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MESSAGE FROM THE STATE GEOLOGIST

This issue of *Unearthing New Jersey* explores some of the new approaches the Survey is pursuing to understand fractured rock aquifers. Greg Herman discusses the ubiquitous rock joints in the Newark Basin which are often cited as pathways for water in the basin's fractured-rock aquifers. Geologists working in the basin have noted steep joints occur in two directions, one parallel and the other normal to the strike of strata. A closer look at these structures shows a more complex and variable-orientation. They record a tectonic history of the region that included crustal stretching, sagging, and eventual faulting of a thick pile of rift basin sediments.

Laura Nicholson summarizes the use of temperature as a tool for interpreting the interaction of ground water and its surrounding environment. She presents a new method of evaluating fracture interconnections by monitoring ground-water temperature trends during aquifer tests. Temperature and water-level data are analyzed together to better define the hydrogeologic framework of a fractured-rock aquifer.

Continuing the series of historic articles, Ted Pallis and Jeff Hoffman recount the important role that canals and water-power raceways have played in the economic development of New Jersey. Early settlement and industry gathered in areas with water transportation and water power. Although many canals have been forgotten, others are still in use as a water resource and for recreation.

Finally Larry Müller provides a detailed description of the mineralogy of copper deposits in New Jersey. These range from the common elemental native copper, copper sulfides, carbonates and oxides to the rarer phosphates and arsenate.

The Survey welcomes your feedback on the content or format of the newsletter. Other recent geologic activities and digital publications of the Survey are noted in the newsletter and elsewhere on the Survey's Web site. Printed maps and reports are available to the public through the DEP Maps and Publications Fulfillment Office (609) 777-1038, PO Box 402, Trenton, N.J. 08625-0402. Due to fiscal constraints, over-the-counter purchases are no longer available. Go to our website for more information. A publications price list is maintained on the Web. Unpublished information is provided at cost by writing the State Geologist's Office, N.J. Geological Survey, PO Box 427, Trenton, N.J. 08625-0427. Staff are available to answer your questions 8 a.m. - 5 p.m. Monday through Friday by calling (609) 292-1185.

Karl W. Muessig,
New Jersey State Geologist

Rock joints in Wickecheoke Creek, Lockatong Formation, near Locktown, Kingwood Township, Hunterdon County. *Photo by G.C. Herman*

ROCK JOINTS IN THE NEWARK BASIN

By Gregory C. Herman

Rock joints in the Newark Basin are common structures that are often cited as having a significant hydrogeological role in the basin's fractured-rock aquifers. In the past, most geologists have characterized steeply-dipping (>60^{o}) joints as having formed in two primary directions, one striking parallel and the other normal to the strike of strata. A close look at these ubiquitous structures tells us that they are much more complex and variably-oriented than originally portrayed. They also record the tectonic history of regional crustal stretching, sagging, and eventual faulting of the mid-Atlantic margin of the North American continent.

The Newark Basin is one of many down-dropped basins formed in a continental rift zone during the breakup of the Pangea supercontinent (fig. 1) before subsequent growth of the Atlantic Ocean Basin beginning about 180 million years ago. The basin spans New Jersey and extends laterally

Figure 1. Reconstruction of the supercontinent Pangea during the Upper Triassic period showing the locations of rift zones and exposed rift basins before continental drift and growth of the Atlantic Ocean. (Adapted from Olsen and others, 1996)

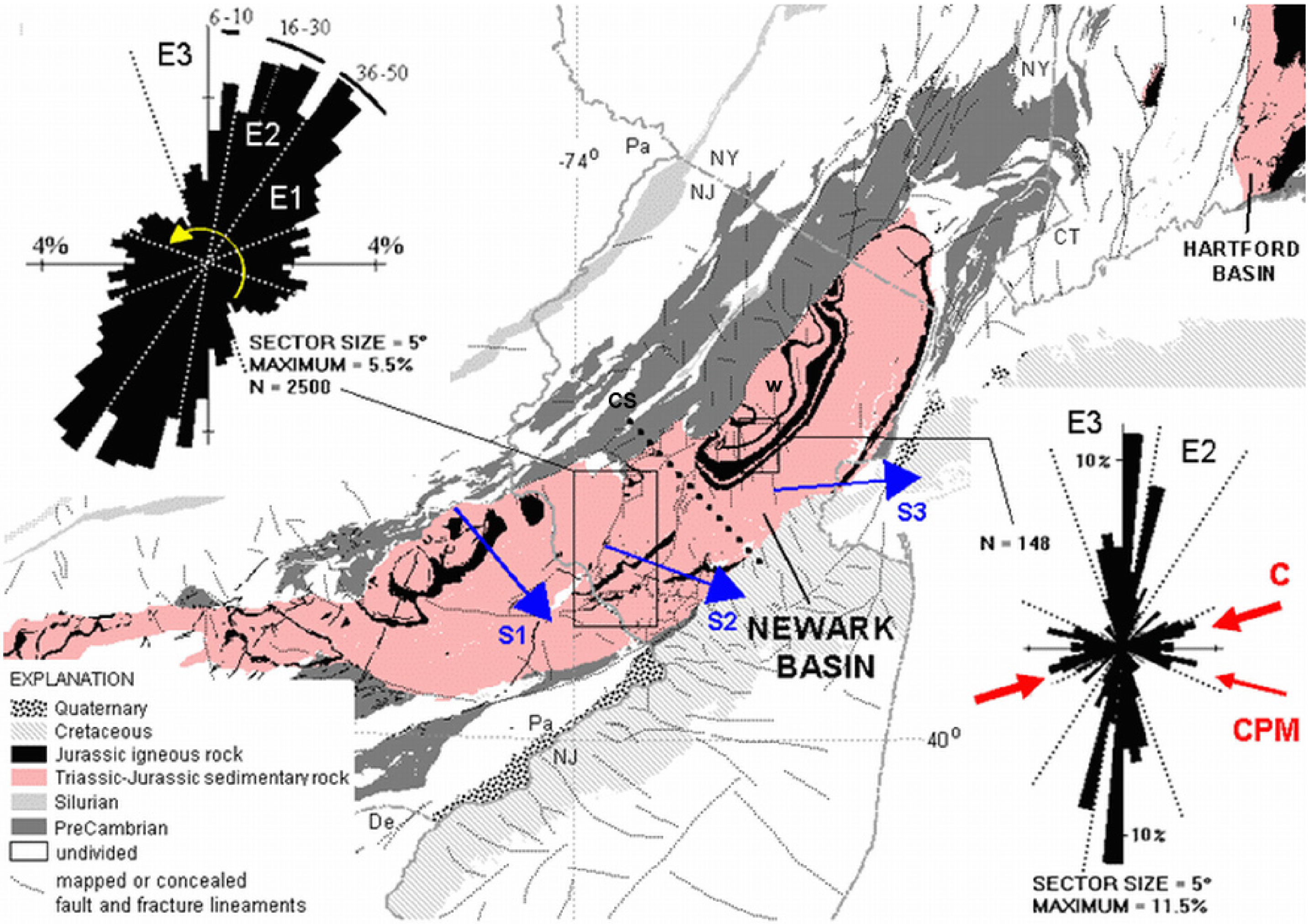

Figure 2. Bedrock geology in the vicinity of the Newark Basin and joint-strikes histograms for Late Triassic rocks in the center of the basin (Herman, 1997) and for Early Jurassic rocks (Monteverde and Volkert, 2005) in the Watchung Mountain region (w). Red arrows show directions of present-day tectonic compression (C; Golberg and others, 2003) and tectonic-plate motion (CPM). **CS**--Trace of figure 3 cross section.

into Pennsylvania and New York (fig. 2). It is filled with as much as 20,000 feet of Early Mesozoic sedimentary strata (fig. 3) including red and gray shale, mudstone, siltstone, sandstone and conglomerate. These strata are locally intruded and interlayered with Early Jurassic igneous diabase and basalt. Basin strata are fractured and faulted from episodes of tectonic extension and collapse during the Mesozoic Era and subsequent tectonic compression and uplift during the Cenozoic Era. At least three groups of steeply-dipping extension fractures (E1-E3, fig. 2) occur in the basin as a result of regional tectonic extension. These fractures are locally cut by gently-dipping shear fractures and other steeply-dipping extension fractures stemming from later tectonic compressions (figs. 2 and 4). The steeply-dipping fractures are the most abundant in the basin and are important for storing and transmitting ground water in fractured-bedrock aquifers.

Extension fractures are brittle cracks in rock that form perpendicular to the direction of incremental stretching (fig. 4, min). They have elliptical surfaces (fig. 5a) that are commonly straight, planar, and continuous over distances of a few to tens of feet (figs. 5b and d). In outcrop they are mapped as joints because their two sides show no visible differential displacement or secondary minerals filling fracture interstices. However, it is important to note that most joints occurring in outcrop and the shallow subsurface were probably once filled or healed with secondary minerals (fig. 6) such as calcite and therefore formed as tectonic veins. Most of the healing minerals are soluble when contacted by weakly-acidic ground water and are therefore easily dissolved and removed from fracture openings near land surface. Dissolution and removal of these minerals deeper

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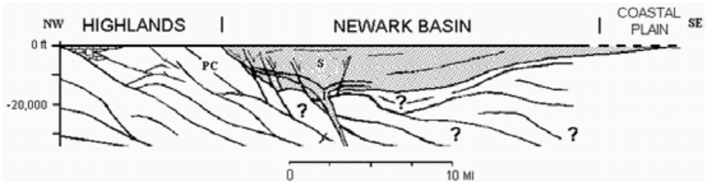

Figure 3. Schematic cross section showing crustal structure in the vicinity of the Newark Basin. The Newark Basin if filled with about 20,000 feet of Lower Mesozoic sedimentary (S) and igneous (I) rocks. Approximate section location shown in Figure 2 (**CS**). (PC -- Precambrian rock, S -- Paleozoic carbonate rock)

in the subsurface is sporadic and incomplete (fig. 6e).

Steeply-dipping extension fractures formed in structural arrays having the geometry of normal dip-slip shear zones (fig. 7). They group, according to strike and morphology into early (E1), intermediate (E2), and late-stage (E3) sets (fig. 2) with early ones locally cutting across and terminating against older ones (fig. 6). Older fractures are also locally folded from stratigraphic compaction (fig. 6c) and have the most complex cements. Fractures belonging to the different groups display progressive 3-dimensional (3D) linkage and spatial clustering that probably controlled incipient fault growth. Extension fractures stretched basin strata up to a few percent and tilted strata a few degrees in a direction opposing fracture dip (fig. 8). But current stratigraphic dips in the basin are generally greater than those attained by

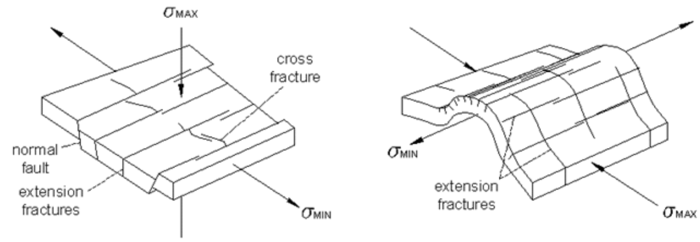

Figure 4. Steeply-dipping (>60^{o}) extension fractures form during crustal extension (left) and compression (right). Maximum and minimum principle stress directions are shown for each case.

fracturing alone and therefore must also stem from fault-slip strains and episodes of tectonic inversion. Together, the three groups of steeply-dipping extension fractures record about 50^{o} counterclockwise rotation of the incremental stretching direction for the continental margin from NW-SE to E-W during the Mesozoic Era (fig. 2). This resulted in upward-twisting, helical arrangements of extension fractures and associated faults in the basin and helps explains why the map traces of large faults in the center of the basin curve upwards (fig. 9).

Structural analysis of extension fractures in the Newark Basin not only gives us insight into their distribution, orientation and tectonic role but also their hydrogeologic relevance in storing and conveying ground water. Because extension fractures are more open and conductive near land surface

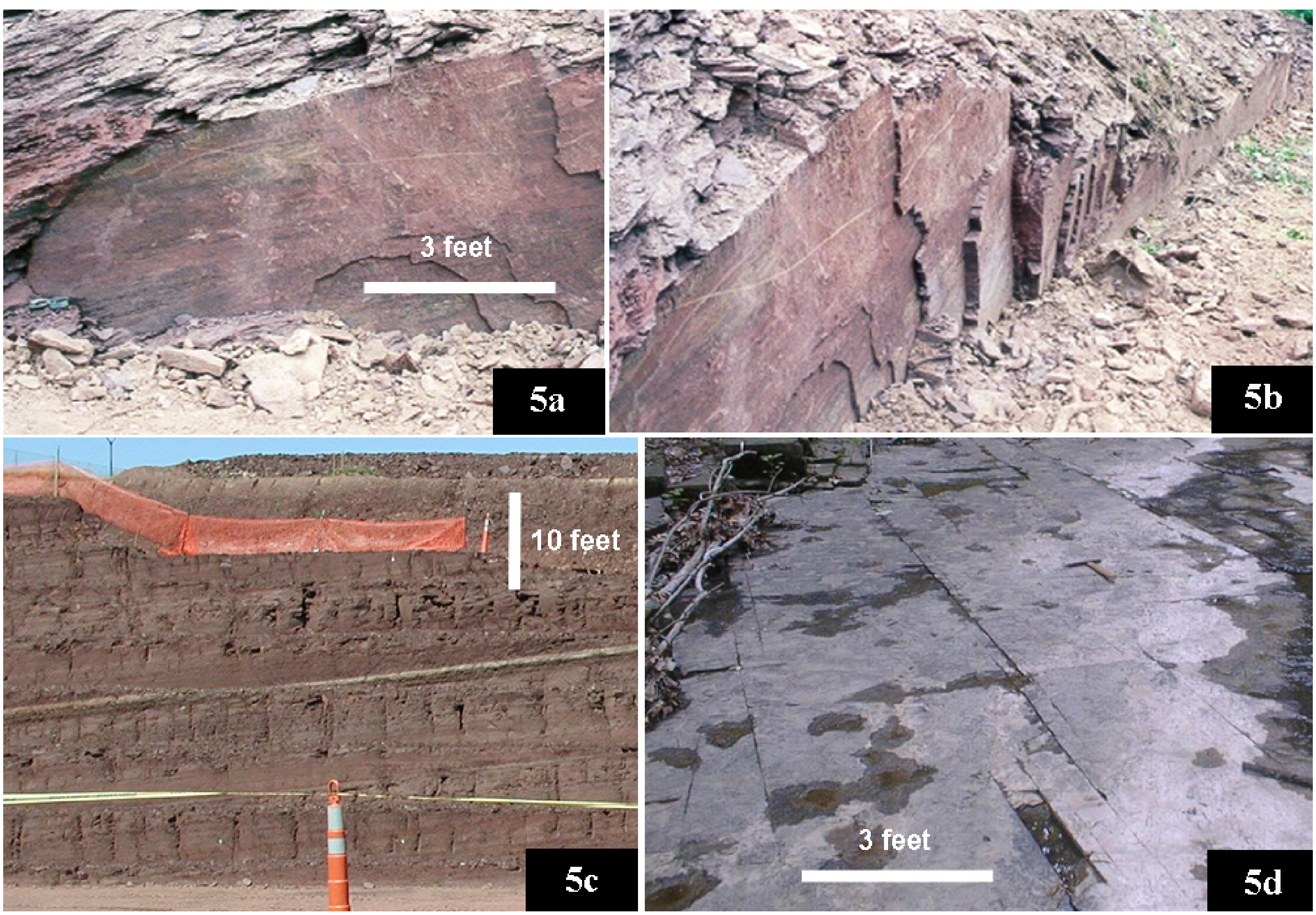

Figure 5. Profile [a-c] and map [d] views of steeply-dipping extension fractures that are typically mapped in outcrop as joints. A-c, red mudstone of the Passaic Formation; d, gray argillite of the Lockatong Formation.

than in deeper bedrock, they are important hydrogeologic features in the shallow bedrock interval, typically extending from land surface to about 60 feet in areas lacking thick, unconsolidated overburden. Their main hydraulic role in deeper bedrock is to leak ground water through thick sequences of low-transmissive strata into high-transmissive, bed parallel water-bearing zones. Their systematic geometry provides some predictive insights as to their dip direction if strata dips are known, but local site characterization is complicated by their wide-range of strike orientations and 3D spatial variability. It is safe to say that close to a mapped fault, the most common joints probably strike parallel to the fault (Herman, 1997). But in areas away from mapped faults, these fractures can parallel bed strike or occur in any of the different group orientations, and with variable densities. We are continuing to assess the hydrogeological role of rock joints with detailed mapping and subsurface investigations to identify the types and distribution of water-bearing features encountered in bedrock wells and how these features interact.

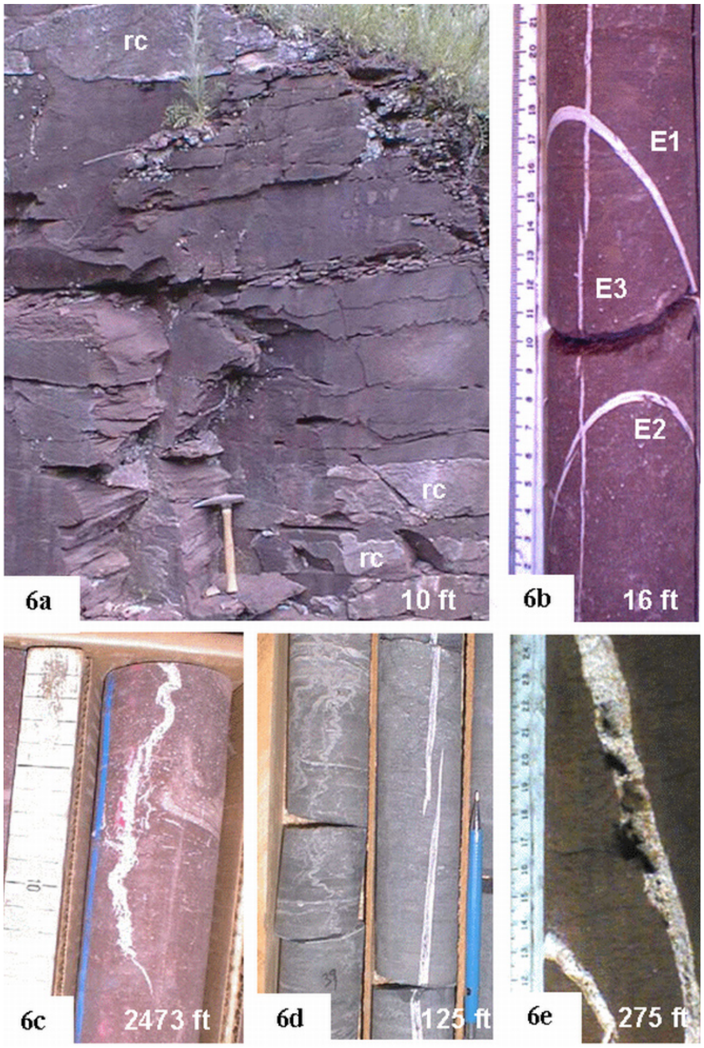

Figure 6. Fractures in the subsurface are typically filled with secondary crystalline minerals including calcite, a-e. A, shows remnant calcite (rc) on fracture walls along a railroad excavation near Pennington Borough, Mercer County. B-d, veins in core samples of the Passaic Formation. Depth below land surface indicated in the lower right of each photo.

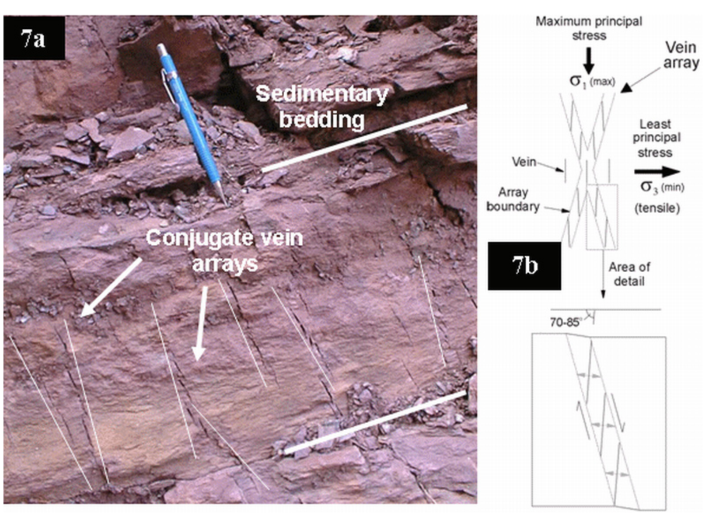

Figure 7. Joints in the Newark Basin formed in stepped alignment in conjugate veins arrays having the geometry of normal dip-slip shear zones. 7a shows profile view of vein arrays in red mudstone of the Passaic Formation in the hanging wall of the Flemington fault.

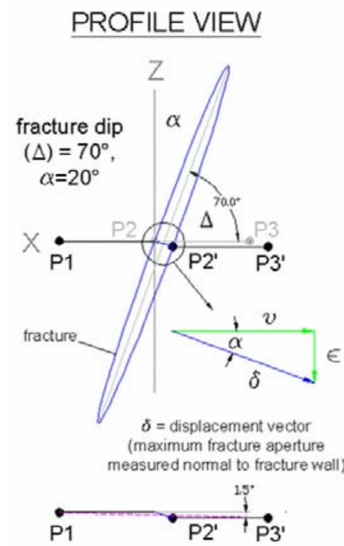

Figure 8. Profile geometry of a steeply-dipping extension fracture. The surface trace of pre-fractured, horizontal strata corresponds with the x-axis. As the fracture opens, strata are stretched and stepped down across the opening. P2 and P3 are displaced into fractured positions P2' and P3' and bedding is rotated downward in a direction opposing fracture dip.

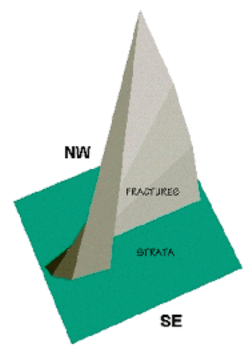

Figure 9. Joints in the Newark Basin twist upward with respect to the age of strata; younger fractures are rotated counter-clockwise with respect to older ones. This helps explain why map traces of faults curve in the center of the basin.

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USING GROUND-WATER TEMPERATURE TO EVALUATE FRACTURE CONNECTIVITY

By Laura Nicholson

Temperature is a useful tool for interpreting the interaction of ground water with its surrounding environment. It is used in a variety of ways to provide information about ground-water flow systems. Contrasts between ground-water and surface-water temperature can help locate areas where ground water discharges to a lake, or determine whether a pumping well is intercepting water from a nearby stream. Areas where precipitation recharges an aquifer have also been identified using water temperature data. In developing supply wells in fractured-rock aquifers, borehole temperature logs are often analyzed with other data to locate productive water-bearing zones, as ground water entering the well may be warmer (or cooler) than water in the borehole. A new method is currently being explored by the New Jersey Geological Survey (NJGS) for evaluating fracture interconnections by analyzing ground-water temperature trends during aquifer tests (Nicholson, 2006; Nicholson, 2007).

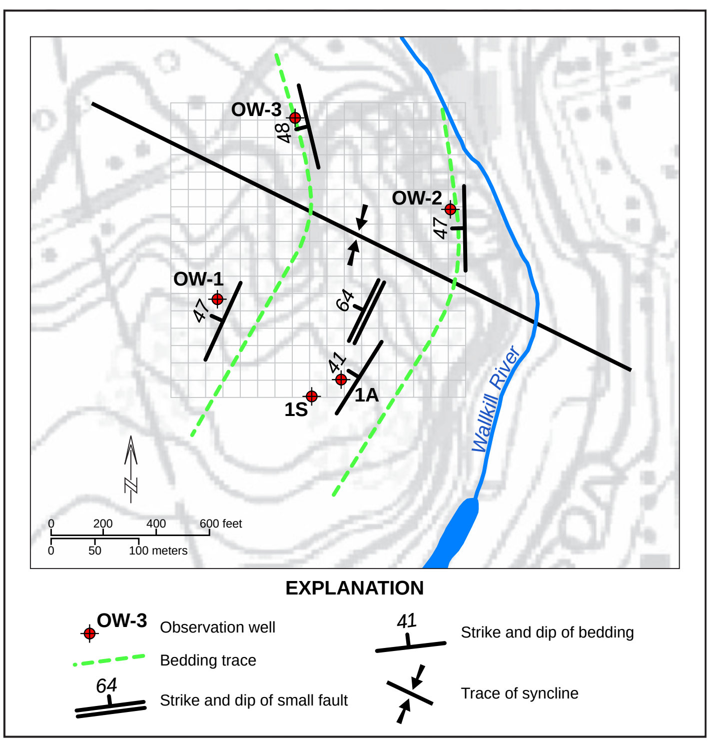

Figure 1. Simplified geologic map of the study area. *Modified from G. Herman*

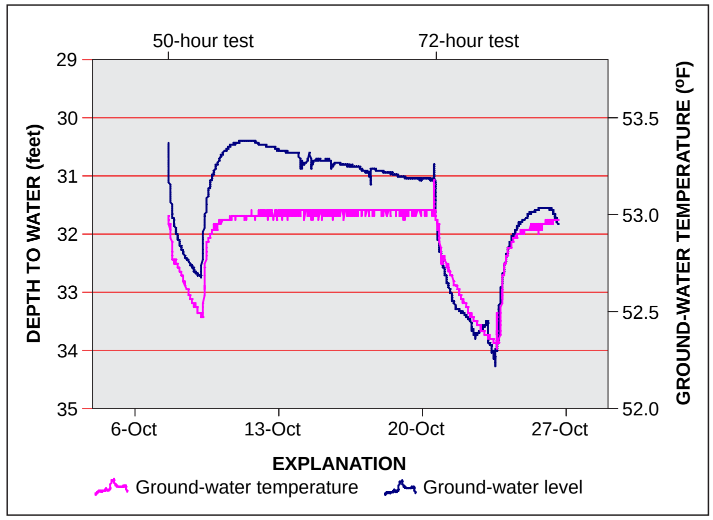

Figure 2. Hydrograph of OW-3 during aquifer tests.

Aquifer tests are routinely performed to assess the potential impact of a new supply well or increased pumpage from an existing one. During the test, a well is pumped at the specified withdrawal rate and water levels in the pumping and observation wells are monitored to determine how much drawdown occurs. The data is then used to determine aquifer properties that are in turn used to assess whether the proposed pumpage will cause adverse impacts to other water supplies or the environment. Typically, automatic water-level recorders used in aquifer testing have the capability to record both ground-water level and temperature, although the temperature data is largely ignored. However, analysis of temperature data collected during October 2003 aquifer tests in fractured dolomite in Hamburg Borough, Sussex County, revealed an interesting phenomenon. In some of the wells, small changes in borehole water temperature accompanied the changing water levels. In other wells, no temperature change

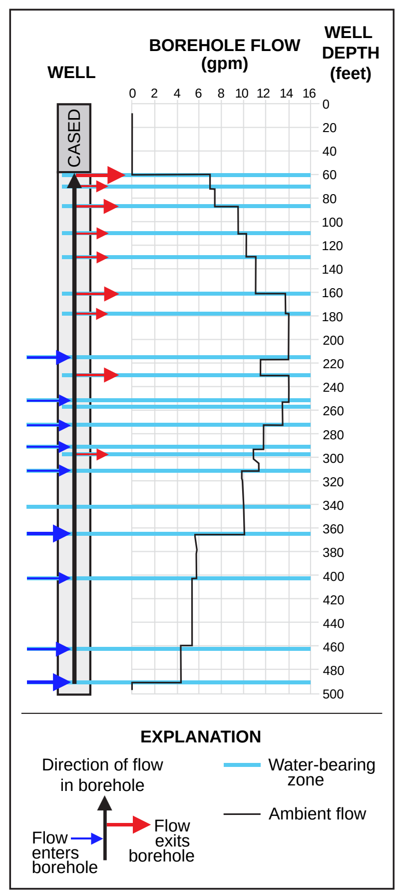

Figure 3. Diagram of borehole flow in OW-3. *Data from G. Herman*

was noted. Data suggest that the observed temperature trends are related to the degree of interconnection of the shallow and deep fracture zones in the well vicinity. This hypothesis was investigated more fully through additional research at the site. Data from two observation wells, OW-3 and OW-2, show how temperature can be used to better define the fractured-rock flow system.

Figure 1 is a simplified geologic map of the study area. OW-3 is 550 feet deep and located in fractured dolomite of the Allentown Formation 767 feet from Pumping Well 1A. Figure 2 is a hydrograph of OW-3 during two aquifer tests conducted in October 2003. Well 1A was pumped at a rate of 250 gpm for both tests. The first test was stopped after 50 hours due to heavy rain. After water levels recovered, a second 72-hour test was successfully completed. Temperature data for both tests show a similar trend to the water-level data. In the first test, the water-level in OW-3 decreased by approximately 2.3 feet and the temperature by 0.5 degrees Fahrenheit (°F) in response to pumping, and both rose when pumping ceased. In the second test, drawdown was just under 3 feet and the temperature decreased by approximately 0.7 °F in response to pumping, before rising when the pumping ended. It should be noted that the temperature trends were not due to the removal or replacement of the well cap and exposure to the colder air temperature. The timing of the temperature changes occurred as a near-instantaneous response to pumping and correspond to pump on and off times. Also, the changes are not related to heating of the water due to operation of the pump as OW-3 is located far from the pumping well, and, even if it were in close proximity, the OW-3 borehole water cooled while the pump was running. Although the Wallkill River traverses the site just east of the wellfield, the interception of river water did not cause the observed temperature change as this response was also observed in OW-1 in the opposite direction of the river from the pumping well (fig. 1).

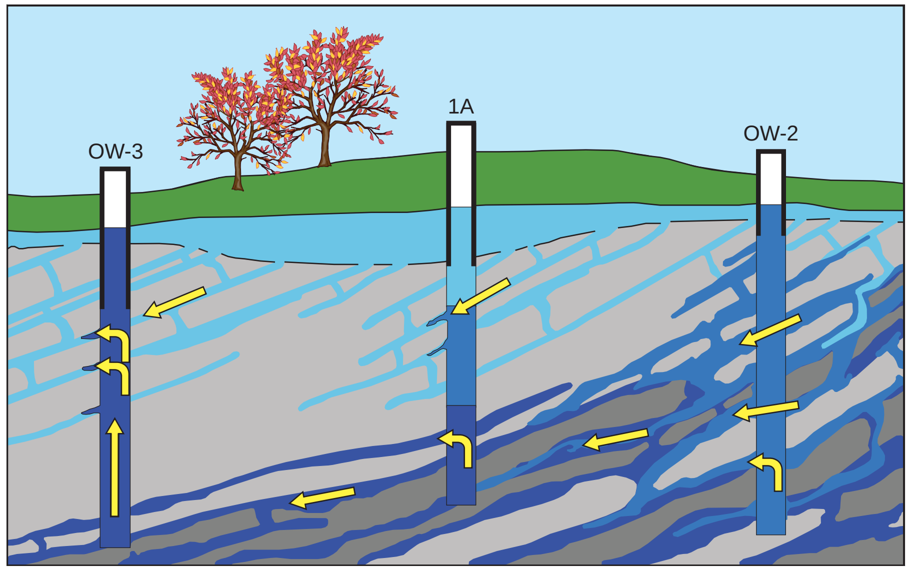

Figure 4. Schematic diagram of ground-water flow prior to pumping.

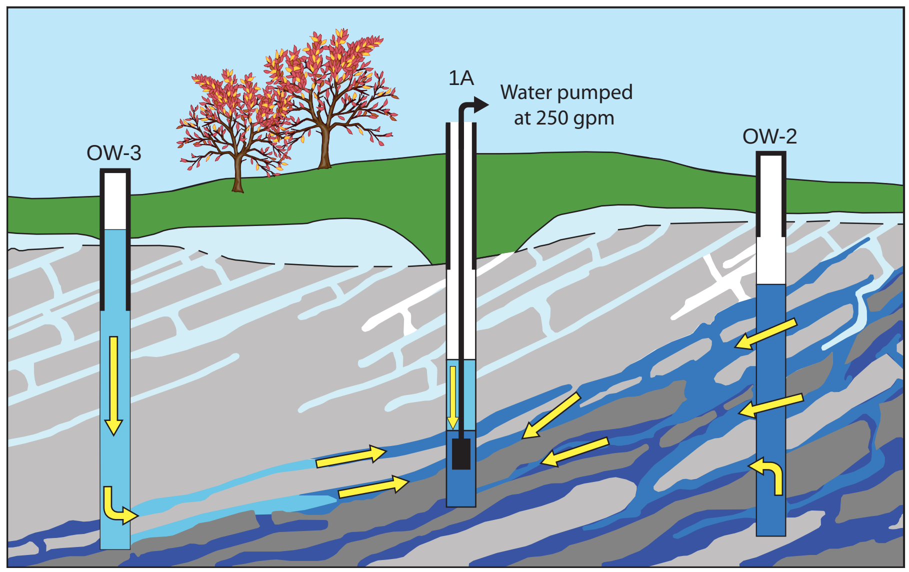

Figure 5. Schematic diagram of ground-water flow during pumping.

Detailed characterization of the fractured-rock aquifer in the vicinity of OW-3 indicates little connection between shallow fractures, those above a depth of approximately 200 feet, and the deeper fracture zone. Greg Herman of the NJGS used a heat-pulse flow meter to record upward and downward flow in the borehole under static, non-pumping conditions. The data indicate that water flows up the borehole at a maximum rate of 14 gpm (fig. 3). Ground water at a higher head enters through deeper fractures in the dolomite and flows up the borehole to discharge to the shallow fracture zone. This suggests that the borehole connects two discreet fracture zones. Subsequent testing at the site supports this theory. When a packer was inflated at a depth of 200 feet in OW-3, the water level in the zone beneath the packer rose 14 feet, an indication that ground water in shallow and deep parts of the aquifer flow under different pressures and hydraulic conditions. When the aquifer was pumped with the packer inflated, drawdown occurred only in the deeper fractures, not in the shallow ones; further indication of little or no intermingling of ground water in the two zones. The open borehole of OW-3 therefore acts as a conduit, providing the sole hydrologic connection in the well vicinity and allowing cross flow between otherwise separate fracture zones.

Change in ground-water temperature is another indicator of the hydrologically-separate flow zones in the vicinity of OW-3. At the time the aquifer tests were conducted in October 2003, mean air temperature in Sussex County did not exceed 51° F (Office of the New Jersey State Climatologist, 2005). Additionally, daily minimum temperatures at the weather station closest to the site (National Weather Service Cooperative Weather Station SUSSEX 2NE) were below

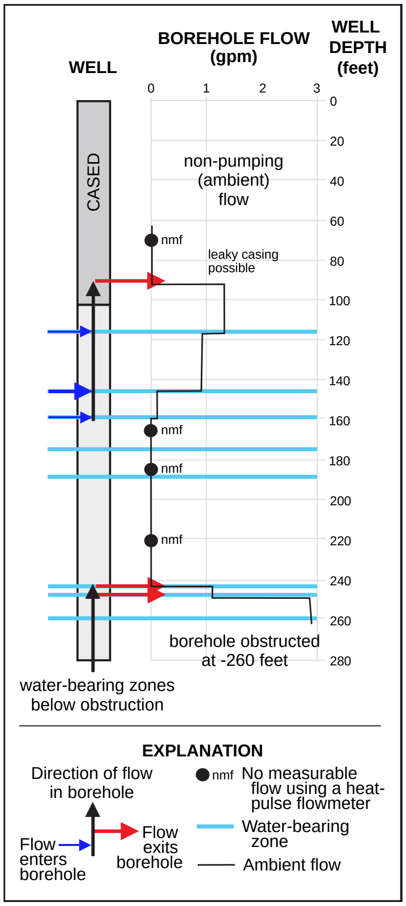

Figure 6. Diagram of borehole flow OW-2. *Data from G. Herman*

freezing just prior to the test (David Robinson, written communication of 3/12/05). The cool air temperatures and colder, possibly frozen, ground act to cool ground water in the near-surface fractures, providing a temperature contrast with warmer water at depth. This pattern is typical of ground water in northern climates during late-autumn and winter months. Figure 4 depicts the test site and illustrates borehole flow in OW-3 prior to pumping of Well 1A. Figure 5 depicts flow in OW-3 after pumping was initiated. Under non-pumping conditions (fig. 4), warmer water at higher head flows up the borehole to discharge into the shallow fracture zone. When pumping is initiated (fig. 5), this trend is reversed. Colder water from shallow fractures is induced to flow down the borehole to the pumping well, resulting in the temperature changes shown in figure 2.

The hydrogeologic framework in the vicinity of OW-2 contrasts greatly with OW-3. Stratigraphic data indicate that OW-2 likely taps both the Allentown and highly-productive Leithsville Formations. The driller's log, along with borehole geophysical and optical-televiewer data collected by NJGS, shows that the well intercepts many large fractures, voids and cavernous zones. Despite the numerous large openings in the rock, the heat pulse flow meter indicates that no measurable flow (nmf) occurs over much of the length of the borehole (fig. 6). Total flow (upward or downward) under non-pumping conditions is less than 3 gpm, much less than in OW-3. This suggests that ground-water entering the borehole is at equilibrium with water in the well. Possibly, water flows through the borehole in a generally horizontal direction so that it is not recorded by the flow meter. When two packers were installed in the well to separate what appeared to be different flow zones, there was little or no head change. Also, the amount of drawdown that occurred in response to pumping was similar regardless of whether or not a packer was used during the test. Both the water-level and drawdown data indicate that the presence of the well bore made little difference to ground-water flow paths in this area.

Figure 7 is a hydrograph of OW-2 during the October 2003 aquifer tests. The well is 550 feet deep and located 589 feet from the pumping well (fig.1). In OW-2, approximately 7 feet of drawdown occurred during the first test, and approximately 8 feet in the second. However, unlike in OW-3, ground-water temperature did not change as a result of the pumping during either of the tests. There is a very slight decrease in temperature, measured in hundredths ºF, that occurs over the testing period and appears unrelated to the pumping. Also, the data shows upward spikes in temperature when the pump is turned on or off, but these were also observed in the OW-3 data. It is likely that these are anomalous readings due to the rapid change in water level and do not reflect actual temperatures.

In figures 4 and 5, OW-2 is shown to the right of Pumping Well 1A. Due to the very open fracture network, ground water in shallow and deep fractures is vertically well-mixed both prior to and during the aquifer tests. In contrast to the temperature changes observed in OW-3, no temperature change occured in OW-2 while pumping because the presence of the borehole has not substantially changed ground-water flow paths in the well vicinity. Additionally, no change in temperature was measured in Shallow Well 1S (fig. 1), because it intercepts only very shallow subsurface flow.

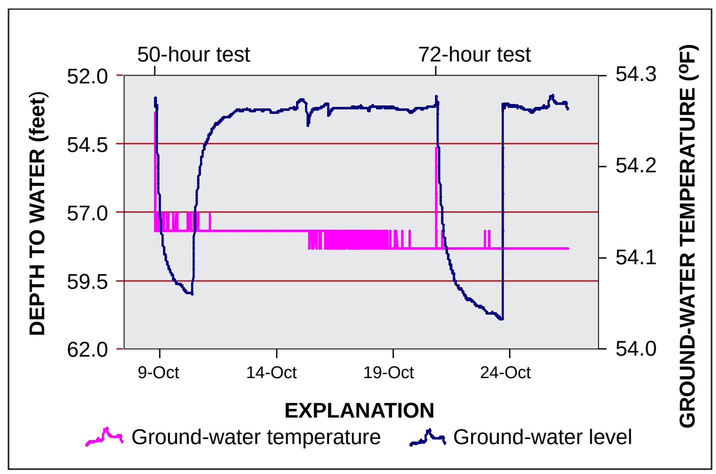

Figure 7. Hydrograph of OW-2 during aquifer tests.

NJGS research indicates that ground-water temperature data collected during aquifer testing in fractured-rock is useful for interpreting fracture interconnections. A change in ground-water temperature may be indicative of the presence of hydrologically-separate flow zones. Conversely, a lack of temperature change may indicate thorough mixing of ground-water over the tapped interval, or occur when a well is open to only one aquifer flow zone. Tests in fractured dolomite indicate that the hydrogeologic framework may vary greatly over a test area. This may be an important consideration in assessing travel times for contaminant plume migration or identifying areas where impacts from a new supply well may occur. It should be noted that this method may only be useful when seasonal conditions allow for a significant temperature contrast between water at different depths within the aquifer. Preliminary analysis of tests in fractured shale in Hopewell Township, Mercer County, and Milford Borough, Hunterdon County, suggest that temperature-trend analysis may be useful in this rock as well. As with any data set, temperature trends should be interpreted within the context of the hydrogeologic setting. However, in the absence of more technologically advanced methods, ground-water temperature trends during aquifer tests can provide for a useful (and inexpensive) preliminary assessment of fracture interconnections. This information can help form the basis for the design and implementation of more detailed hydrogeologic studies.

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CANALS AND WATER-POWER RACEWAYS OF NEW JERSEY

By Ted Pallis and Jeff Hoffman

INTRODUCTION

Canals and water-power raceways have played an important part in the history and economic development of New Jersey. Much of the early settlement and industrial activity focused around areas of water transportation and water power. Many of these canals and raceways have been lost and forgotten. Others have been filled and covered. Some are still in use, either for their original intent or for recreational purposes.

In the nineteenth century, water was considered a mineral resource and for this reason was included in the early work of the New Jersey Geological Survey (NJGS). Cornelius Carkson Vermeule conducted a thorough survey of the water-power potential of New Jersey. This was published in 1894 as Volume III of the Final Report of the State Geologist, *Report on Water Supply, Water Power, the Flows of Streams and Attendant Phenomena*. Vermeule's report included descriptions of the major canals, lists of water-powered mills, and estimates of the available horsepower at potential hydro-power sites in the State. It is now available at the NJGS website.

The New Jersey Geological Survey has just finished researching and mapping the current and historic canals and water-power raceways of the State (fig. 1). This mapping effort included historic canals and raceways of which no trace remains but can be located on historical maps or photographs. Their locations are available as a GIS shapefile

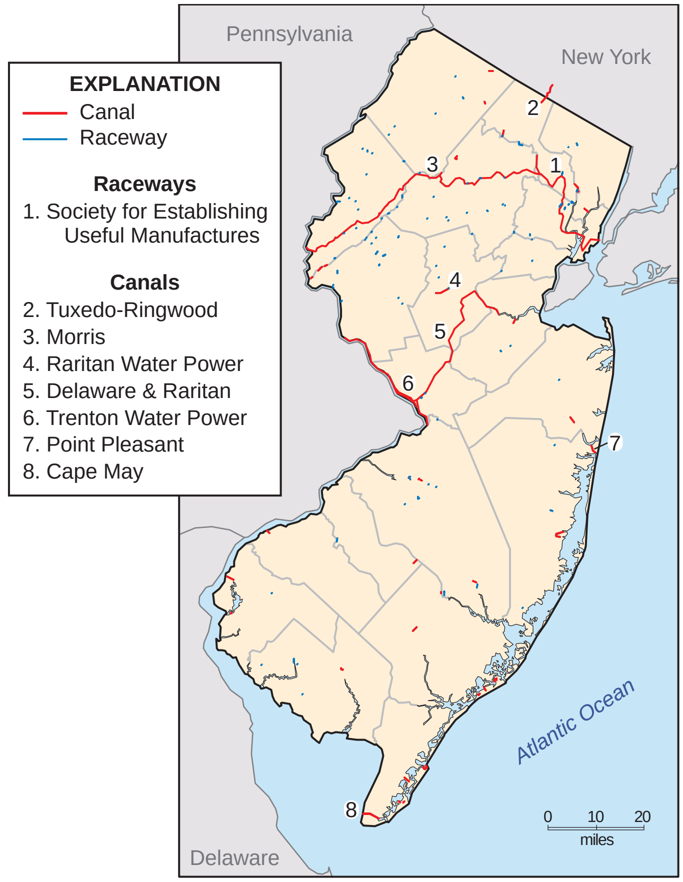


Figure 1. Canals and water-powered raceways in New Jersey.

that can be downloaded from the NJGS website. Some raceways which were mentioned in texts but not located on a map or were less than 100 feet in length were excluded.

In general, a water canal either provides transportation or delivers water for other uses over a long distance. A water raceway is a shorter feature that provides the water power to run a mill. Some canals were built for the purpose of delivering water to raceways.

CANALS

Canals in New Jersey transported goods, and powered industries before steam, rail and electricity replaced them, and provided water supply and drainage.

The first major canal known to have been constructed was the Tuxedo-Ringwood Canal in Passaic County and Orange County, New York. It was built in the 1760's to move timber from the Tuxedo Lake area to iron forges near the Ringwood Creek in New Jersey (Lenik, 1965).

Two major canals cross the entire State of New Jersey: the Delaware & Raritan (D&R) and Morris Canals. The D&R was built between 1830 and 1834 by engineer Canvass White, a leading canal engineer of the time. It consists of a 44-mile main canal between Bordentown and New Brunswick, and 22-mile feeder canal extending north along the Delaware River from Trenton to Raven Rock in Delaware Township, Hunterdon County. The canal shortened the water passage from Philadelphia to New York City by 200 miles and eliminated the necessity of venturing into the open sea.

D & R Canal use peaked in 1859 at 1,699,101 tons of material, most of which was anthracite coal bound for New

York City. The canal system could not successfully compete with railroads, however, and slowly declined in importance during the late 1800's. Its last year of service was 1932. After the canal closed, the State took charge and converted it to a water-supply system, a use it serves to this day. (D & R Canal Commission).

The Morris Canal, built between 1824 and 1831, was the longest canal in the state. At 102 miles long, it connected Jersey City on the Hudson River in the east to Phillipsburg on the Delaware River in the west. The highest point was just over 900 feet near Lake Hopatcong. The canal was unusual in that it included 23 inclined planes or dry portions where canal boats were raised and lowered over mountains using a pulley system (fig. 2).

Figure 2. Morris Canal inclined plane 2 east, Morris Canal Park, Roxbury Township, Morris County. *Photo by T. Pallis, 2008*

The Morris Canal provided a convenient means of transporting coal from the mines of northeastern Pennsylvania to the furnaces of New York City. But, like the Delaware and Raritan Canal, it had only begun profitable operation when it ran into competition from railroads. Use declined throughout the end of the 1800's. It went out of business by 1900, and was formally abandoned in 1924.

Many areas of the Morris Canal have been filled in but some portions are preserved. At Hugh Force Park, a Morris County Park in Wharton Borough, Morris County, a mile-long section of the canal is one of the best preserved sections (fig. 3). Waterloo Village in Byram Township, Sussex County, contains another beautifully preserved section of the Morris Canal (fig. 4). Some open-space planners in northern New Jersey envision turning the entire length of the Morris Canal into a public greenway.

There are still a number of transportation canals operating in New Jersey. On the Atlantic coast, the Point Pleasant Canal marks the northern end of Intracoastal Waterway while the Cape May Canal provides passage across the Cape May peninsula. There is also a series of small navigational canals on New Jersey's southern Atlantic coast that provide access to the back bays.

WATER-POWER RACEWAYS

Raceways provide hydropower to mills. They must be located close to a stream with enough drop in elevation to supply sufficient energy. Sometimes a dam on the stream was built to create a pond that increased the elevation drop

Figure 3, *top*. Morris Canal and towpath, Hugh Force Park, Wharton Borough, Morris County. Figure 4, *bottom.* Morris Canal, lock 3 west, Waterloo Village, Byram Township, Sussex County. *Photos by T. Pallis, 2008*

and also stored water to power the mill during dry periods. A raceway usually consisted of two parts, the head race (from the stream or pond to the water wheel) and a tail race (from the water wheel back to the stream). The height from which the water would fall when it reached the mill is called the head and determines the amount of water power. A shaft attached to the water wheel transmitted the power to the mill.

Mills were important economic centers. Vermeule (1894) states that the towns of Paterson, Trenton, Passaic, Bridgeton, Millville, Lambertville and Boonton owe their being and industrial importance directly to water power. Other cities and towns that had multiple mills on water power canals and raceway systems were Belvidere, Raritan, Passaic and Frenchtown.

Many mills were located on a raceway that powered just one or two mills. But in some areas larger canal and raceway systems were created to power extensive industrial areas. Three manufacturing centers located on impressive water power canals were Paterson, Trenton and Raritan.

The system at Paterson was the first major control of water power in the United States (fig. 5). The drop of the Passaic River over the Great Falls provides the necessary change in elevation. The Society for Establishing Useful Manufactures was incorporated in 1791 to promote industry in Paterson (A.S.C.E., 1977). The project was conceived by Alexander Hamilton (first U.S. Secretary of the Treasury) and initially designed by Pierre Charles L'Enfant (architect of the District of Columbia). The first raceway was built in 1794

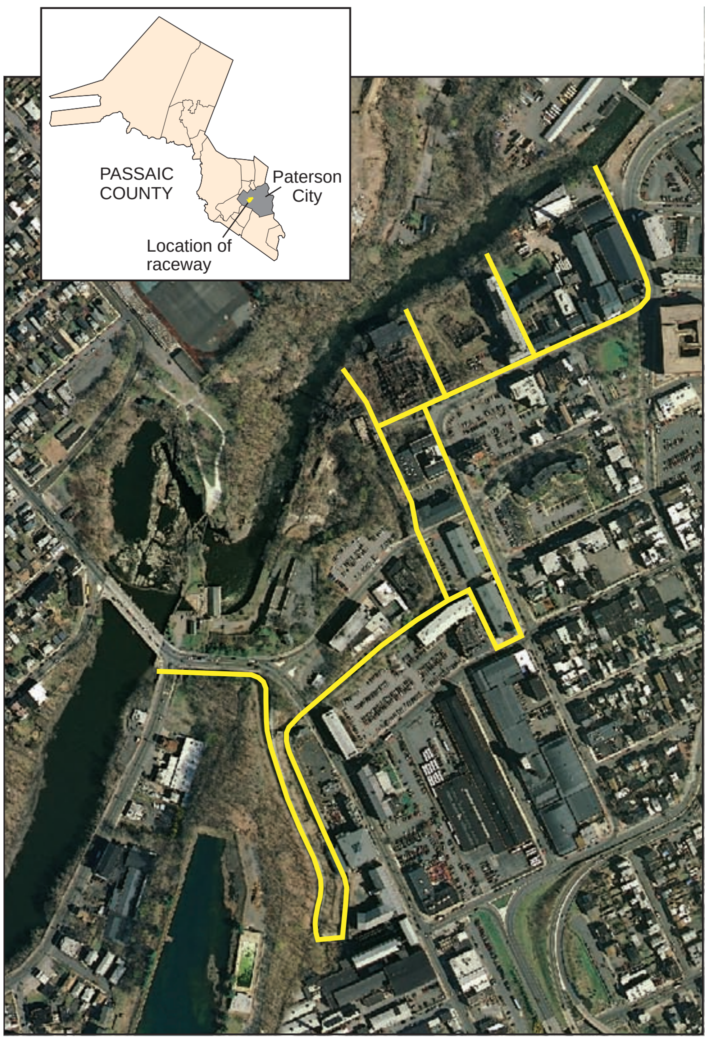


Figure 5. Approximate location of Society for Establishing Useful Manufactures raceways system (in yellow) along the Passaic River, Paterson City, Passaic County. *New Jersey 2007 orthophotography*

and more were built over time to provide additional power. They continued operation into the early 20th century when an electrical hydropower generator was built on the falls, and operated until 1969. Parts of the raceways have been filled in but some of the mills remain as part of a National Historic District (A.S.C.E., 1977).

At Trenton, a series of small falls on the Delaware River mark the upstream limit to navigation. The Trenton Water Power company built a seven-mile canal in the early 1830's on the bank of the Delaware River to take advantage of this elevation drop (fig. 6) (Hunter, 2005). The canal spurred industrial development along the waterfront in Trenton through the mid- and late-1800's. But by the early 1900's the industries had been retooled with steam and electric power.

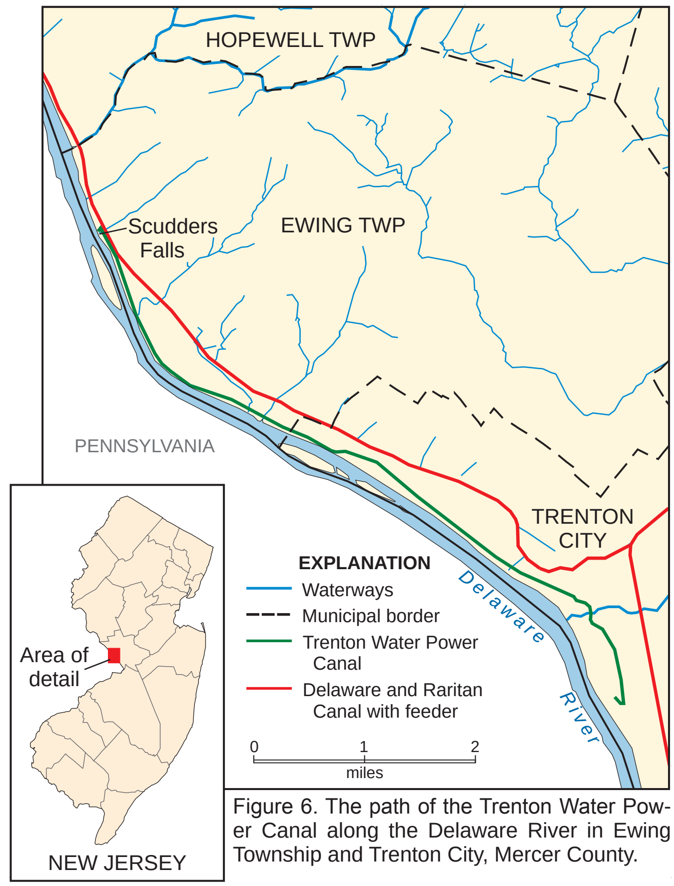


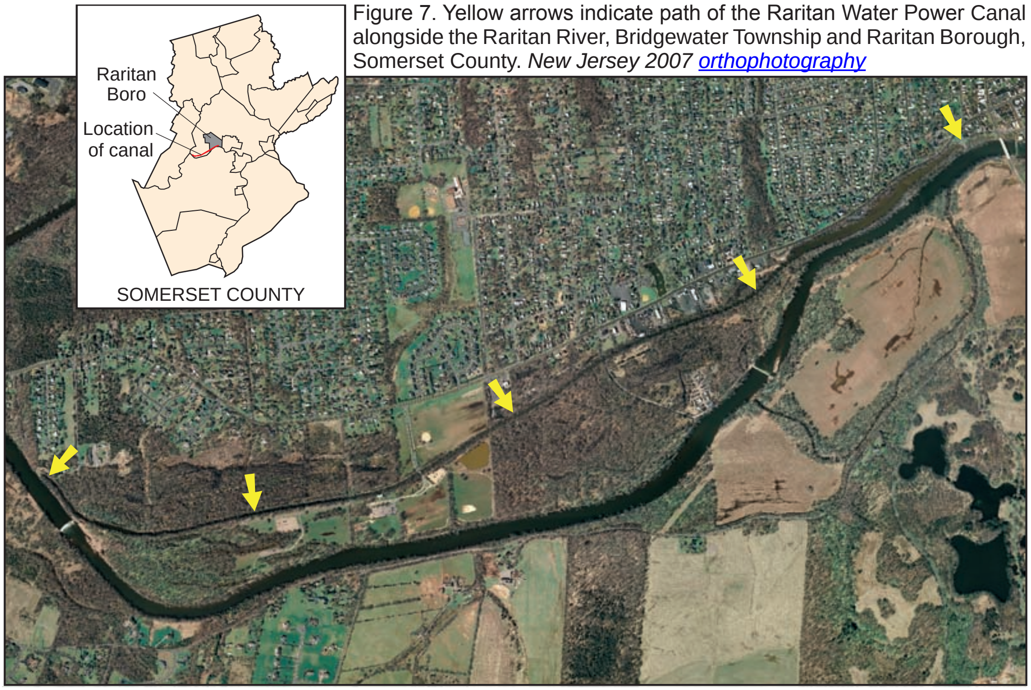
Figure 6. The path of the Trenton Water Power Canal along the Delaware River in Ewing Township and Trenton City, Mercer County.

The canal was filled in and the mills along its course have long since been demolished. Remains of the wing dam and intake are visible in the Delaware River at Scudders Falls.

The Raritan Water Power Canal, constructed during the early 1840's, is a three-mile raceway system used by various water-powered industries in Raritan, Somerset County, throughout the 19th century. Most of this canal still exists, though it is no longer used for water power (fig. 7).

When Vermeule's report was published in 1894, there were 903 water-powered mills in the State. These included grist, cotton, flouring, saw, rubber, iron-work, textile, and electric-generating mills. In the years following his report, water-power use declined as electricity from new sources proved to be more reliable. In 1914, only twenty years later, just 127 water-powered mills and six water-powered motors continued operating in New Jersey (NJ Department of Labor, 1915). Some mills were reborn as museums, such as the Red Mill Museum in Clinton Town, Hunterdon County (fig. 8) and the Cooper Mill Museum in Chester Township, Morris County (fig. 9). Surprisingly, there is consideration of retrofitting a few of the raceways at some old mill sites with a new generation of more efficient water powered electric

Figure 7. Yellow arrows indicate path of the Raritan Water Power Canal alongside the Raritan River, Bridgewater Township and Raritan Borough, Somerset County. *New Jersey 2007 orthophotography*



generating equipment to produce clean renewable energy.

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Figure 8. Red Mill Museum, Clinton Town, Hunterdon County. *Photo by T. Pallis, 1993*

Figure 9. Cooper Mill Museum, Chester Township, Morris County. *Photo by T. Pallis, 1987*

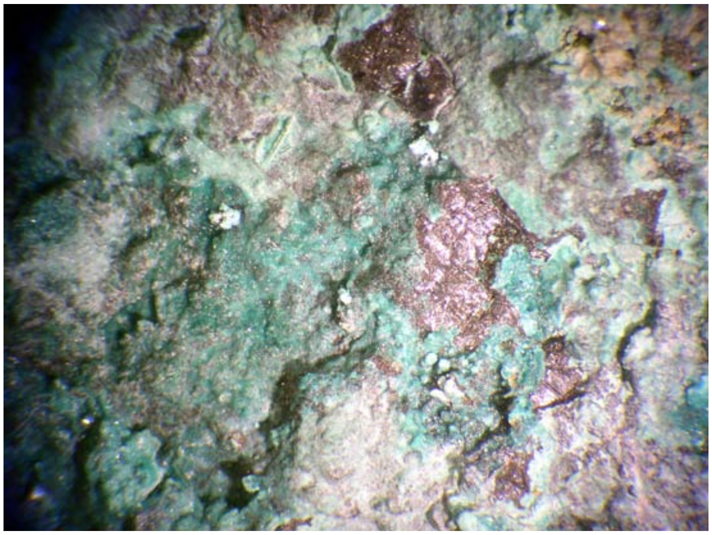
Cu

COPPER IN NEW JERSEY

By F. Larry Müller

When humans emerged from the Stone Age, one of the first metals they refined was copper. In Western culture ancient mines were discovered in Britain, Europe, Africa and the Middle East. Many in Britain, for example, were extensive. It is little wonder that one of the first metals sought in the New World was copper. First prospectors in New Jersey found copper at contacts between igneous flows and sills and red beds and sandstones of the upper Delaware River area. A few of the mines Colonials developed were in Pahaquarry, North Arlington, Flemington, Somerville, New Brunswick, and Griggstown.

The minerals which they found ranged from the elemental copper (native copper) to copper sulfides, copper carbonates and others. These minerals, dispersed in the rock and in fissures and pods, constituted the ore that was



Chalcocite and malachite from the Schuyler Mine, North Arlington Borough, Bergen County. *Photo by J.H. Dooley*

originally shipped back to Europe for smelting, but later was done in the colonies. This first brief article will address the copper minerals found in these early mines. A subsequent article will focus on the history of copper mining throughout the state.

Native copper is found in its elemental state. It is soft (hardness of 2.5-3.0 on Mohs' Hardness Scale), ductile, and an excellent conductor of electricity. It is red-brown with occasional halos of blue-green, black or red which are the oxide, carbonate or silicate phases. Some samples are crystalline and/or occur as dendrites in the host rock. It is thought (Woodward, 1944) to be a hypogene mineral--formed by ascending fluids coming from the original emplacement of magma of the sills and flows. The native copper in New Jersey is known to have small amounts of gold and silver with it. The indigenous peoples of New Jersey are known to have had tools and ornaments of native copper. But the native copper artifacts tested came from the west or were trade items (Kraft, 1996). Native copper was a common ore mineral, but the most important ore mineral in New Jersey was chalcocite.

Chalcocite is a sulfide of copper with an empirical chemical formula of Cu_2S. It, like native copper, is a hypogene mineral (Woodward, 1944), and was the primary ore mineral in most New Jersey mines, especially at Griggstown, Schuyler, and Pahaquarry. Chalcocite is a lead-gray to black mineral with a metallic luster. It leaves a dark gray to black shiny streak when scratched across a piece of unglazed tile known as a streak plate. It is relatively soft (2.5-3.0 on Mohs' Scale) and is found in sandstones, in the fissures and cracks, pods or other gaps in the host rock. Chalcocite is non-brittle and fractures in a shell-like, conchoidal form.

Another sulfide of copper, bornite, Cu_3FeS_3, was never common in the New Jersey mines although it is present at Griggstown, American, and Raritan mines. It may have been deposited originally as a hypogene mineral from hot waters (Woodward, 1944). Because it oxidizes to an iridescent blue it is often referred to as "peacock ore." On a fresh break it is a "reddish silver gray with a violet cast" (Hochleitner, 1994). Its streak is dark gray on unglazed tile. Its hardness is 3.0. Bornite is not brittle and it has a conchoidal fracture.

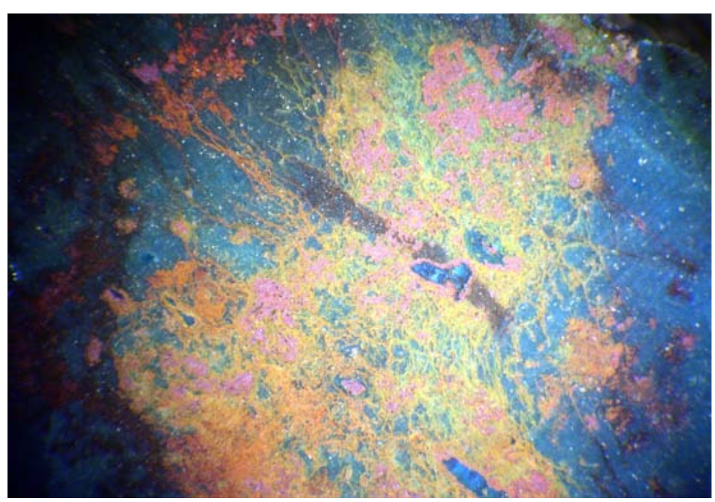
A third sulfide of copper present at New Jersey mine sites was chalcopyrite, $CuFeS_2$. Although on a world wide scale it is a chief copper ore, it was never that important in New Jersey. The mineral is yellow, brassy in color and somewhat greenish in its metallic luster; its streak is black. With a hardness of 3.0-4.0 on Mohs' Scale, it is brittle with a uneven fracture. The mineral is generally found in igneous rock, sandstones, and shales but never in a quantity to be economically important. Chalcopyrite is thought to be of hypogenic origin here coming from rising magmatic solutions. Most of the original mineral was destroyed by the descending waters (Woodward, 1944).

Covellite, another copper sulfide, has a chemical formula of CuS but was not economically important in New Jersey. One theory has covellite forming after chalcocite while another contends that it formed at the same time. Although rare it is known to occur with chalcocite at Arlington (Woodward, 1944). This mineral is deep blue, soft (1.5 to 2.0 on Mohs' Scale), has a blue-black streak, metallic luster, and lamellar fractures. It usually occurs as coatings, that is, on other sulfides (Hochleitner, 1994; Bonewitz, 2008).

Another copper mineral, $Cu_4(SO_4)(OH)_6$, brochantite, a sulfate, is found at Arlington (Woodward citing Manchester, 1944) with selenite lining small openings. Green with a green to light green streak, it has a vitreous luster, a hardness of 3.5-4.0 on Mohs' Scale and it is likely that it is more common than reported as it can be confused with malachite, a copper carbonate.

Two oxides of copper, cuprite, (Cu_2O), and tenorite, (CuO), occur in the New Jersey deposits. Neither is common, tenorite being the rarer. Cuprite is red to reddish brown, and tenorite is black to gray. Both minerals have similar hardness 3.0 for tenorite and 3.5-4.0 for cuprite. Both are supergene minerals--formed by the alteration of hypogene minerals by descending water. Cuprite is reported from many of the mines, but tenorite only from Griggstown and Stony Brook. Neither have been important ore minerals in New Jersey.

Prospectors for copper often look for a show of blue or green colors. These colors are particularly intense on fresh surfaces of copper carbonate and copper silicate. Malachite,



Native copper, azurite, and malachite found at the contact of the Passaic Formation with the Orange Mountain Basalt, Bridgewater Township, Somerset County. *Photo by J.H. Dooley*

$Cu_2(CO_3)(OH)_2$, and azurite, $Cu_3(CO_3)_2(OH)_2$, are copper carbonates, and chrysocolla, $Cu_2H_2[Si_2O_5](OH)_4$, is a copper silicate. All are very common in New Jersey. Early miners hoped that shows of these colors would point to a "great mother load" of copper. They were more often than not disappointed. Malachite is green with a green streak and azurite is blue with a blue streak. Both have similar hardness--azurite 3.5 to 4.0 and malachite 4.0. Both have a vitreous luster. Chrysocolla displays a range of blues and greens with a vitreous luster. It has a hardness of 2.0-4.0, is brittle with a conchoidal fracture, and usually occurs in masses. Some of these minerals have been cut and polished as decorative slabs and as cabochons.

Two other blue-green copper minerals have been found at Arlington: pseudomalachite, $Cu_5(PO_4)_2(OH)_4$, a phosphate, and conichalcite, $CaCu(AsO_4)(OH)$, an arsenate. Pseudomalachite occurs as reniform or fibrous crusts at Arlington. It is dark green to blackish green or bluish with a vitreous luster, green streak, and with a hardness of 4.5 on Mohs' Scale. It is brittle with a crystal habit which can be acular, tabular or radiating masses. Conichalcite is light green, vitreous, and has a hardness of 4.5. It forms as crusts, reniform or acular. Also like pseudomalachite, it occurs in the oxidation zone. Neither was important as an ore mineral.

All New Jersey copper mines are now closed, and collectors are no longer welcome at the old sites (even if they still exist). Do not trespass. One can, however, find old specimens at area mineral shows. If you are interested in the mines please refer to the publication on the NJGS web site.

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LET'S PLAY: GUESS THE MINERAL

Here it is:

$$(Mg,Fe,Al)_3\ (Al,Si)_4\ O_{10}\ (OH)_2{\cdot}4H_2O$$

If you think you know this mineral, send your answer to:
njgsweb@dep.state.nj.us

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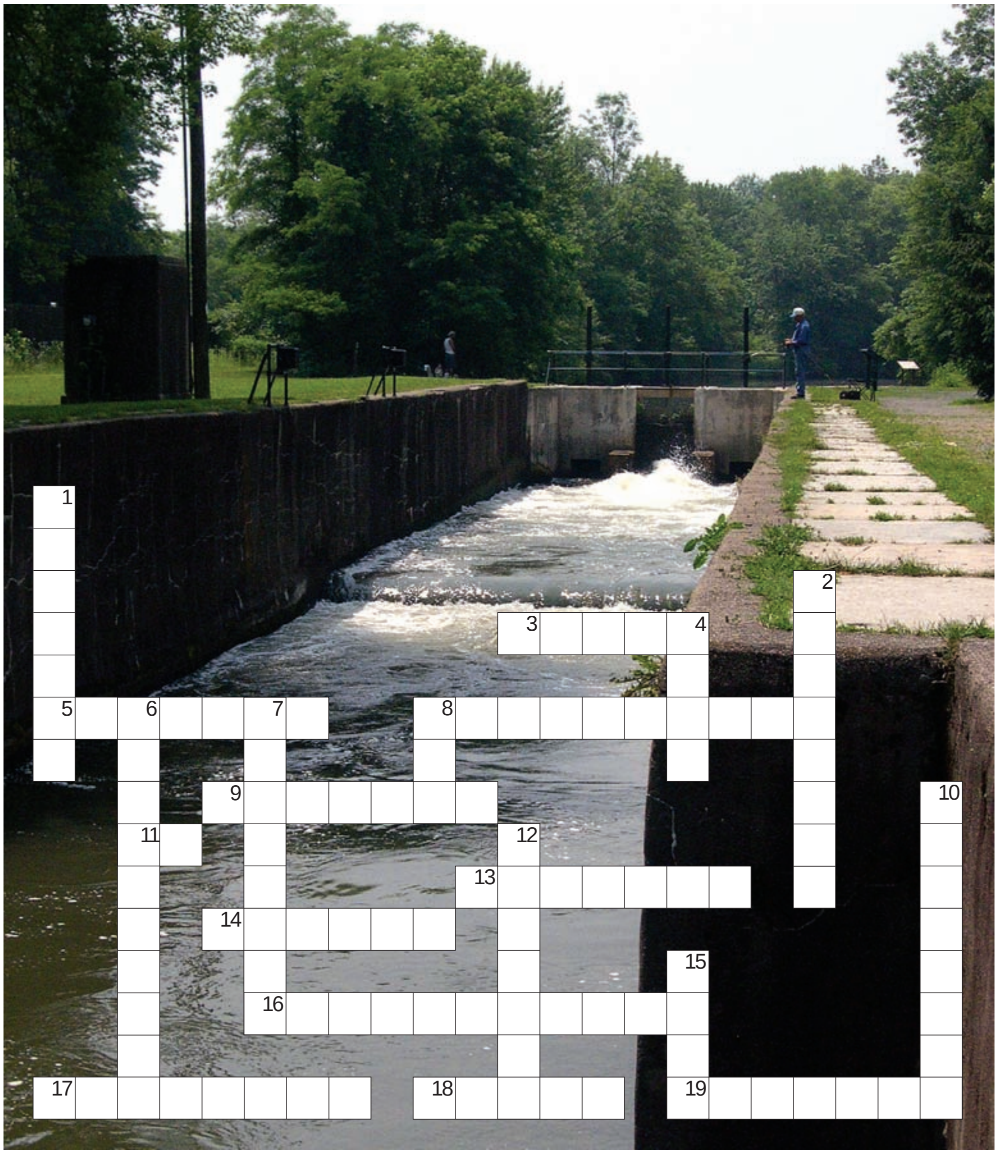
NEW MAP. OFM 74, Surficial Geology of the Bernardsville Quadrangle, Morris and Somerset Counties, New Jersey, Stanford, Scott D., 2008, scale 1 to 24,000, size 36x46, 4 cross-sections and a 13-page pamphlet. $10.00. Available for download.

DELAWARE & RARITAN CANAL SPILLWAY

Delaware and Raritan Canal spillway at Kingston, Franklin Township, Somerset County. Spillways were built into the bank of a canal to allow excess water to spill out into adjacent waterways. *Photo by Z. Allen-Lafayette, 2004*



Canal lock along Delaware and Raritan Canal, Kingston, Franklin Township, Somerset County. *Photo by Z. Allen-Lafayette, 2004*

CROSSWORD LOCKS

ACROSS

3. Artificial waterway for navigation
5. Passage or channel for water
8. To explore for mineral deposits
9. Molecule bearing sulfur
11. Copper
13. Cu_5FeS_4
14. Quantity of water available for use
16. Measure of heat and cold
17. Carbonate rock containing calcium and magnesium
18. Hardness scale for minerals
19. Flexible

DOWN

1. Crack or opening
2. Appearance of glass
4. Enclosure used for raising and lowering vessels
6. Smoothly curving fracture like the surface of a conch
7. Structure carrying a canal over a river or hollow
8. Gap in rock
10. Opening in rock through which ground-water may flow
12. Track along a canal used by draft animals
15. Water level based on elevation and pressure

Copper is one of the most useful metals. We mold it into cooking pans to prepare our meals, roofs to keep us dry, and wire to carry our electronic messages. Although our blood chemistry is based in iron, a small amount of copper is essential to human health. Since humans first discovered copper they have used it for tools, jewelry, and as a base metal in brass, bronze and other alloys. Here in New Jersey, it was one of the first metals mined by the colonials.

By F. Larry Müller
Banner photographs by J.H. Dooley

FACTOID ZONE

Q. Who is the only author of a New Jersey Geological Survey publication to win the Nobel Prize?

A. Selman A. Waksman, author of *The Peats of New Jersey and Their Utilization* (Bulletin 55, 1943). Waksman won the 1952 Nobel Prize in Physiology or Medicine for his development of the antibiotic streptomycin, which is active against tuberculosis.

Knowledge is an unending adventure at the edge of uncertainty.

--Jacob Bronowski, scientist--
(1908-1974)

CROSSWORD PUZZLE ANSWERS. ACROSS: (3) Canal, (5) raceway, (8) prospector, (9) sulfide, (11) Cu, (13) bornite, (14) supply, (16) temperature, (17) dolomite, (18) Mohs, (19) ductile. **DOWN**: (1) Fissure, (2) vitreous, (4) lock, (6) conchoidal, (7) aqueduct, (8) pod, (10) fracture, (12) towpath, (15) head.