

Reports

Origin of the Sudbury Complex by Meteoritic Impact: Neodymium Isotopic Evidence

Abstract. *Samarium-neodymium isotopic data on whole rocks and minerals of the Sudbury Complex in Canada gave an igneous crystallization age of $1840 \pm 21 \times 10^6$ years. The initial epsilon neodymium values for 15 whole rocks are similar to those for average upper continental crust, falling on the crustal trend of neodymium isotopic evolution as defined by shales. The rare earth element concentration patterns of Sudbury rocks are also similar to upper crustal averages. These data suggest that the Sudbury Complex formed from melts generated in the upper crust and are consistent with a meteoritic impact.*

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The Sudbury geological structure in Ontario, Canada, may be the most profitable igneous rock body on this planet. The complex is the largest single supplier of nickel, although the original interest in

the Sudbury ore was in copper, which is found in equal abundance with nickel. In addition to nickel and copper, the Sudbury rocks have produced significant amounts of cobalt, platinum, palladium, iridium, osmium, rhodium, and ruthenium. The proposal that the Sudbury structure is an astrobleme, produced by the impact of a large meteorite (1), is still controversial (2). The impact could have caused fracturing in the crust and generated magma in the deep crust which then filled the impact-crater producing the rocks of the igneous complex. We de-

scribe new samarium-neodymium isotopic data on the Sudbury Complex that supports the impact hypothesis.

The nickel and copper found as sulfides, along with the platinum group of metals, are associated with a huge body of igneous rocks, collectively known as the Sudbury Igneous Complex. This complex is outlined at the surface as an elliptical ringlike structure, 60 km long by 27 km wide, elongated in an east-northeast direction (Fig. 1). To the north and west, the complex is surrounded by the Archean granitic and migmatitic rocks of the Superior Province. To the south and east, the country rocks are mainly Proterozoic metavolcanics and metasediments of the Huronian Supergroup and felsic plutons of similar age. Both the Superior Province and Proterozoic rocks in the vicinity of the Sudbury structure are commonly brecciated, with a pseudotachylitic matrix and shock metamorphic features. In general, the complex may be divided into two parts: a lower norite-gabbro rock body, beneath the base of which occur the nickel and copper ore deposits in the sublayer norite, and an upper granophyric rock, commonly referred to as micropegmatite. The outer margin of the complex generally dips inward at 30° to 50° producing a basin-like structure. The ore deposits occur along the margin of the basin and in radial dikes emplaced into the surrounding country rock. Ore deposits also occur in the fractured rocks that underlie the norite. These footwall breccias are characterized by very fine-grained recrystallization and shock-metamorphic features. The basal breccias have a great areal distribution peripheral to the Sudbury structure and may be part of it (2).

The Sudbury Complex is overlain by a sequence of 1800 m of heterogeneous breccias (3) collectively known as the Onaping Formation. This formation consists predominantly of pyroclastic-looking rocks composed of inhomogeneous, devitrified glasses, shocked country rock fragments, and sulfides. These rocks occur only within the Sudbury basin, where they are also intruded by the granophyres of the Sudbury Complex. The origin of the Onaping Formation is thought to be either meteorite-impact related or volcanic. The origin of this unit has an important bearing on the origin of the Sudbury structure (3).

We collected samples principally along two traverses (Fig. 1). The first followed highway 144 across the less-deformed northwestern side of the basin. The second was in the Blezard township of the South Range; the samples came from roadcuts of highway 69 in the uplift-

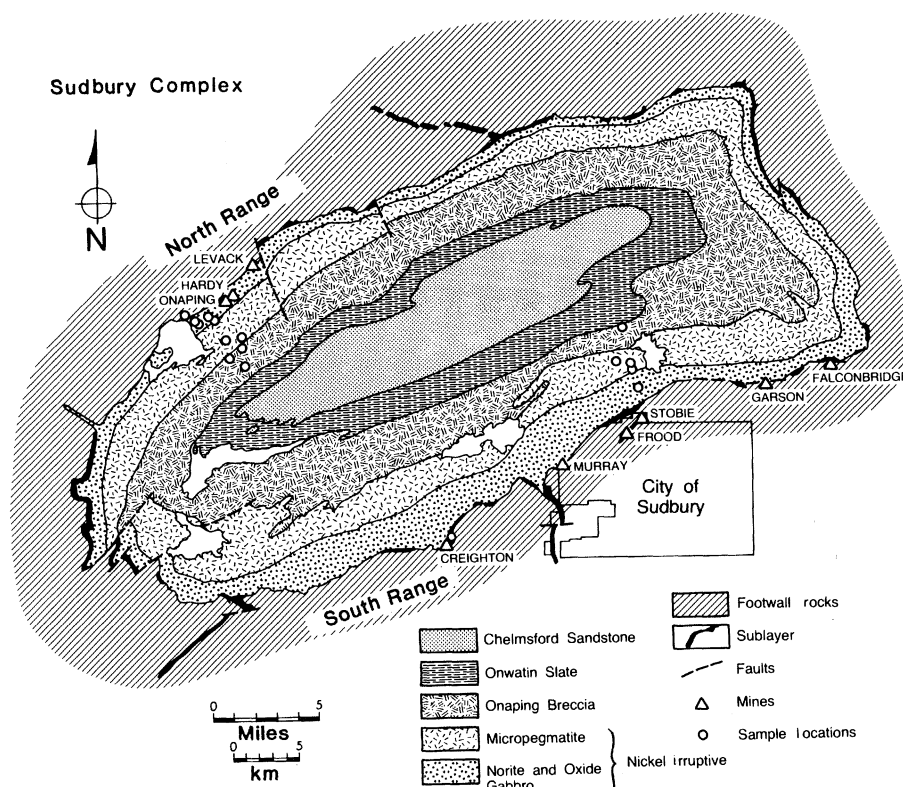


Fig. 1. Generalized geologic map, modified from Pye *et al.* (2), of the Sudbury Complex, showing locations of samples analyzed.

ed, more deformed, southeastern portion of the complex. Additional collections were made from near the Creighton township and along Fairbank Lake on the southern side of the complex. We analyzed the Sm and Nd concentrations and the Nd isotopic compositions of 16 whole-rock samples. Six mineral separates from three of these rocks were also analyzed (Table 1). The Sm and Nd concentrations for the whole rocks were high, 14 to 62 and 32 to 161 times those of the chondritic values for Sm and Nd, respectively. Of these, the sublayer quartz diorite is most enriched in the relative abundances of Sm and Nd, followed by the micropegmatite and the norite. These data support the rare earth element (REE) profiles of the Sudbury rocks (4) that showed the Sudbury Complex to be highly fractionated in the light REE compared to chondritic meteorites and to other mafic layered intrusions with which the Sudbury Complex is often compared.

Four whole-rock norites and six feldspar and pyroxene separates of three of these norites defined a Sm-Nd isochron age of 1840 ± 21 million years, with an initial ϵ_{Nd} ratio (5) of -7.54 ± 1.1 . This age is in excellent agreement with the U-Pb ages of zircons from the norites (6). The initial ϵ_{Nd} values at 1840 million years range from -6.98 for a norite to -8.83 in a quartz diorite sample from the sublayer, with the majority of the rocks at around -7 to -8 (Table 1). The Sm-Nd analyses of whole-rock samples of the sublayer, norite, and micropegmatite do not provide any meaningful isochron age because of the tight clustering of data points (Table 1) in the plot of the ratios $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 2). The whole-rock sample analyses of Onaping breccias also belong to this cluster. In comparison, the analysis of one Archean felspar-rich gneissic country rock, adjacent to the Sudbury Complex, shows distinctly different Sm-Nd isotope characteristics (sample 144-1 WR in Table 1), with an initial ϵ_{Nd} value of -11.5 at 1840 million years.

It has been suggested (8-10) that the melt that produced the rocks of the Sudbury Complex was subjected to contamination by the crustal rocks into which the melt was intruded. The mafic units of the complex contain far more silica than normal mafic rocks (7). The REE abundances throughout the complex are higher and more fractionated than those of other layered mafic igneous complexes (4). Furthermore, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the sublayer rocks are much higher than expected of typical mantle-derived melts (8-9). The oxygen-isotope

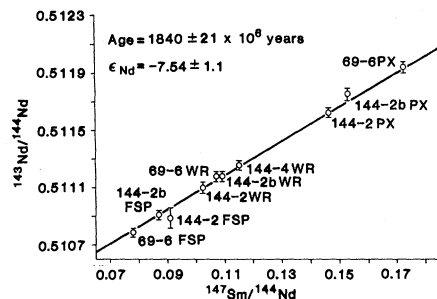


Fig. 2. Whole-rock and mineral isochron for the norites and their mineral separates. FSP, plagioclase feldspar; PX, both ortho- and clinopyroxene; and WR, whole-rock norite. Error bars represent 2σ for analytical error.

ratios of even the most mafic units of the complex are also more akin to those of crustal granitic rocks than rocks of mantle origin (10). The present Sm-Nd isotopic data further support the contention of contamination by crustal rocks. Indeed, the Nd-isotopic signature is overwhelmingly crustal.

Initial ϵ_{Nd} values of the whole rock samples were highly negative, with the quartz diorite of the sublayer showing the most negative value of -8.83 . Although negative ϵ_{Nd} values are not surprising for such rock units as the peripheral quartz diorite or the Onaping breccias, both of which would be expected to show extreme degrees of crustal contamination of an injected melt, such values for so mafic a unit as the norite are quite remarkable. It is difficult to account for such extremely negative ϵ_{Nd} values by way of crustal assimilation by a mantle-derived melt. Indeed, the Nd-isotopic data from all the units of the complex, including the acidic and the mafic types, are more akin to the surrounding country rocks than to the mantle beneath Sudbury.

The Sm-Nd model age (11-12) is the time in the past when major REE fractionation takes place in a rock during derivation from its ultimate parent, the undifferentiated mantle. The model age

Table 1. The Sm and Nd concentration and isotopic composition of Nd in Sudbury rocks and minerals including a migmatitic country rock; ϵ_{Nd} is calculated by the relation defined in (3) with bulk earth parameter from (23).

Sample*		Rock type	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}^\dagger$	ϵ_{Nd}	Model age (10^6 years)
144-2	WR	Norite	3.381	19.979	0.1021	0.51110 ± 2	-7.64	2.47
	FSP	Concentrate	1.452	9.633	0.0909	0.51089 ± 6		
	PX	Concentrate	4.465	30.453	0.1460	0.51163 ± 2		
144-2b	WR	Norite	3.657	20.262	0.1089	0.51118 ± 3	-7.69	2.52
	FSP	Concentrate	1.477	10.270	0.0868	0.51091 ± 3		
	PX	Concentrate	5.039	19.927	0.1524	0.51176 ± 4		
69-6	WR	Norite	2.657	24.760	0.1069	0.51118 ± 2	-7.21	2.47
	FSP	Concentrate	1.112	8.599	0.0780	0.51078 ± 2		
	PX	Concentrate	2.287	8.046	0.1716	0.51195 ± 4		
144-4	WR	Norite	6.905	36.383	0.1145	0.51126 ± 2	-7.46	2.55
144-7	WR	Gabbro				0.51143 ± 3		
144-10	WR	Micropegmatite	9.002	53.240	0.1020	0.51113 ± 2	-7.03	2.42
144-10b	WR	Micropegmatite	8.909	50.064	0.1074	0.51117 ± 2	-7.53	2.50
144-11	WR	Gabbro	6.322	34.642	0.1101	0.51118 ± 2	-7.98	2.56
144-12	WR	Grey Onaping	3.786	19.085	0.1197	0.51128 ± 2	-8.30	2.68
69-1	WR	Grey Onaping	5.007	26.816	0.1127	0.51126 ± 3	-7.02	2.49
69-2	WR	Gabbro	6.732	35.662	0.1139	0.51120 ± 3	-8.49	2.64
69-3	WR	Micropegmatite	10.076	58.634	0.1037	0.51116 ± 2	-6.84	2.41
69-4	WR	Gabbro	3.564	19.551	0.1100	0.51123 ± 3	-6.98	2.47
ST-2	WR	Quartz diorite	12.047	96.456	0.1244	0.51131 ± 2	-8.83	2.79
ST-11	WR	Melt rock	4.182	18.990	0.1329	0.51147 ± 2	-7.71	2.78
ST-18	WR	Black Onaping	4.490	24.458	0.1108	0.51123 ± 2	-7.16	2.49
144-1	WR	Migmatite (country rock)	1.026	7.127	0.0869	0.51072 ± 3	-11.47	2.65

*FSP, feldspar; PX, pyroxene; and WR, whole rock. $^\dagger^{143}\text{Nd}/^{144}\text{Nd}$ ratios are normalized to the $^{146}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219, and correspond to BCR-1 value of 0.51264. Measured blanks were 85 and 250 pg for Sm and Nd, respectively. Analytical errors in the estimation of Sm and Nd contents are 0.3 percent or less and those for the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are 2σ of the mean and correspond to the last figure. Model ages were computed from

$$T_{\text{model}} = \frac{1}{\lambda} \ln \left[1 + \frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{measured}} - 0.512638}{(^{147}\text{Sm}/^{144}\text{Nd})_{\text{measured}} - 0.1967} \right] \text{ where } \lambda = 6.54 \times 10^{-12} \text{ year}^{-1}.$$

is thus represented by the intersection of the rock-evolution curve with the chondritic mantle-evolution curve. This age has been calculated for each of the Sudbury rocks (Table 1). All the Sudbury rocks, including the migmatite country rock, define a narrow range in model ages of 2.56 ± 0.13 billion years. This model age is remarkably similar to the age of the metamorphosed volcanic and sedimentary rocks underlying the Sudbury structure. We suggest that these heterogeneous groups of rocks were melted by an impact event to produce the Sudbury magma or magmas which, in turn, underwent sulfide-rich magmatic segregations to generate the ores in the lower part of the complex (13). This proposal follows directly from these Nd-model ages, which indicate that the event that resulted in the divergence of the Archean crust of the Superior Province in Canada from the undifferentiated mantle growth-curve for Nd (11) is the same event that resulted in the Sudbury Complex. Thus the Sudbury Complex, in its entirety, seems to be of crustal origin.

The Sm and Nd concentration data (Table 1) are similar to concentrations of the REE's reported previously for Sudbury (4, 9). The different lithologic members of the complex show a strikingly similar pattern, although the absolute abundances of the REE's may vary widely. Figure 3 shows a chondrite-normalized plot of the REE abundances of the different rock units of the complex. The much steeper slope of the Sudbury samples in La-Yb ratios with respect to other mafic complexes and extrusive lava flows, such as Keweenaw and Columbia River basalts, has been noted previously (4, 14).

We compared (Fig. 3) the REE abundances of the Sudbury Complex with those of the average upper continental crust as represented by the North American Shale composite (NASC) and by the Peninsular Ranges Batholith mixture (15). There is a general consensus that the REE pattern of the NASC closely approximates the average concentration patterns for these elements in Phanerozoic upper continental crust (15-17). Other investigators (10, 16, 18-20) have shown that shales represent average sampling of large continental areas. In particular, the abundances of the REE in samples of shale are thought to represent the composition of their source area. Because the REE's, having low solubility in water, are not fractionated from each other during exogenous cycles (11, 16), they have been used to study the growth of continental crust through time (11, 21). The average Sudbury pattern is

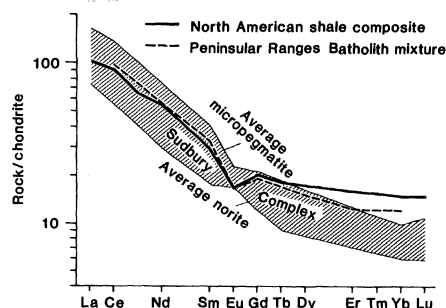


Fig. 3. Rare earth element concentrations, normalized to chondritic abundances, in Sudbury rocks, including average micropegmatite and norite. All other Sudbury rocks fall in the shaded region. The solid and dashed lines represent the North American shale composite and the Peninsular Ranges Batholith mixture (15). This diagram illustrates the similarity between the compositions of the Sudbury rocks and the average upper crustal rare earth elemental abundances. Data from (4, 9) and this study.

similar (Fig. 3) to NASC, with the exception of the heavy REE's. The comparison between the Sudbury and the Peninsular Ranges Batholith mixture of two granodiorites is better with respect to the heavy rare earths.

These comparisons indicate that the average REE composition of the Sudbury Complex is essentially that of the average upper continental crust. Minor discrepancies in the heavy rare earth contents might be due to the presence of heavy REE-bearing minor detrital miner-

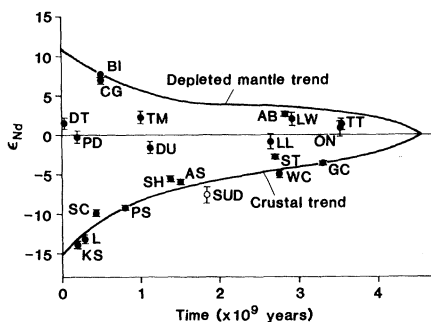


Fig. 4. The ϵ_{Nd} evolution in time with Nd evolutionary curves for the depleted mantle (13-24) and the crustal trend as defined by the Australian shales (21). The 15 Sudbury samples appear within the bar marked with SUD at 1840 million years, essentially on the crustal trend. The most striking aspect of the Sudbury data is the high negative ϵ_{Nd} values, unmatched by any other igneous rock body, and the strong correspondence with the crustal trend. GC, WC, AS, PS, SC, L, and KS are Australian shales of different ages (21); BI, Bay of Islands Complex; DT, Deccan Traps; PD, Palisade diabase; CG, Chunky Gneiss; TM, Town Mountain Granite; DU, Duluth Gabbro; SH, Shabogamo Gabbroic Complex; ST, Stillwater Complex; LL, Louis Lake Granodiorite; AB, Abitibi Belt; LW, Lewisian gneisses; ON, Onverwacht gneisses; and TT, Talga Talga gneisses.

als in NASC (14). Although the two composites in Fig. 3 have pronounced negative europium anomaly, the Sudbury rocks show either a small negative anomaly (5) or no anomaly at all (14). There is a suggestion that the REE patterns of Archean continental sediments, which are perhaps better representatives of the average Superior Province crustal composition near Sudbury, lack pronounced negative europium anomalies (18), and, as a group, may have slightly lower REE contents than post-Archean composites (19). Figure 3 shows the close correspondence between the average REE contents of the Sudbury Complex and those of the upper continental crust.

The comparison between the compositions of the Sudbury Complex and the average upper continental crust can be further extended using the Sm-Nd isotope analysis of Australian shales. Allegre and Rousseau (21) determined the Nd-isotopic composition in a series of Australian shales ranging from 0.2 to 3.3 billion years in geologic age. The initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of these shales decrease through geologic time, displaying a regular curve in ϵ_{Nd} as a function of time (Fig. 4), analogous to the "crustal trend" defined by granitic rocks (22). For comparison with this crustal trend, we also show the depleted mantle trend (23-24). The mantle trend (Fig. 4) is defined by various terrestrial igneous and meta-igneous rocks with high ϵ_{Nd} values, terminating at $\epsilon_{Nd} \approx 10$ for normal mid-ocean ridge basalts.

That the initial ϵ_{Nd} values of all 15 whole rocks at 1.84 billion years fall essentially on the crustal trend as defined by the Australian shales is remarkable. No other igneous rocks, except perhaps the Shabogamo Intrusive Suite of Labrador (25) fall near or below the crustal trend shown in Fig. 4. In other words, the Nd-isotopic signature of the entire Sudbury Complex, at the time of its formation, is indistinguishable from that of shales of the same age. Thus, with respect to the REE concentrations as well as the isotopic signature of Nd, the Sudbury Igneous Complex resembles early Proterozoic-late Archean continental crust.

In conclusion, the large negative initial ϵ_{Nd} values of the Sudbury Complex point to a crustal signature at the time of its origin. No direct mantle-derived component is apparently involved in the origin of this complex. A viable mechanism for producing such a voluminous melt of average upper crustal composition is a meteorite impact. This interpretation is also supported by previous observations

of impact features, such as shatter cones in the surrounding country rocks and shock lamellae within quartz and feldspar fragments of the Onaping Formation. Furthermore, the model Nd-ages of all the rocks analyzed in this study define a narrow range of 2.56 ± 0.13 billion years, similar in age to the early Proterozoic metavolcanic and metasedimentary rocks of the Huronian Supergroup and of the Archean Superior Province-style basement that underlies the Sudbury structure. We propose that this package of metavolcanic, metasedimentary, and plutonic rocks was melted by an impact event some 1840 million years ago to produce the Sudbury Complex.

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A Decline in Lead Transport by the Mississippi River

Abstract. Inputs of pollutant lead to the Gulf of Mexico from the Mississippi River have declined by about 40 percent within the past decade. This decrease has been determined from annual lead loads of the Mississippi River and from the lead record in Mississippi Delta sediments. The observed trend is consistent with reduced consumption of lead in gasoline in the United States. More than 90 percent of the riverborne lead is associated with suspended sediments. Most of this particle-bound lead is deposited within 50 kilometers of the river mouth and is not easily leached at pH values above 3.

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A decade has passed since regulations limiting lead additives in gasoline were put into effect in the United States (1). Already, several instances of decreased lead concentrations in the atmosphere, roadside soil, and human blood have been reported (2). To assess more completely the effectiveness of this costly regulation (1), we must identify and study systems that, by their size and importance, are useful indicators of contaminant transport. The Mississippi River system provides one such frame of reference because it drains more than 40 percent of the contiguous United States and carries more than half of the total sediment and water borne by U.S. rivers (3). Most of the Mississippi River burden of sediments and associated contaminants is deposited on the river's expansive delta. At present, the waters of this river and the sediments on its delta show a trend of declining lead inputs to the Gulf of Mexico.

Water, suspended particles, and bot-

tom sediments were collected from the Mississippi River and Delta (Fig. 1) during May and September 1982 and April and November 1983. These efforts complement our work from 1974 and 1975 (4). To optimize conditions for trace metal collection and analysis, we used a clean laboratory and clean sampling techniques at sea and ashore during both the 1974–75 and 1982–83 studies. Metal analyses of water, suspended matter, and sediment were by flame or flameless atomic absorption spectrophotometry (4, 5). Extreme care and attention to detail were practiced throughout the study (6).

In the Mississippi River, suspended particles play a primary role in lead transport because they typically carry more than 95 percent of the total river lead load. An exception to this trend occurs during the fall when levels of suspended matter often decrease from more than 200 mg/liter to less than 20 mg/liter, and then 80 percent or less of the total lead is particle-bound.

Lead concentrations for all suspended-matter samples ($n = 29$) collected at Head of Passes (Fig. 1) during 1982–83 were consistent at 32 ± 3 $\mu\text{g/g}$ (mean $\pm$ standard deviation) despite a range of values for total suspended matter (TSM) of 200 mg/liter during spring runoff to 20 mg/liter during late fall (7). This trend of spatial and seasonal uniformity in particulate lead concentrations is comparable to our previously reported Mississippi River data (4) and is primarily due to the

Fig. 1. Map of lower Mississippi River and Delta. (●) Station locations with numbers for sites referenced in text; (—) depth contours (in meters); (---) contours for vertically integrated sediment pollutant lead burdens (in micrograms of pollutant lead per square centimeter of sediment). Shaded portions indicate areas where integrated values for sediment pollutant lead are either greater than 1000 or 100 to 200 $\mu\text{g}/\text{cm}^2$. Gulf of Mexico map (inset) shows the study area (small rectangle).

