Labrieville inner OAGN. On a Yb-Al_2O_3 plot (Fig. 10), the same distinctions appear but are more subdued.

Compared to the OAGNs, *REE* abundances in the leuconorites are substantially lower (2–30× chondrites, Figs. 11, 12). The St-Urbain sample is slightly more fractionated than the one from Labrieville (La_N/Lu_N = 15 *versus* 10) but, overall,

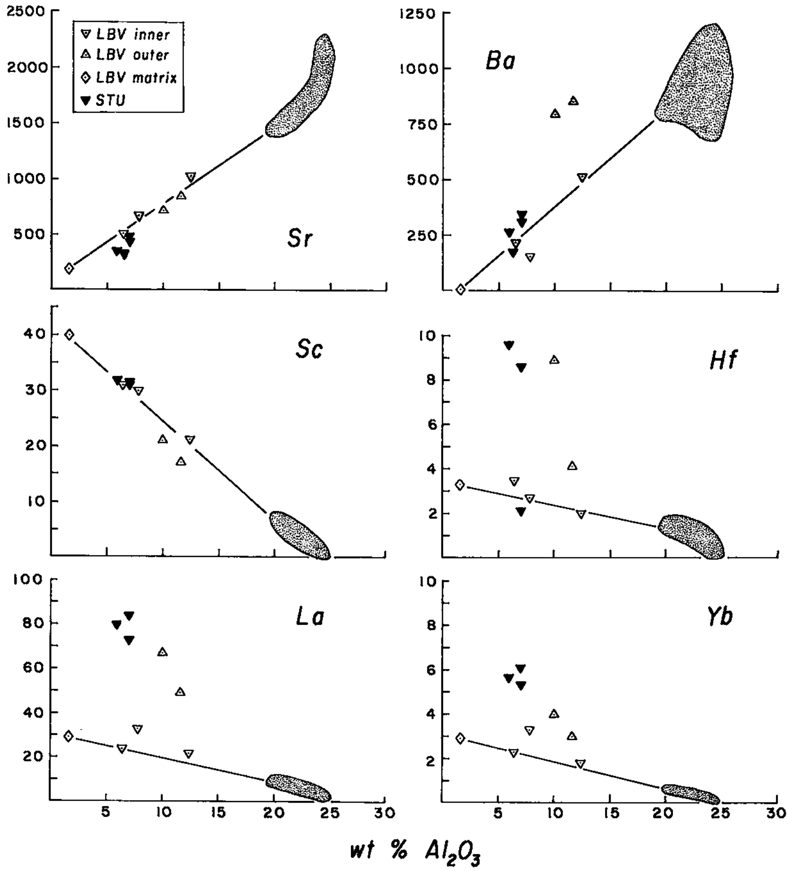

FIG. 10. A plot of trace-element concentrations (in ppm) *versus* Al_2O_3 (in wt % oxide) in OAGNs from Labrieville and St-Urbain. The stippled field corresponds to compositions of anorthositic rocks from Labrieville (Owens, unpubl. data). The lines are drawn from this field to the composition of inner OAGN matrix at Labrieville (see text for discussion).

the two *REE* patterns closely resemble each other, being smoothly fractionated across all the *REE* with prominent positive Eu anomalies.

Others. The concentrations of other trace elements are either very low or approach limits of detection in most cases (*e.g.*, As, Se, Br, Sb, Cs, W, Pb, Th, U), and do not warrant detailed consideration.

DISCUSSION

The Labrieville and St-Urbain OAGNs are certainly rocks of unusual character, by anyone's standards. Rocks with such striking field-relations, mineralogy and composition seem to require an equally unusual explanation for their origin. OAGNs at each locality clearly represent intrusion of oxide- and apatite-rich magmas of broadly similar composition into either anorthosite or country rock, but each OAGN occurrence displays certain distinctive features that preclude a simple generalized model. For example, Labrieville inner and outer OAGNs differ in texture, modal mineralogy, plagioclase composition, and concentrations of K, Ba, Zr, Hf and *REE*. St-Urbain OAGNs contain more calcic plagioclase and higher *REE* with a small negative Eu-anomaly, but otherwise resemble the outer OAGN at Labrieville in mineralogy and texture.

The FTP component of these magmas seems to be similar in each case. This is confirmed by the clustering of data points on a triangular oxide–apatite–pyroxene plot (Fig. 13), *i.e.*, the modal proportions of these phases are roughly the same

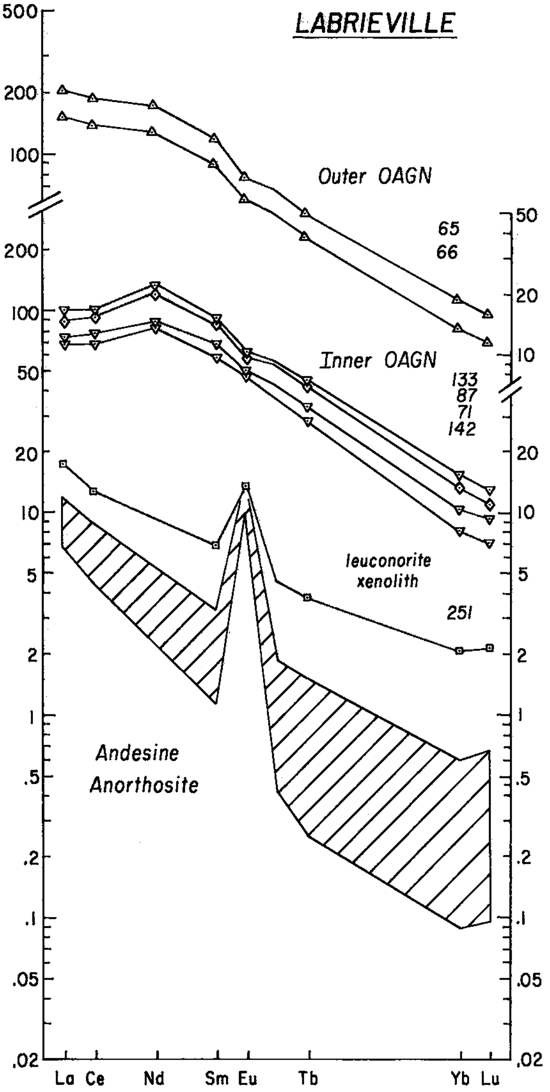

FIG. 11. Chondrite-normalized rare-earth-element plot of OAGNs and a leuconorite xenolith from Labrieville. Cross-hatched field encompasses a range of compositions of Labrieville anorthosite (Owens, unpubl. data). In this diagram and in Fig. 12, we use the chondritic concentrations reported by Anders & Ebihara (1982) multiplied by 1.38, which represents a least-squares fit to the earlier chondrite composite of Haskin *et al.* (1968) (R. Korotev, pers. comm.).

in each rock. This feature suggests that the OAGNs are not simply cumulates, which would no doubt show some degree of modal segregation, layering, banding, *etc.* Rather, these rocks appear to represent the intrusion of true Fe-, Ti- and P-enriched magmas.

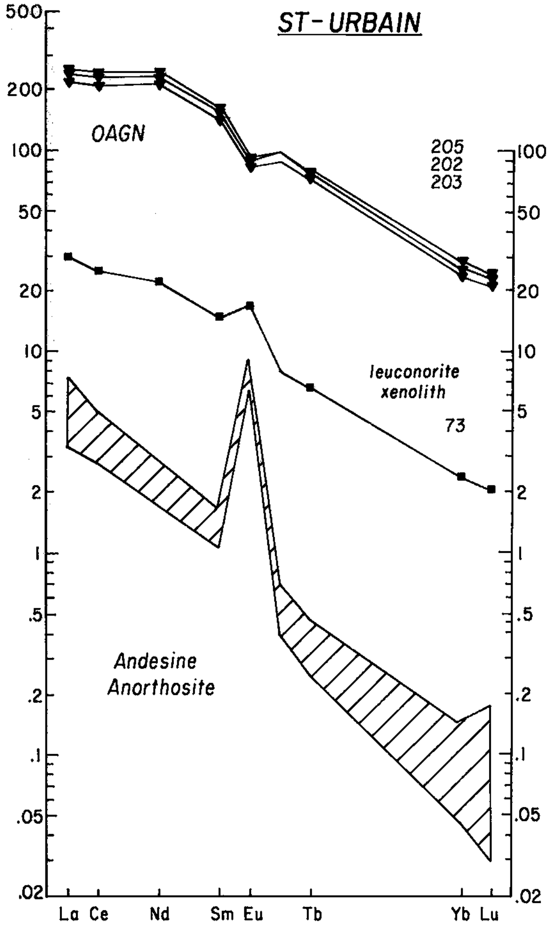

FIG. 12. Chondrite-normalized rare-earth-element plot of OAGNs and a leuconorite xenolith from St-Urbain. Cross-hatched field encompasses the range of compositions of andesine anorthosite at St-Urbain (Dymek, unpubl. data).

However, the nature, proportion and distribution of the felsic component (primarily plagioclase, but also K-feldspar and quartz) in these magmas appear to have been extremely variable. The field relations and petrography of the inner OAGNs at Labrieville suggest intrusion of an extremely mafic liquid (now represented approximately by the matrix) with suspended plagioclase crystals. The presence of anorthosite xenoliths, some of which are preserved in an "arrested" state of disaggregation, as well as the compositional distinctions between megacryst and matrix plagioclase (Fig. 4), indicate that some of the megacrysts were probably derived from the anorthosite. However, the almost complete overlap in plagioclase composition be-

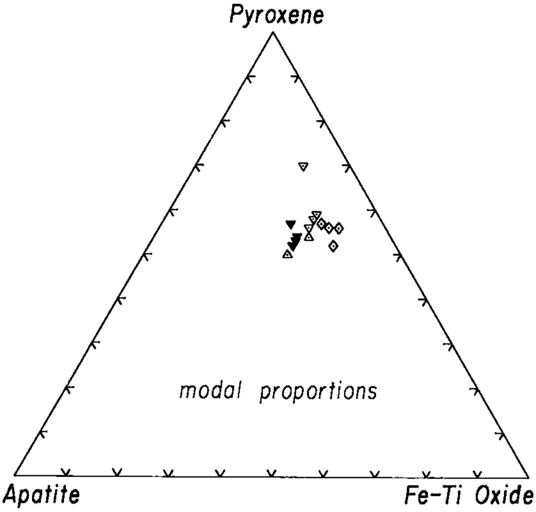

FIG. 13. Modal proportions of pyroxene, Fe–Ti oxide and apatite in OAGNs from Labrieville and St-Urbain (see Tables 1 and 5; symbols as in Fig. 9).

tween OAGN megacrysts and anorthosite suggests that the origin of all plagioclase in the inner OAGN may not be resolvable. Nevertheless, a plausible interpretation of the linear trends shown on Figures 9 and 10 is that of mixing between plagioclase (from the anorthosite) and matrix. This simple interpretation is obviously complicated by a certain real variability in the matrix composition (Table 5), especially for CaO and P_2O_5, but is consistent with field and petrographic observations.

The same interpretation cannot be applied to the outer OAGN at Labrieville, which is characterized by a more homogeneous texture and more evolved plagioclase compositions, as well as modal K-feldspar and quartz. The felsic component in this unit was obviously not derived from the anorthosite, but was an integral part of the magma. In addition, the compositional differences (K, Ba, Zr, Hf, *REE*; see Figs. 9, 10, 11) between the inner and outer OAGNs confirm that the two units are not identical rock-types, and may not even be related directly. However, some of these differences may be attributable to the effects of assimilation of different host-rocks (anorthosite *versus* quartzofeldspathic gneiss) for each unit.

The St-Urbain OAGN represents yet another situation, as it shares certain textural and compositional characteristics of both the inner and outer OAGNs at Labrieville. For example, much of the OAGN at St-Urbain is texturally heterogeneous, which can be linked to interaction with anorthosite and leuconorite xenoliths, analogous to the inner OAGN at Labrieville. However, more homogeneous variants of this OAGN also occur and, in such cases, the St-Urbain rocks resemble more closely the outer OAGN at Labrieville. Therefore, the St-Urbain OAGN probably contains both xenocrystic plagioclase from the anorthosite, as well as indigenous plagioclase, K-feldspar and quartz. To complicate the issue further, abundant xenoliths of various country-rock lithologies also occur in the St-Urbain OAGN, implying further compositional modification due to assimilation.

In summary, each OAGN occurrence displays certain unique textural, mineralogical and compositional characteristics. However, the most notable feature of these rocks, *i.e.*, their extreme enrichment in Fe, Ti and P, suggests that they crystallized from similar, though clearly not identical, magmas at each locality.

This interpretation for the emplacement of the Labrieville and St-Urbain OAGNs is unusual but not unique, as a number of other investigators previously have presented scenarios involving infiltration of anorthosite by FTP-magmas to account for associated oxide-rich rocks. For example, Hargraves (1962, p. 174) suggested "... injection and permeation of mafic magma into a crushed zone in the anorthosite ..." for the origin of oxide-rich norite sheets in the Allard Lake massif. Emslie (1975, p. 33) proposed a similar origin for oxide-rich monzodiorite intrusive into the Morin anorthosite: "If the base of the [pyroxene quartz monzonite] magma body were in contact with anorthosite which had already solidified then fracturing of the anorthosite could result in infilling by an apatite–oxide crystal mush in the manner of clastic dykes." In the Rogaland anorthosite region, Norway, Wilmart *et al.* (1989) postulated mixing between ilmenite norite and anorthosite to account for a range of rock types associated with the Tellnes ore deposit. Others have invoked emplacement of melts having jotunitic (see above discussion on terminology) or nelsonitic compositions (Philpotts 1981, Force & Carter 1986, Herz & Force 1987). The observations and conclusions reached by others in different massifs and in different contexts indicate that a process similar to the one we have suggested is probably not uncommon in the evolution of massif anorthosite complexes. Our main contribution to these earlier ideas is the marshalling of combined field, petrographic, mineral-chemical and whole-rock-chemical data in support of our interpretations. Although we consider the evidence for the existence of such FTP-magmas to be compelling, the precise *origin* of these magmas is a matter of some uncertainty.

Source of the FTP magma: residua of anorthosite crystallization?

At Labrieville, the inner OAGN lenses occur within anorthosite, whereas the St-Urbain occurrence lies between anorthosite and country-rock gneisses. These observations permit some kind of genetic link between OAGN and anorthosite. Chemically, OAGNs are enriched in virtually all plagioclase-incompatible elements and, as such, represent plausible candidates for material derived from any number of parent magmas by fractionation of plagioclase. In this scenario, the proposed FTP magma was generated at some late stage of anorthosite crystallization, and was then able to intrude partially consolidated anorthosite or country rock to varying degrees. The fact that the compositions of OAGN pyroxenes overlap with and extend the trends of the pyroxenes in anorthosite from both massifs offers some support for this simple interpretation (Fig. 5).

However, when considered in detail, a direct genetic link between OAGNs and anorthosite is somewhat problematic. Specifically, any model deriving the postulated FTP magma from anorthosite must account for the following facts: [1] the change from ilmenite in anorthosites to ilmenite + magnetite in OAGNs; [2] the shift to a more calcic plagioclase, especially in the OAGN matrix at Labrieville; and [3] the relatively small to negligible negative Eu anomalies shown by OAGNs.

Fe–Ti oxide assemblage. If anorthosites and OAGNs are indeed comagmatic, then the change from ilmenite to ilmenite + magnetite could be accounted for by an increase of Fe/Ti during differentiation at relatively constant $f(O_2)$. However, crystallization of ilmenite (Fe ≈ Ti) and orthopyroxene (Fe >> Ti), the dominant ferromagnesian phases in the anorthosites, would seem to cause the opposite effect. Alternatively, a decrease in $f(O_2)$ at constant Fe/Ti might initiate the crystallization of magnetite. Anderson (1966) suggested that differentiation of the Labrieville complex proceeded under conditions of decreasing $f(O_2)$, based largely on low (relative to the anorthosite) values of $f(O_2)$ estimated for two samples from the adjacent Sault-aux-Cochons complex (Fig. 1). If, as we contend, the Sault-aux-Cochons complex is in fact not directly related to the Labrieville massif proper, this conclusion becomes invalid. Furthermore, it is unclear why a decrease in $f(O_2)$ should produce abundant Fe–Ti oxides in the OAGNs rather than Fe-enriched silicates.

It has been suggested (B.R. Frost, pers. comm.) that the change from an ilmenite assemblage in anorthosite to an ilmenite + magnetite assemblage in OAGN may not require a change in $f(O_2)$, but could be explained by progress of the reaction: Ilm + Opx = Qtz + Usp ("QUILP", Lindsley *et al.* 1990), once X_{Fe} in the system had exceeded some critical threshold value (about 0.4 for orthopyroxene in the present case). The presence of quartz "moats" surrounding some ilmenite grains may be evidence for such a reaction, although quartz is equally common around magnetite, and most ilmenite–orthopyroxene grain boundaries are undecorated by quartz. Nevertheless, modal analyses of OAGNs, as well as mineral compositions, provide a means of testing this possibility. Consider the reactions:

$$3FeTiO_3\ (Ilm) + 3FeSiO_3\ (Opx) = 3SiO_2\ (Qtz) + 3Fe_2TiO_4\ (Usp) \qquad \{1\}$$

$$3Fe_2TiO_4\ (Usp) + 1/2O_2 = 3FeTiO_3\ (Ilm) + Fe_3O_4\ (Mag) \qquad \{2\}$$

One would expect that magnetite produced as a result of {1} would be Ti-rich, but analyses show that magnetite in OAGNs is uniformly low in Ti, and most grains are virtually pure Fe_3O_4. It must therefore be argued that any ulvöspinel produced by {1} was completely converted to ilmenite + magnetite *via* reaction {2}. Reactions {1} and {2}, in tandem, would thus conserve the modal amount of ilmenite, while producing magnetite and quartz at the expense of orthopyroxene.

Direct application of reaction {1} predicts that for every mole of ilmenite (or orthopyroxene) consumed, one mole each of quartz and ulvöspinel are produced. Modal analyses (Table 1) reveal a deficiency of quartz and an excess of magnetite compared to values predicted from {1}, together with highly variable proportions of ilmenite and magnetite. The quartz "problem" may involve a magmatic reaction that merely causes $a(SiO_2)$ to increase, while leading to little quartz precipitation. However, a second source of magnetite seems essential.

Perhaps the problem lies in trying to accommodate results for St-Urbain and Labrieville within a framework developed for the Laramie anorthosite complex, where anorthosites are characterized by two oxide phases, and other associated plutonic rocks with high Fe/Mg ratios contain only ilmenite (Frost *et al.* 1988). Different conditions of crystallization seem necessary to explain the reversed order of mineral appearance (if the rocks are comagmatic), probably involving different compositions of magma and certainly different ranges of $f(O_2)$.

Plagioclase compositions. With regard to plagioclase (if OAGNs are residua of anorthosite crystallization), the shift to more calcic compositions is not the expected consequence of ordinary magmatic differentiation. This problem is particularly acute in OAGN matrix at Labrieville, which contains plagioclase as calcic as An_{51} (in contrast to the more typical An_{35} compositions from the main body of the massif).

There are a number of possible ways to account for this compositional shift. An increase of $P(H_2O)$ in OAGNs could perhaps produce a more calcic plagioclase, and the ubiquitous presence of biotite in OAGNs provides circumstantial support for this idea. However, biotite is by no means abundant, particularly in the inner OAGN matrix at Labrieville, which contains the most calcic plagioclase compositions. Furthermore, there is no spatial correlation between such calcic grains and biotite, where H_2O concentrations presumably were highest (*cf.* Morse & Nolan 1984).

A second possibility, suggested by S.A. Morse (pers. comm.), involves a shift of equilibrium plagioclase compositions to higher An due to an increase of augite component in the melt (see Morse & Nolan 1984 for discussion). However, this hypothesis seems applicable only to liquids that have not, in fact, begun to crystallize clinopyroxene with plagioclase, for plagioclase should then become more sodic with continued crystallization. In the Labrieville inner OAGNs, matrix plagioclase grains appear to have crystallized along with, or even after clinopyroxene, suggesting that such a process cannot apply in this case.

The presence of plagioclase-lamellae-bearing pyroxene megacrysts in the inner OAGN at Labrieville may have a strong bearing on the plagioclase problem. Specifically, the compositions of plagioclase lamellae are similar to those of OAGN matrix plagioclase. Moreover, these lamellae, like matrix plagioclase, are reversely zoned. If, as noted previously, some of the polygonal grains of pyroxene comprising part of OAGN matrix represent recrystallized megacrysts, then their plagioclase lamellae might now resemble matrix plagioclase grains. It is doubtful whether this interpretation can account for all of the plagioclase within inner OAGN matrix, which comprises as much as 10% in some thin sections. Nevertheless, this interpretation provides a plausible explanation for at least part of the chemical data at Labrieville, and is consistent with the observed textures of the pyroxene.

Pyroxene megacrysts have not been recognized in the St-Urbain OAGNs, and thin section textures suggest that they probably never were present. Consequently, this idea has no bearing on the slightly more calcic plagioclase compositions found there (relative to "typical" St-Urbain An_{40} andesine anorthosite). We note, however, that this more calcic plagioclase composition makes it difficult to view the St-Urbain OAGNs as the final product of differentiation of the massif. Rather, based on plagioclase composition alone, OAGNs must have formed at some earlier stage of anorthosite crystallization. However, this interpretation seems at variance with pyroxene data (Fig. 5).

Eu-anomalies. OAGNs as a group display negligible (Labrieville) to only moderate (St-Urbain) negative Eu-anomalies. This feature is difficult to account for if OAGNs represent the last small percentage of melt following the crystallization of vast amounts of plagioclase to form the anorthosites. Of course, mixing of cumulus plagioclase with residual liquids in exactly the right proportions may mask any negative Eu-anomaly, as suggested by Ashwal & Seifert (1980). Although plausible, especially in light of our mixing hypothesis for the inner OAGNs at Labrieville, this idea is not supported by our results. In particular, matrix sample 087 contains no plagioclase megacrysts, but shows only a slight negative Eu-anomaly. In fact, the nearly identical patterns shown by the inner OAGNs (Fig. 11) indicate that plagioclase, which ranges from 3 to 58 modal % in these rocks, has a minimal effect on *REE* relationships. This point can be evaluated further by a simple mass-balance calculation. Inner OAGN sample 142, with the highest amount of modal plagioclase (58%), should most clearly show the effect of plagioclase on its *REE* pattern. If the sample is considered to consist essentially of two components, cumulus plagioclase and matrix, then it is possible to calculate the *REE* concentrations in the matrix, given data for plagioclase and the whole rock. *REE* data are not available for plagioclase separates, but as an approximation we have used the concentrations in a typical sample of Labrieville anorthosite (see Fig. 11). The calculated *REE* pattern of the matrix obtained in this way shows virtually no Eu-anomaly, in agreement with results for matrix sample 087.

Furthermore, the close correlation between *REE* and P_2O_5 concentrations in OAGNs suggests that apatite is the predominant reservoir for these elements, and that the corresponding *REE* patterns are dominantly those of apatite (*cf.* Emslie 1985). Mineral/melt partition-coefficient data (*e.g.*, Watson & Green 1981) indicate that apatite excludes Eu^{2+} relative to the adjacent trivalent *REE*, and therefore shows a negative Eu-anomaly. The absence of a pronounced negative anomaly in the OAGNs implies, therefore, that the liquids from which these grains of apatite crystallized could not have had a negative anomaly, and may in fact have had a positive one!

Although we consider the *REE* patterns shown by OAGNs to be compelling evidence against their derivation as residual liquids from anorthosite, we offer the following *caveat*. The magnitude of the Eu-anomaly shown by rocks purported to be residual to anorthosite is strongly dependent on the choice of starting composition as well as oxygen fugacity (or melt structure), factors which are, at best, difficult to quantify. Therefore, we suggest that the recognition of residual (or parental) magmas associated with massif anorthosite based *primarily* on the criterion of an Eu-anomaly is a practice fraught with pitfalls, as discussed in the previous paragraph.

Source of the FTP magma: derivation from mangerite

Another possibility is that the FTP magma was derived from an external source, perhaps with no direct genetic link to anorthosite. A previously proposed idea for the origin of the St-Urbain OAGN (Powell *et al.* 1982a,b) involved the separation of an immiscible FTP-type liquid from the magma parental to nearby quartz mangerite plutons (*cf.* Philpotts 1981). In this scenario, a dense, highly fluid mafic liquid settled out of the felsic liquid and ponded at the contact with anorthosite. In support of this idea, Powell *et al.* (1982a, b) noted: [1] the broad similarity in *REE* patterns between OAGN and quartz monzodiorite; [2] overlapping pyroxene compositions; [3] the presence of ilmenite and magnetite in both lithologies, but only ilmenite in anorthosite; and [4] similar initial $^{87}Sr/^{86}Sr$ ratios, which are distinct from those of the St-Urbain anorthosite. To this list, we add three additional observations from St-Urbain: [1] the presence of quartz and K-feldspar in OAGN; [2] the An content of plagioclase in OAGN, which is only slightly more calcic than in adjacent mangerite, consistent with the postulated early separation of OAGN; and [3] the presence of OAGN-like zones within mangerite, including the recent discovery (summer 1990) of a large (~75 m in length, unknown width) body of OAGN many kilometers removed from any known anorthosite. [An analysis of this material yields 38.9% Fe_2O_3, 7.3% TiO_2 and 4.5% P_2O_5, which is remarkably similar to Labrieville OAGN matrix (Table 5).]

At Labrieville, the Sault-aux-Cochons complex and a number of other nearby mangeritic plutons are known to contain similar oxide- and apatite-rich lithologies (Anderson 1962, 1963a, Hocq 1977). Our own recent field observations of the unit mapped as "ferrodiorite" by Hocq (1977), within the Lac Gouin mangerite to the northwest of Labrieville, indicate it to be virtually identical to OAGNs. Therefore, OAGN-like rocks are not restricted to the Labrieville massif, and it appears that they may in fact be more common outside the massif proper. We also note the presence of significant quartz and K-feldspar in the outer OAGN, and the observation by Anderson (1966) of 18% modal K-feldspar in a sample designated "syeno-gabbro" from the western end of the largest inner OAGN lens (the southeast lens of this study, Fig. 1). We suspect that the arrangement of OAGN lenses in the Labrieville massif may be due to injection of FTP magma into previously foliated anorthosite, with the Sault-aux-Cochons complex being the most likely source of the magma. This interpretation is strengthened by the fact that no OAGN-like rocks have yet been found at the northern or northeastern border of the massif, *i.e.*, regions not in contact with the Sault-aux-Cochons complex.

OAGN versus jotunite-ferrodiorite and nelsonite

Although we have noted the differences between OAGNs and more "typical" jotunite-ferrodiorite, it could be argued that OAGNs were derived as cumulates or segregations from such magmas. However, OAGNs are clearly distinct from these other FTP rocks (jotunites, ferrodiorites, ferrogabbros, *etc.*), as shown on Figure 14, a plot of TiO_2 and P_2O_5 concentrations. Also included on this figure are data points for several OAGN-like rocks from other areas: "oxide-rich pyroxenite cumulates" from the Adirondacks (Table 5, #6 & 7), "magnetite-ilmenite-rich rock" from the Desgrosbois ore deposit in the Morin anorthosite (Table 5, #8), "ultramafic jotunite" from the San Gabriel complex, and "ferrodiorite" from the Lac Gouin complex. Rocks within the OAGN field are clearly enriched in both Ti and P compared to virtually all of the other plotted rocks, apart from a few extreme compositions of monzonorite from the Rogaland area, Norway (Duchesne *et al.* 1989).

Overall, the distribution of data points on Figure 14 could be explained by the accumulation of Fe–Ti oxide and apatite from a jotunitic liquid to produce OAGN-type rocks, and the very high concentration of TiO_2 in Adirondack sample AA-122 is perhaps an indication of oxide accumulation. However, the contrasting densities of Fe-Ti oxide (~5), apatite (~3.2) and pyroxene (~3.4) would certainly lead to differential settling rates, regardless of melt density, and result in at least some modal segregation of phases. Although we recognize that this is an oversimplification of crystal-accumulation processes, the relatively constant modal proportions of these phases (Fig. 13) argues against a cumulus origin for OAGNs. Rather, the field relations, petrography, and modal data suggest nucleation and growth of crystals essentially in place, from FTP magmas of similar composition.

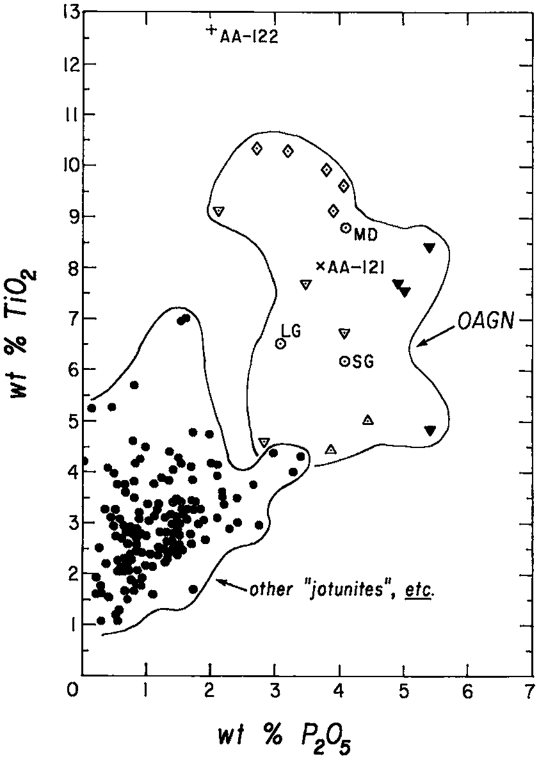

FIG. 14. Plot of wt% TiO_2 *versus* wt% P_2O_5 for the OAGNs of this study and other jotunites, ferrodiorites, *etc.* from numerous anorthosite localities worldwide. The OAGN field encompasses samples from Labrieville and St-Urbain (symbols as in previous figures), and other rocks of similar composition elsewhere, including: AA–121,122 (Adirondack "oxide-rich pyroxenites", Table 5, this study); MD (Morin, Desgrosbois ore, Table 5, this study); SG (San Gabriel "ultramafic jotunite", Carter 1982); LG (Lac Gouin "ferrodiorite", Hocq 1977). Filled circles correspond to compositions of "jotunites", *etc.*, from other areas. Source of data, locality, nomenclature and number of data points plotted: Carter (1982), San Gabriel jotunite (1); Demaiffe & Hertogen (1981), Rogaland jotunites (3); de Waard (1970), Roaring Brook, Adirondacks jotunites (4); de Waard & Romey (1969), Snowy Mt., Adirondacks jotunites (7); de Waard & Wheeler (1971), Nain jotunites (4); Duchesne *et al.* (1974), Rogaland monzonorites (2); Duchesne *et al.* (1989), Rogaland monzonorites (33); Emslie (1965), Michikamau ferrodiorites (2); Emslie (1975), Morin monzodiorites (7) and oxide-rich dikes (8); Emslie (1980), Harp Lake ferrodiorites (17); Herz & Force (1987), Roseland ferrodiorites (8); Hill (1988), Nain, Flowers River ferrogabbros (12); Martignole (1974), Morin ferrodiorites (2) and jotunites (7); McLelland & Chiarenzelli (1990), Roaring Brook, Adirondacks jotunite (1); Papezik (1965), Morin ferrogabbros (4); Philpotts (1966), Belleau-Desaulniers and Grenville Township areas, Quebec, jotunites (3); Sarkar *et al.* (1981), Chilka Lake, India, oxide-rich jotunite (1); Schrijver (1975), Lac Croche, Quebec, jotunite (1) and dark dike (1); Seifert (1978), Baker Mt., Adirondacks jotunite (1); Wiebe (1979), Nain ferrodiorites (17); Wiebe (1984), Rogaland monzonorites (18).

It might be argued that OAGNs crystallized at high $f(O_2)$ conditions from magmas of jotunite–ferrodiorite composition, which resulted in the production of abundant Fe–Ti oxides. However, TiO_2 and P_2O_5 concentrations would be unaffected by changes in $f(O_2)$. In addition, OAGNs are not merely enriched in Fe–Ti oxide minerals relative to jotunite, but also are enriched in total Fe. Perhaps such magmas could be linked to jotunite by immiscibility (*cf.* Herz & Force 1987), or be on the liquid line-of-descent of a jotunitic magma, with OAGNs representing the accumulation and segregation of a very dense, low-viscosity liquid.

Although we see no straightforward way of linking OAGNs to jotunites at St-Urbain and Labrieville, rocks of more "typical" jotunite composition have been recently recognized in both areas. At St-Urbain, such rocks occur at the borders of mangeritic plutons, whereas at Labrieville they form discrete dikes intruding anorthosite; preliminary data suggest that jotunites may also comprise a significant portion of the Sault-aux-Cochons complex. Based on these observations, the derivation of OAGNs from jotunite becomes a viable possibility, but in principle is equivalent to their derivation from mangerite, to which the jotunitic rocks appear to be directly related.

As a final possibility, OAGNs could be related genetically to the extreme example of FTP rocks known as nelsonites (oxide–apatite rocks, *cf.* Kolker 1982), to which they bear some casual resemblance. However, at both St-Urbain and Labrieville, nelsonites are found only as minor zones within massive oxide ore deposits (see next section), many kilometers away from OAGN in each case, and there is no evidence that these nelsonites ever existed as liquids independent of their host ilmenite ores. Furthermore, at both Labrieville and St-Urbain, nelsonites contain only ilmenite, whereas both ilmenite and magnetite occur in OAGN.

Relationship between OAGNs and Fe–Ti oxide ore deposits

Because of the Fe–Ti-oxide-rich nature of OAGNs, it is tempting to suggest that they are somehow related to massive oxide deposits in anorthosite. OAGNs might then represent "proto-ores", or rocks from which significant amounts of oxide could be concentrated by some mechanism (crystal settling, remobilization, coalescence of immiscible oxide droplets, *etc.*). The presence of massive ores in both the St-Urbain and Labrieville massifs provides an opportunity to explore this hypothesis.

At both St-Urbain and Labrieville, the massive ores are found in completely different areas from OAGNs, being separated by many kilometers of anorthosite in each case (Fig. 1). Furthermore, no significant concentrations of pure oxide are found in the vicinity of any OAGN occurrence yet examined.

Ores at both localities lack magnetite and consist almost exclusively of ilmenite. The St-Urbain ores also contain rutile, which is never found in OAGNs. Whereas OAGNs contain two pyroxenes, only orthopyroxene is found in the ores, as part of rare ilmenite norite layers in deposits at St-Urbain. If ores were derived from OAGNs, it is difficult to account for these mineralogical differences.

Ilmenite in ores at both St-Urbain and Labrieville can be clearly distinguished from that in OAGNs on the basis of Mg and Mn contents (Fig. 7). Specifically, ilmenite in the ore is enriched in Mg, whereas that in OAGN is Mn-enriched. In terms of these components, ore oxides appear to be "primitive" relative to "evolved" oxides in OAGN. Furthermore, the ilmenite in ore from both massifs is enriched in the hematite component, relative to ilmenite in OAGNs, as indicated by the abundance and width of hematite exsolution lamellae. At St-Urbain, the orthopyroxene in ilmenite norites is considerably more magnesian (Fig. 5) and aluminous than those in OAGN, and in fact contains the highest Mg and Al values of any pyroxene in the entire massif. Similar systematics hold for biotite, a common accessory in both ores and OAGNs at St-Urbain. In summary, ores and OAGNs can easily be distinguished on the basis of the compositions of all the minerals they have in common.

Other differences could be noted, particularly for trace elements, but the above observations are sufficient to demonstrate the difficulty of making a direct genetic link between OAGNs and ores. Although a similar process (oxide melt immiscibility?) may have been involved in the formation of both rock types, the mineral chemical distinctions cited above indicate that the timing of formation was different for the two lithologies. Ores appear to have formed "early", whereas OAGNs formed "late", as suggested by Anderson (1966), based primarily on differing Fe_2O_3 contents of ilmenite in the two rock types at Labrieville. We suggest, alternatively, that ores in both massifs are directly related to their host anorthosites, but that OAGNs were derived from a separate source.

This distinction between OAGN-like rocks and ore deposits seems to have some applicability beyond St-Urbain and Labrieville. In particular, the massive Lac Tio ore deposit at Allard Lake consists exclusively of ilmenite, whereas oxide-rich norites (similar to OAGNs) contain both ilmenite and magnetite (Hammond 1952, Hargraves 1962, pers. comm.). The oxide-rich norite sheets do show basal oxide-enrichment, which is not observed at Labrieville and St-Urbain, but the considerably larger size of the sheets at Allard Lake could have resulted in more efficient settling of crystals. In the Morin anorthosite, a similar distinction can be made between the Ivry deposit (massive ilmenite) and the Desgrosbois deposit (ilmenite + magnetite; Lister 1966). The Desgrosbois deposit occurs within an oxide-rich gabbroic rock clearly intrusive into anorthosite, and our own field and petrographic observations, as well as chemical data (Table 5, #8), confirm the OAGN-like character of this unit. Emslie (1975) linked this rock to other oxide-rich pyroxene monzodiorites at the margin of the massif, and suggested that they represent a basal, mafic-mineral-enriched zone of the surrounding pyroxene quartz monzonite, which intruded the anorthosite (see quotation, p. 180). Clearly, these other occurrences of massive ores and OAGN-like rocks constitute important areas wherein our hypotheses could be tested.

CONCLUSIONS

The origin of FTP rocks associated with massif anorthosite remains a perplexing issue. Available observations and data, including the new results presented here, reveal the existence of a variety of such rocks ranging from OAGNs to more "typical" jotunite–ferrodiorite (Fig. 14), to oxide ores and nelsonites. It is our contention that the relationships among these rock types are poorly constrained, to say nothing of the more compelling problem of their collective relationship to the anorthosite proper. It is apparent, however, from differences in mineralogy and composition (Fig. 7), that OAGNs and ilmenite ores cannot be comagmatic at either St-Urbain or Labrieville, although the ores probably are related genetically to their host anorthosites.

The Labrieville and St-Urbain OAGNs crystallized from FTP magmas of similar overall composition (Fig. 13), which contained variable quantities of suspended plagioclase phenocrysts (or in some cases xenocrysts). This liquid-crystal "emulsion" intruded massif anorthosite and country rock, and probably underwent some internal differentiation in the process. The presence of various xenoliths in the OAGNs suggests that minor compositional modification may have occurred *via* assimilation. Some of the differences among inner and outer OAGNs at Labrieville and OAGNs at St-Urbain probably reflect this process.

At the present time, we reject the notion that the FTP magmas responsible for the OAGNs represent the late-stage residua of anorthosite crystallization. Alternatively, we favor their derivation, perhaps as a result of immiscibility, from mangeritic sources (such as the Lac-des-Martres batholith at St-Urbain and the Sault-aux-Cochons complex at Labrieville). This interpretation is easier to reconcile with the overall field-relations, mineralogy and composition of the OAGNs, and is supported by the presence of numerous OAGN-like bodies within the mangerites. A more comprehensive evaluation of the relationship between OAGNs and mangerites, including the possible role of immiscibility, will be presented once investigations of the mangerites in each area are completed.

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APPENDIX: ANALYTICAL METHODS

The abundances of the oxides Na_2O, MgO, Al_2O_3, SiO_2, K_2O, CaO, TiO_2, MnO, Fe_2O_3 (= total iron) and P_2O_5 were determined at Washington University by X-ray fluorescence (XRF) analysis of fused glass discs, using procedures described by Couture (1989) and Dymek & Smith (1990). Concentrations of 13 trace elements (V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba and Pb) were also determined at Washington University by XRF analysis of pressed powder pellets using procedures described by Couture & Dymek (in prep.). Analyses for 26 additional trace elements (Sc, Cr, Co, Ni, As, Se, Br, Rb, Sr, Zr, Sb, Cs, Ba, La, Ca, Nd, Sm, Eu, Tb, Yb, Lu, Hf, Ta, W, Th and U) were carried out by instrumental neutron activation (INA) analysis at Washington University using procedures described by Korotev (1987a,b). Several trace elements (Cr, Ni, Rb, Sr, Zr, Ba) were determined by both XRF and INA analysis; values listed in Table 4 represent weighted averages of the two methods as appropriate.

Most mineral analyses reported in this paper were obtained using an automated JEOL 733 electron microprobe at Washington University, although some analyses of material from St-Urbain had been previously obtained using a CAMECA MBX microprobe at Harvard University. However, the identical set of simple oxide and silicate standards was used in both laboratories. Measured X-ray intensities were converted to oxide weight percentages using the methods of Bence & Albee (1968), with correction factors modified from those of Albee & Ray (1970).