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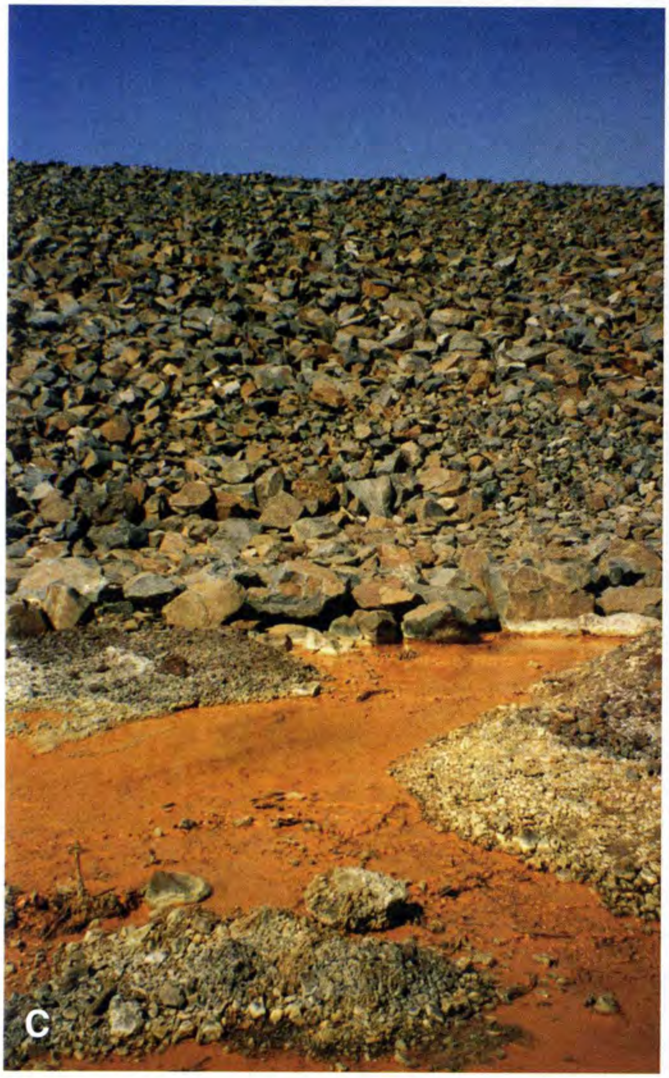
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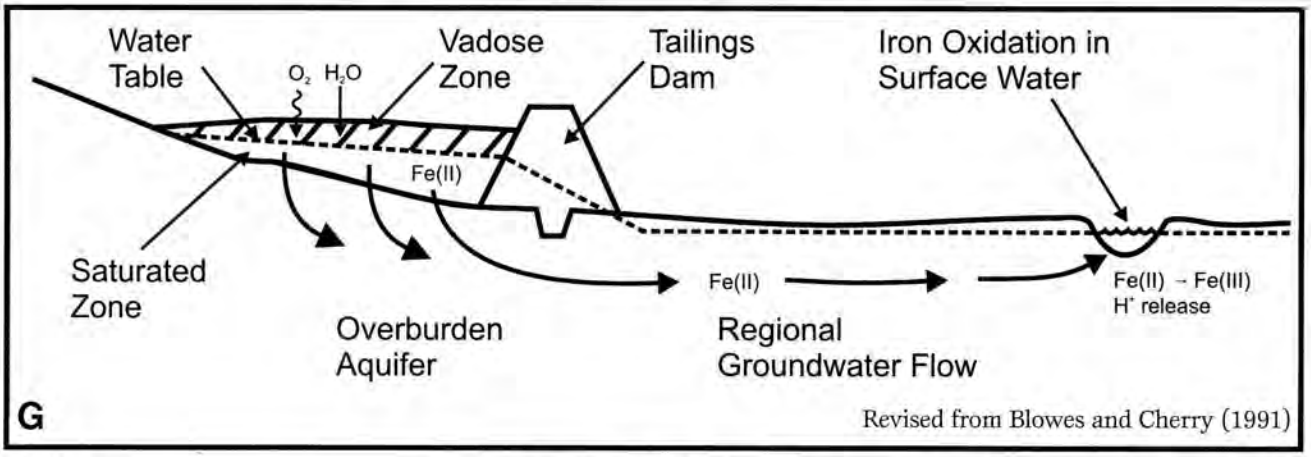
Acid Mine Drainage: Past, Present...Future?

Michael C. Moncur



Revised from Blowes and Cherry (1991)

Introduction

Canada is one of the world's leading producers of economic minerals. The mining of base and precious metals results in the production of immense quantities of waste rock, mill tailings, and waste related to refining processes. The generation of acid mine drainage (AMD) and release of water containing elevated concentrations of metals from mine wastes is an environmental problem of global scale. AMD is caused by the oxidation of sulfide minerals in the mine waste that occurs when these materials are exposed to atmospheric oxygen (O_2). This oxidation can continue to release acid and metals to the surrounding environment for decades to millennia (Moncur *et al.*, 2005).

The annual worldwide production of mine wastes exceeded 4.5 giga-tonnes in 1982 (ICOLD, 1996). The annual production of mine wastes in Canada was 650 million tonnes in 1991, adding to the billions of tonnes of waste already accumulated (Government of Canada, 1991). In the United States it is estimated that more than 22 000 km of streams and 180 000 acres of freshwater reservoirs are adversely affected by AMD which will eventually cost US taxpayers between $32 billion and $72 billion to remediate (Kleinmann *et al.*, 1991). In Canada, even though the mining industry spends over $100 million annually in the collection and treatment of mine effluent, estimates for the cleanup of existing AMD sites are between $2 and $5 billion (EMCBC, 2000). Estimated costs for remediating mine wastes internationally total in the tens of billions of dollars (Feasby *et al.*, 1991).

The ratio of economic and precious metals recovered to mine waste produced is very low. For example, the average grades of copper deposits in Canada are less than 1 %, meaning that for every tonne of copper produced 99 tonnes of waste material is generated (EMCBC, 2000). The wastes associated with gold mining provide additional examples on a scale most people will be familiar with. In order to extract enough gold for a typical wedding band about three tonnes of waste material will be generated (EMCBC, 2000).

History

There are documented accounts of environmental problems associated with mining that can be traced back

Cover: The impact of mine drainage on a lake after receiving effluent from an abandoned tailings impoundment for over 50 years.

A. Relatively fresh tailings in an impoundment.

B. The same tailings impoundments as in figure A after 7 years of sulfide oxidation. The white spots in figures A and B are gulls.

C. Mine effluent discharging from the bottom of a waste rock pile.

D. Shoreline of a pond receiving AMD showing massive accumulation of iron hydroxides on the pond bottom.

E. Precipitation of the secondary Fe mineral melanterite at a groundwater discharge zone in a tailings impoundment.

F. Heading out for water sampling at an acid mine lake.

G. Groundwater flow through a tailings impoundment and discharging into lakes or streams.

thousands of years. As early as 2750 BP descriptions of AMD were made by the Phoenicians of Southern Spain when they discovered a river the colour of red wine flowing into the blue waters of the Mediterranean Sea. The source of the red water was one of the world's largest sulfide deposits now known as the Rio Tinto Mine. Even in Greek and Roman times concerns about the environment effects of mine drainage were noted (InfoMine, 2005). The German physician Agricola Georgius expressed his concerns over the environmental impacts of mining in his book *De Re Metallica* (1556) and stated, "The strongest argument of the detractors is that the fields are devastated by mining operations... Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away… Thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces". While AMD is a more recent problem in North America, references to mine related impacts can be found as early as 1698 by G. Thomas. The long history of mining and mining wastes gives us some perspective for evaluating the potential longevity of the environmental impacts associated with mining activities. Recent studies of an ancient mining site in Southern Jordan have revealed elevated concentrations of metals in soils adjacent to the mine wastes despite 2000 years of weathering.

Sulfide Oxidation and the Generation of AMD

The principal environmental concerns related to mine wastes are the oxidation of sulfide minerals within the waste materials and the subsequent release of oxidation products to the adjacent groundwater and surface waters. The most common sulfide minerals in mine wastes are pyrite [FeS_2] and pyrrhotite [$Fe_{1-x}S$] both of which have little commercial value. For example, the oxidation of pyrite by atmospheric O_2 can by represented by:

$$(1)\qquad FeS_{2(s)} + \frac{7}{2}O_{2(g)} + H_2O_{(l)} \rightarrow Fe^{2+}{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 2H^+{}_{(aq)}$$

In reaction (1) when 1 mol of pyrite is oxidized, 1, 2 and 2 moles of Fe(II), SO_4 and acid are produced, respectively. The Fe(II) generated by reaction (1) can be further oxidized to form Fe(III), which under mildly acidic to near-neutral pH conditions, will precipitate as a ferric oxy-hydroxide:

$$(2)\qquad Fe^{2+}{}_{(aq)} + \frac{1}{4}O_{2(g)} + \frac{3}{2}H_2O_{(l)} \rightarrow FeOOH_{(s)} + 2H^+{}_{(aq)}$$

Under very low pH conditions ($pH < 3$), Fe(III) can remain in solution and react with the sulfide minerals through:

$$(3)\qquad FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \rightarrow 15Fe^{2+}{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 16H^+{}_{(aq)}$$

Reaction (3) indicates that for every mole of FeS_2 oxidized by Fe(III), 16 moles of acid are generated. In addition to the oxidation of pyrite and pyrrhotite, the oxidation of other sulfide minerals that may be associated with the mine wastes, including chalcopyrite [CuFeS2], sphalerite [ZnS], galena [PbS], and arsenopyrite [FeAsS] may also occur. The acidity released from the sulfide oxidation reactions is of concern because the low-pH solutions increase the solubility of potentially toxic trace metals and semimetals such as Pb, Zn, Cu, Cd, Cr, Co, Ni, Al, Sb, and As, making them more mobile. In dissolved form, metals are more readily absorbed and accumulated by plant and animal life and therefore more toxic than they are in solid phase (EMCBC, 2000). The uptake and accumulation of metal by aquatic life can be passed along the food chain and may also damage subaqueous and subareial habitats. In trace amounts, metals are essential for life, however, in high concentration they can be very toxic.

Acid Neutralization Reactions

The acid produced through the oxidation of sulfide minerals reactions can be neutralized along the groundwater flow path through reaction with gangue minerals incorporated in the mine wastes. Example gangue minerals which can contribute to acid neutralizing reactions include carbonate minerals and aluminosilicate mineral phases. Dissolution of these gangue minerals typically leads to a distinct sequence of pH-buffering plateaus (Blowes et al., 2003). The final composition of pore waters in a mine waste pile will depend on the composition and abundances of the sulfide minerals and the composition and abundances of the gangue minerals. The ratios of the various phases and reaction rates will determine whether a waste pile will be acid generating or remain neutral over time.

Ore and country rock typically contain carbonate minerals such as calcite [$CaCO_3$], dolomite [$CaMg(CO_3)_2$] and ankerite [$Ca(Fe,Mg, Mn)(CO_3)_2$]. In the early stages of sulfide oxidation, the dissolution of carbonate minerals, such as calcite, results in maintaining the pH of the pore water near neutral (pH 6.5-7.5) through:

$$(4)\qquad CaCO_{3(s)} + H^+{}_{(aq)} \leftrightarrows Ca^{2+}{}_{(aq)} + HCO^-_{3(aq)}$$

In reaction (4) the dissolution of one mole of calcite results in the consumption of one mole of acid. The pH of the pore water will remain neutral providing that there is a sufficient mass of primary carbonate minerals remaining in the mine wastes (tailings and waste rock). As calcite is depleted the pore water pH decreases until a mineral with a lower solubility, siderite [$FeCO_3$], forms the next pH buffering plateau:

$$(5)\qquad FeCO_{3(s)} + H^+{}_{(aq)} \leftrightarrows Fe^{2+}{}_{(aq)} + HCO_{3(aq)}$$

The dissolution of siderite will buffer the pore water between a pH of 4.8 to 6.3. As the dissolution of carbonate minerals occur, the dissolution of the most soluble aluminosilicate minerals (eg. biotite $[K(Fe)_3[AlSi_3O10(OH)_2])$ may release dissolved aluminium to the pore water and precipitate as gibbsite $[Al(OH)_3]$ or another Al hydroxide mineral phase:

(6) $Al(OH)_{3(s)} + 3H^{+}_{(aq)} \leftrightarrows Al^{3+}3H_2O_{(s)}$

When siderite has become depleted, the dissolution of gibbsite will maintain the pore water pH between 4.0 to 4.3. Upon the dissolution of of the Al hydroxide phase, the dissolution of Fe oxyhydroxides will be the primary buffering mineral maintaining the pore water pH between 2.5 and 3.5:

(7) $FeOOH_{(s)} + 3H^{+}_{(aq)} \leftrightarrows Fe^{3+}_{(aq)} + H_2O_{(l)}$

After the depletion of the carbonate minerals, soluble Al hydroxides and Fe oxyhydroxides has occurred, the dissolution of aluminosilicates becomes the primary process contributing to acid neutralization.

Tailings impoundments

Mine tailings are the fine-grained material (clay sized to medium sand) that remains after the ore extraction process. The surface area of tailings impoundments can range in area from a few ha to several km and from 2 to 50 m in depth. The tailings are typically deposited into an impoundment as a slurry with up to 30 wt.% solids. After the tailings disposal is complete, the water table within the impoundment falls to an equilibrium position controlled by the rate of precipitation, evapotransperation, and hydraulic properties of the tailings and underlying geologic materials (Blowes *et al.*, 2003). The drainage of the tailings enhances their structural stability but also leads to sulfide oxidation within the unsaturated zone (vadose zone). The atmospheric O_2 which diffuses into the vadose zone reacts with the sulfide minerals within the tailings, releasing acid, Fe^{2+} and metals to the adjacent pore waters. Metal laden water affected by the sulfide oxidation reactions in the tailings is gradually displaced downward through the impoundment into the underlying geological materials by the infiltration of rain water. Ferrous iron is relatively soluble and the water flowing through the tailings commonly contains elevated concentrations of Fe^{2+} (Blowes and Cherry, 1991). The Fe^{2+}-rich groundwater may travel along groundwater flow paths for years to decades before discharging to lakes or streams. This change from reducing to oxidizing conditions at the freshwater interface will result in the oxidation of Fe^{2+} and the subsequent precipitation as an oxy-hydroxide (equation 2) generating acidic conditions which could have large impacts on aquatic life.

Waste Rock Piles

The term waste rock is used to describe the coarse grained component of mine waste and includes rock that cannot be processed economically ranging in size from fine-grain sands to blocks several meters in diameter. Waste rock piles range in height from 30-500 m and can cover several kilometres in area (Blowes *et al.*, 2003). As with mine tailings the oxidation of sulfide and subsequent generation of acid is the greatest environmental concern associated with waste rock piles, however, there are a couple of key differences between the two types of waste. Due to the coarse nature of the waste rock, the rock piles tend to have very high permeabilities allowing the penetration of large volumes of atmospheric O_2 which promotes sulfide oxidation. In addition to increased penetration of O_2 because of high permeabilities, very high temperatures within waste rock piles (e.g. in excess of 60°C) can further induce oxidation reactions. Waste rock piles were often constructed on permeable geologic material; acid and metals released to the pore water can be displaced downwards into the underlying geologic material by infiltrating precipitation.

Remediation and Prevention

There are a number of approaches to prevent and treat the degradation of groundwater and surface water from mining effluent. Among the various remediation strategies to treat AMD are the emplacement of covers to prevent the ingress of atmospheric O_2 and infiltration of precipitation, collection and treatment of the contaminated groundwater and surface water, passive treatment of surface water using constructed wetlands, and permeable reactive barriers to treat the groundwater in-situ.

Immediately after the tailings or waste rock has been deposited, the first approach is to control the entry of atmospheric O_2 and infiltrating water. This approach involves the addition of a cover over the mine wastes. Physical barriers that have been applied or proposed include water covers, soil covers of fine-grain material to maintain high moisture content, covers composed of organic materials, or the emplacement of a synthetic cover such as plastic, asphalt, or concrete. Covers also contain the tailings and waste rock preventing erosion by wind and water. To be most effective, covers must be applied either at the time that mine-waste deposition ceases or shortly thereafter because the rate of sulfide oxidation is greatest immediately after the mine waste is deposited (Blowes *et al.*, 2003).

Collection and treatment involves collecting the mine effluent and treating the contaminated water prior to discharge from the mine site. This method of remediation is common and used at many mine sites in North America. For this method of treatment, the pH is neutralized through the addition of lime, with the subsequent precipitation of metal as a ferric hydroxide sludge. However, the cost of maintenance of these facilities is large and the disposal of the metal laden sludge produced from the treatment is an environmental concern.

Constructed wetlands perform as a passive water treatment facility. Contaminated mine effluent is directed into the wetland where metals are scavenged and the pH is increased through a combination of bioaccumulation reactions and sulfate reduction. This method of remediation has demonstrated to be efficient and effective but it is not known how long the wetland will remain stable over long periods of time or if the wetland will withstand the metal loadings.

Permeable reactive barriers are used to treat and prevent contaminated groundwater from mine sites that has infiltrated into underlying or adjacent aquifers. A trench is excavated through a portion of the aquifer down gradient from the mine disposal area. The trench is then filled with a permeable material composed of reactive components such as composted municipal wastes, wood wastes, by-products from pulp-and-paper manufacturing, zero valent iron, limestone, and phosphate based absorbent materials (Blowes et al., 2003). The reactive mixtures are designed to promote the bacterially mediated reduction of sulfate and precipitation of metals. Permeable reactive barriers have advantages over the conventional approaches for groundwater remediation because succeeding installation, the barrier requires little or no maintenance and its performance can persist for several years to decades.

Conclusions

Although metals are essential for life and our current standard of living, the waste produced from the extraction of the metals may contain an abundance of sulfide minerals. The oxidation of sulfide minerals from the exposure to atmospheric O_2 results in the generation and release of acid, Fe(II) and potentially toxic metals. Oxidation products transported from the mine site can discharge to streams and lakes having a negative impact on the water quality. Over the past few decades advancements in remediation technologies to prevent AMD are being applied to past and present mining operations thereby decreasing the impact to the surrounding environment. The next time you decide to dispose of an aluminium can, scrap iron, copper tubing, old car battery, or any other metal in the garbage instead of the appropriate recycling depository, think of the impact you my be causing not only to the environment but also to the economy.

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Interesting Stuff!

Several information guides have appeared aimed at the public at large and with a special emphasis on children and it seems appropriate to provide a brief description of each in this issue.

The first of these is a compact but detailed booklet about everything you wanted to know on diamonds.

Entitled "**Canada's Northern Diamonds ...from rocks to riches**" the lavishly illustrated (over 200 images) small book focuses on the recent major discoveries in Canada's north and relates them to what is happening on the world scene. The book describes the origins of diamonds and follows each stage of the production sequence right from the initial field work through to the final stages as jewelry.

The book is easy to read and should appeal to all ages. As far as diamonds are concerned, the friendly layout, timelines, foldouts and a map helps anyone from student (~ Gr 3) to adult audiences understand what is happening, as well as where and how it happens.

This 46 page book is written by Gayla Meredith, an award winning northern educator and is in paperback format, coil bound. The cost is $22.95 and the ISBN 0-9735581-0-5

The second is an illustrated fold-out laminate entitled "**A Field Guide to the Identification of Pebbles**". By Eileen Van der Flier-Keller, of the Geography Department at the University of Victoria. The guide is available in laminated version (ideal for drizzly rain conditions on beaches on the west coast). Inside the guide commences with a brief overview of what rocks are and where pebbles come from. This is followed by beautifully illustrated examples of igneous, sedimentary and metamorphic pebbles as well as "Other Neat Stuff". The last part of the foldout covers information on how minerals are used.

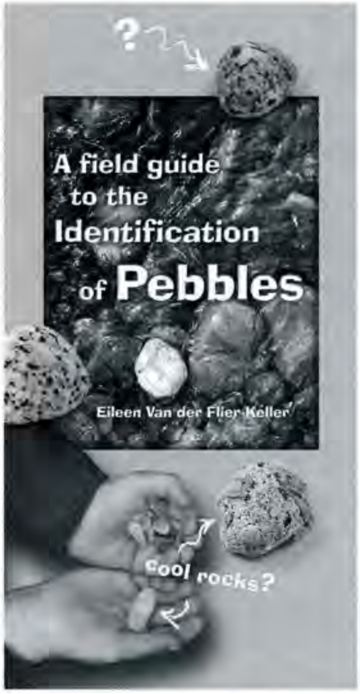
This guide will help parents (and teachers) when children bring in interestingly-coloured or patterned rocks, especially if they have been picked up on beaches, and ask the usual, inevitable, questions; What's this and how was it formed?

The photographic illustrations of the various pebbles are excellent and they will help you narrow your search whether you live on the west coast or elsewhere.

A Field Guide to the Identification of Pebbles is available from:

SEOS, University of Victoria, P.O. Box 3055, Victoria, V8W 3P6 (Phone) – (250)-472-4019.

The cost is $10.00 for the laminated guide. Mailing is extra.



INSIDE THIS ISSUE

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Graphite

This carpenters pencil is the oldest known pencil in existence. It was found in the roof of a 17th-century German house, and is part of the Faber-Castell private collection.

Graphite is an opaque, non-metallic carbon polymorph that is blackish silver in colour and metallic to dull in sheen. Since it resembles the metal lead, it also known colloquially as black lead or plumbago.

Formation of Graphite

Graphite is most often found as flakes or crystalline layers in metamorphic rocks such as marble, schists and gneisses. Graphite may also be found in organic-rich shales and coal beds. In these cases, the graphite itself probably resulted from metamorphosis of dead plant and animal matter. Graphite is also found in veins and sometimes in basalt. Graphite also occurs in meteorites.

Molecular structure of Graphite

Graphite consists of a ring of six carbon atoms closely bonded together hexagonally in widely spaced layers. The bonds within the layers are strong but the bonds between the layers are less in number and therefore weaker. Graphite is therefore soft and flakes easily. Graphite is the stable form of carbon - diamonds at or near the Earth's surface are gradually changing to graphite. Fortunately this process is extremely slow.

Differences between Graphite and its Carbon Polymorph, Diamonds

Diamond is another carbon polymorph; although composed of the element carbon, like graphite, diamond does not have much else in common. Each has a lot of contrasting properties. For instance, diamond is the hardest mineral, but graphite is one of the softest. Diamond is usually transparent, but graphite is opaque. Also, diamond is often used as an abrasive, whereas graphite makes a good lubricant. Graphite is an excellent conductor of electricity, while diamond makes a good electrical insulator.

Uses of Graphite

Named in 1789 by the German chemist and mineralogist A.G. Werner, the name for graphite is derived from the Greek word, graphein, which means: to write. The name therefore denotes the primary use of graphite as an ingredient used to make the lead for writing pencils. Other uses of graphite include:

Additive in ceramics

Aerospace: Rocket Nozzles, Stealth F-117A and B2 bomber aircraft

Baseball Bats: (graphite and kevlar composite)

Canisters & Aluminum Extrusion Boards

Chemical: Vessels and Reactors, Bushings, Bearings, Packing Rings, Seals, and Rollers

Electrical, Electrochemical, Electronic, Electrodes, Semiconductor: Brushes, Anodes, Cathodes, Current Collectors, Sliding Contacts, EDM Electrodes

Fluxing (Degassing) Tubes, Molds, Dies, Furnace Parts, Foundry Accessories

Graphite electrodes

Guides, Valves, Rotors & Vanes

Lubricant

Metallurgical Crucibles

Nuclear: High Purity Structural Components, Reflectors, Moderators

Resistors, Brazing Tips, Heaters, Seed Holders

Hardener in steel making

History of the Pencil

Graphite was first discovered in Cumbria in North England at the beginning of the sixteenth century. Although it resembled coal, it would not burn. It did, however, prove to be an excellent marker of sheepskins.

The government of England took charge of the mining operations of graphite when it was discovered that it also served as an excellent mould for cannonball production. As such, the value of graphite increased dramatically in a short period of time. During the reign of Queen Elizabeth I, graphite was transported to the capital under cover of the local guard.

Dubbed 'Wad' by the locals, graphite soon became a precious commodity. In 1752, the government made the stealing and trade of stolen graphite a criminal offense, punishable by hard labour or transportation.

The first documented use of graphite as a pencil occurred in 1565. The use of graphite as an art material became popular, sold by Flemish merchants throughout Europe. At first, pencils consisted of rough pieces of graphite wrapped in sheepskin. The Italians first began using pencils that consisted of pieces of graphite embedded in wood.

In the early days of pencil making, a small cottage industry started in Keswick, England making artists' pencils. These were all made by hand and the method was briefly as follows:

A piece of Cumberland Graphite was cut into slabs. A square groove was then carved into a piece of wood. The slab of graphite was inserted in the groove; the graphite was then broken off, so that it was level with the top of the groove; a thin slat of wood covered the graphite, leaving the graphite encased.

This wood was shaped by hand-plane and the shape of the knife in the plane determined the shape of the pencil, round, oval, etc., and all this work was carried out by hand. Later, small primitive types of lathes were introduced which were foot-operated with a treadle similar to a treadle sewing machine and all the shaping was done in this manner. All the pencils were hand-made; many families in Keswick made these pencils in their cottages, the origin of the pencil industry.

In the mid-eighteenth century, the relationship between Britain and France deteriorated. As a result, supplies of graphite from England to France dried up. In 1795, the French artist Conte discovered that graphite could be mixed with clay to produce pencils with varying degrees of hardness. In the mid-1830s, the pencil making industry in Keswick had started to set up factories; it turned more and more to the use of powdered graphite mixed with powdered clay to make pencils.

Graphite Mines

Plumbago Mine, Borrowdale, England:

This mine was famous for producing graphite that did not come from bedded shales or embedded in rock but was associated with an igneous intrusion connected to a hydrothermal vein that contained wads of graphite along it. The mineral was found along a 400 m stretch of the vein in lumps and nodules. A market for it opened up around the end of the sixteenth century. German miners from Keswick in the early sixteenth century had made more progress mining the graphite from the site.

Lots of graphite could be mined in a short period of time with little expense so in order to maintain the sale value of the graphite, the owners of the mine agreed not to reopen it for a certain period of time. As a result, stealing of graphite, or "wad" as they called it at the time, became quite common. For that reason, a security lodge was built outside the upper part of the mine, with an armed guard to keep watch over the mine day and night. In the 1760s, the mine briefly reopened but only eight workmen were chosen to mine it. Several times each day the miner's pockets were checked by six different overseers, to make sure that they were not stealing any wad while mining it.

In 1800, the Grand Pipe was finally dewatered, which opened other parts of the mine, which could be used for the extraction of graphite. Workmen continued to mine the cave for graphite and three year later, their efforts were rewarded by the surprisingly late discovery of a large accumulation of wad known as Dixon's Pipe.

First Graphite Mine in Canada

Canada's first graphite mine was the Miller (Keystone) mine, Grenville, Quebec.

Graphite from Ontario

Graphite is found primarily among the rocks of the Precambrian Grenville Province of Eastern Ontario.

In 1889 graphite was discovered on the shore of Whitefish Lake, Renfrew County. This later became Ontario's richest graphite mine, the Black Donald Mine. The graphite mine location is now under the waters of Black Donald Lake. People may visit the town site by scuba diving.

Graphite was mined at the National Graphite Mine, Graphite, Monteagle Township, near Bancroft. The mine operated from 1912 to 1919.

Graphite spheres embedded in crystalline calcite were found exposed by a roadcut on Haliburton County road about 3.6 km south of Gooderham, Ontario, Canada.

Graphite from Mine in Cesky Krumlov:

The mine in Cesky Krumlov was first discovered around 500 BC in Southern Bohemia in the outskirts of the small village of Cesky Krumlov. The graphite was mined by the Celts as an additive to ceramics. The first modern mining of graphite took place around the middle of the 18th century. The mine became famous for its rich deposits of graphite with layers that were about 1 metre – 20 metres in thickness and extended for, at times, over one kilometre.

During the mid-eighteenth century, graphite first began to be mined by modern methods at Cesky Krumlov. Other graphite mines were found nearby. The presence of lots of highly metamorphosed rocks such as gneisses were found along the two rivers known as the Danube and the Vitava (which was called the Moldau in German). The entire geologic structure was thus dubbed the moldanubic crystallinicum as it incorporates the names of both rivers and refers to the crystalline structure of the gneisses found there that contain graphite.

Resources:

http://www.cumbria-industries.org.uk/wad.htm

http://www.galleries.com/minerals/elements/graphite/graphite.htm

http://geology.asu.edu/ ~ glg_intro/diamonds/letsmake.htm

http://webmineral.com/data/Graphite.shtml

http://johnduffyart.com/history.htm

http://www.pencilpages.com/

http://www.pencils.co.uk/p_history.asp

http://www.grafitnetolice.cz/

http://www.infoplease.com/ce6/sci/A0821577.html

http://www.showcaves.com/english/cz/mines/CeskyKrumlov.html

www.nrcan.gc.ca/mms/cmy/content/1994/29.pdf

http://www.graphtekllc.com/

http://www.infoplease.com/ce6/sci/A0821577.html

http://www.bbc.co.uk/history/timelines/britain/geo_seven_war.shtml

Graphite, Colombo, Sri Lanka

Sir William Logan - Rock Star!

Sir William Logan's publication "Geological Survey of Canada: Report of Progress from its Commencement to 1863" has been chosen one of the 100 most important Canadian books. The list was put together by an expert panel for the Literary Review of Canada.

The Library and Archives Canada has launched two new websites about Logan. "Written in Stone" (http://www.collectionscanada.ca/logan/) is aimed at the professional researcher (scientific, historical, social, etc.). Pertinent to today's news, it includes all 983 pages of Logan's magnum opus, scanned from the original. This searchable website also includes his journals and notebooks (again scanned from the originals and in his own elegant and sometimes difficult to decipher hand), maps and lots more. Now, from your computer, you can access a mountain of material about Logan that comes from widely dispersed collections: McGill University Archives, the National Library of Wales, Natural Resources Canada (Geological Survey of Canada/Earth Sciences Information Centre) and the Toronto Public Library, and Library and Archives Canada. This is an exceedingly valuable resource.

"Life of a Rock Star" (http://www.collectionscanada.ca/rock/) is a companion website aimed at youth. Check it out. It's fun. Logan, Tyrrell, Dawson, Selwyn are all featured.

William Edmond Logan (1798-1875) Knighted Canadian Geologist an anthology by C. Gordon Winder

The book was published in 2004 by Trafford. It is available from http://www.trafford.com at $22.50. This interesting book is a compilation of articles published in a variety of professional journals and public media.

Naples and Mt. Vesuvius

Two issues ago I started a brief review about the geologically hazardous position of Naples, Italy, snuggled between the volcanically active area of Campi Flegrei in the west and the Somma-Vesuvius volcanic complex to the east.

The position of Naples in both space and time is surely a matter of grave concern for Italian volcanologists. The City of Naples is located between two potentially catastrophic eruptive areas and both volcanic complexes have been quiescent for more than half a century. This is compounded by the fact that more than one million people live in Naples and an extra 1.3 million live in an area that could be threatened by a major eruption.

Vesuvius is arguably the best known volcano in the "western" world largely because of the eruption of AD 79. This caused the destruction of two moderately large towns, the best known being Pompeii and Herculaneum, but also Oplontis, Boscoreale and Stabiae, that were situated on the flanks of the volcano and downwind of the eruptive centre. The eruption has provided a name for one on the nastiest types of volcanic outbursts; the Plinian type. The eruptive phase took place in a shockingly brief 30 hours or so and with considerable devastation.

So why should we be so concerned about Vesuvius and what might be the possible results of activity in this complex? In order to examine the potential for disaster we need to look to the past and review what happened in those fateful few days of August in the year 79 AD. Geologists have spent a long time reviewing the petrology of the ejecta from this eruption, analyzing the effects of eruption from physical evidence left behind in the pyroclastic deposits and also re-examining the accurate description left by Pliny the Younger (nephew of Pliny the Elder) as he watched the eruption from Misenum on the west side of the Bay of Naples.

Pliny the Elder was admiral of the Roman Fleet based as Misenum, an ardent "natural historian" and heroic figure, who died in a rescue effort near Stabiae. In early August AD 79 the population of the towns on the flanks of Monte Somma had little idea that they were residing on the slopes of a volcano since the area had been free from eruptions for about 700 years. In retrospect perhaps there had been some warnings; a fairly large earthquake that had rattled the region in A.D. 62, some 17 years earlier, followed by numerous smaller earthquakes that created damage to homes and frescoes on interior walls. There was also a small swarm of localized earthquakes in the days immediately preceding the eruption, but perhaps nothing that would signify to the populace that their lives were soon to be altered forever.

The younger Pliny (Gaius Plinius Caecilius Secundus) recounted the following about his uncle's death in a letter requested by and sent to Tacitus, another famous Roman historian. This account has been modified from the literal translation.

He (Pliny the Elder) was at that time with the fleet under his command at Misenum. On the 24th of August, in the early afternoon, my mother desired him to observe a cloud which had appeared of a very unusual size and shape. A cloud was ascending (from which mountain was uncertain at this distance), the form of which I cannot give you a more accurate description than by likening it to that of a pine tree, for it shot up to a great height, in the form of a very tall trunk, which then spread itself out at the top into what looked like branches. (The cloud) appeared sometimes bright and sometimes dark and spotted according as to how it was more or less impregnated with earth and cinders.

Pliny had ordered a galley so that he could observe the phenomenon more closely. As he was leaving the house a letter from Rectina — the wife of a friend who lived in a villa in or near Herculaneum — was delivered, saying that she needed help escaping the eruption and had to leave by sea. Realising that there were many others in a similar situation he ordered the quadrireme galleys of the fleet to put to sea, and went himself on board with an attention of assisting the towns that lay thickly strewn along the beautiful coast (on the far side of the bay of Naples). Passing vessels that were fleeing the eruption he held course for Herculaneum, but could not approach because of shoals and ash and rocks "blackened and burned and shattered by fire" that were falling into the ships. He was now so close to the mountain that the cinders, which grew thicker and hotter the nearer he approached, fell into the ships, together with pumice stones and black pieces of burning rock.

A rescue at Herculaneum was impossible and so he ordered the ships toward the port at Stabiae (Figure 1) *where he joined another commander, Pomponianus, who was waiting to put to sea when the contrary winds diminished. Unfortunately they were now trapped by the northwest winds on this shore.*

Pliny landed at Stabiae, bathed and dined and eventually went to bed. Meanwhile, broad flames shone out in several places from Mt. Vesuvius, which the darkness of the night contributed to render more brighter and clearer. As the ashfall continued and the villa continued to be rocked by earth tremors he and his companions decided that it would be more prudent to leave in case the building collapsed. Pliny and his colleagues left the villa with pillows tied over their heads as protection from falling rocks. It was now day everywhere else, but there a deeper darkness prevailed than in the thickest night; which, however, was alleviated by torches and other lights of various kinds. They made their way to the sea shore, but again could not leave. Then came a strong smell of sulphur and clouds of ash and flames. His breathing was obstructed by the dust-laden air and he collapsed and died. When the air cleared some two days later his body was found, unharmed, and dressed in the clothes that he had died in. He looked as though he was asleep.

This account, embellished by personal anecdotes from surviving members of Pliny's party remains as an accurate description for what is now called a "Plinian Eruption". Pliny the Younger was forced to leave the villa at

Misenum and sheltered on a hill that was rocked by many earth tremors during that day and night, and eventually assaulted by clouds of ash from the eruption.

So what can we deduce from this account and the physical evidence? The most obvious facts first; that the eruption was unexpected by the populace, although we would realise today that earthquake swarms close to a vent are a potential fore-runner to a volcanic outburst.

The eruption was initiated by a phreatomagmatic (steam-generated) explosion that "unbottled" the volcanic conduit. This was perhaps just before midday, on August 24th, when Rectina sent her message to Pliny asking for naval assistance. The initial blast was almost immediately followed by tremendous up-rush of gases and magma that threw ejecta (largely pumice and ash) 30 km into the atmosphere. As the ash reached its maximum height, upper atmospheric winds pulled the cloud out into the characteristic "pine tree" effect noted by Pliny (Figure 2) somewhere about 1 to 3 p.m. The first tephra that descended was white in colour (Figure 3) and attained local thicknesses of 2 – 3 m at Oplontis and Pompeii. People would have survived this phase, but if they decided to take shelter (as many did) they were likely doomed for the worst was still to come. Through that afternoon (when the fleet neared the shoreline) and into the early evening the outbursts continued, with the tephra fall changing to grey pumice (Fig. 3). About 8 p.m. the force of the upward rushing gases diminished and the eruption cloud gradually subsided initiating a third stage that involved the collapse of the main eruption column. The weight of suspended material above the vent allowed what is called a "pyroclastic surge" where ash, hot-gases and large particles fell down and then surged outward from the main conduit. One such surge destroyed Herculaneum, some 8 km from the summit of Vesuvius.

Shortly after midnight the eruption changed to a series of phreatomagmatic explosions — perhaps as many as four to six. Each explosion allowed pyroclastic flows (seen as the ash-flow deposits in Figure 3) to take place. It is likely that Pliny the Elder was caught at the very edge of one such surge. Even Pliny the Younger who was over 20 km to the west of Vesuvius perhaps was caught in this final "base surge" phase. The citizens of Pompeii and Herculaneum as well as other smaller settlements were caught in similar surges much closer to the vent and died in far more gruesome manners.

By the early afternoon of August 25th the eruption was practically over and it ceased in the early evening. The whole region was blanketed with thick pumice and ash deposits and heavy rains associated with steam and storm activity mobilized mudflows (lahars) that spread across the area. Pompeii, Herculaneum, Oplontis, Stabiae and numerous smaller settlements and farms were destroyed and often buried. Forgotten within two or three generations, the cities, settlements and villas remained for 1,600 years before being re-discovered by well-diggers in the 1700's.

The effects of the eruption

Today as you walk through the streets of Pompeii and Herculaneum it is difficult to imagine what happened here almost 2,000 years ago. Our excursion visited Herculaneum, a small "resort" style town in AD 79. This was the town that Rectina lived in or near, and it was the initial destination of Pliny's rescue efforts. Herculaneum was destroyed by the first major collapse of the eruption cloud likely between 8 p.m. and 1 a.m. This sent a searing wall of gases and fragmental rocks down to the coast. pushing the coastline hundreds of metres out to sea.

People fleeing the eruption were overwhelmed by this "base surge" which swept from the crater of Vesuvius to the sea at Herculaneum in a matter of minutes. Although only 30 to 40 bodies had been found in the town in the original excavations, one group of almost 300, together with several dogs and a horse, was found huddled under one of the arches probably used for sheltering boats at the water's edge. The gases in the pyroclastic flow were so hot, at about 500° C, that their flesh had seared away and the bones were charred. A singularly nasty death!

Nearby excavations uncovered a huge villa along the (old) waterfront just outside Herculaneum known as the "Villa of the Papyri". Slaves were surmised to be evacuating the library and carrying scrolls away from the area when they were killed. In the mid-1700's when excavations began, many scrolls were thrown away during discovery. No-one realised just what they were — they were assumed to be charcoal blocks — and only about 1,750 still exist. There is a possibility that there could be many more still hidden in other parts of the villa. It has also been suggested that many of the scrolls could contain records of the history of Rome and of the works of Aristotle, Sophocles and other Greek writers and philosophers. Multi-spectral digital imaging developed in the last few years allows the possibility that these carbonised rolls can now be read by this new 3-dimensional imaging technique (Gregory, 2004).

Ironically the nature of the eruption, hot gases that carbonized the scrolls followed by massive ash and mud flows, ensured that the scrolls were sealed away in a waterproof and airtight manner. Recent arguments are being made pro and against excavation of the villa; those arguing for, say that priceless literature, long lost to history, might be concealed and should be recovered immediately. Those against state that it would be far better for funds to be spent renovating and repairing what has been already uncovered; that the scrolls have been there for almost 2,000 years and a few decades more will not make any difference. Of course the unknown factor is Vesuvius itself and the nature of the next eruption when it happens!

Herculaneum is a fascinating glimpse into an affluent portion of Roman society silenced in a matter of minutes in one, horrific and eventful day. You can see the house and shop where one of the wine sellers lived (Figure 4) you can walk along narrow streets that were silenced by the volcano (Figure 5) and you can stroll up the ramp through the walls where those hundreds of people fled in the

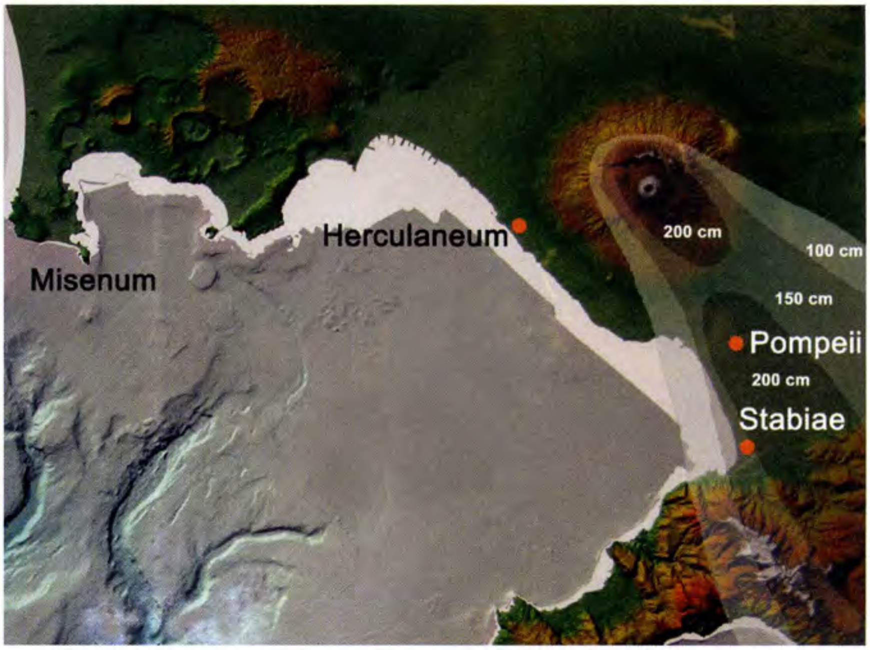

Figure 1: Pliny sailed from Misenum toward Herculaneum and eventually landed at Stabiae where he was killed the following morning. The ash fall from Vesuvius is shown with approximate thicknesses. Modern Naples is located at the top of the bay above Herculaneum.

Figure 2: ***"A cloud was ascending (from which mountain was uncertain at this distance), the form of which I cannot give you a more accurate description than by likening it to that of a pine tree, for it shot up to a great height, in the form of a very tall trunk, which then spread itself out at the top into what looked like branches."*** *– Pliny A.D. 79.*

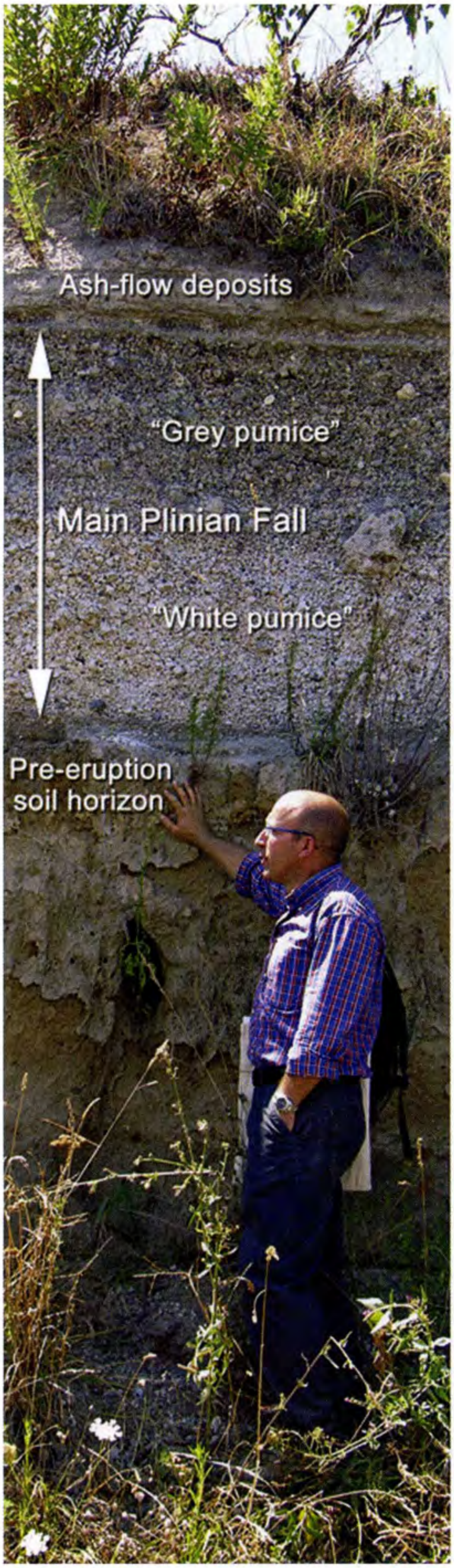

Figure 3: Section near the Traianello Quarry on the north side of Monte Somma. Here the pre-A.D. 79 soil can be seen overlain by the thin phreatomagmatic explosion ash (grey above hand), and then the white and grey ash of the main Plinian blast, topped by pyroclastic (ash-flow) deposits from the closing stage surges.

Figure 4: Herculaneum; house of the wine seller. Many of the wine amphora can be seen on the second floor.

Figure 5: Street scene in Herculaneum. Note the thickness of pyroclastic debris in the distance.

Figure 6: Herculaneum; one of the massive doorways. The beams above the gateway are charred from the base surge.

Figure 7: View from the edge of Herculaneum toward Vesuvius (upper right). Modern Ercolano is built above.

Figure 8: Pompeii; in the "Garden of the Fugitives" a pathetic group of children and adults lie in the corner of the vineyard, huddled a few tens of metres from one of the southern gates of Pompeii. The families were overcome by gases; their bodies revealed by the "plaster casting" technique developed 150 years ago.

Figure 9: Pompeii; a street scene at Via Delle Terme looking north toward Vesuvius. The ruts of chariots and carts can be seen in the volcanic slabs that make the surface of the roadway. At the fork in the road a horse trough and drinking fountain can be seen.

Figure 10: Pompeii; mural on the garden wall in the "House of Venus in a Sea Shell".

Figure 12: Pompeii; the Statue of Apollo, Temple of Apollo.

Figure 11: Pompeii; "The Blue Vase", Naples Museum.

Figure 13: Pompeii; a Roman "fast food" centre. Note the urns (dolia) set into the stone countertop. These housed food heated from small ovens below.

Figure 14: View east over Naples from near the eastern edge of the Campi Flegrei volcanic area. This is the area that would be threatened by the next eruption of Vesuvius.

hours before the hot gas-charged particulate clouds raced down from the summit. You can see the charred beams still in place over many doorways (Figure 6) and gaze at the 25m or more of solidified tuff that mantles the sides of the exposed city. Perhaps, if you are really a thinking person, you can also wonder about the people who have now live in Ercolano, on top of Herculaneum, and wonder about their fate in the next paroxysm from the mountain behind them (Figure 7).

Pompeii, some 15 kilometres to the south and east is better known than Herculaneum and involves an almost complete excavation of this city of ~ 20,000. We are unsure just how many died at Pompeii. We do know that over 2,000 bodies have been recovered and the nature of their positions and the materials/objects found near them tell us something about their lives, occupations and perhaps, characters. The reason for this is the nature of the volcanic deposits that entombed the unfortunate individuals. In the middle of the last century, Guiseppe Fiorelli, the director of excavations at the site realised that "hollow" sounds indicated that there had been "something" buried in the ash. A technique where liquid plaster of Paris was poured into the cavity (now replaced by quick drying resins) was developed with some amazing results. In some cases the subsequently revealed casts showed inanimate objects (bed frames or cupboard doors with handles), but in many cases stark and horrifying details of people and animals that had been escaping the eruption when overcome by fumes, hot gases and dust clouds. Figure 8 is part of a scene at the "garden of the fugitives", a vineyard near the Nocera Gate where what appears to be several families were overcome by the eruption. The bodies were covered in the fine ash that hardened and voids were left as the bodies — or other organic materials — decomposed.

This "casting" technique has allowed us to reconstruct the fate of many of the citizens in those last few hours. The families traveling together — one small group that had sheltered beneath a staircase when it collapsed and crushed them — the muleteer with his mule nearby, the dog that someone forgot to release from its chain, the children who were lost or abandoned. The same applies to the 54 gladiators in their barracks and the woman with expensive jewelry who was visiting or hiding with them. And then there were those who had left it too long — people trapped trying to break through walls to get out — or trying to escape with household possessions and sometimes valuable hoards of silver. All of these are preserved where they fell in that black afternoon and night of August 24th, and 25th 79 A.D.

The eruption has allowed us to see a town preserved in time; - from the richly decorated homes, to lavish villas and humble dwellings. You can walk along the narrow streets and broader avenues, and through public and private places. You can see the chariot and cart tracks preserved in roadways (Figure 9). Paintings and frescoes (Figure 10) still adorn walls, daily utensils — pots, pans and glassware (Figure 11) — are all there, as well as art objects such as statues and bronzes (Figure 12) and mosaics, Billboards advertising gladiatorial conflicts, graffiti on walls, the Roman equivalent of "fast-food" diners for people in a busy world (Figure 13), all the life-styles of the empire paralysed in one day.

Pompeii and Herculaneum still can be visited, and you should do so. It took me exactly half a century from the time that my growing interest in geology and volcanoes made me aware of these Roman cities to the day that I set foot onto those sun-drenched streets. The fascinating irony is that now uncovered, they have the potential risk of being destroyed again and perhaps we should briefly look at what he future might hold.

Potential Hazards

As I mentioned above, Italian volcanologists and other European geologists are extremely concerned about a major, active, eruptive centre in the middle of a very densely populated area (Figure 14). Just what are the risks involved and how can they be mitigated? Civil defence choices are limited to an examination of the past eruptive history and "best guesses" as to what might happen in the next eruption.

The potential risks from an eruption can be placed in three major categories. The first would be a catastrophic Plinian or sub-Plinian (as in 1631) eruption, consisting of major ash ejection, hot gas clouds with glowing magmatic fragments and with potential surges. The second would be substantial ash falls as seen during the 1906 eruption. These could be accompanied by small pyroclastic flows and mudflows. The third would be lava flows similar to those seen in earlier centuries.

Each of these categories poses different styles of risk and generates different responses. Generally it is thought that a truly catastrophic "Plinian-type á la A.D. 79" eruption is unlikely (nothing of that significance has happened in over 2,000 years). There is a higher probability of a sub-Plinian eruption, considered to be a "worse-case" scenario and this is the one on which the Emergency Plan is based. Here in the "Red Zone" of about 200 km^2 the populace immediately around the volcano would have to be evacuated. This is an area that could (based on geologic evidence and computer simulations) suffer from pyroclastic flows, mudflows and major ash fall and gas problems. In 1631 some 20% of this area was affected by pyroclastic flows.

In a "Yellow Zone" extending 50 km eastward and up to 25 km NE and SW of the vent ash thicknesses observed during the 1906 eruption can be plotted with houses that are present today. Isopachs (lines of equal depth) show that ash falling on rooftops in the danger area will vary from 100 to over 600kg/m^2. Any thicknesses greater than 100kg/m^2 has the potential of collapsing roofs, especially if the ash is water-saturated Based on these figures approximately 6,500 homes would be adversely affected and over 30,000 residents would face potential roof collapses.

A third "Blue Zone" occupies an area immediately north of the volcano and this is in a region in which flooding could be an additional problem.

Unfortunately people were allowed to move back into areas that had been affected by the last (1944) eruption. Had efforts been made to prevent "population creep" into these more risky areas the problems that will have to be faced during the next evacuation would have been considerably simplified. Current fiscal inducements (about 40,000 Euros) for families to voluntarily move from the main danger zones are simply insufficient and the establishment of a "Vesuvius National Park" (my term) as an "unoccupied zone" seems unlikely, at least until the next major eruption forces people away. The Emergency Plan does dictate what sectors around the volcano will be evacuated and where the populace will have to move elsewhere in Italy. Modes of transport — ferries, trains, busses — are also proscribed, but the evacuation, in narrow streets and on crowded roads, depends on time and a well-organised and "passive" populace.

Civil defence estimates are that a minimum of one week will be needed to move the population at risk. Will the volcano provide one week of warning? The short answer is possibly. The area around Vesuvius is heavily monitored with GPS stations, gravimetric stations, tiltmeters, levelling benchmarks, tidal gauges, analog and digital seismic stations and geochemical analytical collection positions. It is assumed that gas content changes and/or magma movements from 6 to 8 km below the vent will give advance notice. Such activity moves the alert status from "Normal" to "Attention!" and the technical monitoring is reinforced. If further variations in monitoring are detected, the warning rises to "Pre-Alert" and simulation of events commences. Further activity, such as ascending earthquake swarms moves the alert to "High" status. Monitoring is continued by automatic stations. It is in this range that evacuation would begin on the assumption that an eruption could take place within weeks.

I do not envy the geologists that have to advise in such a situation. Call it correctly and thousands if not hundreds of thousands of lives could be saved. Call it incorrectly and two scenarios emerge. One that substantial numbers could be killed if the warning is left too late, or that politicians do not react in time since the evacuation order has to be triggered by (likely) the Prime Minister. For example, people will be limited in what they can take with them (remember the citizens of Pompeii overwhelmed when trying to escape with precious household items). If you leave houses full of expensive objects such as plasma screen TV's, computers, and art works who wants to stay behind to "serve and protect"? The second scenario would inevitably cause deaths (heart attacks; road accidents; possible drownings) but with no eruption! This then leads to questions about the science, the cost of the evacuation, and likely a resistance by sectors of the populace to take the next warning seriously; thus increasing the likelihood of an even more catastrophic loss of life "next time"!

And there will be a "next time". Our knowledge of volcanic behavior has improved dramatically in the last few decades, particularly with Mt. St Helens and Pinatubo as examples. But every volcano is different and one thing that Vesuvius can illustrate is that the eruptive styles can be quite different, and, in some cases, truly terrifying. We can only wait and see!

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(There are many other references on the web, including travel information. I suggest using Google and enter Pompeii and Herculaneum).

Acknowledgments

Although this article provides a review of observations made on the International Geological Congress Pre-Congress Excursion B28, much of the information is from data provided by Giovanni Orsi and the co-leaders of this excursion (Andronico, et al., 2004), as well as from the additional references and web URL's provided above. Any errors should be attributed solely to the author. One final comment is a suggestion to read a fascinating (non-fictional) account of the eruption and its aftermath by Robert Harris. "Pompeii" is the story of a young aqueduct engineer, Marcus Attilius Primus, in the week leading up to and including the eruption of Vesuvius.

Alan V. Morgan.

The Champlain Sea: here yesterday, gone today

Paul F. Karrow PFK16

Figure 1
Lake Champlain including areas where vertebrate remains have been found (white dots).

One of the surprising things of the "Ice Age" is that about 10,000 to 12,000 years ago, a large embayment of the Atlantic Ocean extended up the St. Lawrence Valley into southern Quebec and eastern Ontario. The seashore extended across from the Lake Ontario basin near Kingston northeastward near Carleton Place to the Ottawa Valley as far as Pembroke. All of Ontario east of that shoreline, including Ottawa, and much of the St. Lawrence Valley of Quebec was flooded by sea water to depths as great as 100m (Fig. 1).

It has long been debated as to whether the sea extended into the Lake Ontario basin after glacial Lake Iroquois drained down to a level far below present Lake Ontario level. The latest information suggests Ontario basin water got as low as sea level but the narrow connecting strait at Kingston and runoff from the land kept the water fresh in the Ontario basin. These conjoined waters only lasted a few centuries before uplift of the Kingston sill raised Lake Ontario above sea level.

The great weight of glacial ice that covered Canada pressed the Earth's crust downward so that part of it was below sea level. As the ice sheet gradually thinned and melted away, the St. Lawrence and Ottawa valleys became open to the sea and residual glacial lakes mixed with sea water and became salty. The slower process of isostatic rebound as the ice disappeared raised the area over a 2000-year period and drained off the sea. As a result, the seashore was slowly moved eastward to where it is today. At Covey Hill, south of Montreal, these sea beaches are well displayed down the slope.

We know the waters of the Champlain Sea were marine (salt water) because the fossil shells in the beaches and deep-water clays are species found in the ocean today. We know the water was very cold, as you would expect from the retreating glacier, because many of the species are found today in the arctic. Analysis of the porewater in the clay also shows that the water in which the sediments were deposited was salty; the low permeability of the clay has preserved some of the salty water in the clay.

The kinds of fossils found in the sediments of the Champlain Sea include molluscs (snails and clams: Fig. 2, most common and obvious), barnacles, urchins, sponges, foraminifera, ostracodes, and vertebrates (sorry, no corals–too cold). Many species of molluscs have been identified from the Champlain Sea, although only a dozen or so are common. Barnacles are common, fastened onto rocks, boulders, or molluscs. At some places fossil molluscs are so abundant hundreds or thousands can be collected in a short time.

The vertebrate fossils of the Champlain Sea include several species of whales and seals. Their bones are usually found in gravel pits in beach deposits along the old sea shore, suggesting they beached themselves as they sometimes do today, or were carried by waves onto shore after death. Figure 1 shows where Champlain Sea vertebrate remains have been found. Near Ottawa, carbonate concretions in the clay contain fossils (fish, molluscs, even a bird feather!). These have been dated as 10,000 years old, i.e. from near the end of the Champlain Sea.

The clay of the Champlain Sea (referred to by engineers as Leda clay from a characteristic fossil) is "sensitive" so that when disturbed by construction, earthquakes, or stream erosion it liquefies and causes spectacular earthflow landslides. Areas along the South Nation River in eastern Ontario; and many others in Quebec, show the ribbed or chaotic landslide topography that results, particularly evident on air photos, sometimes with loss of life and often much property damage.

Marine invasions in other parts of Canada

Other former seas of similar origin have also been named, such as the Goldthwait Sea east of Quebec City, and the Laflamme Sea along the Saguenay Valley. The area flooded by the sea inland from Hudson Bay is called the Tyrrell Sea. Over 100,000 years ago the Bell Sea occupied the same area at the close of the second last glaciation – geologists know well that history repeats itself. Other areas submerged by the sea because of crustal downwarp from glaciation include southwest British Columbia (Victoria, Vancouver) and large areas in the arctic islands of northern Canada.

For further reference: Gadd, N.R. (ed.), 1988. The Late Quaternary development of the Champlain Sea basin. Geological Association of Canada Special Paper 35, 312p.

Figure 2a.
L. Hiatella arctica, Portneuf. Que.
*C. Portlandia arctica, Ste. Genevieve, Que.**
R. Macoma balthica, Ste. Genevieve, Que.
**Originally Leda glacialis, then Yoldia arctica*

Figure 2b.
L. Mya truncata, Ste Genevieve, Que.
R. Neptunea despecta tornata, Ste Genevieve, Que.

Figure 3. Fish in a carbonate concretion from the Ottawa area.

Figure 5. At about 1815 h December 11, 1963, a large landslide took place at Saint-Joachim-de-Tourelle, Québec. The earthflow involved sensitive marine clays (otherwise known as Leda Clay) which flow like a liquid when in the remodeled state.

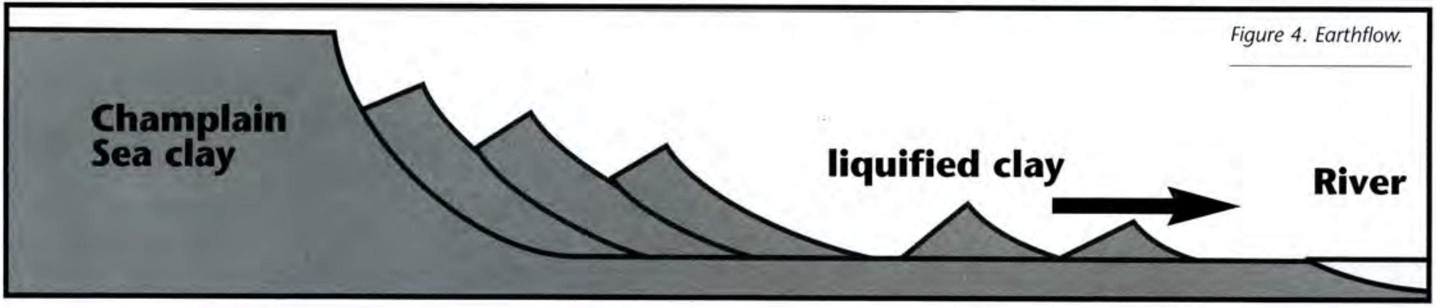


Figure 4. Earthflow.

2005 Wood Bursary Winner Amy Nicoll

A UW Earth Sciences undergraduate student received the Wood Bursary for the second year in a row. This year's winner of the prestigious $6000 award from the Women's Association of the Mining Industry of Canada Foundation is Amy Nicoll (see photo above), who accepted the award at a ceremony in Toronto in October. Michelle Sabourin was the UW recipient in 2004.

As Amy said in her acceptance speech: "I am very honoured to receive this award. It has been very encouraging as a young woman in Earth Sciences and has reaffirmed my study direction. I think it is high time women get to be explorers of the Earth and I thank the Foundation for providing opportunities for us to do so. Thank you very much."

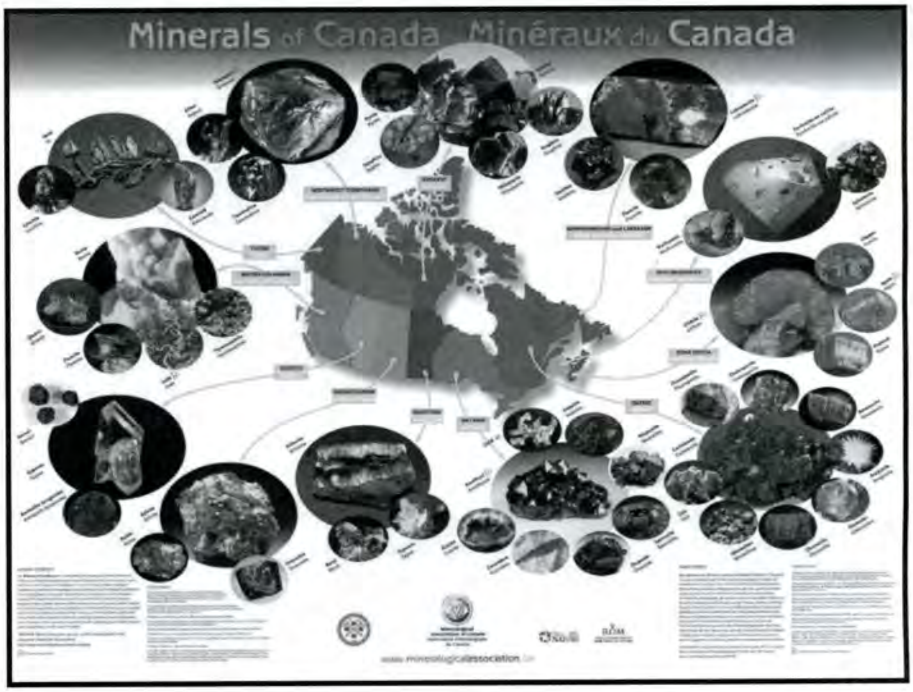
The Wood Bursary is awarded annually to deserving Canadian undergraduate students in the geosciences in honour of Sophia Wood (1907-1985), who prospected in northern Ontario and northwestern Quebec for many years with her husband John Marsh Wood, from home bases in Noranda and Toronto. Two other awards in 2005 went to students at the University of Manitoba and the University of Calgary.

Michelle Sabourin, UW's 2004 award winner.

Minerals of Canada Poster

In 2005 the Mineralogical Association of Canada published a 60 cm x 80 cm full-colour poster titled "Minerals of Canada" This poster is included with subscriber copies of What on Earth courtesy of the Mineralogical Association of Canada. The poster consists of a map of the Canadian Provinces in the centre surrounded by pictures of the minerals, grouped by province. Canadian teachers may request copies for classroom use from the Mineralogical Association of Canada. Contact Pierrette Tremblay at: pierrette_tremblay@inrs-ete.uquebec.ca

Lesson plans are available at: www.mineralogicalassociation.ca/poster



Jesse's Rock

Margaret Ingleton and Peter Russell

Deep under a mountain range I was a part of a great mass of granite. I started my second rock cycle as molten magma, which gradually cooled over millions of years. When the mountains of which I was part of were eroded by wind and rain, my tiny particles became mud and sand. My quartz crystals were ground down and formed sand. This sand was just like the sand you play with on the beach in the summer.

The other minerals, feldspar and mica in my granite were ground and decomposed into fine mud and clay. These materials were transported from the north west of Ontario to a growing river delta. A great wedge of sand, gravel, silt and clay grew. As more layers were deposited on the top of my eroded material, water was squeezed out of the mud and sand. Over time sand turned to sandstone and silt and clay turned into siltstone and shale.

More mud was added to the pile and time moved on. Two continents moved together pushing thousands of metres of rock into a stack of layers 10,000 metres high or more. Some of the beds were flipped upside down as they rode over each other.

Jesse's parents Bob and Marg Ingleton in the Peter Russell Rock Garden on the University of Waterloo campus, with the rock donated in memory of their son Jesse who died in a tragic work-related accident on October 19th 2004. In Jesse's honour always remember to work hard, work safe and work happy!!

The rocks at the bottom of the pile including the remains of my granite, moved ever deeper to about 25 kilometres below the mountains. It was very hot down there. The rocks became squishy, and moved slowly. The layers of sandstone and shale gradually heated up. Shale turned to slate and then changed to sparkly mica flakes. Sandstone hardened into quartzite. All this material then flowed slowly and folded without melting.

Cracks opened up in the rocks and the mineral quartz crystallized in the cracks.

Half a billion years of erosion washed away the mountains forming other rocks. My new crystals were then exposed to the atmosphere again. I saw interesting things happening for 500 million years. Living things moved across the surface of the Earth and flew in the sky. Ice scrubbed my surface a few thousand years ago, during the Ice Age. Recently humans found my sparkles irresistible, cracking out lumps of my rock to decorate their homes and gardens. To break the rocks from the ground, holes are drilled into me using a drill bit covered with a hard mineral called diamond. You can see some of the holes in Jesse's rock drilled so my rock could be free from the surrounding ones at Red Bridge, near North Bay, Ontario.

Jesse found rock stories exciting. As a boy he used to collect rocks and imagined all the interesting stories they could tell.

When Jesse grew up his interest in rocks became his career. He worked as a Hydrogeological Technician in the Earth Science Dep't at the University of Waterloo then later became an Environmental Driller for Geo-Environmental Drilling Company. In order to read the messages in the rock, Jesse drilled into mud and sand deposited during the Ice Age.

He did this to find useful things for people, such as groundwater and sources of pollution, which needed cleaning up.

A Humbling Thought

Jacqueline Kreller, winner of the 2005 David M. Forget Essay Competition

Any physical representation of history fascinates me. I look at a centuries-old painting and I wonder about all the events that painting has co-existed with and witnessed, if paintings can be said to have witnessed things. Even more amazing to me are ancient artefacts like Egyptian mummies or flint tools made by the first humans. The amount of time those objects endured to finally sit serenely in museums and private collections is almost inconceivable. It gives me such respect for human culture, that we managed to make things last so long. Now, in modern times, scholars can take these artefacts and reconstruct our own long, rich, varied past.

All the long span of human existence is insignificant, however, when compared to the lifespan of a single, nondescript rock. That rock has seen millions upon millions, if not billions, of years go by. That rock existed as the very face of the Earth changed; it witnessed cataclysms unimaginable by us and yet endured. The human species is but a tiny blip in the long march of its lifetime. That rock began long before us, and it will continue long after we are gone. For me, looking at an ordinary paving stone or roadside pebble gives a much greater sense of history than observing anything preserved in a museum.

Our greatest failing, as a race, is hubris. We believe that we are invincible and supremely right. We believe that the world exists solely for our enjoyment and use. This attitude is evident in our absolute disregard for the delicate balance of our Earth and the reckless abandon with which we have mined her and stripped her of her resources.

Rocks are oblivious to our existence, but they tell a story, if we can learn to read it. Just as historical scholars and anthropologists can determine the human race's past from the evidence we have left behind, geologists can determine the Earth's past from the records left behind in the rocks. I believe geology to be the most important of all the sciences, because it allows us to place ourselves within a larger context: the history of the Earth, rather than simply our own. Understanding the Earth and our role in it is essential to the survival of the human race.

There is a belief, common to many people, that if we do not become more responsible in our use of the Earth, we will destroy it. This belief is false; another symptom of our collective hubris. It is the human race, not the Earth, which will be destroyed. One need only make the briefest cursory survey of geology and palaeontology to realise that the Earth's processes cannot truly be disturbed by the puny efforts of any one species. Even asteroid impacts, considered one of the biggest catastrophes that could ever occur, do not cause permanent damage to the Earth. The human race could launch a thousand nuclear bombs, blow itself to tiny smithereens, and cause a nuclear winter, and eventually, after a few hundred thousand years, the earth would dust itself off and start fresh. That ordinary, boring rock would still be around, living its rocky life. The demise of the human race, such a monumental, shattering concept for us, would not perturb it in the least.

The study of geology is the only way to break down our long-standing tradition of selfishness and cause us to consider, truly, where we stand in the grand scheme. If only more people, and more world leaders, understood the sheer magnitude of the geological time scale and our miniscule potion of it. We must stop looking at environmentalism as an altruistic venture, as some vague way to 'save the Earth,' but as a simple matter of self-preservation. It is not the Earth we should be trying to save, it is ourselves, and this can only be accomplished by obtaining a throrough understanding of earth history and our place in it. The Earth will not care if we are gone, and that is a truly humbling thought.

Jesse's Rock continued from the previous page

Jesse's rock is here to remind you that we all have a life cycle. We touch other people's lives transforming them in wonderful ways which continue when we let go of the material forming our bodies. This material continues on through Planet Earth's cycles of life, water, and rock. Given enough time a part of you may find it's way into a sparkly mineral like diamond or mica. What an adventure!

Rock description for geologists:

Gneiss formed from sedimentary rocks during the Grenville Orogeny, 1 billion years ago. From McLaren's Bay Mica Stone Quarries. Red Bridge, near North Bay, Ontario.
http://www.micastone.com/
Commercial name: Sea Mist Green Gneiss.

The Dec 26/05 Tsunami meets the Water Table, Banda Aceh, Sumatra Island, Indonesia

Peter Gray beside rubble filled dug well

Flooded well in foreground

Hope

The magnitude 9.0 earthquake that struck the area off the western coast of northern Sumatra on Sunday morning, 26 December 2004, at 7:59 am local time (00:59 GMT) triggered massive tsunamis that inundated coastal areas in countries all around the Indian Ocean rim, including India, Indonesia, Sri Lanka and Thailand. The region is historically prone to seismic upheaval due to its location on the margins of tectonic plates. However, tsunami waves of this magnitude are rare and the level of preparedness was very low. This area of the earth has also become one of the most tectonically active zones on the face of the earth since the Dec 26/04 earthquake.

An estimated 5 million people were directly affected, and the death toll is one of the highest in recorded history – some 280,000 individuals. The economic and environmental impact of this disaster has also been devastating and will affect livelihoods, economies and natural systems for years to come.

While this article focuses on the impacts of the tsunami in Indonesia, the effects I witnessed in Sri Lanka were equally compelling, and devastating. However, since much of the footage and video we observed on the TV were taken from tourists on vacation in Sri Lanka, I will take you to a place where no tourists – or ex-Patriots were allowed prior to the tsunami – Banda Aceh, Indonesia.

On Friday May 13, 2005 I found myself standing on the very shores where the tsunami waves broke ground, while working on a contract with World Vision Canada / CIDA to conduct community based environmental assessments (EA's) on projects being implemented in the tsunami effected countries of Indonesia, Sri Lanka, India and Thailand. Although only five months had passed since the tsunami, the effects of it were obvious, and will haunt my memory for my lifetime.

The results of our EA work have been published under separate cover to World Vision Canada and their partner countries, so the intention of this article is to pose some questions and present some antidotal evidence that I'm sure you will find interesting, if not awesome in scale. There are so many directions that this article could go; however I am going to focus on the effects of the tsunami on the shallow water table.

One of the first things I picked up from reading the rapid environmental assessment reports, or other reports that I read in preparation for our overseas trips was that more than 30,000 shallow wells in the immediate vicinity of Banda Aceh had become salinized as a result of the tsunami. While not reading of the mechanism of how this actually happened, I have to admit that I was skeptical that this was actually the case, both in terms of the number of wells impacted and the degree to which they were salinized. I had so much to learn.

When I first looked around the landscape I was struck by the sheer degree of destruction that the tsunami left behind, as shown on the figures attached. I will note also that all of the stories and anecdotes were collected first hand by meetings with the survivors of the tsunami. And while we all speak of the tsunami, there were actually several tsunami waves – reportedly up to four waves that broke ground at Banda Aceh, but most particularly two primary waves that caused all of the destruction.

As we all know, the source of the tsunami waves was a magnitude 9.0 earthquake located off the western shore of Sumatra. As I learned while in Banda Aceh, most earthquakes last 30 seconds or less (I was actually rocked out of bed one night by a magnitude 5.6 earthquake with the epicenter only 30 km away – which did not create a tsunami -fortunately), while the December 26/04 earthquake lasted reportedly up to 10 minutes. This must have seemed like hell on Earth for the people there.

The first mentionable wave was reportably 10 m high, of which most people apparently survived, and this wave arrived some time after the earthquake had subsided – possibly 10 - 20 minutes later. This caused panic, severe flooding and chaos. The water then withdrew and collected again up to two kilometers off shore – leaving fish flapping on the sea bed while some fisherman and villagers ran out to collect what they could – others turned and ran. The time between this 10 m wave and the next killer wave was in the order of minutes. As one survivor put it *"I looked back and thought that there was a storm on the horizon, only to be swept up seconds or minutes later and become separated from my wife and daughter who were never to be seen again"* as the killer 30 m high tsunami broke ground. There is real evidence to support a 30 high tsunami, waste in the tops of trees, boats on the top of buildings, and more telling the removal of the light beacon from the top of the tower on the very shore where the waves broke.

When I surveyed the land, I noticed that basically every house had its own well and latrine (open ended pit). Surveying base maps and talking with survivors I could now understand why the reported number of 30,000 wells had been affected in this area alone. This was a very densely populated area – and I had no idea that every house had its own shallow (dug) well. Attached are numerous pictures of the remains of these wells. The concrete casings were destroyed, their caps were destroyed and the wells were filled with whatever rubble the tsunami left behind.

Between the first and second wave survivors reported a "sucking" sound from the wells and noticed that they had dried up. We have learned that the shallow unconsolidated aquifer, with a high water table level of approximately 1-2 metres below grade, is significant in depth (10's of metres), and comprised basically of medium sand. However, the freshwater / saline water interface (or bottom of the aquifer) is located at a depth of approximately 6 metres, resulting in an available drawdown of 4-5 metres. Under typical conditions the wells pump saline water from beneath the six metres depth, so the bottom of the wells were terminated at a depth of six metres below grade.

When the second wave broke ground, these shallow wells then reportedly geysered in front of the advancing wave. The result after the floodwater subsided – and many months later, was a salinized shallow water table aquifer and thousands of rubble / waste filled shallow dug wells. Reportedly one of the NGO's on the scene decided to undertake a well cleanout program whereby the waste was removed from some wells and the wells were pumped dry many times, although these efforts proved unsuccessful, as the wells continued to pump salinized water many months later.

So questions I will leave for you to ponder include what happened to the shallow water table aquifer? Did it become dewatered – or drained when the second wave collected two km off shore? How did all the wells become salinized? What was the result of the force from the tsunami on the shallow water table? Was all the fresh water forced out of the ground by the advancing waves? Is the groundwater between the wells salinized or just in the immediate vicinity of the wells themselves? How long will it take (or how many monsoon seasons) for the shallow water table aquifer to re-establish itself? How do the survivors in the coastal areas that have been affected in a similar manner as Banda Aceh secure a safe and potable water supply? Can the shallow water table aquifer be protected from another tsunami?

The other aspect of the tsunami that I did not describe is the emotional and psychological trauma that has affected people all over the world. Talking with the survivors and seeing the looks of absolute fear on peoples faces when earthquakes struck the region while I was in country only gives me a glimpse of what really happened, and what they have survived. The human ability, desire, instinct – call it what you want - to simply survive is indescribable. People coming together from around the world, and from different communities or villages to help each other out speaks to this. I feel truly blessed to have been able to participate in some small way with the tsunami assessment / clean-up related efforts and have a much greater appreciation for just how small the world is and how dynamic the forces are that shape the earth and its inhabitants on a daily basis.

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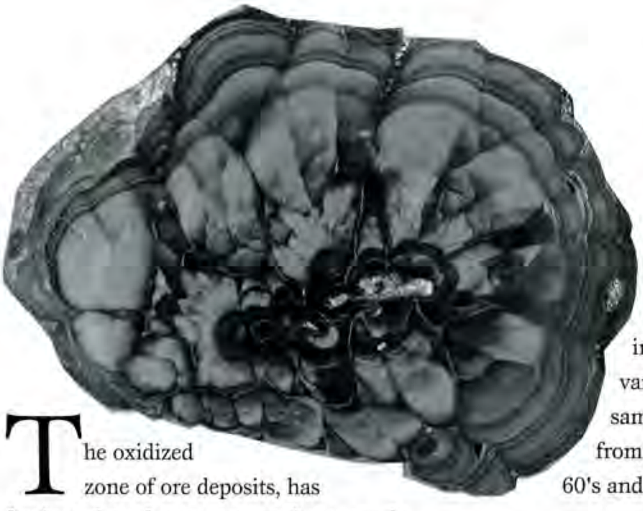
Oxidized Zone Minerals

Peter Russell



The oxidized zone of ore deposits, has fascinated me for many years because of the process of their formation and the resulting reddish brown rocks. The colourful rocks are a signal to prospectors that economic ore cannot be far away. Stories abound of rusty outcrops luring prospectors across the southwestern U.S.A. to grub in the rocks to find a fortune, or a flicker of hope, which faded rapidly. Many generated a flurry of penny stocks, which changed from promise to worthless paper.

Voisey's Bay nickel deposit in Labrador was found in 1993 by Albert Chislett and Chris Verbiski of Archean Resources, a small St. John's, Newfoundland based company. These observant Newfoundlanders clued in on a rusty outcrop while flying into Nain after a summer of prospecting. They encouraged the helicopter pilot to land on an outcrop so that they could collect samples. These were analyzed and proved to contain nickel. The finding at Voisey's Bay shows that using your eyes may still lead to a bonanza, if you are lucky to find rich ore samples when you step on the ground. The ultimate extraction of the ore became entangled in litigation and politics. INCO's Voisey's Bay deposit will finally produce nickel in 2006 after huge amounts of money were spent on acquisition and exploration and agreements with governments of Newfoundland and the first nations.

Oxidized zone mineral deposits produce spectacular colourful mineral specimens, though the fact that they occur near the surface means that it is a depleting resource. My interest was sparked by the variety of colourful mineral samples, which became available from Tsumeb, Namibia in the late 60's and 70's.

Original sulphide sources of mineralization.

Black Smokers.

In order for an oxidized deposit to be formed, an original sulphide ore body must be present. The sulphide ore body may be formed by cold alkaline oxidizing seawater migrating through sediment and other rock beneath the sea. This seawater circulates and turns into a hydrothermal fluid near a magmatic heat source from an active ocean ridge. This type of deposit is being formed today off the coast of Vancouver Island on the Juan de Fuca Ridge. This enriches the concentration of metals and hydrogen sulphide. These minerals precipitate out of solution at huge areas of chimney-like vents called "black smokers" on the sea floor. The hot water containing sulphides forms chimneys and showers the surrounding area with a rain of particles as the water cools from about 400-300 degrees C. The mounds of sulphide rich material are then covered with other rocks and eventually moves to the surface over millions of years allowing oxidation and enrichment to begin.

Porphyry Copper Deposits

A Porphyry Copper Deposit derives its name from a porphyritic stock located at the center of the mineral deposit. A stock results from a cylindrical mass of magma, which moves up through the Earth's crust underneath a stratovolcano and cools. Stratovolcanoes are formed of a mixture of lava flows and fragmentary ejected material. Mount Fuji in Japan, Mount Rainier in the U.S.A.and Vesuvius in Italy (see this isssue) are examples of stratovolcanoes. In a porphyritic rock, some of the minerals are very large crystals (up to 10 cm in length) and the rest are microscopic. In the ore deposits we generally find that the upper parts of the stratovolcano have been eroded away. The surrounding rock, which has been intruded, is often metamorphosed by heat and pressure. During metamorphism, sulphide minerals form in the rocks surrounding the stock or magma chamber. An enriched mineral blanket or oxidized zone will then form near the surface of these deposits. The porphyritic stock at the center of the system may not contain enough of the copper minerals to be an ore deposit. The rock that surrounds the stock however may be rich in copper mineralization.

The porphyritic stock is the engine that allows the development of the minerals. The ore minerals are found in a series of zones radiating outwards from the stock. Each of these zones contains a specific suite of minerals. These minerals include azurite, malachite, gold, silver, chalcocite, and chalcopyrite.

Oxidation and Reduction

Chemical reactions in the upper part of a sulphide ore deposit begin when naturally acidic rainwater and oxygen dissolved in groundwater attacks pyrite or other sulphides. The absorption of oxygen by pyrite causes it to change into iron oxyhydroxides and sulphuric acid. This acid works its way down through the ore-body taking copper, lead and other elements with it. Masses of spongy insoluble limonite (insoluble ferric-oxy-hydroxides) are produced. The rusty mass of limonite is characteristic of ores containing pyrite. German miners called this material "iron hat." The equivalent term in English is gossan.

Once the iron sulphide oxidizes and generates sulphuric acid and limonite, the acid reacts with other sulphide minerals. Copper sulphide reacts forming copper sulphate. On contact with carbonate ions from a source such as limestone, the copper sulphate reacts to form the copper carbonates, malachite and azurite.

Native gold present in the sulphide ore will not be affected by the chemical reactions and would be left behind in the gossan.

Enrichment

When the acid solution enriched with copper arrives at the water table, the descending water loses oxygen and the oxidation of sulphides cannot continue, unless Fe^{3+} ions are present. Fe^{3+} may oxidize FeS_2 forming Fe^{2+} and more sulphuric acid. The dissolved copper sulphate interacts with copper sulphides and enriches them forming minerals such as bornite, chalcocite and covellite. The copper content of chalcopyrite is 34% and that of covellite 66%. Enrichment takes away copper from the upper part of an ore body and drops it off at the water table. This process is called supergene enrichment. The oxidized zone and zone of enrichment may contain profitable mineralization. The original sulphide bearing rock may not have contained sufficient ore to pay for deep mining, pumping of water and treatment of the ore.

Other sulphide minerals such as sphalerite (zinc sulphide) and galena (lead sulphide) are broken down in the oxidized zone. Galena will form cerrusite, anglesite and wulfenite. Sphalerite forms smithsonite.

Oxidized zones are found in many deposits, frequently found in arid areas of the world including the United States, Mexico, Peru, Chile and Africa. The oxidized zone of mineral deposits found in the Arizona and New Mexico are around 122 metres or 400 feet deep.

Cyprus – The Copper Island

Cyprus is the island, which gave its name to the metal. The word copper comes from cuprum, the Roman name for Cyprian metal. The first copper found was native copper, which could easily be fashioned into useful objects. Mining began in the 4th millennium B.C. The islanders then discovered that green stones (malachite – copper carbonate) when heated in a fire produced copper metal. They then learned to collect blue-green water seeping from the rocks, containing copper sulphate and process this to produce the metal. The Romans used copper sulphate from mines, where they would collect the water as it dripped through cracks in the rock. This was a labour intensive process and they used slave labour to dig the tunnels just below the water table and collect the copper solution in jars. The water was evaporated and the material was used for medicine, pigments and other copper products. In AD 162 Galen, geographer and personal physician to the Roman emperor Marcus Aurelius, visited mines of Cyprus in search of hydrated sulphates of copper, zinc, and iron, which were used extensively in medicines at the time. He wrote a journal of his visit with a description of the mines and tools used in mining.

Skouriotissa is a copper mine in a hilly region on the foothills of the Troodos mountains in Cyprus. It is one of the oldest copper mines on the island. The ancient Romans leased the mines to the highest bidder. In 12 BC rights to mines in the area went to King Herod, who was allowed to keep half the profits. This area is still producing copper from sulphide minerals found in pillow lavas.

Rio Tinto, Spain.

The Moors who occupied Spain in the Middle Ages found out that copper could be extracted from the sulphide ore. The ore was crushed and water percolating through the mass would produce copper sulphate. This technique is called "heap leaching" and is still in use today. The Rio Tinto area is highly polluted by natural weathering of the primary minerals plus the spoils produced from hundreds of years of mining.

Copper extraction at the Asarco Ray Copper Mine, Hayden Arizona.

Oxide leaching and solvent extraction.

Copper ore is piled onto a thick high-density polyethylene liner. Sprinklers are placed in the surface to spray a weak acid solution onto the pile. This dissolves the copper in the ore. The copper bearing solutions are collected and pumped to an extraction plant where an organic extractant removes the copper from solution. The resulting solution is then transferred to the electro-winning process, where copper is plated out as a cathode. The leaching of the oxide ores is relatively easy by using sulphuric acid. Leaching of sulphide materials requires a chemical oxidizing agent - ferric ions (Fe^{3+}). These ions are generated by reactions with the atmospheric oxygen. Oxidation can be assisted by either pressure (as in an autoclave) or more commonly with bacteria. Sulphuric acid is not the only reagent that can dissolve copper from a concentrate.

BHP Billiton has patented a process using ammonia to dissolve part of the copper concentrate. This process is used at the Coloso Plant in Chile.

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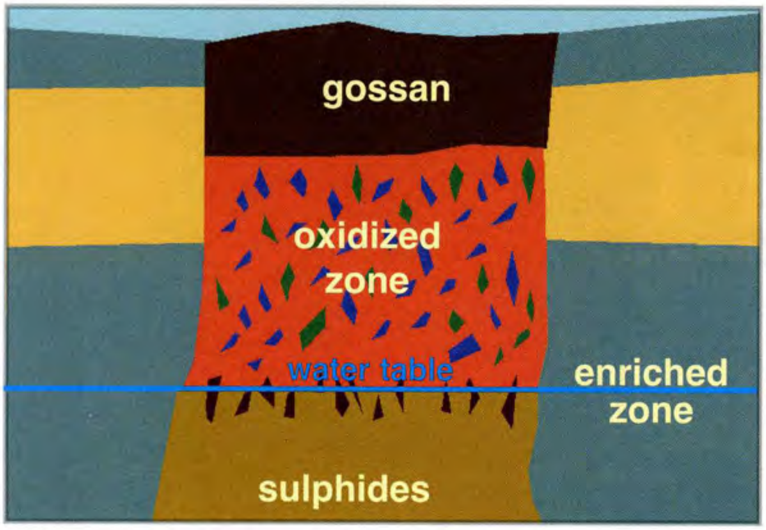
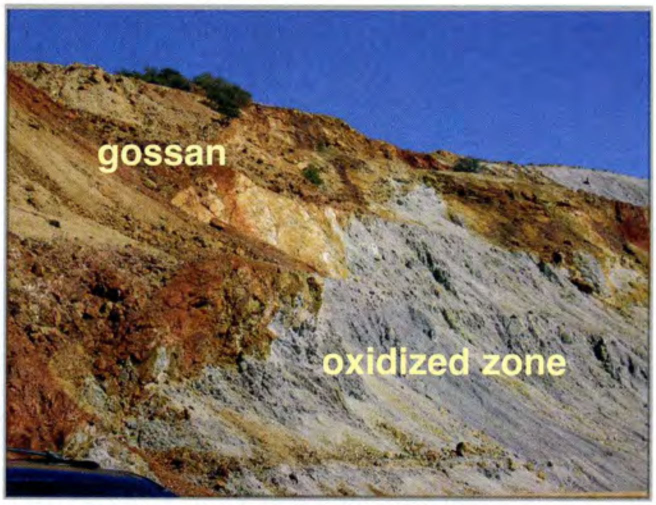
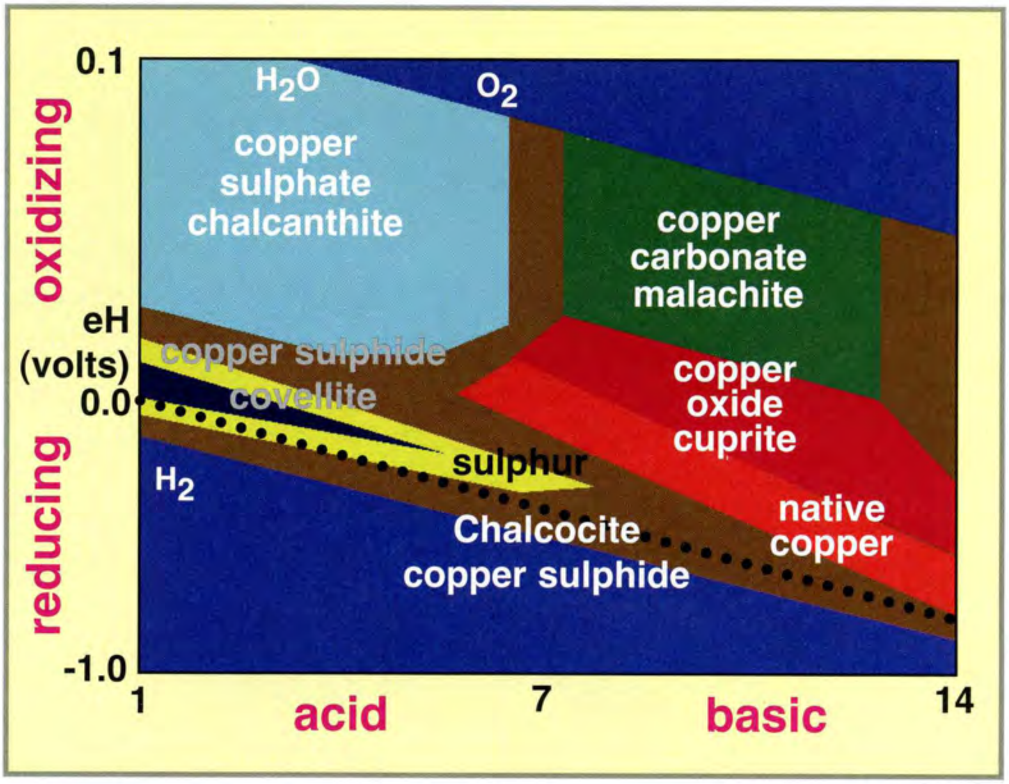


Cross section of an oxidized sulphide deposit.

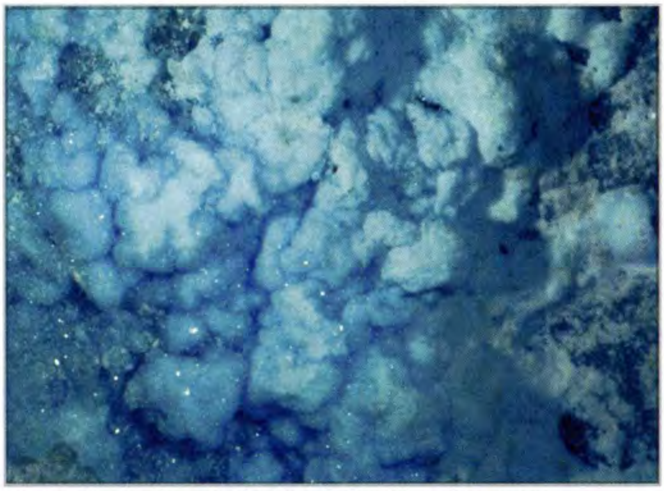


Gossan at the Lavender Pit overlook, Bisbee Arizona.

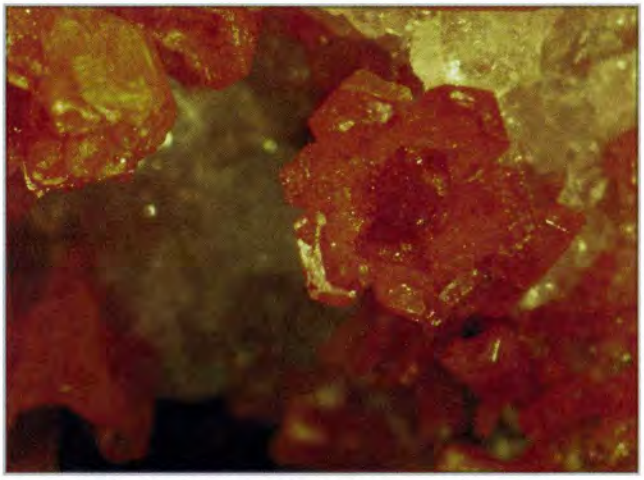
Acid leaching of copper ore, Ray Copper Mine, Arizona. All water on the mine property must remain there or be allowed to evaporate, with no runoff.



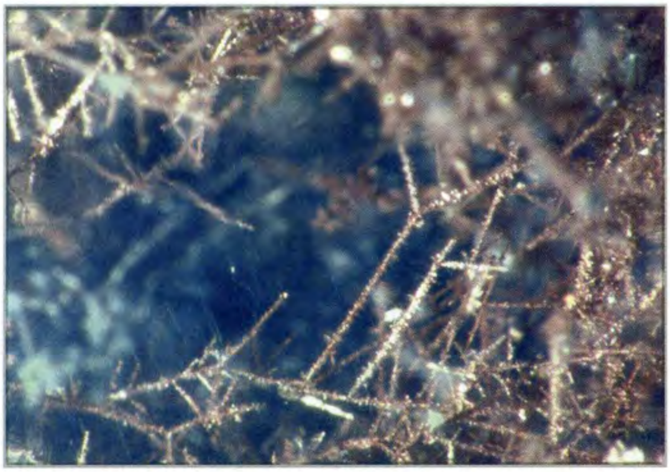
Eh-pH diagram for a copper deposit. Oxidation and reduction (Redox) reactions play an important role in the geochemical processes that produce enrichment of ores. Eh is a measure of reduction potential. Redox reactions are reactions in which electrons are transferred. The species receiving electrons is reduced, that donating electrons is oxidized. The black dotted line is the watertable. The reaction stops here and the sulphide ore is enriched.



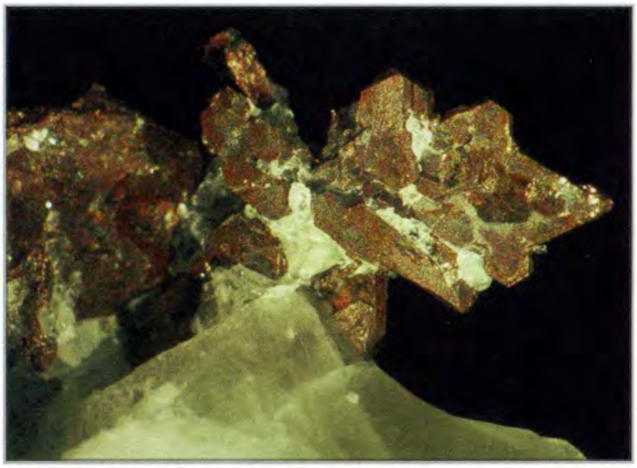
Chalcanthite (copper sulphate) Inspiration Mine, Miami, Arizona.



Vanadinite (lead chlorine vanadate), Grey Horse Mine, Pinal County, Arizona.



Copper in gypsum, Tohono O'odham First Nation, Pima County, Arizona.



Native copper, ASARCO Ray Copper Mine, Pinal County, Arizona.

Lavender Pit, Bisbee, Arizona.

Gossan underground in the Queen Mine, Bisbee, Arizona.

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