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Geological and Geographic Setting

David A.B. Pearson and J.Roger Pitblado

The Sudbury area lies near the southern edge of the Precambrian Canadian Shield, just north of Lake Huron (46°00'N–47°30'N; 79°30'N–81° 30'W) (Fig. 1.1) Although the rocks are old, the rugged landscape is young and dominated by rocky hills and ridges, rounded and scoured by glaciers. Lakes and rivers are plentiful and often lie in fractures or weak zones in the bedrock that were more easily eroded by the moving ice. A generally thin veneer of sandy glacial sediment covers the bedrock and supports a thin soil and widespread forest. The focus of geological as well as current economic interest is the Sudbury Basin (Fig. 1.2). It is a puzzling elliptical feature that many geologists believe was produced by a meteorite collision nearly 2 billion years ago. Nickel and copper ore has been mined for more than a century from more than 90 mines around the edge of the structure.

Prevailing winds have carried pollution from smelting over a wide area to the east and northeast, causing the damage to vegetation and lakes described in Chapters 2 and 3. Unfortunately, the bedrock and glacial sediment have contributed very little acid neutralizing capability to the lakes and soils affected by these emissions.

Sudbury Basin

Sudbury is the site of the largest known concentration of nickel on the surface of the planet. Nearly 20 million tons of the metal have either already been extracted or are known to be available in ore reserves. Only the Noril'sk deposits (Box 1.1) north of the Arctic Circle in central Siberia, with a known total of about 15 million tons, are in the same class as Sudbury (Naldrett 1994). Almost all the earth's nickel is concentrated in the core of the planet, and just a very tiny fraction is found in surface rocks. Only about two dozen significant deposits are known (Fig. 1.3).

The Sudbury ore deposits (Dressler et al. 1991) lie in sporadic pockets around the 150-km rim of what is widely known as the Sudbury Basin (see Fig. 1.2). Strictly speaking, geologists reserve this term for the low-lying ground, underlain by sandstone and slate, in the center of the structure. However, in this book, *Sudbury Basin* will be used for the geological structure as a whole. On the surface, the basin is enclosed by the once molten rocks of the Sudbury Igneous Complex. In cross section, the igneous rocks underlie or cradle the rocks of the basin like a spoon. It is an enigmatic feature, and even after 40 years of intensive study, it is not clear how it was formed. Several characteristics make it clear that it was the result of a violent event. Foremost is the enormous volume, estimated to be 1670 km^3 (Stevenson 1972), of breccia or welded broken rock (the Onaping Breccia) that forms a 1.6-km-thick blanket over the igneous rock within the basin. The fragments of the breccia are

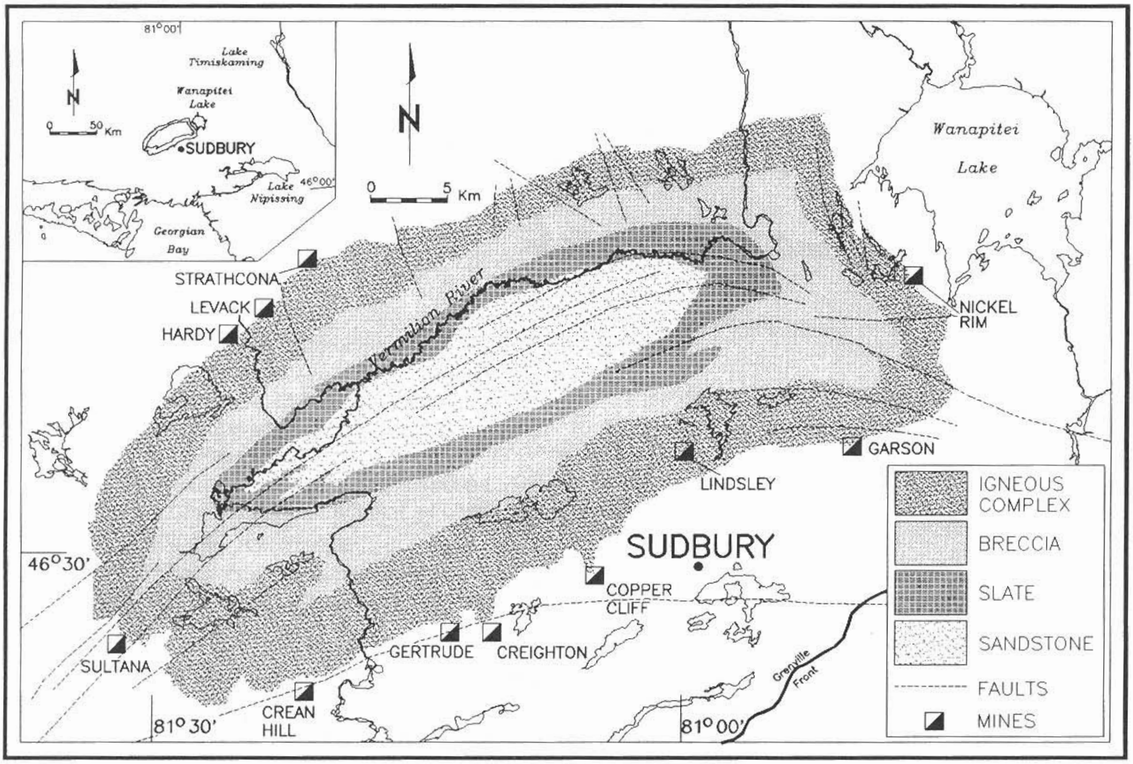

FIGURE 1.1. Generalized location map of the study area and geology of the Sudbury Basin.

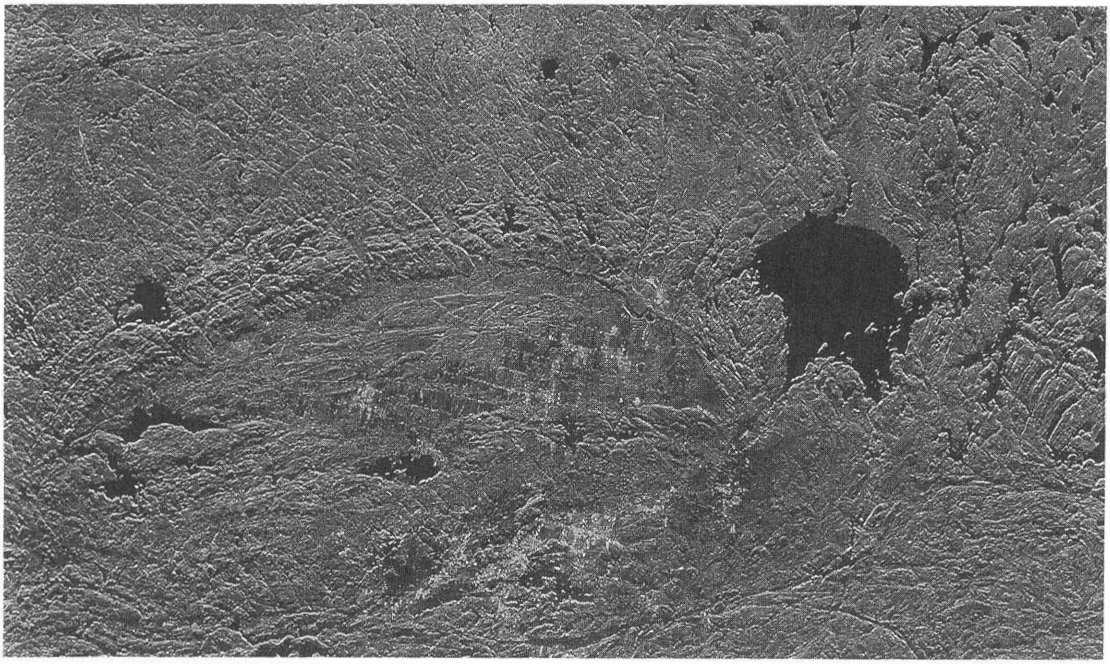

FIGURE 1.2. Radar image of the Sudbury Basin and Wanapitei Lake from 6000 m. (Courtesy of the Canada Centre for Remote Sensing.)

Box 1.1. Noril'sk: The Treasure of Siberia

Open-pit mine near Noril'sk (photo by P. Lightfoot, Ontario Geological Surveys). Noril'sk and Sudbury are the two great nickel sulfide deposits of the world. Also, Noril'sk stands, with deposits in Zimbabwe, as the predominant world resource site for platinum group metals. In relation to Sudbury ore, the Talnakh deposit from the Noril'sk area contains twice the nickel grade, four times the copper grade, and five times the platinum group element grade (Naldrett 1994). The other two areas of Russia where nickel is mined, smelted, and refined are the Kola Peninsula, near the Norwegian and Finnish border, and the middle and southern Urals. Like Noril'sk and Sudbury, the Kola Peninsula deposit is a sulfide ore. The Ural deposits are of the laterite type.

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considered to have fallen back to earth into a crater after either one or more volcanic explosions (Muir 1984) or after the impact of a 10-km-diameter meteorite (Grieve 1994). The explosive violence of this catastrophic event, whatever its cause, also shattered the rock around the crater, producing half-cone-shaped fractures called shatter cones (Fig. 1.4, Box 1.2) as well as open fissures that instantly filled with crushed fragments, now referred to as Sudbury Breccia. The igneous rocks forming the hilly rim of the Sudbury Basin are seen either as impact melt generated on the floor of the crater (Golightly 1994) or as a succession of molten intrusions that rose from lower in the crust at roughly the time the crater was produced (Naldrett and Hewins 1984). The ore is thought to have separated as hot sulfide droplets from the molten igneous rock on the crater floor. It is no longer thought, as was once suggested, to have been melted meteorite.

Age dating of the igneous rock has established that it crystallized about 1850 million years ago (Krogh et al. 1984). This is seen as a more or less accurate date for the origin of the basin as a whole.

The elliptical pattern of the outcrops is inherited from compressive forces that built mountains to the southwest of Sudbury after the structure was formed. Dislocation of the south side of the structure may have shoved it several tens of kilometers over what had been the center of the original crater, effectively halving its diameter (Milkereit et al. 1992).

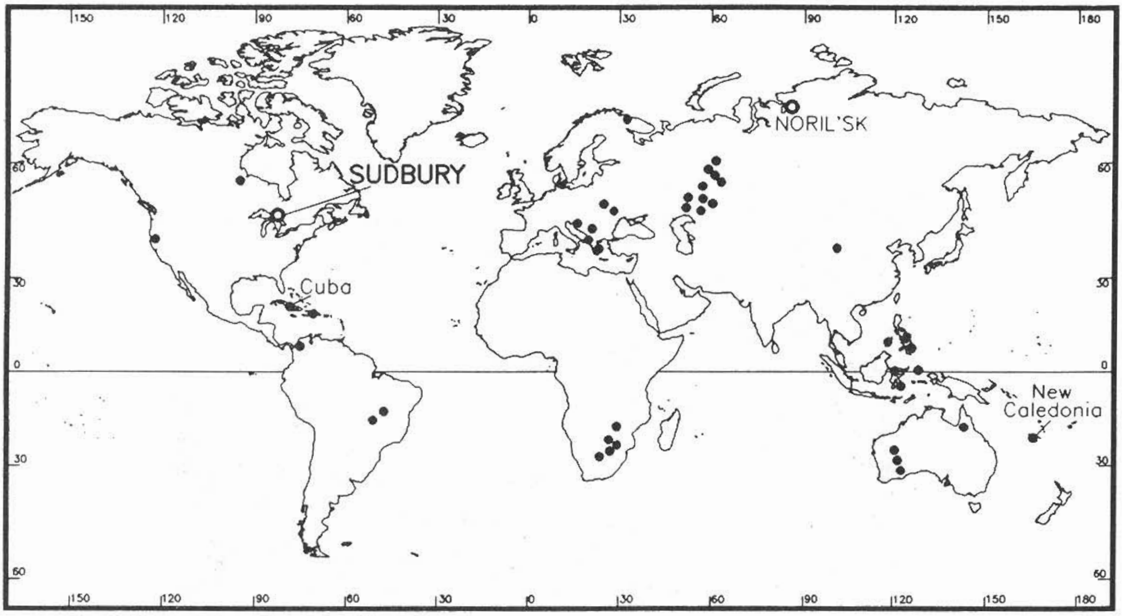
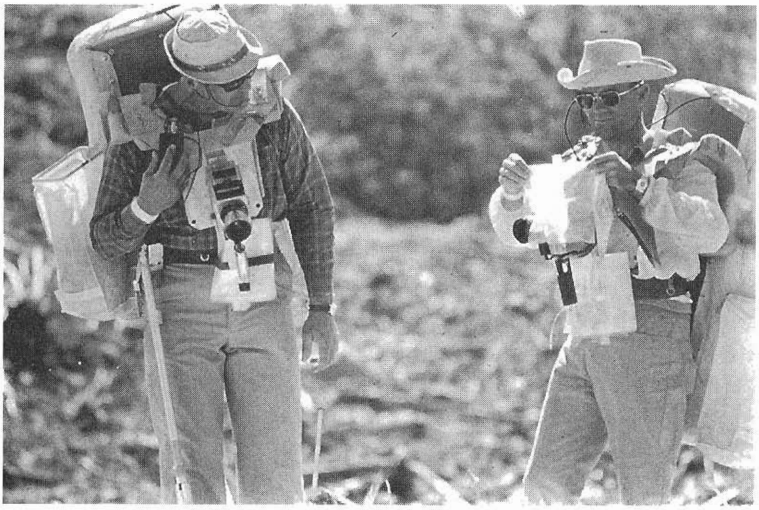


FIGURE 1.3. Nickel mining areas of the world. The two largest producing sites (>100,000 tonnes Ni/yr) are at Sudbury, Canada, and Noril'sk, Russia. At any one indicated site, there may be several individual mines.

FIGURE 1.4. Shatter cones in bedrock outside the southern edge of the Sudbury Basin. Most point toward the center of the basin and are thought to indicate the location of an extremely violent explosion. (Courtesy of Wilf Meyer.)

Box 1.2.



Apollo 16 astronauts Charles Duke and John Young visited Sudbury in July 1971, just a few months before walking on the moon. NASA's purpose was to have the astronauts practice describing the rocks and geological features in preparation for reporting on the geology of the moon. However, this was widely misunderstood by Sudburians still oversensitive to jokes about living in a "moonscape" and deliberately overlooked by outside commentators happy to find an easy target. The Apollo 17 crew, which included Harrison Schmitt, a geologist, also came to Sudbury a year later, but they left their packs behind. Instead of astronauts moonwalking, it was shatter cones (Fig. 1.4) that made the national television news!

Erosion has cut down at least 5 km, but recent seismic reflection work shows the floor of the Sudbury Basin is still between 10 and 15 km below the surface (Milkereit et al. 1992).

Sudbury Ore

Nickel and copper are the main products from the Sudbury ore, but cobalt, platinum, palladium, osmium, iridium, rhodium, ruthenium, gold, silver, selenium, and tellurium are significantly valuable byproducts as well as potential trace contributors to the geochemical environment. Also, zinc, lead, and arsenic are frequently present in trace amounts.

Almost all the minerals in the ore are sulfides, including the waste mineral pyrrhotite, an iron sulfide that dominates the ore, often to the extent of 80–90%. The nickel mineral pentlandite and copper-rich chalcopyrite make up the bulk of the remaining 10–20%. High-grade ore yields between 7 and 10% refined nickel and copper combined, with nickel usually predominating.

Ice and Landscape

A mere 12,000 years ago, the Sudbury area was buried beneath the Laurentide ice sheet, which covered most of Canada with 1–2 km of ice during the last Ice Age. This and several previous advances of ice stripped soil and overburden from the surface, deepened existing rock basins, gouged out many others, and forced the

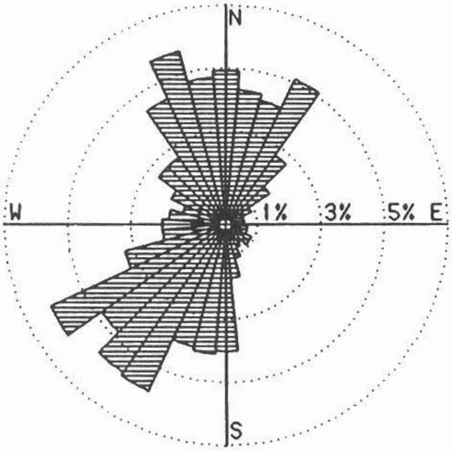


FIGURE 1.5. Frequency distributions shown as a rose diagram highlight the prevailing wind directions.

southward migration of plants and animals (Dredge and Cowan 1989; Trenhaile 1990).

The advancing ice created a bare bedrock surface, in places thinly plastered by a stony and sandy ground moraine (Boissonneau 1968; Burwasser 1979; Barnett 1992). Study of striations scratched into the bedrock and the dispersal of boulders of distinctive lithologies (Shilts 1989) has shown that the ice in Ontario moved toward the southwest or south.

Over the next 2000 years, the landscape was dramatically altered as the ice melted. Meltwater spilled out from the ice front in countless streams and rivers to form massive glacial lakes. One example is Lake Algonquin, which at one time occupied much of what is today Lake Huron and Georgian Bay. All of the area from the north rim of the Sudbury Basin southward was engulfed until the Mattawa-Ottawa river outlet became ice-free to the east. Locally, lakes formed, drained, and re-formed in response to the progressive lowering of post-Algonquin lakes and altering drainage patterns. It was at this time that massive amounts of ice-contact and glaciofluvial materials were deposited to the north and east of the Sudbury Basin. These included the eskers in the vicinity of Falconbridge and sand-gravel deposits to the north and south of Wanapitei Lake. Concurrently, clay and silt were deposited in great quantities in the proglacial lake that formed within the Sudbury Basin itself as well as along the outer margin of the southern basin rim.

Today, the majority of landscapes can be described as rock knobs or ridges of rolling, undulating, sometimes rugged topography of moderate elevation or relief. A wide variety of interesting landforms built from glacial deposits are interspersed. Low relief deposits of silt, silty clay, and organic terrains are scattered throughout the region. The most extensive level areas are the glacial lake and river sediments within the Sudbury Basin itself and, toward the east, parts of the sandy Lake Nipissing lowlands.

Climate

The Sudbury area is alternately buffeted by very cold-dry continental arctic, cool-dry continental polar, hot-dry continental tropical, and warm-moist maritime tropical air masses. The flow of these air masses generates prevailing wind directions from the north and southwest (Fig. 1.5). These prevailing winds have had a profound influence on where airborne pollutants have had an effect on terrestrial and aquatic ecosystems in the region.

The modified continental climate of the area is characterized by relatively long severe winters and short temperate summers. Based on 1951–1980 normals (Environment Canada 1982) for the Sudbury Airport climate station, mean daily minimum and maximum temperatures for the year are 1.6°C and 8.3°C, respectively. The average daily temperature in the month of January is –12.3°C, increasing to 19.8°C in July, the warmest month of the year. Precipitation is uniformly distributed throughout the year, although highest in the summer months. Over the 30-year period from 1951 to 1980, total precipitation has averaged 860 mm/year, with just less than 250 cm of snowfall annually.

Since 1895, the mean annual temperature for Canada has increased by 1.1°C (Gullett and Skinner 1992). Locally, although there have been great variations in monthly total precipitation, the mean monthly temperature shows little variation over the past 100 years. In the past few decades, however, the Sudbury climate has moderated, taking on more of the climatic characteristics associated with parts of southern Ontario.

Soils

With the retreat of the Laurentide ice sheet dated at only 9,000–10,000 years ago, relatively little time has passed for the development of mature mineral soils on the exposed bedrock outcrops. Well-drained to excessively drained shallow, stony, sandy soils, known as regosols, have accumulated in pockets of exposed rock knobs and ridges, in depressions, and along small stream valleys. Similarly, widespread but localized occurrences of poorly drained gleysols (formed when soils are saturated with water either continuously or for long periods during the year) and organic soils are important.

The dominant soil-forming process in the region is podzolization, a process in which organic acids form in the surface horizons, leach basic elements such as calcium, magnesium, iron, and aluminum from the upper layers, and then deposit them in soil horizons immediately below (Canada Soil Survey Committee 1978). Under a coniferous or mixed conifer-deciduous forest cover, this process is enhanced by the cool humid climate and the acidic parent materials produced by the silica-rich Precambrian bedrock. Podzols are very well defined on well-drained sandy tills of the area and are characterized by their dark organic surface layer, a white to ash-gray leached horizon immediately below, followed by yellowish-brown or reddish-brown subsoils.

Vegetation

It is tempting to suggest that today's vegetation (see Chapter 2) represents postglacial communities that followed a simple progression from tundra, to boreal, and finally to the current mixed coniferous-deciduous woodlands. Mounting evidence suggests that is not the case. Pollen analyses (Webb 1985; Gajewski 1988) in the midwest and eastern United States indicate that temperatures 6000 years ago were 1.5°C higher than at present, allowing for increased rates of soil formation and the expansion of temperate vegetation species well beyond their present-day ranges. But over the past 2000 years, there has been a long-term gradual cooling. The latter would permit an expansion of boreal elements at the expense of more-temperate tree species and similarly a decrease in the rates of soil formation.

Similar patterns have been found from pollen studies in Canada (Ritchie 1966, 1988). These indicate a southward extension of the boreal forest in the west and a significant increase in spruce in the transition zone between the boreal and temperate forest of southern Quebec. It is very unlikely that such changes in climate, rates of soil formation, and shifts in species distribution were not experienced as well in the Sudbury area.

Lakes

For both visitors and residents alike, one of the most striking features of the Canadian Shield is the enormous number of lakes that dot the landscape. It has been estimated that within the province of Ontario there are more that 226,000 lakes, and approximately 20,000 of these are within 100 km of Sudbury (Cox 1978). A good impression of the number and complex distribution of these lakes is provided in Figure 1.6. The landscape is strewn with lake basins controlled by bedrock faults and glacial

FIGURE 1.6. Principal lake patterns derived from a 1:250,000 scale topographic map.

scour, or areas of glacioloacustrine deposits (Sudbury Basin, Nipissing lowlands) virtually unoccupied by lakes. The principal exception is the largest of the lakes, Wanapitei, located in the center of the figure. This is a crater lake created 37 million years ago by meteorite impact (Grieve and Robertson 1987).

Geological Influence on Environmental Geochemistry

The chemical make-up of the bedrock and overlying glacial deposits, as well as processes of soil formation, are critical factors in the ability of aquatic and terrestrial ecosystems to withstand the effects of chemical pollutants. In the Sudbury area, several studies have investigated these relationships in ecosystems affected by acidic precipitation and heavy metals (Conroy and Keller 1976; Semkin and Kramer 1976; Griffith et al. 1984; Jeffries et al. 1984).

With regard to acidification, efforts have been made at a very general level to assess and map "sensitivity" to acidic precipitation (Shilts et al. 1981; Cowell, 1986). Sensitive areas are those in which the bedrock, overlying glacial material, and soil have little ability to neutralize or buffer the acid (Fig. 1.7). Buffering capacity is provided by minerals that accept protons (or hydrogen ions) from acid solutions. The minerals themselves may be dissolved in the process, as occurs with calcite (calcium carbonate), the main mineral of limestone, or they may be altered to another mineral in the case of fine-grained clay.

The most effective buffering is provided by either limestone bedrock or finely ground-up limestone in glacial drift. However, in the hinterland of Sudbury's smelters, limestone is rare. The only extensive outcrops are in the Hudson Bay lowland more than 500 km to the north. Although it is possible for material to be carried that far, Karrow and Geddes (1987) found that the carbonate content of glacial debris fell to less than 10% about 175 km north of Sudbury. Nevertheless, two local sources must be borne in mind: an outlier of limestone around Lake Timiskaming near the Ontario-Quebec border, and small outcrops of Precambrian limestone north of Wanapitei Lake. An example of the influence of the Lake Timiskaming outlier may well be elevated calcium and magnesium levels in near-neutral and alkaline lake

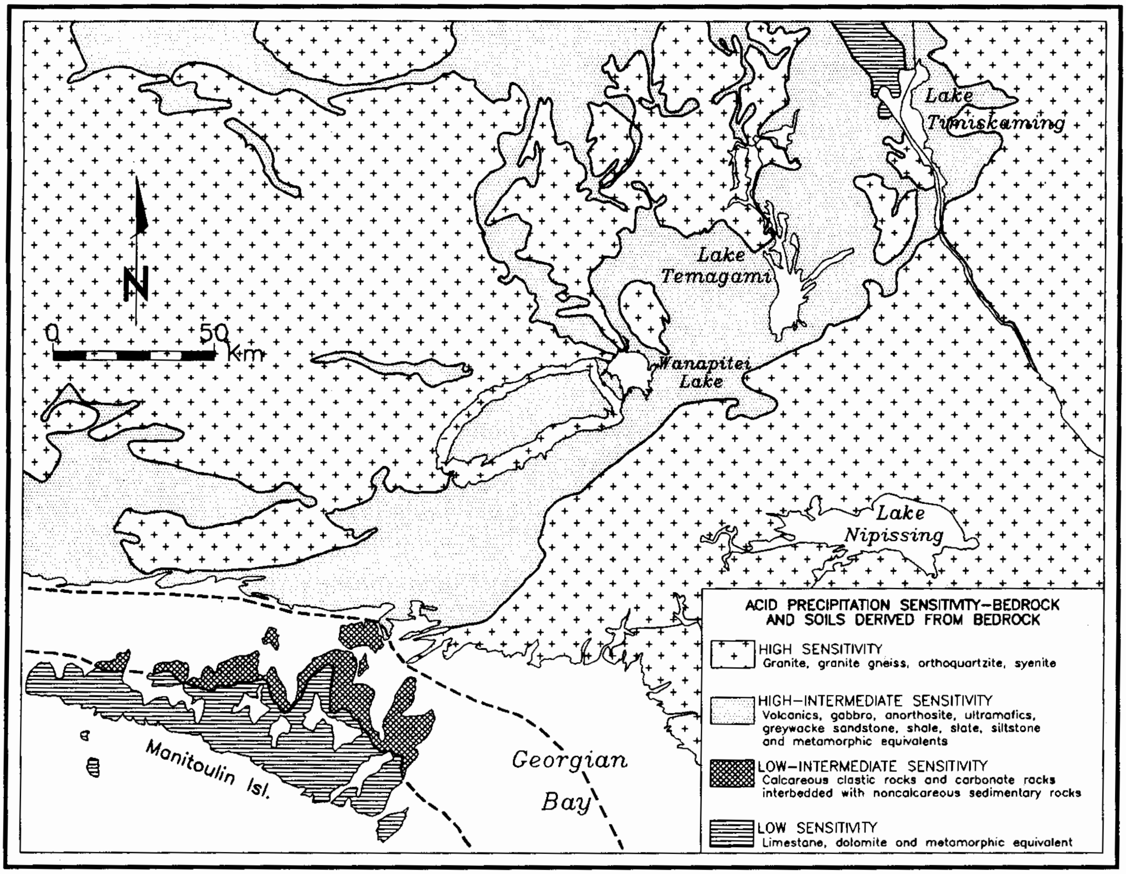


FIGURE 1.7. Sensitivity of bedrock and derived soils to acid precipitation (Shilts et al., 1981).

water in two areas 70 and 115 km north of Sudbury reported by Fortescue (1985). It is also possible that calcite or other carbonate minerals in veins cutting the bedrock may be responsible for surprisingly effective buffering (Drever and Hurcomb 1986).

Acidity is also counteracted by the ability of clay particles to capture hydrogen ions in exchange for other ions such as calcium or potassium. This mechanism may now be significantly effective in areas of former glacial lakes fed by muddy streams as the ice front melted back 9000 years ago. Lake Ramsey, in the shadow of the smelters in downtown Sudbury, may owe much of its remarkable resistance to acidification to the effectiveness of buffering by glacial clay. In small areas with more mature soils, the same mechanism is provided by aluminium and iron hydroxides.

On the whole, transported glacial debris has done little to modify the fundamental pattern of sensitivity produced by the bedrock. To the east, beyond what geologists call the Grenville Front, igneous and metamorphic rocks have produced quartz and feldspar-rich sand and silt. To the northeast, slightly less sensitive terrain is underlain by iron-rich igneous rocks and extensive beds of sandy and silty sedimentary rock. Some slight buffering capacity is provided by clay minerals.

Metal levels in surface environments are also influenced by bedrock. West of Sudbury, near Sault St. Marie, distinct geochemical signatures have been reported for granites, metamorphosed sediments, and two varieties of volcanic rocks. Copper, for example, was closely associated with iron-rich volcanic rocks and uranium with granites, whereas zinc and arsenic were related to the contact between sedimentary and iron-rich volcanic rocks (Fortescue and Vida 1989, 1990). Lake sediment surveys on metamorphic rocks south of Sudbury show regional bedrock-related chemical patterns in lead, zinc, uranium, and cobalt and also arsenic values strongly associated with fault zones (Easton 1992). These and many other examples well known in the literature on mineral exploration are important in the present context because of the potential for acidic water to release these minerals in toxic amounts into the environment. The toxic effect on vegetation of high levels of otherwise innocuous aluminium results from the doubling or tripling of the normal rate of rock weathering or decomposition produced by acid rain. Accelerated weathering also produces more carbon dioxide, which alters the atmosphere and feeds the greenhouse effect. It is a stark reminder that the rocks of the lithosphere, the plants and animals of the biosphere, and the gases of the atmosphere are delicately balanced. The rest of this book deals with understanding that balance, attempting to restore it, and learning to live in ways that protect it for future generations.

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