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SPECIAL ISSUE

Geology and mineralogy of the Meguma Group and their importance to environmental problems in Nova Scotia

Foreword

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The readers of this issue of Atlantic Geology may be surprised by the titles and content of the six papers included, and may wonder what some of them have to do with "environment"; hence the rationale for this introduction. Over the last few years the geological community at large has tended to compartmentalise, and somehow isolate, a discipline designated "Environmental Geology", to encompass geology as it relates directly to human activities. In the process the practice of this discipline has been delegated to geoscientists concerned with groundwater, Quaternary geology, and perhaps volcanology, seismicity and engineering geology, to geographers, and to biologists. Here, we attempt to show how the integration of traditional hard-rock geological information (including mineralogy, lithogeochemistry, structure, metamorphism, and some aspects of geophysics), and an understanding of sampling and analytical limitations, are not only useful, but essential, if we are to understand, and eventually prevent, some of the serious environmental problems that threaten society.

Environmental problems inherent to the Meguma Group

Land subsidence related to former mining in the Goldenville district as described by Hill *et al.* (*this issue*) is only one example of the environmental problems inherent to mineral wealth in the bedrock. The metasedimentary rocks of the Meguma Group that underlie approximately 125,000 km^2 of southern Nova Scotia, are Cambrian to Ordovician in age, and belong to the Meguma terrane, an exotic tectonic province of the Appalachian orogen of Atlantic Canada. The Meguma terrane is host to about 50 gold mining districts that have seen production for over 100 years that owe their metal enrichment to a particular set of sedimentary and diagenetic conditions (e.g., Graves and Zentilli, 1988b; Sangster, 1990; Waldron, 1992), as well as structural and metamorphic conditions during their history (e.g., Graves, 1976; Sangster, 1990). This geologic history makes the Meguma Group stand out as a gold metallotect in the Appalachian orogen, and also led to the formation of deposits of lead-zinc, tungsten, arsenic, tin, and manganese. But the 19th century Nova Scotia gold rush (Malcolm, 1929), and land subsidence and acid drainage related to mining do not constitute the sole nor the most important relationship between humans and geology in the region. In southern Nova Scotia, the most serious concern is that of acid rock drainage (ARD), a problem that is not limited to mining areas, but which extends to much more widespread activities such as highway and airport construction, and the digging of foundations and trenches for municipal services and pipelines (e.g., Pettipas, 1979). The use of slate for construction and the lining of wells, and the lowering of the water table in large regions due to water withdrawal or quarrying are other aspects of the same problem.

A world-class example of ARD is provided by the Halifax International Airport. The airport was built between 1955 and 1960, and to circumvent the fog, at the highest point in the region (145 m), hence in the divide between several drainage basins. The construction of the runways and taxiways disrupted and exposed to oxidation large volumes of sulphide-rich slate (Worgan, 1987). During the Fall following some years of heavy construction, severe fish kills occurred in the Shubenacadie River. It is now believed that sulphuric acid produced from sulphide oxidation was released into the watersheds surrounding the airport during heavy rainfalls, in general following prolonged dry spells. This acidic drainage had very low pH and increased levels of metals toxic to wildlife (e.g., Guilcher, 1987; Albright, 1987; Hennigar and Gibb; 1987; King and Hart, 1987; Lund, 1987; Lund *et al.*, 1987). Initial remedial costs during the 1980s were in excess of two million dollars, with substantial yearly costs since that time. Mitigating measures have included capping the waste rock pile with clay and topsoil, a lime treatment plant, the use of cellulose channels, bacteria and artificial wetlands, as well as experimental techniques such as electrochemical treatment (S. Hicks, Transport Canada, personal communication, 1996). And yet, to this day the airport and associated sites continue to discharge, sporadically, toxic, acidic drainage to brooks.

Several other dramatic cases of ARD and deterioration of water supplies have come to light in southern Nova Scotia. The paper by Fox *et al.* (*this issue*) describes similar ARD problems associated with highway roadcuts and quarries in southern Nova Scotia. A related and common problem in many localities is that of unsuitable, discolouring, iron-rich water from wells drilled into sulphidic slates, which requires expensive and persistent treatment for household or industrial use.

Although sulphides occur in all the known bedrock gold districts and throughout the stratigraphy of the Meguma Group, many of the more serious examples of ARD in southern Nova

Scotia seem to have a common denominator: they are underlain by the transition zone encompassing the uppermost Goldenville and lowermost Halifax Formations of the Meguma Group, often loosely referred to as the "GHT" (Zentilli *et al.*, 1984). The lower Meguma Group contains a thick package of dominantly sandy metawacke and grey to black metasiltstone (the Goldenville Formation) which is overlain by a thick sequence of black, dominantly silty metaturbidites and slates of the Halifax Formation (Schenk, 1983). The GHT was first described sedimentologically and stratigraphically in a type locality in southwestern Nova Scotia, where sandy and slaty facies alternate through a thickness of about 1 km (O'Brien, 1986; Waldron and Graves, 1987). Folding of the strata has caused the outcrop patterns of any sulphide-rich strata to be very complex and irregular.

The anomalous enrichment of sulphides and heavy metals (to several percent) in the GHT was documented at the mineral prospect near Eastville (Jenner, 1982; MacInnis, 1986; Binney *et al.*, 1986) and later lithochemically elsewhere in the Meguma terrane (Zentilli *et al.*, 1986; Graves and Zentilli, 1988a, 1988b). The GHT has anomalous and variable concentrations of manganese, arsenic, lead, zinc, copper, chromium and other toxic elements, and as could be expected, some of these elements are highly enriched in soils (>2000 ppm Pb at Eastville; Binney *et al.*, 1986), and ARD is derived from the anomalous bedrock. The paper by Feetham *et al.* (*this issue*) illustrates and updates the variable composition of the metalliferous metasedimentary rocks in a well studied locality of the GHT northeast of Halifax.

Sulphides are an important component of many of these strata, and when these sulphides oxidize, heavy metals are released in the ARD. But not all toxic elements are contained in sulphides. For example, manganese is accommodated in relatively soluble manganese carbonates, but also in silicates, such as spessartine garnets (Cameron, 1985; Hingston, 1985) and in manganese-rich ilmenite (MacInnis, 1986). As described in the paper by Cameron and Zentilli (*this issue*) zinc is also partitioned into silicates, depending on the regional and metamorphic history of each site. Therefore, a bulk chemical analysis is not sufficient to predict the potential toxicity of leachates derived from a rock, and the partition of zinc in metasedimentary rocks is influenced by contact metamorphism.

And yet the ARD problem at the Halifax International Airport is most definitely related to sulphides. Until recently the offending rocks have been described as "pyritiferous slates" (Nova Scotia Department of the Environment and Environment Canada joint "Guidelines for Development on Slates in Nova Scotia", April, 1991). Pyrite is in fact a mineral phase present in the GHT, but for some time hard-rock geoscientists have been aware of the fact that the prevalent sulphide in the sulphidic slates of the Meguma Group is not pyrite, but pyrrhotite (e.g., Jenner, 1982; Cameron, 1985; Hingston, 1985; MacInnis, 1986; Binney *et al.*, 1986; Pasava *et al.*, 1995; Knee, 1995). Pyrrhotite is responsible for a strong magnetic signature at Eastville (Burke, 1985) and competes with that induced by magnetite elsewhere (McGrath, 1970; Schwarz and McGrath, 1974; Schwarz and Broome, 1994). This point in particular is well documented in the paper by King (*this issue*) where the magnetic signature of the sulphidic strata is used for stratigraphic mapping in an area north of Halifax. Pyrrhotite may be more susceptible to rapid oxidation than pyrite (e.g., MacInnis *et al.*, 1994), both in inorganic reactions and with the involvement of bacteria (e.g., Jones, 1997; Jones and Fox, 1997). The paper by Fox *et al.* (*this issue*) discusses the specific problems related to oxidation of pyrrhotite, and emphasizes that in order to be able to predict the risk of ARD, it may be essential to know the spatial distribution of sulphides (e.g., in veins, in the cleavage, in stratiform lenses), their grain sizes, detailed mineral compositions, textures, and mineral associations. As an example, Haysom *et al.* (*this issue*) present the results of a study on mineralogy and its relationship to structural geology in the Rawdon-Beaverbank area.

As indicated above, sulphide occurrence and ARD risk in the Meguma Group are not restricted to the GHT zone, as its gold districts also contain pyrrhotite, pyrite, arsenopyrite, galena, spahlerite, and locally stibnite, and a wide range of associated trace elements. For descriptions of different aspects of the mineralogy of sulphides and geochemistry of gold deposits hosted by the Meguma Group, the reader is referred to papers by Graves and Zentilli (1982), Smith and Kontak (1990), and references therein.

Acid Rock Drainage (ARD)

ARD develops when water flows through areas where sulphide minerals are oxidizing. The resulting leachate typically has a low pH (between 2 and 4) and high concentration of metals (such as Al, Mn, and Fe), and trace elements (such as Cu, Ni, and Co). As an example, the characteristics of ARD leachate from a waste rock pile at the airport site are shown in Table 1.

Table 1 shows that ARD leachate can have 4 to 5 orders of magnitude more the acceptable concentration of some elements such as aluminum. Fish are respectively adversely affected at pH less than approximately 5.0 (Canadian Water Quality Guidelines, 1987), and metals, in particular aluminum, clog their gills to such an extent that they die of asphyxiation (Fromm, 1980).

As an example of the development of ARD, sulphuric acid is generated when pyrite (FeS_2) is exposed to oxygen and water. The overall process may be described by equation [1] (Bruynesteyn and Duncan, 1979),

$$4FeS_2 + 15O_2 + 14H_2O \Leftrightarrow 4Fe(OH)_3 + 8H_2SO_4 \quad [1]$$

which shows that one mole of pyrite (120 grams) will produce two moles (196 grams) of sulphuric acid. In nature, the chemical oxidation of pyrite is more complex than represented by equation [1] and can be described as a multi-staged process by the reactions below (Stumm and Morgan, 1981). These reactions remind us that oxidation is only an exchange of electrons, and does not require free oxygen to proceed:

$$FeS_2(s)+\frac{7}{2}O_2+H_2O \Leftrightarrow Fe^{2+}+2SO_4^{2-}+2H^+ \quad [2]$$

$$Fe^{2+}+\frac{1}{4}O_2+H^+ \Leftrightarrow Fe^{3+}+\frac{1}{2}H_2O \quad [3]$$

$$Fe^{3+}+3H_2O \Leftrightarrow Fe(OH)_3(s)+3H^+ \quad [4]$$

$$FeS_2(s)+14Fe^{3+}+8H_2O \Leftrightarrow 15Fe^{2+}+2SO_4^{2-}+16H^+ \quad [5]$$

Equation [2] shows that the oxidation of sulphide to sulphate releases dissolved ferrous iron (Fe^{2+}) and hydrogen ions (H^+) into solution, thus lowering the pH. Dissolved ferrous iron is oxidized to ferric iron (Fe^{3+}, equation [3]). Ferric iron hydrolyzes to form insoluble "ferric hydroxide", releasing more hydrogen ions into solution (equation [4]). Ferric iron can also be reduced by pyrite (equation [5]), where sulphide is again oxidized to sulphate and hydrogen ions are released along with additional ferrous iron. The cycle continues through equation [3] where ferrous iron is oxidized to ferric iron and is therefore self-sustaining, even in some environments devoid of oxygen, such as in some groundwaters.

Even after the generation of sulphuric acid, ARD will actually develop only if the minerals in the rock are unable to neutralize it. Many minerals such as calcium- and magnesium-bearing carbonates and silicates, and aluminum, calcium, and magnesium oxide and hydroxide minerals, have at least some ability to neutralize acid produced from the oxidation of sulphide minerals (Sherlock *et al.*, 1995). The net result between acid-producing and acid-consuming reactions will determine the overall quality of the leachate. Recently, Kwong and Ferguson (1997) have made some important observations regarding the short-term acid consuming ability of major rock-forming minerals: calcite and dolomite are the most efficient acid-neutralizing minerals, but silicates such as biotite, chlorite, and amphibole are also effective acid-neutralizers in the short-term (24 to 48 hours). Kwong and Ferguson (1997) also emphasized that acid-consuming ability depends on the variable chemical composition of these minerals, and the need for detailed mineralogical (and microprobe) data before ARD risk can be ascertained.

Conclusion

To be consistent with the goals of attaining a measure of sustainable development, defined by Bruntland (1987) as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs", the geoscientific community needs to focus on prevention of environmental accidents rather than reacting to them after they occur. The requirement of a precautionary or anticipatory approach (Precautionary Principle) is explicitly mentioned in the Nova Scotia Environment Act (SNS. 1994-95, c.1; Brown and Fox, 1997). Prevention will only be possible once the processes responsible for environmental degradation are fully understood. We consider that the geological studies presented in this issue are mere steps toward the understanding of environmental problems associated with the Meguma Group and similar geological areas elsewhere.

Table 1. Characteristics of ARD leachate compared to tolerance levels for aquatic life in freshwater (data from Canadian Water Quality Guidelines, 1987; Lund, 1987).

Airport waste rock pile leachate	Limits for freshwater aquatic life
Fe = 3800 mg/L	Fe = 0.3 mg/L
Al = 3247 mg/L	Al = 0.005 - 0.1 mg/L
SO_4 = 27000 mg/L	SO_4 = none
pH = 2.4 - 3.2	pH = 6.5 - 9.0

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