FORM OF THE SUDBURY LOPOLITH[1]

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Abstract

The mutual concordance of the various elements of the Sudbury lopolith and the overlying sedimentary rocks, and the gravity data, indicate the complex to be essentially a folded double sheet of granophyre above norite. The lopolith lies with complete discordance upon plutonic and metamorphic rocks of complicated structural and metamorphic history, and is overlain concordantly by rhyodacite tuffs which are intruded by the granophyre and are in turn overlain concordantly by sedimentary rocks. The granophyre ("micropegmatite") and the overlying tuffs are strongly alkaline, and share the distinctive chemical composition—low Al_2O_3 and CaO, high iron—that characterizes lopolith-cap rocks elsewhere. The tuffs may be the true cap of the complex, which may have been essentially extrusive in origin.

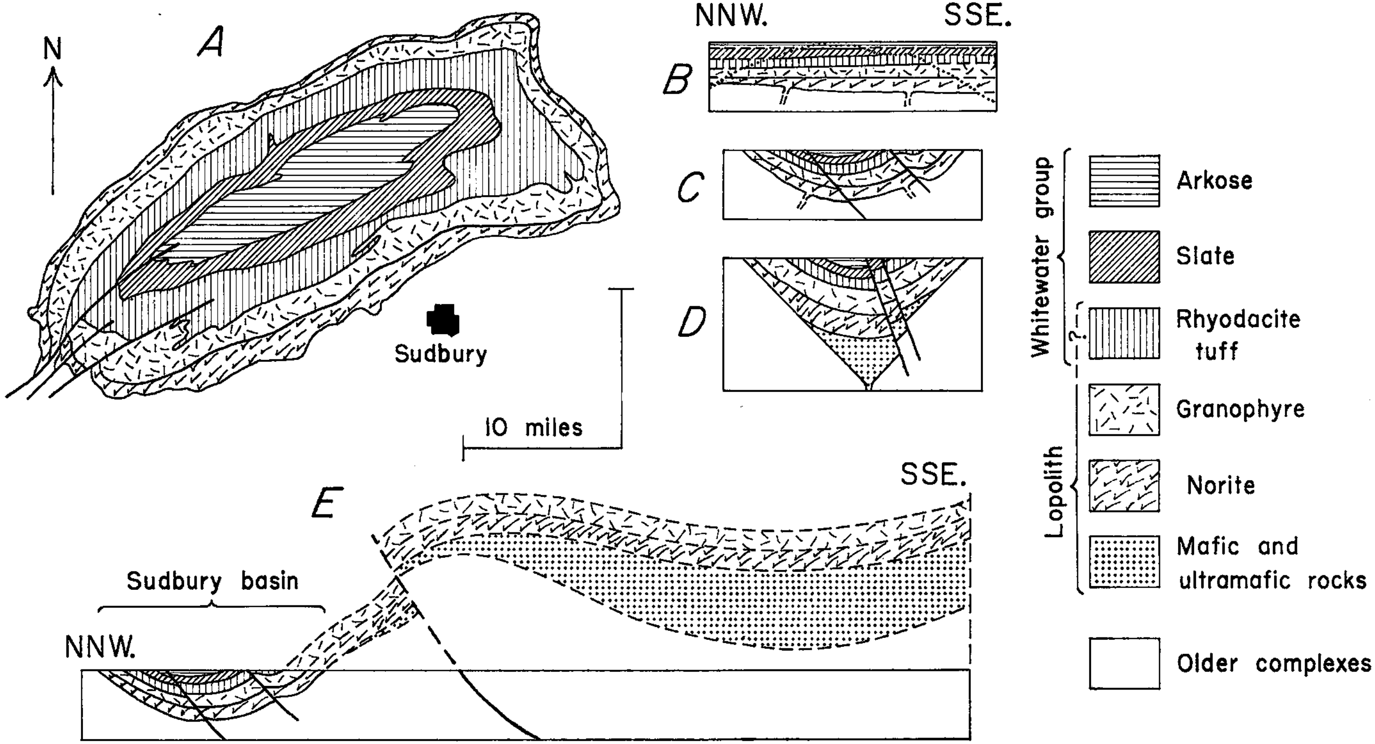
The norite of the lopolith is unlayered and contains abundant interstitial micropegmatite, and is like the upper parts of other great lopoliths. The Sudbury basin may contain only an overflow part of the north flank of a huge lopolith, the bulk of which has been removed by erosion and which contained the missing mafic and ultramafic differentiates.

Introduction

There is much disagreement as to the petrogenesis of the Sudbury lopolith, Ontario, although it is one of the most important economically, and in some ways one of the most studied, of the rock complexes of the world. Geologic work has been done in extreme detail in the metalliferous areas, but largely in reconnaissance fashion elsewhere. Generalizing broadly, it appears that "outside" petrologists, and also the field geologists who did the early regional mapping of the Sudbury region, hold one set of opinions, conditioned greatly by comparisons with similar complexes in other parts of the world; whereas others, and notably many of the Sudbury geologists, are impressed by local details, and hold a conflicting set which, at the extreme, even rejects the conclusion that the Sudbury complex is a lopolith. Complicating this are the fringe opinions.

I have not been to Sudbury. There is new synthesis as well as new interpretation here, but no new data. This note is a byproduct of a broad study of the petrology of the silicic differentiates of lopoliths, which is being published elsewhere.

[1]Publication authorized by Director, U.S. Geological Survey.



N
A
Sudbury
10 miles
NNW.
SSE.
B
C
D
E
Sudbury basin
NNW.
SSE.
Whitewater group
Lopolith
Arkose
Slate
Rhyodacite tuff
Granophyre
Norite
Mafic and ultramafic rocks
Older complexes

I will mention only one paper on each of the other lopoliths brought into the discussion. Daly's paper (1928) on the Bushveld lopolith is better in many ways than more recent summaries, and is particularly relevant to topics presented here. Taylor's 1956 paper describes the south end of the Duluth gabbro, the type example of Grout's useful term "lopolith." I summarized the petrology and field relations of the Wichita lopolith of Oklahoma (1956).

The ideas presented here regarding the original southward extension of the Sudbury lopolith grew during discussions with W. Bradley Myers.

The Lopolith

The Sudbury lopolith of Ontario lies in a structural basin and is exposed as an elliptical ring 35 miles long and 15 miles wide (Fig. 1,A), with moderate inward dips on the north side and moderate to steep dips on the south side.[2] The lopolith overlies a complex of granitic and metamorphic rocks with great unconformity, and is itself overlain concordantly by the Whitewater group of volcanic and sedimentary rocks, dominantly alkaline rhyodacite and rhyolite tuffs in the lower part and sedimentary rocks in the upper. The upper part of the lopolith is of pink granophyre ("micropegmatite"), which is intrusive into the overlying tuffs of the Whitewater group. The granophyre is of broadly uniform composition (Table 1) and is separated from the norite, which is similarly uniform internally, by a zone of smoothly changing mineral proportions a few hundred feet thick. The granophyre is about a mile thick on the south side of the ring and about 3,000 feet thick on the north side. The norite is a mile thick on the south, and not more than 2,000 feet on the north. Neither the lopolith nor the Whitewater group is exposed outside the basin, having been eroded away everywhere else. Great south-side-up reverse faults probably offset the pre-lopolith rocks south of the basin.

The granophyre is pink and is composed of microperthite and micro-

[2]The descriptive information on the Sudbury lopolith is drawn chiefly from Phemister (1926), Collins (1934, 1936), and Collins & Kindle (1935), with specific additions from other papers as cited.

FIG. 1. Map and sections of Sudbury lopolith. All drawings at same scale, horizontal and vertical scales equal.

A: Map of Sudbury lopolith after Zurbrigg (1953).
B: Cross section prior to deformation, according to Collins & Kindle (1935, p. 32). Dotted line indicates present surface.
C: Present cross section, according to Collins & Kindle (1935, p. 32).
D: Funnel-shaped cross section hypothesized by Wilson (1956, p. 297).
E: Preferred cross section, showing possible pre-erosion extent of lopolith south of Sudbury basin. Based in part on a suggestion by W. Bradley Myers.

TABLE 1. COMPOSITION OF SUDBURY LOPOLITH

	Granophyre		NORITE	Complex	Whitewater	
	1	2	3	4	5	6
SiO_2	67.8	64–70	55.2	63.1	65.9	61–70
Al_2O_3	13.4	11.5–15	16.9	14.7	11.6	10.8–12.9
Fe_2O_3	1.3	as FeO	1.9	1.5	1.7	as FeO
FeO	4.4	4.6–9	6.5	5.2	4.9	3.7–10.2
MgO	1.5	0.7–2.3	5.2	2.9	3.6	2.0–5.1
CaO	2.0	1.4–3.4	7.4	4.0	2.7	1.3–4.1
Na_2O	3.4	2.9–4.3	2.9	3.2	3.5	2.9–3.7
K_2O	3.8	2.4–4.5	1.4	2.9	2.9	2.7–3.4
TiO_2	0.7	0.3–1.3	0.8	0.7	0.4	0.4–0.5
MnO	0.07	0.03–0.1	0.1	0.08	0.2	0.1–0.2
P_2O_5	0.2	0.1–0.3	0.2	0.2	0.1	0.1
H_2O	1.2	0.7–1.9	1.3	1.2	1.8	1.7–2.0
CO_2	0.2	tr.–0.5	0.2	0.2	0.3	0.05–0.04

1. Weighted average of 34 analyses of granophyre, from Collins (1934, p. 172).
2. Range of central 30 determinations of each oxide in these 34 analyses.
3. Weighted average of 38 analyses of norite. *Ibid.*
4. Bulk composition of Sudbury norite plus granophyre. *Ibid.*
5. Average of 5 analyses of volcanic rocks of Whitewater group, from Burrows & Rickaby, (1930, pp. 10, 14, 22) and Thomson, (1957, p. 18).
6. Range of central 3 determinations of each oxide in these 5 analyses.

pegmatitically intergrown quartz and potassic feldspar. Sodic plagioclase and separate quartz are subordinate. The mafic material, probably originally mostly hornblende or elongate pyroxene, is largely represented by chlorite and minor biotite. Similar granophyres dominate the silicic rocks which cap other large lopoliths. In common with the granophyres and allied silicic rocks of the Bushveld, Duluth, and Wichita lopoliths, the Sudbury granophyres are alkaline and have very low contents of Al_2O_3 and CaO, a high content of iron, a small compositional range of most of the rocks,[3] and nearly constant amounts of CaO, Na_2O, and K_2O with varying content of SiO_2 (Fig. 2). In each of these characteristics, the silicic rocks of lopoliths are in marked contrast to the calc-alkaline granites and rhyolites of orogenic regions.

The primary minerals of the norite were orthopyroxene, clinopyroxene, hornblende, biotite, plagioclase (An 70–40), and interstitial quartz and alkali feldspar. The rock has been altered variably and secondary hornblende is now the dominant mafic mineral over considerable areas. The lopolith is bimodal: like other lopoliths, its mafic and felsic parts are completely dissimilar, as shown by the numerous mineralogical diagrams of Phemister (1926) and chemical diagrams of Collins (1934).

[3]This is certainly true for the Sudbury, Bushveld, and Wichita complexes, but practically nothing is yet known about the frequency distribution of the rocks of most of the Duluth lopolith.

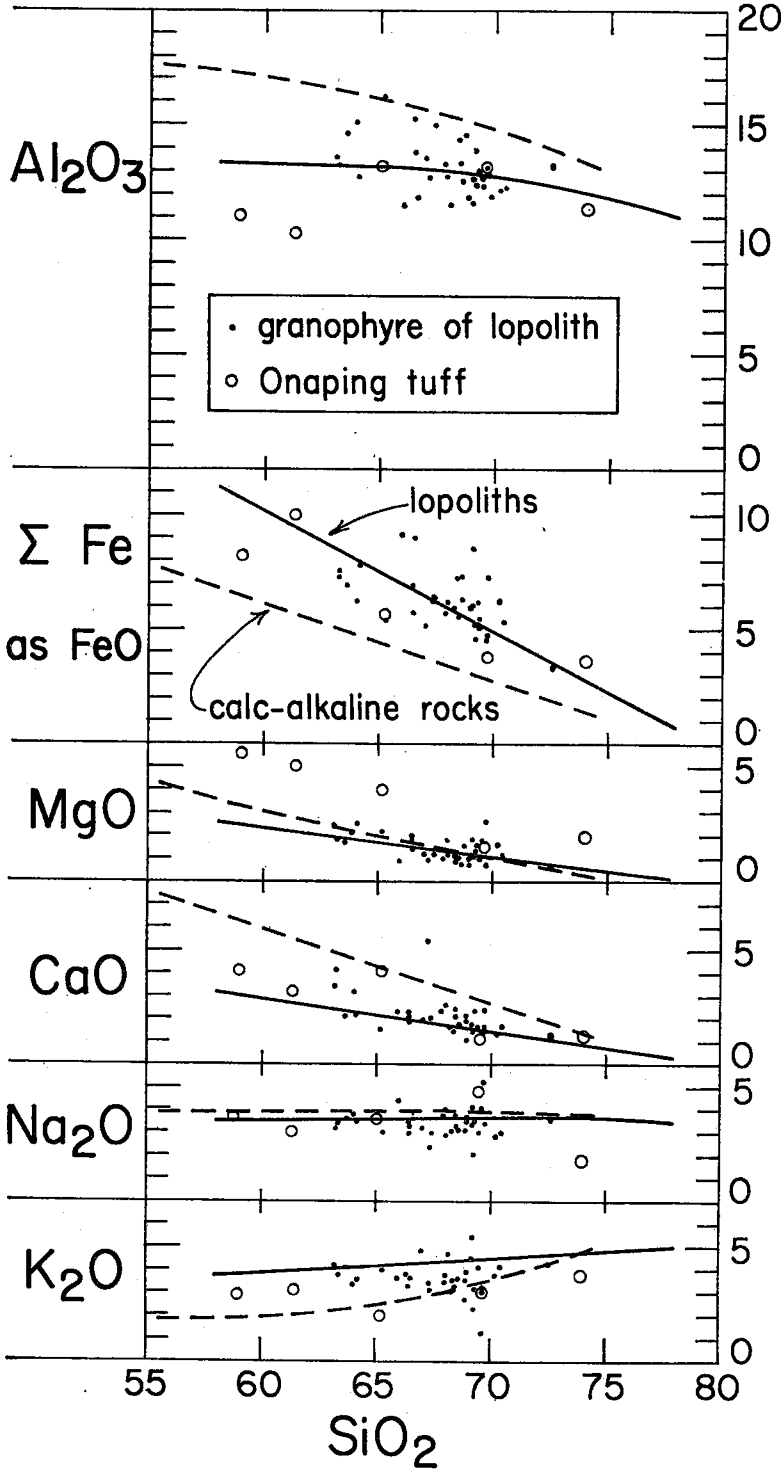


FIG. 2. Variation diagram of analyses of granophyre of Sudbury lopolith (dots) and of Onaping tuff (circles). Analyses lacking TiO_2 and P_2O_5 determinations, hence having erroneously high Al_2O_3, are not plotted. Solid lines indicate general compositional trends in silicic differentiates of Sudbury, Duluth, Wichita, and Bushveld lopoliths; dashed lines indicate trends in calc-alkaline Mesozoic batholiths of western North America and volcanic rocks of Aleutian Islands and of San Juan Mountains, Colorado.

The basal 5,000 feet, the Onaping tuff, of the Whitewater group conformably above (and intruded by) the granophyre is composed of welded tuffs and breccias of alkaline rhyodacite and quartz latite, virtually unbedded and erupted within a short period of time according to Burrows & Rickaby (1930) and Williams (1957). Five analyses of these tuffs, averaged in Table 1, show them to be alkaline and more like the underlying granophyres than like calc-alkaline rocks. They have very low contents of Al_2O_3 and CaO, a high content of iron, and a content of K_2O that varies little with varying SiO_2 content (Fig. 2); however, these five analyses span a greater range of SiO_2 (58–74%) than do Collins' 34 analyses of granophyres (SiO_2 63–73%), and their MgO content is higher than that of the granophyres. (The tuffs are termed "andesites" in most published accounts, but their contents of SiO_2 and K_2O are too high for that rock type, and their very low Al_2O_3 contents show that most of the CaO would probably have been in mafic minerals rather than feldspar.) Above the tuffs, and intercalated with upper ones, are sedimentary rocks.

Despite the coextensiveness and evenness of norite and granophyre, Phemister (1926, 1937), Thomson (1957), Williams (1957), and others have considered them to be separate intrusions. With modifications, their arguments could be applied to each other lopolith—reduced to absurdity, the conclusion could be reached that wherever a vast sheet of gabbro or norite forms, a coextensive and equally vast sheet of alkaline granophyre and allied red rocks intrudes precisely along its upper surface. Such a sequence of unrelated coincidences can not be expected to recur in different continents and at far-different times. Postulation of any other local-coincidental origin (such as a unique type of granitization of special overlying rocks) for the granophyre fails for the same reason. It is far more likely that, at Sudbury as elsewhere, granophyre and norite formed as paired products of inseparably linked processes. As Coleman (1905), Collins (1934), and many others have concluded, and as most petrologists would agree, the granophyre differentiated from more mafic magma. Interstitial micropegmatite is the universal last-crystallized component of silica-saturated diabase. As size of diabase mass increases, so does amount and size of segregations of micropegmatite, and it is clear that in the super-mass of a lopolith such segregation would be on a vastly larger scale.

The norite-granophyre, granophyre-tuff, and tuff-sediment contacts are concordant with each other and with the base of the lopolith (Fig. 1,A). This is strong evidence for the conventional interpretation of a cross section of a layered-sheet complex (Fig. 1,C), as inferred by Collins & Kindle (1935) and by many others before and since.

This conventional interpretation has been strengthened greatly by the 500-station gravity survey by Miller & Innes (1955). The gravity pattern is consistent with a basin-form sheet, but wholly inconsistent with a funnel-form mafic mass. Significantly, "The measurements deny the existence of large underground channels [large dikes] near the centre of the basin" (p. 15). Structural complications at the south margin of the complex seem required by the gravity survey, as Miller & Innes recognized. The gravity data alone apparently disprove the hypotheses of Thomson, Williams, and Wilson (see below).

The widely discussed recent work of Thomson (1957) and Williams (1957) must be mentioned in passing. They assert that the alkaline rhyodacite and quartz latite tuffs conformably above the Sudbury lopolith are contemporaneous with the highly deformed and more metamorphosed basaltic pillow lavas that lie unconformably beneath the lopolith several miles away because (except for the very different deformation and metamorphism!) the minor tuffs and breccias in the basaltic sequence are similar in outcrop appearance to the ubiquitous breccias and tuffs of the silicic sequence. The rest of their conclusions—for example, that norite and granophyre are ring dikes—are based upon this untenable hypothesis.

Wilson (1956) concluded that the difference in thickness and relative proportions of the norite and granophyre on the two sides of the syncline, and the minor irregularities of the base of the norite, indicated that the mass had a funnel shape (Fig. 1,D), with ultramafic differentiates hidden in the bottom. This is incompatible with the gravity data.

The base of the Sudbury complex has vast quantities of fresh norite with chalcopyrite, pentlandite, and pyrrhotite, always of similar paragenesis. Much of the commercial production is from "offsets" in or near breccia zones and late quartz diorite intrusions. At such places, norite is strongly altered, there is much quartz and carbonate, and the ore minerals have a complicated and variable paragenesis (Coleman, Moore & Walker, 1929). According to these men, the field geologists were unanimous: the primary ores are provably magmatic differentiates, and the "offset" ores are of redeposited minerals whose mobilization was due to faults and later intrusions. Most petrologists would certainly agree. Many of the mining geologists, however, working almost exclusively with the "offsets," have considered the ores to be entirely younger than, and unrelated to, the norite (e.g., see summary by Cooke, 1946). Nickel and allied metals are present near the base of other lopoliths, as at Sudbury, and a causal relationship is obviously indicated.

Extrusive Origin

The Sudbury granophyre intrudes the overlying Onaping tuff of the Whitewater group, and the lopolith accordingly has been assumed almost invariably to have intruded precisely along the basal unconformity.

Nowhere (rejecting the untenable conclusions of Thomson and Williams) are Whitewater rocks known beneath the lopolith, and nowhere are basement rocks known above it. The lopolith behaves as a stratigraphic group of mutually concordant formations.

Cooke (1946, p. 59) studied the base of the norite at the east end, and was puzzled: "A long section of the contact is particularly well exposed, and it displays all the irregularity commonly found at the base of a lava flow poured out on an irregular erosion surface" with a local relief of about 300 feet. Yet, as he noted, intrusive contacts of mafic sheets are commonly completely different—straight or gently curving, with abrupt bends about joints. "There is also no evidence that the intrusive attacked or replaced the older rocks" to produce the irregularity at the base. Cooke concluded that intrusion along an unconformity of considerable relief was the cause.

The alternative conclusion, that this *is* the base of a lava flow, is presented here.

Coleman (1905) suggested that the tuffs of the Whitewater group formed from early eruptions of the Sudbury lopolith's magma. Burrows & Rickaby (1930, p. 30) stated that the sandstone of the upper part of the Whitewater group contains clasts of micropegmatite which probably came from the granophyre of the lopolith—a critically important deduction if correct, as it would prove the lopolith to be older than the overlying sediments. They also agreed (p. 27) with Coleman that the tuffs were related genetically to the lopolith. Later workers seem to have largely ignored these suggestions.

The chemical similarity of the tuffs of the Whitewater group to the granophyres of the lopolith, and their dissimilarity to calc-alkaline rocks, was noted earlier, and it is a simple inference that the tuffs, not the granophyres, are the real cap of the lopolith: that the lopolith formed as an extrusive mass, a vast lava lake whose first silicic differentiates formed a crust of huge eruptions of welded tuffs. This may be a characteristic of lopoliths. The Bushveld lopolith is similarly an essentially stratigraphic unit. (The base of the Wichita mass is not exposed, and the Duluth complex has yet to be mapped.) At least the granophyre and granite of the Bushveld lopolith, and probably that of the Wichita also, are similarly overlain by and intrusive into only rhyolites, chemically like the granophyres and unlike common calc-alkaline rhyolites. Coincidences seem inadequate—the conventional explanation of lopoliths as intrusive features must, so far as we can now define the character of great lopoliths, postulate that they intrude only along the unconformities at the bases of thick uniform sections of alkaline rhyolite or rhyodacite tuffs! Daly (1928) concluded that the Bushveld rhyolites were the crust of a roofless lopolith, and similar reasoning appears equally applicable to other lopoliths, including Sudbury. At least some lopoliths are probably extrusive.

The main part of the Duluth lopolith is essentially unknown, but at its southern tip the complex is discordantly intrusive into varied sedimentary and basaltic rocks. This lopolith may be entirely intrusive, or perhaps only marginal intrusion into near-contemporaneous subaerial rocks is indicated.

Southward Extension

The norite of the Sudbury lopolith has much micropegmatite, and contains 55% SiO_2. As Wilson observed (1956), it is like the upper-mafic parts of other lopoliths, rather than like their entire mafic bulks. There is more granophyre than norite, and the overall composition of granophyre and norite, not counting the probably related tuffs, has 63% SiO_2 (Table 1). The overall composition is so unlike that of any common rock type that differentiation from a magma of such material is highly unlikely, despite Collins' conclusion (1934, p. 173) to that effect. The granophyres are very similar to the proved differentiates of other lopoliths of essentially basaltic bulk composition, and the possibility of differentiation from a basaltic magma must be considered. Wilson (1956) did so, but suggested that the mafic and ultramafic differentiates were hidden beneath the exposed rock, a hypothesis contradicted by the gravity data. The tidy concentricity of the map pattern, and the gravity information, argue strongly that the lopolith is a folded-sheet complex.

It seems to have been assumed always that basin and lopolith are related genetically and that the basin contains the bulk of the lopolith and its feeders. The symmetrical closure provides support for this view in its variant forms. However, the long axis of the basin is parallel to the regional trend of great post-lopolith deformation, and the synclinal form might have been superimposed on an originally subhorizontal sheet, long after its formation, by unrelated orogeny. The present basin may be only a small remnant, preserved by downfolding, of an initially much larger mass.

Norite and granophyre both thin northward across the Sudbury basin, and this can be likened to a northward overlap of sedimentary formations. All of the known relationships seem satisfied by the suggestion, following from this, that the main mass of the Sudbury lopolith, many miles thick, lay to the south of the present syncline, and there contained the now-missing differentiates of mafic and ultramafic rocks (Fig. 1,E). The floor of the portion preserved in the syncline would have been miles higher than that of the main mass, and would have received only an overflow of light differentiates. The greater thinning, northward across the basin, of the norite than of the micropegmatite, and the occurrence of most of the nickel at the base of the south limb, are consistent with this.

The great lopoliths, and perhaps the initial Sudbury mass among them, have volumes on the order of 100,000 cubic miles. Very large, proved-intrusive, sills are certainly far more common than very large lava flows, but the gap between the big lopoliths and common thin lava flows is not unbridgeable. Single flows as thick as 1,000 feet, showing slight differentiation, have been described from the Keweenawan series of Michigan and from the Columbia River basalt of Washington. Most of the thick Columbia River sequence may have been erupted within a geologically brief period; had the successive eruptions come within a still shorter period, a lopolith could have resulted.

At least some of the great lopoliths, probably including Sudbury, seem to be of largely extrusive origin. Obvious problems arise from this concept of extrusive lopoliths. Why are there no upper crusts of chilled basalt? Perhaps because in such a thick mass, volatiles moving upward in response to hydrostatic-pressure gradients would force crystallization from the base upwards while keeping the top molten for a long time. (And it should be stressed that roofs of chilled diabase, such as characterize differentiated sills, are similarly lacking.) Then how did molten rhyolite rise through molten basalt without mixing when laboratory work shows them to be miscible? Mixing need not accompany miscibility; salt water and fresh water long remain in sharp contact. Why did the early rhyolitic differentiates extrude as welded tuffs? . . . In the pictures emerging from work in the Bushveld, Duluth, and Wichita lopoliths of complex sequences of local intrusions of both mafic and felsic liquids, of new introductions of at least the mafic liquids, and of complex surges of separately-differentiating materials, it is already possible to see hazy answers for many such questions.

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