Environmental Geology of the Highlands

Field Guide and Proceedings

Edited by
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GEOLOGICAL ASSOCIATION OF NEW JERSEY

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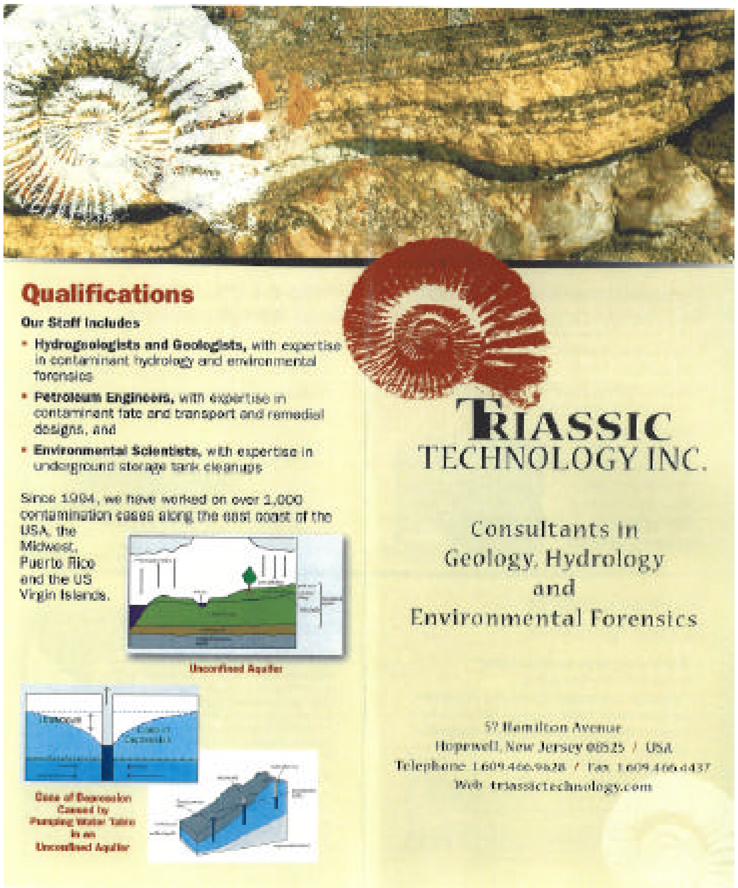

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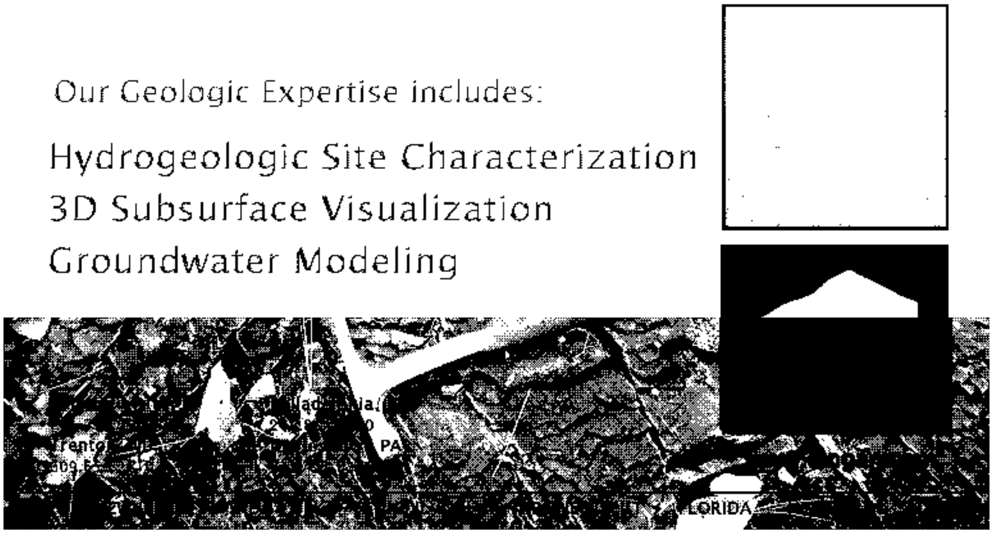

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Conference Schedule

Friday, October 13, 2006

Registration - 11:00 am to 5:00 pm

12:00–12:10	Welcoming Remarks - GANJ President Alexander E. Gates, Rutgers University-Newark
12:10–12:30	Acid-Mine Drainage at Phillips Mine, Putnam County, NY - Sivajini Gilchrist, Rutgers University-Newark
12:30–12:50	Effects of Land Use on Baseflow Water Quality Along a Development Gradient in the Hudson Highlands of New York = Paul Heisig, U.S. Geological Survey
12:50–1:10	Hydrogeological Framework of the Middle Proterozoic Gneiss and Granite Based on Optical Televiewer Surveys at Two Ground Water Pollution Sites in Morris County, NJ - Greg Herman, New Jersey Geological Survey
1:10–1:30	Pesticides in Highlands Water: Issue of Science and Policy - Howard Horowitz, Ramapo College of New Jersey
1:30–1:50	Iron Deposits of the Hudson Highlands - Marian V. Lupulescu, Rutgers University-Newark
1:50–2:10	Asbestiform Minerals in the Bedrock of the New Jersey Highlands: Geology and Environmental Health Implications - John H. Puffer and Donald N. Smith, Rutgers University-Newark, and Mark Germine, Mount Shasta, CA
2:10-2:30	Break
2:30-2:50	Glacial Aquifers of the New Jersey Highlands - Scott Stanford, New Jersey Geological Survey
2:50-3:10	Radon-222 Occurrence in Ground Water in New Jersey, with Emphasis on the Highlands Province - Zoltan Szabo, U.S. Geological Survey
3:10-3:30	Fracture Systems in the Western Hudson Highlands - David Valentino, State University of New York-Oswego
3:30-4:00	An Integrated Geoelectric Approach for Predicting Groundwater Flow Direction in Fractured Media - Debonne Wishart, Rutgers University-Newark
4:00-4:30	Conditions and Evaluation of Water Resources of the New Jersey Highlands - Otto S. Zapeca
4:30-5:15	Teacher's Workshop - "A Shot in the Dark" - An Introduction to the Scientific Method -Richard L. Kroll, Kean University
5:30-6:15	Keynote Speaker – Linda C.S. Gundersen, Associate Director of the U.S. Geological Survey - Geologic Controls on Natural Environmental Issues in the Reading Prong
6:30	Banquet and Business Meeting

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PRESENTATION ABSTRACTS

GEOCHEMISTRY OF ACID MINE DRAINAGE FROM SULFIDE-RICH SPOILS AT PHILLIPS MINE, PUTNAM COUNTY, NY

Sivajini Gilchrist and Alexander E. Gates, Department of Earth and Environmental Sciences, Rutgers University, Newark, New Jersey

Geochemical studies of the water, soil and sediment at Phillips Mine, Putnam County, New York, show pollutant concentration of heavy metals and trace elements resultant from extensive weathering and oxidation of sulfurous tailings and waste rocks. Metals of environmental concern in water appear to occur below pH 3.0. The low pH is also an indication of the lack of a buffering capacity to neutralize the acidic waters. With increasing pH downstream from the tailings pile, metal loadings dropped precipitously, suggesting sequestration by oxides into sediments. Sediment samples were collected two hours after heavy rainfall to assay for metal loadings from high flow conditions. Metal pollutants, As, Ni, Se and Zn, were enriched in sediments with increasing pH downstream, diluted by rainwater. Sediment rich in organic matter appear to sequester the most metals. Significant amounts of Cu, Cr, Ni and Se were present in the mine soil samples. Mine soil color at the dump is primarily brownish-yellowish, reflecting presence of Fe-oxides and hydroxides. The oxides may be the dominant secondary minerals for sorption of the metals at the mine dump.

RESPONSE OF STREAM BASE FLOW CHLORIDE AND NITRATE CONCENTRATIONS TO INCREASING INTENSITY OF UNSEWERED RESIDENTIAL LAND USE IN THE HIGHLANDS OF SOUTHEASTERN NEW YORK (CROTON WATERSHED)

Heisig, Paul M., U.S. Geological Survey, 425 Jordan Rd., Troy, NY 12180, pmheisig@usgs.gov.

Concentrations of chloride and nitrate in stream base flow were positively correlated with road and septic system densities, respectively, in the Croton watershed, located largely within the Highlands of southeastern New York. Base flows of 30 streams that cover the range of residential land-use intensity were sampled seasonally for 1 year to characterize the quality of ground-water contributions to streams, which ultimately feed several New York City reservoirs. Subbasin selection criteria included: 1) small unsewered subbasins (=1.5mi^2), which provide the best control over land-use characteristics, 2) no upstream point sources, which could alter the ground-water quality signal, and 3) no upstream water impoundments, which could add a storm water-quality signal to stream base flow.

Road density and unsewered housing (septic system) density were used as measures of the intensity of development within each subbasin. Two-lane road density was used as an indicator of annual road-salt application rate because the application-rate estimates for two-lane roads were relatively uniform; basins with four-lane highways were omitted from the analysis. Unsewered housing density was used to indicate the intensity of wastewater disposal within each subbasin. The subbasins with riparian wetlands were omitted because of the potential for nitrate loss through denitrification.

Chloride concentration was used as an indicator of road-salt application because it is conservative and is a component of all types of road salt used in the study area. Nitrate concentration was used as an indicator of domestic-wastewater because it is typically the most stable nitrogen species in domestic wastewater plumes in oxygenated ground waters.

Log base flow chloride concentration was positively linearly correlated with log two-lane road density (30 stream basins) and base flow nitrate concentration was positively linearly correlated with unsewered housing density (27 stream basins). The chloride relation with road density varies little with season, whereas the nitrate relation with unsewered housing density changes seasonally, with the highest observed nitrate concentrations during the winter and the lowest concentrations during the summer. These variations are attributed to increased biologic activity (denitrification, algal and plant uptake) during the warmer months. Base flow nitrate concentrations in unsewered basins with wetland buffers between residential development and the stream are typically lower than concentrations predicted by their respective unsewered housing density.

These findings suggest that chloride and nitrate concentrations in base flows can be predicted in small currently developed subbasins or in subbasins where unsewered residential development is contemplated. The full report can be accessed on line at: http://ny.water.usgs.gov/pubs/wri/wri994173.

HYDROGEOLOGICAL FRAMEWORK OF MIDDLE PROTEROZOIC GRANITE AND GNEISS FROM BOREHOLE GEOPHYSICAL SURVEYS AT TWO GROUND-WATER POLLUTION SITES, MORRIS COUNTY, NJ.

Gregory C. Herman, NJ Geological Survey

The New Jersey Geological Survey collected borehole geophysical data in a set of six-inch-diameter deep bedrock wells drilled into Middle Proterozoic granite and gneiss in Morris County, New Jersey. The data were collected at two ground-water pollution sites in 2002 and 2004 to identify and characterize the subsurface geology that controls the storage and movement of ground water and associated volatile organic compounds resulting from commercial manufacturing and waste disposal activities. Both sites are underlain by hornblende granite (Drake and others, 1996) and are about three miles apart along the structural strike. Data were collected in one well at the first site and five wells at the second. The depth of investigation for the geophysical investigations ranged from 17 to 511 ft below land surface. Optical televiewer, fluid temperature and fluid electrical resistivity or conductivity data were used to establish the hydrogeological framework. Heat-pulse flowmeter data were collected in three wells at the second site to locate water-bearing zones and to characterize borehole cross flows under natural conditions.

HERBICIDE USAGE IN HIGHLANDS LAKES: DISTRIBUTION, FREQUENCY, AND CONSEQUENCE

Howard Horowitz, Ramapo College of New Jersey

Aquatic herbicides are widley-used in the NY-NJ Highlands. State regulatory agencies issue hundreds of permits annually in the region; maps of treated lakes reveal how widespread the usage is. Lakes are usually re-treated each year, often in combination with multiple applications of copper-based algaecides. The stated purpose of these pesticide treatments is to control unwanted plants – most frequently Eurasian watermilfoil – although the pesticides do nothing to reduce the causes of the weed problems and provide only a temporary control. An array of alternatives exists and will be described. Although various combinations of alternatives are more effective and less expensive than pesticides, the regulatory system neither requires nor encourages the consideration of less-toxic options. USGS monitoring has revealed the presence of pesticides in over 90% of regional water samples, but residue monitoring of operational lake treatments is not required. The very few sites that have been monitored suggest that residues are both widespread and persistent, especially in sediments. The ecological impacts and potential health impacts of these aquatic pesticide programs are inadequately studied and poorly known.

IRON DEPOSITS FROM HUDSON HIGHLANDS, NY: SYSTEMATICS, MINERALOGY, MINERAL CHEMISTRY, AND TECTONIC SETTING

Marian Lupulescu, New York State Museum, Research and Collections, Albany, NY 12230 and Alexander Gates, Department of Earth and Environmental Sciences, Rutgers University, Newark, NJ

Recent field, mineralogical, geochemical and structural investigations of the iron occurrences and deposits from the western Hudson Highlands (HH) of southern New York (NY) reveal new data on their systematics, mineralogy, mineral chemistry of the ore components, metasomatic-hydrothermal alteration, character of the fluids and tectonic setting.

Four types of iron deposits can be recognized in the Grenville metasedimentary, metaigneous and metavolcanic rocks from the HH region of NY based on their mineralogy and geochemistry: a. Fe oxide; b. Fe oxide – (Fe + Cu) ± Ni, Co, Mo sulfides; c. Fe oxide – Fe and (Fe + Cu) sulfide – U oxide; d. Fe oxide ± Fe and (Fe + Cu) sulfide + REE. These deposits are hosted by calc-silicate, quartzofeldspathic gneisses and amphibole-rich gneisses and contain a main iron oxide (magnetite) sequence overlapped in places by sulfide mineralization. They display a large array of metamorphic and metasomatic-hydrothermal features revealing their diverse origin and complex geologic evolution.

The principal oxide mineral is magnetite. It is associated in places with ilmenite, pyrophanite-rich ilmenite and uraninite. The sulfide sequence has pyrrhotite, chalcopyrite, pyrite, rare pentlandite, cobaltite and molybdenite. The main rock-forming minerals accompanying the ore are: hastingsite, diopside, salite, enstatite, ferrosilite, almandine, olivine (hortonolite to ferrosiderite), phlogopite, F-dominant phlogopite, and Cl-dominant annite. Crystallographycally oriented exsolutions of ulvospinel, hercynite and gahnite in magnetite are of metamorphic origin.

The alkali-halogen metasomatism is characteristically accompanied by spatially associated (related?) iron oxide, sulfide and REE or U occurrences and generated a distinctive suite of chlorine-, fluorine- and potassium-rich silicate minerals including Cl-, F- and K-rich/dominant amphiboles and phlogopite-annite. The halogen incorporation in the amphiboles and micas is controlled by crystal chemistry and has significant contributions to their thermal stability. The hydration reactions between halogen-bearing crustal-derived fluids and pyroxenes and/or Fe-Ti oxides from the host rocks and ore formed the halogen- and potassium-rich/dominant amphiboles and subsequently, phlogopite-annite minerals. The mineral composition of the ore, the absence of martite, the Fe^{3+}/Fe^{2+} ratio suggest a relatively low $f(O_2)$ for the fluids. If the source of potassium can be attributed to a locally K-rich in situ isochemical metamorphism or to the K-rich igneous rocks, the source for both Cl and F is not clear, but high saline crustal brine can be considered.

There are several modes of emplacement for the magnetite ore. Early occurrences and deposits appear to have formed through metasomatic-hydrothermal replacement within the host rock. Partial melts in the granulite facies followed by late hydrothermal activity remobilize some of the early metasomatic ore in dilatational zones (pull apart and stepover structures) in late transcurrent faults.

Tailings from the mining operations in these deposits pose environmental threats with the release of sulfur through oxidation reactions ultimately producing sulfuric acid and the release of inorganic pollutants in the form of secondary (weathering-derived) toxic metallic and radioactive compounds.

ASBESTIFORM MINERALS IN THE BEDROCK OF THE NEW JERSEY HIGHLANDS: GEOLOGY AND ENVIRONMENTAL HEALTH IMPLICATIONS

John H. Puffer, Donald N. Smith, and Mark Germine*, Department of Earth & Environmental Sciences, Rutgers University, Newark, NJ 07930,
***Mount Shasta, CA 960607**

Bedrock exposed at several locations throughout the New Jersey Highlands and adjoining areas contains asbestiform minerals. Among the localities where fibrous tremolite bearing marble is exposed are the active Limecrest (Southdown, now Cemex) quarry near Sparta, and the inactive Williams quarry in Forks. Crocidolite bearing protomylonite is exposed at Mendham, and bedrocks containing asbestiform minerals are exposed in many other localities. Each of these exposures could potentially contaminate air and water supplies. Evidence is presented that some air and water supplies have already been contaminated. Pulverized marble containing fibrous tremolite from the Limecrest Quarry has been used on lawns and gardens throughout the Mid-Atlantic region, creating an additional potential for exposure. The issues of the analytical definition of asbestos fiber are discussed, and it is concluded that most mineralogical definitions have little relevance to health issues, i.e., asbestos-related diseases. An asbestos contaminated play sand issue is reviewed as a case-in-point. The carcinogenicity of chrysotile seems to be related largely to traces of fibrous tremolite in chrysotile ore. The effects of weathering on amphibole fiber genesis are discussed, and formation of an oxidation product that may be the agent of carcinogenesis of amphibole asbestos is documented.

GLACIAL AQUIFERS OF THE NEW JERSEY HIGHLANDS

Scott D. Stanford, New Jersey Geological Survey, P. O. Box 427, Trenton, NJ 08625
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Glacial aquifers in the New Jersey Highlands are valley-fill deposits of sand and gravel laid down in glacial lakes and glacial river plains during the Illinoian and late Wisconsinan glaciations. In places they are interbedded with less-permeable silt, clay, fine sand, and till, which act as confining or semi-confining layers. The distribution of sediments within a valley-fill aquifer is determined by the geologic setting of the valley and on the volume of glacial sediment it received. There are four types of valley fill. Three (filled lake basins, unfilled lake basins, and stacked valley fills) are in valleys that contained glacial lakes and one (fluvial valley fills) is in valleys that did not contain glacial lakes. Filled lake basins have an upper unconfined sand and gravel overlying a confining or semiconfining layer of silt, fine sand, and clay, in turn overlying a lower, confined sand and gravel aquifer. Unfilled lake basins are similar but lack the upper unconfined sand and gravel. Stacked valley fills contain multiple layers of sand and gravel, silt and clay, and till. Fluvial valley fills have just a single unconfined sand and gravel aquifer. Where glacial sediments are too thin to be productive aquifers themselves, they nevertheless provide storage to feed stream baseflow and recharge underlying bedrock aquifers. Large areas on uplands north of the late Wisconsinan terminal moraine are exposed bedrock without a mantle of glacial sediment and so have little groundwater storage potential.

RADON-222 OCCURRENCE IN GROUND WATER IN NEW JERSEY, WITH EMPHASIS ON THE HIGHLANDS PROVINCE

Szabo, Zoltan, and dePaul, Vincent T., U.S. Geological Survey, 810 Bear Tavern Rd., W. Trenton, NJ 08628, zszabo@usgs.gov; Gardner, Patricia L, Kopera, Anita J., and Goodman, Jenny, New Jersey Department of Environmental Protection, Bureau of Environmental Radiation, Box 415, Trenton, NJ 08625, patricia.gardner@dep.state.nj.us.

Draft: Pursuant to the provisions of the Safe Drinking Water Act 1996 Amendments, the U.S. Environmental Protection Agency (USEPA) proposed a 300 pCi/L (picocuries per liter) Maximum Contaminant Level (MCL) and a 4,000 pCi/L Alternate MCL (AMCL) for radon-222 (Rn-222) in drinking water. The USEPA also developed guidelines for multimedia mitigation (MMM) programs, which are designed to reduce Rn-222 concentrations in indoor air for those states and community water-supply systems choosing to comply with the AMCL. As of 2006, however, the USEPA-proposed MCL, AMCL, and MMM program had not been adopted. State agencies seeking to implement such MMM programs or choosing to proceed with their own MCL for radon in water must maximize risk reduction for both air and water exposure. To address possible approaches to the Rn-222 in drinking-water issue, the New Jersey Department of Environmental Protection (NJDEP) has requested a review, to be completed by 2007, of occurrence data, analytical methodology, and studies of health effects by the New Jersey Drinking Water Quality Institute. A draft (unpublished) statewide ground-water Rn-222 occurrence map had been assembled by NJDEP from concentration data compiled cooperatively by the U.S. Geological Survey (USGS) and NJDEP. Rn-222 concentrations in about 500 raw-water samples collected from production, domestic, and observation wells by the USGS were combined with those in more than 1,500 raw-water and point-of-entry samples collected from community-water-supply systems and domestic wells by NJDEP; all concentrations were determined by liquid scintillation. The arithmetic mean concentrations for each of the incorporated communities were grouped on the basis of whether this value did or did not exceed the proposed MCL and AMCL of 300 and 4,000 pCi/L, respectively. (The arithmetic mean was used because this value is strongly affected by outliers and thus represents the “worst-case” scenario. The standard deviation about the arithmetic mean concentration for each township in many cases exceeded the mean, indicating considerable variability in concentration.). The ground-water Rn-222 occurrence map was coupled with a previously developed map of indoor-air radon potential in New Jersey. This map classifies communities as having high, moderate, or low indoor radon potential on the basis of the percentage of indoor-air Rn-222 concentrations that exceed the Action Level of 4 pCi/L. By combining air and water Rn-222 occurrence information, communities might be identified where risk reduction for both air and water exposure could be maximized.

The high-indoor-radon-potential areas of the State include most of the western and central two-thirds of the Highlands Physiographic Province and the western one-third of the Piedmont Province as well as a small southwesterly part of the Valley and Ridge Province. About 15 percent of the samples from the Highlands Province had Rn-222 concentrations greater than 10,000 pCi/L (maximum, 170,000 pCi/L, Mansfield Township, Warren County) and about 35 percent were greater than 4,000 pCi/L; Rn-222 concentrations greater than 4,000 pCi/L were infrequent in the Piedmont Province and absent in the other Physiographic Provinces. The results of this initial assessment indicate that the risk solely from water ingestion probably is greatest in the Highlands Province. Indoor-air radon-abatement programs such as “radon-resistant” building codes are already mandatory in communities in the high-indoor-radon-potential areas of the State.

Water samples from production and observation wells and from distribution systems from community water supplies containing Rn-222 concentrations that approach the USEPA-proposed AMCL (between 3,000 and 4,000 pCi/L) were mostly from the high-radon-potential areas in the central and north-central parts of the State; primarily, but not exclusively, centered on the Highlands Province, and occasionally in moderate-indoor-radon-potential areas of the State. The ground-water Rn-222 concentrations in the moderate-radon-potential areas in the north-central, northeastern, and southwestern parts of the State (corresponding roughly to the east-central part of the Highlands Province, the east-central part of the Piedmont Province, and the northern two-thirds of the inner part of the Coastal Plain province, respectively) generally fall between the proposed 300-pCi/L-MCL and the 4,000-pCi/L AMCL. Residents in the communities in the moderate-indoor-radon-potential areas may face risk from inhalation of Rn-222 degassed from ground-water supply because construction of radon-resistant housing is not mandatory. The presence of some local clustering in the data indicates that additional monitoring of Rn-222 concentrations in ground water in the high- and moderate-indoor-radon-potential areas may result in identifying physical or geological variables not yet considered that may associate with the highest Rn-222 concentrations and might be used to generate a more detailed understanding of Rn-222 occurrence.

JOINTS AND FAULTS IN THE HUDSON HIGHLANDS, NEW YORK

David Valentino, Department of Earth Sciences, State University of New York at Oswego, Oswego, NY

In conjunction with bedrock mapping for the StateMap program in NY State, joint maps, including joint attitude and joint density for multiple sets were produced for the Monroe, Sloatsburg, Thiells, Popolopen Lake and Greenwood Lake 7.5' quadrangles, located in the Hudson Highlands, southern New York State. This area of the Hudson Highlands is mostly underlain by high-grade metamorphic and igneous rocks that experienced a long history of ductile deformation associated with the Grenville orogenic cycle (Gates et al., 2004). Joint orientations are highly consistent across the entire Grenville massif of the western Hudson Highlands and some joint sets correlate with mapped faults and topographic lineaments. Minor joints that are parallel to foliation occur in all bedrock units. The general strike of these joints is northeast-southwest, and the dip is variable depending on the attitude of the local foliation. Although most topographic lineaments are parallel to, and can be correlated with bedrock units, there are many, that range in length from 1-5 km, that cross the regional bedrock structure. These lineaments are most pronounced west of the Ramapo Fault in the Sterling Forest, but a few transect the valley between the western and eastern structural blocks that form the Hudson Highlands. These lineaments extend for 10's of kilometers, and correlate with faults that offset the bedrock Proterozoic structure. This field trip guide will examine the relationship of these faults, joint orientation and joint intensity.

HYDRAULIC AND ELECTRIC ANISOTROPY CHARACTERIZATION OF THE NEW JERSEY HIGHLANDS FRACTURED BEDROCK

DeBonne N. Wishart, Lee D. Slater, and Alexander E. Gates, Department of Earth & Environmental Sciences, Rutgers University, 141 Smith Hall, Newark, NJ 07102

The fractured bedrocks of the New Jersey Highlands hold the principal resource that supplies potable drinking water to 2.5 million people throughout Bergen, Passaic, and Essex counties. Besides the Pinelands, the Highlands represent the last of the pristine lands in New Jersey having clean air and water. The nature of groundwater flow through fractures in the bedrock is extremely complex compared to flow through granular rocks that are porous with well-defined flow paths. Groundwater flow through a fracture network is strongly influenced by the preferential directionality (anisotropy) of fracture strike orientation and contaminants are primarily transported via the fractures in these rocks. The preferential fracture strike orientation makes rocks both electrically and hydraulically anisotropic, whereas the variation in the size and opening of fractures causes heterogeneity. Azimuthal resistivity surveys (ARS) have been used by several previous authors to characterize fractures as hydraulically-active based on the electrical anisotropy associated with the preferential strike of fractures in the subsurface. This assumption often results in the ambiguity of the subsurface fracture characterization.

In this hydrogeophysical investigation, we draw on the potential of the Earth's naturally occurring electrical field using self potential signals generated by subterranean flow. Both the self potential and electrical resistivity techniques are combined and both data sets compared with mapped fracture strike orientation data to interpret the direction of groundwater flow in the study region. We employ asymmetric azimuthal geoelectrical investigations at several sites in the New Jersey Highlands using a type of pole-dipole (non-linear) electrode array-the Arrow Type (AT) Array to perform self potential (SP), electrical resistivity (ER), and induced polarization (IP) measurements of the fractured subsurface. The objective of this study is to (1) characterize hydraulic anisotropy associated with the strike of dominant fractures sets and (2) understand the impact of structural heterogeneity on groundwater flow within this regional-scale fracture system.

AN OVERVIEW OF HYDROGEOLOGIC CONDITIONS AND WATER RESOURCES IN THE NEW YORK-NEW JERSEY HIGHLANDS REGION

Otto S. Zapecza, Donald R. Rice, Vincent T. dePaul, and Leon J. Kauffman
U.S. Geological Survey, West Trenton, New Jersey

The Highlands Region of New York and New Jersey, underlain predominantly by crystalline rock, is the source of water supply for more than 5 million people. The availability and sustainability of Highlands water resources are of particular concern because of its proximity to the New York City metropolitan area and corresponding developmental pressures. Geology and the degree of urbanization affect the infiltration, storage, availability and quality of Highlands water. Highlands reservoir systems supply more than 450 MGD (million gallons per day), 90 percent of which is transferred out of the Highlands to major metropolitan areas to the east. Ground water is the primary source of water used within the region, where bedrock and glacial valley-fill aquifers supply more than 145 MGD.

More than 1200 high capacity production wells draw water from Highlands aquifers for municipal supply, industrial, commercial, irrigation and mining uses. These aquifers include bedrock aquifers composed of crystalline, carbonate and clastic rock and unconsolidated buried valley fill aquifers of glacial origin. Glacial aquifers are the most productive with approximately 60 million gallons per day withdrawn in 1995. All bedrock aquifers combined produced approximately 56 million gallons per day in 1995. Domestic wells are the only source of potable water over wide areas of the Highlands that remain rural. Total domestic withdrawals for 1995 in the Highlands region are estimated to be 30 million gallons per day.

Changes in ground-water levels reflect the general response of Highlands aquifers to seasonal variations in precipitation, evapotranspiration, water use and ground-water withdrawals. Long term water-level monitoring has recorded water-level declines of about 5 to 15 feet during drought conditions over the last decade. Water levels have declined locally as much as 25 to 30 feet in the past 35 years in the Glacial aquifer system of the Whippany River Basin in eastern Morris County, New Jersey. Declining water levels are the result of ground-water withdrawals exceeding the natural recharge rate of the aquifer.

To assess the potential effects of continued suburban development on Highlands water resources, the U.S. Geological Survey, in cooperation with the U.S. Forest Service, used a watershed model (TOPMODEL) to simulate the effect of projected future growth including increases in impervious surface, population and water use on resource sustainability and to develop water budgets for 182 Highlands watersheds. Simulation results showed that on average, ground-water discharge to streams (baseflow) accounted for 73% of total streamflow over the region. The percentage of baseflow in relation to total streamflow indicates the water yielding capacity of an aquifer and a streams ability to sustain flow. Variations in the percentage of total streamflow that occurs as base flow depend mainly on the geology and degree of development in a watershed. Base flow accounts for more than 80% of streamflow in watersheds where the geology is characterized by a high percentage of carbonate-rock and glacial aquifers, which have relatively high recharge rates and water-storage capacities and well yields. In contrast, base flow accounts for less than 50% of streamflow in some of the most urbanized areas with large ground-water withdrawals such as Rockland County, New York, and Morris County, New Jersey. The model predicted the change in stream runoff, base flow, and evapotranspiration increases substantially for watersheds with a projected increase of 15% or more in impervious cover with respect to 1995 conditions, and that runoff may increase 50% or more, and base flow may decrease 10% or more, in these watersheds.

The U.S. Geological Survey in cooperation with the New Jersey Highlands Council is evaluating ground-water capacity and demand in 183 subwatersheds within the New Jersey Highlands Region. These subwatersheds range in size from three to 21 square miles. A comprehensive analysis of low flow statistics of Highlands streams and the physical characteristics of the regions watersheds are used in conjunction with water use data to evaluate ground-water capacity. The 10 and 25-year baseflow recurrence intervals and the difference between the September median flow in a stream and the lowest total flow over seven consecutive days during a ten year period, the 7Q10, are stream low-flow statistics that indicate the probable amount of water in streams from ground-water discharge through a range of climatic and ecologically based conditions. This allows for an evaluation of the water supply potential of surface and ground-water systems in the region over a wide range of hydrologic conditions. The difference between the amounts of water estimated using stream low-flow statistics and consumptive ground-water use is then used as an indicator of ground-water capacity in Highlands subwatersheds.

GEOLOGIC CONTROLS ON NATURAL ENVIRONMENTAL ISSUES IN THE READING PRONG

Keynote Speaker – Linda C.S. Gundersen, Associate Director of the U.S. Geological Survey

The long and fruitful mining history of the Reading Prong, coupled with the great diversity of rock types that comprise this Proterozoic terrain, create a complex background with which to understand the environmental geology of the region. The Reading Prong has been mined since the 1700's for a wide range of minerals and mineral materials ranging from iron, sulfur, copper, zinc, and graphite in the past to the present day crushed stone, sand, and gravel. Exploration for rare earth elements and uranium in the past century, lead to the discovery that a number of the iron mines and certain distinctive rock types contained significant radioactive minerals. The awareness in the early 1980's of radon as an indoor air toxicant further provided extensive research and testing for radon in water, soils, and rocks and indoor air in the region; identifying anomalously high concentrations of radionuclides related to mineralization in certain kinds of rocks, veins, and faults. Notably, uranium mineralization is most often found as uraninite in magnetite ore and its host gneiss and in pegmatites, uraninite and U-bearing allanite in pyroxene gneiss, U-bearing monazite and xenotine in biotite-bearing paragneiss, and U-bearing minerals variably concentrated in marbles, veins, faults, and shear zones. A distinct linear trend of uranium and radon in rocks, soils, water, and homes found in the Boyertown, Pennsylvania area is one of the better known examples of the concentration of uranium in a mylonitic shear zone.

Because the Reading Prong is a rich mineral province, hundreds of abandoned mines and unmined mineral deposits can be found through-out the region and can potentially contribute metals to the environment though drainage or the use of mine tailings as fill and aggregate. Some of the rock types hosting these mines and deposits have higher potential than others for producing acid or alkaline mine drainage, leading to the mobilization of certain metals found in these rocks such as As, Cu, Cd, Co, Cr, Ni, Ra, U, V, and Zn. Rock types dominated by quartz and feldspar, containing base metal sulfides and hosting iron, copper, uranium and other metal deposits, have poor buffering capacity and can potentially produce acidic ground and surface waters, especially where the rocks are faulted, or weathered. Rocks dominated by calc-silicate minerals and/or carbonate minerals will tend to buffer chemical reactions, have more normal or high pH ground and surface waters, that will be less likely to mobilize certain metal accumulations contained within them. However some of these highly alkaline waters can mobilize certain metals like U given the right chemical conditions. Population growth in the area has increased significantly in the last century, increasing the need for resources - most notably land, aggregates, and water, resulting in conflicts over use and the need for an awareness of the local and regional geology.

TECHNICAL PAPERS

GEOCHEMISTRY OF ACID MINE DRAINAGE FROM SULFIDE-RICH SPOILS AT PHILLIPS MINE, PUTNAM COUNTY, NY

Sivajini Gilchrist and Alexander E. Gates, Department of Earth and Environmental Sciences, Rutgers University, Newark, New Jersey

ABSTRACT

Geochemical studies of the water, soil and sediment at Phillips Mine, Putnam County, New York, show pollutant concentration of heavy metals and trace elements as a result of extensive weathering and oxidation of sulfurous tailings and waste rocks. Metals of environmental concern in water appear to occur below pH 3.0. The low pH is also an indication of the lack of a buffering capacity to neutralize the acidic waters. With increasing pH downstream from the tailings pile, metal loadings dropped precipitously suggesting sequestration by oxides into sediments. Sediment samples were collected two hours after heavy rainfall to assay for metal loadings from high flow conditions. Metal pollutants, As, Ni, Se and Zn, were enriched in sediments with increasing pH downstream, diluted by rainwater. Sediment rich in organic matter appear to sequester the most metals. Significant amounts of Cu, Cr, Ni and Se were present in the mine soil samples. Mine soil color at the dump is primarily brownish-yellowish, reflecting presence of Fe-oxides and hydroxides. The oxides may be the dominant secondary minerals for sorption of the metals at the mine dump.

INTRODUCTION

Before the discovery of iron in the Highlands, early European settlers depended on shipments mainly from Britain (Ransom, 1966). When iron was discovered in the Highlands in the 1730s, a booming iron industry flourished before being abandoned in early 1920s (Smock, 1889; Ransom, 1966; Lenik, 1999). Current mining activities resulted in many environmental hazards including abandoned mines and exploratory pits, tailings and waste rocks, abandoned processing buildings, and equipment. Tailings are crushed or milled rock particles from which the ore has been extracted. Because of their large surface areas, tailings are chemically very reactive. Waste rocks are those that are removed during mining activities that have no commercial value. However, waste rocks may contain raw metal and sulfur compounds, which contribute to acid mine drainage (Ripley, 1996). When exposed to the atmosphere, tailings and waste rocks undergo extensive weathering and oxidation

The Highlands are part of the Reading Prong geologic province composed of the Grenvillian massifs (Offield, 1967; Volkert, 2001) (Figure 1). High-grade metamorphic and igneous crystalline rocks dominate the region. The Highlands geology is composed of many rock types of Precambrian metamorphic and igneous origins with numerous mineral types (Offield, 1967).

The Highlands is a major watershed for many surrounding communities and municipalities. The physicochemical state of the tailings and waste rocks at many of the abandoned mines in the Highlands is an environmental concern because of their potential to generate acid mine drainage (AMD). AMD is the result of water becoming acidic due to metal enrichment of iron, sulfate and other metals. These metals enter the environment through weathering and leaching when geologic materials containing sulfides are exposed to the atmosphere or oxidizing environments. Metal contamination from AMD can destabilize the background concentration of metals in natural settings (Pratt et al, 1996; Nordstrom and Alpers, 1999) at levels potentially deleterious to biota, ultimately impairing the foodchain.

The purpose of this study is to characterize the chemistry of the soil, sediment and surface water at the abandoned sulfurous mine dump at the Phillips Mine in Putnam County, NY (Figure 1). The focus of this study is on the metals weathering significance and the sulfur content.

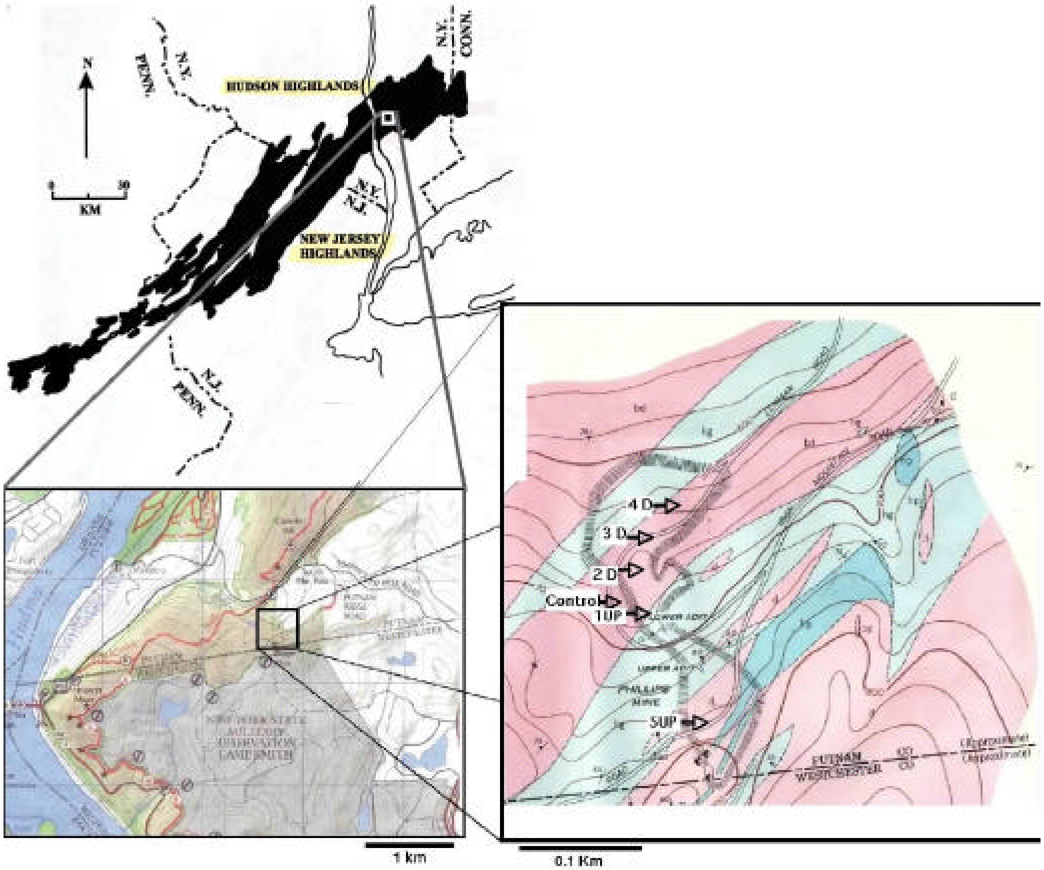


Figure 1. The Reading Prong geologic province of the Grenvillian massifs. The first inset indicates the location of the Phillips Mine. Second inset shows extent of tailing distribution (hachure marks) and soil sample locations (maps adapted from Gundersen, 2004; East Hudson Trail map,2003; Klemic et al, 1959).

SITE GEOLOGY AND MINING HISTORY

Hornblende gneiss, biotite-diorite, and hornblende pegmatite units underlie the study area (Kemp, 1894; Loveman, 1911; Klemic et al, 1959; Campbell et al, 1977). Hornblende gneiss, the oldest unit, was intruded by diorite. Both hb-gneiss and diorite were later intruded by hb-pegmatite (Klemic et al, 1959). The hb-gneiss unit is largely composed of alternating layers of light feldspathic and dark hb-rich materials. Pegmatites are composed of two types of rocks: hornblende pegmatite and oligoclase-quartz pegmatite (Klemic et al, 1959). Hornblende pegmatite contains the radioactive mineral uraninite (Klemic et al, 1959). The lenticular massive pyrrhotite-pyrite ore body is emplaced in the hb-gneiss, dipping steeply northwest and plunging northeast (Klemic et al, 1959).

The fumes from processing the ore were devoid of arsenic, which made it attractive for sulfur mining and production of sulfuric acid (Kemp, 1894). Mining operations began after the Civil war (about 1866) and continued for approximately 10 – 15 years thereafter (Klemic et al, 1959). No smelting was reported but based on the grain size of the vast amount of tailings at the mine dump (Figure 3), some form of milling or crushing might have been performed at the site to extract the ore. Ore was transported to Staten Island for processing into sulfuric acid (Kemp, 1894; Klemic et al, 1959).

Figure 2. Phillips Mine: Coarse to fine-grained tailings in the foreground. Sparse vegetation is present on the tailings but spatially distributed.

Both tailings and waste rocks (source hb-pegmatite, hb-gneiss and diorite) from the mining operations remain uncontained and naturally subjected to extensive oxidation (Figure 2). Surface water from the lower adit (Figure 1) flows through the tailings that are distinctively coated with colloidal iron-oxides. The sparse vegetation on the mine spoil even after 125 years of weathering is an indication of the sulfurous nature of the soil.

The following general stoichiometry sequence of pyrite oxidation generates acid mine drainage and is applicable to the Phillips Mine based on the physicochemical state of the mine spoil (Singer and Stumm, 1970; Forstner and Wittmann, 1981; Nordstrom and Alpers, 1999; Blowes and Jambor, 1990)):

$$2\ FeS_2 + 7\ 0_2 + 2\ H_2O\ ?\quad 2\ Fe^{2+} + 4\ SO_4 + 4\ H^+$$

$$4\ Fe^{2+} + O_2 + 4\ H^+\ ?\quad 4\ Fe^{3+} + 2\ H_2O$$

$$4\ Fe^{3+} + 12\ H_2O\ ?\quad 4\ Fe(OH)_3 + 12\ H^+$$

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O\ ?\quad 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$$

Pyrrhotite, the most vulnerable to microbial oxidation (Blowes and Jambor, 1990), follows a similar pattern of oxidation (Pratt et al, 1996; Jerz and Rimstidt, 2003).

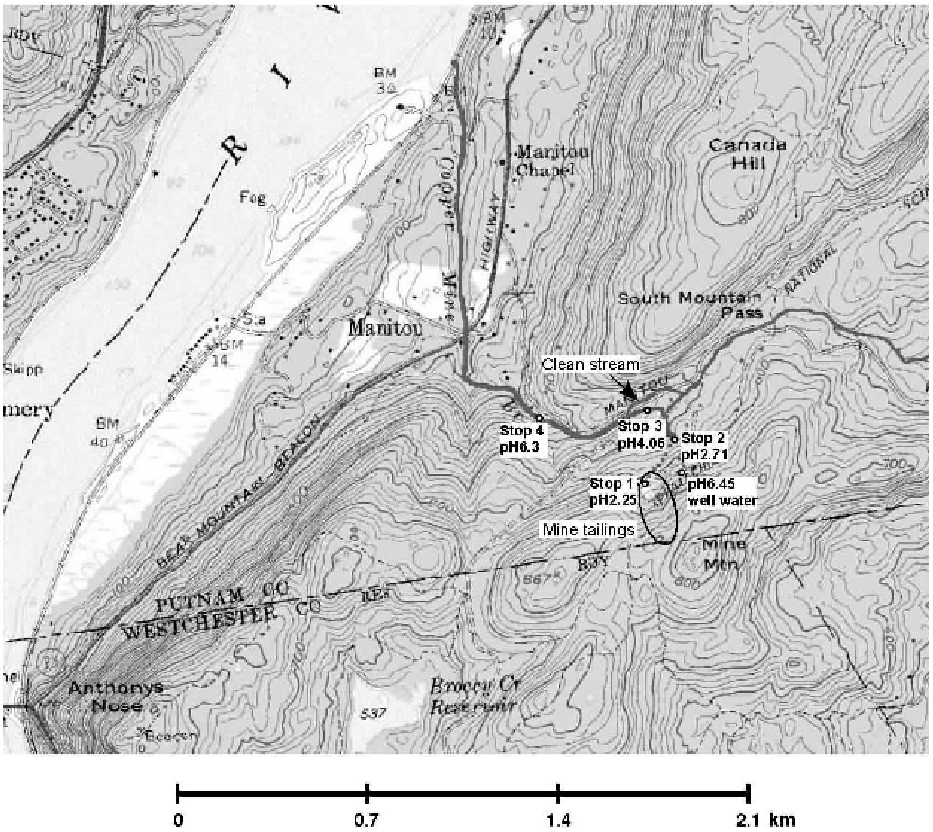
$$Fe_{1-x}S + 9\text{-}3x/4\ O_2 + 5\text{-}x/2\ H_2O\ ?\quad (1\text{-}x)Fe(OH)_3 + H_2SO_4$$

METHODOLOGY

AMD-contaminated surface waters upstream that flow from the lower adit through the tailings, and waters flowing downstream from the tailings pile were collected in acid washed bottles (Figure 3). Groundwater from a well at a nearby location was also collected as a control sample. Waters were acidified to pH 2 or less with ultra pure nitric acid, and dispatched to USGS site in Trenton, New Jersey. Samples were analyzed using ICP-MS by a USGS affiliate in Denver, Colorado.

Field analyses of water samples were performed using YSI pH and temperature meter, ATI Orion conductivity meter, and 2100P HACH turbidity meter. Locations were logged using a hand held GPS instrument. The instruments were calibrated before each collecting trip.

Grab samples of mine soil and sediment were collected on 11/8/05 and 5/16/06, respectively. Sediment samples were collected at the same locations as water samples (Figure 3). Mine soil 5UP was sampled near the main entrance to the mine. A native soil sample was collected at the periphery of the tailings to analyze for soil background levels in the area. Grab samples with moderate to minimal moisture were air dried at room temperature. Moisture-laden grab samples were dried at 400 C in an oven. Dried stream sediments and mine soils were sieved before pulverization at Montclair State University. Only grain sizes 1.0 mm or less were analyzed, as they are chemically most reactive because of their high surface areas. Pulverized samples from each location were analyzed by ALS Chemex, Vancouver, Canada, using ICP-MS and ICP-AES.



Map Source: http://www.topozone.com

Figure 3. Water sample locations relative to mine tailings at the Phillips Mine dump. Copper Mine Brook drains into the Hudson River, west of the mine. Clean stream and well water samples represent control samples.

RESULTS

Chemistry of Water Samples

Concentration of elements of environmental concern in the mine waters is shown in Figure 4. High amounts of Al, Co, Cu, Fe and Ni were recorded for Stop 1 that yielded a pH of 2.25 in Spring 2006. Despite the low pH, Stop 1 Cr and Zn levels were slightly below NYDEC water quality action levels. At increased pH from 4.06 to 6.3 downstream from the tailings dump, the concentration of dissolved metal contaminants decreased precipitously. However, Stop 4 (pH 6.3) showed higher concentration of the Al and greater concentration of Co than NYDEC standards. The bed load at Stop 1 was coated with yellow precipitates and green algal mats. Except for Fe, the control sample (groundwater from a nearby well) metal loadings were well below NYDEC standards.

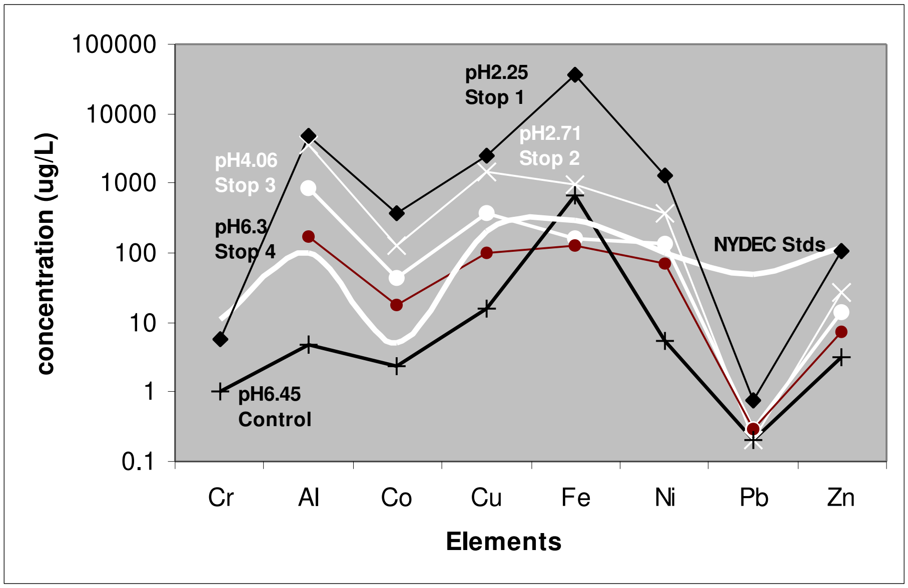


Figure. 4. Metal concentrations in water samples along Copper Mine Brook. Stop 1 sampled by the lower adit. Subsequent stops are downstream from tailings pile.

Chemistry of sediment samples

Sediment samples were collected two hours after heavy rainfall on May 16, 2006 to determine metal enrichment from high flow conditions. The rate of flow of the surface water at Stops 1 and 2 were less rapid than the flow rate at Stop 3, which was raging. Water pH measurements for each stop and oxide concentrations are shown in Table 1.

Table 1
Concentration of oxides in sediments

Sample	Water pH	Fe (%)	Mn (ppm)	Al (%)
5/16/2006				
Stop 1	2.58	34.5	33	0.93
Stop 2	3.07	32	110	1.51
Stop 3	5.47	14.6	404	3.72
Clean Stream (control)	6.53	2.96	642	4.37

There was an increase in pH (Table 1) relative to samples taken at the same locations in April 2006 (Figure 3). At Stops 1 and 2, metal concentrations in the sediments were generally low (Figure 5) except for Cu. Downstream from Stop 1, concentrations in sediments increased with increasing water pH. Manganese levels appeared to have been enhanced in the sediment by 3.3x at pH 3.07 and by 3.7x at pH 5.47 (Table 1 and Figure 5). However, at pH 5.47, Mn approached background levels for Stop 3. Control sample showed slight enhancement in Cu and Ni.

Partially exposed bedrock and mine spoils that form the bed sediment for Stop 1 was coated with iron precipitates, usually known as “yellow boy” (Nordstrom, 1979). Green algal mats of Klebsormidium rivulare (Stevens et al, 2001) dominated the acidic surface water at Stop 1. Similar observation of the algal mats was also found at Stop 2 with a small biomass.

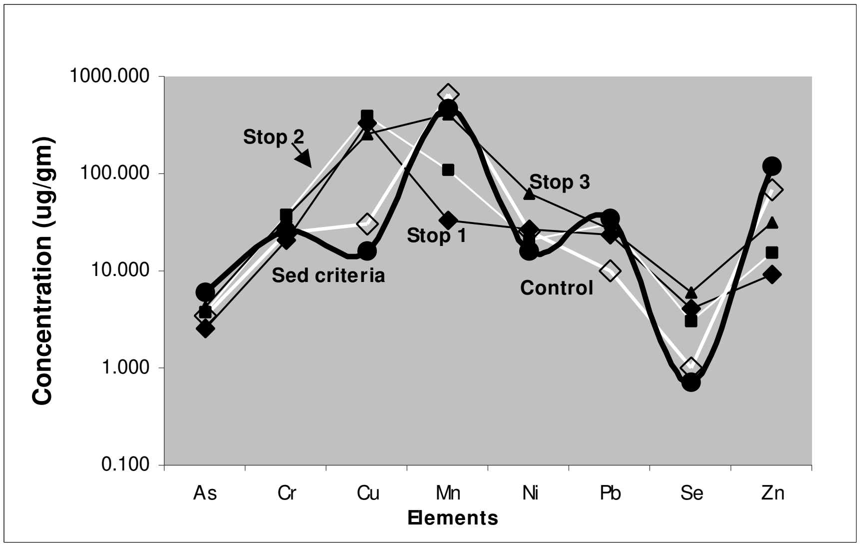


Figure 5. Metal concentrations in sediments along Copper Mine Brook. Sediment criteria based on lowest effect level (LEL) from Persaud et al. (1992) and Long and Morgan (1990).

Chemistry of mine soil samples

Samples 2D, 3D, 4D and 5UP (Figure 6) contained significant amounts of Cr, Cu, Ni and Se. Organic matter was a minor component in these samples. The control sample also showed considerable amounts of Cr, Cu, Ni, Pb, Se and Zn. The control sample,collected at the boundary between lush vegetation (on soil with moderate organic matter) and no vegetation (mine soil with no organic matter) was naturally present. Grain size of the control sample was very coarse and slightly oxidized (reddish black). In general, the mine soil color at the dump was primarily brownish-yellowish. Abundant Fe-Mn-Al oxides were detected in majority of the soil samples (Table 2).

Table 2
Concentration of oxides in mine soil samples

Sample	Fe (%)	Mn (ppm)	Al (%)
1UP	40.2	114	1.65
2D	23.7	1005	3.24
3D	18.3	788	2.03
4D	16.3	729	3.44
5UP	26.1	573	1.53
Control	8.34	160	9.18

Samples of the iron-oxide encrusted mineral grains found on the surface of the mine dump were examined under a petrographic microscope. The yellow coatings were heavily pitted and contained white precipitants. In some samples, small translucent yellow crystals were observed on the coatings.

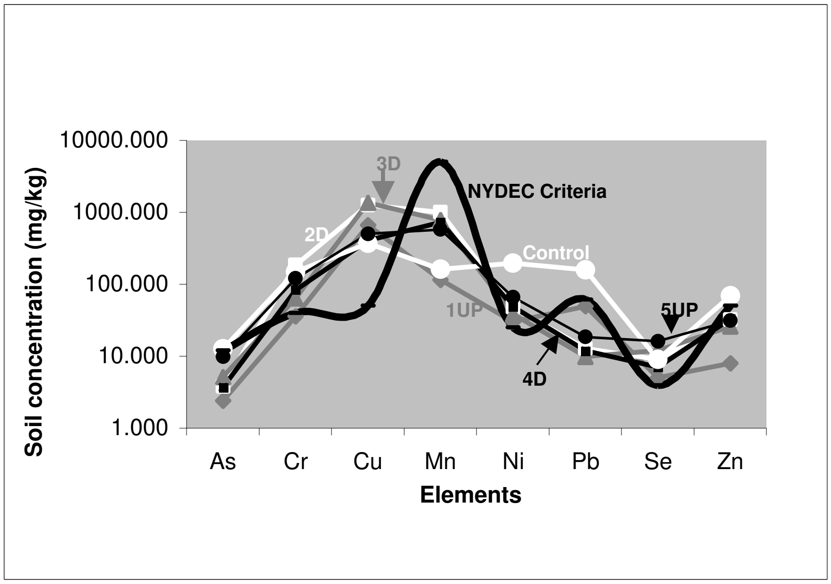


Figure 6. Metal concentrations in mine soil samples at the Phillips Mine dump. NYDEC soil criteria based on recommended soil cleanup objectives derived from average background concentrations for the Eastern USA.

DISCUSSIONS

Water

Water samples were collected to evaluate variability in metal loading with increasing pH downstream from tailings and waste rock piles. Dissolved metals of environmental concern appeared mobilized at pH 3 or less, except for Cr, Pb and Zn. The concentrations of Cr, Pb and Zn at low pH values may be attributable to lack of these elements in the tailings. Thes elements exist as dissolved ions below pH 3 (Lee et al, 2001). The low pH values also reflect the lack of neutralizing agents like carbonates or hydroxides.

The “yellow-boy” precipitates (Nordstrom, 1979) observed in the surface water of Stop 1 occurs as a result of secondary alteration of iron-rich minerals that are in contact with acid mine water. At Stop 1, field pH measurements were consistently within the range of 2.25 to 2.5 at three different periods between 2005 and 2006. The solution SO4/Fe ratio also remained high for each sample collection: 5.5 in the summer (pH 2.44), 8.2 in the fall (pH 2.5) and 9.6 in the Spring 2006 (pH 2.25). It is probable that the solution SO4/Fe ratio may have also aided the formation of the “yellow-boy” precipitates. The green algal mats, Klebsormidium rivulare, are also known to tolerate acid mine waters because of their capacity to accumulate metals (Stevens et al, 2001).

At increased pH downstream, the mobility of dissolved metal contaminants decreased precipitously and was below NYDEC water quality standards. Metal attenuation downstream may be due to sequestration of metals by oxide precipitates, which forms at high pH, into bed sediments. Increased amounts of Al and Co greater than NYDEC standards at Stop 4 suggest that precipitation of these cations may not occur when pH is 6.3 or less. The groundwater from the well showed background levels of metal ions far below those of the NYDEC standards, except for Fe, suggesting no contact with mine waters or tailings. The high Fe content detected in the well water may be attributable to the water in contact with rocks enriched in iron in a natural environment. The high pH value relating to the control sample also suggests the presence of a buffering capacity like carbonates (17.9 mg/L Ca in sample) or hydroxides.

Sediment

Increasing pH downstream from Stops 1 and 2 (Table 1 and Figure 5) was the result of dilution from the heavy rainfall two hours prior to collection. Enrichment of metal ions in sediments, especially As, Ni, Se and Zn, suggest precipitation with increasing pH and sequestration of these precipitates into solid phases like iron-aluminum-manganese oxides and sulfates that precipitate as secondary minerals as well. Sequestration of metal pollutants controls their concentration in the water column.

The water flowing over the control sediment sample was observed to be from another nearby source, labeled "Clean Stream" on Figure 3. The pH of 6.53 suggests that the tailings or the mine water may not be impacting the source. Additionally, the clean source was also found to be very enriched in Ca concentration (5.56%) in the sediments, providing a buffer even if there is seepage of mine water through the banks of this brook. Therefore, it is believed that the high Cu and Ni content in the control sample may represent a natural concentration of the bed load in the non-contaminated water.

Under high-flow conditions such as at Stop 3, where fast flowing water was encountered due to the heavy rainfall, metals adsorbed as colloids in bed loads were flushed out and mobilized downstream (USGS, 1997; Rosner, 1998). Stops 1 and 2 experienced low flow rates, which may not have contributed to metal attenuation at these locations. The low metal precipitates in the bed sediments at these stops were probably a consequence of the low pH that maintained the metals as dissolved solids.

Stop 3 sample was rich in organic matter at the surface and this may be a factor for the high metal concentration in this sample. Organic materials are known for their strong affinity for metals because of their large negatively charged surface area. In the uncontaminated control sediment sample, Mn, Cu and Ni exceeded the sediment criteria. The control sediment color was determined as greenish black with a clayey texture. The excess metals may be attributable to the absence of organic matter and the presence of the strong influence of the clay on metal sorption.

Soil

The mine spoil was stained with brownish-yellowish coatings indicating the presence of Fe-oxides and hydroxides. Iron-oxides and hydroxides may, therefore, have been the dominant secondary minerals for sorption of the metals at this mine dump. The coatings inhibit the underlying layers of the tailing grains and waste rocks from further oxidation if the surfaces are kept moist. If the surfaces are exposed to prolonged dryness, dessication will occur. Following dessication, spalling of the protective coating will occur exposing the underlying sulfide surface to oxidation and leaching (Pratt et al, 1994). The Phillips Mine dump is located in a temperate zone, and, hence, the mine spoil may be subjected to both circumstances during different times of the year.

Sample 1UP soil (Figures 3 & 5) received acidic surface flow discharged through the lower adit. A component of 1UP soil sample had a fairly consistently high sulfate concentration (368 mg L-1, 349 mg L-1 and 353 mg L-1) over three different periods (7/28/05, 11/8/05 and 4/15/06, respectively) reflecting the low pH (2.44, 2.5 and 2.25, respectively) due to sulfide oxidation. Weight percent of sulfur in 1UP soil sample amounted to 2.33% in comparison to 0.82% for 2D and 3D, 0.75% for 4D and 0.4% for the control sample. These analyses present an understanding for the low metal retention in sample 1UP soil compared to samples 2D, 3D, 4D and 5UP, which were only moistened by precipitation or humid air. The constant wetting by the acidic water probably maintains the 1UP soil in a reduced state and most of the metals may be in dissolved form in soil pore waters. Due to the poor metal retention at the 1UP soil location, metals may be mobilized into the subsurface soil during rainfalls increasing bioavailability to plants (Clemente et al, 2003). If not intercepted by plants, mobilized metals may reach groundwater over time.

The sparse vegetation at the Phillips Mine dump is an indication of the acidity of the mine soil but certain plant species have taken root in areas where they may be accessing the metal nutrients from soil pore waters in the subsurface at depth. Therefore, areas with plant growth suggest soil with low pH. Areas with no growth may suggest soils are intensely oxidized with increasing pH, promoting precipitation of Fe-Mn oxides that were adsorbing metal cations, immobilized and bio-unavailable. The authors have conducted metal uptake by the plants and found two of the species with detectable amounts of translocated heavy metals in their above-ground plant tissues.

In ranking Cu retention in the soil samples, 2D and 3D contained the highest amount of this cation. This suggests that the mine soils at these sample sites are highly oxidized and enriched in Fe-Mn oxides and are sorbents for Cu (Vega et al, in press). This interpretation also correlates with the significant amounts of Fe and Mn concentrations at these sites (Table 2).

The high Pb content in the control sample containing organic matter agrees with results found in another study (Vega et al, in press) in which the organic matter was found to promote fixation of Pb through sorption by soils. Although complexation with the organic matter reduces concentration in water and sediment, it increases Pb mobility in soil when soil pH decreases (EPA, 1992). Sample 1UP was concentrated in Pb content relative to samples 2D, 3D, 4D and 5UP all of which showed low retention with decreasing Fe in weight percent. This leads us to believe that Fe-oxide preferentially adsorbs Pb than Mn-oxide, which was high in 2D, 3D, 4D and 5UP, in the absence of organic matter in mine soils.

Elevated levels of Cr retention in 2D – 5D soils may be the result of the highly oxidized nature of these soils that is probably exhibiting a strong affinity for Cr retention (Vega et al, in press). In the case of the control sample, Fe-Mn ion concentrations are low but high in Al in this sample relative to the mine soil samples. Chromium may possibly be adsorbed onto Al-oxides in the control sample. Additionally, the low Fe-Mn amounts in the control sample also seem to indicate that it may be young soil that has yet to undergo intense oxidation. Historical glacial advances in the region would have stripped the paleosoil.

The abundant Fe-oxides recorded in the soil samples also point to the degree of advanced weathering of the tailings that has been progressing since deposition. The white and yellow precipitants found on the pitted tailings and waste rocks may either be the result of precipitation of infiltrating groundwater, or evaporation during prolonged dry periods (Nordstrom, 1979; Blowes and Jambor, 1990).

CONCLUSIONS

The constant low pH values upstream indicate an absence of alkalic rocks to buffer the AMD, or insufficient concentration of buffering ions (ex: oxides, hydroxides or oxyhydroxides).

Copper Mine Brook receives AMD from tailings through contaminated groundwater and runoff, particularly during heavy rainfalls. Water flowing downstream becomes diluted by rainfall events or at the confluence with a clean brook nearby, or neutralizing material. Water is buffered when flowing past carbonate materials, or neutralized by the dissolution of iron-hydroxides or oxyhydroxides. Metals are flushed out in considerable amounts during high flows.

Fewer metals were sequestered in sediments when water was acidic. With increasing pH downstream, metal pollutants become enriched in sediments.

Metals become enriched in soils during dry periods. Iron-oxides and hydroxides may have been the most significant secondary minerals for sorption of the metals in the mine soil at the dump.

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HYDROGEOLOGICAL FRAMEWORK OF MIDDLE PROTEROZOIC GRANITE AND GNEISS FROM BOREHOLE GEOPHYSICAL SURVEYS AT TWO GROUND-WATER POLLUTION SITES, MORRIS COUNTY, NJ.

Gregory C. Herman, New Jersey Geological Survey

INTRODUCTION

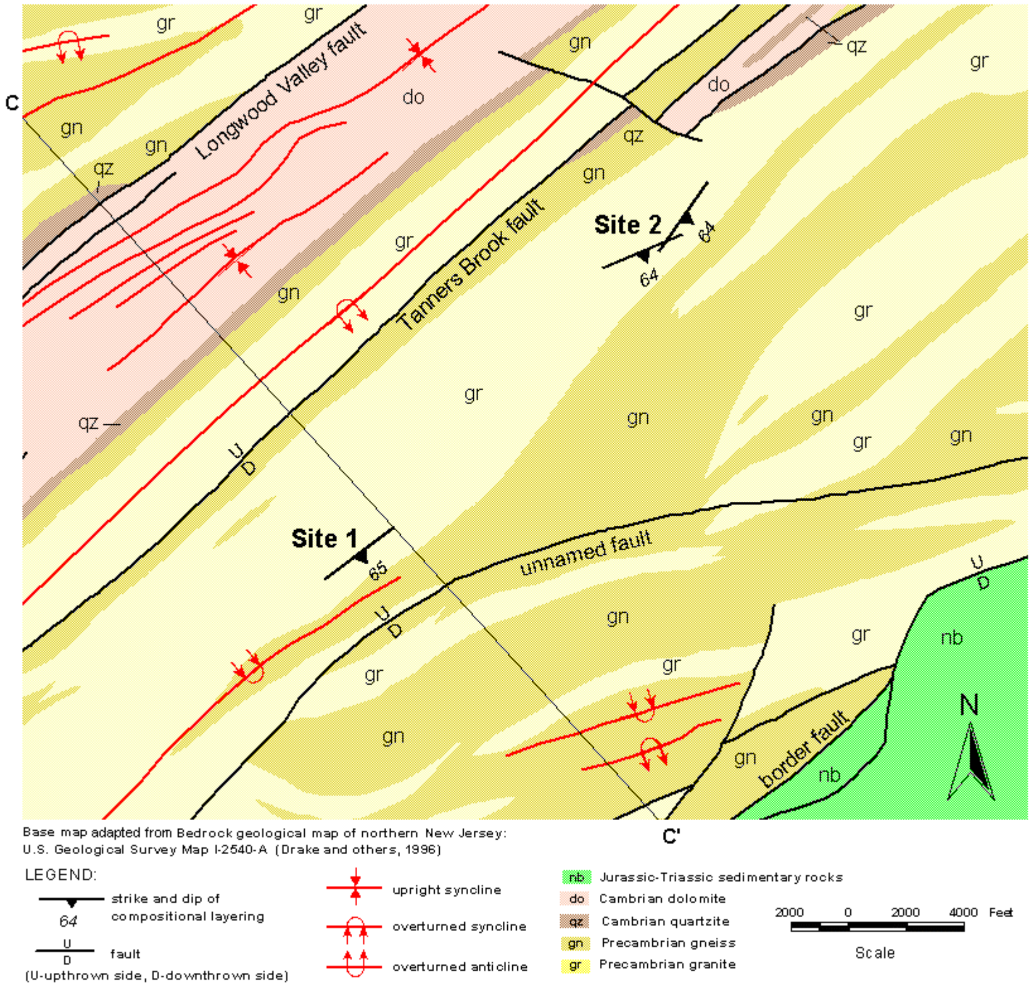
The New Jersey Geological Survey (NJGS) collected borehole geophysical data in a set of 6-inch-diameter deep bedrock wells drilled into Middle Proterozoic granite and gneiss in Morris County, New Jersey. The data were collected at two ground-water pollution sites in 2002 and 2004 to identify and characterize the subsurface geology that controls the storage and movement of ground water and associated volatile organic compounds (VOCs) resulting from commercial manufacturing and waste disposal activities. Both sites are underlain by hornblende granite (Drake and others, 1996) and are about 3 miles apart along the structural strike (Figure 1). Data were collected in one well at the first site (Site 1) and 5 wells at the second (Site 2). The depth of investigation for the geophysical investigations ranged from 17 to 511 ft below land surface (bls). Optical televiewer (OPTV), fluid temperature and fluid electrical resistivity or conductivity data were used to establish the hydrogeological framework. Heat-pulse flowmeter (HPFM) data were collected in 3 wells at Site 2 to locate water-bearing zones (WBZs) and to characterize borehole cross flows under natural conditions.

HYDROGEOLOGICAL INTERPRETATION

Borehole data were collected at Site 1 (Figure 1) in December 2002 in an abandoned water-supply well located within an industrial center. The well lies within an extensive contaminant plume having VOC concentration levels exceeding NJ Dept of Environmental Protection maximum-contaminant-level standards (Gallagher and Volkert, 1990). The well is open to bedrock between 17 and 230 ft bls (Figure 2). Well logs at Site 2 (Figures 3 to 5) were collected from October to December 2004 in a set of test wells drilled to develop a public supply for a proposed housing development. The development is located immediately northeast and adjacent to an old landfill. VOC contaminants were detected in water from many of the test wells following a June 2004 sampling event at concentrations of as much as 218 parts-per-billion (Figure 3). The 5 wells chosen for analyses were based on their depths, areal distribution, and reported contaminant levels. The wells logged at Site 2 were open to bedrock at depths ranging from 200 to 511 ft bls (Figures 4 and 5).

Analyses of bedrock structures using OPTV records

The orientations of bedrock structures interpreted from the OPTV records were calculated using software supplied by the instrument manufacturer. Details of the OPTV instrument design and methods of deployment are covered in Herman (2005). Figure 6 shows how OPTV records represent borehole geometry with respect to traces of planar structures seen on the borehole walls. A dip-value (1o to 90o)/dip-azimuth (0o to 359o) convention is used for specifying structural orientation of planar features unless otherwise noted.



Base map adapted from Bedrock geological map of northern New Jersey: U.S. Geological Survey Map I-2540-A (Drake and others, 1996)

Figure 1.Generalized bedrock geology in the vicinity of two ground-water pollution sites in Morris County, New Jersey. Cross-section trace C-C' from Drake and others (1996).

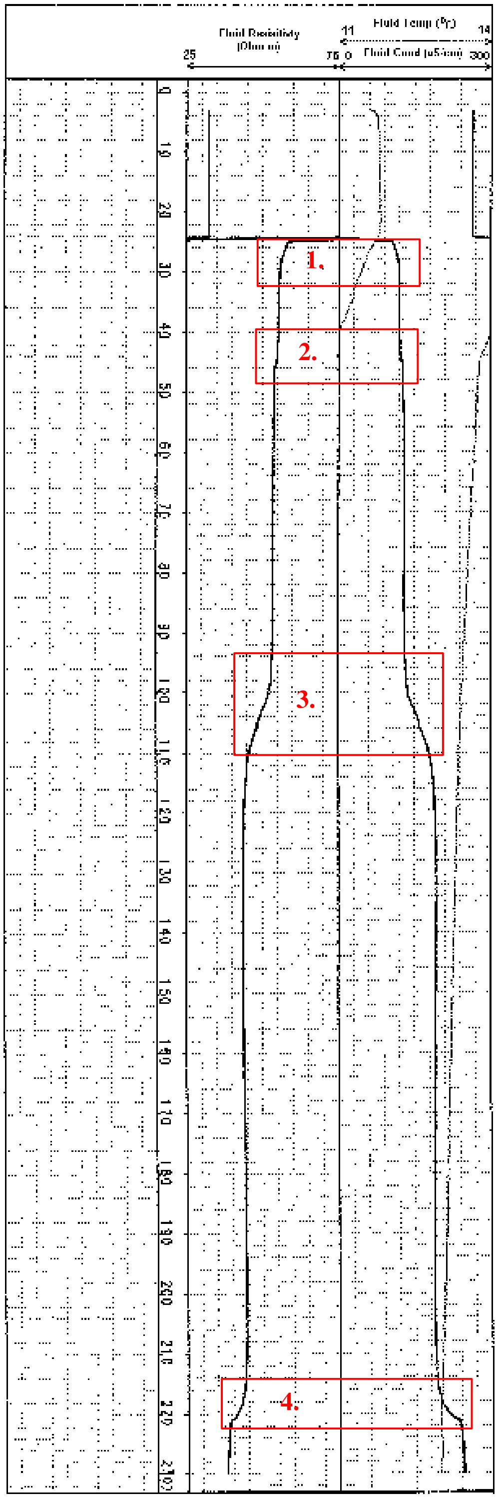


Figure 2. Fluid temperature, electrical resistivity and conductivity logs for the well at Site 1. Fluid temperature and electrical resistivity and conductivity anomalies are boxed and numbered. Anomalies 1 and 2 correspond to conductive structures shown in Figure 13. Anomalies 3 and 4 correspond to conductive structures shown in Figure 14. Figure 12 only shows conductive fractures over the lower part of interval 3. Other conductive, altered, gently- to moderately dipping fractures in the 93- to 110-ft interval are not shown.

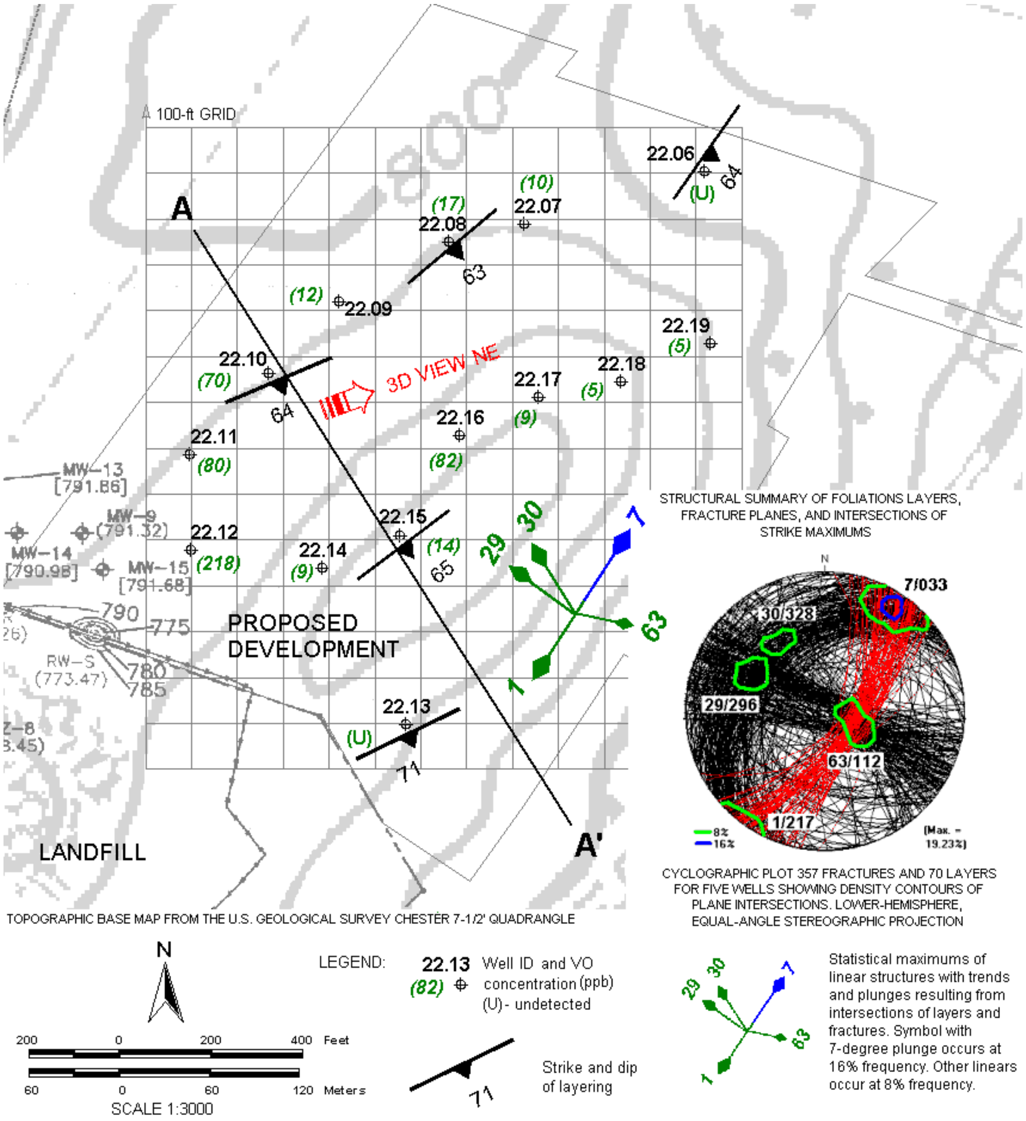


Figure 3. Site 2 map showing the location of test wells, contaminant concentration levels from the June 2004 sampling event, and structural summary of structural planes and plane intersections interpreted from OPTV records.

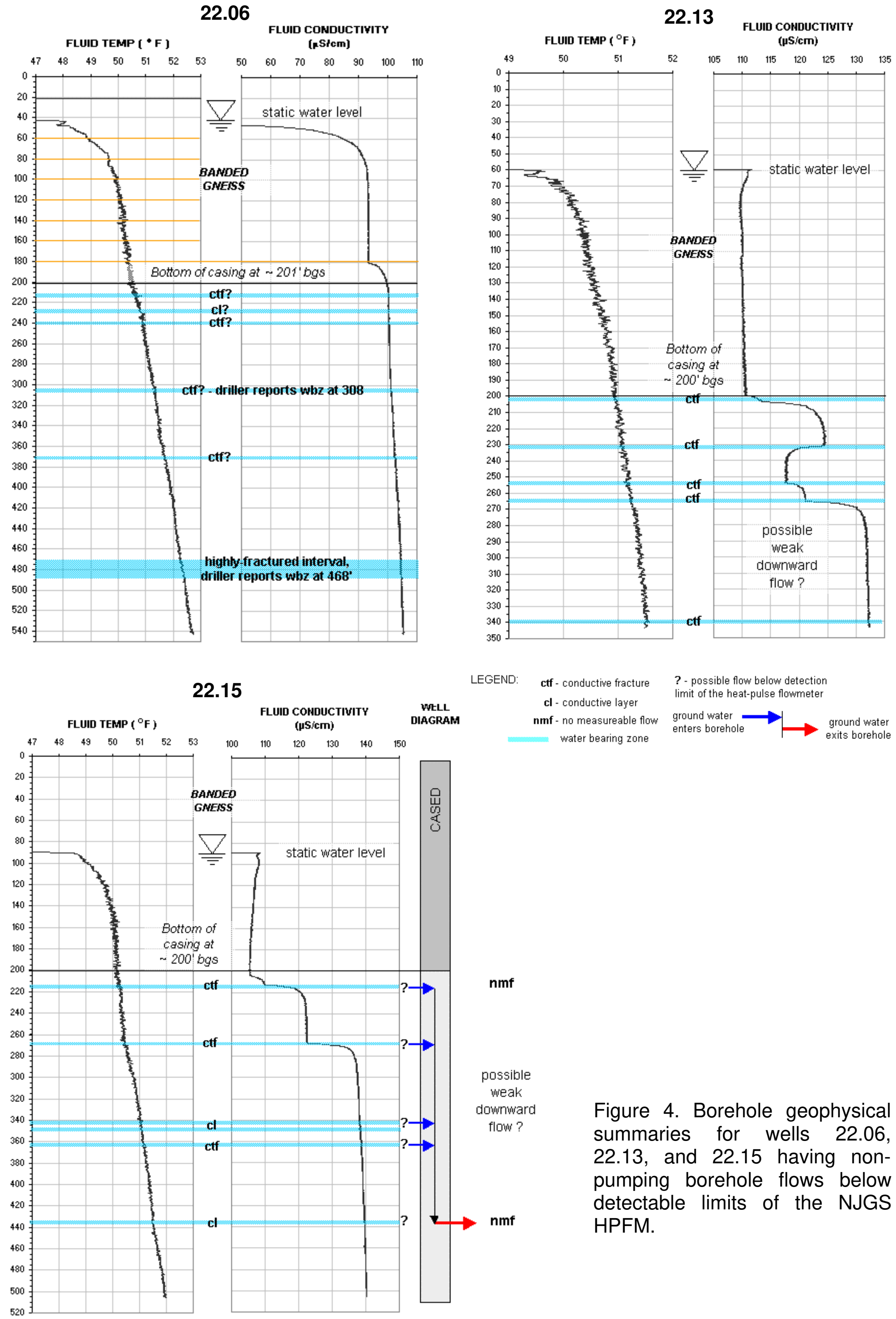


Figure 4. Borehole geophysical summaries for wells 22.06, 22.13, and 22.15 having non-pumping borehole flows below detectable limits of the NJGS HPFM.

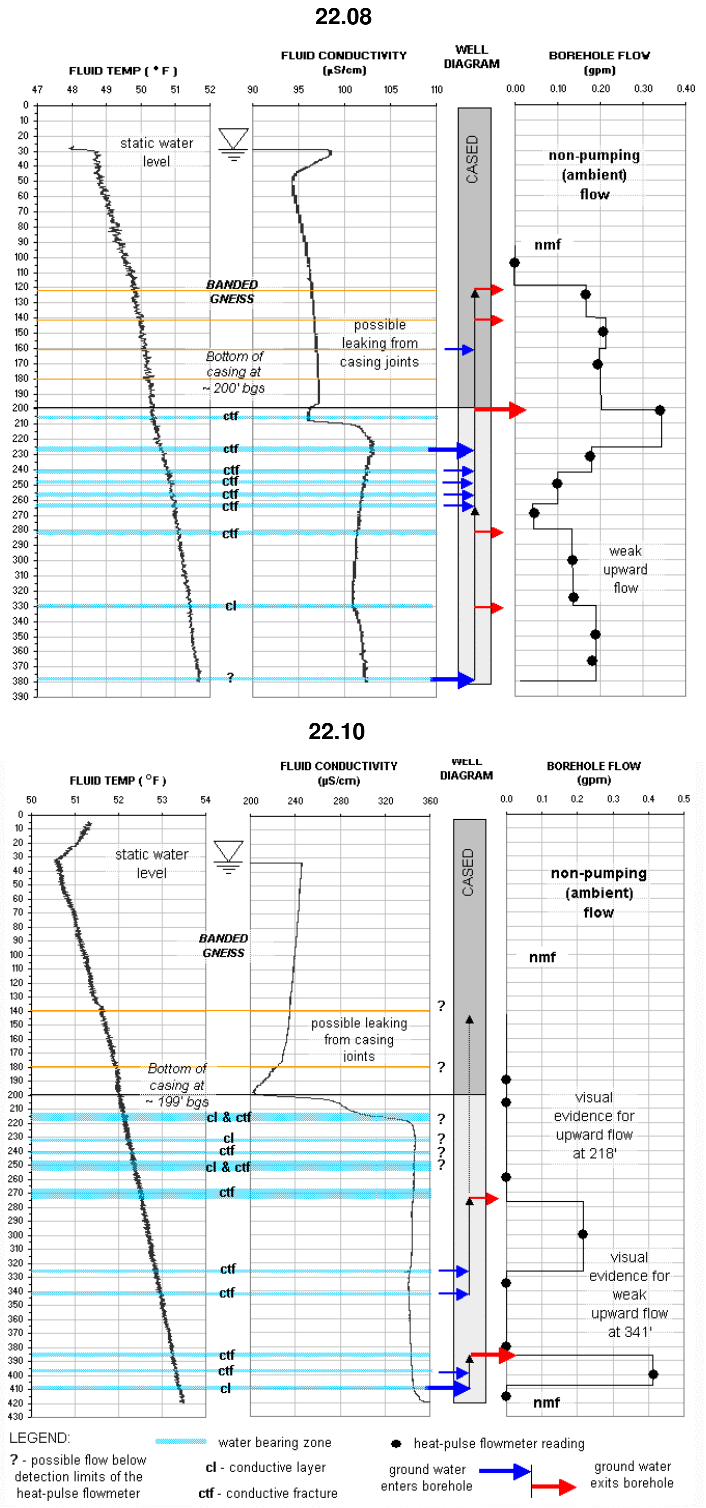
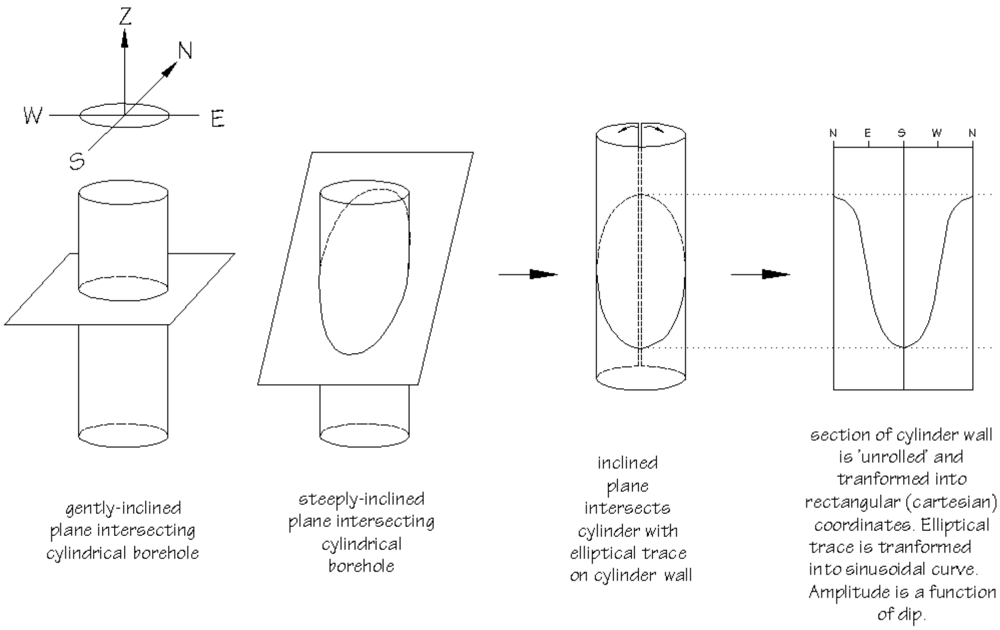


Figure 5. Borehole geophysical summaries for wells 22.08 and 22.10 having non-pumping upward flows measured with the NJGS HPFM



gently-inclined plane intersecting cylindrical borehole

steeply-inclined plane intersecting cylindrical borehole

inclined plane intersects cylinder with elliptical trace on cylinder wall

section of cylinder wall is 'unrolled' and tranformed into rectangular (cartesian) coordinates. Elliptical trace is tranformed into sinusoidal curve. Amplitude is a function of dip.

Figure 6. Structural diagrams summarizing the orientations of bedrock features interpreted from OPTV logs

Three primary types of planar structures were identified and measured (Figure 7):

Compositional layering – Alternating dark-to-light lithologic layering or banding, corresponding to granitic or gneissoid foliation. Dark layers are probably amphibole (hornblende) rich whereas light layers are probably composed mostly of quartz and feldspar (Volkert, 1989).

Fractures – Brittle, planar discontinuities but no visible shear offset of any other bedrock features cut by the fracture. Fractures were noted as mineralized wherever visible accumulations (~> 0.05 in. thick) of secondary minerals were visible in the fracture plane.

Shear fractures – Fractures that show shear offset of any other planar features cut by the fracture. Where visible accumulations of secondary minerals occur in the shear plane, these were noted.

The structural analysis relied on selective sampling of imaged borehole features. Individual layers and fractures were measured in 5-meter (~16 ft) stacked intervals. Fractures commonly cluster in sets with individual fractures arranged in stepped, parallel (en echelon) alignment (Figure 8). Measured features are believed to represent numerous, closely spaced structures within the sample interval. Multiple measurements were taken of a particular feature within a sample interval where the strike or dip differed from a similar, previously measured feature by more than 5o.

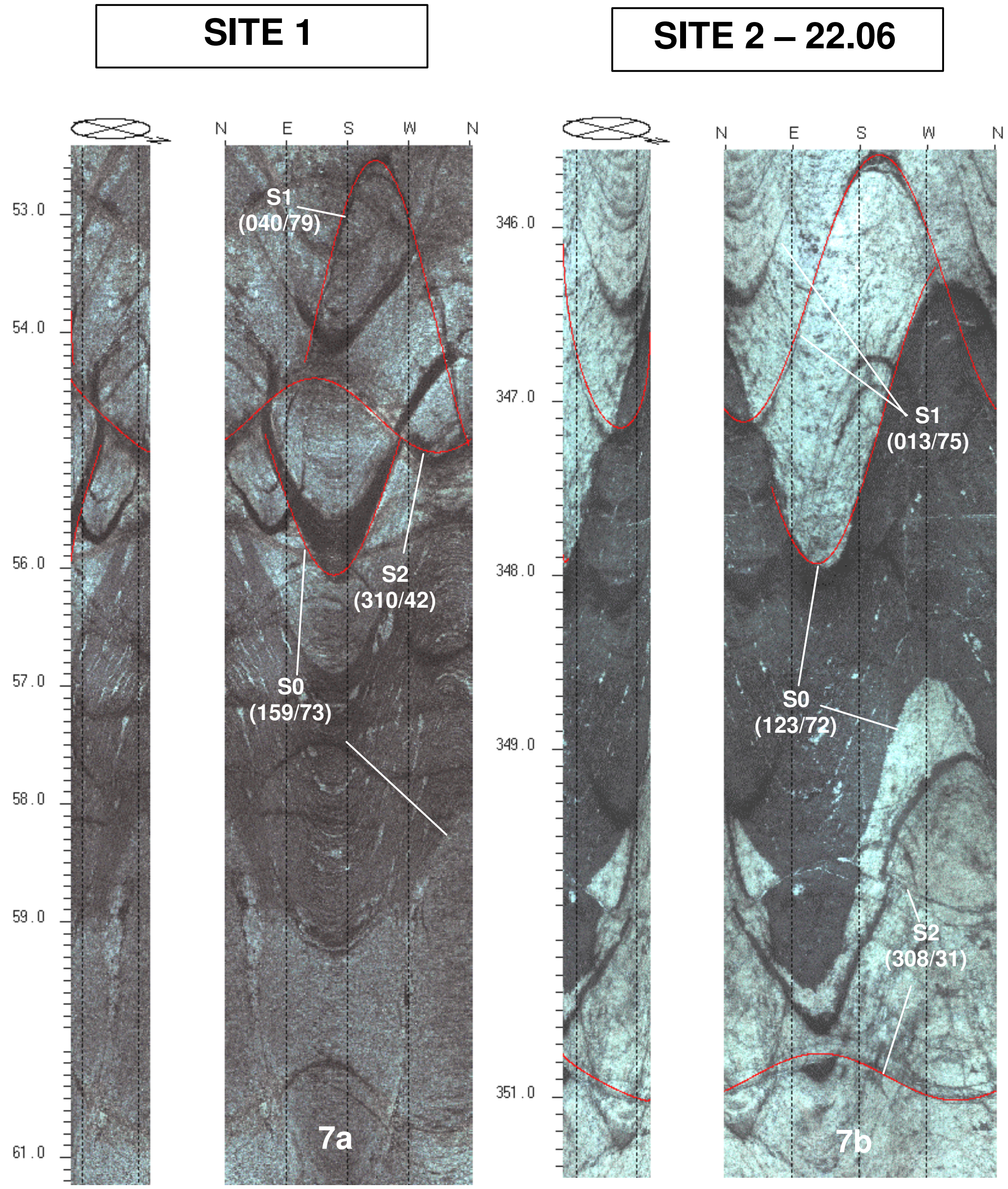


Figure 7. Representative OPTV records showing structural relationships common to both sites. Compositional layering (S0) is locally offset by steeply dipping cross fractures (S1) having normal dip-slip shear. Late-stage, gentle-to moderately dipping mineralized fractures also show localized shearing and offset of both S0 and S1 planes.

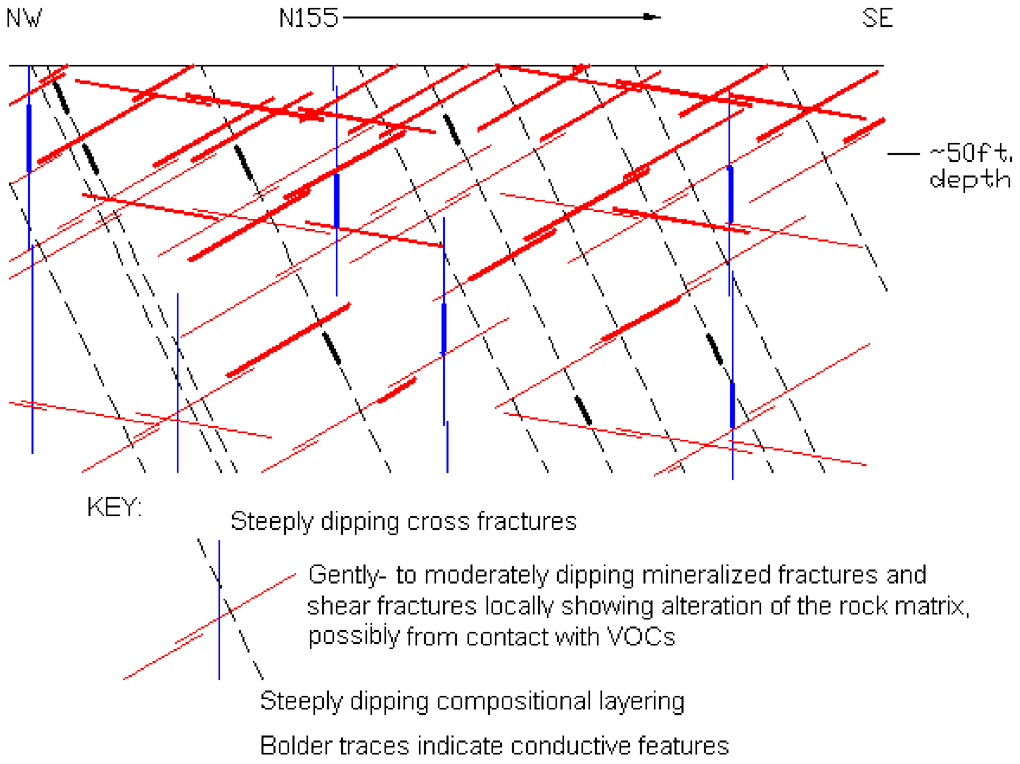


Figure 8. Schematic profile of the hydrogeologic framework of fractured bedrock at Sites 1 and 2. Bolder lines indicate structural planes that are locally conductive based on the fluid temperature and electrical conductivity/resistivity logs, the HPFM analyses, and alteration of bedrock close to fracture walls seen in the OPTV records (see text for further explanation). The most abundant conductive structures are mineralized fractures and shear planes dipping gently-to-moderately northwest. Effective secondary porosity in the bedrock results from the interaction of all of the different planar structures.

Structural orientations of lithologic layers and fractures interpreted from OPTV records are summarized in Figures 9. The mean orientation of compositional layers and of fractures was determined using stereographic-projection diagrams. All measured fractures were combined for this analysis. The mean orientation of layering at Site 1 (65/156 = strike and dip N66oE/65SEo) agrees closely with the strike and dip of granite foliation measured in outcrop about 3000 ft to the southwest, about N65oE/66SEo (Volkert, 1989). The mean strike of layering at Site 2 (N32oE) is rotated about 30o counterclockwise relative to Site 1, but the mean dip of layering at both sites is about the same, 65o to 66o SE. Layers and fractures at both of these sites exhibit similar geometry and interrelationships. For example, both sites have primary sets of mineralized fractures and shear planes dipping northwest at gentle angles (1o to 39o) to moderate (40o to 59o) ones (Figures 7 to 9). Shear fractures commonly cut and offset layering and other steeply-dipping (60o to 90o) fractures with a reverse dip-slip sense of shear (Figures 7 and 10). Subordinate mineralized sets of fractures dip gently- to moderately southeast, and steeply dipping cross fractures (or cross-joints) strike at complimentary angles to layering

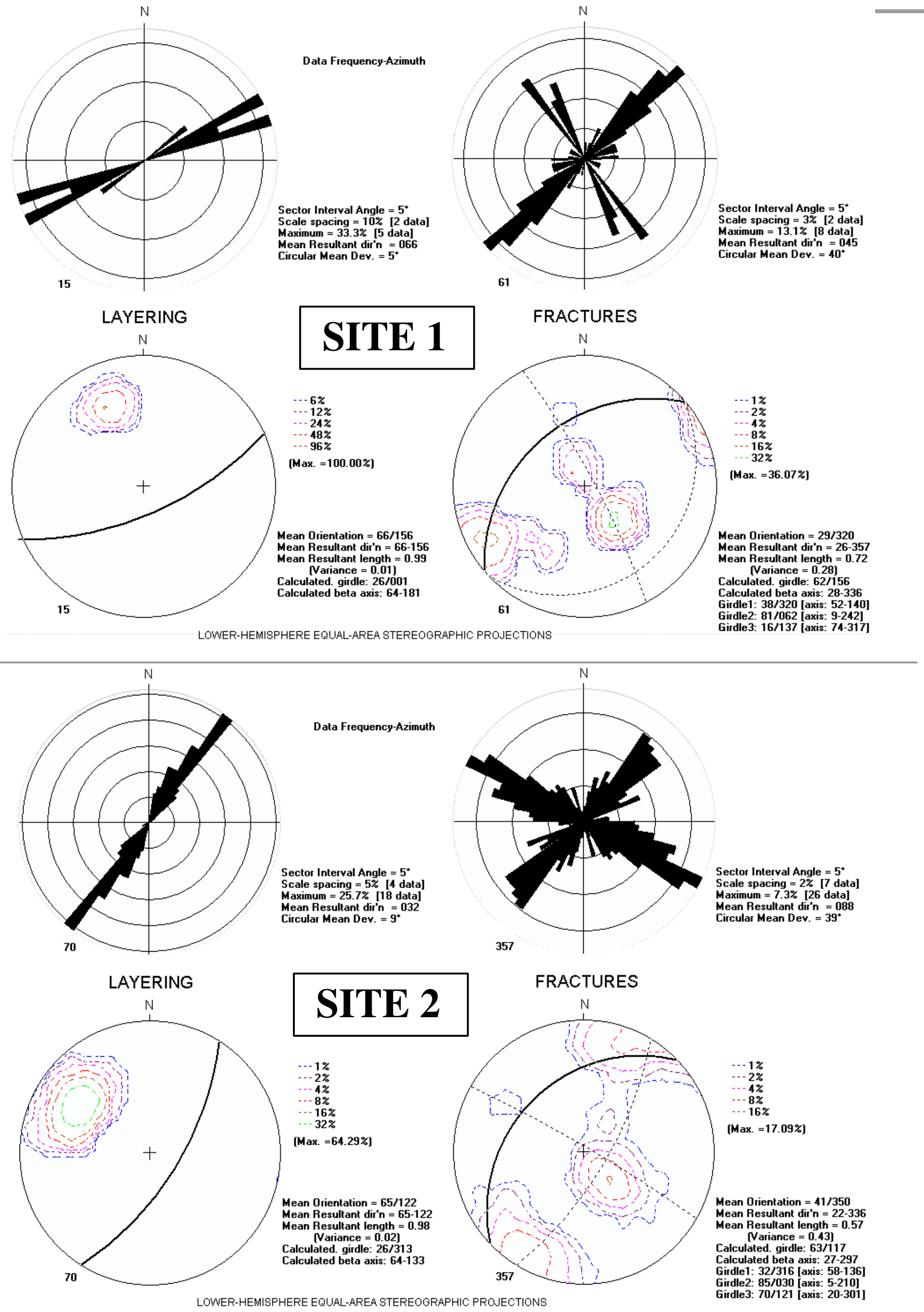


Figure 9. Diagrams summarizing the orientation of bedrock structures interpreted from OPTV logs for Site 1 (top) and Site 2 (bottom).). The mean orientation of layering and the primary fracture set are represented as bold, solid lines following the traces of great circles. Two subordinate sets of fracture planes at each site are identified using dashed lines following traces of great circles.

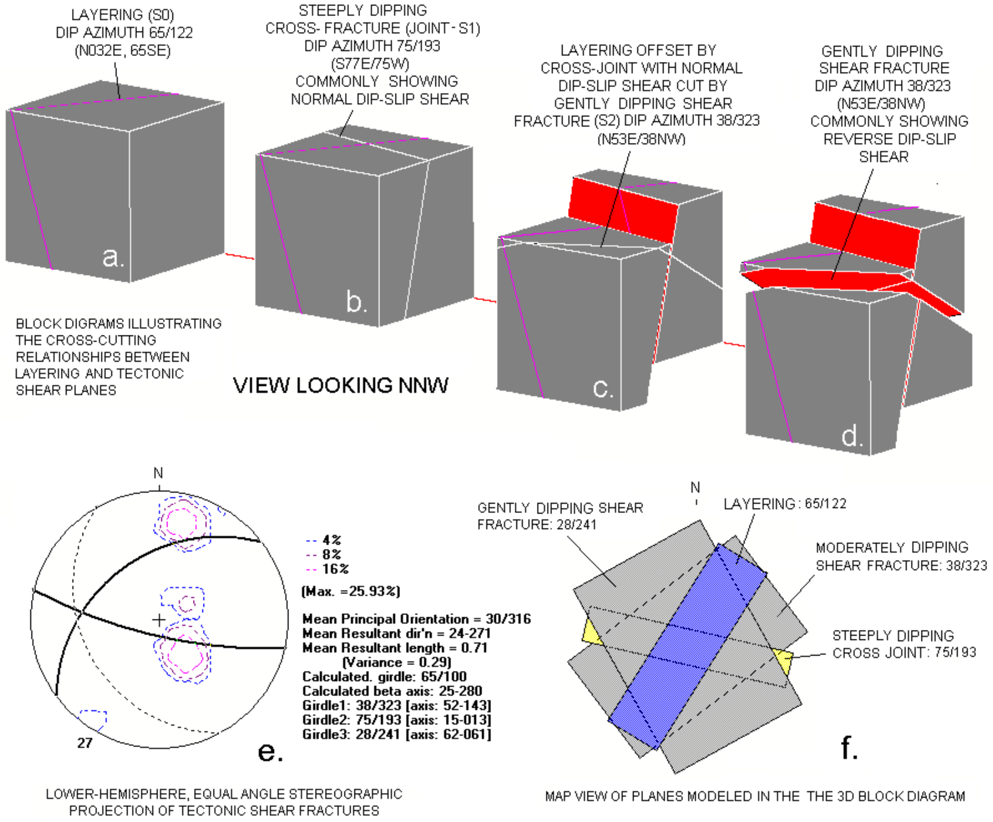


Figure 10. Structural diagrams illustrating the geometric relationship between layering and shear planes observed in the OPTV data at Site 2.

(Figures 7 to 9). Cross fractures typically have dark, secondary minerals in the fracture plane, offset layering with a normal dip-slip sense of shear (Figures 7 and 10), and display the same counterclockwise rotation of strike between sites as for layering (Figure 9). These crosscutting relationships provide a relative sense of timing of structural development. Layering is the primary (S0) structural plane that is cut and locally offset by cross-strike extension fractures (S1). Both S0 and S1 structures are themselves cut and locally offset by gently-to-moderately-dipping fractures and shear planes (S2) respectively (Figures 7 and 10).

Subsurface S2 fractures imaged with the OPTV are measured in outcrop throughout the New Jersey Highlands where they are commonly filled with dark-green, chlorite and/or chloritoid secondary minerals (Figure 11). Map and profile plots of these fractures measured through the northeast highlands along a cross-strike traverse near Route 23 shows that these fractures also commonly dip northwestward (Figure 12). Their origin probably stems from internal shearing strains associated with the emplacement of basement-cored, stacked fault slices in the region (Herman and others, 1997).

Figure 11. Example of outcropping, chlorite-filled shear fractures in Middle Proterozoic basement of the New Jersey Highlands, US Geological Survey Newfoundland 7.5 minute quadrangle. Spaced sets of anastomosing shear fractures oriented ~N75E/25NW cut and offset foliation in pyroxene granite. Lens cap for a 35-mm camera shown for scale in Figure 11a. Mechanical pencil shown for scale in Figure 11b.

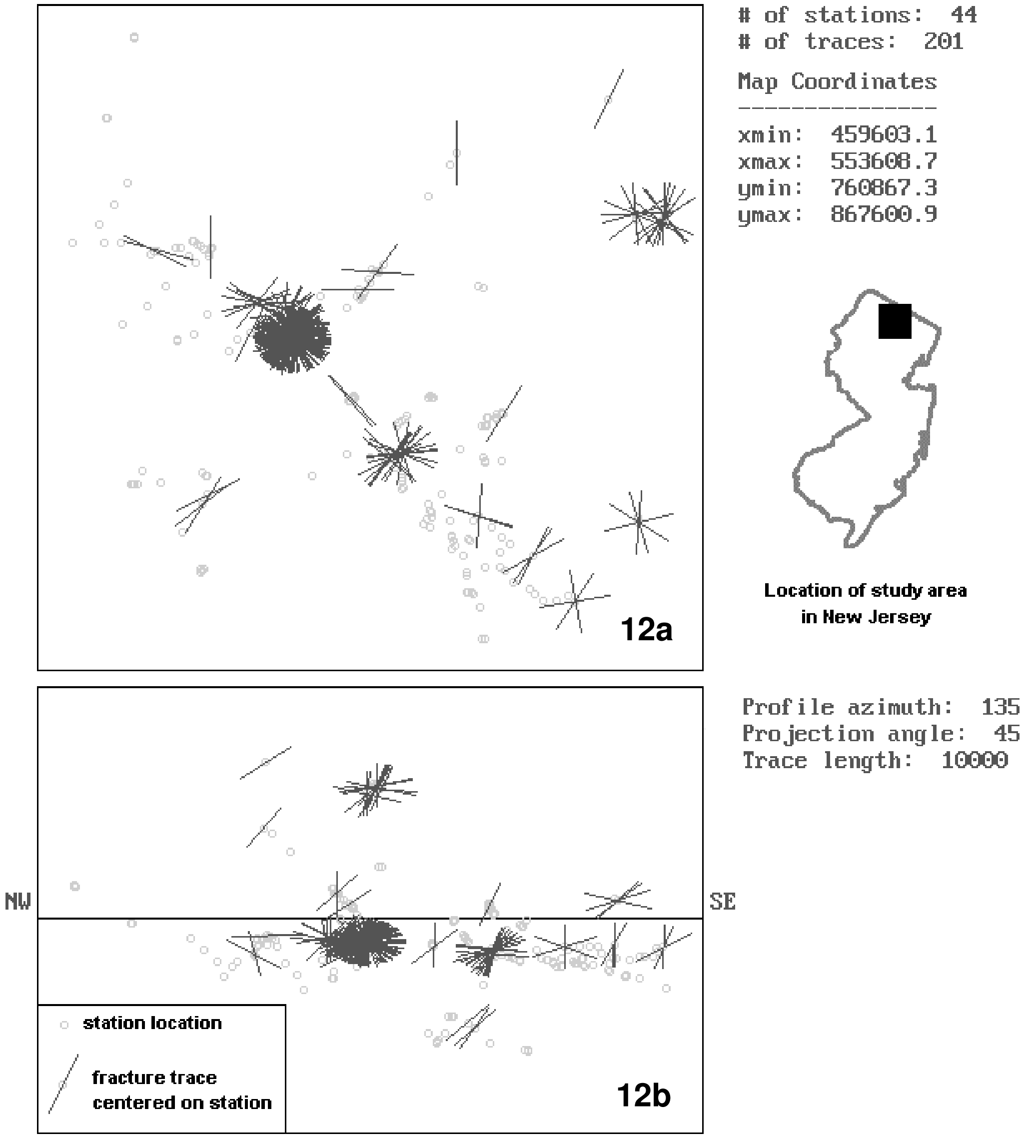


Figure 12. Map (12a) and profile projection (12b) of 201 chlorite- and epidote-filled shear fractures measured in outcrop along a northwest (NW) to southeast (SE) traverse through the New Jersey Highlands in 1985-86.

Identification and Interpretation of Hydraulically-conductive Features and WBZs

Layering and fractures are noted as conductive (hydraulically) where they exhibit visible secondary porosity and correlate at depth to measured changes in the properties of the borehole fluids, or show other signs of ground water transmission. Changes in fluid properties include fluid-temperature and/or electrical resistivity/conductivity anomalies (Figures 2, 4, and 5), and/or measured differences in borehole flows as determined with a HPFM (Figure 5). Other visible signs of fracture conductivity include dark staining of the rock matrix close to a fracture (Figures 13b, 14a and 15a), or points where fractures intersect layers or other fractures (Figure 16a). Staining of the country rock as much as an inch from the fracture walls is probably an indication of ground-water contamination along mineralized fracture planes. Bedrock in uncontaminated wells and along nonconductive fractures shows no apparent staining along correlative fracture sets (Figures7b, 14b and 15b). Staining may stem from chemical alteration of iron-rich minerals, such as chlorite, that fill fractures and shear planes. Although the process chemistry is unclear, a series of chemical reactions may involve the oxidation of iron and reductive dechlorination of VOCs in aqueous media (EnviroMetal Technologies, Inc., 1998).

<u>Site 1</u>

Fluid temperature and fluid electrical resistivity anomalies in the well logs at Site 1 indicate at least four potential WBZs (Figure 2). The shallowest zone is near the static-water level where the bedrock is highly broken from 24 to 30 ft bls (Figure 13a). A second zone at shallow depths of 44 to 46 ft and coincides with gently dipping fractures showing chemical alteration of fracture walls (Figure 13b). A third zone at an intermediate depth from 98 to 110 ft bls also corresponds with conductive, moderately-to-gently-dipping fractures (Figure 14a). The deepest zone occurs at 218 to 222 ft and coincides with secondary porosity developed along a layer-parallel fracture at a depth of 220 ft (Figure 14b). Altered fracture sets are most abundant in the shallow subsurface at depths down to about 50 ft, where fluid temperatures show many small fluctuations (Figures 2 and 8).

<u>Site 2</u>

Geophysical data in the wells at Site 2 show many WBZs resulting from all three types of structures, at all logged depths (Figures 4 and 5). However, WBZs at conductive fractures outnumber those from compositional layering at about a 3:1 ratio. Most of the conductive fractures are S2 fractures that dip gently- to moderately northwest. The HPFM analyses show that borehole cross flows in some wells range from about 4 gpm to less than 0.5 gpm under natural (non-pumping) conditions (Figure 5). The NJGS flow meter has been shown to be about 80 percent accurate in measuring upward-directed fluid flow at rates of about 0.7 to 25.0 gpm in standard, 6-inch bedrock wells (Herman, 2006).

Low-flow rates below 0.5 gpm are more qualitative and rely on delayed heat-pulse arrival times, the geometric form of fluid-temperature and electrical anomalies, and visual evidence for the direction of flow from OPTV records (Figure 15b, 341-ft depth).

Wells marked by the highest recorded contaminant levels are in the valley (Figure 3 and display upward-directed flows (Figure 5). Upward-directed cross flows stem mostly from inflows along northwest dipping S2 fractures. Wells exhibiting upward-directed flows are probably recharged at higher topographic elevations to the east (Figure 3) under

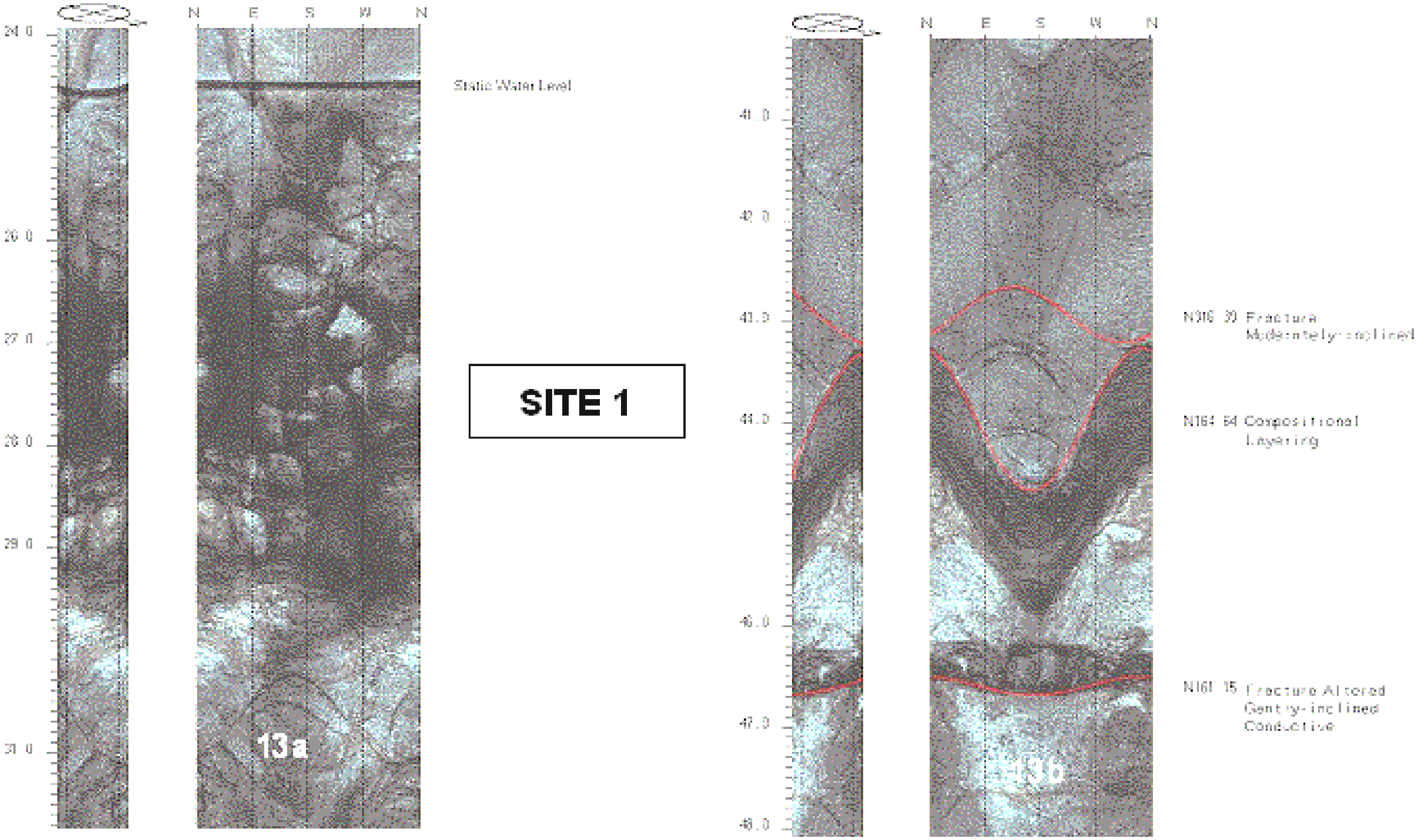


Figure 13. OPTV records of the two, uppermost water bearing zones in the well at Site 1. Locations of the zones correspond to fluid temperature and electrical resistivity/conductivity anomalies noted in Figure 1.

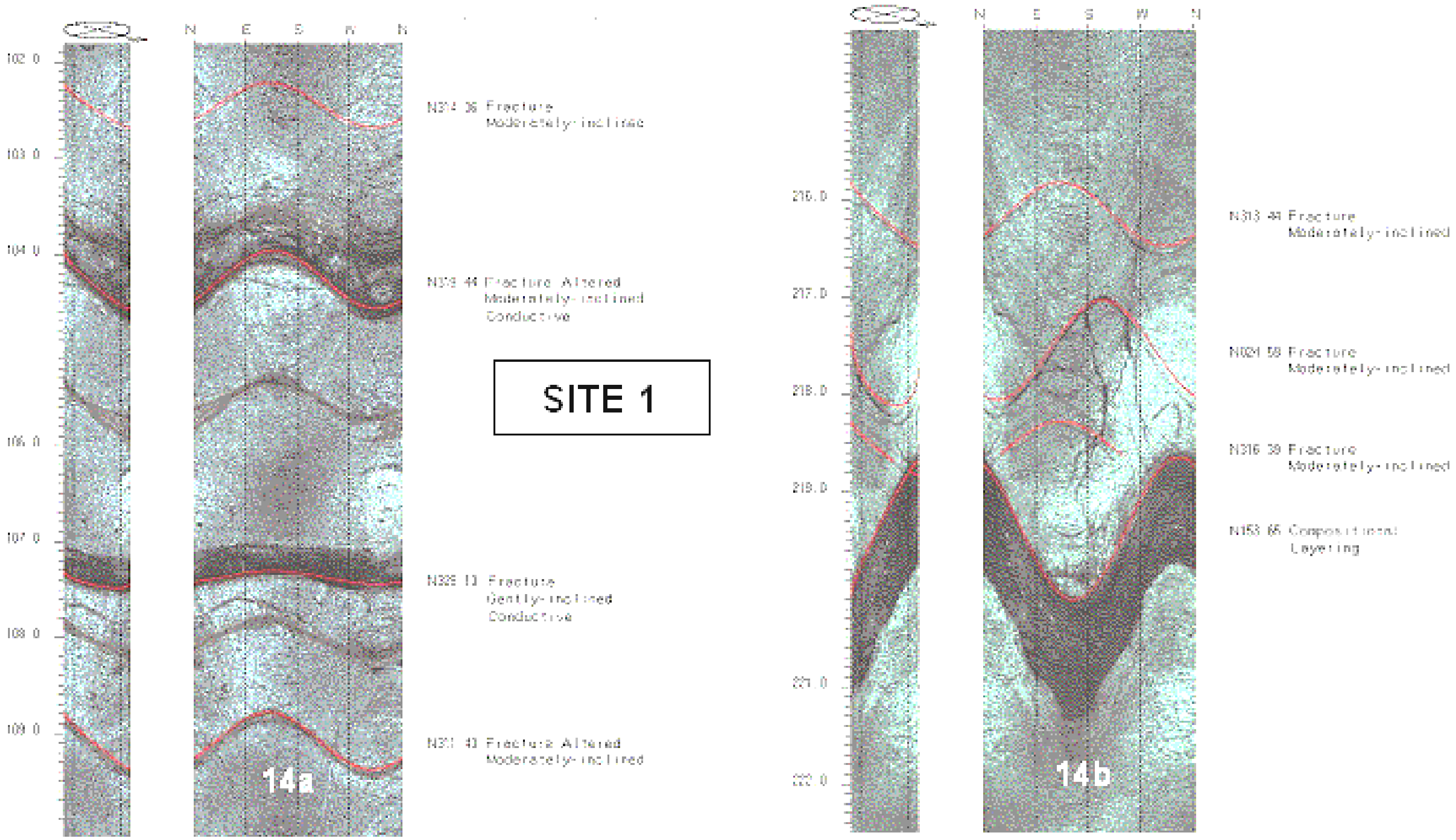


Figure 14. OPTV records of the lowermost WBZs in the Site 1 well. Locations of the zones correspond to fluid temperature and electrical resistivity/conductivity anomalies noted in Figure 1. Conductive, moderately dipping fractures from ~ 93 to 99 ft depth show staining of the rock matrix adjacent to the fracture planes.

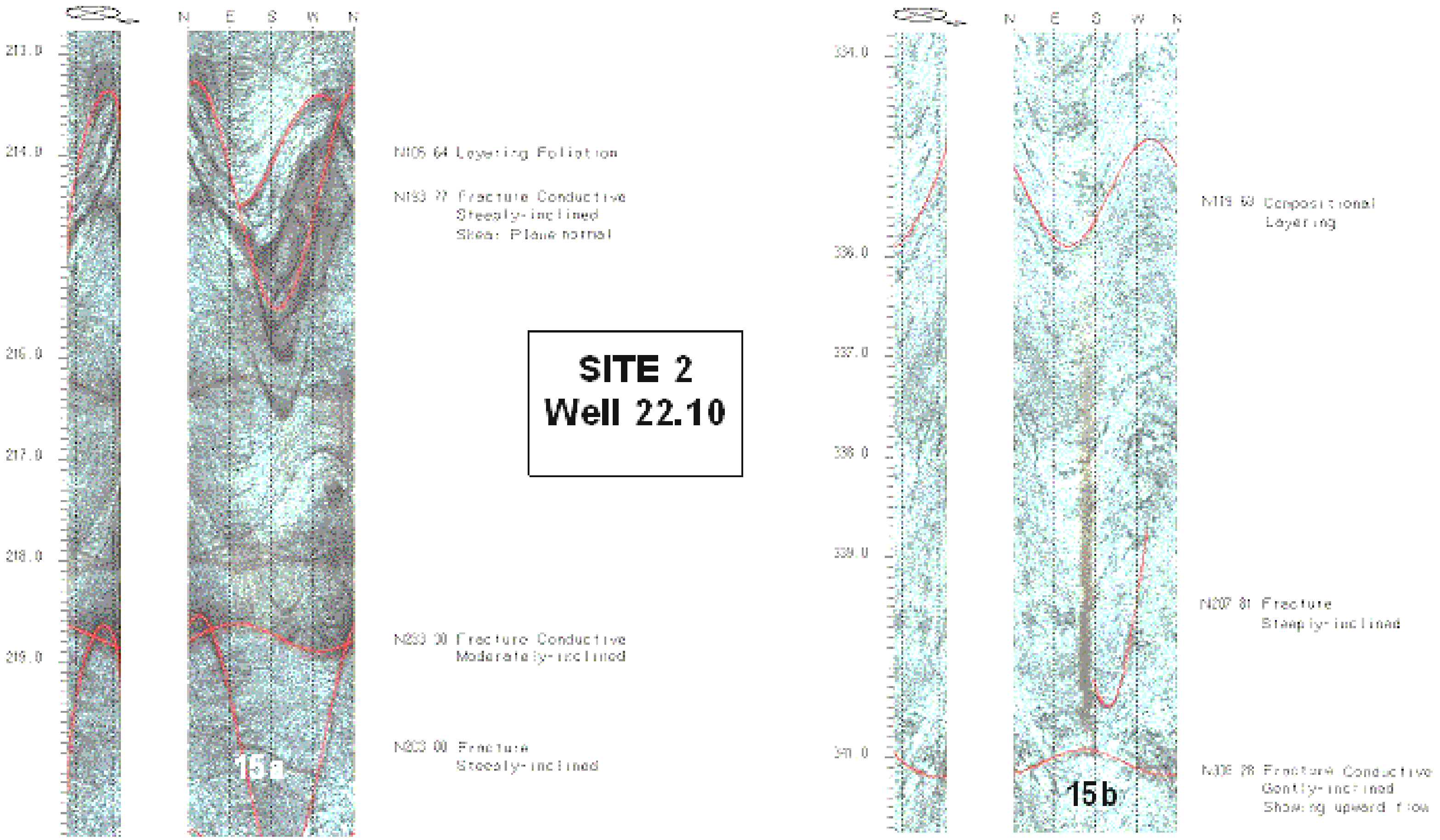


Figure 15. OPTV records of conductive structures in Site 2 well 22.10. Locations of the zones correspond to fluid temperature and electrical resistivity/conductivity anomalies noted in Figure 5. Conductive, gently-dipping fracture at 341' shows visual evidence of upward cross flow in the well where rust-colored stain emanates from the conductive fracture.

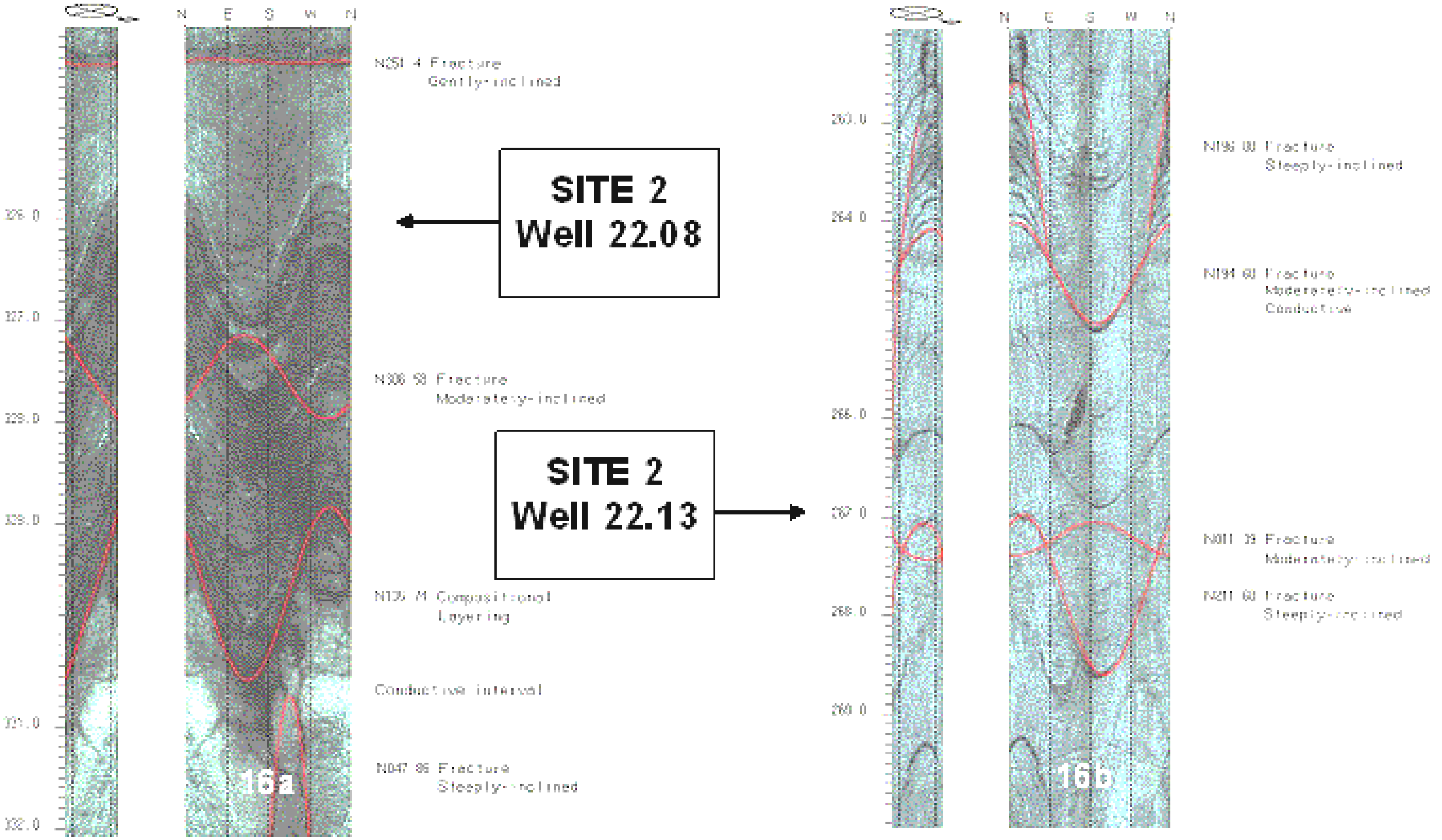


Figure 16. OPTV records of conductive structures in Site 2, wells 22.08 and 22.13. Locations of the zones correspond to fluid temperature and electrical resistivity/conductivity anomalies noted in Figures 4 and 5.

semiconfined conditions. These wells provide a conduit for vertical cross flows and cross contamination of the aquifer under natural conditions. Wells situated toward the ridge crests probably harbor weak downward flows that lie below the detection limit of the HPFM (Figure 4). Fluid-temperature and fluid electrical conductivity anomalies in the cased parts of wells 22.06 and 22.08 indicate local cross flows in some cased intervals, probably attributable to water leaks at threaded pipe unions (Figures 4 and 5). A measurable cross flow was found in the cased part of well 22.08 (Figure 5). HPFM measurements in well 22.08 also showed temporal variations in flow rate during data sampling. This suggests local well interference and transient water-table fluctuations in the area, probably from intermittent pumping of nearby domestic wells located on the flanks of the northeast-trending ridge extending through the proposed development.

Fracture alteration and staining are found at the deepest intervals imaged with the OPTV but are the densest at intermediate depths in wells 22.10 and 22.08 (Figure 17). This suggests that concentration gradients diminish downward from 400 to 500 ft bls approaching the valley (and plume?) axis (Figure 17). Contaminant concentrations at depths shallower than 200 ft bls are not characterized because these intervals are cased off.

DISCUSSION

The hydrogeological framework of fractured gneiss and granite in this area includes fractures associated with compositional layering, brittle jointing and tectonic shearing of bedrock. The densest concentration of fracture intersections follows the trend of regional strike and plunge gently northeast (Figure 3). Therefore, structural intersection of layering fractures with subparallel, tectonic shear fractures probably results in pronounced horizontal conductivity in deep bedrock oriented along regional strike. However, ground-water transport in the shallow subsurface (~above 50 ft bls) presumably follows local topographic gradients resulting form the pronounced weathering and ‘openess’ of tectonic fractures (as noted for Site 1) at shallow depths. It is important to note again that most of the conductive brittle fractures dip gently-to-moderately northwest, so that DNAPLS can migrate through shallow- to-intermediate depths in directions other than that of layering dip under natural flow conditions.

The eastern boundary of the contaminant plume near Site 2, at the time of the June 2004 sampling event, is formed by a topographic ridge along the southeast of the valley (Figure 17). A cross-strike (northwest-southeast trending) topographic divide also separates the proposed housing development and the adjacent landfill into separate surface-water basins draining to the northeast and southwest respectively. The development is therefore situated at the head of the northeast drainage. Migration of the plume from the landfill area into the valley to the northeast would be facilitated by the trend of geological structures. But migration past the crests of the ridges flanking the valley to the northwest and southeast probably would be minimal, so that the plume would be chiefly situated along the axis of the valley. Ground water probably is recharged from the two flanking ridges into the valley where it flows under natural hydraulic gradients northeastward to local surface discharges mapped just beyond the limits of the development. Natural, upward-directed cross flows in the valley, and in the test wells, may promote natural remediation of the VOC plume in the bedrock aquifer bybringing deep pollutants upward into contact with conductive fracture planes filled with iron-bearing minerals. Natural, upward-directed cross flows in the test wells facilitate rapid transport of pollutants out of bedrock to more shallow levels close to surface discharge over time. Contamination of the bedrock aquifer probably extends below the 500-ft depth of the OPTV investigation. The vertical extent of the pollution plume is estimated to extend to about 700-ft bls based on the distribution of contaminated wells, interpolated contaminant concentration gradients, and the distribution of ‘altered’ fractures noted above. However, the lower limit of the plume is queried due to uncertainty (Figure 15).

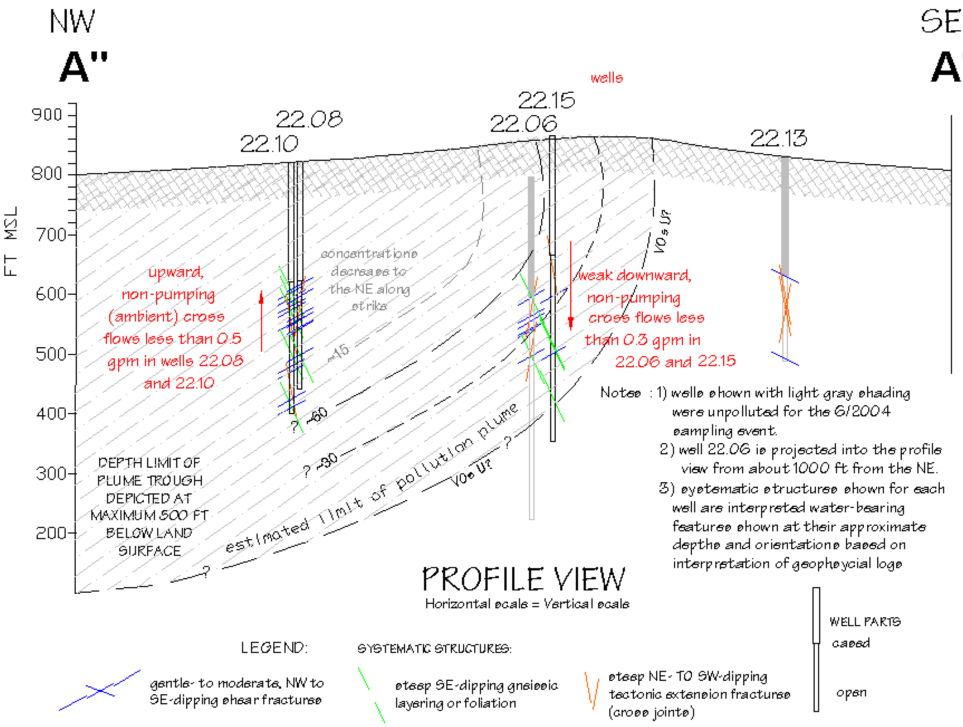


Figure 17. Schematic profile of the hydrogeologic framework of fractured bedrock near well CIC41D. Bold red lines indicate probable conductive planes based on the visible occurrence of bedrock alteration along fracture walls in the OPTV record (Figure 5).

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IRON DEPOSITS FROM HUDSON HIGHLANDS, NY: SYSTEMATICS, MINERALOGY, MINERAL CHEMISTRY AND TECTONIC SETTING

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INTRODUCTION

The Hudson Highlands region of New York together with New Jersey Highlands and Reading Hill of Pennsylvania form the Reading Prong, a Grenville-age massif that outcrops along eastern North America and connects the Blue Ridge and Green Mountains as part of the Appalachians (Gates et al. 2001a). The bedrock composition shows sequences of metasedimentary, metavolcanic and quartzofeldspathic units intruded by sheets of granites, coarse diorite bodies and pegmatite dikes (Gates et al.2001a). The peak metamorphic conditions for the Hudson Highlands rocks occurred at around 1,159-1,008(±4) Ma (Aleinikoff & Grauch, 1990; Drake et al. 1991; Ratcliffe & Alleinikoff, 1990; Ratcliff 1992; Gates et al. 2004; Gates et al. 2006). Reported ages of 1,460 – 2,800 Ma are not typical Grenville ages and could indicate an exotic terrain (Gates et al. 2004; Gates et al. 2006).

Gates (1995), Gates and Costa (1999), Gates et al (2004) described a major late Grenville dextral strike-slip shear system in the Reading Prong represented by the Ramapo and Reservoir Faults. This shear system was active at around 1008 – 980 Ma (Gates et al. 2006). This or previous deformational events are linked to the development of the high-grade iron oxide occurrences, overlapped in places by iron or iron-copper sulfide and/or REE or U mineralizations that are well-known in the Hudson Highlands of New York (Gundersen, 2004).

The first discovery of the iron ore deposits in the Highlands dates back to 1730 (Lenik, 1996). Since then, but especially from the middle of the 18th to the end of the 19th century, many iron occurrences were found and mined in the Hudson Highlands. The first substantial contribution to the geology and iron mines of the Hudson Highlands is the report of Mather (1839) with an appendix by Horton that records the iron mines that operated at that time. A sedimentary origin of the deposits was first proposed (Wendt, 1885; Ruttman, 1887) but later it was challenged with a magmatic hypothesis (Koeberlin, 1903 and Ames, 1918), magmatic replacement of the host rock (Colony, 1923), metasomatic replacement of “preexisting rocks by iron-bearing solutions or vapors derived from a magmatic source, possibly represented by the hornblende granite” (Holtz, 1952), metasomatism accompanying regional metamorphism and granitization (Hagner et al, 1963) or hydrothermal genesis (Foose and McLelland, 1995; Martinko and Gates, 2000). Klemic et al. (1959) considered that uraninite had a pegmatitic origin and magnetite and sulfides were precipitated from hydrothermal solutions. Gundersen (2004) proposed an exhalative volcanogenic back arc setting for the source of some of the magnetite deposits and related uranium and REE occurrences. It has become clear that there are multiple modes of emplacement for the magnetite bodies of the Hudson Highlands.

Recent textural, mineralogical, geochemical and structural investigations showed that some of the iron oxide deposits are spatially associated with an extensive alkali-halogen metasomatism produced by Cl- and/or F- and K-rich crustal fluids (Gates, 1995; Lupulescu and Pyle, 2005) having relatively low $f(O_2)$. For some deposits the fluids were probably channeled along shear zone-related dilatational fractures (Gates 1998; Lupulescu and Gates, 2004).

Distribution of iron deposits

Some of the magnetite occurrences and ore deposits from Hudson Highlands are confined to define linear trends in some areas (Figure 1). Smock (1889) and especially Colony (1923) described three belts of iron mines that are parallel with the general strike of the host rock.

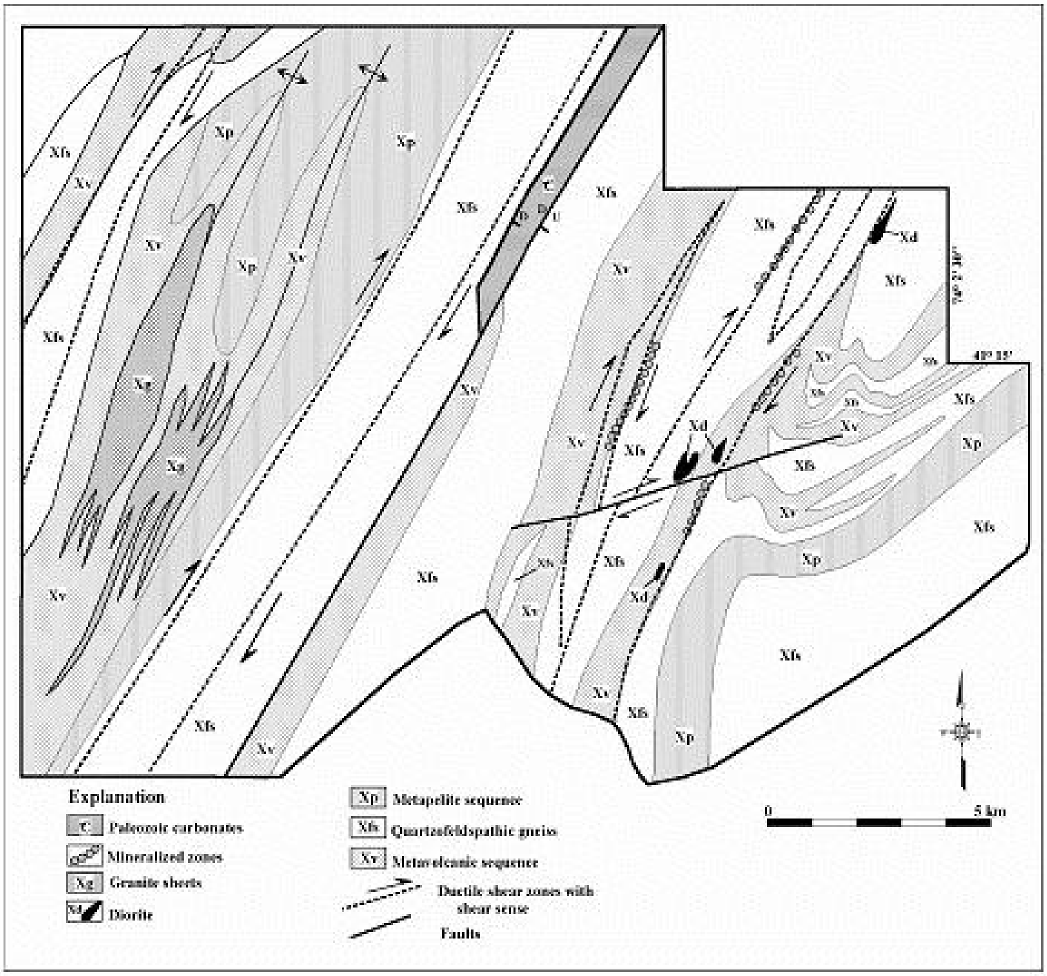

Figure 1. Mineralized zones display linear trends in some areas of the Hudson Highlands.

The first belt, the broadest, is located west of Hudson River in Orange County and extends into New Jersey. The second one is located in Putnam County, just east of Hudson River and the third belt, in the eastern part of the Hudson Highlands, starts at Brewster and crosses into the Westchester County. Besides these wide belts there are random occurrences of iron oxide in Orange, Putnam and Rockland Counties that seem to be isolated prospects.

Our study focuses on the occurrences and iron deposits from the Harriman State Park as well as the Monroe iron mines (O'Neil, Forshee and Clove Mines). All other mines are presented only for the general systematics of the iron deposits from the Hudson Highlands.

Morphology of the iron ore bodies

Magnetite is commonly an important accessory mineral in the rocks from Hudson Highlands, but it forms also ore bodies that were extensively mined in the 18th and 19th centuries. The magnetite bodies show varying morphologies, but all seem to be similar to ore shoots. Generally, the primary ore forms medium-grained irregular-shaped lenses, pseudo-veins, or layers where magnetite is around 90%. These ore shoots have very sharp contact with the country rocks, pass into very low magnetite bodies (disseminated magnetite) without any economic importance and/or contain a reaction rim of scapolite and feldspar apparently produced by the alkali metasomatism between the ore and the host rock. The remobilized magnetite is coarse-grained and is mostly associated with felsic partial melts or pegmatoid associations of feldspars and pyroxenes.

Classification of the iron ores

Based on their main mineral compositions, the iron deposits from Hudson Highlands are separated in the following mineralogical types:

1. Fe oxide: *Boston, Surebridge, Black Ash, Cranberry, Spanish Mines.*
2. Fe oxide – (Fe + Cu) ± (Ni, Co, Mo) sulfides: Mine locations at *Daters, O'Neil, Bradley, Lewis, Hasenclever, Nickel, Greenwood, Hogencamp, Pine Swamp, Redback Mines.*
3. Fe oxide - Fe and (Fe + Cu) sulfides + U oxide: *Phillips Mine.*
4. Fe oxide +/- Fe and Fe - Cu sulfide + REE: *Wilks (Clove) Mine.*

This is only a mineralogical and geochemical classification which is the simplest one. Some of the iron deposits were formed at the peak of the metamorphism (Cornell, Spanish, Lewis, Black Ash, Harris mines), other are shear zone-related deposits (Boston, Hogencamp, Pine Swamp, Surebridge and Greenwood Mines), others, like Daters mine seems to be associated with a metagabbro. Standish mine (Gundersen, 2004) and Sterling mines group could be related to a volcano-sedimentary sequence, and so on. The varied composition of the host rock and the diversity of the tectonic settings seem to point out a different origin for the iron deposits from the Hudson Highlands. The same observation has been made for the magnetite deposits in the New Jersey Highlands (Puffer, 2001).

In all of these types of deposits magnetite is the dominant ore mineral. It is associated with clino or orthopyroxenes, fluorapatite, feldspar, calcite and quartz. The sulfide sequence overlaps the main magnetite ore. Basically, the sulfides are present in all the locations, but they develop more at the above mentioned mines. Uraninite and REE-bearing minerals are disseminated in the host rock or in the felsic, pegmatoid rocks.

Mineral composition

Optical and analytical investigation recorded the mineralogy of the ore bodies. Three main classes of minerals contributed with the main minerals to the complex composition of the ore: oxides, sulfides and silicates. Other minerals were also identified, but their contribution to the ore composition is not significant from a genetic point of view.

Oxides. The main oxide mineral is magnetite. It forms compact bodies or disseminations and contains metamorphic exsolutions of ulvöspinel, hercynite and spinel-gahnite solid solution (Plate 1). Ilmenite and very rare pyrophanite rich-ilmenite were described in the ore composition. Uraninite is present at Phillips Mine in association with magnetite or as rounded grains disseminated in the host rock. The chemical data obtained using the Rensselaer Polytechnic Institute electron microprobe on the oxide minerals are presented in Table 1.

Table 1. Electron microprobe data of ilmenite and spinel-group minerals

Oxide	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	0.000	0.000	0.000	0.000	0.000	0.040	0.260	0.270	0.229	0.455	0.070	0.090
TiO_2	49.85	50.30	49.60	52.79	0.270	0.790	0.120	0.000	33.60	26.32	0.580	0.940
Al_2O_3	0.096	2.130	0.030	0.290	0.560	0.590	57.72	58.62	9.880	1.854	61.09	61.49
Cr_2O_3	0.050	0.000	0.020	0.000	0.000	0.010	0.020	0.020	0.018	0.000	0.030	0.030
V_2O_3	nd	nd	nd	nd	0.000	0.000	0.020	0.040	2.146	1.735	0.000	0.000
$Fe_2O_3{}^*$	0.000	0.000	0.000	0.000	68.51	66.84	1.365	3.50	0.000	13.23	1.541	0.000
FeO	48.12	41.24	44.86	32.06	31.09	31.94	36.54	26.15	53.77	50.43	8.113	7.710
MnO	1.240	2.46	3.70	14.67	0.060	0.060	0.870	0.880	0.455	5.200	0.160	0.130
MgO	0.057	3.13	0.020	0.170	0.300	0.000	1.980	7.710	0.854	0.458	12.34	11.60
CaO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.00
ZnO	nd	nd	nd	nd	0.020	0.010	1.350	3.140	0.080	0.000	16.64	18.55
Total	99.41	99.26	98.23	99.98	100.8	100.3	100.3	100.3	101.0	99.69	100.6	100.5
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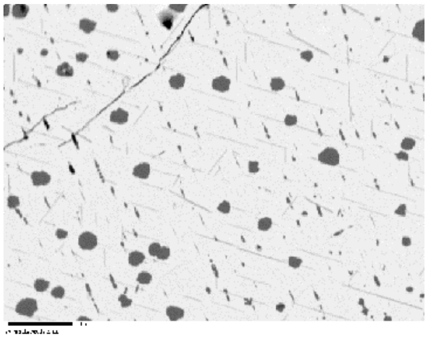
Si^{4+}	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.06	0.06	0.14	0.02	0.02
Ti^{4+}	0.97	0.94	0.97	1.00	0.06	0.18	0.02	0.00	7.09	5.86	0.09	0.15
Al^{3+}	0.00	0.06	0.00	0.01	0.20	0.21	15.60	15.29	3.27	0.65	15.53	15.69
Cr^{3+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
V^{3+}	nd	nd	nd	nd	0.00	0.00	0.00	0.01	0.48	0.41	0.00	0.00
Fe^{3+}	0.00	0.00	0.00	0.00	16.68	15.40	0.24	0.58	0.00	2.95	0.25	0.00
Fe^{2+}	1.04	0.86	0.98	0.67	7.91	8.18	7.01	4.84	12.61	12.49	1.46	1.40
Mn^{2+}	0.03	0.05	0.08	0.31	0.02	0.02	0.17	0.17	0.11	1.30	0.03	0.02
Mg^{2+}	0.00	0.12	0.00	0.01	0.14	0.00	0.68	2.54	0.36	0.20	3.97	3.75
Ca^{2+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn^{2+}	0.00	0.00	0.00	nd	0.00	0.00	0.23	0.51	0.02	0.00	2.65	2.97
Total	2.04	2.03	2.03	2.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00

1. Ilmenite (Surebridge Mine);
2. Ilmenite (Pine Swamp Mine);
3. Ilmenite (Bradley Mine);
4. Pyrophanite-rich ilmenite (O'Neil Mine);
5. Magnetite (Pine Swamp Mine);
6. Magnetite (Bradley Mine);
7. Hercynite in magnetite (Surebridge Mine);
8. Hercynite in magnetite (O'Neil Mine);
9. Ulvöspinel (Black Ash Mine);
10. Ulvöspinel (O'Neil Mine);
11. Spinel-gahnite (Pine Swamp Mine);
12. Spinel-gahnite (Pine Swamp Mine);

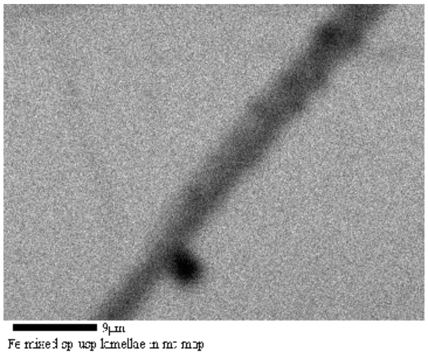
* Calculated by stoichimetry from electron microprobe analyzes;

nd = not determined

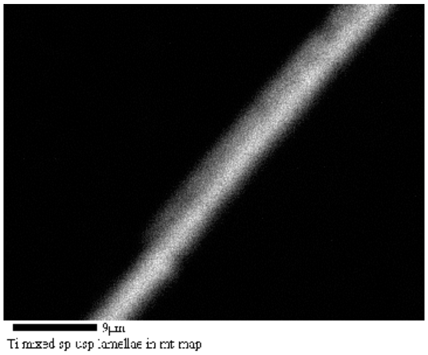
Plate 1. Spinel exsolutions in magnetite



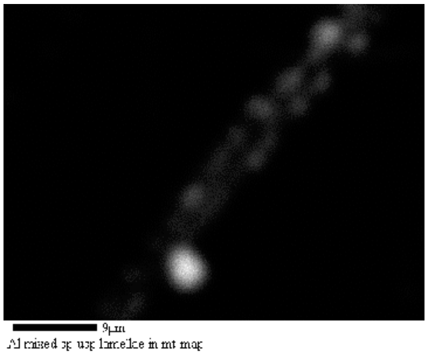
Two types of spinel exsolutions in magnetite at Hogencamp mine. The rounded, large blobs are hercynite and the other ones that were exsolved along the octahedral faces of magnetite are complex spinel associations.



BSE image of iron distribution in one of the complex spinel exsolutions along the {111} face of magnetite



BSE image of titanium distribution in the same elongated complex spinel exsolution.

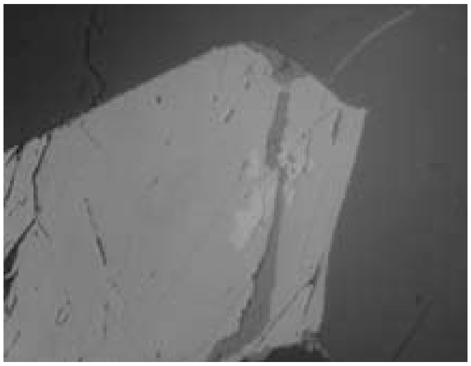


BSE image of aluminum distribution for the same exsolution lamella.

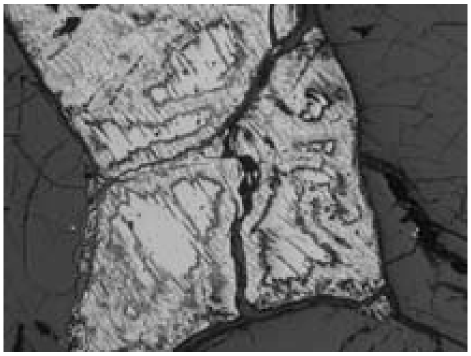
Sulfides. The sulfide sequence overlaps the magnetite ore. It is present at almost all the mines analyzed for this study, but only at some deposits it is well developed. The primary sulfides are pyrrhotite (dominant), followed by chalcopyrite, rare pentlandite formed along the pyrrhotite-chalcopyrite contact, cobaltite and molybdenite. Marcasite is the weathering product and (Plate 2)

Plate 2. Relationships between sulfides in the iron mines from Hudson Highlands

Pyrrhotite (light gray), chalcopyrite (medium gray), cobaltite (light) in silicates (dark). Hogencamp Mine.



Pyrrhotite (light gray), as host for pentlandite (light). Both are crosscut by magnetite from a second generation. Hogencamp Mine.



Marcasite, product of weathering, replaces pyrrhotite. Nickel Mine.

Silicates. Minerals from this group were formed at different moments in the evolution of the iron deposits from Hudson Highlands and accompany the magnetite ore as gangue minerals. They belong mainly to the following mineral groups: olivine, pyroxene, amphibole, biotite, scapolite and garnet. Selected electron microprobe data for the silicates accompanying the iron ore are presented in Table 2.

Table 2. Selected electron microprobe data on ferromagnesian minerals from the iron deposits

Oxide	1	2	3	4	5	6	7	8	9	10
SiO2	36.90	34.59	54.82	50.80	52.35	38.11	38.88	58.07	40.49	39.77
TiO2	0.000	0.000	0.018	0.037	0.090	0.980	0.110	0.000	0.110	0.194
Al2O3	0.000	0.000	0.683	0.408	2.910	15.46	12.89	0.220	10.29	13.51
V2O3	0.000	0.000	0.000	0.000	0.000	0.120	0.020	0.020	0.030	0.000
Cr2O3	0.000	0.000	0.023	0.006	0.000	0.040	0.010	0.010	0.010	nd
Fe2O3*	0.000	0.000	0.000	0.000	2.710	4.200	5.820	3.620	5.320	0.000
FeO	31.95	44.54	18.40	33.95	2.111	12.33	15.55	1.910	18.99	11.63
MgO	29.91	20.00	24.98	12.93	15.57	9.800	7.58	21.69	6.680	19.66
MnO	2.000	1.880	0.434	1.671	0.160	0.210	0.410	0.110	0.200	0.000
CaO	0.030	0.030	0.443	0.748	24.98	12.04	11.32	11.69	11.13	0.000
Na2O	nd	nd	nd	nd	0.140	1.290	1.460	0.830	1.240	0.328
K2O	nd	nd	nd	nd	0.000	3.110	2.670	0.390	2.930	9.560
F	nd	nd	nd	nd	nd	0.89	0.52	2.350	2.230	2.627
Cl	nd	nd	nd	nd	nd	0.95	3.05	0.020	0.610	0.728
H2O**	nd	nd	nd	nd	nd	1.310	0.860	1.070	0.700	nd
O=F,Cl	nd	nd	nd	nd	nd	-0.57	-0.91	-0.99	-1.08	-1.27
Total	100.79	101.04	99.80	100.54	101.02	100.25	100.28	101	99.88	93.46

1. Olivine (hortonolite), O'Neil Mine;
2. Olivine (hyalosiderite), O'Neil Mine;
3. Enstatite, Boston Mine;
4. Ferrosilite, O'Neil Mine;
5. Diopside, Hogencamp Mine;
6. Potassicpargasite, Hogencamp Mine;
7. Potassichastingsite, O'Neil Mine;
8. Fluorotremolite, Redback Mine;
9. Fluoro potassichastingsite, Greenwood Mine;
10. Phlogopite, Wilks Mine.

* Determined by stoichiometry from electron microprobe data.
** Determined by stoichiometry.
nd: not determined

The olivine and pyroxene mineral groups yield information on the initial protolith and metamorphic grade. The amphiboles, scapolite and phlogopite yield information on the composition of the fluids involved in the evolution of the iron deposits. According to the relationships of these fluid sensitive minerals with other silicates, magnetite and sulfide sequences three stages of amphibole formation can be distinguished:
Rock-forming amphiboles: hastingsite and magnesiohornblende;
Metasomatic-hydrothermal amphiboles: fluoro potassichastingsite, potassichastingsite, potassicpargasite, magnesiohastingsite, and edenite;
Late hydrothermal amphiboles: fluorotremolite, tremolite and actinolite.

The amphiboles from the first stage are regular amphiboles that are commonly seen in gneisses. The metasomatic-hydrothermal amphiboles have the following characteristics:

- They have a regional distribution;
- They are halogen- and potassium-rich amphiboles from the group 2 calcic amphiboles: hastingsite, pargasite +/- ferro-edenite series with K_2O = 3.2%, Cl = 3.66% and/or F = 2.26%;
- They replace the rock-forming amphiboles characterized by Fe-rich and moderate high $^{[IV]}$Al content (hastingsite *sensu lato*), and pyroxenes. The same sequence described for the Reservoir Fault (Gates, 1995) emphasizes the extension of the metasomatic-hydrothermal event along the Highlands in New York and New Jersey

Chlorine-rich amphiboles were described in different environments such as contact metamorphism, skarns and metasomatic iron deposits (Krutov, 1936; Dick and Robinson, 1979; Suwa et al. 1987; Mazdab and Barton, 2001), regional metamorphism (Kamineni et al 1982; Matsubara and Matayoshi, 1985; Henry, 1988; Leger et al. 1996), ocean floor metamorphism (Vanko, 1986), geothermal systems (Enami et al 1992), pegmatite (Suwa et al. 1987) and shear zones (Kullerud, 1996; Georgen et al. 1999). The mechanism of chlorine incorporation into the amphibole structure (Volfinger et al. 1985; Makino et al. 1993; Oberti et al. 1993) is controlled by the crystal chemistry showing a significant bonding interaction between ^{A}K and $^{O3'}$Cl.

The incorporation of Cl requires expansion of the tetrahedral chain primarily by the increased substitution of $^{[IV]}$Al for Si. Increasing Cl content requires increasing Fe^{2+}, K and $^{[IV]}$Al. The homogeneity of the chlorine distribution is related to the reactions with saline brine that can coexist with an immiscible CO_2-dominated vapor during the granulite facies metamorphism (Zhu et al. 1994).

The chemical data on the amphiboles from the iron deposits from Hudson Highlands show a positive linear correlation between the concentrations of K and Cl, and a positive logarithmic correlation between both ^{IV}Al and ^{VI}Fe (total) and Cl. The negative correlation between the Mg and Cl concentration is consistent with the Mg-Cl avoidance rule. The calculated Fe^{3+}/Fe^{2+} ratios support the crystallization at relatively low oxygen fugacity in a reducing environment. The *A*-site occupancy, based on chemical data, was calculated for all the analyzed amphiboles between 0.65 and 0.97. The K-dominant and F/Cl-rich species shows the highest *A*-site occupancy.

Amphiboles containing significant amounts of fluorine were described in different igneous and metamorphic rocks (Petersen et al. 1982). Fluorine incorporation into the amphiboles is also controlled by crystal chemistry. Experimental studies have used synthetic fluoro-amphiboles to obtain thermodynamic data to understand the behavior and stability of their natural analogues (Holloway and Ford, 1975; Graham and Navrotsky, 1986). Some of the first syntheses of amphiboles were F-bearing species (Bowen and Schairer, 1935; Grigoriev and Iskuld, 1937). The substitution of F for OH in amphiboles is thought to contribute to their higher thermal stability by replacing Mg-O bonds with shorter and stronger Mg-F bonds.

The third stage contains fluoro-tremolite and OH-dominant amphiboles. This observation is important and will be used further to discuss the evolution of the fluids.

Phlogopite is another hydrous phase in the mineral composition of the iron ore. It develops on the amphibole expense or forms late patches composed only from phlogopite. The F, Cl and OH content varies, but fluorine- and chlorine-dominant species were described (Leger et al. 1996; Lupulescu & Pyle, 2005). When phlogopite replaces the amphiboles it has significant amount of fluorine and chlorine. The late phlogopite has relatively reduced fluorine and high OH in composition.

The only high content REE- silicate mineral, with some relevance quantitatively, that was described (Lupulescu & Hawkins, 2003) in the iron ores is chevkinite-(Ce). It was collected from the Clove (Wilks) Iron mine and appears as rounded isometric or elongated patches, from 1 mm to 1 cm in size in a granitic pegmatite (partial melt) with oligoclase and hornblende cutting the iron ore; it is surrounded by a thin white rim composed mainly of cryptocrystalline silica, a mixture of secondary titanium oxides, and probably some clay minerals. It has $Ce_2O_3$14.8-20.6%; La_2O_3 7.3-11.1%; Y_2O_3 0.02-0.6% and ThO_2 1.9-2.0%. Chevkinite-(Ce) is the product of a Ti and REE-saturated residual phase from a low-degree melt in a medium-high metamorphic environment (granulite facies). Its crystallization was possible in a residual phase with low Ca and high REE activity, where the TiO_2 content has not been critically lowered by the earlier precipitation of a Ti mineral.

Structural setting

The peak of the Grenville orogeny in the Hudson Highlands is characterized by thickening of the crust through fold nappe generation and resultant granulite facies metamorphism. Fold nappes are characterized by NE-trending fold axes and subhorizontal axial planes. The folds are tight to isoclinal with a sheared out lower limb demonstrating westward emplacement. Anatexis produced granite sheets that were emplaced along the nappes during peak conditions. Some of the high temperature magnetite deposits marked by olivine and high temperature minerals were formed during this event.

Gates et al. (2004) describe a steep, NE-striking dextral strike-slip shear system in the western Hudson Highlands. The exposed shear system is > 35 km wide and composed of an anastomosing system of 1-2 km wide individual shear zones. The fault rocks within the zones are S-C mylonites formed at

upper amphibolite facies. Kinematic indicators show consistent dextral offset but locally exhibit significant pure shear and flattening. Shear strain varies across the zones ranging to > 6 based upon rotated S fabric.

Magnetite deposits and veins of related gangue minerals occur along the edge of some of the dextral shear zones. They occur late in the deformational sequence and are cross cut by undeformed pegmatites which appear to intrude along the veins. The magnetite deposits occur in areas where the veins are wider, ranging to > 10 m. In these deposits, the vein-rock contact is sharp and slightly discordant to the mylonitic foliation. There can be some compositional banding of the vein along the margins but the vein filling is overwhelmingly

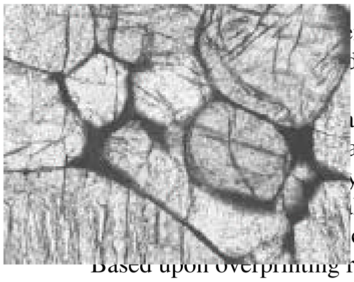


Figure 2. Diopside (light) replaced by hedenbergite (dark).

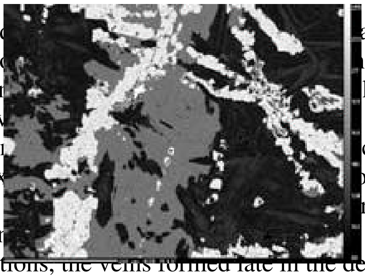


Figure 3. Veinlets of magnetite (white) surrounded by ferropyrosmalite (light gray) that passes to actinolite (dark).

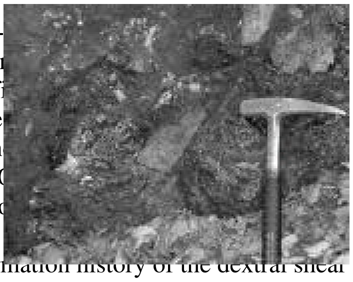


Figure 4. The large diopside crystal reacted with massive coarse-grained magnetite to form hastingsite (dark rim around diopside). Hogencamp Mine.

Based upon overprinting relations, the veins formed late in the deformation history of the dextral shear zones. The general shape of the vein-like occurrences, lack of deformational fabric, and large random (open-cavity fill) crystals suggest that they formed in a rhombic right step-over or pull-apart structure. The thin, connecting strands accomodated the minor dextral shear associated with the opening of these zones. Fluids were likely drawn into these zones probably by seismic pumping and the lower pressure conditions induced precipitation of the ore minerals.

DISCUSSION

The iron deposits from the Hudson Highlands are hosted by units of calc-silicates, quartzo- feldspathic gneisses and amphibole and pyroxene bearing gneisses. In a few situations the calc-silicates were transformed into iron ore-bearing skarns as at Bradley Mine. Their mineral composition is simple to complex and two main mineralizing stages were distinguished. The magnetite sequence is the main one and the sulfides overlapped it. In order to reconstruct a genetic model for the iron deposits the discussion has to focus on the following facts:

a. Relationships between ore minerals;
b. Metasomatic alteration;
c. Character of the fluids;
d. Structural setting

a. ***Ore minerals and their relationships.*** Magnetite is the main ore mineral in all the deposits and occurrences we studied. It forms massive ore bodies or sub-economical disseminations in the country rocks. The relationships between magnetite, the gangue and rock-forming minerals pointed out three generations of magnetite that can be linked to three different genetic events. The massive magnetite ore forms ore shoots that seem to have a NE – SW strike which is concordat with that of the metamorphic country rocks. In many occurrences, pyroxenes with low iron content (diopside) were replaced by pyroxenes with higher iron (hedenbergite) as in Figure 2. Replacement of pyroxenes, especially in calc silicate compositions, is very common.

When the halogen-enriched fluids infiltrated the country rocks they reacted with the rock-forming minerals, partially leached the iron and deposited it as a second generation (Figure 3). This appears to be synchronous with the incipient formation of the Cl- and/or F-rich amphiboles.

These fluids were responsible for the formation of amphiboles, in places following reaction:

Diopside + (K^+, Cl^-, H_2O) + Magnetite = (K, Cl) Hastingsite (Figure 4).

The third generation of iron oxide is represented by the coarse grained magnetite remobilized by the partial melts in the granulite facies and hosted by the quartzo-feldspathic pegmatoid separations. The metasomatic replacement trend seems to be the following: low iron pyroxene- high iron pyroxene – magnetite - sulfides + amphiboles – phlogopite – microcline – albite – low halogen amphiboles.

The gangue minerals reflect the control of the host rock on the mineralogical composition of the ore. For example, at Hogencamp, Bradley, Forshee and O'Neil mines where the host rock is in part composed by marbles, calcite is a major component for some ore bodies. At Greenwood and Lewis mines, where the host rock is partially a quartzofeldspatic gneiss, quartz is a significant a gangue mineral.

b. ***Metasomatic alteration.*** The metasomatic alteration accompanying the iron ores from the Hudson Highlands has an alkali – halogen character. It has regional distribution and is represented mainly by the halogen- and potassium-rich/dominant amphiboles, phlogopite and rare scapolite. The amphiboles contain K_2O up to 3.2%, Cl up to 3.66% and/or F up to 2.36% and replaces the rock-forming amphiboles characterized by Fe-rich and moderate high $^{[IV]}$Al content (Figure 5). Potassium could be derived from locally K-rich *in situ* isochemical metamorphism or associated with K-rich igneous rocks and affiliated metasomatism. The alkali – halogen metasomatism generally results from fluxing of hypersaline brines through rocks and creates a distinctive suite of halogen-rich minerals such as scapolite, amphiboles and phlogopite.

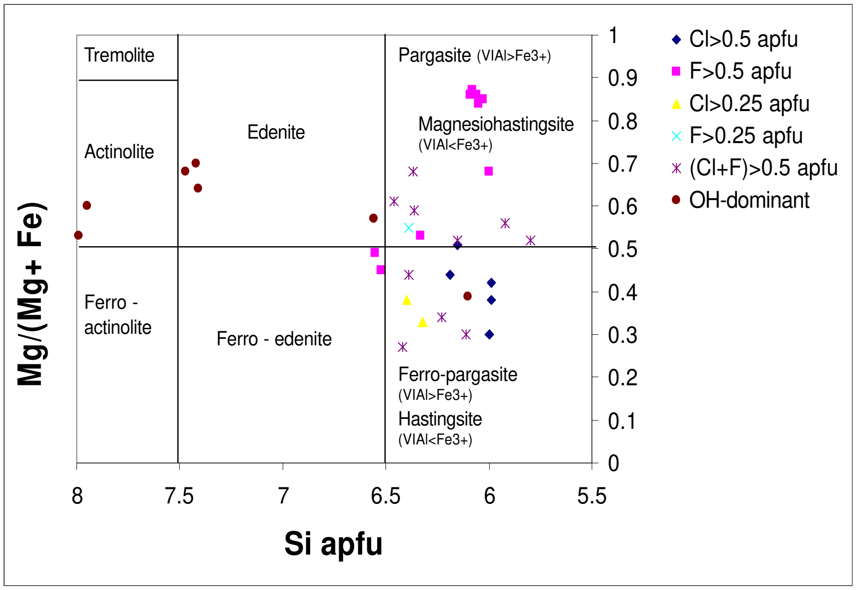


Figure 5. Classification of the amphiboles from the iron deposits from the Hudson Highlands. The potassium- and halogen-rich/dominant amphiboles are Fe-rich and moderate high $^{[IV]}$Al species.

c. ***The character of the fluids.*** The composition of the metasomatic fluids is modeled by analyzing the EMP data for the volatiles hosted by the amphibole *O3* site. The calculated Fe^{3+}/Fe^{2+} values for the amphiboles suggest crystallization under conditions of relatively low f(O2). The precipitation of the amphiboles at reducing conditions as shown by Figure 6.

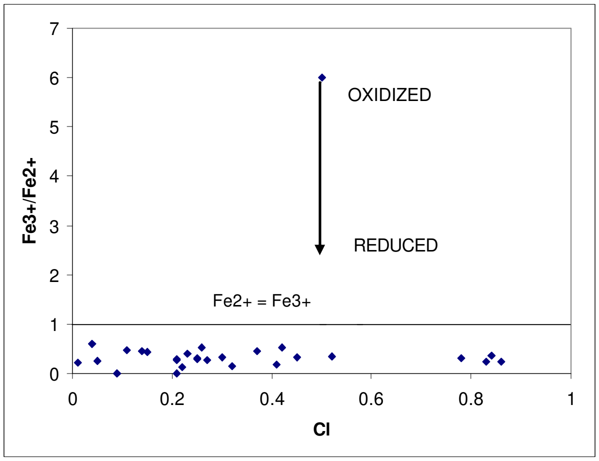


Figure 6. Plot of Fe^{3+}/Fe^{2+} versus Cl for the amphiboles from the iron deposits from the Hudson Highlands. All the amphiboles seem to be precipitated at reducing conditions.

Two chemically distinct fluids seem to be responsible for the formation of halogen- and potassium-rich amphiboles (Figure 7):

a) An initial low-activity halogen fluid that became a Cl- and/or F-rich fluid with time from which the Cl- and F-rich amphiboles crystallized; and

b) A late OH-rich fluid that generated the green actinolite and tremolite.

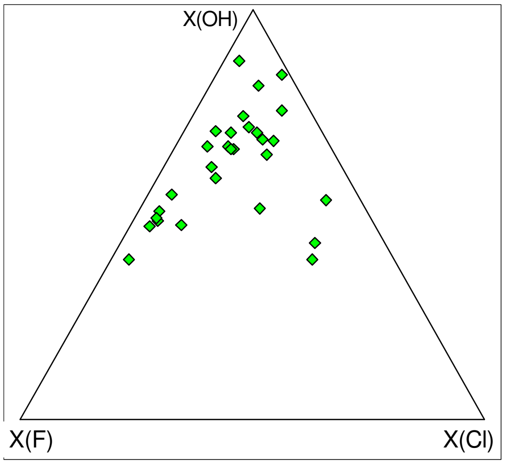


Figure 7. The composition of the fluids that generated the amphiboles.

The amphibole compositions shows that the Cl-content varies between 0.1 and 0.9 apfu, F between 0.1 and 1.1 *apfu* and OH between 0.8 and 2 *apfu*. The multivariant analysis shows that the variations in the amphibole composition can be related to a Cl- and/or F-free component $\mathit{AB}_2\mathit{C}_5\mathit{T}_8\mathrm{O}_{22}(\mathrm{OH})_2$ and a complex vector exchange component with $(\mathrm{Cl}_{0.9}\mathrm{OH}_{-1.1})$ or $(\mathrm{F}_{1.1}\mathrm{OH}_{-0.9})$ in *O3* site. The compositional variations of amphiboles along the exchange vectors are caused by the ratio of the fluid activity (Kullerud, 1996). In our case the ratios are ***a*** of HCl in fluid **/** ***a*** of H_2O in fluid and ***a*** of HF in fluid **/** ***a*** of H_2O in fluid. We explain the amphiboles composition accounting for a fluid with a relatively low activity ratios $\boldsymbol{a}_{\mathrm{HCl}}/\boldsymbol{a}_{\mathrm{H2O}}$ and $\boldsymbol{a}_{\mathrm{F}}/\boldsymbol{a}_{\mathrm{H2O}}$. Because OH is easily and preferentially accommodated in the amphibole structure, the initial interaction between the rock-forming minerals and the fluid had as a result an increase of the Cl- and F-content into the amphiboles and further into phlogopite. Chlorine is a large anion and its incorporation into the amphibole structure requires significant structural modifications. On the other hand, fluorine is a smaller anion that can be easily be accommodated into the amphiboles structure. For this reason, in time, the fluid became F-depleted and the Cl-content of the amphiboles increased toward the end of the mineralization process. The mineral relationships show that the halogen-depleted fluid is a late, separate fluid.

The source of both Cl and F is not clear, but high saline crustal brine is most likely.

d. ***The structural setting.*** The extensive dextral shear system formed vertical anisotropies in the otherwise subhorizontal layering. This permitted the movement of fluid in both a vertical and lateral sense. As the temperature of the metamorphic pile decreased during deformation the rocks became more rigid. Late movement allowed the development of dilational zones within transtensional segments of the fault system. As fluid flushed into these lower pressure areas, solubility changes allowed the precipitation of the fault-controlled mineralized zones. Within the dilational areas, minerals could grow large and randomly oriented under conditions of near hydrostatic stress. These areas are marked by the magnetite deposits and the classic Hudson Highland skarns. Interaction with the fractured host rock drove exchange reaction allowing the local buffering of fluids as described. The connecting fault strands continued to slip and the fluid deposited minerals under conditions of differential stress where possible. The rocks there are composed of the same or similar minerals but they are foliated and much finer grained.

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ASBESTIFORM MINERALS IN THE BEDROCK OF THE NEW JERSEY HIGHLANDS: GEOLOGY AND ENVIRONMENTAL HEALTH IMPLICATIONS

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ABSTRACT

Bedrock exposed at several locations throughout the New Jersey Highlands and adjoining areas contains asbestiform minerals. Among the localities where fibrous tremolite bearing marble is exposed are the active Limecrest (Southdown, now Cemex) quarry near Sparta, and the inactive Williams quarry in Forks. Crocidolite bearing protomylonite is exposed at Mendham, and bedrocks containing asbestiform minerals are exposed in many other localities. Each of these exposures could potentially contaminate air and water supplies. Evidence is presented that some air and water supplies have already been contaminated. Pulverized marble containing fibrous tremolite from the Limecrest Quarry has been used on lawns and gardens throughout the Mid-Atlantic region, creating an additional potential for exposure. The issues of the analytical definition of asbestos fiber are discussed, and it is concluded that most mineralogical definitions have little relevance to health issues, i.e., asbestos-related diseases. An asbestos contaminated play sand issue is reviewed as a case-in-point. The carcinogenicity of chrysotile seems to be related largely to traces of fibrous tremolite in chrysotile ore. The effects of weathering on amphibole fiber genesis are discussed, and formation of an oxidation product that may be the agent of carcinogenesis of amphibole asbestos is documented.

INTRODUCTION

The content of a recent USGS publication by Van Gosen (2005) was widely reported by the New Jersey press. The publication *"Reported historic asbestos mines, historic asbestos prospects, and natural asbestos occurrences in the eastern United States"* included 55 occurrences in New Jersey and Staten Island, New York. However, the sole data source of the New Jersey portion of the USGS publication was a previously published report by Germine and Puffer (1981). This report also draws heavily on the Germine and Puffer (1981) publication but in addition includes some updates on activities that were initiated in response to potential environmental problems related to these asbestos occurrences. Eighteen of the 55 occurrences are chrysotile and anthophyllite asbestos occurrences related to serpentinite exposures throughout Staten Island and Hoboken and to asbestos occurrences associated with faults through Jurassic basalt flows and sills with the remaining 37 occurrences in the rocks of the New Jersey Highlands (Fig. 1 and Table 1.). The Highlands asbestos occurrences can be grouped into three general categories: 1.) Tremolite bearing marble exposures particularly at the Limecrest or Southdown quarry, and the Williams Quarry. 2.) Crocidolite bearing protomylonite exposures particularly at Mendham. 3.) Mixed asbestos occurrences particularly the Franklin and Sterling Hill zinc mines, some historic iron mines, and various highway road cuts.

ASBESTOS

Asbestos minerals do not possess any distinct crystal chemistry or structure that distinguishes them from their non-asbestos analogues. Rather, "asbestos" as defined by (Germine and Puffer, 1989), is a morphological term which refers to silicate minerals that generate a significant proportion of fine, high aspect-ratio fibers on mechanical or chemical degradation.

Although there are several minerals that can occur in asbestiform habit, the currently regulated varieties of asbestos are one serpentine group mineral, chrysotile, and five amphibole group minerals, some of which are known by their commercial names: 1 and 2) tremolite and actinolite, a continuous series, tremolite-actinolite, with actinolite distinguished only by its higher iron content; 3) crocidolite, or “blue asbestos,” mineralogically the asbestiform type of magnesioriebeckite-riebeckite, a continuous series with riebeckite only distinguished by its higher iron content, 4) amosite, or “brown asbestos,” and, 5) anthophyllite.

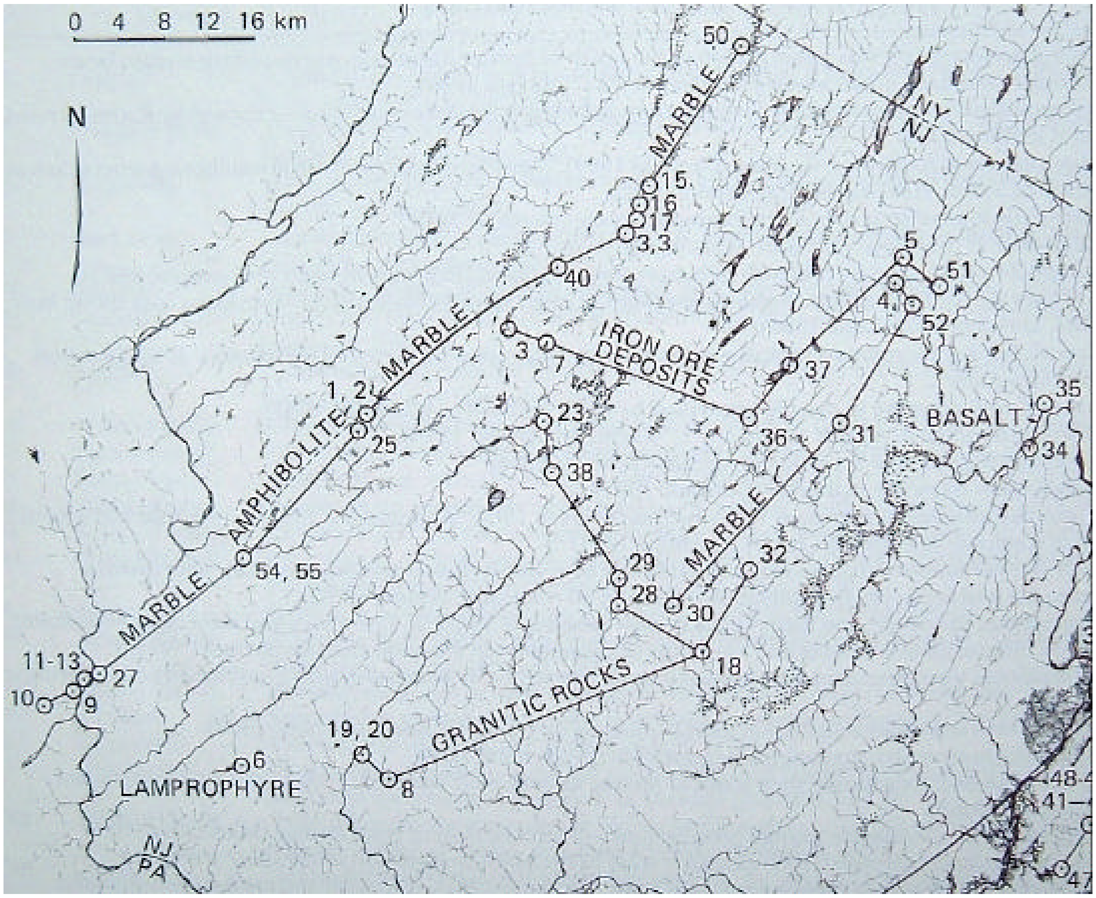


Figure 1. Map of the New Jersey Highlands area showing the locations of documented asbestos-bearing bedrock occurrences. Labeled tie-lines connect asbestos occurrences of similar lithology after Germine and Puffer (1981).

Chrysotile $Mg_3Si_2O_5(OH)_4$ is by far the most abundant asbestos mineral. It has a characteristic tubular structure, and is almost always a major constituent of serpentinite. Chrysotile is known as “white asbestos” and constitutes about 95 percent of asbestos use.

All five of the amphibole-group asbestos minerals are hydrous magnesium/iron silicates, with calcium and/or sodium as major cations. All possess a double chain structure. Crocidolite and amosite have been the most commonly used commercial varieties of amphibole. Although crocidolite possesses some very desirable commercial qualities, especially for high temperature applications, its use has been all but phased out due to high rates of mesothelioma associated with its use. Because tremolite-actinolite is often relatively brittle, it is poorly suited for commercial use and has rarely been used as such. It has, however, been locally used as stucco, and this use has been associated with mesothelioma at a number of localities. Anthophyllite also has unfavorable commercial qualities that made it uncommonly used commercially. It is almost invariably intergrown with talc.

Most uses of asbestos were banned by the EPA in 1989 because of health effects (lung cancer, mesothelioma, and asbestosis). In addition, it has recently been determined that asbestos can also cause cancer of the larynx (Associated Press, 2006). Just before the ban took effect the 1988 uses of asbestos included roofing products 28%, friction products (break lining) 26%, asbestos cement pipe 14%, packing and gaskets 13%, paper 6% and other 13%. Usage of asbestos peaked in the 1970s although most of the health risks were already known in the 1960s. Common uses in the 60s and 70s included floor and ceiling tile, insulation, wire insulation, lab table tops, lab gloves, caulking / putties, spackling compounds, chalkboards, roofing felt, and boiler insulation. Additionally, asbestiform minerals have been a common contaminate in vermiculite, lawn and garden lime, play sand, crayons, talc (commercial, consumer, and pharmaceutical), iron ore, road aggregate, and drinking water. The use of talc containing large amounts of asbestiform tremolite and anthophyllite has, to our knowledge, been phased out in the United States after a widely-publicized report to the press. Contaminated talc was reportedly derived from mining operations in New York State, and was used to impart strength to crayons.

Insurance companies and businesses have paid $70 billion due to asbestos litigation so far and are estimated to eventually pay out $108 to 275 billion (Coscarelli, 2004). About 730,000 people have filed claims related to asbestos exposure while an estimated 15 victims die each day from asbestos poisoning (Coscarelli, 2004). The Johns Manville Corporation, once based in Somerset County, New Jersey was the first of 66 asbestos manufacturing companies to go into bankruptcy.

Figure 1 shows individual locations where chrysotile and asbestiform amphiboles have been identified, some of which we will be discussing in the text of this report. Table 1 gives a brief description and citations for these localities. A precise location of these localities in terms of latitude and longitude is also available, along with chemical analyses and X-ray diffraction data for many of the localities and for asbestos standards (Germine, 1981).

Table 1. Documented Occurrences of Asbestos in the Bedrock of the New Jersey Highlands (after Germine and Puffer, 1981)

Site	Location	Description with Selected References
1	Allamuchy	Two abandoned asbestos mines on top of hill north of Spruce Mountain. Surrounding terrain bears “considerable dark green asbestos of good quality” (Valiant, 1903).
2	Allamuchy	Asbestiform tremolite-actinolite in marble, amphibolite, pegmatite, and diabase exposed by Rt.80 roadcut (Germine, 1981).
3	Andover	Blue asbestos at Andover Iron Mine (Canfield, 1889). Bluish-green asbestiform actinolite in garnet skarn at Sulfur Hill Iron Mine (Germaine, 1981).
4	Bloomingdale	Chrysotile in marble at the Green Swamp Dam site (Germine, 1981).
5	Bloomingdale	Chrysotile in marble at Old Blue Mine (Cook, 1879).
6	Bethlehem	Asbestiform actinolite-hornblende in lamprophyre on Rt. 78 roadcut (Germine, 1981).
7	Byram	Light bluish-green asbestos with straight fibers up to 70 cm long at Roseville Iron Mine (Cook, 1868).
8	Clinton	Crocidolite in Precambrian rock exposed during excavation on Rt. 78 (Markewicz, 1980 personal communication to Germine).
9	Easton	Asbestiform tremolite in marble exposed by sewer excavation (Germine, 1981).
10	Easton	Fibrous tremolite in marble at “Quarry L” (Geyer et al., 1976).
11	Forks	Asbestiform tremolite-actinolite in marble (Germine, 1981).
12	Forks	Asbestiform tremolite in marble (Germine, 1981).
13	Forks	Tremolite asbestos in marble at Williams Quarry (Peck, 1905; Montgomery, 1955). Chrysotile and asbestiform tremolite at Williams Quarry (Germine, 1981).
15	Franklin	Crocidolite, chrysotile, and tremolite-actinolite asbestos in Franklin zinc mines and mine dumps (Palache, 1935). Asbestiform tremolite and chrysotile in shear zones in Franklin zinc ore (Frondel, 1972). Fibrous or needle-like light blue magnesioriebeckite at the Trotter Dump, and anthophyllite and chrysotile at Franklin (Kusher, 1974).
16	Franklin	Asbestiform tremolite-actinolite in marble outcrop on Cork Hill road (Germine, 1981, 1986).
17	Franklin	Asbestiform tremolite-actinolite in marble quarry (Germine, 1981).
18	Harding	Crocidolite in Precambrian rock south of Mount Kemble, near Rt. 202 (Markewicz, 1980, personal communication to Germine).
19	High Bridge	Crocidolite in Byram granite outcrop north of athletic field (Markewicz, 1964).
20	High Bridge	Crocidolite in Precambrian rock along the trace of the High Bridge fault (Markewicz, 1964).
23	Hopatcong	Crocidolite-richterite in Precambrian rock exposed by railroad cut (Germine, 1981)
25	Independence	Asbestos on Davis farm (Chester, 1901). Asbestos in talcose prominence on Davis farm (Valiant, 1903).
27	Lopatcong	Asbestos in serpentine at the Green Marble Quarry (Lewis, 1909). Tremolite asbestos at the Green Marble Quarry (Montgomery, 1955)
28	Mendham	Crocidolite in Precambrian outcrops on India Brook (Markewicz, 1965; Germine, 1981; Puffer and Germine, 1982; Zdenek et al., 2001).
29	Mendham	Crocidolite in Precambrian water well drill cuttings (Puffer and Germine, 1982).
30	Mendham	Chrysotile in marble at Sander’s Marble Quarry (Germine, 1981)
31	Montville	Chrysotile in marble quarry (Merrill, 1888; Shannon, 1927; Kalousek and Muttart, 1957; Faust and Fahey, 1962; Germine, 1981).
32	Morristown	Blue asbestos and Morristown (Manchester, 1931). Crocidolite in precambrian rock near Speedwell Lake (Germine, 1981).
33	Ogdensburg	Chrysotile inclusions in willemite at Sterling Hill (Metsger et al., 1966; Kusher, 1974). Asbestiform tremolite-actinolite and chrysotile in shear zones in ore at Sterling Hill (Frondel, 1972; Germine, 1981, 1986).
36	Rockaway	Light green asbestos with fibers several inches in length frequently seen in hanging wall of ore at the Beach Iron Mine (Cook, 1868).
37	Rockaway	Chrysotile in marble and pyroxene skarn, asbestiform actinolite in hornblende skarn at Split Rock Pond Iron Mine (Germine, 1981).
38	Roxbury	Actinolite asbestos in Precambrian rock on Rt. 80 roadcut (Germine, 1981).
40	Sparta	Asbestos at the Limecrest Quarry (Widmer, 1962; Wood, 1969). Asbestiform tremolite in marble at the Limecrest Quarry (Germine, 1981, 1986).
50	Vernon	Asbestiform tremolite-actinolite in outcrop in marble on Rt. 517 (Germine, 1981).
51	Wanaque	Chrysotile at the Kanouse Mine (Canfield, 1889).
52	Wanaque	Chrysotile in seams up to 1.2 cm thick in Debow’s marble quarry (Canfield, 1889; Manchester, 1931). “Beautiful specimens” of chrysotile in Debow’s quarry (Cook, 1874).
54	White	Tremolite asbestos found frequently on slickensided surfaces in marble at waste dumps of the Edison Quarry (Johnson, 1929).
55	White	Asbestiform actinolite in amphibolite at the Oxford Quarry (Germine, 1981).

Tremolite-bearing Marble Occurrences:

Limecrest (Southdown) Quarry (Site 40)

The Limecrest Quarry in Sparta New Jersey was operated as the Limestone Products Quarry, then as the Southdown Quarry, and, most recently, as the Cemex Quarry. It is located on a detached Precambrian marble band south of the Franklin band. The Franklin marble at the Limecrest Quarry is a white calcitic to dolomitic marble that contains minor amounts of phlogopite, sericite, graphite, tremolite, actinolite, hornblende, chondrodite-norbergite, quartz, diopside, and scapolite (Haque and others, 1956). Tremolite commonly occurs in the quarry as coarsely crystalline light gray to green prisms but when ground produces asbestiform fibers. Asbestiform tremolite is also generated through westhering of prismatic crystals (Figure 2). Tremolite-actinolite much less commonly occurs in slickensided zones at the quarry as thin layers of greenish to white slip-fiber aligned parallel to fault lineations (Germine and Puffer, 1981).

Figure 2. Scanning electron photomicrograph of asbestiform tremolite forming through weathering of prismatic tremolite from the Southdown (Limecrest) Quarry in Sparta (from Figure 3, Germine and Puffer, 1989a). Bar scale equals 10 microns.

Germine (1986) measured the amphibole content present in 50 pound bags of commercial Limecrest Quarry products including “Barn calcite”, “90-200 filler”, “Granular limestone”, and two bags of “Pulverized limestone”. He found that the concentration of material insoluble in dilute HCl (largely silicates) ranged from 8 to 13 percent. The amphibole content of the insoluble fraction, as measured against a tremolite standard using X-ray diffraction, ranged from 2 to 7 percent, consisting largely of prismatic and acicular amphibole grains of tremolite, actinolite, and hornblende in approximately equal proportions. However, asbestiform grains less than 3 mm possessing a silky luster that brake into fibrous aggregates under a needle probe were found as a persistent trace constituent. Tremolite fiber content was measured using light microscopy as 42 fibers per milligram of which 7.6 fibers per milligram were respirable (having a Stokes fluid-dynamic diameter less than 5 microns). The data from this report (Germine, 1986) show that the respirable fraction contains a much higher proportion of high aspect ration (length/ width) fibers, reflecting the lower settling velocity of such fibers. It should be noted that the resolving power of light microscopy is limited, and that the concentrations reported are just a very small fraction of the total fiber content as would be measured by transmission electron microscopy.

Williams Quarry area (Sites11-13 and 27)

The rocks of the Williams Quarry in Forks, Pennsylvania, (Sites 11-13) include tremolitic rock, dolomitic marble, talc schist, and pegmatite (Montgomery, 1955), and are in a large fault zone running through the area. Tremolite asbestos is abundant and occurs predominantly in slip-fiber veins. Most of the tremolite is tightly bound, relatively brittle, and commonly partially altered to talc. Less commonly the tremolite is highly flexible fiber (Germine and Puffer, 1981; Germine, 1981). The transition from brittle, tightly bound tremolite was noted to be a product of progressive weathering (Germine and Puffer, 1989a).

The flexible fiber tremolite resembles chrysotile and samples in the mineral collections of Rutgers University and the Morris Museum were misidentified as chrysotile. Some of the tremolite at the quarry occurs in a silky, flexible, fiberized form that can be twisted into rope (Figure 3). Yet, by commercial asbestos standards, it is still relatively brittle. Soft, massive, and easily carved light green veins composed of chrysotile are also common in the quarry. Tremolite asbestos in serpentine at the near-by Green Marble quarry (Site 27) was reported by Montgomery, (1955).

Figure 3. Photomicrograph of tremolite asbestos from Forks under crossed polarized light. Scale in micrometers is shown (Plate 21 of Germine 1981).

Crocidolite bearing mylonite occurrences:

India Brook, Mendham (Sites 28 and 29)

A large outcrop of protomylonite pegmatite is exposed on the east side of a steeply cut bank of India Brook, located in northern Mendham New Jersey (Germine and Puffer, 1981). A protomylonite by definition consists of 10 to 50% crushed and foliated matrix compared with mylonite containing 50 to 90% matrix. The protomylonite exposed along India Brook is a striking, colorful assemblage of orange potassium feldspar and white plagioclase in a blue matrix containing foliated soft and friable bright blue highly fibrous crocidolite. Quartz is found intergrown with crocidolite. Most of the slickensides and joints through the protomylonite are covered with blue crocidolite (Figure 4). Blue crocidolite mud occurs in some of the fractures in the rock, and some of this crocidolite has a pasty consistency due to weathering. Common fragments of crocidolite bearing protomylonite have been eroded by India Brook and deposited along both banks south and southwest of the outcrop.

The crocidolite of India Brook is largely confined to a fault zone along the base of an allochthonous slab of Byram Granite. It was probably derived from the dynamometamorphic alteration of primary igneous amphibole in Byram Granite pegmatite during shearing (Puffer and Germine, 1982; Zdenek and others, 2001). Markewicz has estimated that the Mendham Fault zone through India Brook may be in excess of three hundred feet wide.

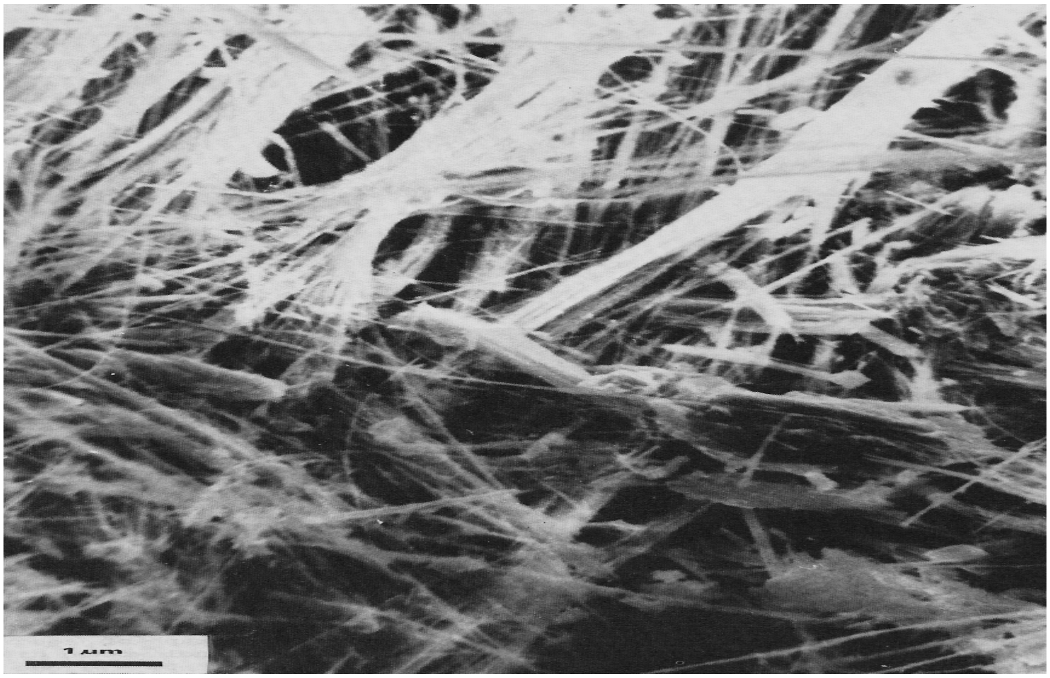


Figure 4. Scanning electron photomicrograph of crocidolite from Mendham, NJ. (Figure. 4 of Puffer and Germine, 1982).

Mixed Asbestos Occurrences

Franklin and Sterling Hill Zinc Mines (Sites 33 and 15-17)

The zinc ore bodies of Franklin and Sterling Hill are two of the most well know mineral collecting locations in existence. Palache (1935) described over 140 minerals found in the Franklin area including several asbestos minerals. Palache (1935) states that *"Tremolite is found rarely as simple isolated gray or white crystals in the limestone (marble) wall rock of both ore bodies. It is common in the form of asbestos, the white or pinkish fibers being mixed with calcite in stiff columnar masses that form a transverse filling of secondary veins."* Germine (1981) describes tremolite-actinolite from the Franklin and Sterling Hill mines that varies from non-fibrous (prismatic) through acicular to asbestiform. Germine (1981) also describes some flexible, readily fiberized tremolite in one ore sample. His analyses indicate that it contained appreciable zinc and sodium.

In addition Palache (1935) describes *"Veins filled with a bright-blue fibrous mineral, mixed with calcite and sphalerite… which, with its blue color and fibrous form, seem to indicate crocidolite …"* He reports that crocidolite was once found in abundance at the Trotter Dump in Franklin. Germine (1981) described a dark blue slip-fiber sample of crocidolite on ore from the Franklin mine with fibers up to several centimeters in length. His EDXS analyses indicate a magnesium crocidolite composition containing enough zinc to qualify as a zincian crocidolite.

According to Palache (1935). *"Serpentine is found in massive, compact, cryptocrystalline, and fibrous forms, also as pseudomorphs. It is not uncommon at Franklin but does not seem to have been found at Sterling*

Hill." However, Germine (1981) notes that chrysotile could be very abundant at Sterling Hill if as suggested by inconclusive PLM and XRD studies the serpentine inclusions in the red and flesh-colored willemite from the Sterling Hill mine are chrysotile. Chrysotile asbestos has also been observed in the Franklin ore deposit as coatings on zincite (Fushner, 1974), silky fibers in calcite (Foshag, 1926), and as slip-fiber chrysotile on calcite and franklinite ore (Germine, 1981).

Iron Mines (Sites 3, 5,7, 36 and 37)

Germine (1981) has found light green and silky chrysotile asbestos in serpentinized chondrodite from insoluble residues of marble at the Splitrock Pond iron mine located in Rockaway, NJ (Site 37). He also found slip-fiber chrysotile in a slickenside zone in a magnetite pyroxene skarn there. Germine (1981) also reported fibrous actinolite on fault surfaces at the Sulfur Hill mine located in Andover, NJ (Site 3), and noted previously published reports of asbestos at several Highlands iron mines including blue asbestos (crocidolite) at the Andover mine in Andover (Site 3) (Canfield, 1889); light bluish-green asbestos at the Roseville mine in Byram (Site 7) (Cook, 1868); and light green asbestos at the Beach mine in Rockaway (site 36) (Cook, 1868). Cook (1879) also describes chrysotile in marble at the Old Blue Mine near Bloomingdale (Site 5). Several additional asbestos occurrences associated with iron mines that are not listed in Table 1 are also described by Germine (1981).

Highway Road Cuts (Sites 2, 6, 8, 38, 50) and Some Previously Unreported Sites Along Rt. 287.

Highway road-cuts where Germine (1981) reports the occurrence of asbestos include: asbestiform tremolite-actinolite observed in marble and amphibolite, exposed by a Rt. 80 road-cut through Allamuchy (Site 2) (slip-fiber tremolite-actinolite is particularly common in the marble where it occurs with calcite in schistose masses); asbestiform actinolite and some tremolite asbestos found in lamprophyre exposed at a Rt. 78 road-cut through Bethlehem (Site 6), where the asbestos occurs as a slip-fiber layer up to three mm thick on fracture surfaces and in veins; crocidolite was observed by Markewicz in Precambrian rock exposed during excavation on Rt. 78 through Clinton (Site 8), as described to Germine as a personal communication in 1980; actinolite asbestos observed in Precambrian rock at a Rt. 80 roadcut through Roxbury (Site 38); and asbestiform tremolite-actinolite observed in marble exposed in a Rt. 517 road-cut through Vernon (Site 50).

Road-cut exposures along Rt-287 are currently being examined for asbestos content by Costa, Puffer, and Germine. The study area is in the Pompton Plains, NJ Quadrangle at the southeast corner of Kinnelon Borough, Morris County. One Rt-287 road-cut through a mafic, highly sheared Precambrian host-rock has exposed a network of common, thin (<2.0 cm) amphibole asbestos veins. The amphibole optically resembles the winchite asbestos found at Libby Montana but need further examination to verify. The northwest-southeast-trending road-cut intersects mylonites that have developed along the Ramapo fault. The road-cut is located approximately 2.5 miles southwest of the Rt-287/Rt 23 interchange. The height of the road-cut is approximately 100 feet and is partially covered by "shot-crete" applied as a slope stability measure.

ENVIRONMENTAL IMPLICATIONS

Water Contamination

Two public water supply wells (Knollwood #2 and #3) were drilled at the India Brook crocidolite site and both are used for public supply purposes. Knollwood #2 (permit # 25-15323) was drilled to a depth of 325 feet below the ground surface ("ft bgs") on November 18, 1969, is used by the Mendham Borough public water supply. It was tested on October 15, 1969 to yield 578 gallons per minute ("gpm"). Before pumping the static water level was 15 ft bgs but after 8 hours of pumping the drawdown was 61 ft bgs. A 12-inch casing was extended to 67 feet. The log for this well, prepared on August 14, 1979, lists the stratigraphy as:

0-24' Clay & Rotten rock and hard stones.
24-34' Jagged granite rock and rotten streaks
34-68' Hard Granite with soft streaks
68-325' Limestone

Several crocidolite fibers were filtered from Knollwood #2 (Puffer and Germine, 1982). One example was photographed through a Transmission Electron Microscope ("TEM"), measured 0.82 um x 0.061 um with an aspect ratio (length/width) of 14. An electron diffraction pattern consistent with crocidolite was presented (Puffer and Germine, 1982).

Knollwood #3 was drilled to a depth of 325 ft bgs on February 20, 1980 for New Jersey-American Water Co. It was tested on March 12, 1980 to yield 200 gallons per minute. The static water level before pumping was 30 ft bgs, but after 24 hours the drawdown was 50 ft bgs. An 8 inch casing was extended to 88 feet. Puffer and Germine observed fresh cuttings at the well during their initial examination in 1981 and found crocidolite in water from this well. As noted on the log for Knollwood #3, prepared on July 2, 1980, the stratigraphy was identified as:

0-86 top soil, clay, sand, fractured rock
86-325 limestone

Both Knollwood wells penetrated the same allochthonous slab of Precambrian Byram granite and drilled into younger but deeper early Paleozoic dolomite ("limestone" on the well logs). The most productive zone appears to be a mylonite zone near the fault contact between these two rocks.

A water sample was also collected by Puffer and Germine in 1981 at the Hilltop Elementary School located near the center of Mendham Borough. The Hilltop sample was analyzed by means of the Anderson and Long (1980) method utilizing a Phillips 400 scanning-transmission electron microscope (STEM) equipped with a field emission gun. Asbestos fibers were characterized chemically by energy dispersive X-ray spectroscopy ("EDXS") and characterized structurally using electron diffraction ("SAED") then photographed. Crocidolite was measured by Puffer and Germine (1982) at 4.7 million fibers per liter ("MFL") +/- 2.0 MFL at a 95% confidence interval. This exceeds the 0.3 MFL level proposed by the EPA guideline that was in affect at the time of this investigation. The data was, therefore, reported by Puffer and Germine to the Mayor of Mendham as soon as it was measured but was rejected by the Mayor. In response to urging by Puffer and Germine, Mendham water sampling supervised by the Major was conducted and samples were sent to the USEPA lab in Cincinnati, Ohio for conformation. In 1984, the USEPA reported a total of 3.3 MFL asbestos in a Knollwood well (including 2.2 MFL amphibole asbestos (presumably crocidolite) together with 1.1 MFL chrysotile), a number generally consistent with the Puffer and Germine data.

The health effects of asbestos in drinking water have not been studied to the degree afforded asbestos inhalation. However, to the degree that asbestos contaminated potable water is used for bathing and to clean household laundry and home surfaces, entry into home air supplies is probable. In addition, the National Academy of Science (1977) has studied the effects of asbestos in drinking water and concluded the data *"strongly suggests that ingestion of asbestos mineral fibers can result in an increased risk of cancer of several sites."*

Quarry and Mine Product Contamination

During the last few years, particularly 1999 and 2000, the Limecrest (or Southdown) Quarry (Site 40) was the subject of considerable news coverage. Aun (1999) reported that *"The struggle surrounding Southdown dust emissions has focused in large part on a disagreement among geologists about the amount of tremolite in the quarry and whether it is of a form that can be carcinogenic. Volkert, having conducted extensive studies of the quarry and of six, 150-foot-deep core samples of its subsurface, determined there is only a minimal amount of tremolite in the rock. He and Southdown officials contend most of the tremolite is not fibrous and not a health hazard. However, Dr. Mark Germine, a geologist, physician and surgeon who specializes in asbestos-related medical problems, said he believes the quarry is a significant danger to those in the area."*

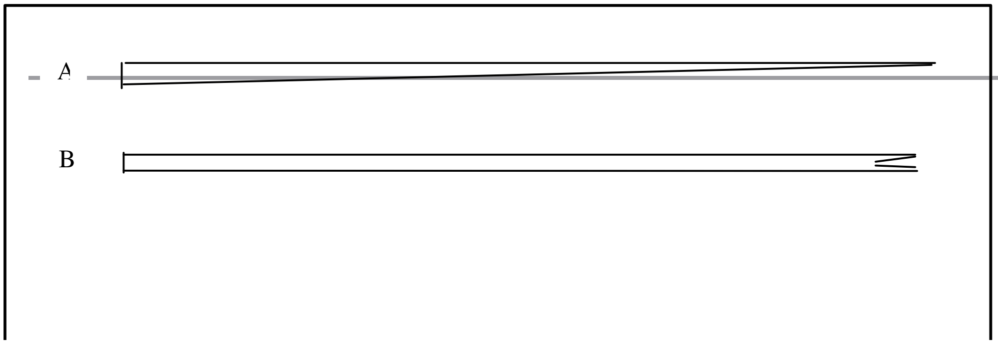
Aun (1999) went on to report that *"John Puffer, a Rutgers professor … said ' To the extent tremolite fibers have been recovered from a Sparta homeowner's air filter, a potentially dangerous situation is probable and should obviously be rectified immediately'. Southdown officials said the air filter tests are meaningless, since there is no proof the dust in the filter came from the quarry."* It is noteworthy that TEM analysis of stack emissions from the Sparta quarry showed extremely high tremolite fiber concentrations, several orders of magnitude higher than would be found in the ambient air outside the quarry. At first, it was claimed that the fibers were "cleavage fragments" and therefore should be treated as "nuisance dust," The USEPA protocol for identifying asbestos fibers was essentially ignored. Residents in the proximity of the quarry were alarmed by the results of these stack tests. Riley (1999) reported that affidavits submitted by Southdown's lawyer included the statement of pathologist Edward Ilgren, who *"…concluded it was unlikely the tremolite found at the Southdown quarry is the rare type that produces lung cancer."* Lockwood (2000) reported that Southdown Inc. had acknowledged that tremolite fibers were emitted, but said they pose no health threat because they were not carcinogenic and were of negligible amounts. The stack emissions test results were later "thrown out" as a result of finding a single chrysotile fiber on a control blank. Unlike tremolite, which is very rare in ambient air samples, chrysotile, is ubiquitous in ambient air and is a frequent contaminant and shows up frequently in blank controls. The Southdown stack test results are not readily available, but had been examined by one of the authors of this paper. The aspect ratio distribution of the tremolite found in these tests was significantly higher than the distribution found by Germine (1986), reflecting the increased suspension of high aspect ratio fibers, with the lower aspect ratio fibers settling out in the stacks.

A logical question is "How can some tremolite fibers be very carcinogenic while others that are virtually indistinguishable from them reportedly pose no health threat?" The logical answer is that all tremolite fibers are dangerous. However, a series of clever obstacles have been introduced into the legal literature that make it extremely difficult to prove that what appears to be a tremolite fiber is actually a tremolite asbestos fiber. For example, it is said that an amphibole asbestos fiber must be a complete crystal and not some portion or fragment of a crystal. Berman (2003) in his *"Analysis and interpretation of measurements for the determination of asbestos in core samples collected at the Southdown Quarry in Sparta, New Jersey"* concluded *"…that there is little short or long-term risk to nearby residents attributable to asbestos exposure from operations at the quarry."* Most of his 53 page report goes into considerable detail regarding the distinction between asbestos fibers (dangerous) versus near identical cleavage fragments that did not fit the *legal* definition of asbestos and were, therefore, presumed to be not dangerous. Several terms are used by Berman (2003) and others in the growing field of asbestos litigation that most mineralogy students might find baffling such as "protocol structures", "7402 structures", "true asbestos", "long asbestos" and "asbestiform". The term "cleavage fragments" has been generally applied to particles that are formed by cleavage of larger crystalline units. In analytical practice, the criteria for distinguishing individual particles as "cleavage fragments" or "asbestiform fibers" have varied. Flexibility as evidenced by curvature of fibers has frequently been used as a distinguishing criterion, however, Germine and Puffer (1989) demonstrated that flexibility and curvature in amphibole fibers is a function of fiber diameter, and, hence, can also be present in thin fibers derived from larger crystal units (i.e., cleavage fragments).

Cleavage fragments of most ground, prismatic amphiboles rarely exceed aspect ratios of 20 that are more typical of "asbestos", but there are amphiboles of acicular and semi-asbestiform varieties, which have higher aspect-ratio profiles, and amphiboles of different habits are frequently intergrown (Germine, 1986). The so-called "mineralogical criteria" employed by many to define asbestos reflect properties of amosite and crocidolite, and the generalization of these properties to affects on human health is unwarranted by any body of credible scientific evidence. Tremolite, for example, is characteristically of poor commercial quality. Yet, Davis et al, (1985), found South Korean fibrous tremolite, to be extremely carcinogenic on an exposure study in mice, stating that the tremolite was *"the most dangerous dust that we have studied,"* even more hazardous than the crocidolite they had studied. Among the studies of Davis and others (Weill et al., 1989) *"Of particular note is the fact that a sample of tremolite which had fibers of aspect ratio greater than 3:1, but which did not appear to be asbestiform, produced mesothelioma in approximately twenty percent of animals after long exposure."* The long exposure caveat is consistent with the oxidation and splitting of fibers *in vivo*, which we will discuss shortly.

The criteria often used to distinguish cleavage fragments from asbestiform structures are that the fiber must be a single crystal and must: 1) have an aspect ratio of greater than five, 2) have parallel sides, and 3) have a curved shape (flexible), or if not have perpendicular ends (tapered or split ends are not permitted, although bundles of parallel fibers, matted masses of fibers, and fiber bundles are permitted). Determinations are generally made using TEM on particles less than 0.5 um and structural and chemical determinations made using SAED and EDS are required to confirm the mineral identification of each fiber.

Under the reasoning used by Berman (2003) and R.J. Lee (the primary analytical lab for the Berman study) single crystal amphibole structures A. B., and C. in Figure 5 would not qualify as asbestiform and would be characterized as cleavage fragments, interpreted by Ilgren (2004) as "not biologically harmful." Only Structure D would qualify as asbestiform and, therefore, as a potentially



Of the four single crystal amphibole structures, longer than 5 µm and thinner than 0.5 µm, of identical chemical composition: A does not have parallel sides; B has an irregular termination, and C does not have perpendicular ends. Therefore, only D is asbestiform.

Figure 5. Diagram illustrating non-asbestiform and asbestiform fibers according to Berman (2003)

dangerous structure. However, we would personally **not** expect anyone to bet their life or good health on this interpretation and would instead recommend acceptance of the Germine and Puffer (1989) morphological definition of asbestos discussed above.

A more rigorous determination now sometimes required includes an internal diffraction contour examination to check for irregularities that are not permitted and an SAED pattern examination to check for non-streaking and/or non-twinned structures that are not permitted in "true asbestos".

The Berman (2003) report on the Limecrest Quarry finally concluded that the asbestos content of crushed samples of cored marble throughout a 150 m depth interval was concentrated at depths of less than 70 feet. They found an average of 22.8 "protocol structures" and 12.5 "7402 structures" per microgram of core sample in the depth interval 60 to 70 feet. Lower concentrations were found at greater depths, which may correspond to of lower degrees of weathering.

Of the total "protocol structures" 38% were found qualify as "true asbestos" while 17 % of the "7402 structures" were found to qualify as "true asbestos" (Table 7 of Berman, 2003). Berman (2003) defines "protocol structures" as structures composed of an asbestos-related mineral that are longer than 5 micrometers and thinner than 0.5 micrometers; and "7402 structures" as structures composed of an asbestos-related mineral "… that satisfy the requirements for PCME structures (as defined in NIOSH Method 7402, 1989)."

Berman (2003) estimated that mining of rock containing these levels would expose neighboring residents to a cancer risk of less than one in one hundred thousand. This risk is in general agreement with the previous air and dust sampling study by Lioy et al, (2002) that concluded: *"Based on the measured concentrations of biologically relevant asbestos structures in air, those results indicate a small elevation in lifetime cancer risk of two-in-a million to three-in-a hundred thousand for area residents, which is within the range generally considered de minimus and thus acceptable for purposes of air emissions permitting."*

The study of Lioy et al. (2002) employed the protocol structure definition discussed above, and included air sampling at residences 0.5 to 1 kilometer from the quarry, under various wind conditions. Most of their air filters contained no protocol amphibole fibers, consistent with the low level of ambient tremolite fibers in the air that we have previously discussed. Three contained one fiber, and one contained two fibers. The standard deviation of fibers per filter, the low number of fibers counted, and the variation in wind conditions could lead to no meaningful calculation of mean airborne fiber levels in the areas chosen. A single fiber on a filter does not give one a significant airborne fiber concentration, by any stretch of the statistical imagination. Yet the significantly greater amphibole fiber concentrations found coming from the stacks were dismissed!

Depending on the quarry activity and wind direction at the time of sampling, the levels of amphibole fiber in the air would be expected to be highly variable. Tremolite fibers tend to be suspended rather briefly and airborne concentration are very much dependent on the level to which the tremolite-bearing dust has been disturbed and on local atmospheric conditions.

The pulverized lawn and garden limestone from the Limecrest Quarry has had widespread use throughout the Mid-Atlantic region. When applied to lawns and gardens in this area, an insoluble residue will accumulate, and, according to our observation, there will be progressive fiberization and generation of long, thin amphibole fibers (Figure 2) that are easily airborne. This is probably a far larger problem than the emissions from the Limecrest Quarry itself with respect to mesothelioma. The incidence of mesothelioma is relatively high in New Jersey, indicating that many individuals have already had significant asbestos exposure. New Jersey has 12 counties in the top 100 U.S. counties for total number of deaths from mesothelioma plus asbestosis. (http:/www.ewg.org/reports/asbestos/tables/death details_top100.php). It needs to be underscored that what was compiled was total deaths, not incidence of disease. When one looks at the ratio of mesothelioma to asbestosis in these 12 counties, Bergen County, which was #37 on the national list, is an outlier, with a relatively high mesothelioma to asbestosis rate. Bergen County is a relatively wealthy, mostly suburban area, characterized by well-kept lawns. Thus exposure to the Limecrest lawn product is likely to be relatively high. This would be consistent with the hypothesis that low level exposure to tremolite fibers is one of the causes of mesothelioma in this area.

Other Environmental Issues

Additional potential environmental problems caused by naturally occurring asbestos exposures include (among several), 1) use of asbestos contaminated products, 2) wind blown asbestos, 3) air quality near highway exposures, and 4) real estate development issues.

Use of asbestos-contaminated products

In addition to the contamination of pulverized lawn and garden limestone several commercial products have been contaminated with asbestos. We offer the contamination of play sand (Germine, 1986a) as an important additional example that supports our contention that some mineralogical definitions of asbestos have little relevance to asbestos diseases

It is often stated by selected mineralogical experts that an amphibole asbestos fiber must be a complete crystal, and not some portion or fragment of a crystal. The American Thoracic Society (ATS) (Weill et al, 1989), in response to a play sand issue raised by Germine (1986a), convened a committee of leading experts. While analyses by carefully chosen mineralogical experts had reported that the tremolite fibers in the play sand product were cleavage fragments and therefore no more dangerous than ordinary silica dust, studies of the play sand product and another play sand product from New York by Abraham (Weill et al., 1989) revealed the presence of long, high-aspect ratio fibers, considered by most medical experts to be highly carcinogenic. All of the play sand products in question were derived from crushed, tremolite-bearing marble. Despite the conclusions of the Consumer Products Safety Commission (CPSC) that the plays sands in question contained fibers that were cleavage fragments, and that the products were therefore safe, the team of biomedical experts (Weill et al, 1989), who conducted two independent analyses, concluded: *"Results from both laboratories are generally consistent with those previously reported by others – long, thin, high aspect ratio fibers (respirable) are unequivocally present. It remains possible that rigorous application of crystallographic criteria would not show in every fiber the exact structural detail required by the mineralogic criteria used by CPSC…"* The central issue for our consideration involves the implications for potential exposure-related health effects. Even if mineralogical distinction is valid in the present instance (by no means certain), we are not persuaded that present knowledge appropriately leads to the conclusion that non-asbestiform minerals are unlike asbestos in their potential for these effects after dimension, durability and amount of exposure are taken into account. The products in question were eventually taken off the market, but there was no recall. It remains uncertain whether other play sands containing amphibole asbestos are still on the market, as CPSC has maintained its position.

Wind blown asbestos

Although the mining of asbestos contaminated vermiculate was terminated in Libby Montana 16 years ago, Raloff (2006) reported on some research indicating widespread environmental contamination. She reported that Tony Ward of the University of Montana and has colleagues recently found between 40 million and 540 million asbestos fibers per gram of bark on trees within 4 miles of the mine, and 19 million fibers per gram of bark near a railway siding 15 miles from the mine where trains took on vermiculite.

Pan et al. (2005), in a study involving 1,033 mesothelioma victims in California between 1988 to 1997, controlling for occupational exposure, found robust statistics indicating that the odds of mesothelioma decreased by 6.3% for every 10 km. of residence from the nearest naturally occurring asbestos source. This study was initiated in response to high concentrations of fibrous tremolite, occurring as veins in serpentinite, in

El Dorado County, and to the relatively high mesothelioma incidence in the same county. So, we would expect that fibrous tremolite may be, at least in part, responsible for their findings. Although wind blown asbestos may have caused this distribution, frequent or even occasional visits to the contaminated site by area residents may be a more likely cause. In either case these findings need to be noted, as residence at such a distance reflects relatively low or episodic exposures to fibers that are not of commercial quality.

Highway roadcut dust

Asbestos exposed along highway road-cuts, particularly during highway construction or widening may expose both construction workers and highway users to asbestos during windy days when highway dust may blow into open windows. Road-cut exposures are commonly uncovered and in the case of soft and friable asbestos enriched rocks, may erode potentially dangerous sediment onto highway shoulders or surfaces.

Real estate issues

Bedrock asbestos exposed at any construction site clearly poses a potentially serious problem. Construction workers are clearly at risk but property users especially home owners are also put at risk.

Where asbestos has been identified in the bedrock it should be the responsibility of the government to restrict building permits; it should be the responsibility of developers to take appropriate action wherever new or unknown asbestos exposures are encountered, and it should be the responsibility of home owners and real-estate agents to report any occurrence of asbestos to potential buyers.

However, in the real world of asbestos related issues few of these obvious “should be” solutions are spontaneous. For example, Raloff (2006) reported on some serious tremolite contamination in the El Dorado Hills near Sacramento, Calif. One home owner (Terry Trent) tried to cover tremolite asbestos exposures he found in his front yard with 1,000 tons of clean-fill dirt. It might have temporarily solved the problem, however, nine years later construction on a plot next to his re-exposed the tremolite. The insurance company that Trent used refused to compensate him for the contamination; government officials that he turned to did not provide any solution, and finally in 1998 he had to abandoned his house. It wasn’t until last year that the county government enacted new controls on dust from construction sites, and home sellers must now disclose the presence of asbestos in their soil, where known (Raloff, 2006).

CARCINOGENESIS OF AMPHIBOLE ASBESTOS

There is no clear dose response relationship between asbestos exposure and mesothelioma, meaning that there is no clear distinction in the incidence of mesothelioma at low levels of exposure versus high levels of exposure (Kleinfield, 1973). Susceptibility may be an important factor in carcinogenicity of asbestiform minerals (Becklake, 1976). Relatively wide, low aspect tremolite fibers may also be implicated in mesothelioma (Magee et. al., 1986), calling into question some of the basic assumptions used in epidemiological predictions.

Risk assessments for mesotheliona are often based primarily on exposure to chrysotile, which seems to have a much lower potential to cause mesothelioma than the fibrous amphiboles, and it is questionable that chrysotile causes mesothelioma at all, since fibrous tremolite contamination seems to be related to mesothelioma in chrysotile exposed populations. Certainly, chrysotile has a much lower capacity to cause mesothelioma than the fibrous amphiboles. This makes epidemiological assessments of fibrous amphibole exposure which use data on chrysotile exposure invalid.

In a study of mesothelioma in the general population (Passeto et. al., 2005), low level exposure to amphibole fibers, particularly tremolite, was documented as the primary associative factor. In studies of individuals exposed to asbestos in the Quebec chrysotile mines (McDonald and McDonald, 1997), there was no significant increase of lung cancer or mesothelioma relative to the general population associated with those mines that lacked fibrous tremolite, while there was such an association in those that did. Even though it is likely that tremolite, as a contaminant of Quebec chrysotile, is the cause of mesothelioma and possibly lung cancer, in this study and others, it has been reported that a prominent asbestos mineralogist, Dr. Arthur Langer, was unable to find it in samples of Quebec chrysotile (Weill et. al., 1989): *“Langer…was also unable to find tremolite in any sample of Quebec chrysotile, even though studies of the lungs of both miners and those living in the neighborhood of mines clearly indicate the presence of large quantities of tremolite…Thus, the lung has the ability to concentrate tremolite, and to what extent effects ascribed in animal studies to chrysotile are really effects of tremolite is unclear…”* Chrysotile, which is relatively soluble, is eliminated relatively quickly from the lungs, whereas tremolite persists.

Exposure to fibrous amphibole, derived from a vermiculite mining operation in Libby, Montana, has been associated with mesothelioma and lung cancer (Weill et. al., 1989). The Libby vermiculite was examined by Germine and Puffer (2001), using transmission electron microscopy, who found abundant fibers of winchite, a calcic-sodic amphibole closely related to tremolite. Fibers were noted to have pointed or tapered terminations, no streaking of selected area electron diffraction spots, and no evidence of twinning, thus clearly not meeting the definition of asbestos fibers of Berman (2003). Fiber splitting by formation of an amorphous oxidation product, a result of weathering, was noted (Germine and Puffer, 2001), as well as thin coating of amorphous oxidation product (Figure 6). The tapered and pointed ends of these fibers are the result of oxidative splitting. Fibers split from larger crystalline units do not meet most mineralogical definitions of asbestos.

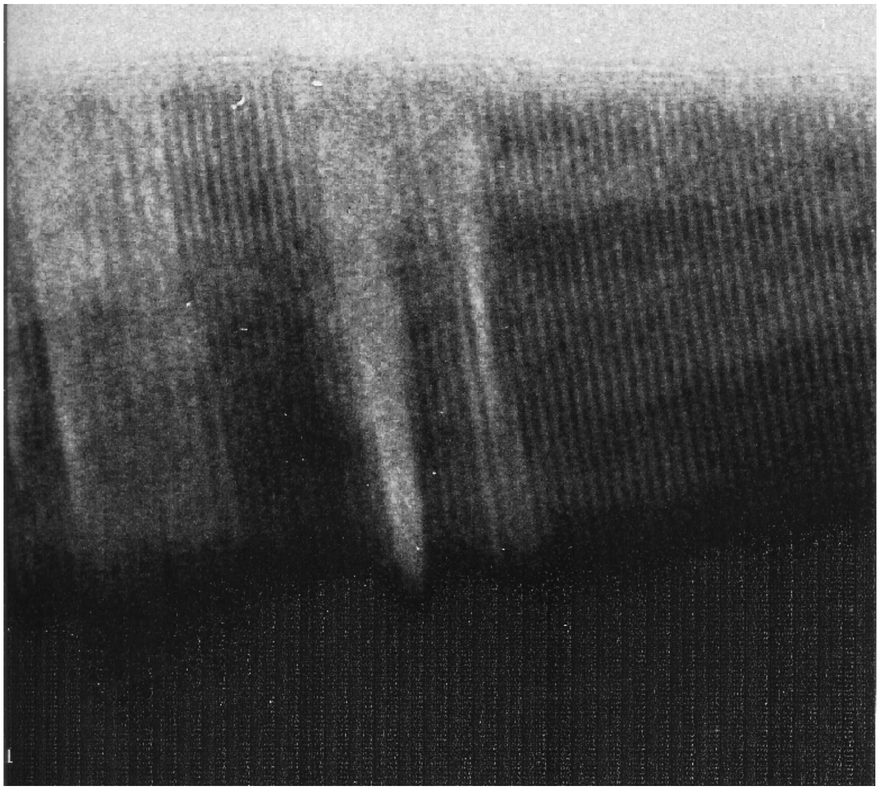


Figure 6. High resolution transmission electron photomicrograph (HRTEM) of a specially-oriented winchite fiber from the Libby vermiculite, showing characteristic double chain amphibole structure (stripes) and the lighter shaded, amorphous oxidation product, as well as incipient fiber splitting. Band width serves as a scale.

Asbestos fibers in the lungs become the target of macrophages, which release powerful oxidants in an attempt to destroy the foreign body. Thus it is likely that the process of oxidation, fiber splitting, and formation of an amorphous alteration product in the manner show in Figure 6 also occurs in the lungs. If this is the case, than the amorphous alteration product is the surface presented to tissues, and is thus likely to be the phase involved in carcinogenesis. Since amphiboles, in general, have a very rigid double chain structure, along with a low redox and oxidation potential, it is doubtful that the amphibole itself is carcinogenic, as has been born out by experimental studies. The amorphous phase, is, as an oxidation product, itself oxidizing, and has none of the structural constraints for exchanging electrons that the amphiboles have, giving it a high redox and oxidation potential. Since oxidation is a principle cause of carcinogenesis, it is likely that this amorphous phase is the true oxidant. This has important implications for carcinogenesis of weathered amphibole fibers, as well as for wider fibers that may be split *in vivo* by the oxidation process. The key features that would than make an amphibole fiber carcinogenic would be its respirability and biopersistence.

The HRTEM photomicrograph (Figure 6) was obtained by orienting the fiber directly down (001) and gathering the image by computer for one minute with a very powerful high electron-volt TEM. This is a technically difficult process because the microscope stage must have a full tilt stage on two axes and must be tilted perfectly in reciprocal lattice space. Figure 6 is probably the first HRTEM image of a single asbestos fiber to appear in any scientific publication.

The observation that the amorphous alteration product of amphibole asbestos is the likely phase involved in asbestos related carcinogenesis is potentially important. It is a new idea that is currently being developed by Germine and Puffer, and will be submitted for publication in an appropriate journal.

ACKNOWLEDGMENTS

This report is dedicated to the memory of Donald N. Smith who was unable to complete his Masters Thesis research pertaining to the environmental implications of the asbestos content of bedrock, particularly marble, throughout the New Jersey Highlands. His untimely death, Sept. 16, 2005, cut short an important and successful career as an environmental geologist, a career that was rapidly advancing with growing potential.

We also acknowledge the contribution of Ralph Costa of Weston Solutions, Inc. for his discovery of a network of amphibole asbestos veins exposed along I-287 that are currently being investigated.

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GLACIAL AQUIFERS OF THE NEW JERSEY HIGHLANDS

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ABSTRACT

Glacial aquifers in the New Jersey Highlands are valley-fill deposits of sand and gravel laid down in glacial lakes and glacial river plains during the Illinoian and late Wisconsinan glaciations. In places they are interbedded with less-permeable silt, clay, fine sand, and till, which act as confining or semi-confining layers. The distribution of sediments within a valley-fill aquifer is determined by the geologic setting of the valley and on the volume of glacial sediment it received. There are four types of valley fill. Three (filled lake basins, unfilled lake basins, and stacked valley fills) are in valleys that contained glacial lakes and one (fluvial valley fills) is in valleys that did not contain glacial lakes. Filled lake basins have an upper unconfined sand and gravel overlying a confining or semiconfining layer of silt, fine sand, and clay, in turn overlying a lower, confined sand and gravel aquifer. Unfilled lake basins are similar but lack the upper unconfined sand and gravel. Stacked valley fills contain multiple layers of sand and gravel, silt and clay, and till. Fluvial valley fills have just a single unconfined sand and gravel aquifer. Where glacial sediments are too thin to be productive aquifers themselves, they nevertheless provide storage to feed stream baseflow and recharge underlying bedrock aquifers. Large areas on uplands north of the late Wisconsinan terminal moraine are exposed bedrock without a mantle of glacial sediment and so have little groundwater storage potential.

INTRODUCTION

The Highlands are a critically important surface–water source for northern New Jersey. Recognition of the importance of this resource has spurred conservation efforts since the Newark and Jersey City reservoir systems were built in the late nineteenth century, and is the principal scientific basis for the Highlands Water Protection and Planning Act of 2004. Maintaining the quality and quantity of streamflow is therefore a paramount management goal. Streamflow includes both runoff and baseflow. Runoff is determined in part by the infiltration capacity of surficial geologic material, and baseflow is supplied from groundwater reservoirs. In both cases, knowing the distribution and hydrologic properties of glacial sediment is essential for a full understanding of the surface-water resource. Additionally, in valleys filled with a sufficient thickness of glacial sand and gravel, the glacial deposits themselves are productive groundwater reservoirs that provide water for a number of Highlands communities.

This paper will review the history of glaciation in the New Jersey Highlands, describe the deposits that the glaciers laid down, examine the manner in which these sediments are arranged in valley-fill aquifers, and discuss how they affect runoff and streamflow. The observations made here are based on geologic mapping conducted since 1983 by the New Jersey Geological Survey. The mapping includes compilation of records of wells and borings that provide control for bedrock-surface topography and valley-fill stratigraphy. Results of the mapping are published at 1:100,000 scale for the entire Highlands (Stanford and others, 1990; Stone and others, 2002) and at 1:24,000 quadrangle scale for most of the Highlands north of the terminal moraine (maps listed at http://www.nj.gov/dep/njgs/pricelst/geolmapquad.htm). The quadrangle maps provide logs of wells and borings, contours of rock-surface elevation, and cross sections of valley fills. Hydrogeologic studies of valley-fill aquifers have been completed for the Lamington valley (Nicholson and others, 1996), Rockaway valley (Canace and others, 1993; Schaefer and others, 1993; Dysart and Rheaume, 1999), and the Ramapo valley (Vecchioli and Miller, 1973; Hill and others, 1992).

GLACIAL HISTORY

The New Jersey Highlands are at the southernmost limit of the area covered by the Laurentide ice sheet. The Laurentide ice sheet expands outward from accumulation centers in northern Quebec and Labrador. It has grown and melted away about 10 times within the past 2 million years. The Highlands were glaciated by the Laurentide at least three times within this period. It is possible that additional advances entered the Highlands, but their deposits have been eroded by subsequent glaciations and no evidence of their presence survives. This section will describe the extent, age, deposits, and landscape effects of these three glaciations.

Pre-Illinoian Glaciation

The oldest glaciation is known as the pre-Illinoian. It covered the entire Highlands, except, possibly, for a small part of Musconetcong Mountain in the extreme southwest (Figure 1). Deposits of pre-Illinoian age are deeply eroded and intensely weathered. They are preserved only as remnant patches, generally less than 20 feet thick, on flat hilltops and divides where they have been protected from erosion. The most extensive deposits are on flat to gently sloping terrain on carbonate bedrock in the Pohatcong, Musconetcong, and Long valleys. In these valleys the pre-Illinoian deposits lie on remnants of the former broad valley floor. Modern stream channels are inset in inner valleys that are as much as 200 feet below the pre-Illinoian valley floor. The old glacial deposits are preserved in this setting because carbonate bedrock is highly permeable due to solution channeling, and most surface water on carbonate rock drains via underground channels rather than by surface runoff. Thus, under natural conditions, there is little erosion of surface material by gullying or slopewash. This is not the case on gneiss, quartzite-conglomerate, and shale, which are the other common rock types in the Highlands, and so there is much less preservation of pre-Illinoian deposits outside the carbonate valleys. On gneiss uplands, there are some patches of pre-Illinoian till on the flat top of Schooleys Mountain and a few very small patches on flat cols and saddles elsewhere.

Most of the pre-Illinoian deposits are till, an unsorted, nonstratified deposit laid down directly by glacial ice. In the Pohatcong valley and on the southern edge of the Highlands there are a few small deposits of pre-Illinoian sand and gravel that were laid down in glacial river plains and glacial lakes. In all the deposits, pebbles and cobbles of sandstone and gneiss are fully decomposed or have thick (>0.5 inches) weathering rinds because feldspar minerals have altered to clay. Clasts of carbonate rock are fully decomposed to yellow silt due to dissolution of the carbonate minerals. Quartzite and chert clasts are generally intact and hard because they are composed almost exclusively of quartz, which does not weather easily. Some are easily broken with a hammer owing to incipient weathering along fractures and grain boundaries and most have a surface stain of iron oxide. Matrix material in the till is typically a yellowish red to reddish yellow silty sandy clay. The pre-Illinoian till has significantly more clay and is redder in color than younger glacial deposits. The clay is from weathering of feldspar minerals. The red color is from accumulation of iron oxides and hydroxides that are produced by weathering of mafic minerals.

The intensity of weathering in the pre-Illinoian deposits, and their patchy preservation and topographic position, indicate a late Pliocene or early Pleistocene age (Stanford, 2000a). In the time since pre-Illinoian glaciation, streams have cut valleys into bedrock as much as 200 feet deep, in contrast to the more recent glacial deposits, which rest within modern valley bottoms. There are two additional lines of evidence concerning age. The pre-Illinoian deposits in New Jersey correlate westward to magnetically reversed glacial deposits in central and eastern Pennsylvania (Gardner and others, 1994; Sasowsky, 1994), indicating an early Pleistocene (pre-788 ka) or older age. Pollen from a depth of 46-60 feet in a 60-foot core of lake sediment in Budd Lake contained 64% pre-Pleistocene taxa (Harmon, 1968). Budd Lake lies just outside the late Wisconsinan and Illinoian glacial limits, and the pre-Pleistocene pollen are contained in a finely laminated clay that may have been laid down in a lake dammed by pre-Illinoian deposits (Stanford and Witte, 1997). If this is so, then the pre-Illinoian deposits may be of late Pliocene age. The earliest Laurentide glaciation to reach as far south as the United States is dated by volcanic ash stratigraphy in the Missouri River valley to about 2.1 Ma (the pre-Illinoian K glaciation of Richmond and Fullerton, 1986). The pre-Illinoian deposits in New Jersey may be this same glaciation.

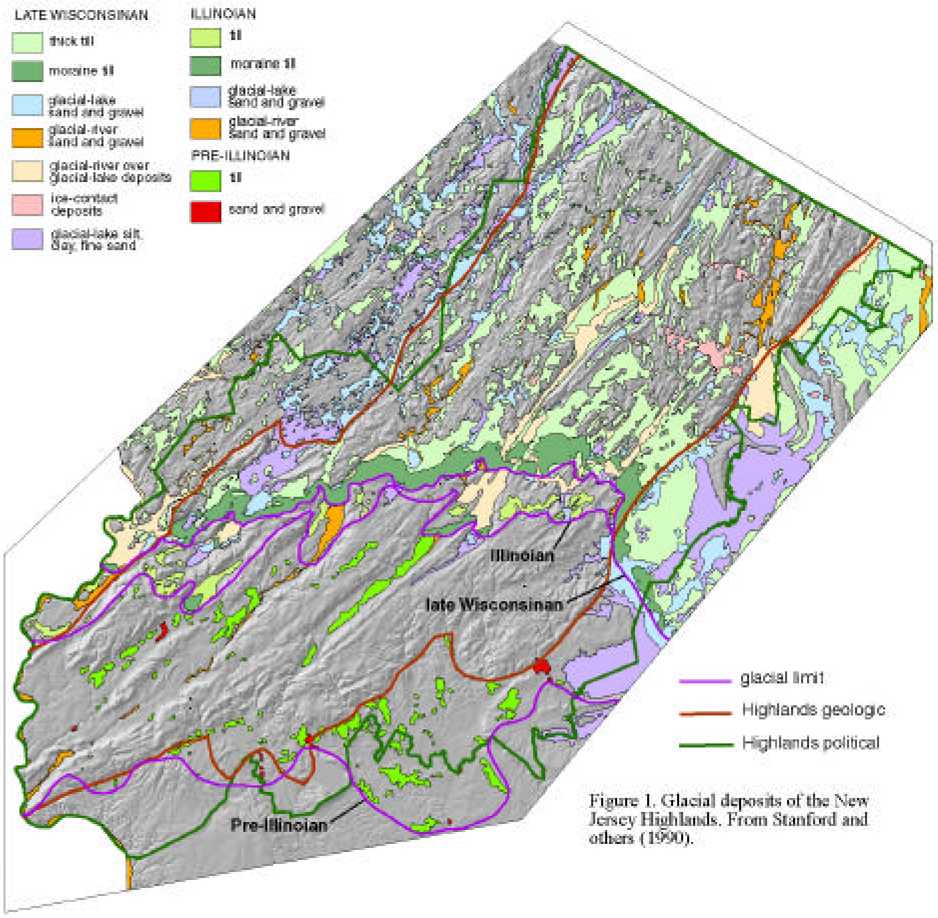

Figure 1. Glacial deposits of the New Jersey Highlands. From Stanford and others (1990).

Illinoian Glaciation

Illinoian deposits crop out in a belt about 4 miles wide south of the late Wisconsinan limit to the west of Morris Plains. They also occur in valley fills beneath late Wisconsinan deposits in the vicinity of the terminal moraine in the Lamington, Rockaway, Musconetcong, and Pequest valleys. North of the terminal moraine, Illinoian till also occurs in the cores of some drumlins, beneath late Wisconsinan till. The limit of Illinoian glaciation is marked by moraines in the Lamington valley, Long Valley, and the Pohatcong valley, and by the outer limit of Illinoian till on intervening uplands. The limit is noticeably embayed by topography, with ice lobes extending several miles down the Delaware, Pohatcong, Musconetcong, and Long-Lamington valleys. This geometry suggests a lower ice-surface profile (a rise of about 200-300 feet per mile) than that of the late Wisconsinan glacier (about 400 feet per mile). The Illinoian terminal moraine is also much smaller than that of the late Wisconsinan glaciation, a difference that is too large to be attributed to greater erosion. This difference indicates that Illinoian ice did not remain at its terminal position as long as did late Wisconsinan ice. The brief occupation time might also explain the embayed geometry of the Illinoian limit, as ice did not have time to thicken and overtop ridges.

Unlike the pre-Illinoian deposits, Illinoian deposits fill valley bottoms and are preserved on gently sloping upland surfaces. Illinioan glacial-lake deposits are as much as 250 feet thick in the valley fills north of Budd Lake and in the Lamington valley, and as much as 100 feet thick in the Musconetcong and Rockaway valleys. Original depositional landforms are preserved in places. For example, paired moraine ridges are preserved in subdued form near Washington in the Pohatcong valley, near Flanders in Long Valley, near Ironia in the Lamington valley, and north of Shongum Lake in the Rockaway valley (places named are shown on Figure 2). The persistence of double ridges in widely separated locations indicates that the ridges are an original depositional feature marking successive ice margins rather than erosional remnants of once-larger moraines. There is also a well-preserved glacial-river plain at Flanders, a well-preserved glacial-lake delta at Ironia, and somewhat more eroded but still recognizable deltas in several valleys north of Shongum Lake.

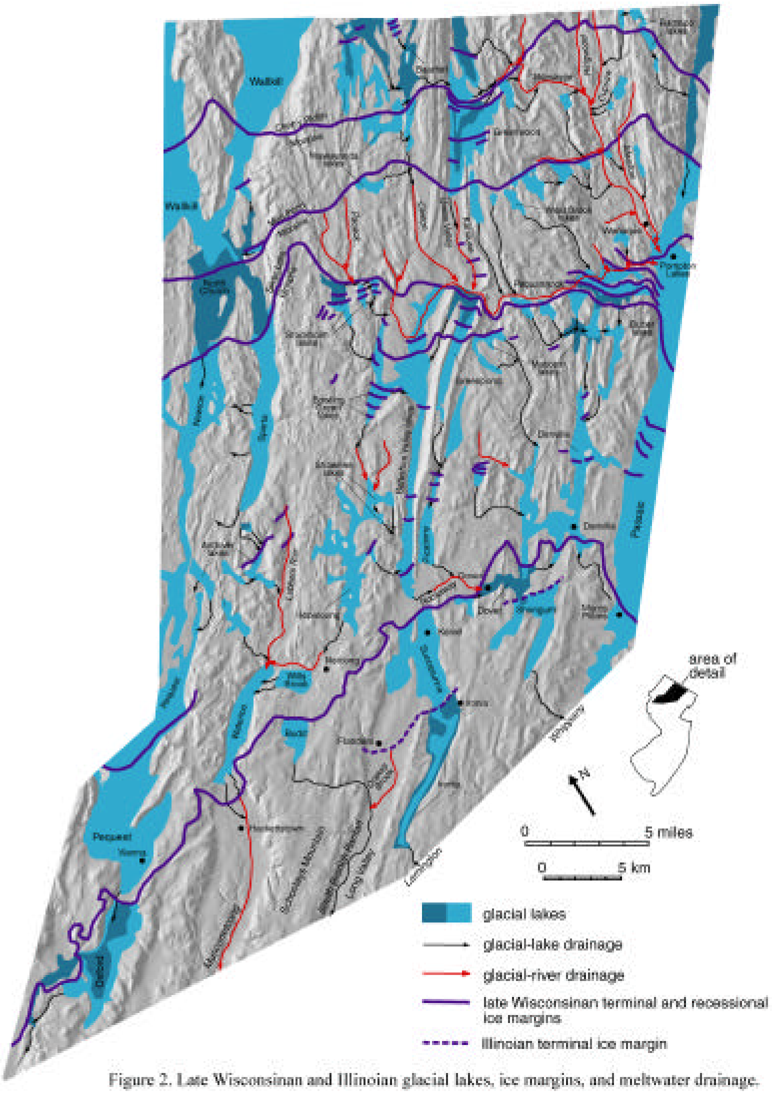

Figure 2. Late Wisconsinan and Illinoian glacial lakes, ice margins, and meltwater drainage.

Weathering is less intense than in pre-Illinoian deposits. Matrix color is brown and yellowish brown rather than reddish yellow. Gneiss and sandstone pebbles and cobbles have thin weathering rinds (<0.25 inches) but are otherwise intact. Both these features indicate only incipient weathering of feldspar and matrix minerals. Carbonate clasts, however, are entirely decomposed to yellow silt, as in pre-Illinoian deposits, owing to the rapidity of carbonate-mineral dissolution.

The distribution of meltwater deposits indicates that glacial-river plains were laid down in the Delaware, Musconetcong, and Drakes Brook-South Branch Raritan River valleys during Illinoian glaciation. All of these valleys drain southward, away from the glacier, and so meltwater could drain freely down them. The upper Lamington valley, which at the time was a tributary to the Rockaway, and the Mill Brook and Den Brook valleys in the Rockaway basin around Lake Shongum, drained northward and so were dammed by the ice margin. Lake Ironia formed in the upper Lamington valley, and Lake Shongum formed in the Mill and Den Brook valleys (Figure 2). Lake Ironia spilled southward down the lower Lamington into the Raritan basin, and Lake Shongum spilled southward into the Whippany valley. Illinoian glacial lakes also occupied parts of the

Rockaway, Musconetcong, and Pequest valleys, and a former north-draining valley north of Budd Lake, as indicated by thick glacial-lake deposits of interbedded sand and gravel and silt, clay, and fine sand that are buried beneath late Wisconsinan deposits in those valleys. The elevation, extent, and drainage history of these lakes cannot be fully determined owing to erosion and burial of the deposits, but they likely were similar to the late Wisconsinan lakes Oxford, Budd, Waterloo, Dover, and Denville. The Illinoian deposits have not been directly dated. East of New Jersey they correlate to till on Nantucket that is overlain by marine deposits that are about 125,000 years old (oxygen-isotope stage 5) (Oldale and others, 1982). The Illinoian glaciation (oxygen-isotope stage 6, about 150 ka) immediately preceded the stage 5 marine highstand, and has an extent similar to that of the late Wisconsinan glacier, based on the amplitude of the marine oxygen-isotope record at this time. Thus, it is the most likely age of the till. Soil development and weathering intensity in Illinoian deposits in New Jersey are similar to that of the type Illinoian tills in the midwestern United States. Some workers have considered these deposits, and correlative deposits in Pennsylvania, to be early Wisconsinan (about 70 ka) in age (Sevon and others, 1975). Early Wisconsinan glacial deposits occur in the Great Lakes basin but sea-level and marine oxygen-isotope records indicate that there was insufficient ice volume at this time to overtop the Allegheny Plateau and bring ice south to New Jersey. Also, the degree of weathering and erosion is excessive for an early Wisconsinan age (Ridge and others, 1990).

Late Wisconsinan Glaciation

Late Wisconsinan deposits and erosional landforms cover the entire Highlands north of the late Wisconsinan limit (Figure 2). In valleys along the terminal moraine, and in the cores of a few drumlins, ice did not erode deeply and Illinoian deposits and weathered bedrock are preserved beneath late Wisconsinan deposits. Nearly everywhere else, the ice eroded all previously existing surficial material and the late Wisconsinan deposits lie directly on bedrock. In a few spots, preglacial gneiss saprolite and carbonate-rock residuum as much as 200 feet thick are preserved beneath till. These are remnants of thick or narrow, deep zones of weathered rock that were not entirely removed by glacial scour.

Unlike the older deposits, late Wisconsinan sediments show little weathering. Gravel clasts of all lithologies except carbonate rock are unweathered, although till near the glacial limit includes a few percent weathered gneiss and sandstone pebbles that have been reworked from Illinoian deposits. Where carbonate-rock clasts are not abundant (<10% of total clasts), they are commonly decomposed to depths greater than 10 feet thick, but where abundant the carbonate is much less weathered. Matrix color commonly reflects that of the constituent rock fragments rather than weathering effects. Similarly, glacial landforms are only slightly modified by postglacial erosion. Significant erosion is limited to some steep slopes where the till has moved downslope to accumulate as aprons of colluvium, and to some bank erosion along larger streams. Small-scale details like ridges, basins, and knolls in moraines, and esker ridges, deltas, and fans in glacial lakes are preserved largely intact.

Radiocarbon dates on peat, organic sediment, shells, wood, and organic concretions recovered from above and below the late Wisconsinan till in New Jersey and on Long Island (summarized in Stanford, 2000) indicate that late Wisconsinan ice advanced into the New Jersey Highlands about 22 ka (in radiocarbon years before present) and had retreated north of the Highlands by about 18 ka. The orientation of striations and drumlins, and the provenance of clasts in till, indicate that ice advanced southward across the Highlands from the Kittatinny-Wallkill valley (Stanford, 1993). During advance, till was laid down in ramps and tongues on northwest-facing hillslopes that faced the advancing ice, and in drumlins. Till in ramps is as much as 100 feet thick; in drumlins, as much as 200 feet thick.

Most till in the Highlands is very pale brown to yellowish brown silty sand till with many cobbles and boulders (the Netcong Till of Stone and others, 2002) derived from erosion of the local gneiss bedrock. Pebbles and cobbles are chiefly gneiss, gray sandstone, and, in the eastern Highlands, purple conglomerate. Boulders are chiefly gneiss and conglomerate. Along the west edge of the Highlands, yellowish brown silty till (Kittatinny Mountain Till of Stone and others, 2002), derived from carbonate rock and shale of the Wallkill and Kittatinny valleys, locally extends as tongues up to several miles into the Highlands. These till tongues, and scattered erratic boulders of carbonate rock through the western Highlands, reflect southerly ice flow. Locally in Berkshire and Union valleys there are scattered deposits of reddish silty till derived from red shale of the Longwood Shale. Much upland terrain on resistant gneiss and quartzite-conglomerate is glacially eroded bedrock outcrop with little or no till cover (refer to Figure 6 below). Northwest and north-facing slopes were abraded to form smooth, sloping ledges, while southeast and south-facing slopes were plucked to form cliffs and blocky outcrops.

Ice advanced to the east-west trending linear valley across the Highlands that is formed by segments of the Rockaway valley (between Denville and Kenvil), the Musconetcong valley (between Netcong and Hackettstown), and the Pequest valley (west of Vienna). This topographic trough acted as a pinning line and halted further advance. The ice front remained in this position for several hundred years, possibly a thousand years, and deposited the terminal moraine. The terminal moraine is a belt of till averaging about two miles wide and up to 150 feet thick, with ridge, knoll, and basin surface topography. It was built gradually by lodging of till at the base of the glacier and by sliding and melt-out of debris from the glacier surface and from detached ice blocks.

As the terminal moraine was forming, meltwater laid down stratified sediments in glacial lakes in the Rockaway valley (lakes Denville and Dover), the Lamington valley (Lake Succasunna), the Musconetcong valley (lakes Budd and Waterloo), and the Pequest valley (Lake Oxford) (Figure 2). All of these valleys drained toward the glacier margin, and so were dammed by the ice. The Musconetcong below Hackettstown, and the Delaware, slope away from the glacier and so meltwater drained freely down the valley and deposited glaciofluvial plains.

As the glacier front retreated from the terminal moraine, meltwater deposited stratified sediment in a succession of glacial lakes and river plains (Figures 2 and 3). Glacial lakes formed in valleys that, as was the case with glacial lakes at the terminal moraine, sloped toward the retreating ice margin and so were dammed by the glacier, or that were blocked by previously deposited glacial sediment. Most of the recessional lakes are of the first type. These include: Lake Newton, which was in a north-draining segment of the Paulins Kill valley; lakes Sparta, North Church, and Wallkill, which were in the north-draining Wallkill valley; Lake Bearfort, which was in the north-draining Longhouse Creek valley (a tributary to the Wallkill); the Wawayanda lakes, which are in small north-draining valleys on Wawayanda Mountain; Lake Greenwood, which is in the north draining Belcher Creek valley (a tributary to the Wanaque); the West Brook lakes, which are in north-draining tributary valleys in the Wanaque basin; the Ramapo lakes, which are in a north-draining valley on Ramapo Mountain; Lake Greenpond and the Stockholm, Macopin, and Butler lakes, all of which are in north-draining valleys on the south side of the Pequannock basin; and the Shawnee, Wills Brook, Bowling Green, and Andover lakes, which are in north-draining valleys in the Musconetcong, Musconetcong again, Rockaway, and Pequest basins, respectively.

Sediment-dammed lakes include Lake Pequest, Lake Hopatcong, the Berkshire Valley lakes, and Lake Picatinny, all dammed by the terminal moraine. The northern reaches of Lake Pequest and the Berkshire Valley lakes are dammed by delta deposits laid down in the earlier, more southerly parts of the lakes dammed by the moraine. Because these deltas include a topmost river-plain deposit that lies above lake level, the more northerly lakes have water levels that are slightly higher than the original, moraine-dammed lakes. In other cases, erosion of the sediment dams caused lake levels to lower as the ice front retreated, permitting river plains to be deposited atop drained lake beds or in shallow relict ponds. Figure 3 summarizes the temporal sequence and drainage history of these lakes.

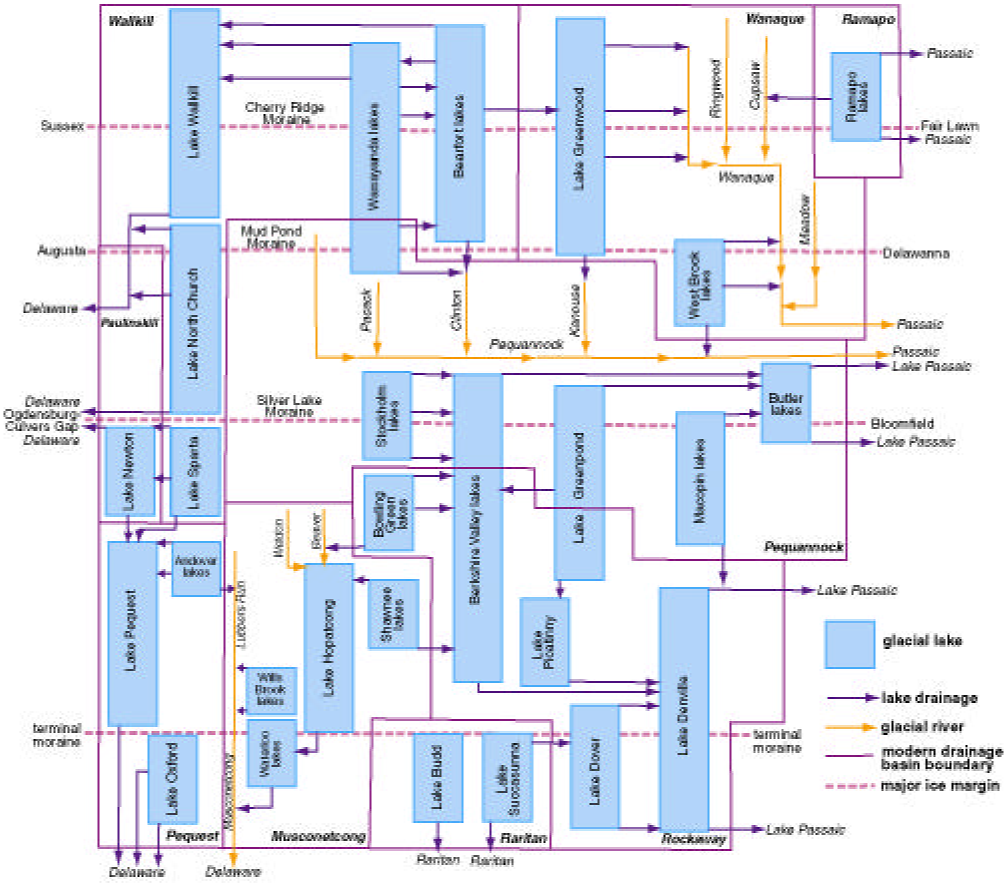

Figure 3. Correlation of late Wisconsinan glacial lakes, meltwater drainage routes, and ice margins. Modified from Stanford (1993).

The meltwater deposits are well-sorted and stratified. Gravel and sand composition closely mimics local bedrock. Glaciofluvial deposits range from cobble-to-boulder gravel close to ice-margin positions, or where glacial rivers eroded bouldery till, to pebbly sand in downstream areas. Coarse gravels are typically in thick, structureless beds. Pebbly and sandy deposits are typically channeled and cross-bedded. Glaciolacustrine sediments include sand and gravel deposited in deltas and fans, and silt, clay, and fine sand deposited on lake bottoms. Deltas are flat-topped ridges or terraces of sand and gravel built out into lakes from ice margins. They are fed by meltwater issuing from tunnels beneath or within the ice, or by meltwater draining from uplands along the edge of the ice. They typically consist of a thick section (as much as 150 feet) of inclined beds of sand and pebbly sand, known as foreset beds, that are laid down as sediment lobes prograde into the lake. The foreset beds are overlain by thin (generally less than 15 feet) horizontal beds of pebble-to-cobble gravel, known as topset beds, that are laid down as a plain atop the delta by streams draining across the delta. The contact of the topset and foreset beds marks the former lake level. Generally, deltas coarsen upward from sand through pebbly sand to pebble and cobble gravel, as a result of progradation.

Lacustrine fans are knolls and ridges of sand and gravel deposited on lake bottoms along ice margins. They are fed by meltwater issuing from tunnel channels beneath or within the glacier. They consist of interbedded pebble-to-cobble gravel, pebbly sand, and sand. Beds are typically subhorizontal or gently inclined and bounded by scour surfaces. Sands typically show planar lamination, cross bedding, and some climbing ripples, indicating rapid current velocities and high sedimentation rates. Gravels are thick bedded and massive and have little fine material, again indicating high current velocities. Meltwater in the tunnel channels flows under high hydraulic head, and velocities drop sharply when the water exits the tunnel into the lake, accounting for the rapid changes in grain size and the scour and bedding structures. As deposits aggrade at the tunnel mouth, the tunnel will shift laterally or vertically, creating a deposit with multiple ridges and knolls. Laucstrine fans are as much as 100 feet thick. Along stable ice margins, lacustrine fans may aggrade to the lake surface and then prograde into the lake as deltas.

Clay, silt, and very fine sand remain in suspension and are carried out onto the lake bottom by high-density turbidity flows. These flows travel down the delta and fan fronts and collect in the lowest spots in the lake basin. The sediment settles out and aggrades to form lake-bottom deposits. These deposits are typically horizontally laminated. Silt and fine sand laminations reflect individual turbidity flows carrying in pulses of sediment. Clay layers record winter sedimentation, when lakes are frozen over, meltwater production is minimal, and the finest clay particles settle out. These annual laminated deposits are known as varves. Lake-bottom deposits are as much as 150 feet thick.

Most sediments laid down during retreat are stratified meltwater deposits in valleys, but there are a few noteworthy till and till-like recessional deposits. Three recessional moraines (the Silver Lake, Mud Pond, and Cherry Ridge moraines, from south to north) traverse Hamburg and Wawayanda mountains (Stanford, 1993). They tie to the Ogdensburg-Culvers Gap, Augusta, and Sussex ice margins, respectively, in the Kittatinny Valley (Witte, 1997), and link eastward to the Bloomfield, Delawanna, and Fair Lawn ice-margin positions in the Newark Basin (Stanford and Harper, 1991). Like the terminal moraine, these recessional positions are pinned by deep east-west trending valleys in the Highlands east of the moraines, specifically the Pequannock valley, the West Brook valley, and the Hewitt Brook valley for the Silver Lake, Mud Pond, and Cherry Ridge moraines, respectively. Thicker ice in these valleys slowed the retreat of the ice margin. The recessional moraines are discontinuous and much smaller than the terminal moraine, but in places may have 50 feet of relief.

In several upland valleys, and in the deep Pequannock valley downstream from Kanouse Brook, there are deposits of sandy, bouldery, noncompact till-like sediment with subdued ridge-and-basin topography ("ice-contact deposits" on Figure 1). These deposits are in settings where ice masses could have become separated from the main glacier by downwasting during retreat. Sediment released from, or deposited around, the ice masses, would be noncompact and poorly sorted, and would have a hummocky landform due to slumping and collapse when the ice melted. In the Pequannock valley the deposits include collapsed delta and lacustrine-fan sand and gravel that were laid down around stagnant ice in lakes in north-draining tributary valleys on the south side of the main valley (Macopin and Butler lakes, Figures 2 and 3).

Postglacial Deposits

As ice retreated, glacial lakes drained and glacial river plains became abandoned. Postglacial streams established new courses through the glacial landscape, incising channels and floodplains into the valley-fill deposits. Some former lake bottoms in valleys, and numerous glacially scoured rock basins on uplands, remained as postglacial lakes. Many of these were gradually filled with silt, clay, and peat to form marshes and swamps; others were deeper or received little sediment and so remain as lakes. Pollen preserved in these postglacial organic sediments provide an important record of postglacial vegetation and climate. Talus accumulated, and continues to accumulate, at the base of glacially plucked cliffs. The postglacial alluvial, wetland, and talus deposits are generally less than 15 feet thick, although some of the wetland deposits are as much as 40 feet thick.

VALLEY-FILL AQUIFERS

Glacial aquifers occur where valley fills exceed 50 feet in thickness (Figure 4). Within this zone, aquifers occur where permeable sand and gravel is of sufficient saturated thickness or, in the case of confined aquifers, has sufficient pressure head, to supply usable quantities of water to wells. These conditions generally are met only in select areas of a given valley fill. However, recharge of these select aquifers, and groundwater flow paths within them, are governed by the stratigraphy of the entire valley fill, the geometry of the valley-fill sediments, and the geometry of the bedrock surface containing the valley fill.

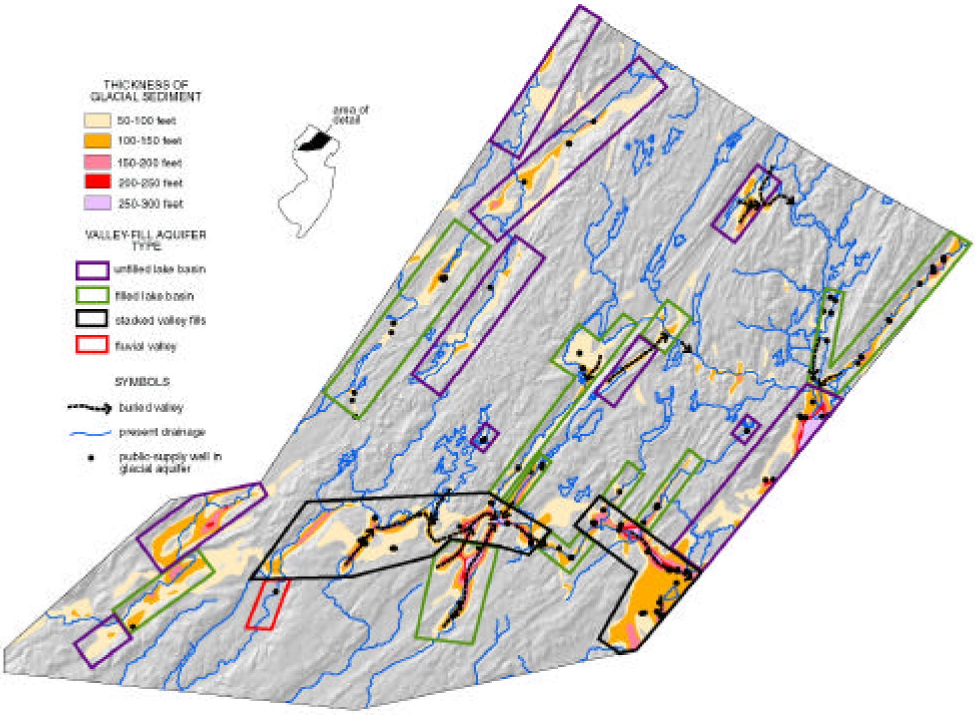

Figure 4. Valley-fill aquifers and thickness of glacial sediment.

Valley-Fill Aquifer Types

There are four basic types of valley fill in the Highlands (Figure 5). Fluvial valley fills (Figure 5a) are in valleys that drained away from the glacier, and were not blocked by sediment dams, and so did not contain glacial lakes. In the Highlands, only the Delaware, Musconetcong below Hackettstown, the Lubbers Run valley, some northern tributaries of the Pequannock, and parts of the Wanaque valley are in this category. In these valleys, plains of sand and gravel are laid down from successive ice margins. Each plain rises in altitude and coarsens in texture toward the ice margin from which it was deposited. As the ice margin retreats, the plains are eroded and reworked by meltwater draining from the up-valley ice margins. In the narrow valleys of the Highlands, this erosion tends to reduce the plains to terrace fragments along the valley sides and the reworking tends to homogenize the texture of the deposits. Because there is no lake to act as a settling basin, silt and clay remain in suspension and are flushed from the valley. The valley fill deposits are pebbly sand, pebble-to-cobble gravel, sand, and, locally, boulder gravel. Because no basin is being filled, the deposits are generally less than 50 feet thick. In places, glacial erosion during advance may have scoured rock basins in the valley floor (for example, beneath Lake Lackawanna in the Lubbers Run valley) that are then filled with lacustrine sand and silt before being covered by glaciofluvial sand and gravel. Because there is little or no fine-grained sediment, fluvial valley fills are unconfined, and there is generally excellent hydraulic connection between lakes, streams, and the valley fill. The thin fill depths, and fragmentary distribution due to erosion, limit their use as aquifers. However, shallow wells positioned to induce infiltration from streams or lakes may be highly productive. Only the fluvial valley fill on the Musconetcong near Hackettstown is sufficiently thick to warrant consideration as a potential aquifer.

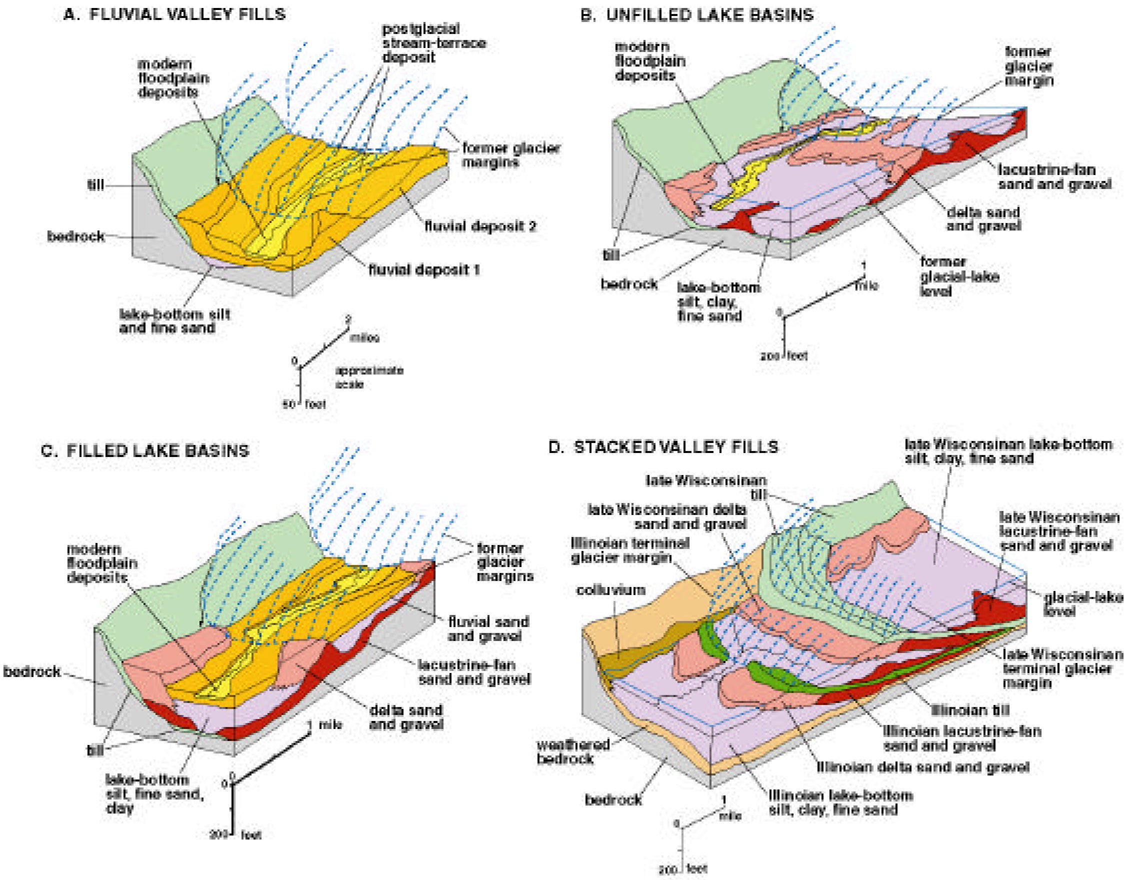

Figure 5. Types of valley-fill aquifer.

Unfilled lake basins (Figure 5b) are in valleys containing glacial lakes that were too large, or received too little glacial sediment, to fill completely with deposits. Landforms in these basins are typified by deltas and fans separated by lake-bottom plains. The lake-bottom plains are commonly occupied today by floodplains, marshes, and swamps. In this type of valley fill, lacustrine-fan deposits may be highly productive confined aquifers where they are covered by lake-bottom silt and clay. The lacustrine-fan deposits, however, are discontinuous and may be hard to locate where they are buried by lake clay. In places (for example, in the Wallkill valley) the fans were laid down sequentially at the mouths of long-lived tunnel channels, and so form linear tracks up the valley. Elsewhere, fan deposition is more random owing to ephemeral or shifting tunnel channels. Where not covered by lake clay, deltas and outcropping fans may be unconfined aquifers if sufficiently thick and saturated and may act as recharge conduits for the confined lacustrine fans. Recharge is particularly feasible where deltas with large surface extent are in contact with outcropping fans that, in turn, are continuous with confined fans. Lakes Oxford, Pequest, Sparta, North Church, Wallkill, and Passaic are all large unfilled lakes; smaller unfilled lakes include Hopatcong, Greenpond, and Greenwood.

Filled lake basins occur in valleys where lakes were small enough or received enough glacial deposition to fill completely. As in unfilled lakes, lacustrine-fan deposits occupy the valley floor, are overlain by lake-bottom deposits, and extend upward in places to connect with deltas. However, because these lakes filled or drained while ice was still releasing meltwater and sediment into the valley, there is an upper sand and gravel above the lake-bottom deposit. This upper sand and gravel was laid down as a river plain or a shallow-water delta from up-valley ice margins. Thus, there is an upper, unconfined aquifer in addition to the confined lacustrine-fan aquifer. In many cases this upper aquifer is too thin to be a significant source of water, but where it is contiguous with deltas, or with outcropping fans, there may be sufficient saturated thickness for production. As with the fluvial valley fills, there is excellent hydraulic connection between the upper aquifer and surface water. Thus, the upper aquifer may act as a recharge conduit for surface water moving into the confined aquifer. Filled lake basins most commonly occur in narrow valleys that contained small glacial lakes, such as Berkshire Valley, the upper Pequest valley, lakes Picatinny, Dover, and Denville, and the Ramapo and lower Wanaque valley. In larger valleys they occur only adjacent to major ice margins, such as Lake Succasunna and parts of lakes Oxford and Pequest, all near the terminal moraine, and the Germany Flats section of Lake Newton, which fronts the Ogdensburg-Culvers Gap moraine. In these settings, deposition was prolonged due to the long residence time of the ice margin at that position.

Stacked valley fills (Figure 5d) occur in glacial lakes along the terminal moraine. Here, late Wisconsinan ice did not erode deeply, in part because the glacier thins at its edge and in part because lake water buoyed the glacier off its bed. Preexisting Illinoian deposits were not completely eroded as they were further north, and late Wisconsinan till and lake deposits were laid down on top of similar Illinoian deposits. The valley fill thus consists of stacked layers of till, lacustrine-fan sand and gravel, lake-bottom silt, clay, and fine sand, and delta sand and gravel. Although not depicted in Figures 5d, there may be a topmost layer of glaciofluvial sand and gravel, laid down after lakes drained or filled and ice retreated up-valley. The lake-bottom deposits and, to a lesser degree, till, are confining beds. Till in the Highlands has a silty sand matrix but the matrix is generally compact, reducing the permeability. As in filled lake basins, the lacustrine-fan beds may be confined aquifers and the topmost delta and river-plain deposits are unconfined aquifers. In the Highlands, stacked valley fills occur along the terminal moraine in the Musconetcong valley between Hackettstown and Lake Hopatcong, in the buried valley beneath the terminal moraine north of Budd Lake, in the upper Lamington valley, and in the Rockaway valley. In most of these valley fills the principal aquifer is thick lacustrine-fan sand and gravel laid down during retreat of Illinoian ice. Overlying late Wisconsinan deposits include till, lake-bottom silt and fine sand, and unconfined delta and glaciofluvial sand and gravel.

Flowpaths

Groundwater flow in the valley-fill aquifers depends in detail on the distribution of permeable and impermeable sediment within the valley fill, land-surface topography, topography of the bedrock surface, and location of lakes and streams. As a general rule, flow in unconfined aquifers conforms to land-surface topography, with flowpaths trending down-valley and towards the main stream in valley bottoms. In confined aquifers, flow may follow the axis of the bedrock valley or trough containing the valley fill, which in places differs from land-surface topography and modern stream drainage owing to glacial drainage dislocations. These buried valleys are shown by arrowed, dashed lines on Figures 4. For example, flow in the lower confined aquifer in the Rockaway valley fill follows a buried valley east of Denville, where the modern Rockaway River turns north (Schaefer and others, 1993). Flow in the upper unconfined aquifer, in contrast, follows the present river. Similarly, flow in the confined aquifer in the Lamington valley fill is generally northward, along the slope of the buried valley, although the potentiometric surface is altered from its natural condition in places by well pumpage (Nicholson and others, 1996). Flow in the unconfined aquifer is southward, following the modern drainage of the Lamington River. Similar divergence of confined-aquifer and unconfined-aquifer and surface-water flow likely also occurs in buried valleys north of Budd Lake and Green Pond. Both are valleys that drained north before the Illinoian glaciation but that now drain south after they were filled with glacial deposits. In both cases, confined flow crosses modern drainage-basin divides. This likely also occurs in confined sand and gravel in the buried valley southeast of Lake Hopatcong, which is a former tributary to the Rockaway that crosses the modern Rockaway-Musconetcong divide. In several other cases, such as the Rockaway at Dover, the Wanaque south of Greenwood Lake and between Wanaque and Pompton Lakes, and the Ramapo at Pompton Lakes, confined groundwater flow deviates from that of the surface drainage within a basin. In these cases, segments of the valleys were filled with glacial deposits and postglacial streams are shifted into former side valleys or across former bedrock ridges.

Vertical movement of water with a valley fill depends on the thickness, lateral extent, and permeability of fine lake-bottom sediment and, in stacked valley fills, till. Thick deposits of silt and clay and compact, silty till are effective confining layers and will impede vertical movement of water from unconfined aquifers, streams, and lakes into confined aquifers. Where such confining layers are present, water must move laterally into confined aquifers from surface sources where the confining layer is absent. For example, lake-bottom deposits are generally absent along former ice margin positions where deltas connect downward to lacustrine fans, along valley walls where sandy till or deltas connect to buried lacustrine fans on the valley bottom, or where buried lacustrine fans crop out. Where lake-bottom deposits contain abundant fine sand, as is the case in many of the filled lake basins, and where till is sandy, the confining unit is leaky and will permit some direct vertical flow from the surface into the lower aquifer.

Field and laboratory tests indicate that the hydraulic conductivity of aquifer sand and gravel in the Highlands ranges from 350 to 2600 ft/d (Gill and Vecchioli, 1965; Vecchioli and Miller, 1973; Hutchinson, 1981; Canace and others, 1983; Hill, 1985; Sirois, 1986; Hill and others, 1992; Nicholson and others, 1996; values summarized in Stanford, 2000b). Laboratory tests on three samples of fine-sandy clayey silt lake-bottom sediment from the Ramapo and Lamington valley fills yielded values of $3x10^{-4}$, $3x10^{-4}$, and $4x10^{-3}$ ft/d (Hill and others, 1992; Nicholson and others, 1996). Clayey silt to silty clay lake-bottom deposits are probably one or two orders of magnitude less conductive than fine-sandy silt. Till has not been tested, but hydraulic conductivities in the range of 10^{-3} to 10^{0} ft/d are likely for the sandy silt to silty sand tills in the Highlands. This range is confirmed by modeling results in the Dover area (Dysart and Rheaume, 1999).

Recharge

The valley-fill aquifers are recharged by: 1) direct precipitation on outcropping parts of the aquifer, 2) infiltration of water from streams and lakes into the aquifer, and 3) flow of groundwater from adjacent bedrock. Direct precipitation is significant for aquifers with large areas of sand and gravel outcrop. In the Highlands, large deltas in the southern end of Lake Pequest, in Lake Newton, Lake North Church, and Lake Succasunna provide extensive sand and gravel outcrop for collecting precipitation. Infiltration of water from streams and lakes is particularly important in narrow valleys with small areas of aquifer outcrop that are traversed by large streams. Such conditions typify most Highland valleys, particularly the Rockaway and Ramapo valleys. Streamflow measurements in these valleys demonstrate losses from the Rockaway and Ramapo rivers adjacent to pumping wells (Vecchioli and Miller, 1973; Schaefer and others, 1991; Hill and others, 1992; Dysart and Rheaume, 1999). Modeling results, streamflow measurements, and field observations in the Lamington and Ramapo valleys also demonstrate losses on tributary streams as they flow from uplands onto sand and gravel in the valley, indicating that they provide recharge to the valley fill (Hill and others, 1992; Nicholson and others, 1996). Elsewhere, or during wet periods, streams may gain flow from the valley-fill deposits. This is particularly true of the main stream in the valley, which flows at the lowest elevation and is generally incised in the valley-fill deposits.

Recharge from bedrock is more difficult to measure, but modeling results and aquifer tests demonstrate good hydraulic connection between solution-channeled carbonate rock in the Pequest and Lamington valleys (Hutchinson, 1981; Nicholson and others, 1996) and overlying sand and gravel deposits, indicating that water moves freely between the two aquifers. Gneiss, quartzite, and conglomerate are much less permeable than carbonate rock, except where weathered, and so probably do not contribute significant recharge to adjoining valley fills.

Stream Baseflow

Only a small portion of the Highlands is underlain by valley-fill deposits. The vast majority of the Highlands are uplands of gneiss or, in places, quartzite and conglomerate, bedrock. South of the terminal moraine the gneiss is mantled by weathered rock material, including clayey sand to sandy clay saprolite and blocky rock rubble, that may be as much as 100 feet thick but is more generally 20 to 30 feet thick. Lower parts of long hillslopes are covered by aprons of colluvium, which is weathered rock material that has moved downslope by creep, solifluction, and slopewash. Colluvium may be as much 50 feet thick. Outcrop is restricted to a few narrow ridgetops, steep slopes, and ravine banks. North of the moraine, glacial erosion removed almost all of the weathered-rock material and colluvium, exposing the underlying bedrock (Figure 6). Till was deposited atop the rock in places, but over much of the upland area till is patchy and less than 15 feet thick (gray areas on Figure 6), and many areas have virtually no surficial material (black on Figure 6). Locally, sandy till more than 50 feet thick, or granular weathered rock preserved beneath till, is thick and permeable enough to supply domestic wells. These thick deposits are present only in the cores of a few drumlins, and in till ramps on north- or northwest-facing slopes (light gray patches outside valleys on Figure 4).

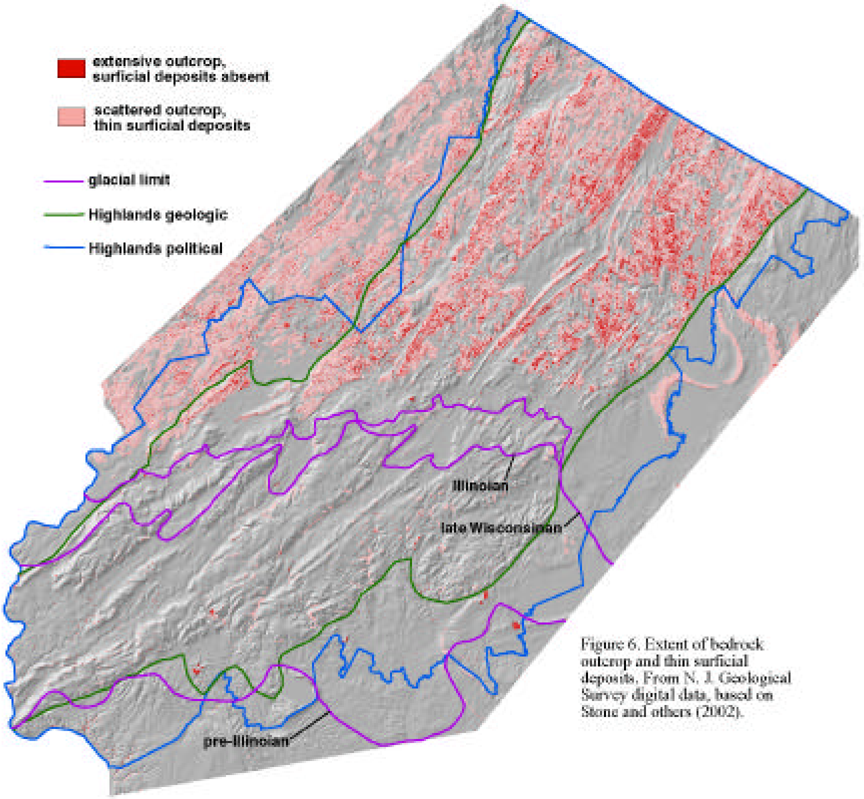

Figure 6. Extent of bedrock outcrop and thin surficial deposits. From N. J. Geological Survey digital data, based on Stone and others (2002).

However, even where till deposits are not thick enough to be aquifers, they serve an important hydrologic role as groundwater storage that supplies baseflow to streams. Sandy till has a porosity between about 25 and 35% (Melvin and others, 1992) whereas gneiss has a porosity of about 2% (Randall and others, 1966). Till is thus about 10 to 20 times more porous than the underlying gneiss. More rainfall and snowmelt will infiltrate till than gneiss (or quartzite) bedrock. Till that mantles lower slopes and upland valley bottoms, which is the usual landscape position of till on uplands in the Highlands, will absorb runoff from upslope rock outcrops. Although no comprehensive studies of factors influencing baseflow have been conducted in the Highlands, research in similar glaciated terrain in New England can be used as a guide to conditions here. Low flows per square mile of drainage basin of streams in New England are much higher in basins containing sand and gravel than in basins containing till and bedrock (Wandle and Randall, 1994). Baseflow differences between till basins and bedrock basins have not been evaluated, but are likely similar to, or greater than, those between valley fill and till, given the similar, or greater, difference in porosity and permeability between the two materials.

Seepage of groundwater from lower parts of till-mantled slopes is commonly observed in the field, in contrast to the dry condition of rock slopes. This observation also demonstrates the groundwater storage capacity of till. Given the vital importance of surface water in the Highlands, the geologic, biologic, and land-use factors affecting runoff, seepage, baseflow, and the exchanges between groundwater, lakes, streams, and wetlands is a subject worthy of detailed study.

A CASE EXAMPLE: THE RAMAPO VALLEY-FILL AQUIFER

The Ramapo valley forms the northeast border of the New Jersey Highlands. Although half is outside the geologic boundary of the Highlands it is nevertheless typical of filled lake basins throughout the Highlands. It is a narrow valley bordered on the northwest by gneiss underlying Ramapo Mountain and on the southeast side by Jurassic and Triassic basalt, sandstone, and shale, which is covered by as much as 150 feet of till in places. Shale and sandstone underlie most of the valley floor. The gneiss is separated from the Jurassic and Triassic rocks by the Ramapo Fault, which underlies the northwest side of the valley. Late Wisconsinan ice within the valley advanced to the southwest and scoured the shale and sandstone in the valley bottom. Topography of the bedrock surface shows that the valley bottom has been overdeepened by as much as 150 feet compared to its preglacial elevation (Stanford, 2004); the valley-fill deposits and groundwater in the valley bottom are thus contained within a bedrock trough.

The valley-fill sediment (Figure 7) was laid down in glacial lakes and river plains during glacial retreat. Tunnel channels on the valley floor at the base of the glacier, and channels draining into the valley along the glacier margin on Ramapo Mountain and, to a lesser extent, the basalt ridges on the southeast side of the valley, carried meltwater that delivered sand and gravel into the lakes. The tunnel channels deposited lacustrine fans on the lake bottom at the glacier margin. As the margin retreated, the fan deposits were left behind as an irregular basal layer on the bedrock surface. Where the margin stabilized for several years the lacustrine fans aggraded to lake level and built outward into the lake as a delta. Small deltas and alluvial fans also formed along the valley wall where the ice-marginal channels entered the glacial lakes. The total thickness of glacial-lake deposits is as much as 200 feet.

There were two lakes in the main valley. The southwestern third of the valley (downvalley from ice margin M3 on Figure7) was occupied by the Totowa stage of glacial Lake Passaic. This lake was held in by a sediment dam that blocked the Passaic valley at Totowa, about 10 miles south of the Ramapo Valley. The level of this lake in the Ramapo Valley was 220-230 feet. Deltas and fans deposited from ice margins M1, M2, and M3 in this lake filled it completely, and fluvial topset beds at the top of the valley fill aggraded to a thickness of as much as 70 feet at ice margin M3. Most of the lake-bottom deposits in this lake are lower foreset and bottomset beds laid down as deltas prograded, and so are primarily silt and fine sand.

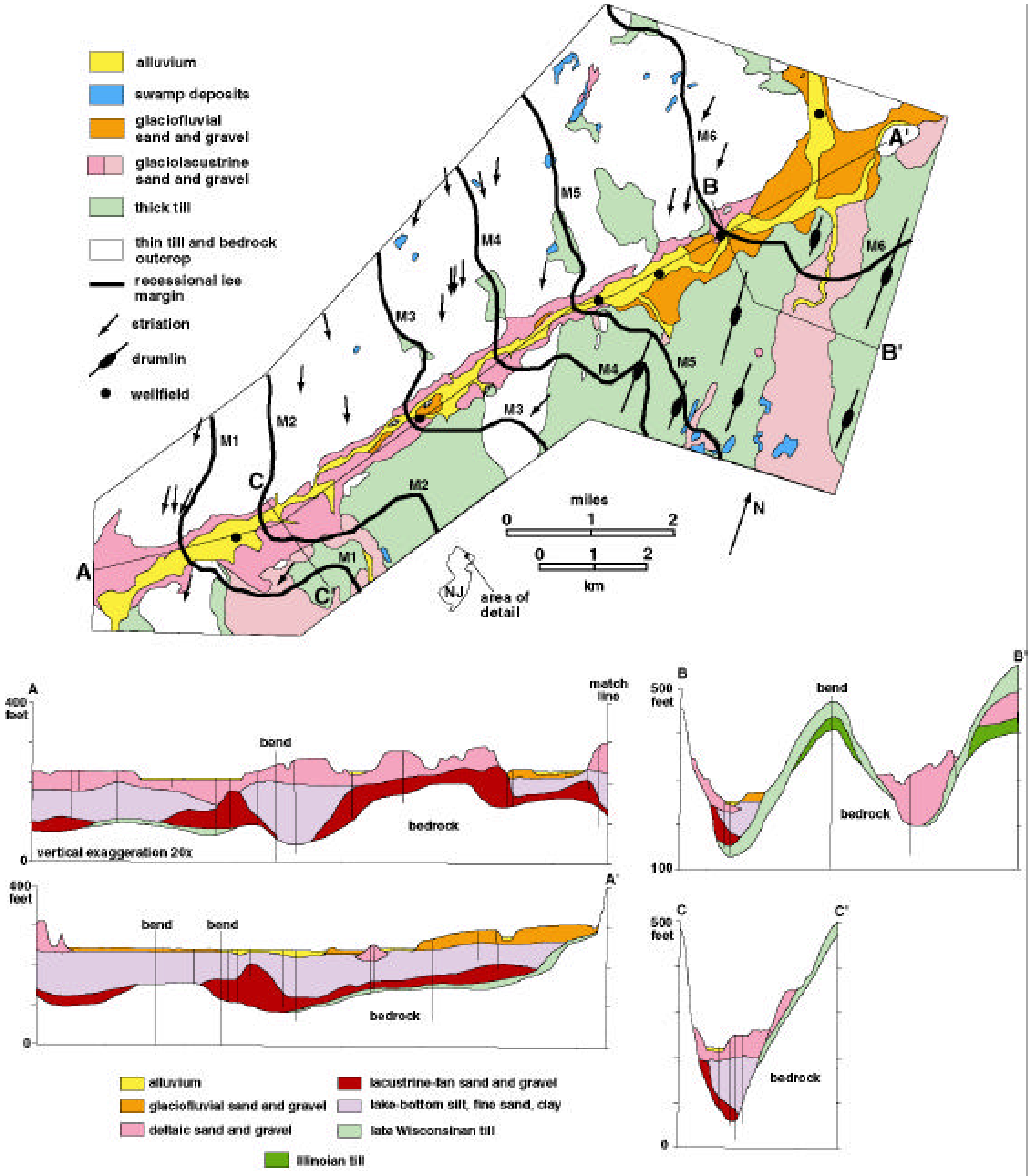

Figure 7. Map and sections of the Ramapo valley fill.

As the ice margin retreated from M3, the aggraded topset beds filling the narrow stretch of the valley south of M3 acted as a dam for a second, higher lake in the valley north of M3. This lake was initially at a level of 290-300 feet but by the time the margin had retreated to M6 erosion of the deposits downstream from M3 had lowered the lake level. Fans and deltas deposited in this lake are not as large as those deposited at and south of M3. Deltas are mostly restricted to the west valley wall, where they were deposited from ice-marginal channels descending Ramapo Mountain. Lacustrine fans on the valley bottom did not aggrade up into deltas. This drop in sediment volume is due to either (1) the ice margin retreating more rapidly north of M3, or (2) subglacial meltwater drainage partially diverting into the Masonicus Valley to the east of the main valley. The reduced influx of coarse sediment, and the widening of the valley, north of M3, allowed clayey, more continuous lake-bottom sediment to accumulate in this reach of the valley.

As ice withdrew northward into New York State the outlet for the second lake continued to lower as erosion south of M3 progressed. Clay and silt accumulated, raising the bed of the lake. Lowering of the outlet and filling of the lake eventually exposed the lake bottom. Meltwater coming down the valley from ice margins to the north deposited a river plain of sand and gravel on the exposed lake bottom. The plain continued downvalley as a narrow terrace south of M3. This river-plain deposit is less than 25 feet thick. When ice withdrew from the Ramapo basin, sediment load and stream discharge declined. The modern Ramapo River began to establish its channel and cut a floodplain into the glacial valley fill. Return of forest cover with warming climate further reduced sediment influx to the river and stabilized the floodplain and channel. The floodplain deposits are generally less than 10 feet thick.

The valley-fill sediments left as the record of the above events are typical of a filled lake basin. They include an upper, unconfined sand and gravel aquifer, a middle confining or semi-confining unit, and a lower sand and gravel aquifer. The upper sand and gravel includes deltas and the river-plain deposit. Where the confining unit is absent, the upper aquifer extends to bedrock and may include lacustrine-fan deposits beneath deltas. The confining unit includes silt, clay, and fine sand laid down on lake bottoms and in the bottomset and lower foreset beds of deltas. In the Ramapo valley fill, the portion of the confining unit north of M5 is primarily a lake-bottom deposit; south of M5 it is primarily a bottomset and lower foreset deposit. Thus, the confining unit is more clayey north of M5 and is mostly silt and fine sand south of M5. Groundwater modeling indicates that the clayey portion of the unit acts as a true confining layer whereas the silt and fine sand do not (Hill and others, 1992). The lower sand and gravel occurs only below the confining unit and consists of lacustrine-fan deposits and possibly a little collapsed deltaic sand and gravel. The thickness of these three layers can be mapped from records of wells and borings, and from surface exposures (Figure 8).

Thick sections of upper aquifer mark stable ice margins where lacustrine fans aggraded up into deltas (chiefly south of M3), or where deltas built into the lake on the side of the valley at the mouths of ice-marginal channels (north of M3). In these settings the confining unit is thin or absent. Conversely, the confining unit is thickest between stable ice-margin positions (south of M3) and in the valley center, away from the ice-marginal channel mouths (north of M3). The lower aquifer is thick in a narrow, elongate string in the deepest part of the valley fill. This geometry marks the location of the subglacial tunnel channel that deposited the lacustrine fans comprising the lower aquifer.

Seepage from the Ramapo River is an important recharge mechanism. Measurements of stream flow and computer modeling of groundwater flow show that water is drawn into the valley fill from the river as it passes by wellfields (Vecchioli and Miller, 1973; Hill and others, 1992). Water is also lost from the river as it crosses more permeable parts of the valley fill, even in the absence of nearby pumpage (Hill and others, 1992). Where the confining unit is present between the river and wells pumping from the lower aquifer, seepage loss from the river may be shifted up or downstream to places where the confining unit thins or is absent. Seepage loss also occurs on tributary streams when they cross from till and bedrock uplands onto the deltaic sand and gravel along the valley walls, with some streams drying completely before they reach the main river.

Potential zones of seepage loss can be identified by mapping where the Ramapo River and tributary streams flow on valley fill where the confining unit is not present (Figure8). These spots include places where the river swings against the valley-side deltas and where the river cuts through the ice-contact zones of deltas that connect directly in the subsurface to lacustrine fans. Water entering the valley fill at these points may descend and then move laterally into the lower aquifer beneath the confining unit.

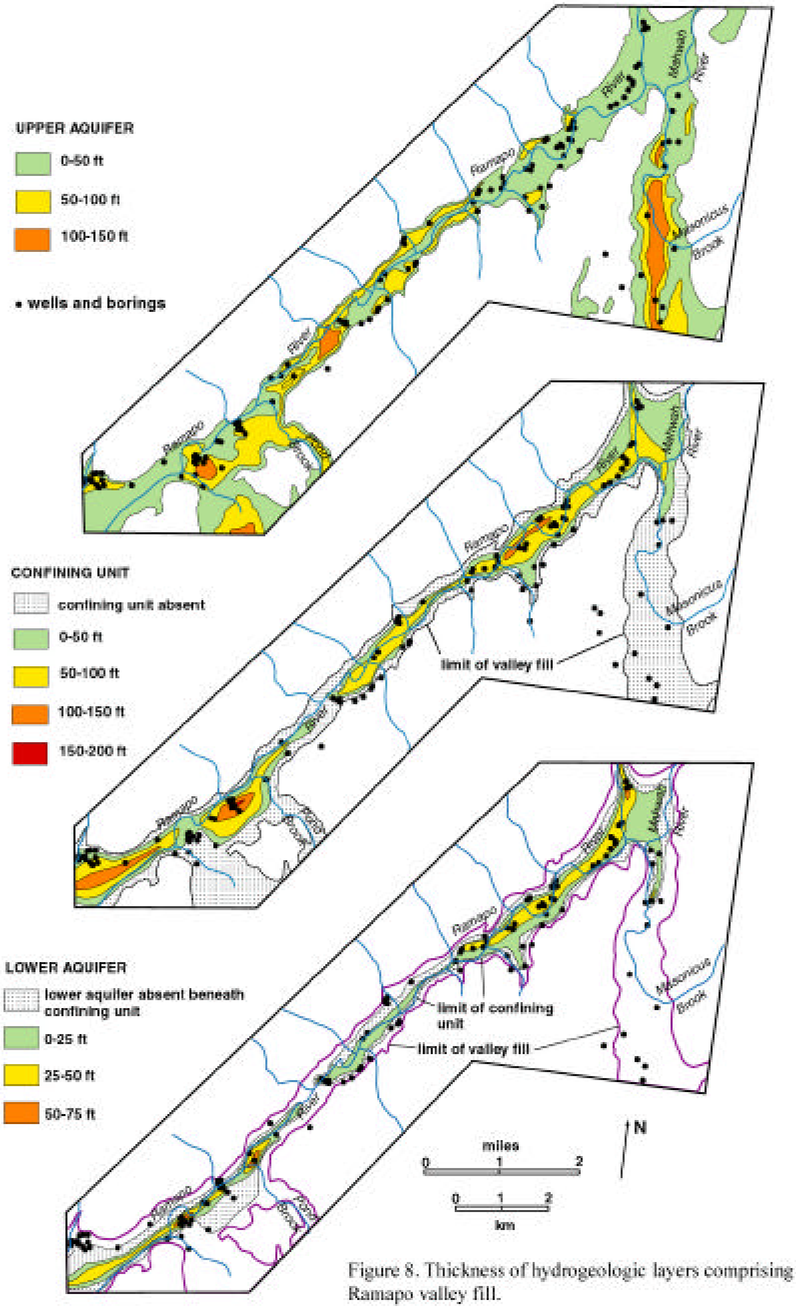

Figure 8. Thickness of hydrogeologic layers comprising the Ramapo valley fill.

CONCLUSIONS

The New Jersey Highlands were glaciated three times within the past two million years. A pre-Illinoian glaciation sometime between 2 Ma and 800 ka covered the entire Highlands. Deposits of this glaciation are deeply eroded and intensely weathered. An Illinoian glaciation at about 150 ka covered the northern half of the Highlands. Deposits of this glaciation are eroded from steep slopes but remain on gentle slopes, are only moderately weathered, and form thick fills in several valleys. The late Wisconsinan glaciation between 22 and 18 ka covered the Highlands at and north of the terminal moraine. Deposits of this glaciation are largely uneroded and only slightly weathered.

Glacial-lake and glacial-river deposits of late Wisconsinan and Illinoian age form locally productive valley-fill aquifers. Fluvial valley fills are unconfined sand and gravel deposited by glacial rivers in valleys that did not contain lakes. Unfilled lake basins were large glacial lakes that contain glaciolacustrine sand and gravel aquifers confined in places by fine-grained lake-bottom sediment. Filled lake basins were smaller glacial lakes that contain both a lower, confined sand and gravel aquifer and an upper, unconfined sand and gravel aquifer separated by a confining layer of fine-grained lake-bottom sediment. Stacked valley fills occur in glacial lakes along the terminal moraine and contain multiple layers of till, glaciolacustrine sand and gravel, and fine-grained lake-bottom sediment. The valley-fill deposits, and till on uplands between valleys, store and release groundwater to a greater degree that the underlying gneiss bedrock and so are an important source of stream baseflow.

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TEACHERS WORKSHOP

"A SHOT IN THE DARK" – AN INTRODUCTION TO THE SCIENTIFIC METHOD

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ABSTRACT

The opening scene of the mystery/comedy movie "A Shot in the Dark" (1964) starring Peter Sellers is reenacted (with considerable liberty). Inspector Clouseau wasn't there to see the crime but must act on the "facts" as he sees them. Looking through the eyes of Clouseau students first observe the facts. The simple facts are that Clouseau hears two gunshots, rushes into the room, and sees a dead man with a bullet wound, and a woman holding a gun standing over him. From these "facts" Clouseau (the students) must draw a conclusion as to what happened here. Is the evidence conclusive enough to warrant a conviction and a possible death penalty?. Are there other possible explanations, other than "she shot him?" Do we need more evidence?

Through TV viewing students are quite aware of detective/crime investigations and enthusiastically try to come up with alternative explanations of the above crime scene.

Scientists observe phenomena, collect the facts (data, experiments, etc) and draw conclusions – hypotheses- gather more facts - and attempt to derive an encompassing theory. But no one was here to "see" the Earth form, or watch the dinosaurs, or note the advance and retreat of the glaciers, but we have some "facts" before us.

We are all Clouseaus.

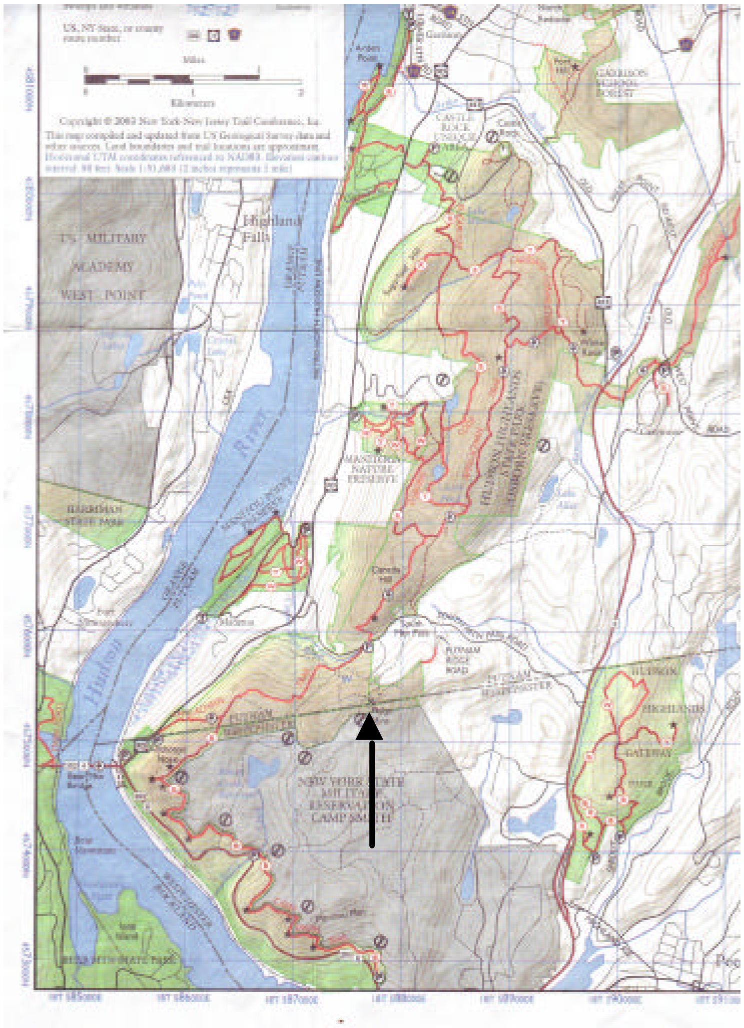
Time: 30-40 min.

FIELD GUIDE

STOP 1: PHILLIPS MINE, PUTNAM COUNTY, NEW YORK, AN ABANDONED SULPHIDE MINE GENERATING ACID MINE DRAINAGE

Sivajini Gilchrist, Department of Earth and Environmental Science, Rutgers University, Newark, New Jersey

INTRODUCTION



The Phillips Mine is located in the Hudson Highlands in Putnam County, New York (Lat. 41^{0}19.601N; Long. 73^{0}57.118W) (Fig.1). Situated in the Peekskill quadrangle, it is about a mile and a half east of the Hudson River. The mine is sited at about 800 feet above sea level in a formerly glaciated area. The mine was opened after the Civil War around 1866 and continued for fifteen years after that. A large vein of pyrrhotite ore was mined for its sulphur content. The ore is embedded in a hornblende gneiss host rock. There are two adits and three portals, all of which are inaccessible and dangerous. The main portal extends 150 feet vertically into the mine and is water-filled. Extracted sulphur was transported to Staten Island for production into sulphuric acid. Due to cheaper sulphur from Sicily,the mine operations were abandoned. Tailings and waste rocks lay exposed to weathering and oxidation, generating acid mine drainage (AMD) (Figure 2).

Figure 1. Location of Phillips Mine (Source: East Hudson Trail Map, 2003).

MINERALOGY

Common minerals found in the tailings and waste rocks include a variety of sulfide minerals (ex: pyrite, pyrrhotite and chalcopyrite), hornblende, biotite, magnetite, apatite, hematite, pyroxene, epidote, quartz, uraninite and feldspars. Alteration minerals like limonite, goethite, and melanterite are also found at the dump site. Intense iron-coatings on the minerals and rocks are a result of oxidation and hydrolysis of sulphide minerals like pyrite.

Figure 2. Tailings and waste rocks.

CHEMISTRY OF THE WATER, SOIL AND SEDIMENT AT PHILLIPS MINE

The following table gives a quantitative analysis of some of the pollutants found at the site:

Contaminant	Soil ppm ^11-8-05	NYDEC Soil Std	Surface Water ppb (pH 2.5) ^11-8-05	NYDEC Water Std	Sediment ppm ^5-16-06	TEL	Clean Str Sediment
As	3.8	^3-12	<1	50	2.6	5.9	3.5
Cr	184	1.5-40	6.4	50	21	37.3	24
Cu	1250	^1-50	3130	200	335	35.7	31
Fe	237K	2K-550K	42400	300	350K	N/A	30K
Pb	12.7	^4-61	1.5	50	23.1	35	10
Ni	48	0.5-25	1740	100	27.1	18	25
U	2	3 (ATSDR)	33.4	30 (EPA)	2.3	N/A	2

ATSDR = Agency for Toxic Substances and Disease Registry
TEL=Threshold Effects Level
NYDEC=New York State Department of Environmental Conservation

In general, the solubility of most heavy and trace metals increases as pH decreases. Dissolved metals are transported downstream, leached into soils, adsorbed by soil or sediment particles in streams. At Phillips Mine, the constant low pH has also released elevated amounts of rare-earth elements (ex: La, Y, Ce, Th, Eu, etc.) into the surface water. As pH increases downstream due to dilution or buffering from carbonate minerals, most metals precipitate and are adsorbed onto stream bed sediments. Adsorbed or precipitated metal pollutants in soils or stream sediments can be flushed out during a rainstorm and transported great distances.

The tailings landscape is generally barren except for a few acid-tolerant plant species – mountain laurel, gray birch and eastern hemlock. Analysis of bioavailability of metals at the Phillips Mine dump shows that the gray birch is the best candidate for phytoremediation strategy if ever considered for this site. Roots, leaves and twigs of the gray birch contain elevated amounts of metal pollutants. Root tissues were found to hold the most pollutants (Cu, Ag, Co, U, Th, Tl, Se, etc). Though the mountain laurel plant species is tolerant of the sulfidic mine soil, it is less abundant than the gray birch but more abundant than the eastern hemlock.

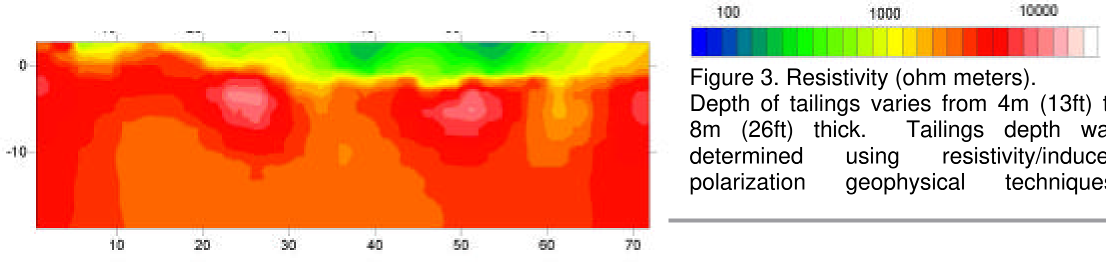


Figure 3. Resistivity (ohm meters). Depth of tailings varies from 4m (13ft) to 8m (26ft) thick. Tailings depth was determined using resistivity/induced polarization geophysical techniques.

(Image produced by Dr. Dimitris Ntarlagiannis, post-grad, Rutgers University, Newark Campus)

Since the mine tailings and the waste rocks contain low carbonate concentrations, buffering capacities are, therefore, lacking at the site to neutralize the AMD.

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STOP 2: JOINTS AND FAULTS IN THE HUDSON HIGHLANDS, NEW YORK

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INTRODUCTION

In conjunction with bedrock mapping for the StateMap program in NY State, joint maps, including joint attitude and joint density for multiple sets were produced for the Monroe, Sloatsburg, Thiells, Popolopen Lake and Greenwood Lake 7.5' quadrangles, located in the Hudson Highlands, southern New York State. This area of the Hudson Highlands is mostly underlain by high-grade metamorphic and igneous rocks that experienced a long history of ductile deformation associated with the Grenville orogenic cycle (Gates et al., 2004). Joint orientations are highly consistent across the entire Grenville massif of the western Hudson Highlands and some joint sets correlate with mapped faults and topographic lineaments. Minor joints that are parallel to foliation occur in all bedrock units. The general strike of these joints is northeast-southwest, and the dip is variable depending on the attitude of the local foliation. Although most topographic lineaments are parallel to, and can be correlated with bedrock units, there are many, ranging in length from 1 km to 5 km, that cross the regional bedrock structure. These lineaments are most pronounced west of the Ramapo Fault in the Sterling Forest, but a few transect the valley between the western and eastern structural blocks that form the Hudson Highlands. These lineaments extend for tens of kilometers, and correlate with faults that offset the bedrock Proterozoic structure. This field trip guide will examine the relationship of these faults, joint orientation and joint intensity.

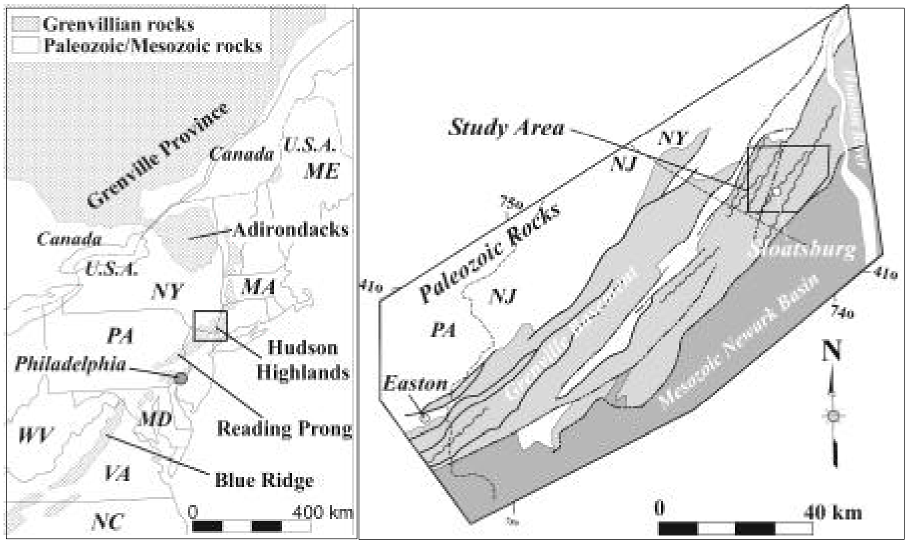

Figure 1. General geologic map showing the location of Proterozoic basement massifs in the Appalachians and a general geologic map of the Hudson-New Jersey Highlands.

BEDROCK GEOLOGY OF THE HUDSON HIGHLANDS, NEW YORK

Previous mapping in the Hudson Highlands area (Figures 1 & 2), divided the bedrock units by discrete rock types (i.e. Dallmeyer, 1974). Gundersen (1986) suggested that lithologic and stratigraphic associations and rock sequences should be grouped as units in a kind of sequence stratigraphy or lithofacies for metamorphic rocks. This system of grouping rock types was adopted for the latest round of geologic maps by

Gates et al. (2001), hence, the lithofacies described below constitute the bedrock of the central Hudson Highlands structural blocks.

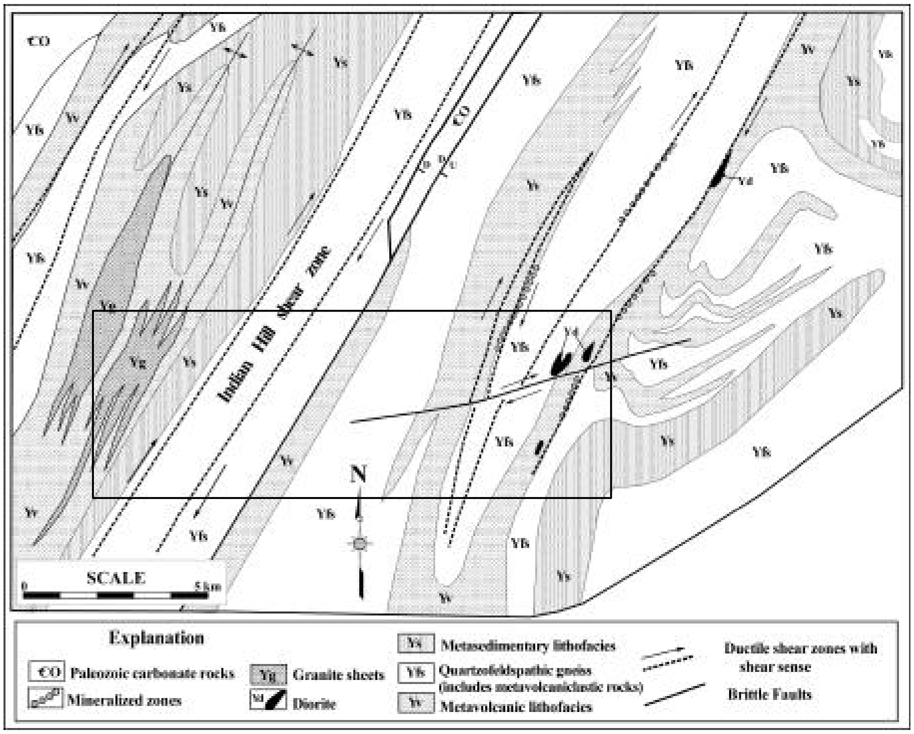

Figure 2. Generalized bedrock geology map of the Hudson Highlands, New York (modified from Gates et al., 2004). The geographic distribution of the three major lithofacies and general structural trends are represented. The rectangle shows the approximate location of Figure 4.

The Highlands Province of the north central Appalachians is also known as the Reading Prong and extends from Pennsylvania to Connecticut (Figure 1). It is composed of crystalline Mesoproterozoic Grenville-age rocks and as such forms a link between the larger Blue Ridge Province to the south and the Berkshires-Green Mountains province to the north. The Highlands are subdivided into western, central and eastern blocks by the Reservoir Fault to the west and the Ramapo Fault to the east. The western Highlands are variably overlain by and disappear beneath the Paleozoic sedimentary rocks of the Valley and Ridge to the west. The eastern Highlands are variably overlain by and tectonically interleaved with Paleozoic sedimentary and metasedimentary rocks of the Manhattan Prong and Taconics to the east and variably overlain by Mesozoic sedimentary and volcanic rocks to the southeast. The central Highlands overthrust and are overlain by early Paleozoic sedimentary rocks to the north and northwest. The Hudson Highlands form the central Highlands within southeastern New York State, primarily within the Hudson River valley north of New York City.

There are numerous geologic maps of the Hudson Highlands that attempted to map every lithology separately. These maps are very complex and do not reveal the structural and stratigraphic relations clearly. The main problem is that it is difficult to even determine if a highly deformed granulite is a metasediment or a metaigneous rock much less detailed relations. In an attempt to resolve these problems, a new mapping project that considers the area in a sequence stratigraphy approach has been underway since 1997. Three primary lithofacies have been identified with several intrusive units.

Metavolcaniclastic lithofacies

A discontinuous sequence of medium to coarse grained massive to layered (10 cm-2 m) quartzofeldspathic gray gneiss is interpreted as the metavolcaniclastic lithofacies. These rocks contain quartz, plagioclase and varying amounts of hornblende, biotite, garnet and K-feldspar as a function of the layering.

They are locally interlayered with, and in gradational contact with metavolcanic rocks. Thinly interlayered K-feldspar-pyroxene calc-silicates are also present in this lithofacies.

Metavolcanic lithofacies

Numerous blocks of thin to thickly banded black and white gneiss are interpreted as the metavolcanic lithofacies. Mafic, intermediate and felsic composition layering occurs at the sub- to meters scale. Mafic layers contain pyroxene, hornblende, magnetite and local biotite. Quartz and plagioclase comprise the felsic layers with minor mafic phases previously listed. These rocks are locally interlayered with calc-silicate gneiss containing diopside, K-feldspar and quartz, and gradational contacts with the metavolcanic lithofacies.

Metasedimentary lithofacies

The metasedimentary lithofacies is inferred from an interlayered group of gneisses including biotite-sillimanite-garnet metapelitic gneiss with cordierite locally, quartzite with minor biotite and/or garnet, K-feldspar-pyroxene calc-silicate, graphite-sulfide gneiss with garnet, sillimanite, biotite, quartz and feldspar and rare thin lenses of calcite marble. Typically, the contact with the metavolcaniclastic and metavolcanic lithofacies is sharp with no obvious gradation as in the other lithofacies.

The three rock units previously described were involved in two main tectonic episodes. The first event is the more pervasive of the two, and reflects the main Grenville orogeny in the Highlands terrane. The rocks were deformed into tight recumbent west-directed fold nappes with subhorizontal, highly attenuated lower limbs and shallowly dipping, more intact upper limbs. This nappe propagation was accompanied by the granulite facies metamorphic conditions, and the age of this event appears to be about 1060 to 1020 Ma (Gates et al., 2004). The second event was a large scale dextral strike-slip episode. It began after the intrusion of the 1008 Ma Tiorati diorite and continued until sometime prior to 981 Ma (Gates et al., 2004; 2006).

There were several periods of igneous intrusion. They include pre- to synkinematic granites and granite sheets, a 1008 Ma diorite-granite suite that intruded after the first tectonic event but at the initiation of the second tectonic event, and coarse pegmatites that intruded at 981 Ma (Gates et al., 2006).

JOINTS IN THE HUDSON HIGHLANDS

There are two dominant joint sets in the Hudson Highlands with other localized sets that appear to be associated with faults. The major dominant joint set is characterized as steeply dipping to subvertical, strikes northeast-southwest, and can be found at almost every bedrock exposure. Joint density varies significantly on the local scale from fracture zones to large areas with no joints. The general joint density ranges from 3-6 per meter counted perpendicular to the joint strike. The strike of these joints generally parallels the foliation in the bedrock (Figure 3).

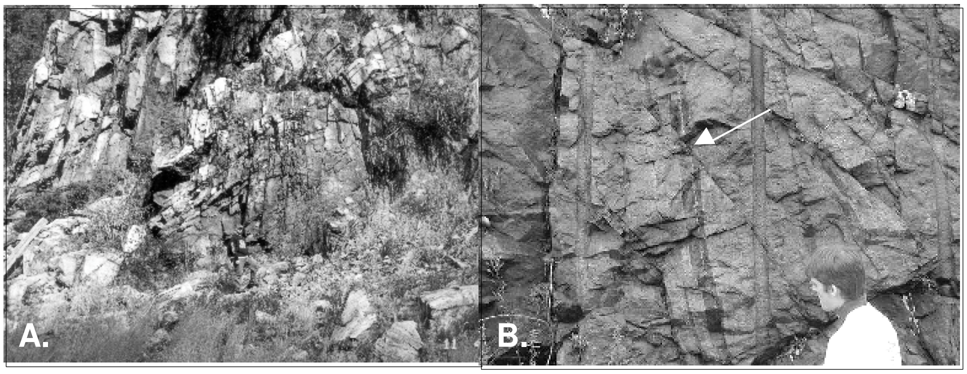

Figure 3. Photographs showing examples of densely spaced joints. A. Metavolcanic lithofacies along the Kanawake fault. Two joints sets are apparent. The one inclined to the left is roughly parallel to the location foliation. The set that is subvertical is subparallel to the Kanawake fault. B. Joints with oblique-reverse displacement in quartzofeldspathic gneiss with minor amphibolite layers. The white arrow points to amphibolite layers offset across a joint.

A second set of very common subvertical joints strikes east-northeast (Figure 4). This joint set appears to be more localized, but occurs in bedrock that is near long topographic lineaments that also transect the regional structural grain of the Hudson Highlands.

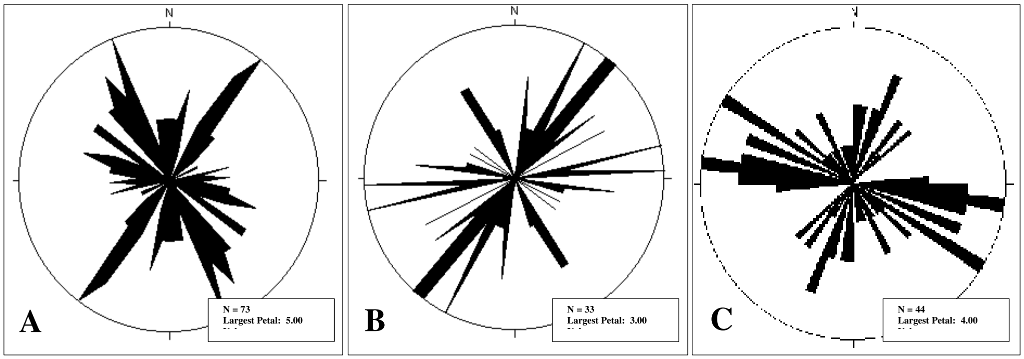

Figure 4. Rose diagrams of joints from three locations in the Hudson Highlands: A. Sterling-Tuxedo Lake area; B. Indian Hill area; C. Torne valley area.

A third set of subvertical joints strikes west-northwest, and appear to be linked to faults with the same attitude that show oblique-dextral displacement (north-side-up) (Figures 3 & 5). Joint surface morphology is highly varied. The joint set that is generally parallel to the regional foliation appear to be Mode I, with no apparent displacement (Figure 3A). However, the second and third joint set commonly exhibits minor displacement and mineralized slick surfaces (Figures 3B & 5).

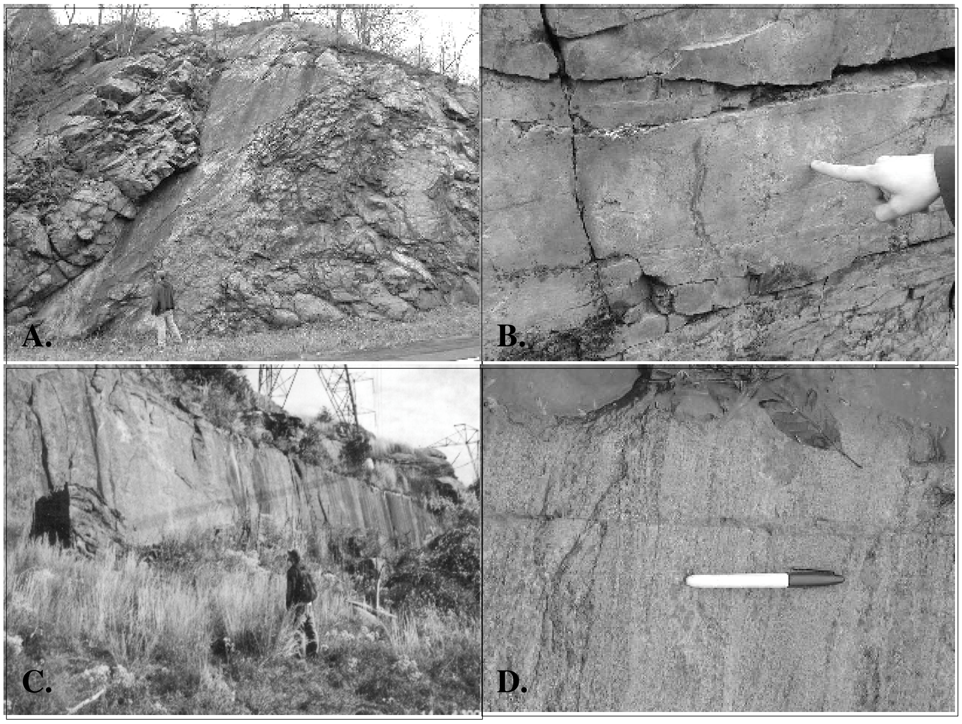

Figure 5. Photographs of joints feature and minor faults in the Hudson Highlands: A. Fault surface in the gneiss of the metasedimentary lithofacies, Seven Lakes Drive, Harriman State Park; B. Close up view of a highly polished, mineralized joint surface at the same location as A.; C. Northeast striking, apparent fault scarp in quartzofeldspathic gneiss near the New York Thruway; and D. Joint with minor dextral displacement in pelitic gneiss in Torne Valley.

ACTIVE (?) FAULTS IN THE HUDSON HIGHLANDS

Using the bedrock geology as a marker, some of the late brittle faults in the central Hudson Highlands appear to have up to 2 km offset. These faults also correlate with strong topographic expression (Figure 6).

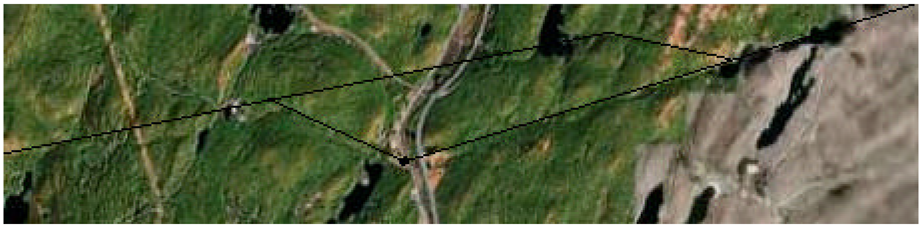

Figure 6. Landsat map for the area of the Hudson Highlands (Gates and Valentino, 2000-2003) including the Kanawake Fault.

One of the more pronounced faults traces eastward across the Sterling Forest into Harriman State Park, and through Lake Kanawake (Kanawake Fault). This fault displaces major geologic units. In the area of north of Tuxedo, NY, the fault jogs northwestward and merges with another east-northeast striking fault that cuts across the Sterling Forest area. Although this region is highly glaciated, some of the Kanawake Fault segments trace through fresh talus slopes. As well, this fault traces into a region of modern seismicity suggesting the fault has minor activity (Figure 7). Seismicity data for the region was obtained from the Lamont-Doherty Cooperative Seismic Network database (Kim, W. Y.-personal communication). Of the numerous earthquake events compiled for the New York City metro area, on that occurred on September 3, 1951 lies approximately along the eastern extension of the Kanawake Fault in Rockland County (Figure 7). This earthquake had a Richter (ML) magnitude of 3.6 and a maximum intensity (MM) of V, and is proposed to be the eleventh largest earthquake in this region though it is the third largest instrumental earthquake. Some of the more notable earthquakes in the area are apparently association with Mesozoic faults such as the Ramapo Fault. However, the joints and the faults associated with the trend of the Kanawake fault appear to be the youngest structural features and may reflect current stress fields.

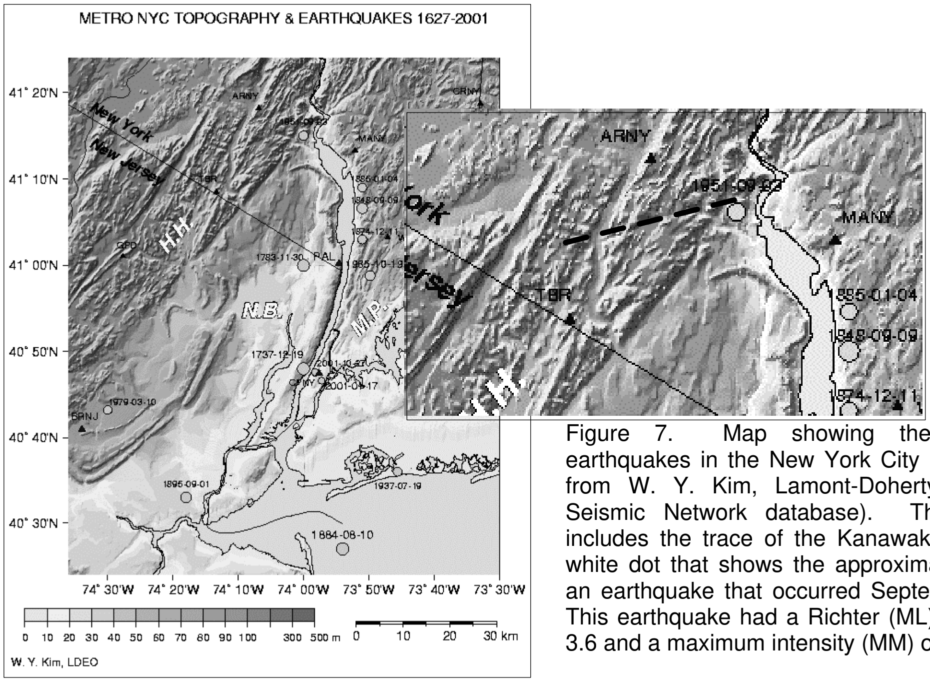

Figure 7. Map showing the location of earthquakes in the New York City area (modified from W. Y. Kim, Lamont-Doherty Cooperative Seismic Network database). The inset map includes the trace of the Kanawake Fault and a white dot that shows the approximate location of an earthquake that occurred September 3, 1951. This earthquake had a Richter (ML) magnitude of 3.6 and a maximum intensity (MM) of V.

There are many other parallel and apparently related faults in the New York metropolitan area. Klewsaat and Gates (1994) found similarly oriented faults that offset the Palisades Sill in central New Jersey. These faults strike into the area in New York Harbor where the largest historical earthquake in the area (1884) has its proposed epicenter (Figure 7). Jointing around these faults in the Highlands is locally intense producing enhanced permeability and groundwater flow. In some areas, there are talus slopes of angular rock fragments that appear relatively young. The intense fracturing appears to have enhanced the ease at which erosion takes place. Many of the lakes and wetlands lie along these faults as a result.

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STOP 3: LAUTENBERG VISITOR'S CENTER, HIGHLANDS ENVIRONMENTAL RESEARCH INSTITUTE, STERLING LAKE MINE COMPLEX (LUNCH)

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Funds for a visitor's center in the new Sterling Forest State Park were donated by Senator Frank Lautenberg. The building overlooks Sterling Lake and contains displays depicting current trails, the old iron mine workings, and the current groundwater system. The Highlands province was one of the principal sources of iron for the colonies beginning in about 1730 through the early republic and the Civil War. Iron from the over 400 mines in New Jersey alone played an integral part in American history from the chain that was stretched across the Hudson River to contain the British in New York during the Revolution to the building of the early railroad system. The mining industry came to an abrupt end around 1900 when the Mosabi Range deposits in Minnesota proved far more economic. Many mines are still accessible but the workings are typically long gone. The Sterling mine workings are the best preserved partly because mining operations lasted longer than virtually all other mines and because it was not disassembled during the Great Depression through WPA projects like many others.

The mine displays show the entire mine complex on a geologic 3D base. The remnants of these workings are less than ½ mile from the visitor's center. Walk down (south) Old Forge Rd to an open field on the right with a flag. Just into the woods is the Sterling Forge. A columned dome was constructed over the forge to protect it after operations ceased. The wooden columns are all that remain. It is unusual for the forge to be located in the mine area. Typically, the ore was hauled to a furnace that was closer to major transportation routes. Smelting requires ore, fuel and a flux. The magnetite is the ore, fuel was provided through charcoaled trees that were locally harvested and the flux was the plentiful Cambrian Wappinger Group (Kittatinny) limestone. The products of the process are iron, slag and a lot of air and water emissions.

About ¼ mile down the road to the right, is a cluster of mine buildings. The major building is a magnetic ore separator. Train cars would be filled with crushed magnetite ore that was lifted out of separator bins by large electromagnets. Tracks led out of the separator building and connected to the main train line for hauling. Behind the separator buildings is a cable house for the now filled Sterling Mine below and along the roadside and a dynamite shed.

Walk back down the road to the intersection with Old Forge Road. There is a small parking area and a spring emptying through a pipe. Walk up the trail to the Lake Mine. This mine is not filled and is surrounded by mounds of tailings. The magnetite is hosted by calc-silicate metasediments. Hydrothermal fluids mobilized the iron from metavolcanic rocks and transported it to this chemically favorable area. Magnetite was deposited primarily by hydrothermal replacement of the gneiss. The ore body is therefore conformable to the foliation and stratigraphy. Late pegmatites are strongly salmon colored from the abundant iron and contain euhedral green clinopyroxene typically with a salite to augite composition.

This mining continues to have a negative impact on the environment. Water flowing through tailing piles and waste rocks around the former mining operations at Sterling Forest were analyzed for heavy metals and trace elements. Results show that concentrations of metals of environmental concern were far below NYDEC Water Quality Standards (Figure 1). The pH for these water samples was slightly above 6.0 but groundwater registered 5.66. At high pH, ferric hydroxide ($Fe(OH)3$) precipitates, a common yellow coating on stream bed sediments. Metals are removed from the water column as they co-precipitate with $Fe(OH)3$ and adsorb to sediments that result in elevated but immobilized metal concentrations (Figure 1). Sediment and water sample data correlate well in relation to metal mobility and retention at elevated pH. The very low metal mobility in water, therefore, does not pose a threat to drinking water quality but potentially dangerous to bottom grazers along sediment bed which eventually affects the foodchain as a result of biomagnification. A decrease in pH < 5.5 will release the metals to surface and ground waters.

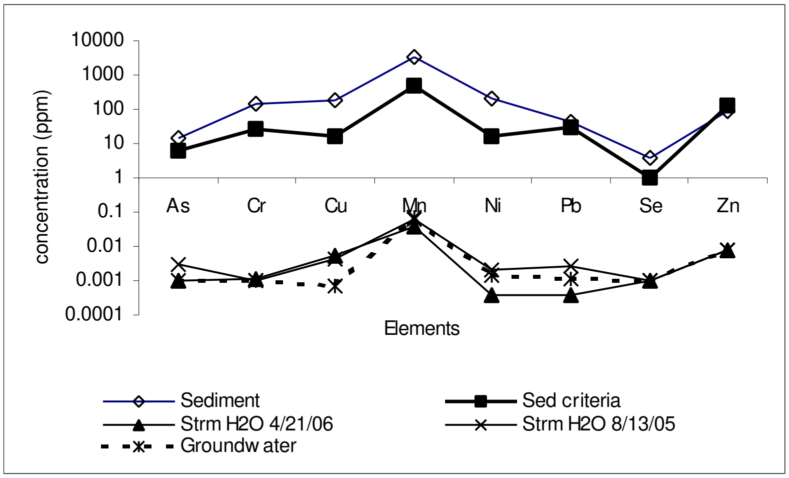


Figure 1. Effect of high pH ranging from 5.66 to 6.59 in water samples increases metal pollutant concentrations in stream sediment (the highest value of three inter-samples within the same site). Stream sediment sampled simultaneously with stream water on April 21, 2006.

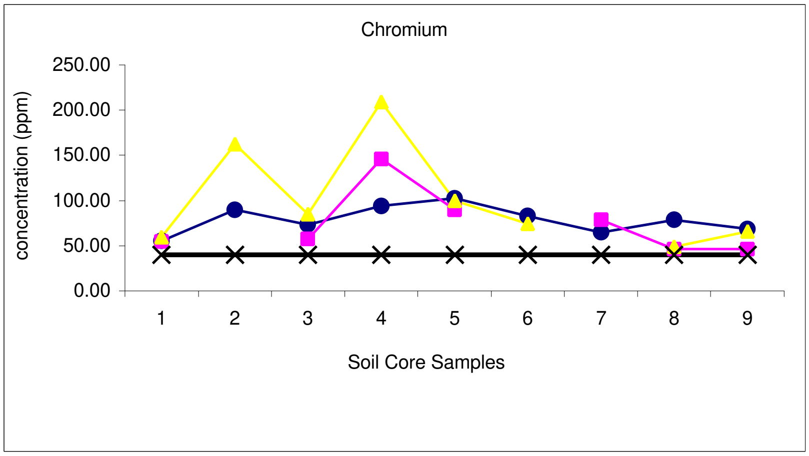
Dissolution of Fe(OH)3 neutralizes acidic mine waters but neutralization may not take effect if iron sulfide concentrations exceed magnetite. Oxidation of pyrite and pyrhotite, sulfide gangue minerals of the host rocks at Sterling Forest, generate acid mine drainage. Magnetite oxidation generates and precipitates ferric hydroxide that can passivate sulfide minerals, thus inhibiting interaction with pore water. In order to derive the benefit from the magnetite oxidation, magnetite has to be present in sufficient amounts to preclude acid generation. Presence of carbonates in tailings or waste rocks can neutralize acid production but this may not be the case at the research site as data shows low Ca concentrations in the water samples (10 mg/L for 4/21/06 and 3.88 mg/L for 8/13/05).

The soil sample data for the same area show high concentrations of Cr and Ni (Figure 2). Although Sr levels (ranging from 70 – 254 mg/kg) exceed typical soil background levels of 0.2 mg/kg, its toxicity is reduced to humans or plant growth since it is most commonly a stable isotope, Sr-88. Aluminum is present in the soil samples at considerable amounts in some of the samples, between 4.36 – 19.46 weight percent. (NYDEC criteria for Al = 3.3 wt %). Plants can uptake Al but at high accumulation it can block the uptake of phosphate. Al solubilizes at pH<5.5 and free Al ions are toxic to humans.

The Highlands Environmental Research Institute (HEnRI) was established in the old Sterling Forest Visitor's Center after the new facility was opened across the street. The Mission of HEnRI is:

> The Highlands Region of Connecticut, New York, New Jersey & Pennsylvania constitute a critically important region that has been recognized by the U.S. Congress as an area of national significance. The Highlands Environmental Research Institute (HEnRI) was established as a clearinghouse to coordinate environmental research, disseminate environmental knowledge, & promote its application in the work of conserving the Highlands natural resources. HEnRI provides unbiased, scientifically based information about conditions in the Highlands, current trends, and probable outcomes. Information and technical assistance from the Highlands Environmental Research Institute aids private landowners, citizens groups, and government agencies in their efforts to conserve the Highlands and build a sustainable future for the region.

HEnRI resources are available to educational, research, legislative and advocacy groups. They also sponsor research projects in the Highlands on geology, ecology, and environmental sciences.



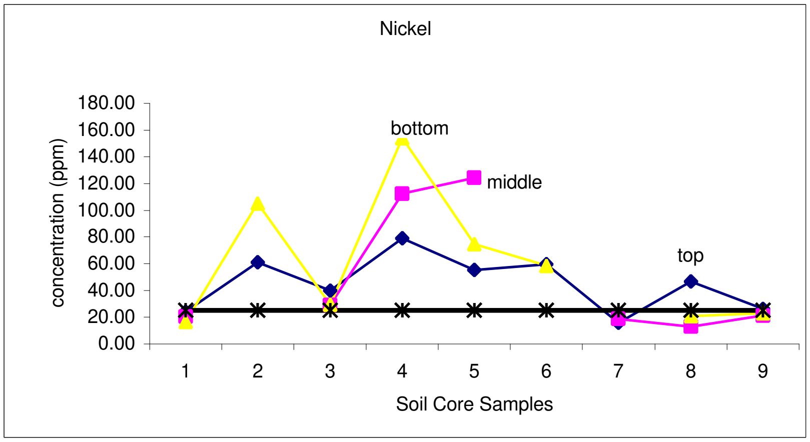


Figure 2. Concentrations of Cr and Ni in soil samples. Black straight lines represent NYDEC soil background levels (i.e. Cr = 40 ppm; Ni = 25 ppm).

Stop 4: Torne Valley: A Typical Glaciated Upland Valley In The Highlands

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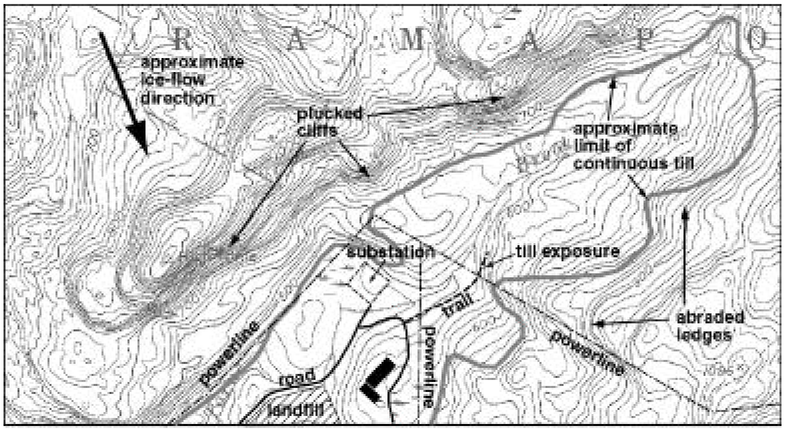
Torne Valley is an excellent example of a glaciated upland valley that is oriented perpendicular to ice flow. The landforms and till deposits in the valley are the products of varying thermal conditions occurring at the base of a temperate glacier as it traverses a corrugated bedrock surface. Ice at the base of a temperate glacier is at or near the pressure-melting point. On the up-ice (here, north-facing) side of bedrock prominences, the moving glacier presses ice against the bedrock surface, increasing basal pressure in the ice. This leads to melting, which produces water, which causes the ice to slide on the rock surface. The sliding abrades the rock surface, forming sloping ledges. Excess water produced by the melting migrates through fractures in the rock away from the pressurized zone. Melting also releases sediment from the ice, which is lodged as till on the rock surface. On the lee (here, south-facing) side of bedrock prominences, the glacier is moving away from the bedrock surface, reducing basal pressure in the ice. This leads to freezing of water to the base of the glacier. Water moving through fractures in the bedrock prominence from the high-pressure zone on the up-ice side freezes onto the base of the glacier, and the freeze front migrates down into fractures in the rock. Ice growing in the fractures pries apart the bedrock, and ice freezing onto the base of the glacier welds the pried blocks onto the glacier. This pry-and-weld action is known as glacial plucking or quarrying, and it creates cliffs. Because material is freezing onto the glacier, there is little till deposition.

In Torne Valley, Late Wisconsinan ice advanced southerly to slightly southeasterly across the area. The south-facing slopes forming the north side of the valley were plucked, creating cliffs. The north-facing slopes forming the south side of the valley were abraded, creating sloping ledges. Till was lodged by melt-out on the valley bottom and along the lower parts of the north-facing slope. The plucked south-facing slope is visible from the first powerline along the trail into the till exposure (see figure). Sloping ledges are visible on the north-facing slope from the second powerline. Till mantling the lower part of the south-facing slope is exposed in a shallow roadcut just past the second powerline. This till is a matrix-supported yellowish brown to very pale brown silty fine-to-medium sand with many pebbles, cobbles, and boulders. Pebbles are 80-85% gneiss and 15-20% gray shale and sandstone; cobbles and boulders are almost entirely gneiss. Gneiss is the local bedrock; gray shale and sandstone are from Paleozoic rocks to the north in the Wallkill and Hudson valleys. This till is typical of gneiss-derived till throughout the Highlands and is referred to as Netcong Till in New Jersey. In many valleys, winnowing and incision by postglacial streams, or by meltwater draining down the valley during glacial retreat, created boulder lags and small boulder-capped terraces in the valley bottom. Boulder lags and terraces occur discontinuously along Torne Brook.



Sandy till is 10 to 20 times more porous than underlying gneiss and so is an important groundwater reservoir that absorbs water running off of upslope bedrock outcrops and, in turn, feeds water as baseflow to upland streams. Seeps and springs at the base of till slopes are evidence of this process. Seepage channels cross the trail leading to the till exposure in a couple of spots, and wet seepage areas are visible downhill along the edge of Torne Brook.

STOP 5: GEOLOGIC CONTROLS ON ENVIRONMENTAL ISSUES IN THE READING PRONG

Linda C.S. Gundersen

THE STANDISH MINE

The Standish Mine is a typical example of the linear magnetite bodies found through-out the Reading Prong. It is part of a large anomaly of strong magnetism and radioactivity that underlies this portion of the Hudson and New Jersey Highlands. The main host rock is calc-silicate gneiss that includes diopside, scapolite, and allanite. Apparent metamorphosed banded iron formation is found on the south side of the main magnetite deposit and extensive pegmatite layers are found adjacent to the magnetite ore. Workings include several adits and linear mined-out pits and trenches. The mines of this area, known as the Warwick Group, were last mined extensively in the late 1800s. The mines that occur on Warwick Mountain include the Standish, Raynor, Parrot, and Green mines (Colony, 1923). To the south of the Warwick mines lies the Taylor mine and the Centennial mine (Figure 1).

Start Point: Intersection of Route 17 and Route 17A in Harriman State Park, New York
Go west on 17A, out of Harriman State Park towards Warwick, New York for 10.7 miles. This route includes many road outcrops of Proterozoic rocks. Pass through the Town of Greenwood Lake and note outcrop of Devonian and Silurian sandstones, conglomerates, minor shales, and limestones. Turn south onto Cascade Road and go 4.1 miles. Turn north onto Birdsall Road go .2 miles. This is a gravel and bedrock road through woods that is difficult driving in portions. Note numerous rock outcrops of quartz plagioclase gneiss, amphibolite, pegmatite, and pyroxene gneiss. Vehicles should park in the grassy clearing to the right, just before the steep hill to the last home on the road.

Walk up short steep hill and a small house will be to the left. Grass path leads north then west and starts with a large flat outcrop of apparent banded iron. A particularly well exposed section, about 15 feet thick occurs along this path and shows vertical and lateral relationships with adjacent rock types. The magnetite forms continuous thin beds alternating with diopside and quartz. Towards the top of this section, feldspar-rich layers increase as diopside layers decrease. Farther up section, to the west of this exposure, calc-silicate gneiss which hosts stratabound, unbanded masses of magnetite and uranium, grades into pyroxene-bearing quartz-feldspar gneiss and eventually to quartz-plagioclase gneiss and amphibolite. Westward, across the narrow valley that separates Warwick Mountain from Rocky Hill, the section is dominated by biotite, garnet, and graphite-bearing gneisses with minor quartz-plagioclase gneiss.

The path forks to the west, north, and east. On the path to the west, are tailings, pits, and the small adits of the Standish mine. Magnetite is concentrated in elongate lenses that are generally concordant with surrounding rock units and foliation, and plunge parallel to major fold axes. Although the magnetite is usually massive, it also forms sequences in which thin layers of magnetite alternate with thick layers of quartz, pyroxene, allanite, pyrite, uraninite, and pyrrhotite. Small discordant veins of magnetite, pyrite, uraninite, and pyrrhotite, are also commonly found in zones of brecciation, cataclaysis, and mylonitization. Pegmatites adjacent to magnetite lenses are common, are of variable composition, and are probably the result of local anatexis. Pyrite, pyrrhotite, uraninite, and minor chalcopyrite are disseminated throughout the magnetite lenses. Molybdenite, sphalerite, galena, covellite, and bornite are rare. The most abundant gangue minerals are apatite, quartz, feldspar, pyroxene, allanite, and sphene, and occur as disseminated crystals and as thin layers in the magnetite. Biotite, chlorite, actinolite, albite, epidote, calcite, rutile, ilmenite, scapolite, pumpellyite, sapphirine, and tourmaline are found in variable amounts in the ore and host rock. Veins crossing the foliation of rock are dominated by pyrite and pyrrhotite but in some instances contain magnetite, molybdenite, and florite. Geochemistry of the ore reveals uranium concentrations in excess of 1000 ppm.
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Figure 1: Geologic map of a portion of the Greenwood Lake Quadrangle showing location of uranium and rare earth bearing magnetite mines. Modified from Gundersen (2004).

ALTERNATE STOP: THE CENTENNIAL MINE

Start Point: From the intersection of Cascade Road and Birdsall Road, turn west onto Cascade Road and go a short distance to the intersection with Brady Road, take Brady Road south for 2.2 miles, it becomes Longhouse Drive as you cross into New Jersey. Stop and park at the Appalachian Trail on east side of road. Take the trail east for .3 miles. This is a short hike with minor hilly terrain. The trail heads east for approx .2 miles then turns south and follows the base of a hill for a short distance before turning east again. Path can be rocky or have numerous tree roots. The Centennial mine is just south of the trail after it makes the sharp turn east. The Centennial mine is of similar vintage to the Warwick and Taylor mines and was last worked in the late 1800's. It is hosted in calc-silicate gneiss with abundant pegmatite bodies. This host gneiss is highly variable and contains quartz, plagioclase, hornblende, pyroxene, K-feldspar, garnet and epidote in various amounts. It appears more altered than the deposits to the north and contains more calcite and less allanite. The mine workings here consist of a deep trench and series of pits stretching north. Uranium concentrations were found in excess of 1000 ppm.

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