Geology in Service to Public Health

Field Guide and Proceedings

Edited by
Pierre Lacombe
U.S. Geological Survey
and
Gregory Herman
N.J. Geological Survey

Eighteenth Annual Meeting
of the
Geological Association of New Jersey
in cooperation with the
New Jersey Section of the American Water Resources Association

October 26-27, 2001
Courtyard Marriott
Exit 8A--NJ Turnpike
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Courtyard Marriott, South Brunswick
New Jersey
2001

Geology in Service to Public Health
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Preface

Most geologic investigations in New Jersey today are for the cleanup of hazardous materials in ground water, and for the siting of new wells for water supply. Study areas for these investigations are usually small, typically less than 1/2 acre at leaking under storage tank sites to 200 or so acres at the largest landfills, industrial sites and public-supply well sites. Usually there are no outcrops. At best, investigations can be thought of as blind geology (or blind hydrogeology). Even for the smallest sites, a formidable effort is required at the outset of investigation to develop enough understanding of the hydrogeologic framework to optimize cleanup efforts or water yield. For non-point contamination, initial investigation commonly involves a similarly formidable task of researching and synthesizing masses of analytical work done for disparate purposes using a wide range of procedures and quality standards. Hydrogeologic investigations at hazardous waste sites, water supply well fields, and non-point source ground water contamination sites focus on public health and welfare, rather than geology. The results of the investigations commonly have substantial economic and planning implications.

Recognizing the importance of applied geology and hydrogeology in New Jersey and the non-geologic considerations common to much geologic work, GANJ in cooperation with the New Jersey Section of the American Water Resources Association (NJ /AWRA) is holding this joint 2001 meeting to bring together New Jersey geologists and water resource managers.

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Greg Herman, GANJ

HYDROGEOLOGICAL FRAMEWORK OF BEDROCK AQUIFERS IN THE NEWARK BASIN, NEW JERSEY

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ABSTRACT

Bedrock aquifers of the Newark Basin underlie the most densely populated part of New Jersey and provide critical ground-water resources for commercial, industrial, and domestic uses. Protecting the integrity of these aquifers from ground-water pollution and depletion from over-pumping requires understanding their hydrogeological properties. This paper summarizes hydrogeological research conducted on sedimentary bedrock aquifers in the central part of the Newark Basin in New Jersey. The Brunswick aquifer is redefined based on a systematic analysis and description of the physical characteristics of the rocks comprising the aquifer and the mechanisms controlling the occurrence and movement of ground water within them. Previous sedimentological, structural, geochemical, and geophysical observations in the scientific literature are combined with new data to explain some of the physical relationships observed between the geological framework and ground water hydrology. New visualization tools developed for use with Geographic Information Systems (GIS) are used to illustrate characteristics of the aquifer at different sites.

INTRODUCTION

New Jersey is blessed with diverse geology that complicates our ability to understand the hydrology of each aquifer system. Environmental-protection efforts focused on the availability and quality of ground water often require estimates of the volume, velocity, and direction of ground water moving through geological materials. These parameters are available for aquifers and confining units of the New Jersey Coastal Plain province where bedrock sand, silt, and clay layers are structurally uncomplicated, relatively homogenous and isotropic. However, the northern half of the State is underlain by bedrock that has been folded, faulted, and fractured during multiple tectonic events spanning hundreds of millions of years. Ground-water flow in these aquifers typically shows directional unevenness or anisotropic behavior because primary sedimentary, metamorphic, and igneous features and secondary geological structures impart local heterogeneity to the aquifer framework. Our understanding of how groundwater is stored and travels in these fractured-bedrock aquifers is often limited by our ability to define complex spatial variations occurring in the aquifer framework. It is necessary to understand the morphology and geometry of primary and secondary bedrock structures in order to understand how they interconnect to store and channel groundwater.

This paper summarizes recent advances stemming from hydrogeological research conducted in the Newark Basin with a focus on Triassic mudstone and siltstone of the

Brunswick aquifer. It attempts to address how geology controls the observed hydrologic response of the aquifer. The focus of the study is in the west-central part of basin where red mudstone and siltstone of the Passaic Formation underlie a significant part of the province and composes a large part of the Brunswick aquifer (Fig.1). The topic is developed by first reviewing the geological setting and tectonic framework of the basin. This provides the basis for further examining the local hydrogeologic framework from both a sedimentalogical and structural viewpoint. The aquifer hydrogeology is then further defined using rock core and geophysical logs from well fields. Together, these data provide the basis for portraying some two- and three-dimensional hydrogeological aspects of the Brunswick aquifer.

GEOLOGICAL SETTING

The Newark basin is a tectonic rift basin covering about 7500 km^2 extending from southern New York across New Jersey and into southeastern Pennsylvania (Fig. 1). The basin is filled with Triassic-Jurassic sedimentary and igneous rocks that are tilted, faulted, and locally folded (see summaries in Schlische, 1992; and Olsen and others, 1996). It is the largest, best-exposed, and most studied Mesozoic-aged basin in a series of such basins extending from Newfoundland, Canada, to the southeast U.S.A (Schlische, 1992). Most tectonic deformation occurred during the Late Triassic to Middle Jurassic (Lucas and others, 1988; de Boer and Clifford, 1988). Multiple tectonic phases are thought to have affected the basin based on stratigraphic, paleomagnetic, and radiometric data. As summarized by Schlische (1992), the Newark basin probably evolved from a series of smaller, isolated sub-basins occurring along several normal fault segments early in the Late Triassic. As continental extension continued the basin grew in width and length and the sub-basins merged to form the Newark basin. Late Triassic sediments record a transition from braided and meandering stream deposits (Stockton Formation) into lake-bed and associated mudflat deposits (Lockatong and Passaic Formations). The variation in thickness of Triassic sediment in the basin reflects syndepositional fault activity and along-strike variation in displacements along both intra-basin and basin-bounding fault systems. Tectonism probably intensified during the latest Triassic into the earliest Jurassic based on widespread igneous activity (tholeiitic basalt and diabase) and a marked increase in sediment-accumulation rates. Tectonic deformation and synchronous sedimentation continued into the Middle Jurassic at which time extensional faulting and associated tilting and folding ceased. At this stage, the basin likely experienced a period of post-rift contractional uplift (basin inversion) and erosion similar to other Mesozoic rift basins (de Boer and Clifford, 1988; Withjack and others, 1995; Olsen and others, 1992). Coastal plain sediment deposited on underlying Mesozoic rocks resulted in flexural loading of the passive, continental margin during the Late Mesozoic through Early Cenozoic (Owens and Sohl, 1969; Owens and others, 1998). Late Cenozoic glacial and fluvial deposits and erosional landforms occur in the Newark Basin as buried valleys, till plains, upland surfaces, and fluvial terraces and scarps (Stanford, 2000; Stanford and others, 2001).

Three primary rock-stratigraphic units occur in the basin. They include in ascending order, the Stockton, Lockatong, and Passaic Formations (Fig. 2). The Stockton Formation unconfomably overlies Proterozoic and Paleozoic basement rocks. It contains

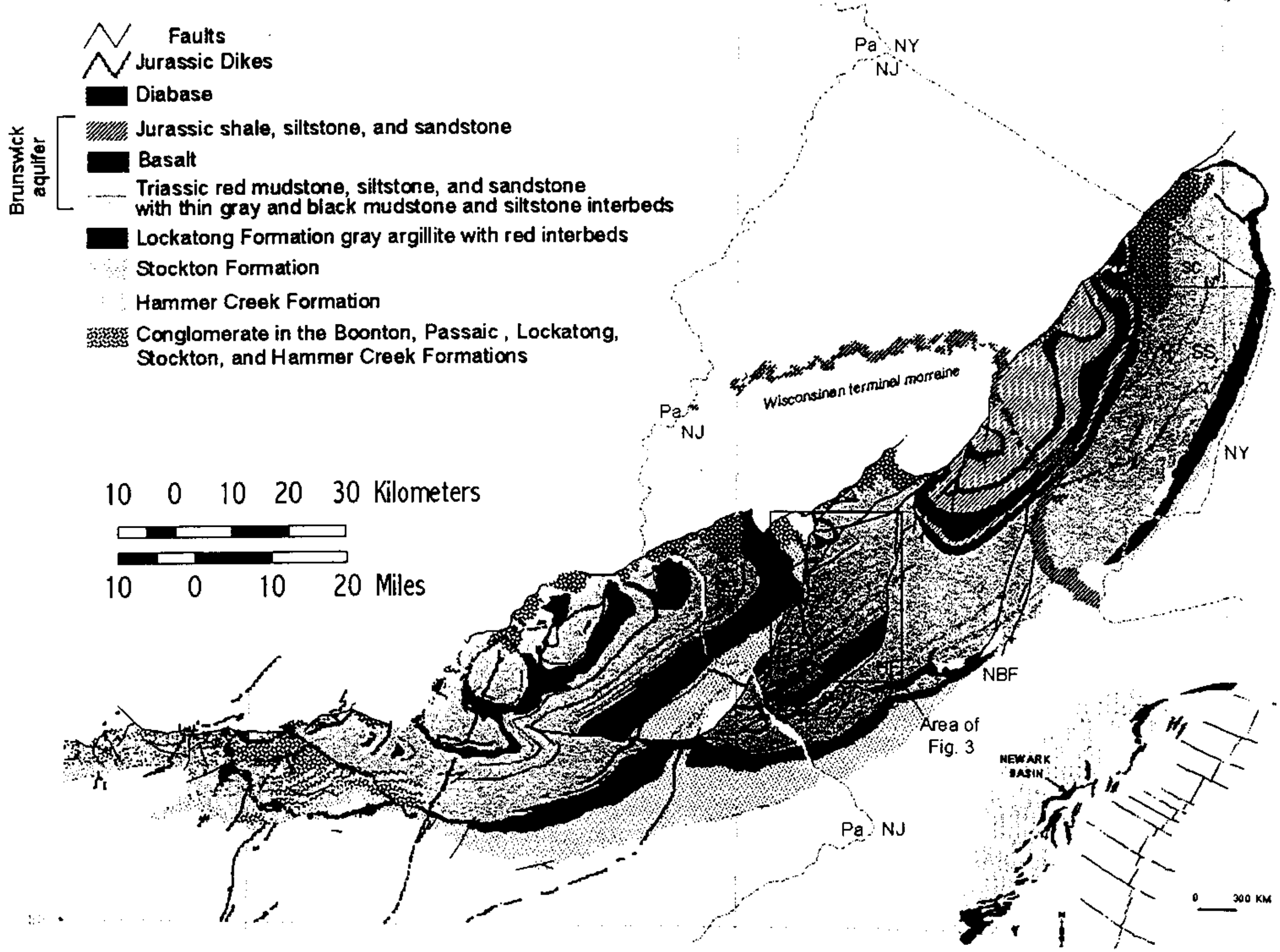


Figure 1. Generalized bedrock geology map of the Newark Basin with location of faults, Jurassic dikes, and sedimentary facies correlated to aquifer zones. Map compiled from geographic information system coverages for New Jersey (1:100,000 scale, N.J. Geological Survey, 2000), New York (1:250,000 scale, www.nysm.nysed.gov/data/lhud_bedr1a.zip) and Pennsylvania (1:250,000 scale, Pennsylvania Geological Survey written communication, February 2000). SC – sandstone and conglomerate facies, SS – sandstone and siltstone facies, NBF – New Brunswick fault system, HF – Hopewell fault system, FF – Flemington-fault system. Index map of Mesozoic basins on the East Coast adapted from Schlische (1993).

basal conglomerates that gradually fine upward into sandstone with progressively thicker mudstone interbeds. The Lockatong Formation is largely composed of black and gray mudstone and siltstone, with red units becoming progressively more abundant upwards in the sequence. The Passaic Formation has lesser amounts of gray and black mudstone and siltstone, and a greater abundance of red mudstone, siltstone, grading into fluvial sandstone and conglomerate along the southwest and northeast lateral margins of the basin. A sequence of interlayered tholeiitic basalt and clastic sedimentary rocks overlies the Passaic Formation. This includes in ascending order, the Orange Mt. Basalt, **Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mt. Basalt, and Boonton Formation. The sedimentary rocks are fluvial-deltaic sandstone, siltstone, and lacustrine mudstone. All sedimentary formations in the basin grade into alluvial fan conglomerate to the northwest along the border fault system (Fig. 1). Each basalt formation is composed of several basalt flows (Tollo and Gottfried, 1992) that are fed by diabase sheets and dikes that intrude and thermally metamorphose older sedimentary deposits in the basin.

Two dominant structural trends occur in the central part of the Newark Basin (Herman, 1997). The first is subparallel with the basin's northwest, faulted margin and the second is subparallel with the trend of the intra-basin faults and diabase dike swarms (Fig. 1). The three major intra-basin fault systems, the Flemington, Hopewell, and New Brunswick, are complex arrangements of isolated, interconnecting- and spay-fault segments (Schlische, 1992; Houghton and others, 1992; Drake and others, 1996). Gently plunging bedding folds trending normal to fault strike occur at varying scales along these fault systems, and reflect variations in dip slip movements along the length of individual and coalesced fault segments (Schlische, 1992).

HYDROGEOLOGIC UNITS

Herman and others (1999) divided Triassic-Jurassic bedrock in the Newark Basin part of the Piedmont physiographic province of New Jersey into five primary aquifers including the Stockton Formation, Lockatong Formation, the Brunswick aquifer, basalt, and diabase. However, these are informal aquifer designations lacking the defined hydrogeological framework suggested by the U.S. Geological Survey guidelines for naming aquifers (Hansen, 1991). Since then, LaCombe (2000) introduced the Stockton and Lockatong aquifers from mapping detailed hydrogeological units underlying the Naval Air Warfare Center in West Trenton, New Jersey. The Brunswick aquifer is formally defined here with a detailed description of its hydrogeologic framework.

Numerous geologic, mineral resource, and ground water studies conducted in the Newark Basin over the past century have resulted in a variety of rock-stratigraphic and hydrogeologic unit designations for the Late Triassic and Early Jurassic clastic sedimentary rocks overlying weakly metamorphosed argillites of the Lockatong Formation. Most reports published during the latter part of the 20th century relied on some form of the 'Brunswick' prefix, stemming from Kummel's (1898) report on the Newark System of New Jersey. In this report, Kummel variously refers to the series of shale, sandstone, and conglomerate beds overlying of the

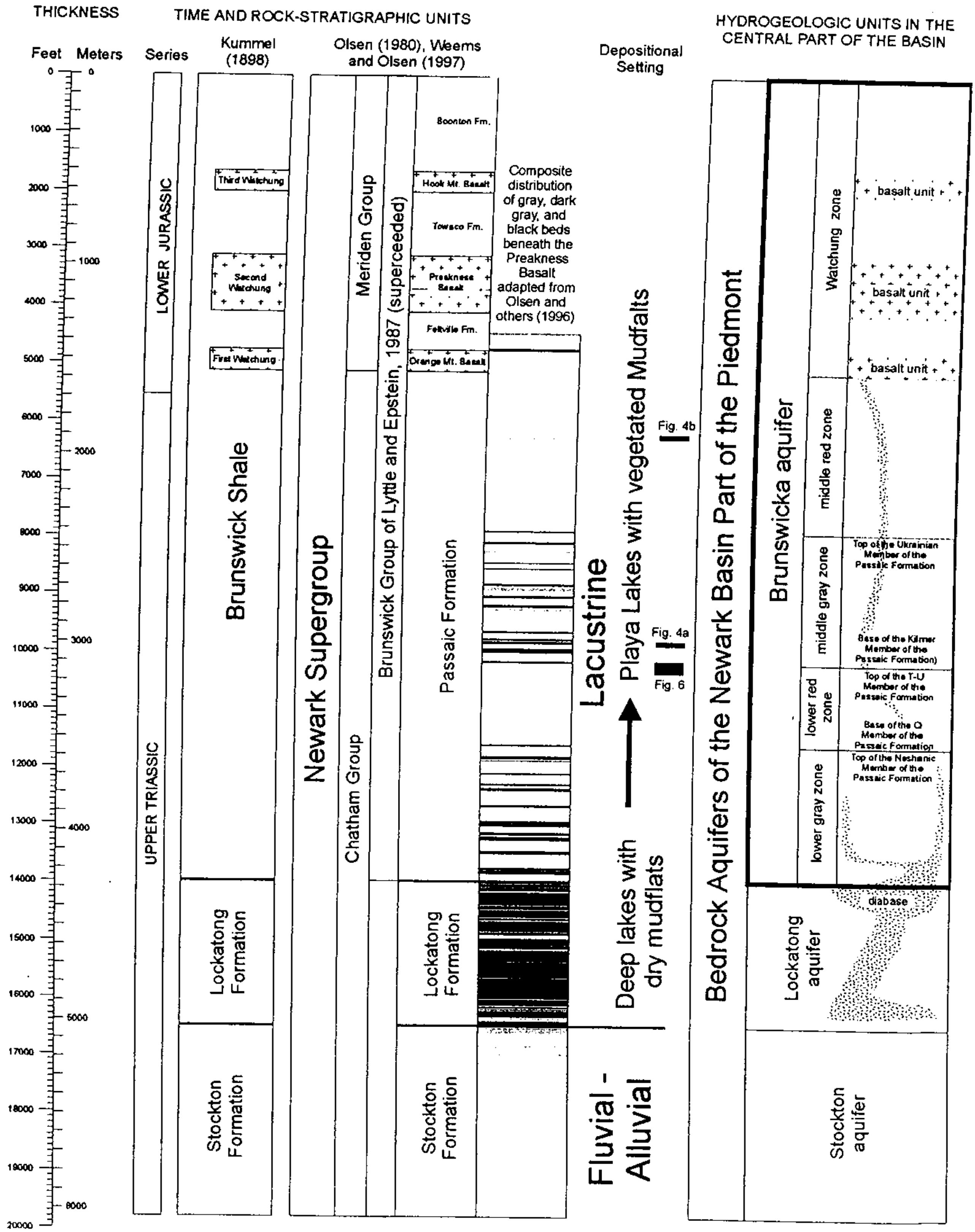


Figure 2 Correlation of time, rock-stratigraphic, and hydrostratigraphic units in the Newark Basin, New Jersey. Location of stratigraphic details shown in Figs. 4 and 6 indicated next to the left of the hydrogeological-units column.

Lockatong series as the 'Brunswick beds', 'Brunswick shales', and 'Brunswick series'. Subsequent usage includes the Brunswick Formation (Bascom and others, 1931; Herpers and Barksdale, 1951) and the Brunswick Shale (Vecchioli and Palmer, 1962;Vecchioli, 1965; 1967, and Vecchioli and others; 1969). Olsen (1980) redefined the Newark System as the Newark Supergroup, reassigning rocks of the former Brunswick series into the Passaic, Feltville, Towaco, and Boonton Formations (Fig. 2). Lyttle and Epstein (1987) include all rock-stratigraphic units overlying the Lockatong Formation in the Brunswick Group on the Newark $1^{\circ} \times 2^{\circ}$ geologic map. This designation was also used on the 1 to 1:00,000 scale geological map of New Jersey (Drake and others, 1996; Owens and others, 1998). However, a formal revision of lithostratigraphic groups within the Newark Supergroup by Weems and Olsen (1997) supercedes the usage of 'Brunswick Group' and divides rocks of the Newark basin into three new groups based on a regional stratigraphic correlation (Fig. 2). Spayd (1985) introduced the term 'Brunswick aquifer' with inference to the Brunswick Formation. Herman and others (1999) included all sedimentary rock formations overlying the Lockatong Formation in the Brunswick aquifer. A standard nomenclature for the Brunswick aquifer is therefore needed to help reduce confusion arising from various usage of the 'Brunswick' prefix, and to set a standardized frame of reference for mapping aquifer zones and compiling hydraulic parameters in the study of ground-water resources.

The Brunswick aquifer is here defined as the hydro-stratigraphic equivalent of the rock-stratigraphic Brunswick Group as defined by Lyttle and Epstein (1987, Fig. 2). This departs from previous designations that exclude the Orange Mt. Basalt, Preakness Basalt, and Hook Mt. Basalt. The Brunswick is a regional aquifer that can be characterized on a local level. Water-bearing and confining units identified in local investigation lack the regional continuity to map the Brunswick as a regional aquifer system. The U.S. Geological Survey guidelines for naming aquifers addresses instances when a rock-stratigraphic sequence behaves hydraulically as a single aquifer and not an aquifer system, even though thin continuous "confining units" are part of the aquifer (Hansen, 1991). This approach is employed here in proposing a standardized nomenclature for the Brunswick aquifer.

Eight zones are proposed for the Brunswick aquifer to facilitate aquifer mapping and cataloguing of aquifer parameters for the New Jersey part of the basin. These include four zones in the central part of the basin underlain by fine-grained clastic rocks (Fig. 2), three zones in the northeast and northwest parts of the basin underlain by coarse-grained clastic rocks (Fig. 1), and a zone comprised of interlayered Jurassic basalt and clastic rocks (Figs. 2). The four zones in the central part of the basin include, in ascending order, a lower gray, lower red, middle gray, and middle red zones (Fig. 2). Strata in these zones show a pronounced cyclicity that facilitates aquifer subdivision (Olsen and others, 1996). The lower gray zone contains cycles of red, gray, and black mudstone and siltstone beds that correlate with the lowermost Passaic Formation from the contact with the Lockatong Formation to the top of the Neshanic Member. The lower red zone mostly contains red mudstone and siltstone that correlates to part of the Passaic Formation from the top of the Neshanic Member to the base of the Kilmer Member. The middle gray zone contains cycles of red, gray, and black mudstone and siltstone and correlates to part of the Passaic Formation from the base of the Kilmer Member to the top of the Ukrainian Member. This sequence forms a distinct set of bed-strike parallel topographic ridges resulting from differential erosion of the red, gray, and black beds (Fig. 3). The middle red unit is mostly composed of red mudstone and micaceous siltstone, with minor gray beds. It correlates with the upper part of the Passaic Formation from the top of the Ukrainian Member to the base of the Orange Mt. Basalt. The igneous and sedimentary rocks overlying the Passaic Formation are included in the Watchung zone. This zone is mostly restricted to the area near the Watchung Mountains but also crops out as small outliers along the Flemington fault system (Houghton and others, 1992). Basalt in the Watchung zone can serve either as local water-bearing units for domestic water supplies, or as confining units for adjacent mudstone and siltstone water-bearing units.

Figure 3. Shaded relief map of the area between Round Valley reservoir and Sourland Mountain in the central part of the Newark Basin, New Jersey. The regional hydrostratigraphic units of the Brunswick aquifer correlate with pronounced topographic ridges and illustrate how the distribution of bedrock influences topographic relief.
db –diabase,
sf – Stockton Formation,
lf – Lockatong Formation,
ba- Brunswick aquifer,
cg – conglomerate,
rv – Round Valley reservoir.
Location of map shown in Figure 1.

Three zones composed of coarse-grained sedimentary rocks occur in the northeast and northwest parts of the basin (Fig. 1) and correlate with mapped lithostratigraphic facies of the Boonton, Passaic Formation, Lockatong, and Stockton Formations (Drake and others, 1991). Diabase intrudes the Brunswick and Lockatong aquifers at various places in the basin (Fig. 1). Diabase can act as a localized water-bearing unit for domestic water supplies , or as confining units for adjacent mudstone and siltstone water-bearing units when intruded as igneous sills. Diabase dikes can act as lateral ground-water flow boundaries.

The nomenclatures for water bearing and confining units in sedimentary rocks of the Brunswick aquifer should use a combination of lithology and color adjectives (Table 1).

Table 1. Descriptive modifiers for designating water-bearing zones and confining units in sedimentary rocks of the Brunswick aquifer

		Color Modifiers		
		Red	Gray	Black
Textural Modifiers	Mudstone	X	X	X
	Siltstone	X	X	
	Sandstone	X	X	
	Conglomerate	X	X	

Bedrock maps show many lateral and vertical facies changes for sedimentary rocks comprising the Brunswick aquifer (Drake and others, 1996;Olsen and others, 1998). Four primary lithologies include mudstone, siltstone, sandstone, and conglomerate. Adjectives used to describe water-bearing zones and confining units should reflect these primary lithologies. The term 'shale' is defined as a laminated, indurated rock with >67% clay-sized minerals (Jackson, 1997). Its use should be restricted to rocks showing a pronounced bedding fissility. Van Houten (1965) and Smoot and Olsen (1988) have shown that a significant fraction of the rock strata composing the Brunswick aquifer is massive mudstone and siltstone rather than shale. Shale-like bed partings often develop in these massive rocks from prolonged weathering near the surface. Although shale is embedded in the literature and existing databases, 'mudstone and siltstone' should be used in its place.

Color adjectives should be restricted to 'red', 'gray', and/or 'black'. Gray and black 'beds' mapped in the basin are typically sedimentary sequences of gray, dark gray, and black laminated to thin-bedded mudstone seldom exceeding a couple meters in stratigraphic thickness. Other colors of mudstone, siltstone, and sandstone are reported in drilling records and map descriptions (such as brown, yellow and green shale) but are included in the 'gray' unit designation as they represent weathered variations of the gray and black beds. Black beds are usually mapped as part of the gray beds on geologic maps but it is important to note them separately. For example, unusually high concentrations of naturally occurring radioactivity and arsenic have been reported from black beds in the Newark Basin (Szabo and others, 1997; Serfes and others, 2000). Black mudstone may also locally confine adjacent red and gray water-bearing units based on outcrop observations and unpublished hydrogeological reports. Therefore, noting black mudstone units in the Brunswick aquifer facilitates ground-water-quality studies and may prove useful for compiling and screening aquifer parameters. After excluding a few improbable combinations, about a dozen likely combinations of descriptive modifiers can be expected from using these three colors and four textures when categorizing water-bearing and confining units in sedimentary bedrock of the Brunswick aquifer. For example, if drilling records report water-bearing intervals associated with red and gray mudstone and siltstone, then the unit designation is 'red and gray mudstone and siltstone water-bearing unit of the Brunswick aquifer'. Similarly, if a confining unit is reportedly composed of gray and black mudstone, then the unit is recorded as a 'gray and black mudstone confining unit in the Brunswick aquifer'.

HYDROGEOLOGICAL FRAMEWORK OF MUDSTONE AND SILTSTONE UNITS

Fracture systems have been suggested to dominantly control ground water flow in sedimentary-rock aquifers of the Newark Basin because ground water preferentially flows along bedding strike (Vecchioli and others 1969, Spayd, 1985; Boyle, 1993; Michalski and Britton, 1997). Michalski and colleagues published a series of manuscripts over the past decade defining the *Leaky Multi-Layer Aquifer System (LMAS)* model for Triassic mudstone and siltstone of the Passaic Formation and outlining useful approaches when conducting hydrogeological investigations at ground-water pollution sites (Michalski, 1990; Michalski and Klepp, 1990; Michalski and Gerber, 1992; Michalski and others, 1992; Michalski and Britton, 1997). Their work is widely regarded as the standard reference for framework characterization and hydrogeological investigations throughout the basin. The LMAS applies to unweathered bedrock where gently inclined bedding 'partings' with the greatest hydraulic apertures act as major, discrete aquifer units. These transmissive intervals are reported as being non-uniformly distributed over vertical distances ranging from about 9 m to more than 45 m and separated by thick, leaky intervals. Overburden and weathered bedrock provide storage and pathways for ground waters recharging the underlying LMAS. Important revisions and refinement to this hydrogeological model are introduced here based on borehole geophysics and the geological analyses of bedrock outcrops, excavations, and rock core.

It is tempting to infer a direct correlation between repetitively spaced water-bearing intervals in the Brunswick aquifer and sedimentary cycles identified in these same rocks. However, this correlation is not easily made. Spatial variations in the hydrogeologic framework reflect varying stratigraphic, structural, and chemical controls occurring in three dimensions. Some of these factors are discussed below along with specific examples of the local hydrogeologic framework.

Cyclostratigraphy of Lacustrine Mudstone and Siltstone

The succession of lacustrine sedimentary rocks within the Lockatong and Brunswick aquifers reflects a gradual climatic change over a 30 million-year period from arid conditions in a narrow basin to sub-humid conditions in an broad basin (Smoot and Olsen, 1994). Sediments deposited in deep lakes with dry, saline mudflats are gradually succeeded upwards by sediments deposited in shallow lakes with wetter, vegetated mudflats (Fig. 2). Superimposed on this succession are a series of graduated sedimentary cycles that reflect the rise and fall of lake level, largely in response to periodic climatic changes occurring over tens of thousands to millions of years (Van Houten, 1962; Olsen, 1986; 1988). The basic rock-stratigraphic cycle is the 'Van Houten' or 'precession' cycle (Olsen, 1986; Schlische, 1992). It marks the successive, gradational accumulation of mudstone and siltstone during transgressive, high-stand, and regressive lake stages controlled by a 21,000-year precession cycle of the earth's axis (Van Houten, 1962). Precession cycles are arranged in a series of larger-order compound sedimentation cycles resulting from orbital variations occurring over 109,000, 413,000, and ~2,000,000 year periods. Some of the characteristics of the precession cycle are briefly recounted here to illustrate how massive mudstone is distributed within parts of the Brunswick aquifer.

A typical precession cycle (~21,000 years) in the Lockatong Formation and lower part of the Passaic Formation includes three recognized sequences:

1) a lower thin-bedded calcareous mudstone and siltstone deposited in shallow, transgressive waters,
2) a middle finely-laminated to thin-bedded, organic-rich black and gray mudstone, siltstone, or limestone deposited in deep, high-stand waters, and
3) an upper thin-bedded to massive[1] mudstone, siltstone, and sandstone deposited in shallow, regressive waters during low-stand periods where the lake was at least occasionally dry with incipient soil development in a subaerial environment.

Average thickness of a precession cycle generally increases upward in the basin, reflecting a gradual upward increase in sediment-accumulation rates over time. However, cycle thickness at the same stratigraphic level varies in the basin, probably in response to a combination of tectonic and climatic controls (Schlische and Olsen, 1990; Schlische, 1992). Cycle thickness increase from the hinged and lateral basin margins inward toward the center (Schlische, 1992). Generally, the Lockatong precession cycles are about 2 to 7 m thick. The Passaic cycles vary from about 3 to 10 m thick. The Jurassic lacustrine cycles are thickest in the basin, from about 11 to 25 m (Schlische, 1992). Identifying precession cycles in the lower and middle red zones of the Brunswick aquifer is complicated by the abundance of red beds with few gray and black marker beds (Fig. 2). These zones are thick successions of red beds deposited during prolonged arid conditions arising from the larger-order climate cycles.

Massive mudstone beds make up a large portion of the sedimentary formations in the Brunswick aquifer (Smoot and Olsen, 1985; 1994). Their geological and geophysical properties are therefore important when addressing the aquifer framework. Four types of massive mudstone include mud-cracked, burrowed, root-disrupted, and sand-patch varieties (Smoot and Olsen, 1988). They represent end members having dominant, distinctive fabrics that relate to specific depositional cycles (Smoot and Olsen, 1994). A detailed discussion of these varieties, sub-varieties, and related depositional cycles is beyond the scope of this paper but it is important to report some fundamental concepts and provide a basis for further examining the hydrogeology.

Mud-cracked and burrowed mudstone is mostly restricted to the Lockatong aquifer and lower gray part of the Brunswick aquifer and represents deposition on dry or occasionally wetted mudflats (Smoot and Olsen, 1994). Root-disrupted mudstone becomes progressively more abundant upwards through the Brunswick aquifer (Fig. 4) and represents deposition on wet mudflats having periodic, fresh, ground-water tables (Smoot and Olsen, 1994). Sand-patch mudstone represents deposition on saline, salt-encrusted mudflats and is relatively scarce in the Brunswick aquifer. All varieties of mudstone locally contain assemblages of millimeter to centimeter scale crystal casts, and linear to ovate syndepositional sedimentary features filled with secondary, sparry cements locally including calcite, gypsum, analcime, albite, potassium feldspar, and dolomite (Van Houten, 1965; Smoot and Olsen, 1994). Calcite and gypsum are

[1] Smoot and Olsen (1988) noted that the term 'massive' in describing mudstone is used "... in a broad sense, encompassing rocks that tend to have a blocky or hackly appearance on a weathered outcrop and that show little obvious internal structure on superficial examination".

most abundant in the Brunswick aquifer and commonly form nodules and fill vesicles, evaporite-crystal casts, desiccation cracks, root structures, and tectonic veins. Examples of these features in the Brunswick, Lockatong, and Stockton aquifers are reported below from outcrop mapping and different hydrogeologic investigations in the central part of the basin.

Hopewell Borough Well No. 6 Hydrogeologic Investigation

Hopewell Borough sited a new public-community water supply well in 1993. Borough supply well No. 6 was drilled in 1995 along with two monitoring wells located about 17 m along bedding strike to the northeast (Obs-1) and about 88 m down-dip to the northwest (Obs-2, Fig. 5). Ground-water-quality testing and analyses for well No. 6 indicated levels of dissolved arsenic at just below the current ground-water quality criteria for drinking water. The N.J. Geological Survey obtained a 400 foot continuous rock core (HBCH-1) alongside well Obs-1 during the summer of 1999 to investigate the source, mobilization, and transport of naturally occurring arsenic as part of a regional study (Serfes and others, 2000). A 3m section of the rock core was scribed and oriented during drilling so that the strike and dip of bedding and fractures logged in the core could be determined. An important ground-water transport mechanism within massive mudstone and siltstone became immediately apparent from this work

Core HBCH-1shows multiple high-porosity intervals occurring within red, root-disrupted mudstone from the dissolution and removal of secondary, soluble minerals that once filled relict root structures (Figs. 6, 7, and 8). Mineral-dissolution cavities form open, tubular conduits for fluid moving within gently dipping beds. Ground water flow was directly correlated to dissolution zones mapped in the core and well Obs-1 through the use of fluid-temperature logs and optical borehole imaging (Figs. 8,9, and 10). It is unclear why some root-disrupted intervals are prone to dissolution while others are not. However, fluid-temperature logs from well Obs-1 under both static and pumping conditions show that the hydraulic continuity of these dissolution zones varies over distances of less than 20 meters (Fig. 10). Ground-water flow zones were noted in the open interval of Obs-1 where sharp, positive fluid-temperature anomalies of about 1° C were induced by flushing water upward from the bottom of the core hole while logging Obs-1 (Fig. 10). Other fluid-temperature disturbances in Obs-1 were noted from pumping well No. 6 at about 125 gpm, but many times these anomalies occurred at different depths and produced sharp, negative temperature anomalies (Fig. 10).

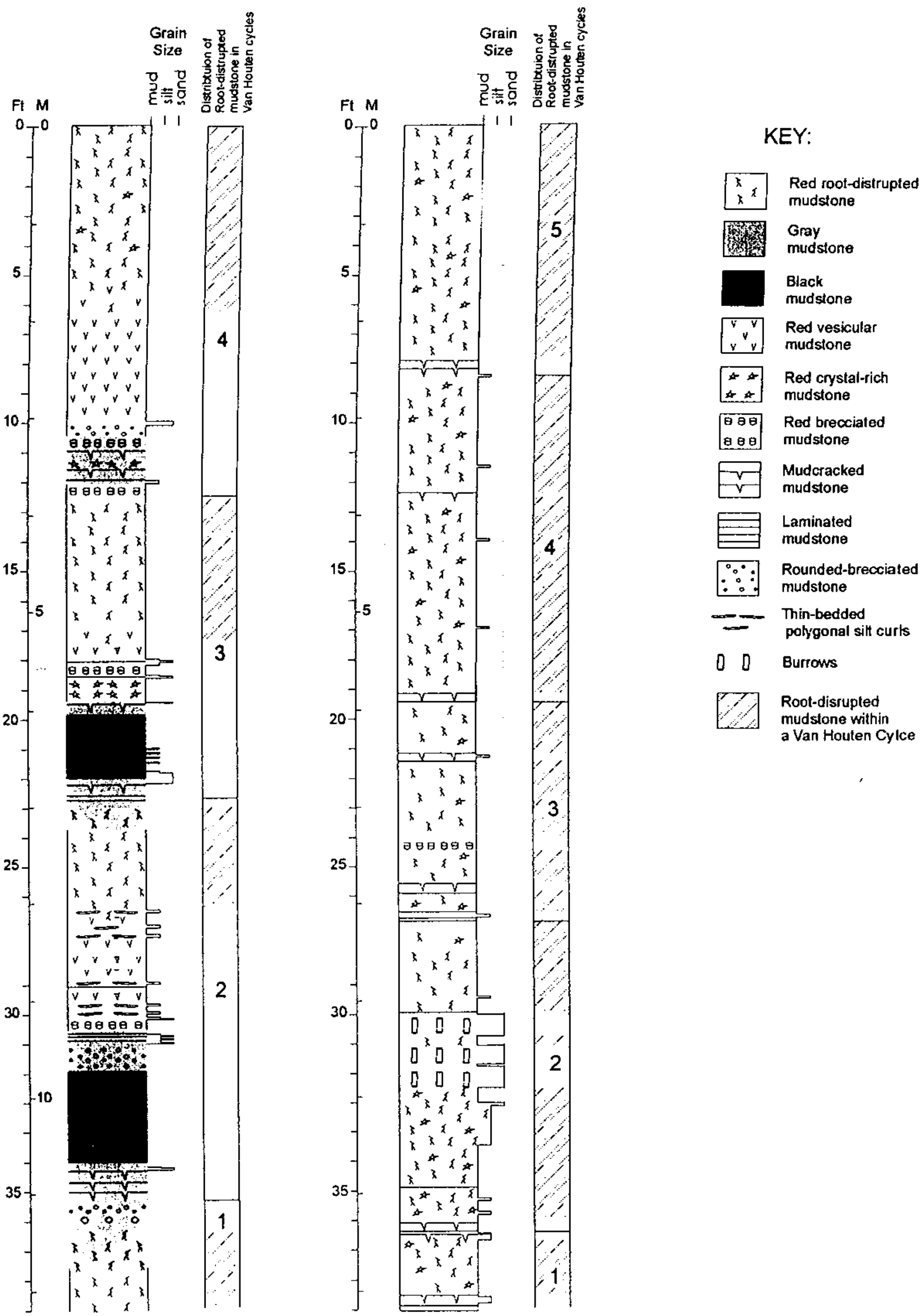
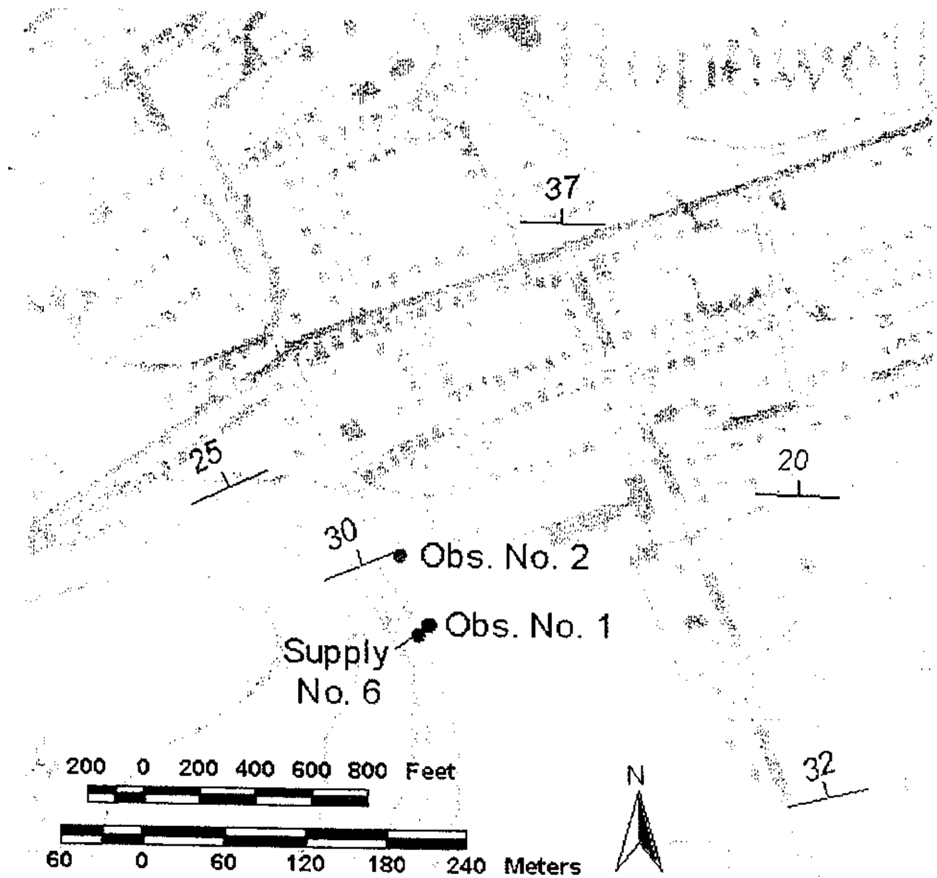


Figure 4. Details of two stratigraphic sequences in the middle gray (a) and middle red (b) zones of the Brunswick aquifer showing key lithologies and the distribution of massive, root-disrupted mudstone in Van Houten cycles. Adapted from Smoot and Olsen (1994). Location of the stratigraphic interval covered by the sections shown in Fig. 2.

About half of all of these flow zones directly correlate to intervals of conspicuous mineral dissolution noted in the nearby core. The remainder either correlate to bed-parallel root zones logged in the core or stratigraphic contacts between mudstone and siltstone units. A flow zone in Obs-1 at a 73m corresponds with a stratigraphic boundary between massive siltstone and mudstone units (Fig. 10). A decreasing step of ~4 Ohm-m fluid resistivity also corresponds to this boundary when pumping well No. 6 (Fig. 10). This indicates that flow zones related to mechanical layering locally carry elevated concentrations of dissolved solids that are separate and different from adjacent water-bearing zones. It is also interesting that large spans of highly fractured rock show no fluid-temperature or fluid-resistivity anomalies (Fig. 10). This aspect is elaborated later.

Mineral-dissolution zones in well No. 6 occur as linear conduits aligned in stratigraphic planes. Although the 3-dimensional geometry of these conduits is unknown, they may resemble stream and karst systems, with hierarchies of branching and coalescing segments reflecting structural control (Ackermann, 1997). The flow volume into or out of well bore would then reflect the hierarchical order of dissolution zone intercepted by drilling. This also helps account for variations in aquifer parameters and contaminant concentrations reported and observed in the Newark Basin. For example, typical transmissivity values for mudstone and siltstone units in the Brunswick aquifer range between 5 to 180 m^2/day (Michalski, 1990; Spayd, 1998; Carleton and others, 1999; Lewis Brown and dePaul, 2000). Transmissivity values of individual water-bearing units can locally range over three orders of magnitude (Lewis Brown and dePaul, 2000) with maximum reported values over 900 m^2/day (Michalski and Britton, 1997. Targeting a stratigraphic horizon that is known to locally produce water nearby can therefore result in drilling a unproductive well when the borehole fails to encounter significant branches of these linear flow systems.

We see that dissolution of secondary minerals within distributed stratigraphic horizons play an important role in the hydrogeological framework of the Brunswick aquifer. This leaves us to ponder the relative significance of the basin's fracture systems. Questions arise as to where, and what type of fractures occur in bedrock, how do they develop, and how do they contribute to the hydrogeological framework?



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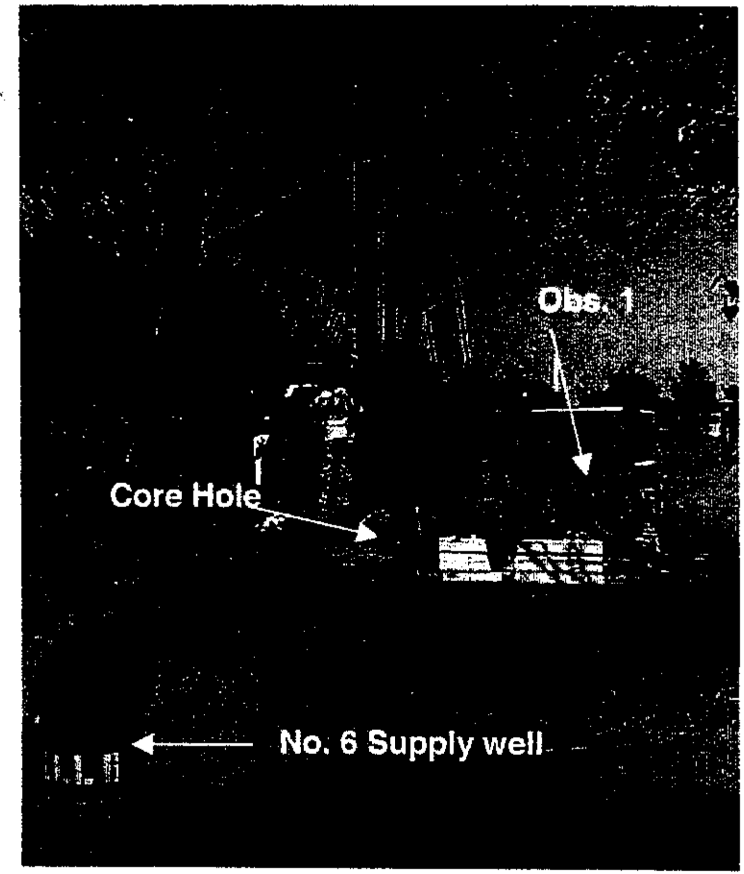


5b

Figure 5. Location of the Hopewell Borough hydrogeological investigation of public-community water supplies Well No. 6. Figure 5a shows the location of the No. 6 supply well and nearby observation wells and stratigraphic bedding orientations on a 7-1/2' topographic base. Figure 5b shows the location of core HBCH-1 in-between wells No.6 and Obs-1.

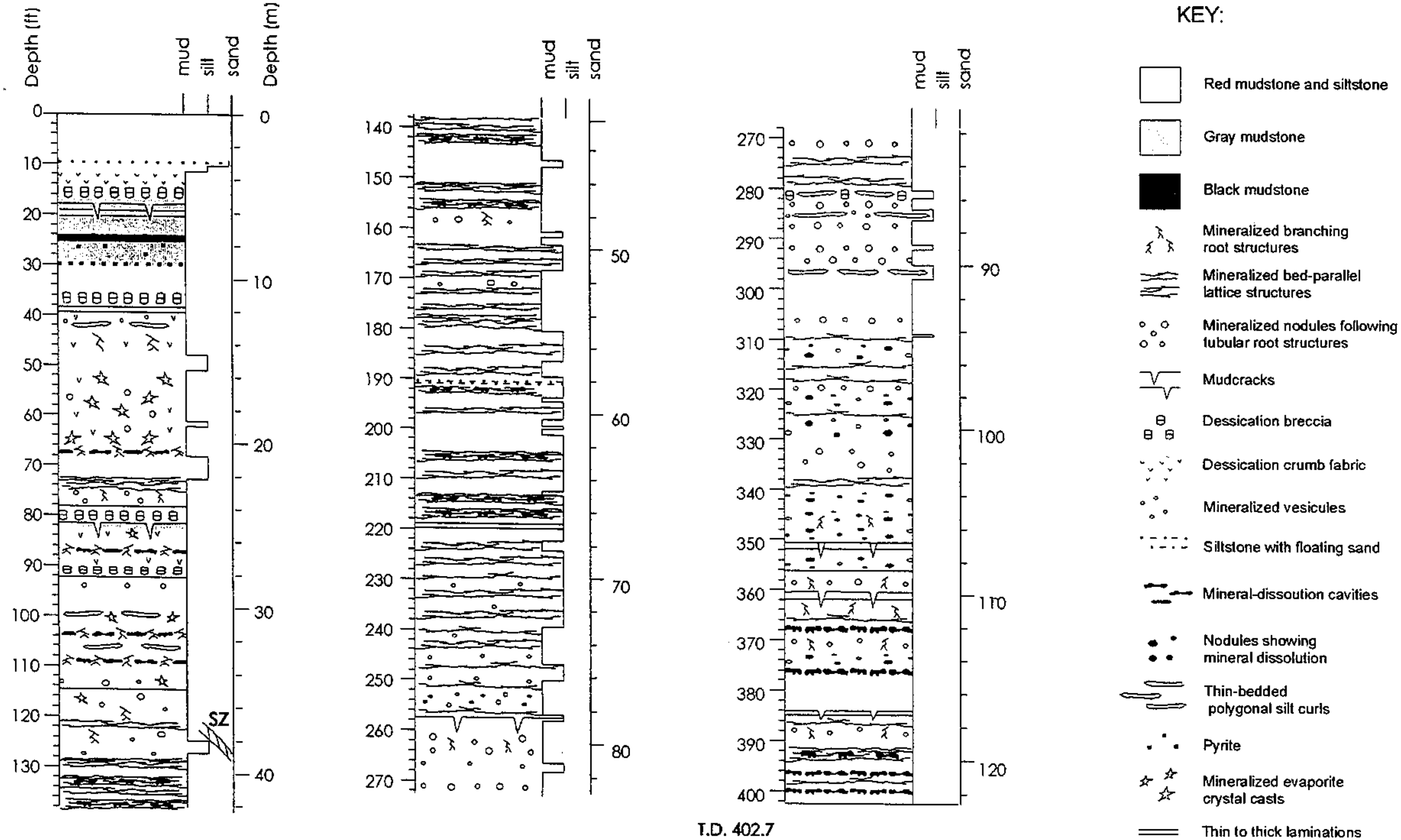


Figure 6. Detailed geological log of core holeHBCH-1 near Hopewell Borough Well No. 6. Location of the stratigraphic interval covered by the core hole shown in Fig. 2. sz – shear zone, T.D. – total depth

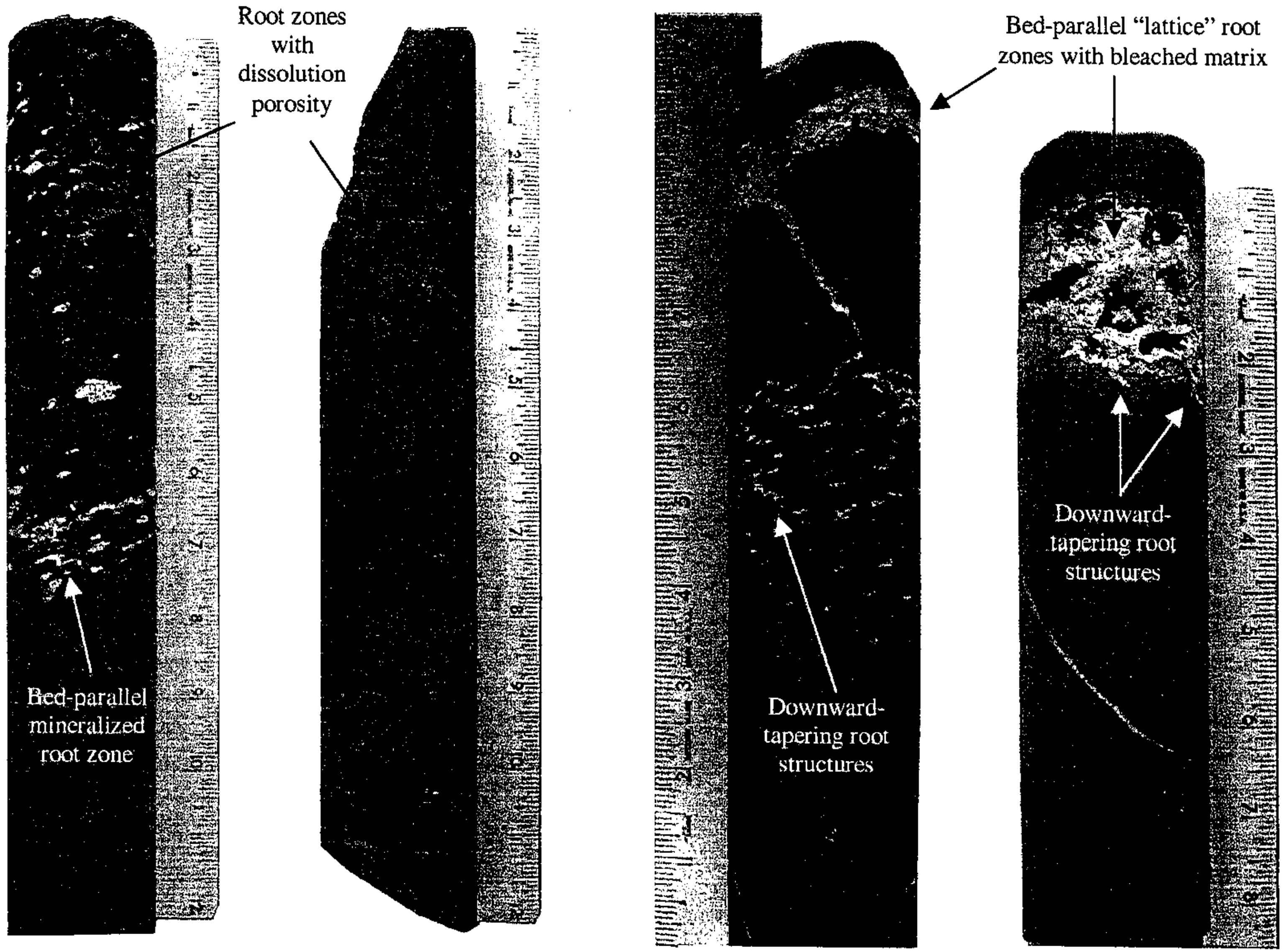


Figure 7a
HBCH-1 @ 109m

Figure 7b
HBCH-1 @ 99 m

Figure 7c
HBCH-1 @ 77m

Figure 7d
HBCH-1 @ 40m

Figure 7. Images of core HBCH-1 from the Hopewell hydrogeological investigation site showing linear- to ovate mineralized (light-colored) root structures, bed-parallel root zones, and associated dissolution cavities (dark pores in Fig. 7a, 7b, and 7d) at different depths. Grayish red (5R4/2 to 10R4/2) mudstone is commonly bleached from reduction to yellowish gray (5Y7/2) near root structures (7c and 7d). Features shown in the images correspond to that logged in Figure 6.

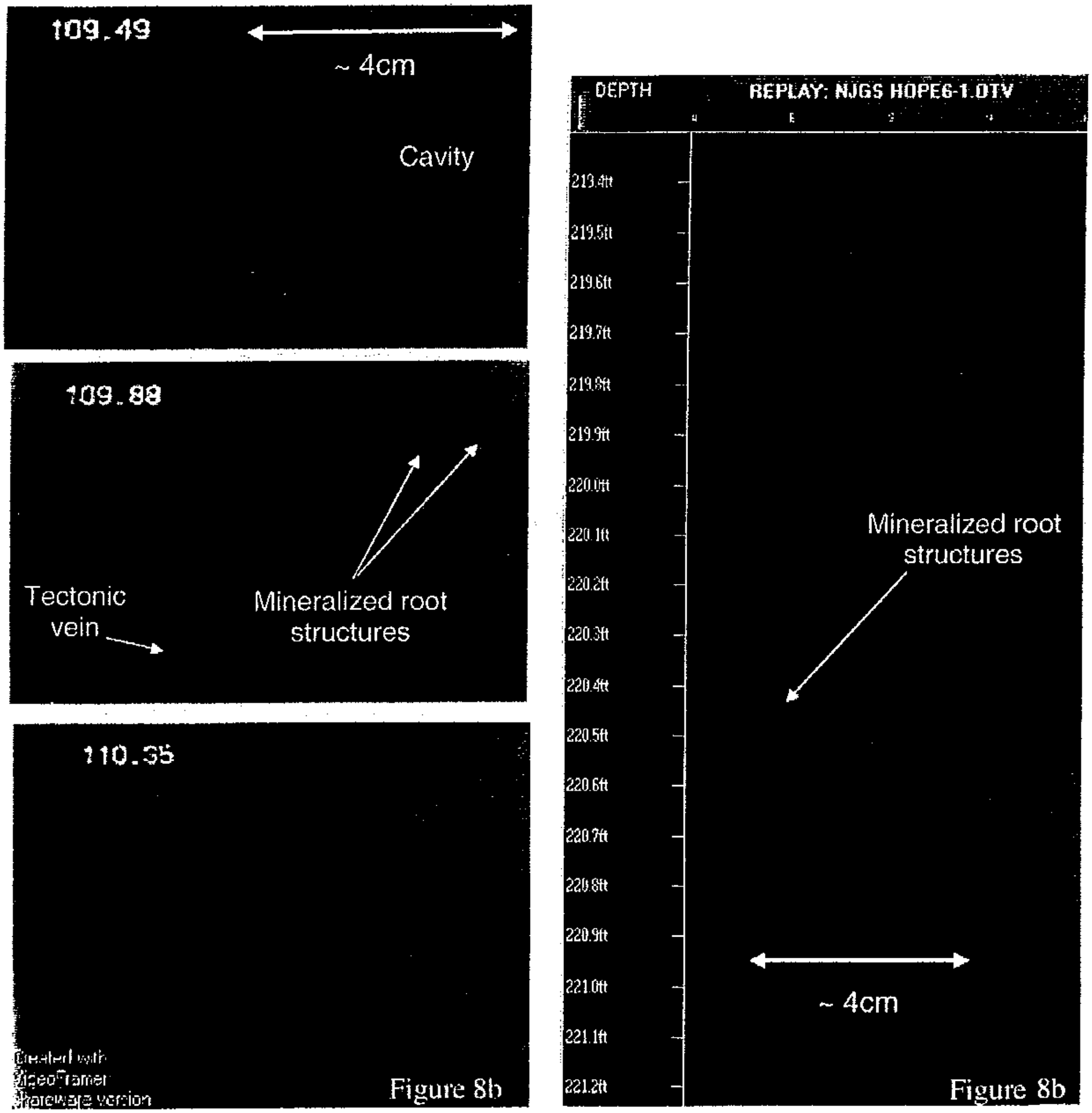


Figure 8. Borehole images of dissolution-induced flow conduits observed in well Obs-1 and core HBCH-1at the Hopewell hydrogeological investigation site (August 18, 2000). Figure 8a is a sequence of still frames captured from a video of the Obs-1 borehole taken with a multi-directional color TV camera provided courtesy of Mid Atlantic Geosciences, LLC. The depth (in feet) below top of casing is shown in upper left corner of each image and the diameter of the borehole is about 15.2-cm (6 in). Figure 8b is a post-processed optical televiewer record of core hole HBCH-1 provided courtesy of Robertson Geologging (USA), Inc. The image shows an unwrapped and flattened 360° perspective of the borehole with a diameter of about 7.6-cm (3 in).

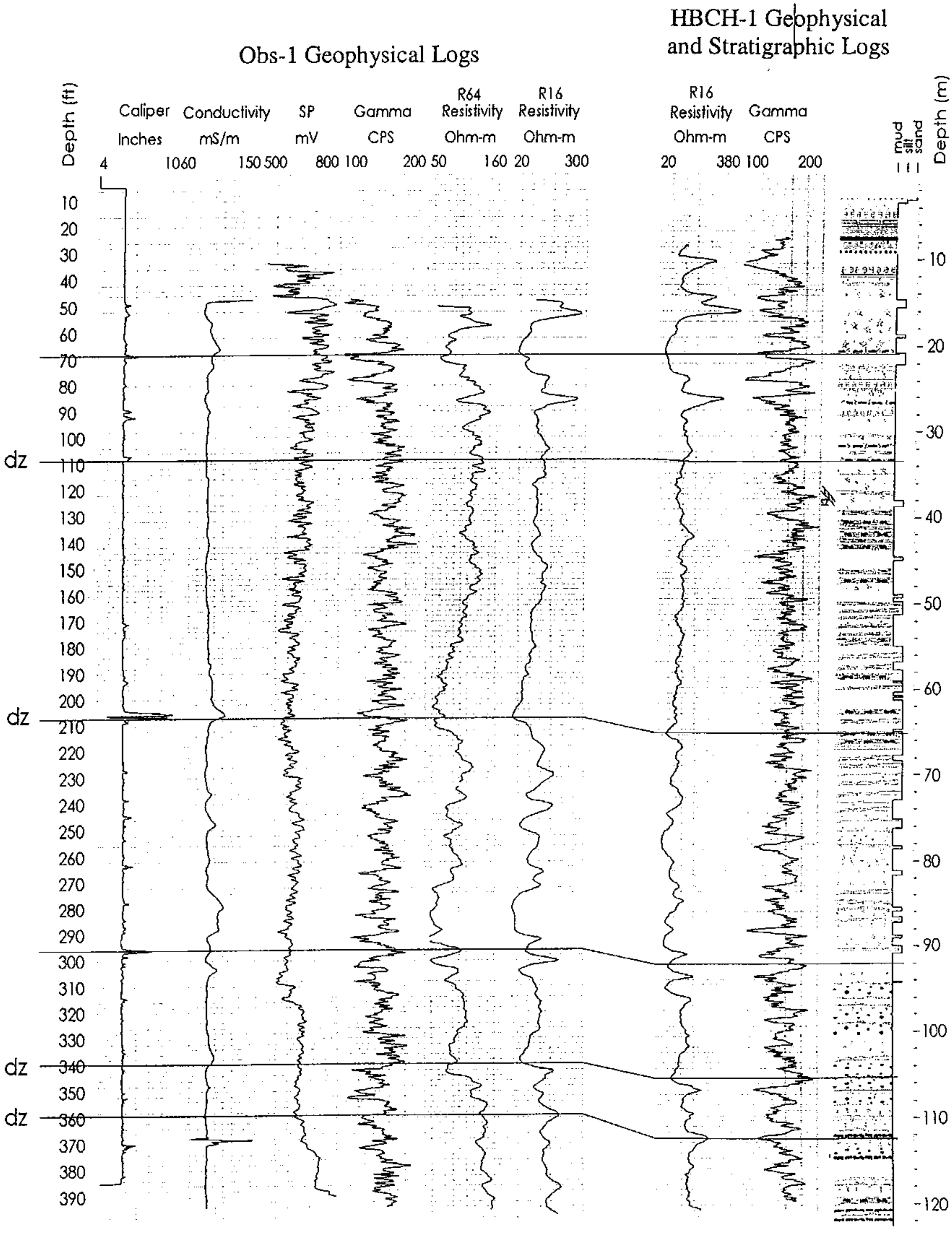
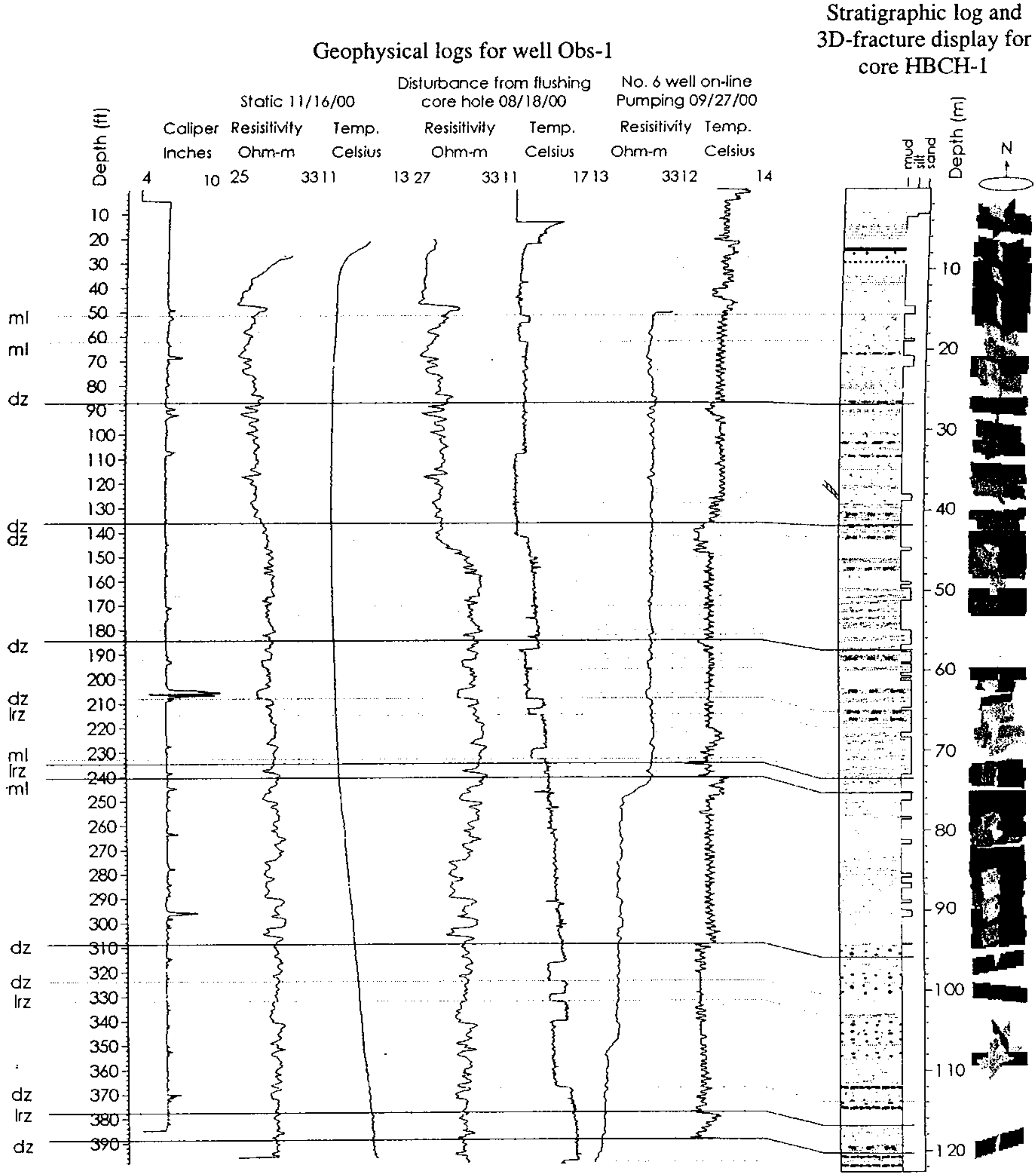


Figure 9. Stratigraphic correlation of well Obs-1 with core HBCH-1 using R16 resistivity and gamma geophysical logs. Discrepancy in depth correlation starting about 40m attributed to sub-vertical drift of the core hole and localized dip-slip faulting along small shear zone (sz). Note the correlation between enlarged borehole events shown in the caliper log and some mineral dissolution zones (dz) mapped in the core. Stratigaphic details and key to symbols from Figure 6.



KEY: flow zone from flushing core hole ——— flow zone from pumping well No. 6

Figure 10. Comparison of fluid temperature and fluid resistivity logs for well Obs-1 during static and pumping conditions with stratigraphic and fracture logs for core HBCH-1. Fluid temperature anomalies recorded in Obs-1 stem from flushing water in the nearby core hole and pumping well No. 6. A good correlation exists between fluid temperature anomalies in Obs-1 and mineral-dissolution zones logged in the core. Positive fluid temperature anomalies result from flushing the core hole whereas negative anomalies are produced from pumping well No. 6. About half of all fluid-temperature anomalies directly correlate with stratigraphic intervals showing dissolution-enhanced porosity in the core located about 15 m along bedding strike. The remainder correlate with mechanical layering between mudstone and siltstone units or mineralized root zones not showing evidence of dissolution in the core. Stratigraphic details and key to symbols from Figure 6. dz – dissolution induced flow zone, ml – mechanical layering boundary, lrz – lattice root zone

FRACTURE SYSTEMS

Most hydrogeologic reports focus on the bed-parallel fractures and tectonic 'joints' occurring in the basin. However, these features comprise only part of the diverse set fractures in the basin resulting from a variety of low-temperatures tectonic processes, erosion, and weathering. Detailed aspects of the tectonic fracture systems are reported below. How fractures resulting from erosion and weathering contribute to the hydrogeologic framework remains sketchy but is conceptualized in the following section.

Three primary tectonic fracture orientations most often reported in the basin include a low-angle set of bed-parallel partings and two steeply inclined, systematic joint sets striking sub-parallel to and sub-normal to bedding strike (Vecchioli, 1965; Houghton, 1990). Detailed structural mapping in the central part of the basin shows that a minimum of four steeply inclined, systematic fracture sets occur here (Fig. 11).

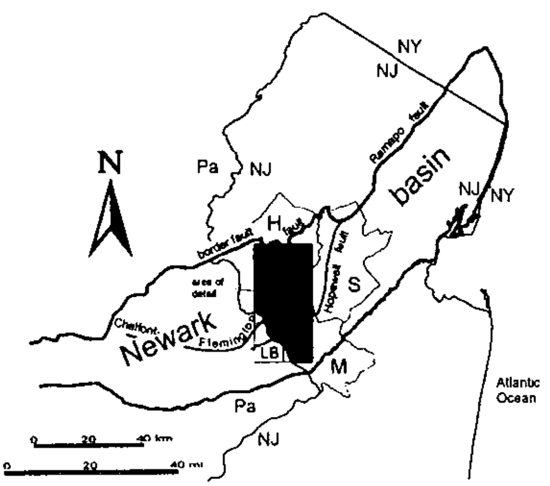
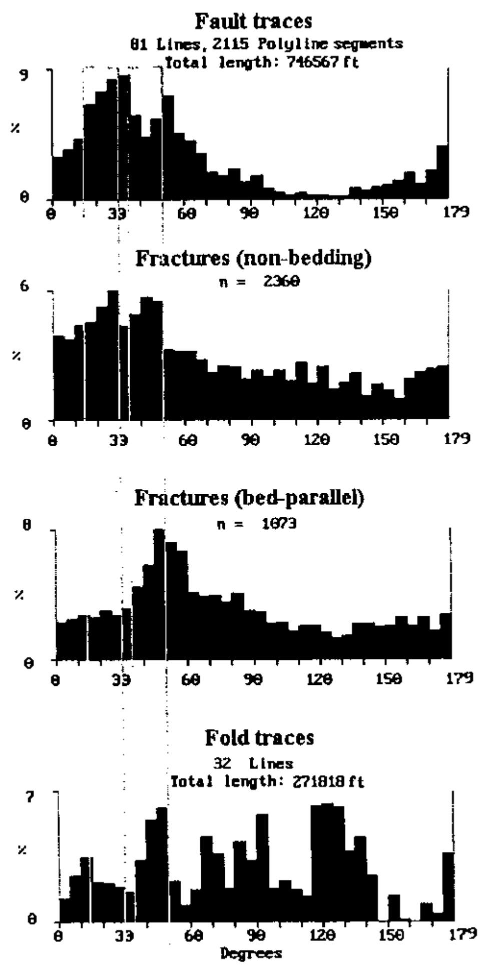


Figure 11. Index map (above) shows the location of a detailed fracture study (shaded area), major faults, 7.5-minute quadrangles, and counties. Quadrangle abbreviations include PT (Pittstown), FG (Flemington), ST (Stockton), HW (Hopewell), LB (Lambertville), and PN (Pennington). County abbreviations include H (Hunterdon), S (Somerset), and M (Mercer). Standard histogram plots (right) compare trend frequencies for fault traces, non-bedding fractures, bed-parallel fractures, and fold traces in the study area. Gray lines bracket the two dominant trends of non-bedding fractures to facilitate comparison of trends. Adapted from Herman (1997).



The two most frequent sets strike subparallel to border faults along the basin's northwest margin (about N35°E to N50 ° E, Fig. 1) and subparallel to intra-basins and regional dike swarms (about N15° to N30 ° E, Fig. 1). Other subordinate sets of curviplanar cross-joints strike at complimentary angles to the fault-parallel sets so that at least four different orientations of steeply inclined fractures commonly crop out in the basin, many times at a single location. Other sets of less-frequent fractures occur near intrusive igneous bodies and in gently folded rocks (Herman, 1997). The morphology and geometry of the primary fracture sets display both tensional and shear strains (Figs. 12, 13, and 14). They classify as joints when the two sides of the fracture show no differential displacement (relative to the naked eye), as healed joints when the fracture walls are completely or partially joined together by secondary crystalline minerals, or as tectonic veins when a considerable thickness (> 1mm) of secondary minerals fill the space between fracture walls (Ramsay and Huber, 1987).

Secondary crystalline minerals including calcite, gypsum, chlorite (Szabo and others, 1997) and quartz precipitated from saturated fluids moving through matrix pores into opening voids between fracture walls. Calcite and gypsum commonly occur as mineral fibers aligned perpendicular to the fracture plane (Fig. 12). Remnant splinters of the host rock are encased as *inclusion bands* within the mineral filling. This indicates that small veins can repeatedly coalesce into larger ones reflecting progressive, incremental strain. Two parallel sets of mineral fibers typically meet along a central suture line (Fig. 12a) and therefore display *syntaxial* morphology (Durney and Ramsay, 1973). This results from mid-point fracturing and secondary crystal growth from the wall toward the vein center; minerals grow outward from the fracture walls and heal the cracks as they form. Individual veins display a stepped geometry with overlapping, subparallel rows, having *en echelon* alignment (Fig. 12 and 13). Sets of stepped veins are themselves arranged in conjugate arrays (Figs. 13 and 14) having the geometry of shear zones (Ramsay and Huber, 1983; Groshong, 1988). The dominant systematic sets of fractures therefore originated as hybrid shear fractures (Engelder, 1999) rather than simple extension fractures (Groshong, 1988). The two sets of systematic tectonic veins are referred to as dilatant en echelon cracks (DEC) in the remainder of this manuscript to facilitate discussion.

A detailed orientation study of DECs striking between N15 °E to N30 °E was conducted in a ~50km^2 area in the Flemington fault hanging-wall (Fig. 15) to test a hypothesis that DECs formed in horizontal strata prior to regional tilting of strata. A 'pre-tilt' orientation was calculated for 63 DECs mapped throughout the gently dipping homocline (Fig. 16). Each pre-tilt DEC orientation was determined by passively rotated it to a pre-tilt alignment by restoring its associated bedding reading to horizontal (analytical solution provided by Ragan, 1985, equations 5.5 to 5.8). The inclination of the average direction of the restored DECs (71 °) directly agrees with the angle of inclined-shear failure (~70°) reported for material moving in a faulted, extended hangingwall (Xiao and Suppe, 1992; Dula, 1991, Withjack and others, 1995). DECs are pervasive throughout the basin. They reflect penetrative tectonic strain in Triassic sedimentary rocks that were stretching and sagging during development of the primary fault blocks (Fig. 17).

Although most DECs display simple syntaxial fiber growths, exceptions occur. For example, DECs can be entirely or partially filled with mosaic quartz and therefore show *antitaxial* or *composite* morphologies. These vein types can reflect many different causes including complex vein-growth related to episodic fracturing, mineral growth that didn't keep up with the rate of fracture extension, or secondary minerals that refilled voids left by the removal of earlier minerals. In some instances, mineral fibers measured in DECs of the border-fault orientation are orientated parallel to fibers found in the DECs of the intra-basin fault orientation (Fig. 18). This indicates counter-clockwise rotation of the progressive strain field of about 20 ° during the Triassic, assuming that DECs oriented sub-parallel to the border faults preceded those formed parallel to the intra-basin faults. Crosscutting and abutting fracture relationships observed at many locations in the basin lend support this strain relationship (Fig. 18).

Structural features commonly found on the walls of DECs, including plumose patterns, rib marks and hackles further substantiate their extensional origin. In contrast, the two sets of subordinate cross-joints commonly extend between, and are approximately normal to the systematic DEC sets. Cross-joints are not usually mineralized, are much less abundant than the DECs, have rough, curviplanar surfaces that commonly terminate on bedding partings or against DECs (Herman, 1997). These fractures probably originate as complimentary structures that accommodate bulk strain in a stretched and saggy pile of heterogeneous, layered rocks.

Another structural relationship worth noting is that inter-fracture spacing and the geometrical aspect (trace length vs. height) of DECs reflect the thickness of the fractured layer. The literature records many instances where joint spacing scales with the thickness of the fractured layer in sedimentary rocks (Pollard and Adyin, 1988; Huang and Angelier, 1989; Narr and Suppe, 1991, Gross, 1993). Generally, thin layers show closer fracture spacing than thick layers. However, parallel fracture sets in the basin show a systematic increase in inter-fracture spacing approaching the map trace of intra-basin faults (Herman, 1997). It is unclear whether this reflects progressive penetrative strain accompanying regional faulting or if the regional spacing existed prior to large-scale faulting. In the latter case, variably spaced swarms of extensional fractures could have developed in the basin at regular intervals that would ultimately influence where large faults subsequently developed (Fig. 17).

Most tectonic fractures mapped in outcrop appear as open and potentially conductive structures. However, they are often healed with calcite and gypsum in many bedrock excavations and most rock cores (Figs. 13). Core samples of the Lockatong and Brunswick aquifers show minimal dissolution of vein-fill minerals below near-surface depths of less than 6 to 15 meters. In contrast, arkosic sandstone in the Stockton aquifer locally displays deep weathering profiles with vacated DECs observed to depths below 60 meters (Fig. 13c). This contrast probably occurs because sandstone has higher matrix porosity and matrix compositions that are less effective in buffering recharged, acidic ground water than the carbonate- and sulfate-laden lacustrine rocks of the Lockatong Formation and Brunswick aquifer.

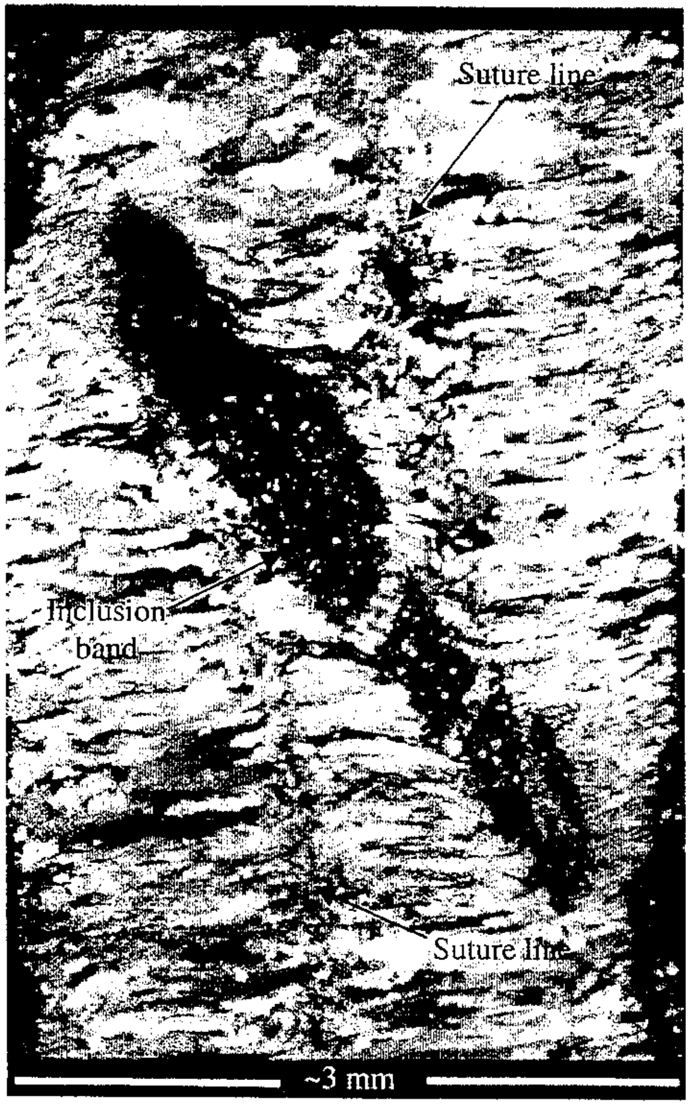


Figure 12a

Figure 12b

Figure 12. Morphology of dilatant en echelon cracks (DEC's). DECs are mostly filled with calcite fibers having centralized suture lines indicating mineral-fiber growth accompanying dilation (Fig. 12a). Remnant splinters from the host rock are locally preserved as 'inclusion bands' (Fig. 12a) within mineral fibers or as bridges (Fig. 12b between adjacent veins occurring in en echelon alignment (Fig. 12b). These features indicate that many individual cracks have coalesced through growth, and document a progressive strain history with the basin rocks subjected to simultaneous tension and shear strains.

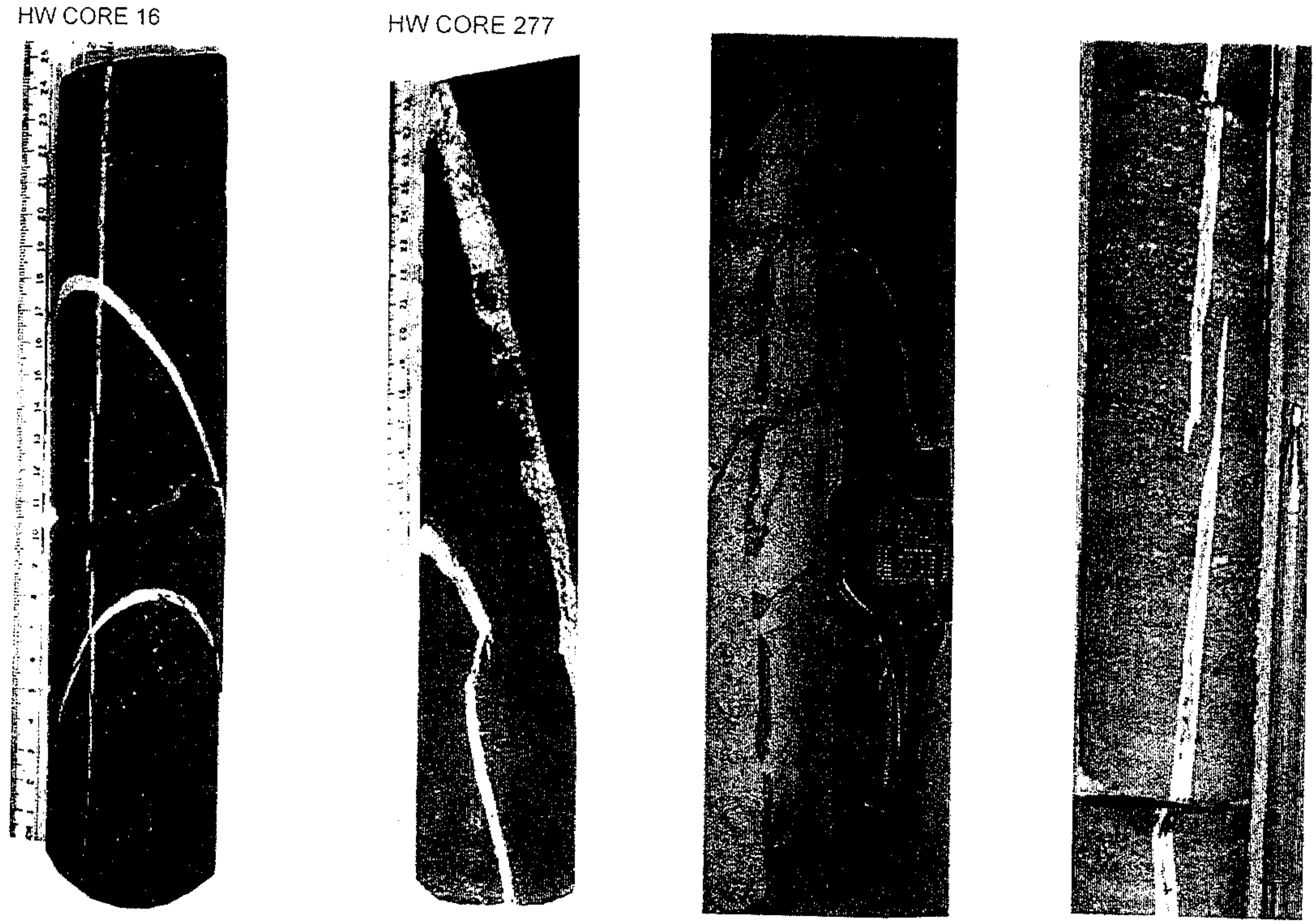


Figure 13a **Figure 13b** **Figure 13c** **Figure 13d**

Figure 13. Samples of DECs in rock core. Figure. 13a shows a DEC set oriented 170/86E that crosscuts two earlier sets oriented 045/66S and 075/62S. Figure 13b shows partially vacated vein in red mudstone of the Brunswick aquifer at a depth of about 84 m. Figure 13c shows DECs in the Stockton Fm. at a depth of about 60 m where the secondary vein fill has been completely removed by dissolution. The surrounding matrix also shows chemical alteration. Figure 13d shows syntaxial mineral growth in DECs in gray mudstone of the Brunswick aquifer

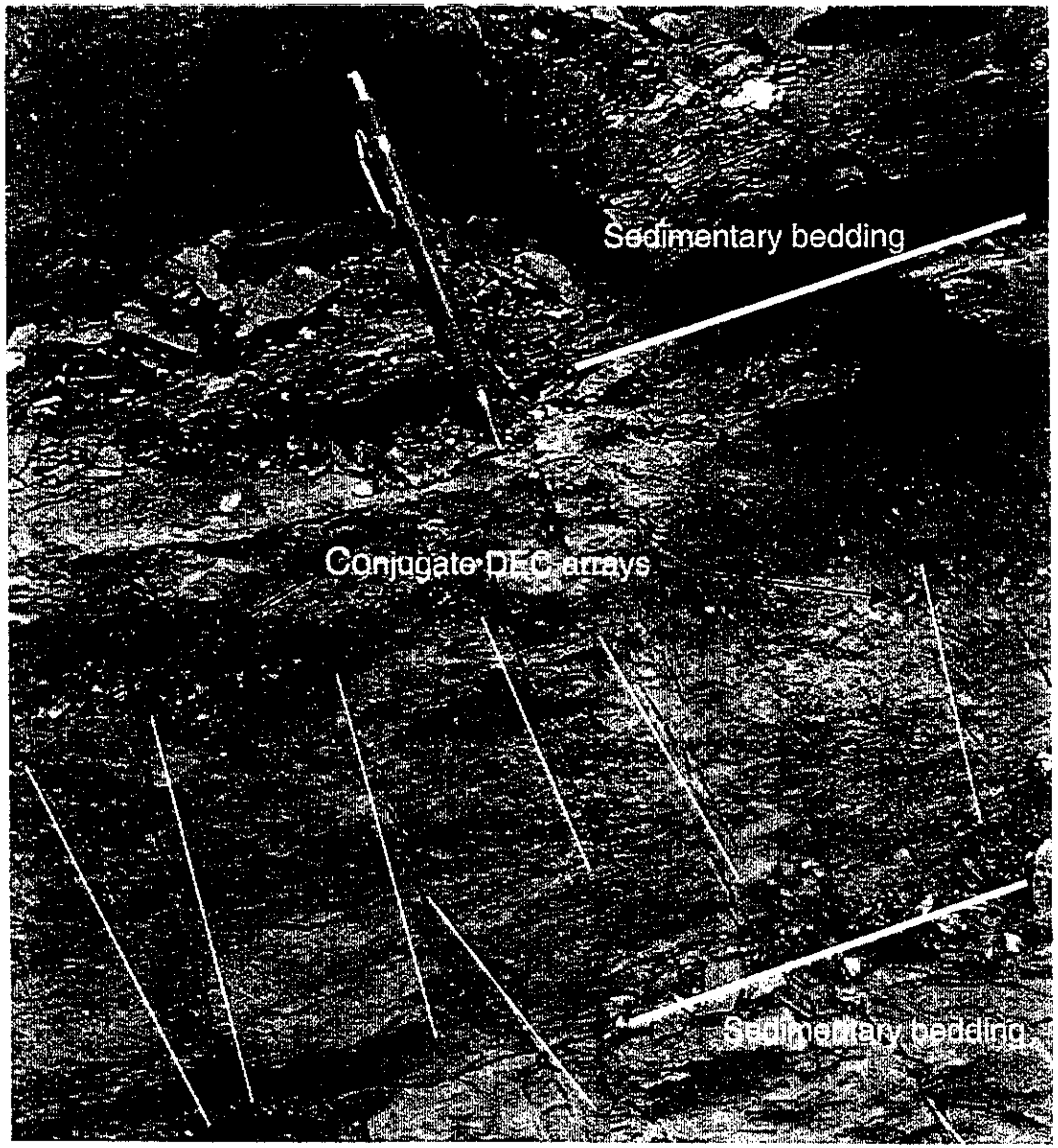


Figure 14a

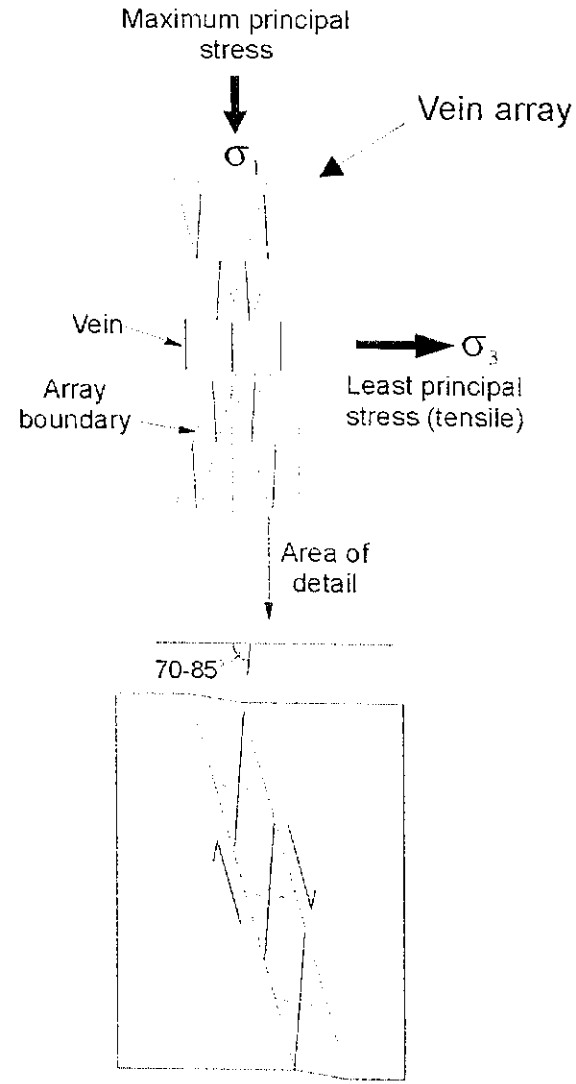


Figure 14b

Figure 14. Dilatant Echelon Cracks (DECs) occur in conjugate, en echelon arrays that dip at steep angles subnormal to bedding. Figure 14b shows that the acute angle between the conjugate arrays corresponds to the local, maximum principal stress direction, and is normal to the least principal stress direction (Fig. 14b). The alignment of these cracks at high angles to bedding results in both extension sub-parallel to bedding (normal to the DEC walls) and simple shear sub-normal to bedding. Figure 14b adapted from Ramsay and Huber (1983, Fig. 3.21).

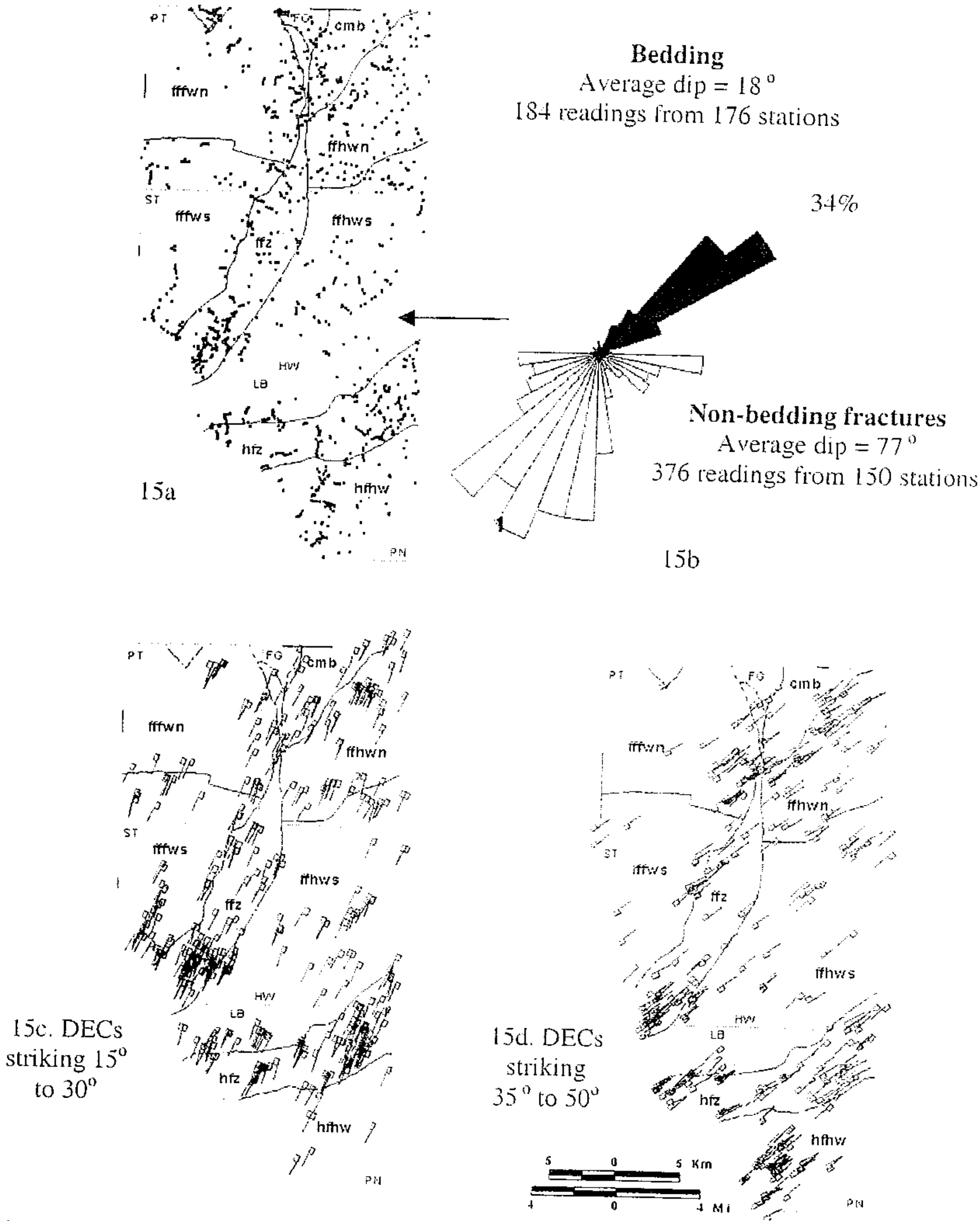
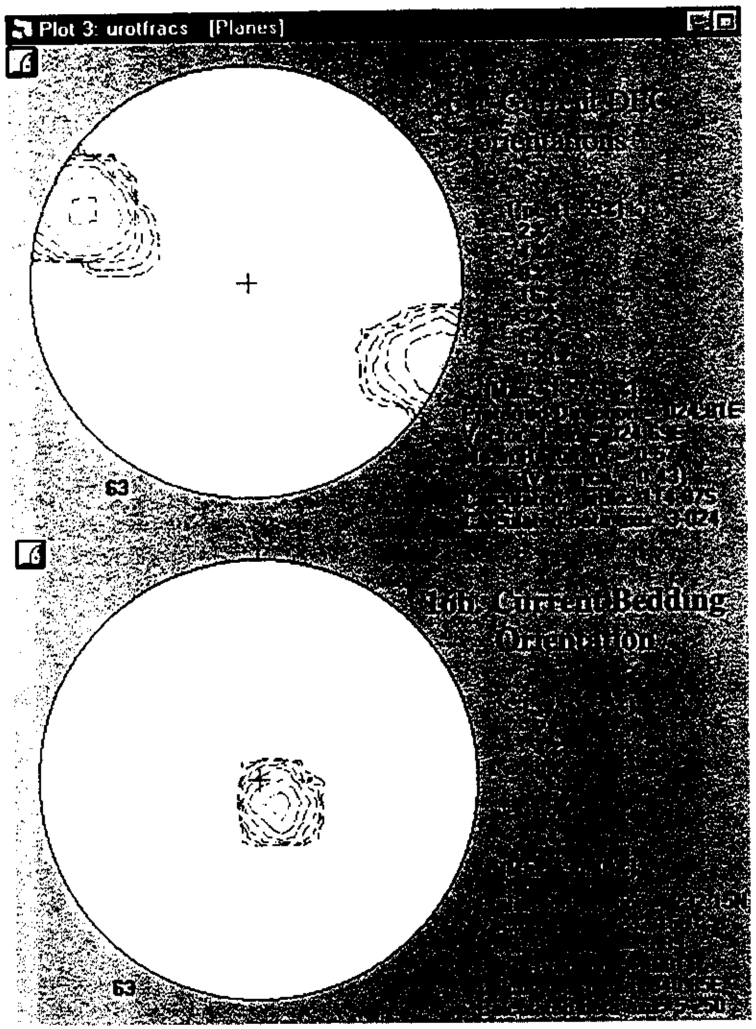
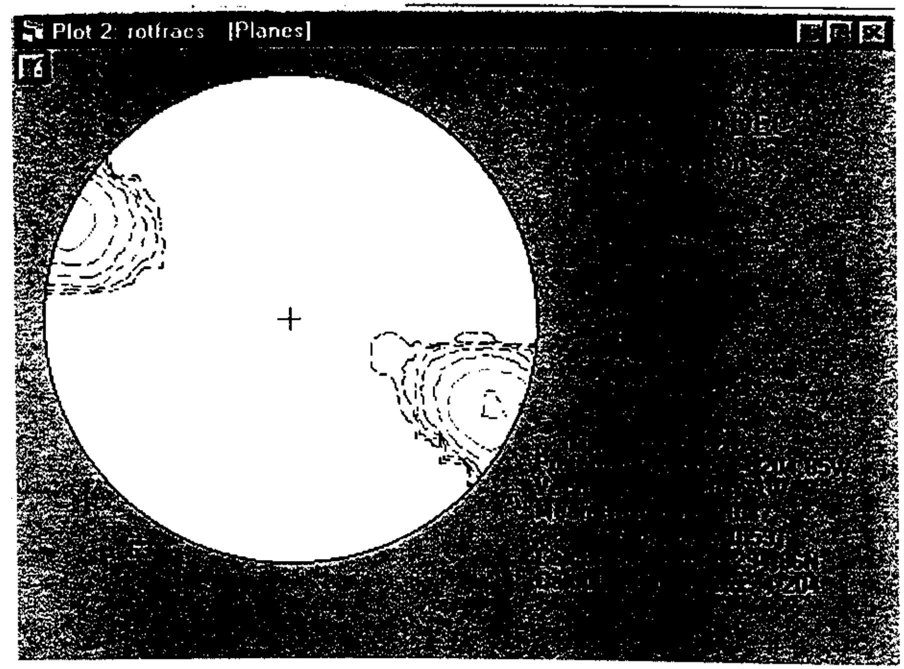
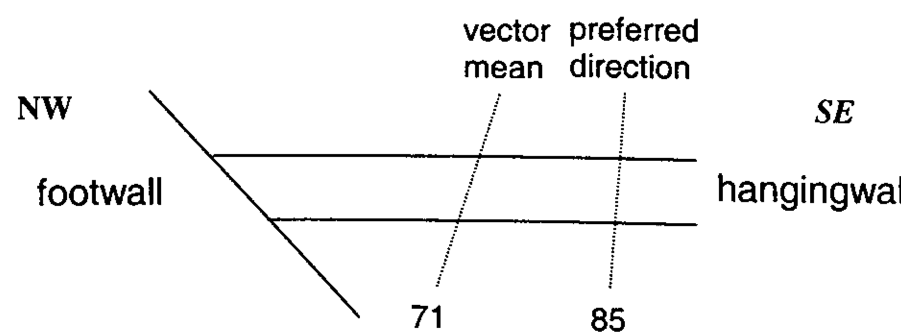


Figure 15a shows the location of field stations and structural domains for a six-quadrangle area in the central part of the Newark Basin (Herman, 1997). Area corresponds to that shown figure 11. Figure 15b shows a circular histogram summary of the bed-parallel and non-bedding fractures mapped in the **ffhws** structural domain. Note the consistent strike of bedding in the domain. Frequency percentages indicated for bin maximums. Figures 15c and 15d show the distribution of the 2 sets of systematic extension fractures (DECs) mapped in the study area. cmb - Cushetunk Mt. block, fffwn - Flemington fault footwall north, fffws - Flemington fault footwall south, ffhwn - Flemington fault hangingwall north, ffhws - Flemington fault hangingwall south, ffz – Flemington fault zone, hfz – Hopewell fault zone, hfhw – Hopewell fault hangingwall. Quadranlge abbreviations same as those in figure 11.







16d. Profile view of pre-tilt DEC orientations

Figure 16. A geometric exercise conducted on the systematic set of DECs striking 15° to 30° shows that the orientation of DECs in horizontal strata directly corresponds to the angle of inclined shear failure predicted for collapse of a hanging wall in an extensional tectonic environment. Stereographic projection diagrams are lower hemisphere equal area plots (GEOrient software, v. 7.2, by Dr. R.J. Holcombe. Figures 16a and 16b show that DEC inclinations are statistically skewed toward the southeast in their current orientation and that bedding is tightly clustered around a single orientation within the ffhws structural domain of figure 15. Figures16c shows the restored, pre-tilt DEC orientations derived by restoring bedding to horizontal using the methods described in the text. The preferred direction for the pre-tilt DECs is 85° W with a vector mean (average direction) of 71° W.

17a

17b

17b

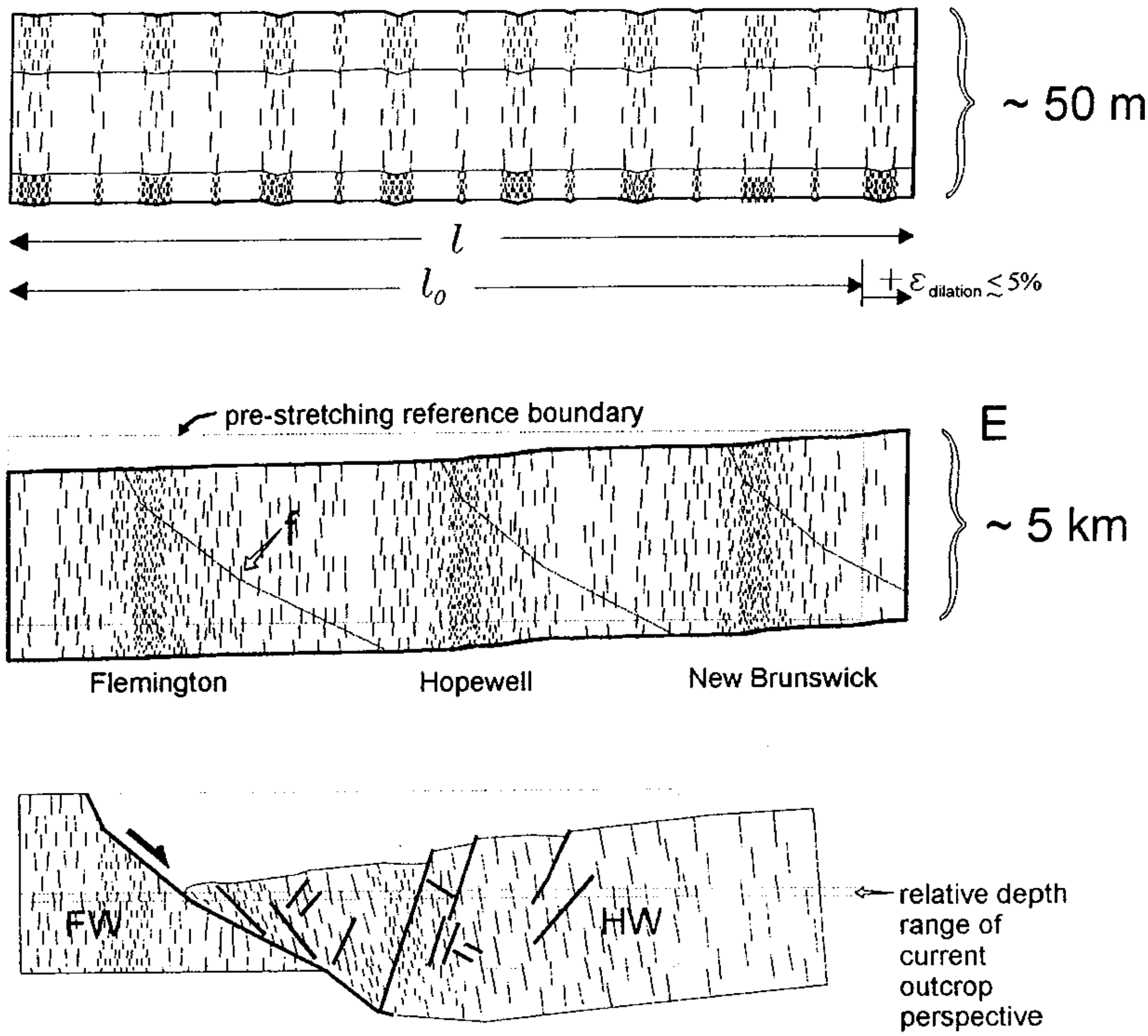


Figure 17. Profile diagrams illustrating some theoretical aspects of DECs occurring in the Newark Basin. Figure 17a shows that DECs occur in spaced sets of varying density in the basin (Herman, 1997) and their inter-fracture spacing is commonly influenced by the thickness of the mechanical or 'fractured' layer. Figure 17b illustrates that inter-fracture spacing generally decreases near the trace of mapped faults (Herman, 1997), and that a preferred direction of inclination toward the west would result in a progressive sagging of the rock pile in that direction. Figure 17c illustrates that DECs are rotated in the hangingwall of faults from their pre-tilt orientation.

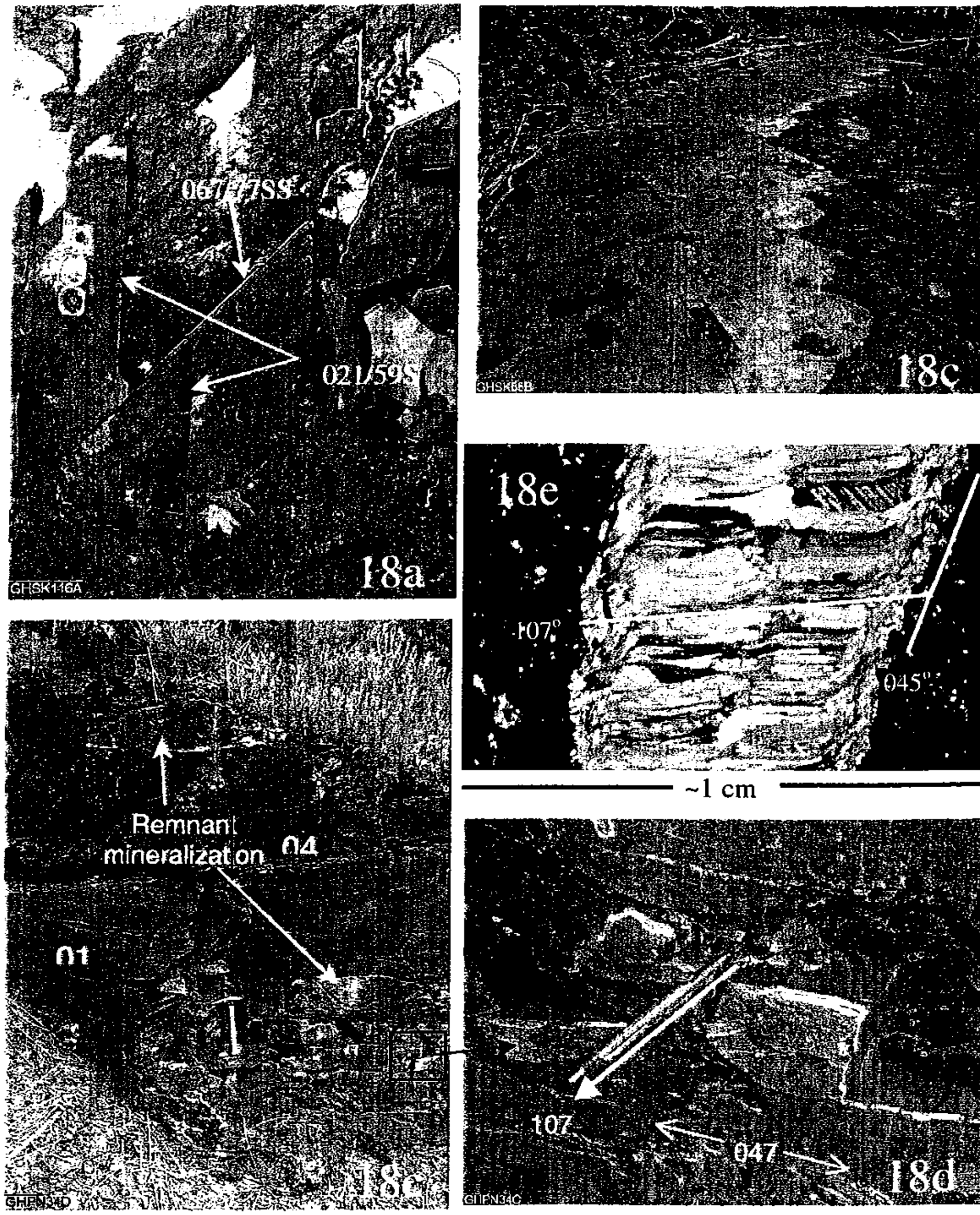


Figure 18. DEC walls commonly appear as ordinary 'joints' in outcrop because secondary minerals that once filled DECs are usually dissolved from weathering. Figure 8a shows DECs within an outcrop of gray mudstone of the Passaic Formation; the set striking subparallel to the intra-basin faults are locally found butting into the set striking subparallel to the basins' northwest margin. Figure 8b shows an outcrop of gray mudstone of the Lockatong Fm. with DECs having a 1 to 3m trace length and variable inter-fracture spacing (rock hammer in the center of the view for scale). DECs seen in shallow excavations often show only partial removal of secondary minerals from weathering. Figure 18c shows the two regional DEC sets in a massive red mudstone of the Passaic Fm exposed in a railroad grade excavation. Figures 18b and 18c shows that calcite mineral fibers within the earlier DEC set (047°) locally grew normal to the later (017°) set, further illustrating that DECs of the border fault trend predate the intra-basin fracture trend.

MODIFICATIONS TO THE LMAS

The hydrogeologic framework of fine-grained sedimentary bedrock the Newark Basin where unconsolidated sediment is generally thin (< 5m) includes shallow, intermediate, and deep intervals having variable hydraulic properties (Fig. 19). The shallow interval correlates to 'overburden' and includes unconsolidated alluvium, colluvium, artificial fill, and bedrock regolith (Michalski and Britton, 1997). Regolith in the Lockatong and Brunswick aquifers includes red, brown, orange, yellow, and gray silty clay to clayey silt residuum containing angular bedrock fragments near competent bedrock. The shallow interval extends to depth of 1 to 5m and often has a perched water table near its base. The underlying, intermediate or 'weathered' interval reflects prolonged weathering of bedrock during a wide range of climatic conditions, including permafrost developed during glacial epochs. Hydraulic gradients mapped at shallow- to intermediate levels commonly mimic topographic slope and display hydraulic responses equivalent to porous media. Conductive features at intermediate depths include partially-dissolved systematic tectonic fractures, stratigraphic zones of mineral dissolution, bed-parallel mechanical layering, and other fractures resulting from erosion and weathering. These probably include release joints oriented sub-parallel to the ground surface and stemming from glacial and stratigraphic unloading, and fractures stemming form freeze-thaw cracking. These combined features provide ample pathways for groundwater flowing under water-table conditions and help explain why workers often cite a 'regional water table' occurring at depth of about 10 to 15 m (30 to 50 ft). Ground-water flow at intermediate depths abruptly decreases about 20m below ground surface in the Lockatong Formation and Brunswick aquifer based on fluid-temperature logs (Figs. 20 and 21) and the depth of well yields reported in bedrock wells (Morin and others, 1997; 2000). The hydraulic connection between the open borehole and overlying parts of the aquifer therefore becomes an important consideration when dealing with near-surface ground-water pollution because the intermediate interval can extend below the 50-ft casing depth required for potable wells. The hydrogeological literature often states that the infiltration of precipitation through fractures is impeded at shallow levels, and that permeability is less than deeper levels because clay and silt derived from weathered bedrock partially fill open fractures (Kasabach, 1966; Lewis-Brown and dePaul, 2000). However, vertical conductivity values reported in the weathered interval are cited as exceeding those in the deep zone by two-orders of magnitude in these same rocks (Lewis-Brown and Jacobsen, 1995). More hydrogeological research is clearly needed to better understand the hydrogeology of this critical recharge and fluid-transport zone.

Ground-water flow in the deep bedrock aquifer generally reflects confined-flow conditions, principally related to stratigraphic control. Deep flow zones become recharged with ground water when they reach intermediate and shallow depths (Michalski and Britton, 1997). Although the deep-level flow zones display anisotropic hydraulic responses under pumping conditions, with maximum horizontal conductivity oriented along bedding strike, the area contributing to their recharge is probably more isotropic at intermediate levels. More research is needed to evaluate this probability. More work is also needed in evaluating aquifer characteristics in areas of intense tectonic fracturing near large-scale faults. These areas typically have multiple sets of tightly spaced fractures having surface coatings of iridescent-blue manganese minerals. Archaic ground-water systems probably developed in these areas from the tectonic mobilization of fluids associated with pervasive hydraulic fracturing accompanying faulting. These areas may display anomalous ground water chemistry and pose exceptions to the LMAS ground-water flow model elsewhere in the basin.

In summary, ground water exhibits complex flow behavior in bedrock aquifers of the Newark Basin. Complexities arise from sedimentalogical and structural variations in the aquifer framework that affect both water table and confined-flow conditions. Ground water is reportedly stored and transmitted along fractures, but the Brunswick aquifer and Lockatong aquifers include stratified intervals with abundant calcium sulfate and calcium carbonate mineralization that is prone to dissolution of secondary, authegenic minerals producing conduits of significant confined flow. The stratified orientation of these dissolution zones helps explain why maximum hydraulic conductivity is commonly aligned along bedding strike (Vecchioli and others, 1969; Michalski and Britton, 1997; Carlton and others, 1999). Transmissivity values reported for these intervals vary significantly because of the variable thickness of the producing interval over which values are calculated. Regional analysis of ambient ground-water quality from bedrock wells shows that calcium-bicarbonate and calcium-sulfate waters dominate (Serfes, 1994). Regional variations in the distribution of carbonate and sulfate in ground water (Michalski and others, 1997) along fractures, but the Brunswick aquifer and Lockatong aquifers include stratified intervals with abundant calcium sulfate and calcium carbonate mineralization that is prone to dissolution of secondary, authegenic minerals producing conduits of significant confined flow. The stratified orientation of these dissolution zones helps explain why maximum hydraulic conductivity is commonly aligned along bedding strike (Vecchioli and others, 1969; Michalski and Britton, 1997; Carlton and others, 1999). Transmissivity values reported for these intervals vary significantly because of the variable thickness of the producing interval over which values are calculated. Regional analysis of ambient ground-water quality from bedrock wells shows that calcium-bicarbonate and calcium-sulfate waters dominate (Serfes, 1994). Regional variations in the distribution of carbonate and sulfate in ground water (Michalski and others, 1997) probably reflect regional sedimentalogical trends of authigenic mineralization and related dissolution processes. Dissolution-induced flow in stratigraphic horizons must be a primary consideration when characterizing the aquifer framework of fine-grained sedimentary rocks of the Newark Basin.

ACKNOWLEDGMENTS

Bedrock geology of the Newark Basin has been extensively studied and reported on by many workers over the past century. Detailed geological studies spearheaded by Paul E. Olsen of the Lamont-Doherty Earth Observatory of Columbia University and Roy W. Schlische of Rutgers University over the past decade has provided unprecedented, detailed insights into the stratigraphy, structure, and geochronology of the basin. Refinement of the geological framework for the Brunswick aquifer draws heavily from their work.

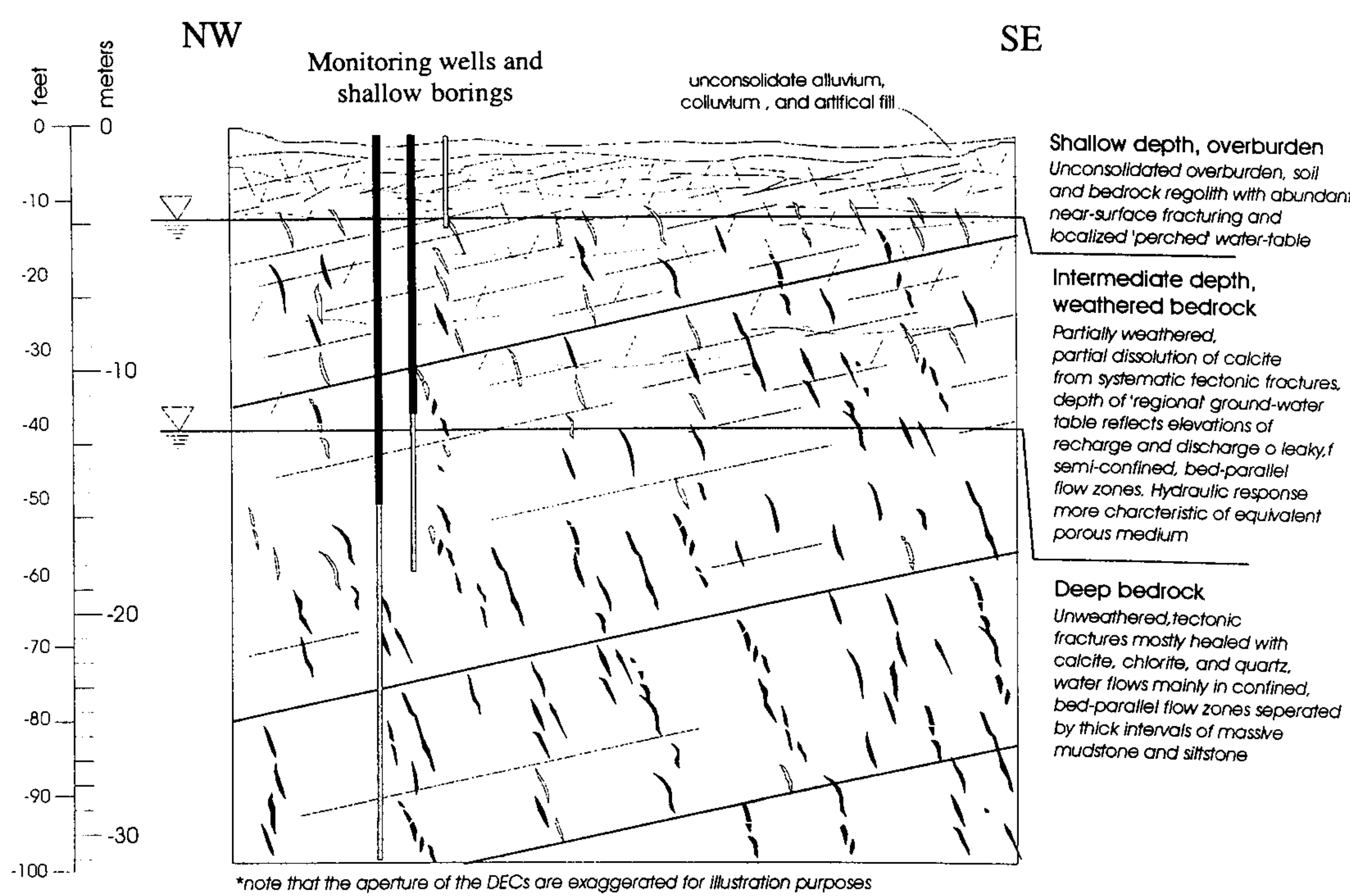


Figure 19. A profile diagram illustrating a three-tiered conceptual framework of fractured-sedimentary aquifers in unglaciated parts of the Newark Basin. Modified from the LMAS with weathered zone and overburden conceptual ground-water flow model for sites in the Newark Basin by Michalski and Britton (1997). DECs plugged by secondary minerals are colored black. DECs with dissolution of secondary minerals are uncolored. Transmissive water-bearing zones along sedimentary bedding represented by black lines inclined gently NW.

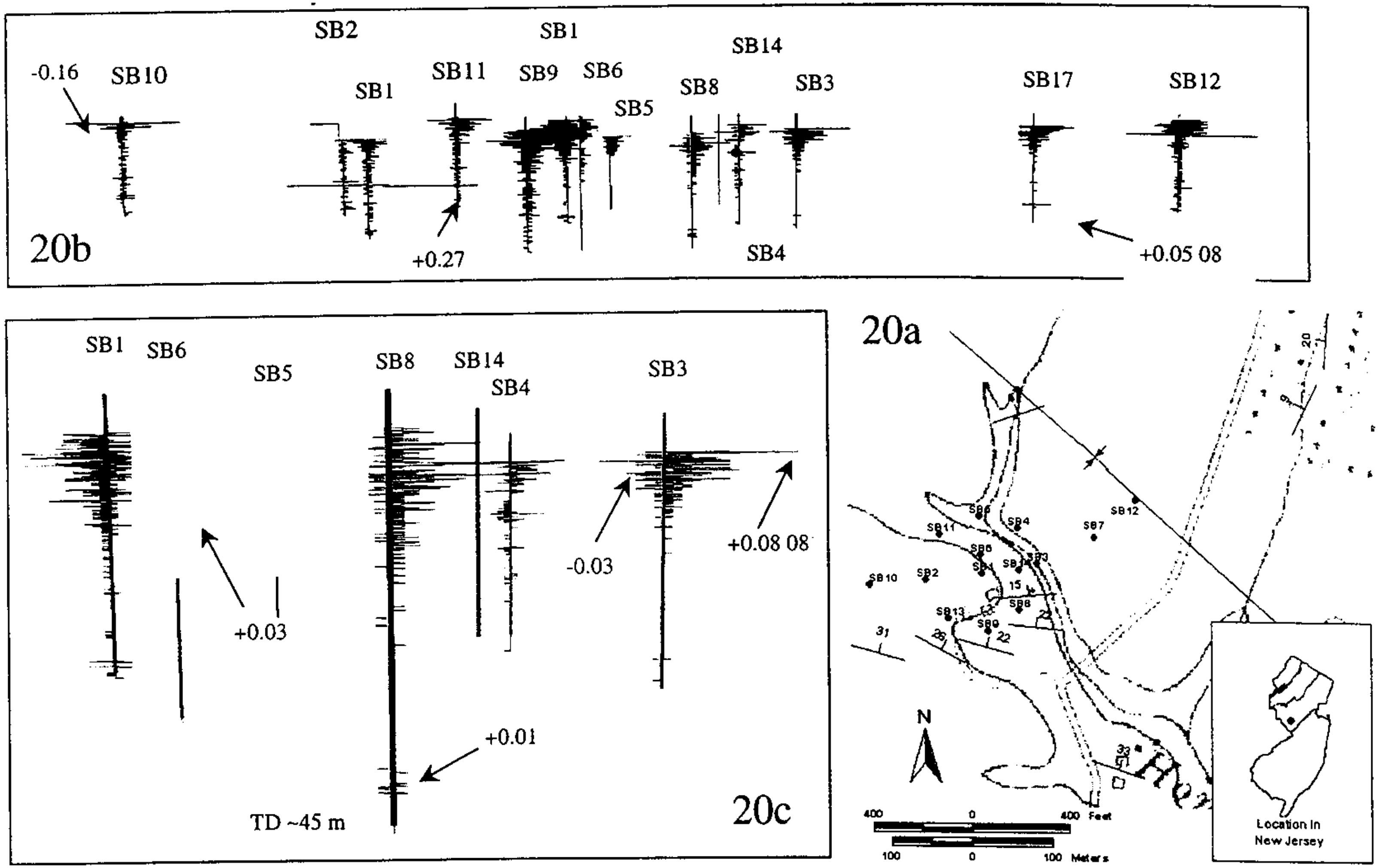


Figure 20. Fluid-temperature logs taken under static conditions from the bedrock well field at the Stonybook-Millstone Watershed Association (SMWA) provide insight into the depth of the weathered zone for mudstone and siltstone of the Brunswick aquifer. Figure 20a shows the bedrock orientation and location of wells at the SMWA preserve. Figure20b is a three-dimensional (3D) profile with a northwest perspective through the well field showing borehole fluid-temperature differentials below casing expressed in degrees Fahrenheit. Differential is calculated by subtracting successive temperature readings every 2.1-cm (0.1-ft). The depth of each well is about 45 m (150 ft) with 6 m (20 ft) of casing. Figure 20c is a close up of part of the well field and shows that fluid-temperature responses greatly diminish below 18 m (60 ft) at the base of the intermediate zone. Occasional temperature anomalies below this depth probably correspond to isolated flow zones in the deep zone. Well data and fluid-temperature logs provided courtesy of Glen Carleton, U.S. Geological Survey, West Trenton, N.J.

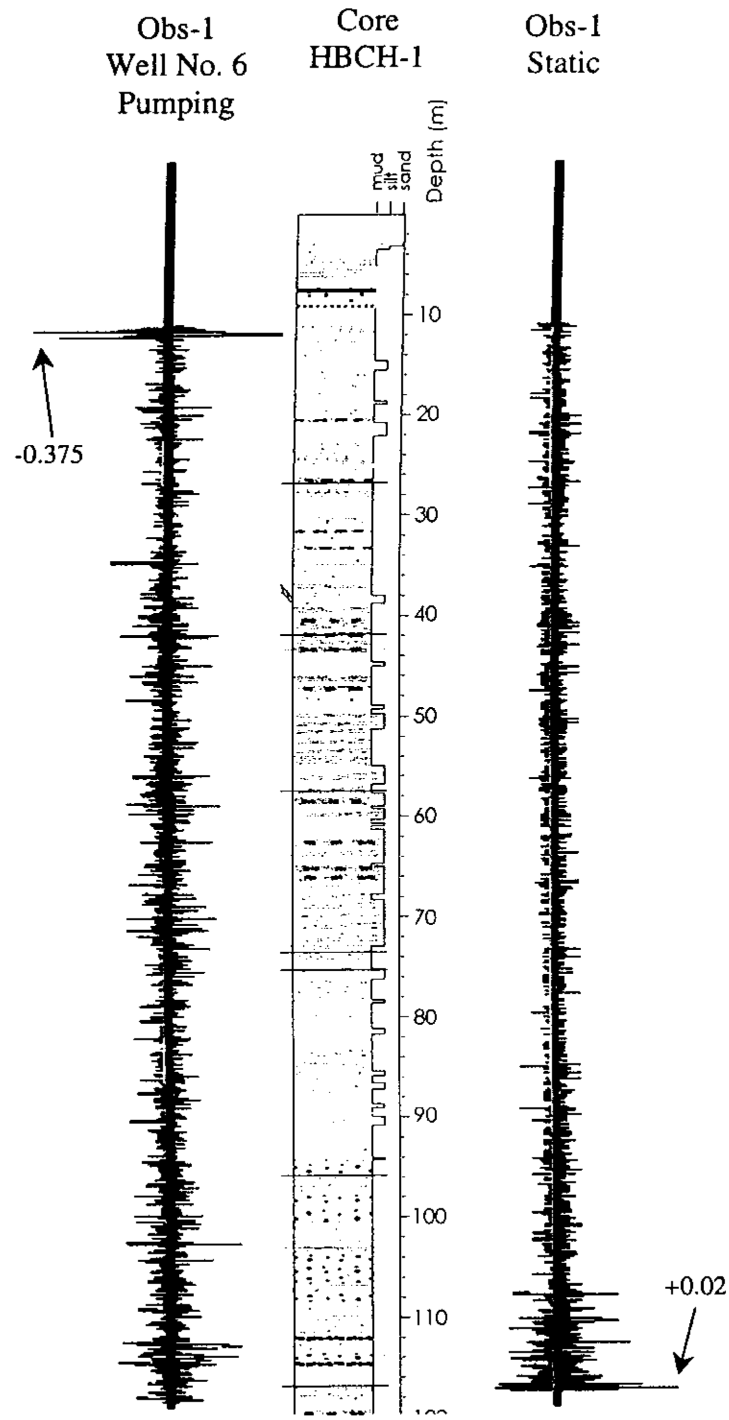


Figure 21. Comparison of fluid-temperature differentials (°F) in Obs-1 under static and pumping conditions in relation to the nearby core log. Differential readings under static conditions are two orders of magnitude lower than for the pumping conditions. Note the correlation between temperature anomalies and dissolution zones logged in the core and the pronounced anomaly directly below casing under pumping conditions. Location of wells and key to lithologic symbols shown in Figs. 5a and 6 respectively.

The N.J. Geological Survey has been mapping the bedrock geology of the New Jersey part of the Newark Basin at 1:100,00 to 1:24,000 scales over the past fifteen years. This work includes cooperative mapping efforts with the U.S. Geological Survey (Drake and others, 1996; Owens and others, 2000) and other 7-1/2-minute quadrangle mapping conducted under the U.S. Geological Survey STATEMAP program. I especially acknowledge Don Monteverde, Bob Canace, Jim Boyle, Mike Serfes, and Steve Spayd of the N.J. Geological Survey for contributing field data, valuable insights, useful methodologies, and manuscript reviews. Hugh Houghton and Jim Mitchell provided structural data from prior bedrock mapping. Seth Fankhauser mapped and compiled digital data in the Princeton 7-1/2' quadrangle during a summer internship with the NJGS.

This work also benefited from interaction and the exchange of data with hydrogeologists from the U.S Geological Survey including Glen Carleton, Pierre Lacombe, Jean Lewis-Brown, Zoltan Szabo, Mark Ayers, and Roger Morin. I also thank Paul Olsen and Mark Zdepski for their enlightening discussions on the geology and hydrogeology of the basin

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A PRACTICAL APPROACH TO BEDROCK AQUIFER CHARACTERIZATION IN THE NEWARK BASIN

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ABSTRACT

Proper hydrogeologic characterization is crucial for the success of any groundwater projects in the bedrock setting, including remedial investigation, aquifer remediation, wellhead protection, and water supply projects. The inherent complexities of fractured bedrock require using a different approach and characterization tools from those routinely used for unconsolidated aquifers.

Our approach starts with the recognition that the hydrogeologic framework of sedimentary bedrock at most sites in the Newark Basin is best conceptualized in terms of a leaky, multiunit aquifer system (LMAS). In this system, the more open bedding fractures act as major discrete aquifer units (and principal lateral flow pathways), while the intervening thick aquitard units provide for leakage via subvertical joints. A weathered bedrock zone and, in some areas, a saturated overburden zone are superimposed on the multiunit bedrock system. Since strong vertical hydraulic gradients are common in such systems, open holes/wells that are installed at random with respect to the multiunit aquifer structure often result in cross-flows that can significantly alter preexisting flow and contaminant migration patterns. Therefore, the hydrogeologic characterization of sites with old supply or monitoring wells should also include the evaluation of impacts of such wells on the patterns.

The use of temporary long open holes offers an effective strategy for rapid characterization and contaminant assessment at most bedrock sites, particularly those with NAPL sources. A long open hole short-circuits the various transmissive bedding fractures (discrete aquifer units) penetrated within the depth of interest, usually between 100' to 300'. Fluid conductance logs and in-well flow tracing results (or flowmeter data) are most revealing in locating such fractures. Packer testing can provide transmissivity estimates for each fracture/test zone and representative water quality samples for individual inflow-producing fractures/zones. Reliable water quality data for exit fracture(s)/zone(s) are obtained after converting the temporary long open hole to a permanent monitoring well screened against the exit zone. For rapid assessment of a DNAPL site, three temporary long holes are recommended. Two of these holes are placed along the strike of the beds; one located upgradient and the other downgradient of the DNAPL source area and at a safe distance from the area. The third temporary hole is installed down-section of the source area. With this approach, contaminant distribution can be characterized in terms of a site-specific

LMAS model. The hydraulic continuity of the discrete aquifer units identified should be verified through short-term pumping test(s).

INTRODUCTION

The Mesozoic bedrock of the Newark Basin (Olsen, 1980) is a half-graben filled predominantly with non-marine shale, mudstone, sandstone and basalt formations which typically exhibit a homoclinal dip of 5°-15°. The 2,700 square mile Newark Basin includes the highly urbanized area of north and central New Jersey where thousands of contaminated sites have already contaminated usable groundwater in fractured bedrock or pose a threat to still operating bedrock supply wells.

The success of any bedrock groundwater projects in the region, including remedial investigation, aquifer remediation, wellhead protection, and water supply/allocation projects, depends on an adequate hydrogeologic characterization of fractured bedrock at a given site. The inherent complexities of fractured bedrock require using a different approach to characterization than routinely used for unconsolidated aquifers. This paper discusses a strategy for a comprehensive hydrogeologic characterization of bedrock sites in the region. The strategy is based on the use of a realistic generic flow model for fractured bedrock and on employing characterization tools that target transmissive fractures. The approach outlined in this paper has worked well at many sites in the Newark Basin.

CONCEPTUAL FLOW MODELS

Various models have been used to conceptualize the flow of groundwater in fractured bedrock in the Newark Basis (Figure 1). The equivalent porous medium (EPM) model enables to extend the use of flow and transport analyses that were originally developed for the granular porous media to fractured bedrock sites. A two-aquifer EPM model (Figure 1) is often used to deal with significant differences in water level elevations between "shallow" and "deep" wells observed at many bedrock sites. This model is sometimes expanded to a three-aquifer EPM system featuring “shallow”, “intermediate” and “deep” bedrock aquifers, with arbitrarily selected depth ranges for such horizontally-sliced aquifer zones. Although widely utilized, the EPM approach ignores the real structure of bedrock aquifer and does not promote an adequate characterization level usually needed for contamination and wellhead protection applications.

A third conceptual model postulates that near-vertical joints subparallel to the strike of beds provide primary flow pathways through the bedrock and produce its anisotropic behavior. This model can be traced back to Herpers and Barksdale (1951) who observed an anisotropic, elliptical drawdown response during a pumping test conducted in Newark, NJ. The idea that anisotropic behavior of bedrock is due to the alignment of near-vertical joints along the strike of strata was echoed in later publications (e.g. Vecchioli, 1967).

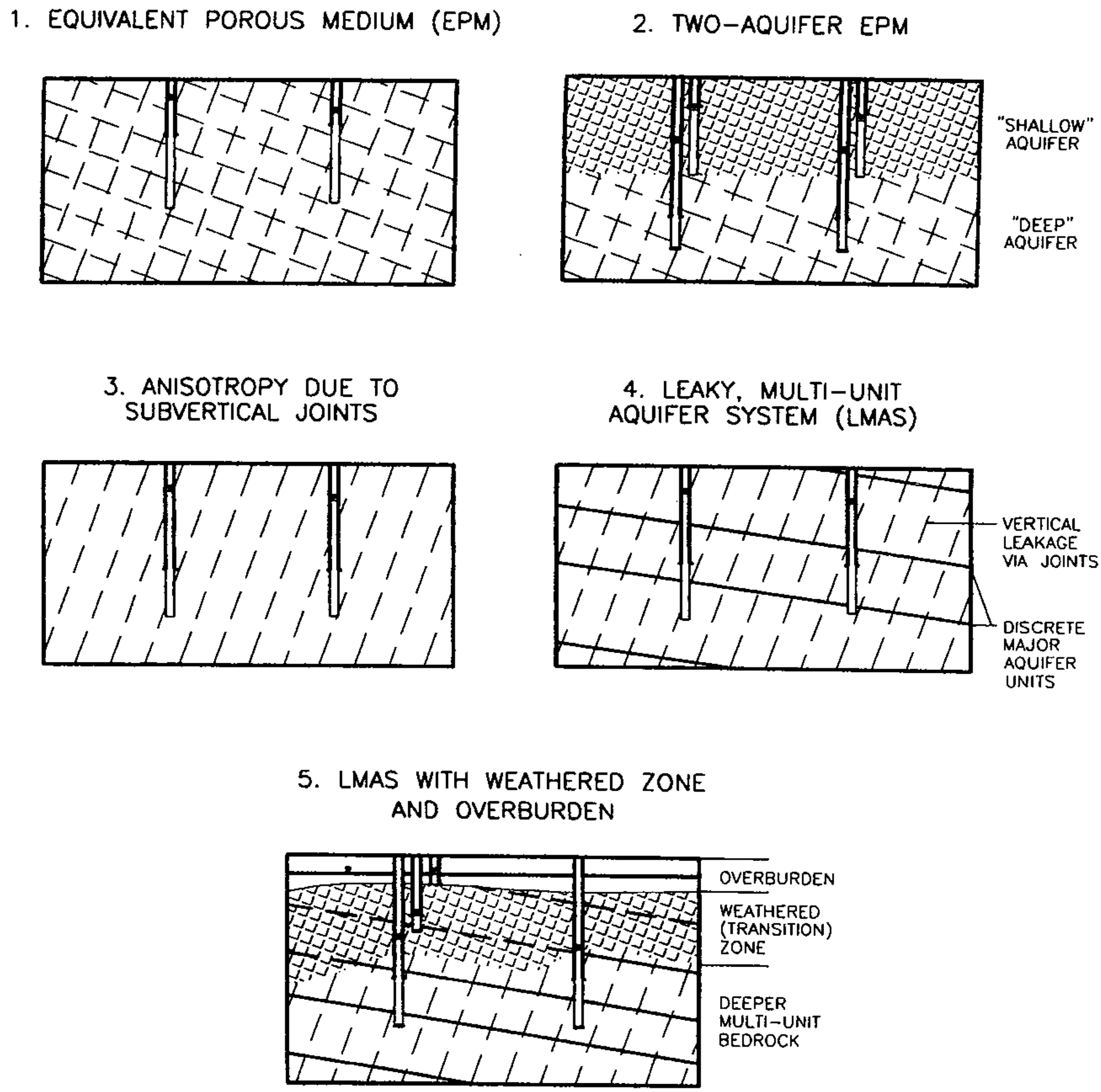

Figure 1. Various conceptual groundwater flow models used for sites in Newark Basin.

The fourth and fifth models in Figure 1 feature a leaky, multiunit aquifer system (LMAS) proposed by Michalski (1990) and Michalski and Britton (1997). In these models, the bedding-plane partings (or bedding fractures) with the greatest hydraulic apertures act as major, discrete aquifer units in the bedrock system. The water transmitting capacity of such larger-aperture partings is disproportionally high, in accordance with the cubic-type of relationship between the flow and fracture aperture. Owing to their high transmissivity and large lateral extent, the large-

aperture bedding fractures become low-head loci and discrete aquifer units attracting flows from adjacent beds. Near-vertical joints in those beds provide for leakage between the aquifer units. Field data indicate that the aquifer units associated with major bedding partings tend to occur at vertical intervals ranging from less than 30' to more than 150'. The layered heterogeneity of the multiunit system in a homoclinal setting imparts a strongly anisotropic behavior to the entire bedrock system.

The fifth model in Figure 1 represents a more realistic extension of the fourth model, whereby a weathered (transition) zone and a saturated overburden are superimposed on the LMAS model. Weathering processes in mudstone and shale tend to produce numerous minute and poorly integrated fractures. Pre-existing major fractures may become clogged. The weathered zone generally exhibits a lower permeability and a greater storage than the deeper bedrock. Nevertheless, the extensions of the major bedding fractures into the weathered zone (Figure 1) still provide the principal pathways for downdip drainage across the weathered zone. Below this weathered zone, the prevailing ground-water flow direction within individual aquifer units tends to be parallel to the strike of beds. The dissolved contaminant plumes within individual aquifer units are known to extend in that direction for distances measured in thousands of feet. Figure 2 illustrates the LMAS model applied for a real site in the northern New Jersey.

VERTICAL CROSS-FLOWS

Strong vertical hydraulic gradients are observed within the bedrock system at many sites in the region. If an open hole/well penetrates two or more major bedding fractures (aquifer units) of the multiunit bedrock, vertical cross-flows can develop. Such cross-flows may significantly alter the preexisting hydraulic head, flow and contaminant migration patterns. By this mechanism, bedrock supply wells, both active and inactive, and old bedrock monitoring wells can play a major role in spreading contaminants, particularly chlorinated volatile organics, over significant distances within the bedrock system. Hydrogeologic characterization of such sites with pre-existing supply or monitoring wells poses an additional challenge, because the impact of each pre-existing well on the flow and migration patterns needs to be evaluated in the context of a site-specific, multiunit bedrock model unknown at the start of the characterization. The cross-flow problems of the past largely stem from the convenience of using the EPM approach in lieu of more realistic models that recognize the multiunit structure of bedrock aquifer systems in the region. To reduce potential vertical cross-flows, the current drilling regulations in New Jersey restrict the length of open-hole (screened) interval in bedrock monitoring wells to 25'.

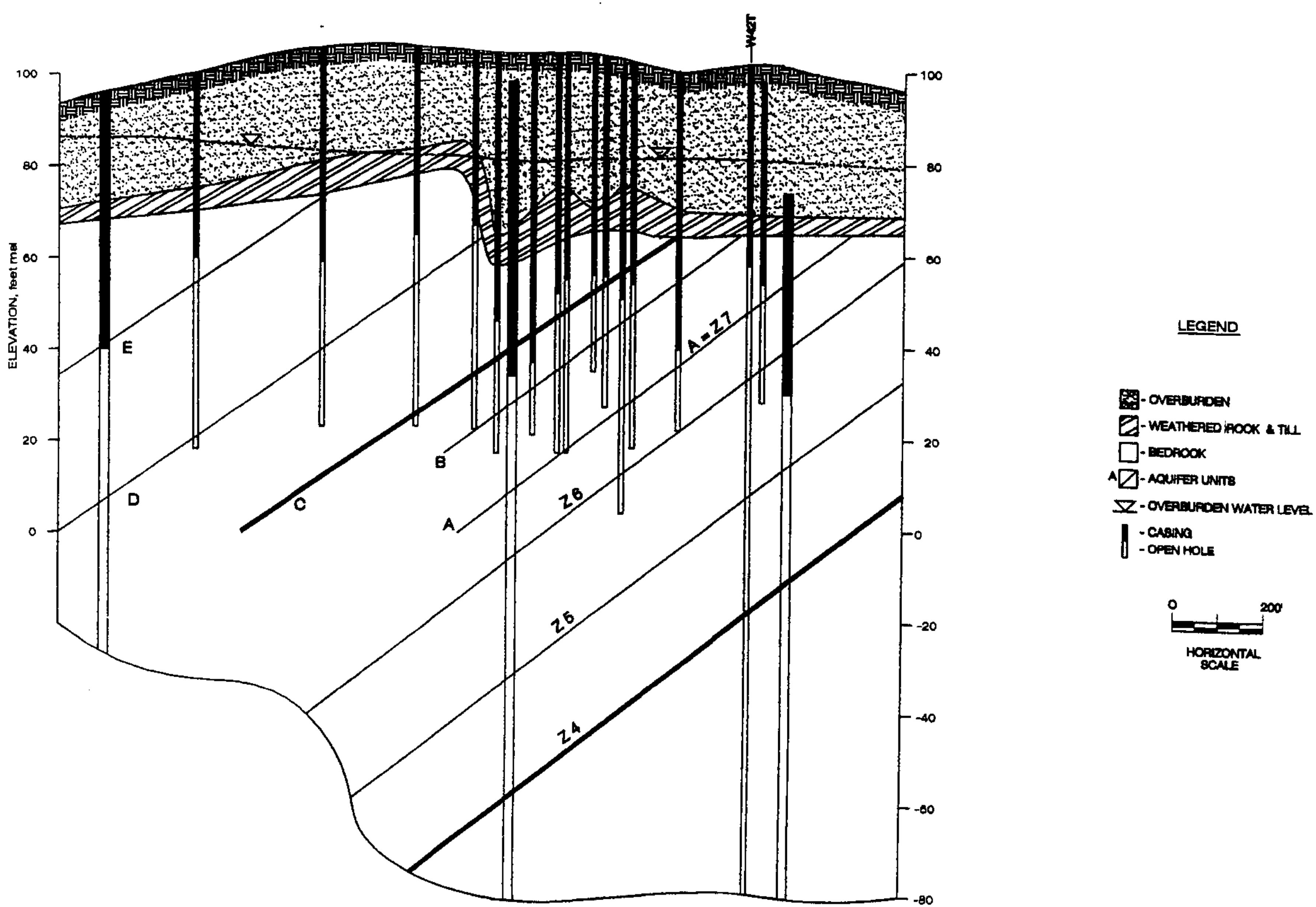

Figure 2. Cross-section showing bedding-controlled major (thick lines) and minor aquifer units interpreted at a site in northern New Jersey.

TEMPORARY LONG OPEN-HOLES AS A CHARACTERIZATION TOOL

While the occurrence of vertical cross-flows in bedrock wells can be harmful and should generally be avoided, long temporary test-holes also offer an effective means of rapid hydrogeologic exploration and characterization of any bedrock systems, if the following two conditions are satisfied: 1) The holes need to be installed and tested under controlled conditions and 2) They remain open only for a limited time period (a few weeks) and then should either be converted to bedrock monitoring wells or sealed.

Figure 3 illustrates the strategy of employing long temporary test holes (TTHs) at a typical site with suspected release of dense solvents (DNAPL) and with no preexisting wells present. The key factors considered in placement of the TTHs include 1) the strike of bedrock beds, which is the controlling factor for groundwater flow within transmissive bedding fractures, and 2) the location of DNAPL entry and DNAPL zone in the overburden. The first test hole (TTH-1) is placed upgradient of the DNAPL zone. This pilot hole is intended to identify and characterize discrete aquifer units penetrated, including background (upgradient) water quality in individual units. The second hole (TTH-2) is placed downgradient of the overburden DNAPL zone along the same strike-line as the first hole (Figure 3). This second hole yields information on the consistency of bedrock hydrostratigraphy beneath the overburden DNAPL zone and on the impact of this zone on downgradient groundwater quality in individual bedrock aquifer units.

The primary role of the third hole (TTH-3) is to explore possible DNAPL penetration into the bedrock. As the dense solvent phase tends to preferentially invade larger-aperture fractures (Kueper and McWharter, 1991), any larger-aperture bedding fracture (i.e. major aquifer unit in the LMAS concept) with its subcrop beneath the overburden DNAPL zone becomes a potential pathway for downward (downdip) migration of the DNAPL. Therefore, TTH-3 should be installed down-section of the overburden DNAPL zone (Figure 3) to a greater depth than the other two test holes so that it intercepts, as a minimum, any major aquifer unit with subcrop beneath the overburden DNAPL zone. A broken line drawn along the bedding (Figure 3B) is a graphical way of estimating the depth of TTH-3. At most sites, the depth would range from 100' to 350'.

The strategy outlined above incorporates the "outside-in" approach (Pankow and Cherry, 1996) in order to minimize the potential for inducing contaminant migration during investigation of suspected DNAPL sites. The investigation starts with assessing impacts of the DNAPL zone on the dissolved phase and then proceeds to assess the DNAPL source itself. The three-hole strategy allows the hydrogeologist for a fast, cost-effective and comprehensive characterization of bedrock hydrostratigraphy and vertical distribution of the dissolved and product phases, in the framework of a site-specific LMAS model. Such a model is developed based on results of tests conducted in each of the three tests holes. The model is then field-tested through performing short-term pumping test.

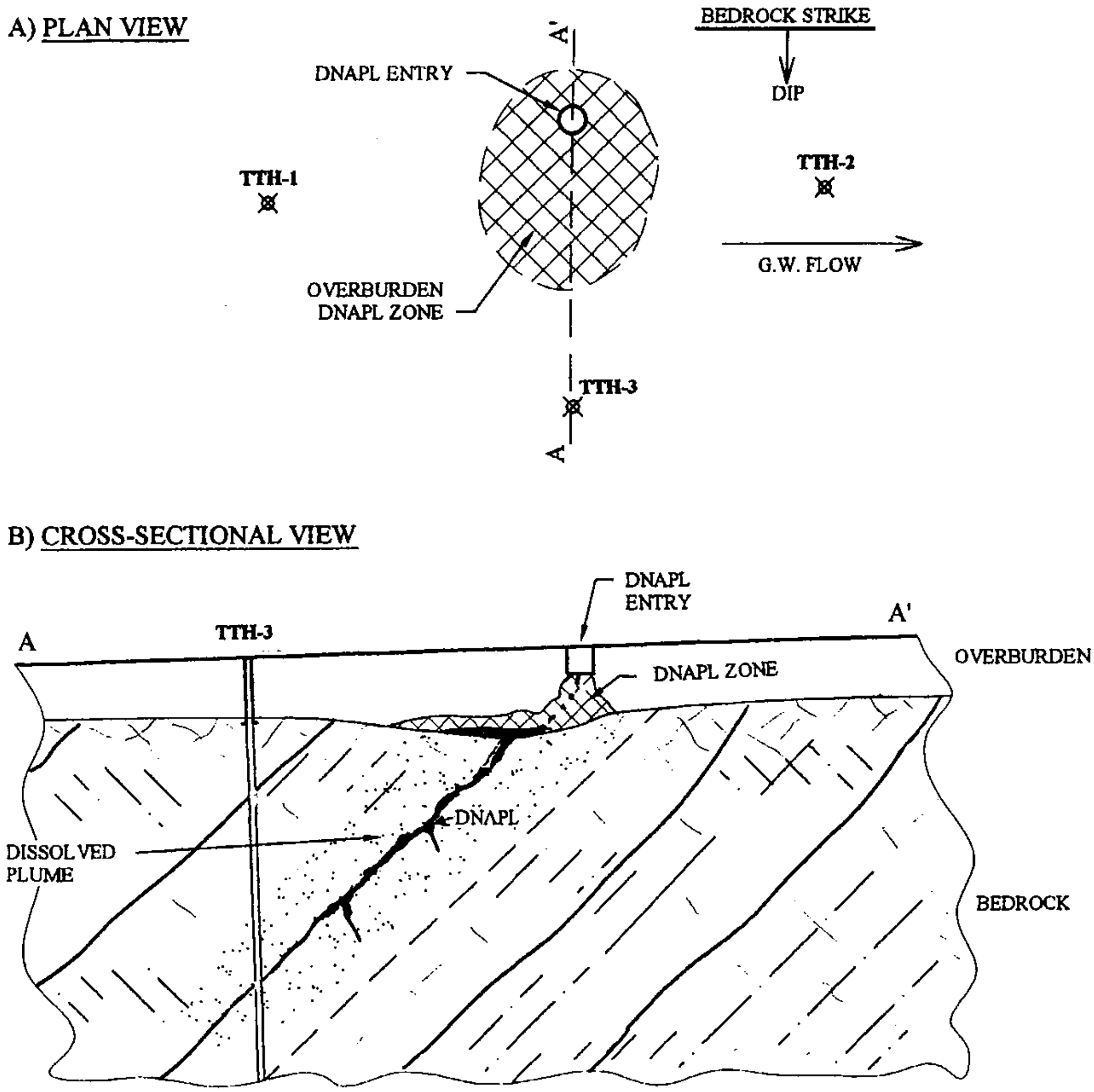

Figure 3. Placement of bedrock temporary test holes (TTH) at a typical DNAPL site.

TESTS PERFORMED IN TEMPORARY TEST HOLES

Identification of Transmissive Fractures

Fracture identification in test holes is usually the domain of borehole geophysics (e.g. Keys, 1990; Hsieh et al., 1993; Paillet and Crowder, 1996). Out of the many fractures commonly observed on rock cores or on the borehole walls in the Newark Basin, only a few usually transmit groundwater flow (e.g. Morin et al., 1997). Identification of such transmissive fractures, as opposed to any fractures present in open holes, is best accomplished through the use of flow-sensitive methods, specifically the following 1) Observation of water flows during air-rotary drilling, 2) Logging of electrical conductance (EC) and temperature along the water column, and 3) In-well flow tracing or flowmeter measurements.

The usefulness of EC and temperature logging stems from the notion that water entering the test hole from a transmissive fracture tends to exhibit a slightly different mineralization (thus different EC) and temperature than the water already present in the hole. The resulting mixing can produce inflections of the EC and temperature logs at the transmissive fracture location. Examples of such inflections can be seen in Figure 4 at approximate depths of 70', 96' and 103' of the background EC log obtained in a test hole prior to a tracer injection. Hole segments in-between the inflection represent aquitard units. Reproducibility of the background EC logs gives a good indication that vertical cross-flows and the mixing have reached a steady-state. This usually takes from several hours to several days following the hole completion. Although the EC log is not as revealing for locating water exit fractures, it provides a speedy means of selecting target depths for flowmeter measurements or injection of saline slugs to trace in-well flow cross-flows.

The in-well flow tracing tests can measure the amount and direction of cross-flows within the water column, thus providing additional data on locations of evidently transmissive fractures that are engaged in the cross-flows. The in-well flow tracing methodology is described elsewhere (Michalski & Klepp, 1990). Essentially, this test starts with the release of a small volume of saline tracer at a target depth, either by means of a weighted tubing or a sampling device. The images of the injected tracer are then tracked through repeated EC logging of the water column. A series of slug images obtained over time (like the series plotted on Figure 4) provides the basis for determining the direction and the amount of vertical flow, the location of water inflow and exit zones, and often the type of flow associated with each zone (discrete versus diffuse). The tracer images plotted on Figure 4 show that, following its release at a depth of 70', the tracer slug moved downward driven by the downward flow of fresh water, as evidenced by a sharp contact of the tops of tracer images taken within 30 minutes after the injection. A major increase in the downward flow below a depth of 96' is indicated by the sagging of the leading (lower) limb of the image obtained 30 minutes after the injection (Figure 4). Nearly all of the injected tracer (>90%) exited the hole through a major fracture at a depth of 122'. Based on the results of this test and two other tracing tests conducted in this hole, the amount of crossflows and water

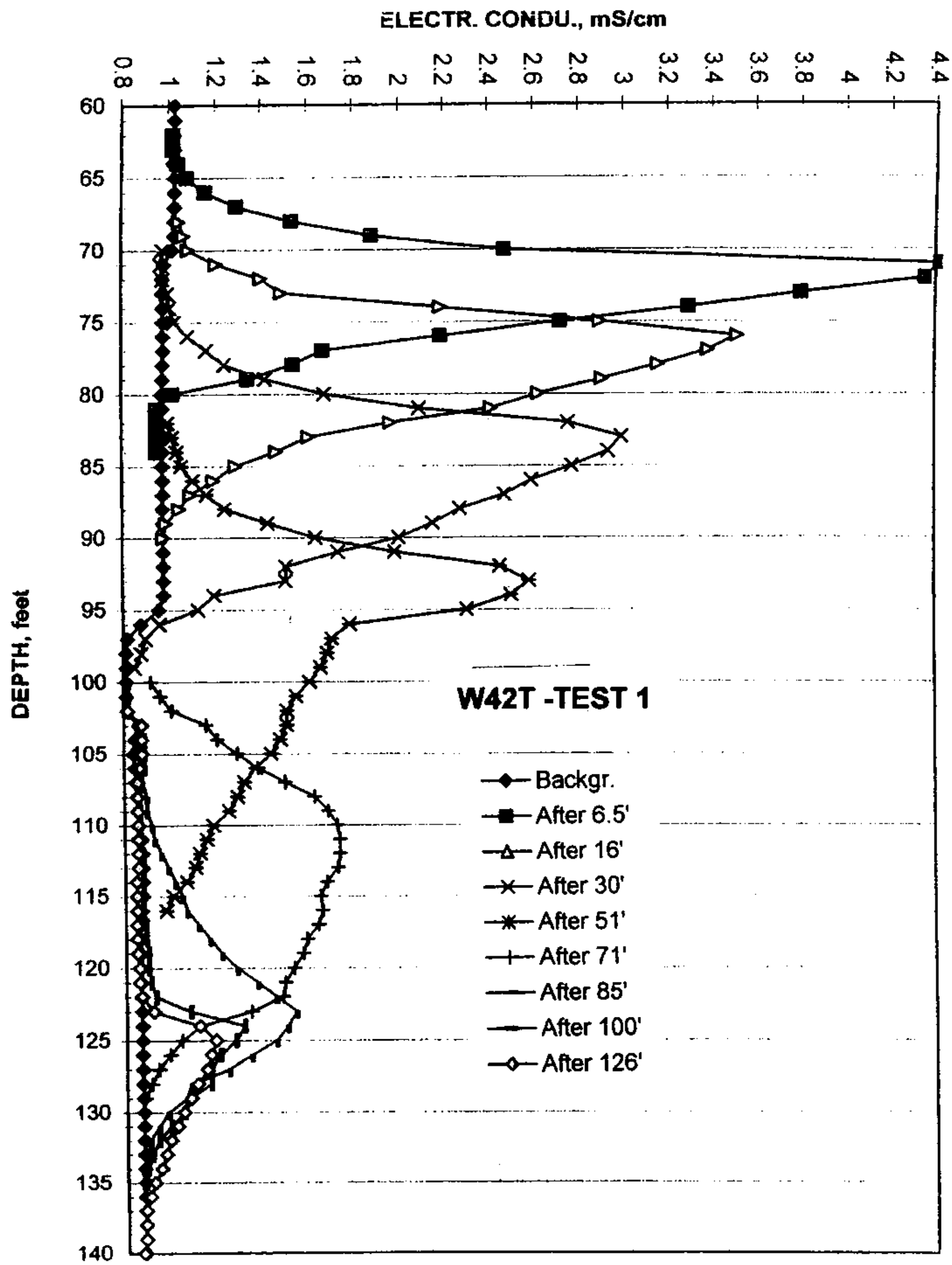

Figure 4. Background electrical conductance (EC) log and EC images of a saline tracer slug obtained at the indicated times (in minutes) after the tracer injection.

inflow/exit associated with each transmissive fracture is determined, as summarized by the middle graph on Figure 5.

The in-well flow tracing method is capable of detecting inflow and vertical flow velocity as low as 0.1 cm/min, which is approximately 20 times better than the reported resolution of the high-resolution heat-pulse flowmeter (Hess , 1985) of 2 cm/min. Most bedrock wells in the region, when tested under non-pumping conditions, show vertical velocities that are below the resolution of the heat-pulse flowmeter but can still be important for a long-term contaminant migration. For a 6" diameter open hole, the resolution velocity of 2 cm/min corresponds to an undetected vertical flow of about 130 gal/day.

Characterization of Individual Fractures (Aquifer Units)

In addition to the flowrate aspect, a complete characterization of a transmissive fracture in a test hole includes a determination of fracture transmissivity, hydraulic head and water quality in the fracture. In cases where the latter aspect is of primary interest, discrete water samples collected just above and below an inflow fracture allow the assessment of contaminant contribution from the fracture, if the amounts of inflow and the vertical flow are also measured. A simple Kemmerer sampler can be used for that purpose (Michalski et al., 1992). No purging is needed because of the self-purging nature of the cross-flows. This type of discrete sampling can be useful for evaluating possible adverse impacts of test-hole installation on contaminant migration and a safe duration of keeping the test hole open.

A more complete characterization of individual transmissive fractures identified in the test hole is possible by means of straddle packer tests. Although the use of packer testing is not uncommon in bedrock wells/holes, its role is usually limited to packer sampling. A full packer test setup consists of two inflatable packers set 5' to 10' apart, a submersible pump set in the test zone with a fracture isolated by the packers, a flowmeter, and pressure transducers set within, directly above and below the tested interval. Prior to inflation of the packers, readings of all transducers are re-set to zero. A stabilized reading of the test-interval transducer obtained after inflation of the packers (but prior to any pumping) corresponds to the hydraulic head value within the fracture tested relative to an ambient head in the test hole prior to the inflating of the packers. (This ambient head is actually a composite of the heads in all transmissive fractures involved in the crossflows.) The left-hand graph on Figure 5 provides an example of relative head distribution obtained by this method in seven test zones of a test hole .

A constant-rate pumping of the packed-off interval is then performed until the following conditions are met 1) the drawdown reaches a stabilized value, 2) an equivalent of at least 1-2 volumes of water in the packed-off interval is removed, and 3) stabilized readings of the EC and temperature of the discharged water are obtained. This pumping serves a dual purpose: First, it allows one to estimate the transmissivity of the packed-off fracture based on the steady-state (Thiem) formula (Cedergren, 1989; p. 53) and the measured flowrate and drawdown values. Examples of the calculated transmissivity values for seven packer-tested zones in a test hole are

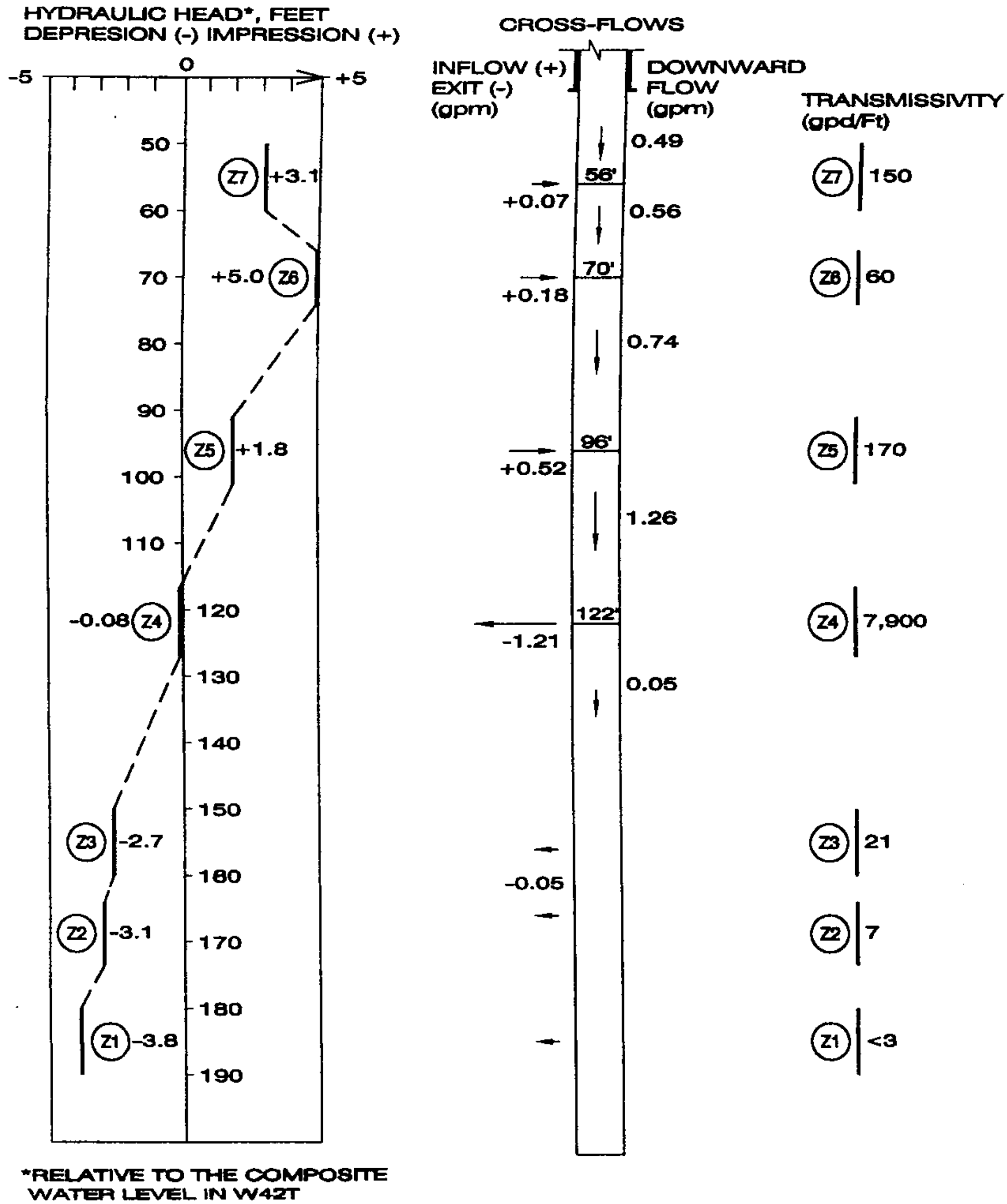

Figure 5. Synthesis of results from in-well flow tracing (the middle graph) and packer testing in test hole W42T. This test hole is also identified on Figure 2.

provided in Figure 5. The most transmissive fracture at 122' shows a transmissivity value of 7,900 gpd/ft and accounts for an estimated 95% of the total transmissivity of this 200' deep test hole. This fracture deserves to be designated as a major discrete aquifer unit, while other transmissive fracture may represent minor aquifer units. Second, the pumping provides for purging of the packed-off segment necessary to collect a sample truly representative of water quality and contaminant concentrations in any of the inflow-producing fractures. In general, packer sampling of the water exit fractures may not provide representative water quality data, as such fractures may to too impacted by the preceding injection of water from the inflow fracture. Therefore, the water exit fracture(s) become the primary targets for monitoring when the temporary test hole is converted to permanent monitoring well(s).

SYNTHESIS OF THE DATA AND VERIFICATION OF SITE-SPECIFIC LMAS MODEL

The information on the position/elevation of transmissive fractures in individual temporary test holes (Figure 5), together with the data on fracture transmissivity values, crossflows, relative heads and, if applicable, contaminant distribution provide the basis for the development of site-specific model of groundwater occurrence and flow in the bedrock as a LMAS system. The information acquired from each temporary test hole (and any other well tested) is projected on a vertical plane drawn perpendicular to the local strike of beds (e.g. Figure 2), and an attempt is made to correlate the various transmissive fractures identified in individual holes under a working hypothesis that these fractures follow the bedding. Fractures whose extent is limited to a single hole/well would not be considered as transmissive bedding fractures (aquifer units).

Such an early conceptualization of site-specific bedrock hydrogeology should be viewed as a draft flow model that needs improvements and should always be verified. Improvements generally require installation of additional test holes and wells/piezometers to address specific issues of concern. The best verification tools for the flow model include short-term pumping tests and, if applicable, the use of contaminants as tracers. A short-term pumping test is sufficient to verify the continuity of a major transmissive fracture between test holes/wells: Owing to the low storativity but high transmissivity of such a fracture, it takes only seconds to a few minutes for the pumping stress to propagate over distances of up to 1,600 ft under a confined condition in the fracture (Michalski and Britton, 1997). The pumping of the various packed-off intervals during packer tests provides the first opportunity of evaluating the degree of lateral hydraulic connections between the various aquifer units penetrated by test holes/wells if additional pressure transducers are placed in the holes. Also, routine well purging prior to sampling can be treated as a short-term pumping test. These verification tests can discern suspected breaks in the continuity of a bedding fractures tested between the pumping and observation holes, either due to faulting (e.g. Lacombe, 2000) or fracture closure/clogging.

On the other hand, the more costly standard-duration pumping tests, when interpreted in terms of conceptual models that do not account for a multiunit structure of bedrock aquifer system, usually produce confusing interpretations and ambiguous results. In a multiunit bedrock system, the determination of true hydraulic parameters and hydraulic gradient values as well as a true direction of groundwater flow (and dissolved plume migration), need to be performed in the context of specific major transmissive fractures treated as major aquifer units. The site-specific LMAS model that is field-verified and characterized on the level of individual major aquifer and aquitard units, provides a sound basis for development of numerical models of the site which can simulate a remediation or well-head protection problem at hand in a realistic and confident manner.

CONCLUDING REMARK

The bedrock characterization strategy outlined in this paper is for DNAPL sites, as such sites usually pose the greatest characterization challenge. However, this strategy can be applied to sites contaminated by gasoline/petroleum releases and can also be adapted to any sites with pre-existing bedrock supply or monitoring wells. A comprehensive approach built into this strategy offers the advantages of time and cost savings during site characterization. Above all, the results obtained provide a realistic and verifiable representation of bedrock hydrogeology and contamination problem, the key factors for a successful completion of any remediation or well-head protection projects.

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SIMULATION OF 3-DAY PUMP TEST FOR MUNICIPAL WATER SUPPLY WELL #12 IN BERLIN, CAMDEN COUNTY, NEW JERSEY

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ABSTRACT

This report presents the findings of a series of Visual Modflow computer simulations of groundwater flow intended to estimate the area of influence under transient pumping and steady state conditions from Berlin Borough municipal Well #12. This modeling effort is based principally on the review of available reports and regulatory records relating to the Berlin Borough municipal water supply Well #12.

Well #12 was constructed in June 1994 to tap the unconfined Kirkwood-Cohansey aquifer. A three day aquifer pump test was conducted at 735 gallons per minute (gpm) to determine the aquifer parameters. Well #12 is located approximately 700 feet south of the headwaters of the Kettle Run Creek which is documented as wetlands and is the habitat for the federally endangered Swamp Pink (*Helonias bullata*). The wetlands contain bacteria in the surficial sediments which is a source area for the isopropyl methoxy pyrazine (IPMP) detected in Well # 12.

In 1997, shortly after the well was turned on at approximately 460 gallons per minute for potable water use, residents complained of foul smelling and undrinkable water. Musty odors in groundwater can be caused by the byproducts of algae found in wetlands. An algae colony of Actinomycetes in the Kettle run was determined to be the source of the IPMP. Well #12 was shut down and retrofitted with a new granular activated carbon filtration system and reactivated on June 12, 2000. Shortly afterwards, residents noticed water level declines in the adjacent wetlands despite considerable precipitation.

The results of the Visual Modflow computer model for Well #12 pumping for three days discharging at 735 gpm does not show a zone of influence extending to the Kettle Run Creek. When the simulation is set with Well #12 pumping at 500 gpm for 100 days a cone of depression extends well beyond the Kettle Run Creek and a drawdown of 0.3 meters. The Visual Modflow program estimated it would take 400 days for the surface water from the Kettle Run Creek to be captured by Well #12. The computer simulation used actual pump test data to show that Well #12, when operating at 500 gallons per minute, is depleting streamflow from the Kettle Run Creek.

In July 2001 the State of New Jersey requested that Berlin Borough turn off Well 12. This report described herein was conducted as a Rutgers University class project with Dr. Ying Reinfelder

INTRODUCTION

The purpose of this groundwater model was to simulate steady state and transient data for approximating groundwater head distributions, flow direction, flowpaths and capture zones at the Berlin Borough municipal Well #12 and adjacent wetlands. Withdrawls from the municipal public water supply Well #12 are suspected of depleting streamflow from the adjacent Kettle Run Creek. Loss of federally protected biota resulting from depleted streamflow in the Kettle Run Creek is suspected. Bacteria contamination that has been detected in groundwater from Well #12 is also suspected to originate from the Kettle Run Creek. The computer simulation used pump test data and basic hydrogeologic assumptions to show that Well #12, when operating at 500 gallons per minute, is depleting streamflow from the Kettle Run Creek.

The model used the three dimensional finite difference groundwater computer program Visual Modflow, Version 2.8, provides a fully integrated graphical environment to recreate the Berlin Well # 12 hydrogeologic characterization. The software program Modflow was originally developed by the United States Geological Survey. The Visual Modflow software developed by Waterloo Hydrogeologic Software, Waterloo, Ontario, Canada uses Modflow with graphical pre and post processors. The program is used to model ground water flow and contaminant transport.

The primary objective of the model was to simulate the pumping condition induced capture zone in the shallow aquifer to evaluate pumping effects near the Kettle Run Creek. The aquifer parameters (transmissivity, hydraulic conductivity, and storativity) were determined through performing pump tests in June 1994. The results of these tests were submitted to the NJDEP.

STUDY AREA DESCRIPTION

Location

The subject municipal water supply Well #12 is located in Berlin Borough, Camden County, New Jersey (see Figure 1). Berlin Borough is situated approximately 20 miles east of the Delaware River and along the boundary line of Burlington and Camden County. The geographic coordinates for Berlin Borough Well #12 are 39° 47' 53" north latitude and 74° 54' 33" west longitude. The study area is located within the Clemeton, NJ USGS topographic quadrangle. The municipal water supply Well #12 is located on Maple Avenue near the intersection of Cooper Road, Berlin, NJ. The study area or domain area of the computer model simulation is located in both Burlington and Camden Counties.

Well #12 is not located in the designated New Jersey Pinelands area, although it is surrounded by the Pinelands on three sides. The Pinelands area surrounds Well #12 to the East, South and West. Some groundwater captured by Well #12 is derived from the Pinelands, which has strict regulations governing surface water, groundwater and land use. The study area is in a rural setting which consists of a combination of undeveloped woods, farm lands, wetlands, residential and commercial land use. A small cemetery, is located approximately 400 feet northwest of Well #12.

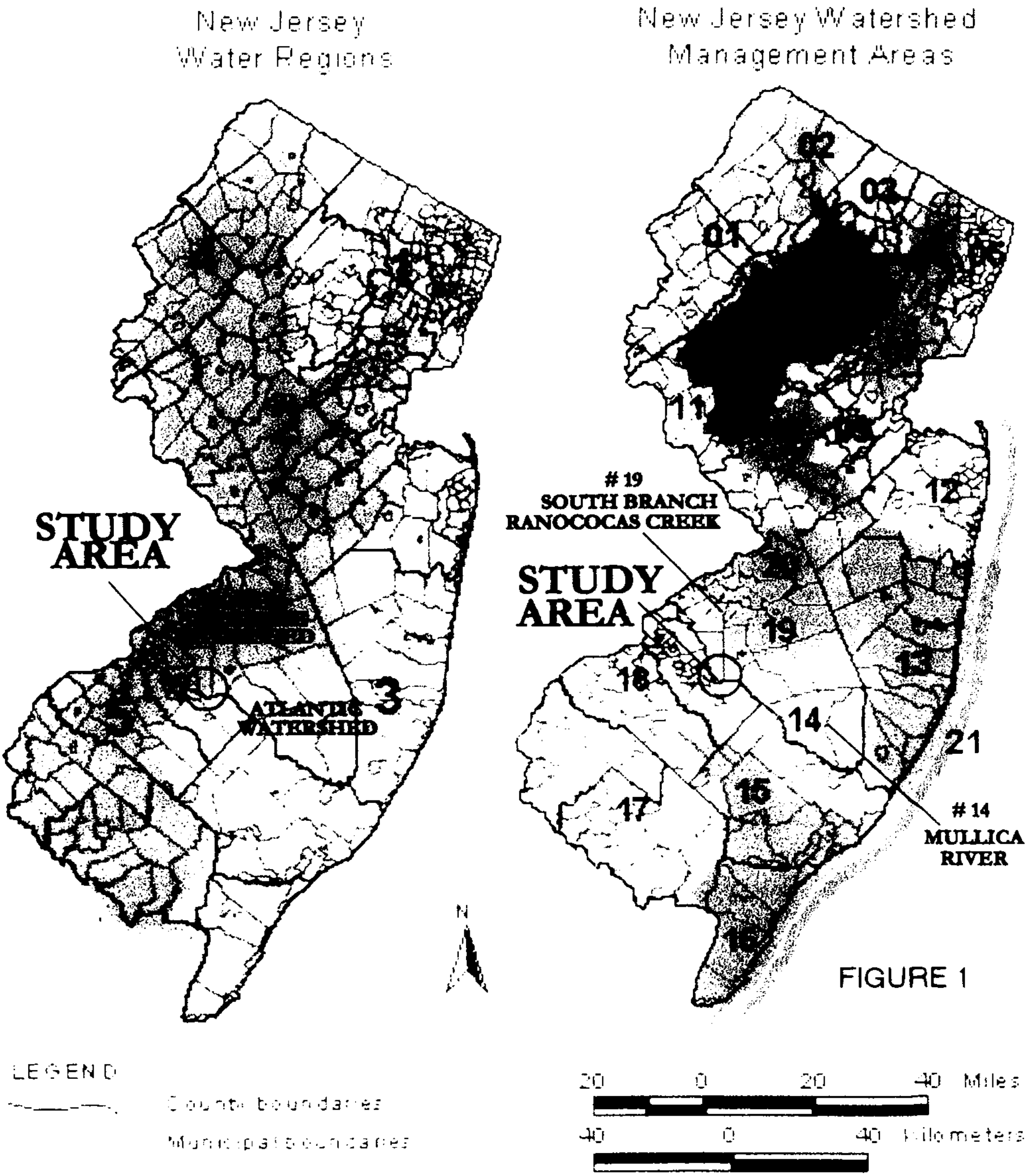

New Jersey Water Regions
STUDY AREA
ATLANTIC WATERSHED
3
N
New Jersey Watershed Management Areas
01
02
03
11
12
13
14
15
16
17
18
19
21
19 SOUTH BRANCH RANOCOCAS CREEK
STUDY AREA
14 MULLICA RIVER
LEGEND
County boundaries
Municipal boundaries
20 0 20 40 Miles
40 0 40 Kilometers

FIGURE 1

Hydrogeologic Setting

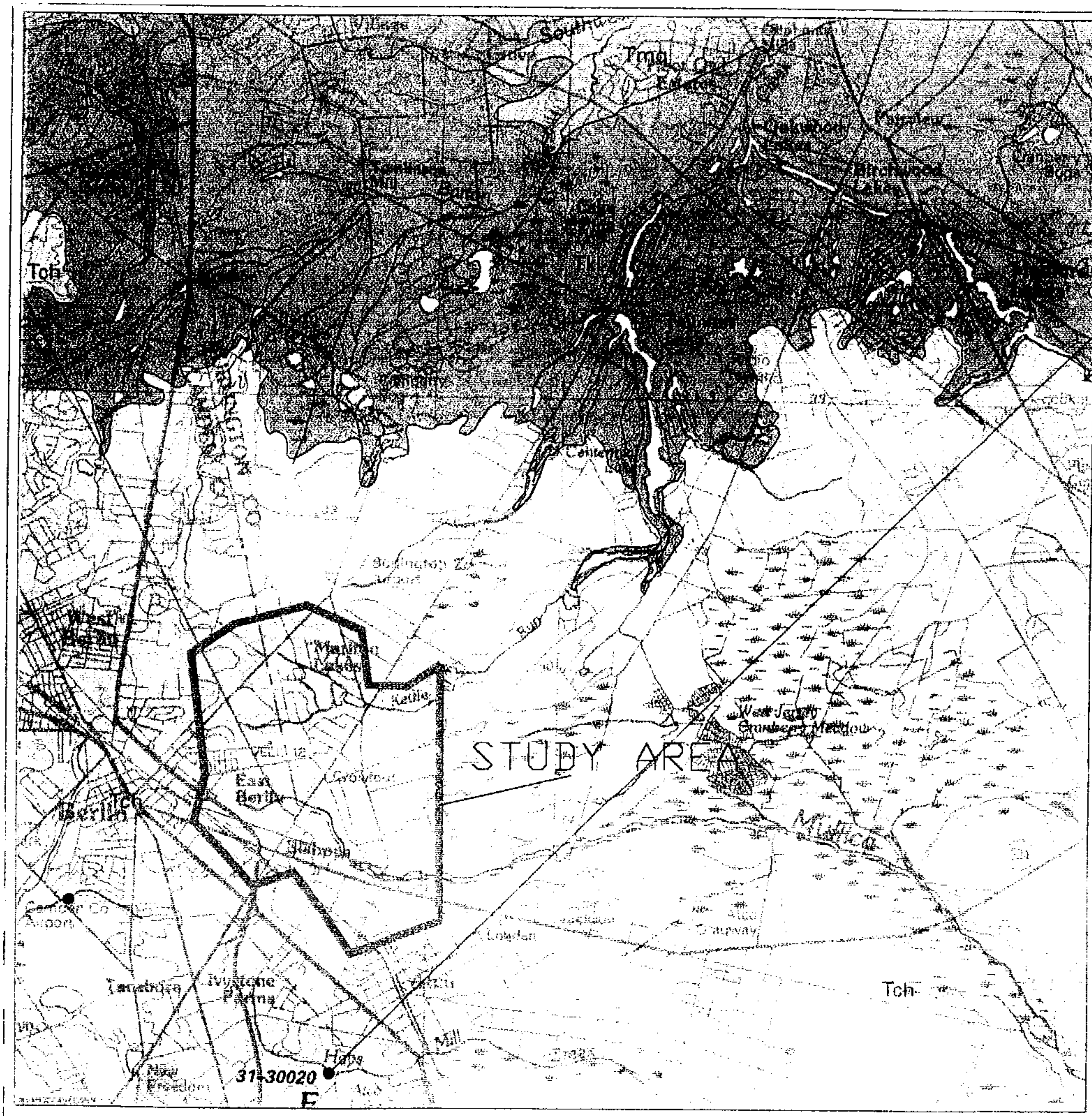
The area is located in the Coastal Plain Physiographic Province. According to available geologic maps and reports, the study area is underlain by Tertiary age unconsolidated deposits of the Cohansey Sand and Kirkwood Formations (see Figure 2). The unconsolidated material consists of clayey silts, sands and gravels.

The topography in the area generally exhibits a slope which dips slightly to the east. Surface elevations in the study area ranges from approximately 219 feet to 100 feet above mean sea level (see Figure 3). Surface and regional groundwater flows towards the east. A groundwater divide is located between the northern and southern boundaries (see Figure 4). North of Well 12 is the headwaters of the Kettle Run Creek which discharges to the Marlton Lakes and eventually to the Lower Delaware Watershed and Delaware River. To the South of Well 12 is the headwaters of the Mullica River and Mullica River Watershed, which ultimately discharges to the Atlantic Ocean.

The study area is within the Cohansey Sands Formation. From a thin outcrop area located approximately two miles North of the study area, the Cohansey Sand Formation dips and thickens southeast to form a wedge. The Cohansey Sand represents most of the surface deposits throughout the New Jersey Coastal Plain. The Cohansey Sand Formation (late Miocene to early Pliocene) consists of fine to medium-grained arkosic quartz sand (well stratified and cross-bedded), with thin clay lenses and quartz and quartzite pebble conglomerate. The unit represents a range of sedimentary environments ranging from fluvial to transitional marine environments (swamps, deltas, lagoons, beach sand, and shallow open marine shelf).

Unconfined ground water in the area is found within the Cohansey Sands deposits and is used as a potable water aquifer. The outcrop areas of the Cohansey Sands Formation provides a major source of recharge to the lower confined aquifers. Beneath the unconsolidated Cohansey Sands deposits, is the Kirkwood Formation (middle Miocene). The Kirkwood Formation consists of a clayey to silty sand with thin pebble lenses deposited in a sublittoral to nearshore environments. The bottom of the Kirkwood sits unconformably on top of older Tertiary units. The thickness is in the range of 100 to 300 feet. Together, the two formations are recognized as the Kirkwood-Cohansey aquifer system. In the study area, at Well #12, the Kirkwood-Cohansey aquifer is approximately 150 feet thick. The bottom of the Kirkwood Formation in this computer simulation is used as the bottom of the aquifer domain.

The study area is located within the area defined as New Jersey's Water Supply Critical Area #2. This area affects groundwater withdrawls from the Potomac-Raritan-Magothy (PRM) aquifer system, which is a confined aquifer located approximate 700 feet below grade. Berlin owns a total of six public water supply wells, three wells are located in the PRM aquifer, one well is in the Mt. Laurel-Wenonah aquifer and Well #12 and Well #14 are in the Kirkwood-Cohansey aquifer. The NJDEP has placed restrictions on groundwater withdrawls from the PRM aquifer and in 1994, Berlin requested from the NJDEP permission to divert water from the unconfined Kirkwood-Cohansey aquifer. Since 1995, the NJDEP Water Allocation Permit # 5044 has allowed for a groundwater diversion of 960 million gallons per year from the six wells. A total of 40 million gallons per month is permitted from the Kirkwood-Cohansey aquifer from Wells # 12 and # 14.



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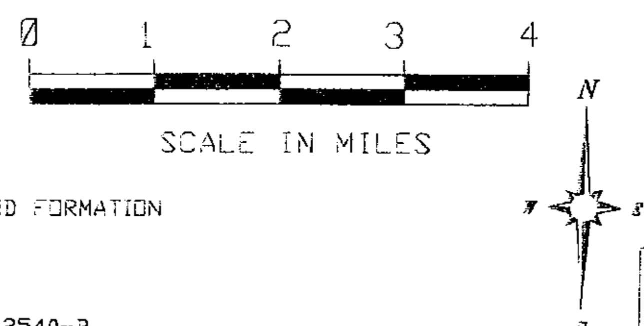


LEGEND

TCH = COHANSEY FORMATION

TKL = LOWER MEMBER KIRKWOOD FORMATION

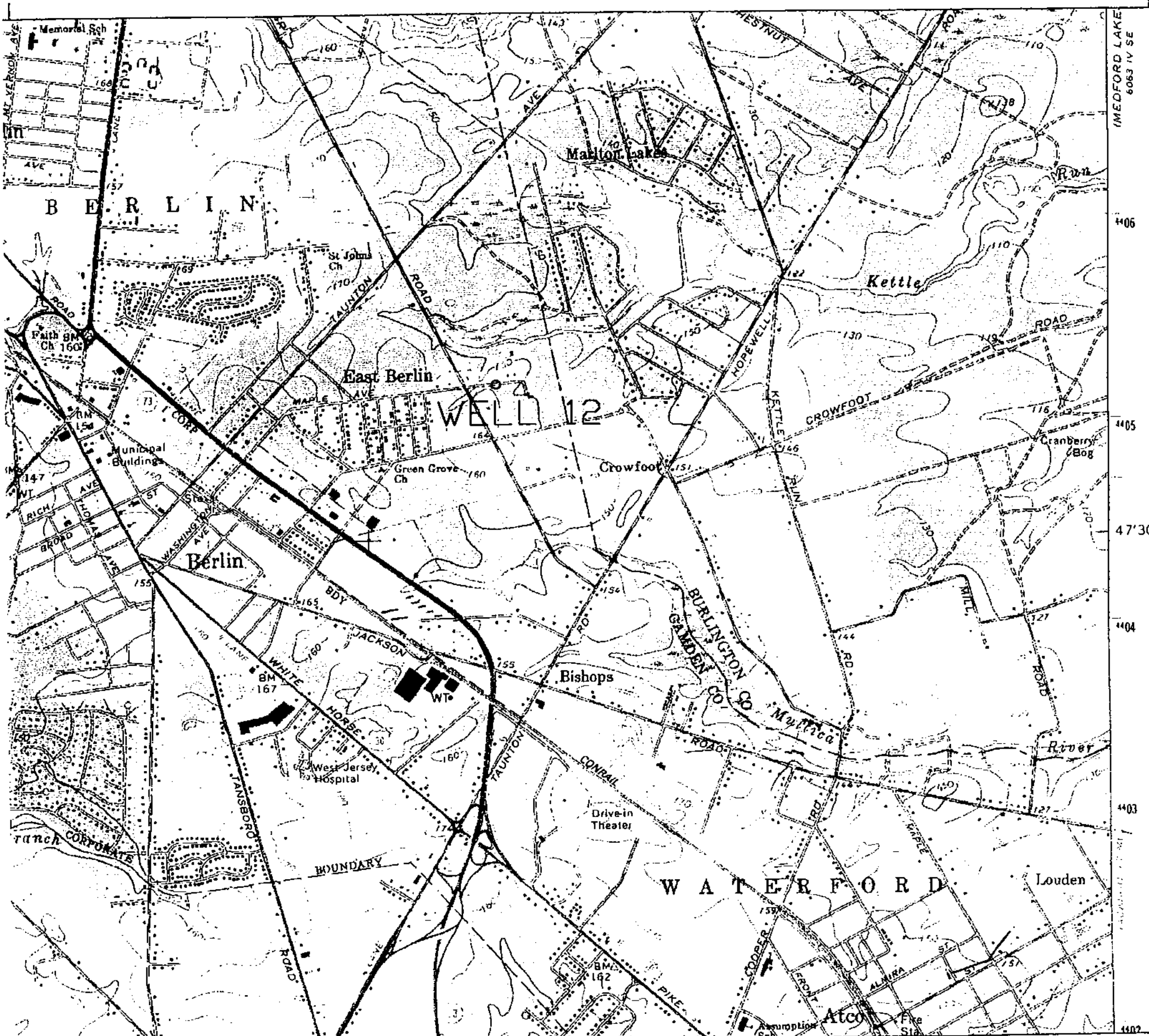
TMQ = MANASQUAN FORMATION

U.S.G.S. MAP 1-2540-B

SOURCE: BEDROCK GEOLOGIC MAP OF CENTRAL AND SOUTHERN NJ

FIGURE 3
REGIONAL GEOLOGIC MAP

BERLIN, NEW JERSEY



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SCALE IN MILES

N W E S

SOURCE: CLEMENTON, NJ USGS TOPOGRAPHIC MAP, 1967

FIGURE 3
TOPOGRAPHIC MAP
BERLIN, NEW JERSEY

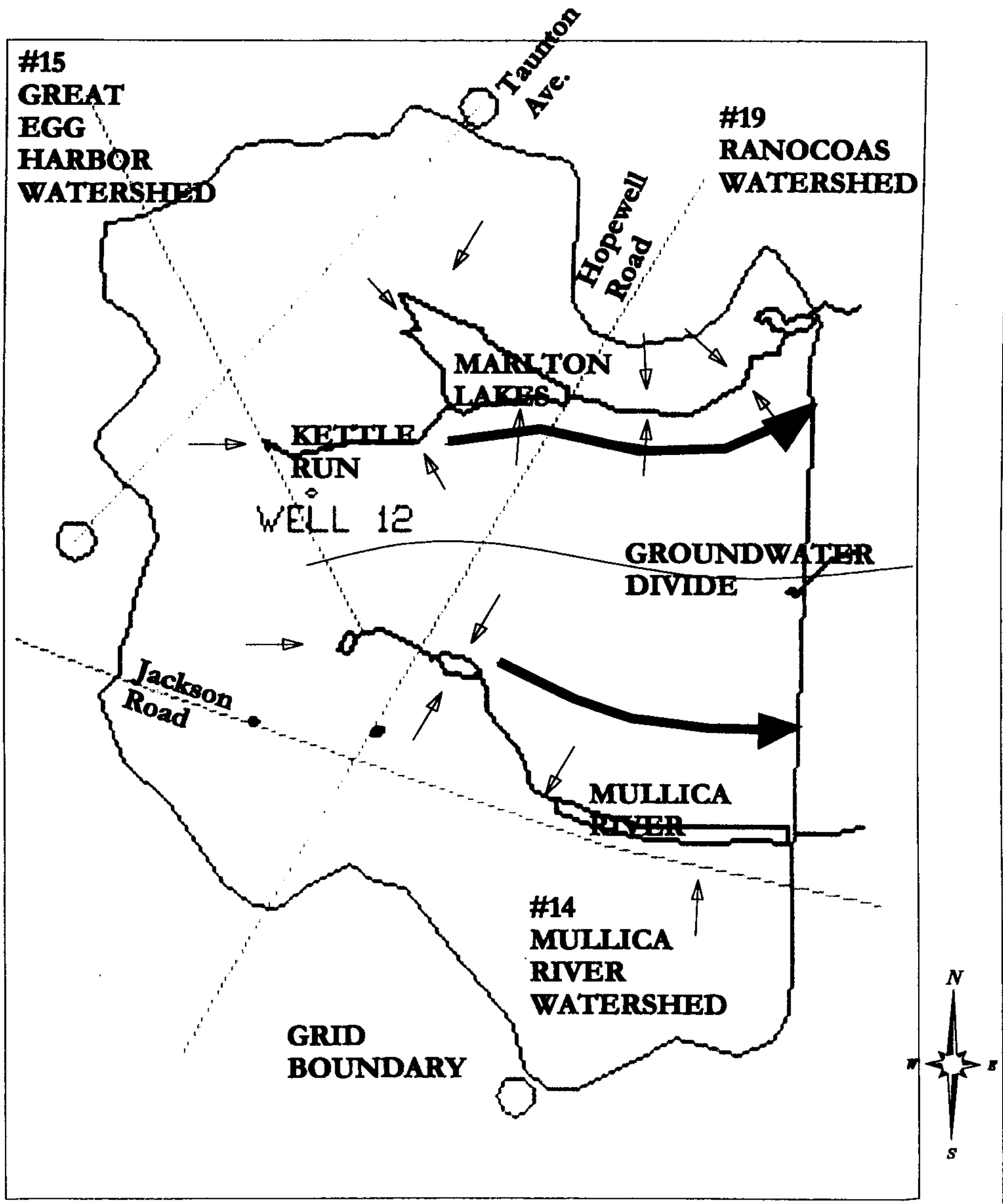


FIGURE 4
CONCEPTUAL MODEL
BERLIN, NEW JERSEY

Within the study area, the depth to ground water ranges from 12 to 17 feet below grade. Based on topographic relief, surface water flows easterly within the study area. Groundwater flow was determined to flow towards the east.

Four wells located within the study area were used in this simulation. The wells range in total depth from 40 to 84 feet below grade. Wells #1, #3, #12, used as observation wells, are located adjacent to Well #12 to measure water levels. The Dynasil well is located 2500 feet to the northwest. Water level data from the USGS was used to setup the initial head values in the computer simulation.

On May 5, 1994, Berlin's Well #12 was completed. Well #12 is 18 inches in diameter, 84 feet total depth, and has a stainless steel well screen 27 feet long, set at 54 to 81 feet below grade. Well #12 is capable of pumping approximately 750 gallons per minute.

Surface Water, Wetlands and Precipitation

Surface Water

The study area is located within two New Jersey Water Regions, specifically the Lower Delaware (5) and the Atlantic Coastal (3) and two Watershed Management Areas specifically the Southwest branch of Rancocas Creek(19) and Mullica River (14) (see Figure 1). The study area has an irregularly shaped domain area containing approximately 8 square miles. Three main surface water bodies occur in the study area; the Kettle Run Creek, Marlton Lakes and the Mullica River. The Kettle Run Creek flows west to east and the headwater originates approximately 1000' northwest of the Berlin Well #12 and discharges to the Marlton Lakes located 2500 feet northeast of Well #12. Water from the Kettle Run Creek eventually discharges to the Delaware River. The Mullica River, which is also the boundary line between Camden County and Burlington County, flows to the southeast and eventually to the Atlantic Ocean. The headwaters of the Mullica River is located approximately 2,500 feet south of Well #12.

Wetlands

Well #12 is located 700 feet south of the headwaters of the Kettle Run Creek. Within the study area, the entire length of the Kettle Run Creek is documented as wetlands. The northwestern portion of Marlton Lakes is adjacent to a large area of wetlands. The headwaters of the Kettle Run Creek and downstream in the area of Hopewell Road, where the Kettle Run continues flowing past the Marlton Lakes, contain the federally endangered Swamp Pink (*Helonias bullata*).

The wetlands contain bacteria in the surficial sediments. Results of bacteria samples collected in August 1997 from the Kettle Run Creek, ranging from 700 feet to 3,500 feet away from the Municipal Well #12 indicate the creek is a possible source area for the isopropyl methoxy pyrazine (IPMP) detected in Well # 12.

Precipitation

Recharge to the aquifer system is through direct percolation of precipitation. Average precipitation in New Jersey is approximately 45 inches per year. Estimated recharge to the Kirkwood-Cohansey aquifer system is estimated to be 22 inches per year. The remaining precipitation leaves the study area either as streamflow or as evapotranspiration.

Sensitive Environmental Receptors

Sensitive environmental receptors are geographic areas that contain one or more significant natural or ecological resources that may receive impacts from adverse environmental conditions. Environmentally sensitive areas are located within the study area. These include surface waters such as the Mullica River and Kettle Run Creek, and wetlands, water supply Well #12, residential wells and critical habitats for endangered or threatened species, such as the Swamp Pink and timber rattlesnake. The US Fish & Wildlife Service has identified a core population of over 300 Swamp Pink plants along the streams and swamps adjacent to Well #12, which has been disappearing since June 2000.

Federal and State Records

The details and specifications of the water supply and observation wells used by the municipality were obtained from the New Jersey Department of Environmental Protection. Specifically the data (Excel files) from hydraulic testing conducted in 1994 were used to calibrate the model. Information regarding water levels for wells within the study area other than the Berlin municipal wells was obtained from the United States Geological Survey (USGS). The USGS maintains a database of synoptic water levels from wells in New Jersey. The USGS provided information on the Dynasil well, which is located approximatly 2500 feet north of Well #12. On June 3, 1996, the water level reported for the 40 foot deep Dynasil well was 16.56 feet below grade.

GROUNDWATER MODEL DESIGN

The conceptual model used features an isotropic flow system to represent the aquifer system composed of sands and interbedded silts and clays. The model area encompasses approximately 8 square miles (5500 by 4000 meters) and was extended beyond the natural hydraulic boundaries including the Mullica River, Kettle Run Creek and Marlton Lakes. At its northern, western and southern boundaries, topographic highs were used to define the model boundaries. The eastern boundary, located 1.8 miles from Well #12, was chosen as a constant head boundary where effects from pumping well #12 would not be detected. The eastern boundary is 3 miles in length. The western boundary is located upgradient and is 0.8 miles from Well #12 (see Figure 3). The top of an eastward dipping, low permeability unit is used as the base of the unconfined aquifer.

Domain and Grid

The model grid was oriented so that the columns are parallel to the North-South direction. The model was discretized horizontally into 55 rows and 40 columns. Model cells are smallest in the center part of the model with each cell size measuring 50 meter by 50 meter. At the edges of the model, cells are 100 meters square. The model is discretized vertically into 7 layers with a vertical exaggeration of 25 times. Model layers were developed to account for the Well #12 screen interval and the top of the Kirkwood Formation that is the base of the unconfined aquifer. The Kirkwood-Cohansey aquifer system in the area is estimated to be 150 feet (45 meters) thick.

Boundary Conditions

The following types of Visual Modflow boundary conditions were used; Constant Head, Drain, and Recharge. The upper boundary of the model represents the water table and a specified flux is applied to the top of this layer to represent areal recharge from precipitation. The northern, western and southern edges are bounded by no-flow cells representing drainage divides. Recharge was originally estimated at approximately 20 inches per year and was subsequently slightly adjusted during the calibration process. Recharge values ranging from 5 to 15 inches per year were published by the NJDEP (Open-File Map OFM-32) however the model would calculate many dry cells along the western domain area with low recharge. During model calibration, however, it became evident that some additional groundwater was required because dry cells were encountered under pumping conditions. Ideally the model domain area should be larger to eliminate the dry cells. The eastern boundary of the model contains a constant head boundary. Constant head values were measured from the USGS Clementon Quadrangle topographic map by using the elevation of the surface water along the Kettle Run, east of the Marlton Lakes, the Mullica River and along the eastern boundary of the model. The drain boundary was used along the headwaters of the Kettle Run Creek for approximately 3000 feet (900 meters) to the southwestern edge of the Marlton Lakes. In addition, approximately 1000 feet (300 meters) of drain boundary was used along the wetlands located northwest of the Marlton Lakes. A conductance value of 20 square meters per day was used for each drain boundary cell. The drain boundary was used to simulate wetlands.

The seven layer system contains unconfined sand units each approximately 20 feet (6 meters) thick. Results from pumping tests indicate the horizontal conductivity (Kx, Ky) of the aquifer unit has a value of 16.1 meters per day (m/d). Vertical hydraulic conductivity (Kz) was estimated to be 1/10 the horizontal conductivity of Kz or 1.6 m/d. Specific yield was determined from pumping tests to be 0.0671. Estimated values included specific storage at a value of 0.0062 m/d. Effective porosity is assumed at 0.2.

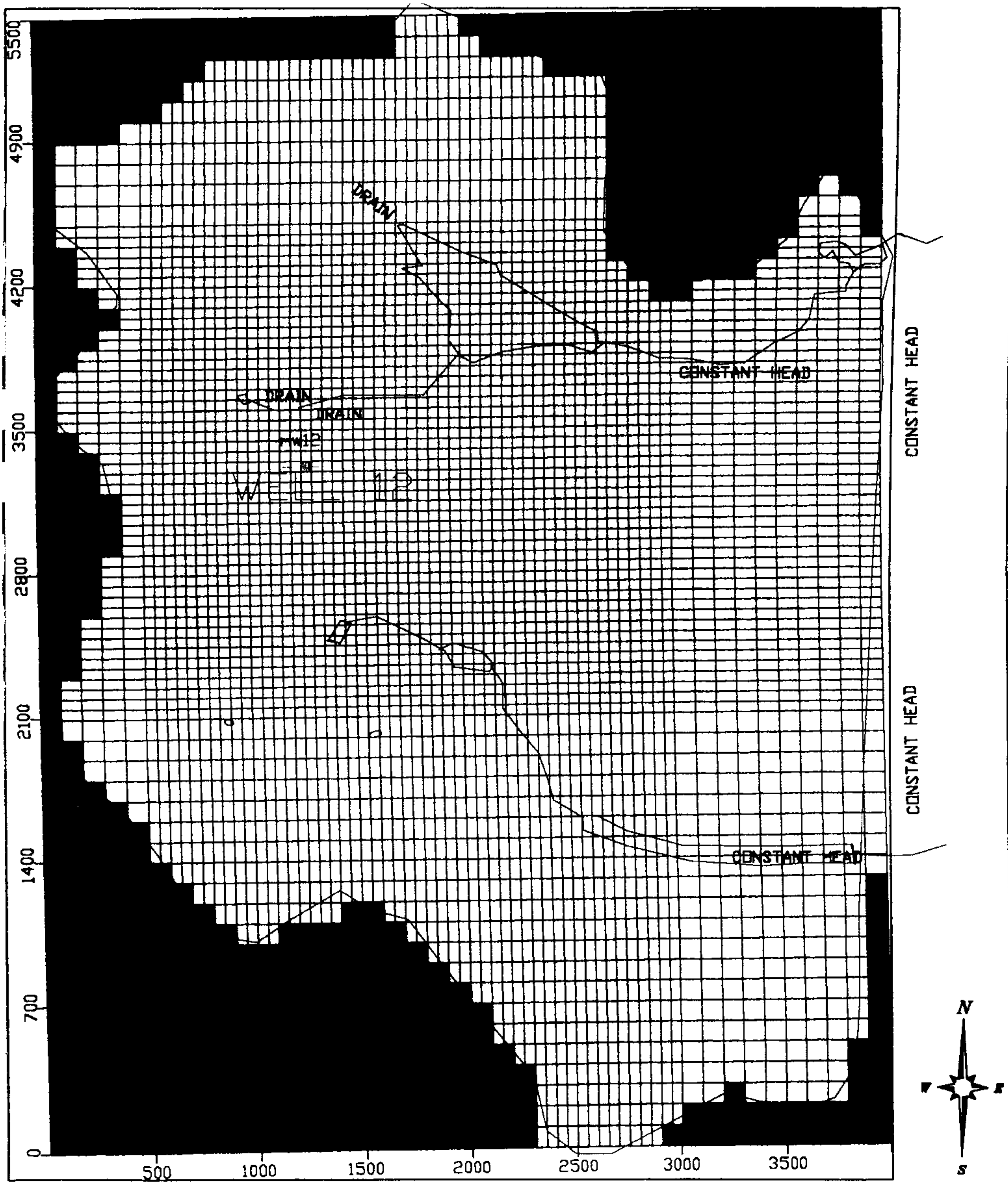
The pumping rates used in simulating and calibrating the computer model were 500 gallons per minute and 735 GPM.

Sources and Sinks

The sources of water used in this model include the constant head streams and recharge boundaries. The Well #12 under pumping conditions and the cells designated as drains located at the headwater of the Kettle Run and Marlton Lakes are the only sinks whereby water is removed from the model.

Packages

The following Visual Modflow packages were used in this simulation, Modflow, Modpath and WinPest. Modflow was used to define the initial heads, output control, and solvers required to run the model. The WHS solver was used in this simulation. Modpath was used to calculate the particle tracking and WinPest was used for model calibration. WinPest provides a scatter plot of calculated vs. observed values of heads. This plot feature was used to examine the transient pump test data from well #1 to ideally obtain a 1:1 fit after adjusting recharge and hydraulic conductivity and storage values.



RECHARGE =~20 INCHES PER YEAR

FIGURE 5
MODEL GRID AND BOUNDARIES
BERLIN, NEW JERSEY

Model Runs

A series of 9 runs using Modflow, Modpath and WinPest were used to develop and calibrate the Berlin project model. Depending on the model run, the equipotential lines, flowpath velocity vectors or drawdown lines were printed after each run to evaluate the simulation results.

The initial steady state aquifer parameters used in the model are provided below.

Well Number		Well #1	Well #12	Well # 3	Dynasil
Total Depth (Ft)		75	87	40	NA
Screen Length (ft)		10	27	10	NA
Elevation		165 Feet	165 Feet	165 Feet	155 Feet
		50.29 m	50.29 m	50.29 m	47.2 m
Observation Point (m)		42.1	28.7	42.1	42.1
Head Value (m)		43.43	43.41	45	43.4
Distance From Well 12 (ft)		146 ft	0 ft	11 ft	2500 ft
Kx (m/d) Hydraulic Cond.	x-axis	16.1	16.1	16.1	16.1
Ky (m/d) Hydraulic Cond.	y-axis	16.1	16.1	16.1	16.1
Kz (m/d) Hydraulic Cond.	z axis	1.6	1.6	1.6	1.6
Ss Specific Storage		0.0062	0.0062	0.0062	0.0062
Sy Specific yield		0.0671	0.0671	0.0671	0.0671
Porosity (Ne)		0.2	0.2	0.2	0.2

From (7/6/94 3 DAY PUMP TEST)

To verify if the conceptual model is valid, the Modflow simulation was run with steady state non pumping conditions. The computer simulated groundwater flowpaths under steady state non pumping conditions is presented in Figure 6. Groundwater flow is to the east with a hydraulic gradient of 0.004. Compared to the conceptual model, there is a good match with the expected flow direction.

To simulate the capture zone at the municipal supply well operating at 500 gpm, Modflow was run to simulate pumping for a period of 100 days. Groundwater flow lines under pumping conditions is presented in Figure 7. After 100 days, the radius of influence extends approximately 1000 meters radially away from Well 12. A drawdown of 0.3 meters was present below the headwaters of the Kettle Run creek located approximately 500 meters from Well 12.The results of the 3 day aquifer test conducted in 1994 was used to calibrate the model. Using Winpest, the calibrated model can approximate the drawdown measured during the aquifer test. This procedure helped optimize the hydraulic conductivity and storage values.

The simulated pump test under pumping conditions at 750 gpm for 3 days is presented in Figure 8. The three day pump test discharging at 735 GPM shows a zone of influence between 0 to 0.2 m, at the Kettle Run Creek. The spatial pattern of drawdown is characteristic of a very transmissive isotropic aquifer. After three days, the radius of influence does not extend to the Kettle Run creek.

After calibration, using the particle tracking feature in Visual Modflow, the pumping was simulated at 500 gpm for 100 days with the capture zone results presented in Figure 9. A travel

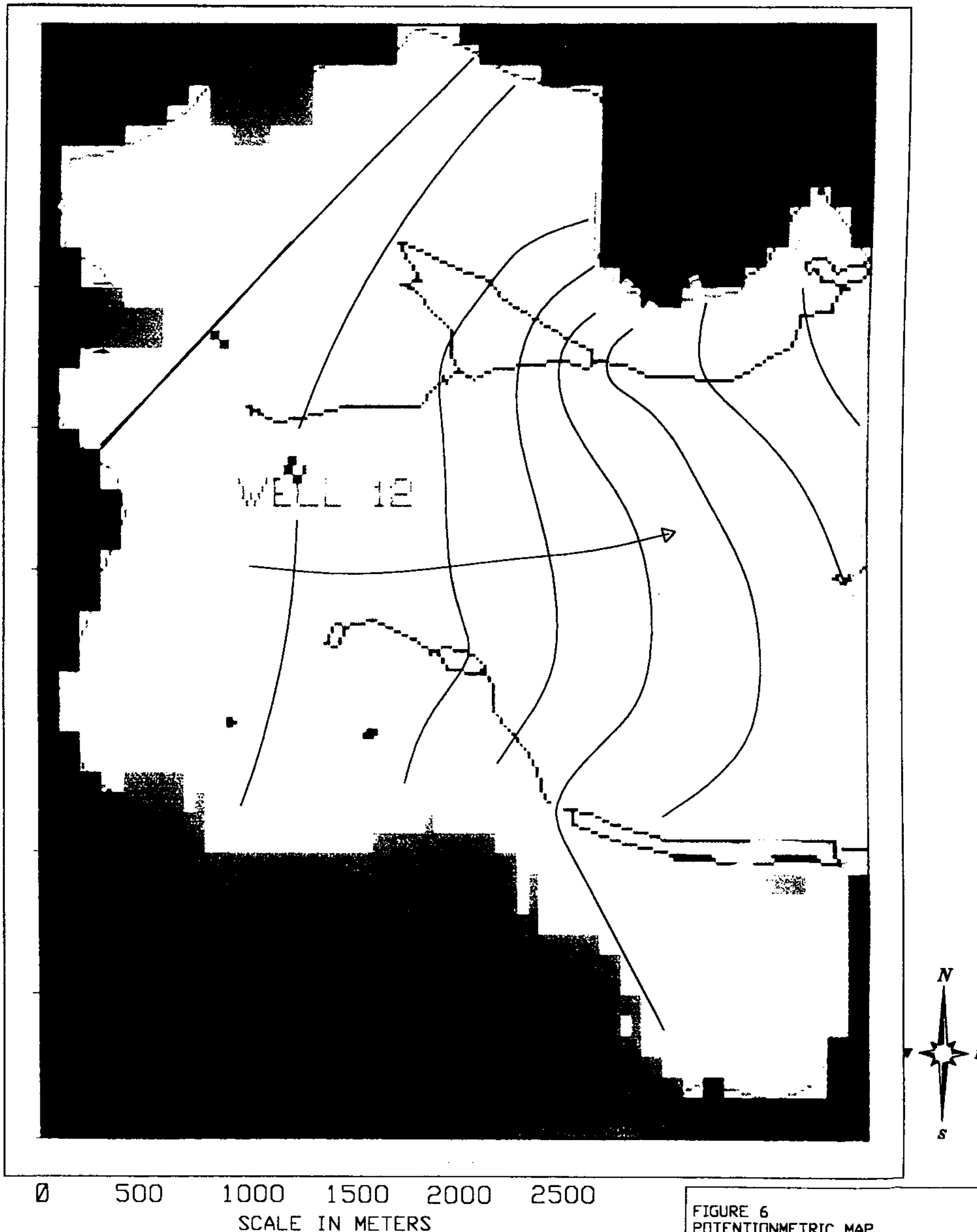


FIGURE 6
POTENTIONMETRIC MAP
STEADY STATE - NO PUMPING
BERLIN, NEW JERSEY

0 500 1000 1500 2000 2500
SCALE IN METERS

FIGURE 7
POTENTIOMETRIC MAP
PUMPING 500 GPM FOR 100 DAYS

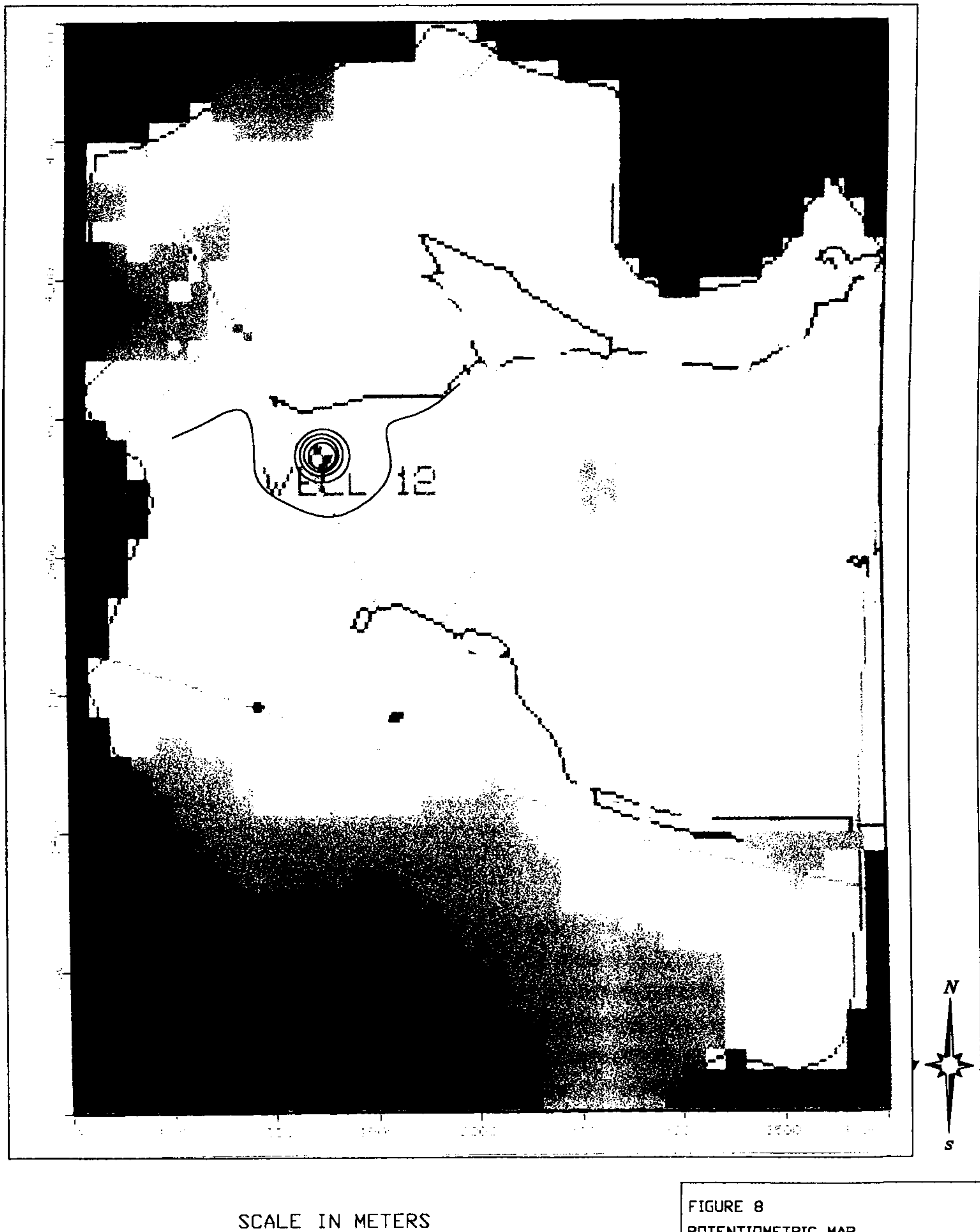
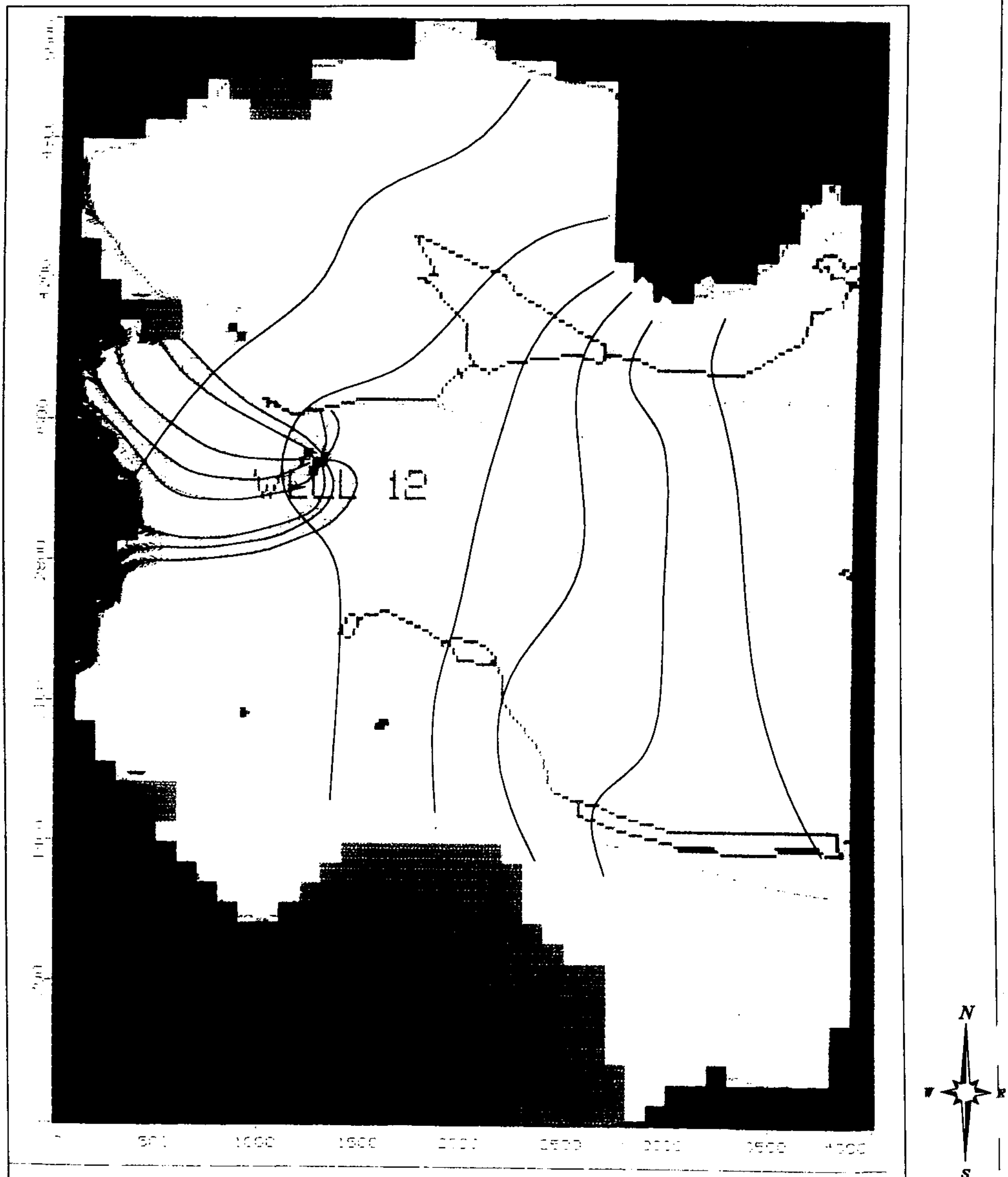


FIGURE 8
POTENTIOMETRIC MAP
PUMPING 735 GPM FOR 3 DAYS



PARTICLE TRACKING WITH PUMPING AT 500 GPM AND 100 DAY TIME LINES

SCALE IN METERS

FIGURE 9
PUMPING CONDITIONS- 500 GPM
PARTICLE TRACKING
100 DAY TIME LINE

time of 400 days was estimated for surface water from the Kettle Run Creek to be captured by well 12.

RESULTS AND DISCUSSION

The results of the Visual Modflow simulations for Well #12 determined that the hydraulic head in the study area under steady state none pumping conditions ranges from 46 to 32 meters above sea level. Groundwater flow was to the east as expected in the conceptual model. The simulation for Well #12 pumping at 500 gpm for 100 days resulted in a cone of depression that extends well beyond the Kettle Run Creek. The radius of influence extends a radial distance of 1000 meters around Well #12. The drawdown at the Kettle Run creek is estimated to be 0.3 meters with Well #12 pumping at 500 gpm after 100 days.

The three day pump test discharging at 735 GPM shows a zone of influence between 0 to 0.2 m, at the Kettle Run Creek. The simulation determined the drawdown experienced at Well #12 after 3 days of pumping at 735 gpm was approximately 1.5 meters. Using the particle tracking feature in Visual Modflow, the groundwater travel time from the Kettle Run creek was estimated. The Visual Modflow program estimated approximately 400 days for the surface water to be captured by Well 12. Thus, the pumping of Well 12 at a rate of 500 gpm for an extended period is expected to reduce stream flow to the Kettle Run creek and may have impacts to the plants and wildlife nearby.

CONCLUSIONS

As the demand for groundwater increases, the effects of public supply wells installed close to sensitive receptors such as wetlands should be considered in the permitting procedure. Computer models could be used to simulate the flow and transport of groundwater and evaluate the pumping effects.

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CROCIDOLITE PROTOMYLONITE OF INDIA BROOK, NEW JERSEY: WATER SUPPLY AND OTHER ENVIRONMENTAL IMPLICATIONS.

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ABSTRACT

Crocidolite protomylonite is exposed along the banks of India Brook, New Jersey. The crocidolite bearing outcropping is approximately 100 m long and is located near water wells that are part of the Mendham municipal water supply. Most of the protomylonite protolith is a pegmatite facies of Precambrian Byram Granite that is the principal lithology of the site area together with some protomylonitic amphibolite. The protomylonitic pegmatite contains wide ranging concentrations of blue crocidolite, blue magnesioriebeckite, orange microcline, white plagioclase, and blue and gray quartz combining to form a rare and attractive largely blue and orange rock. The crocidolite occurs in the fine dark blue matrix of the rock, as soft bright blue coatings on closely spaced slickenside surfaces, and is intergrown with magnesioriebeckite and quartz. Additional crocidolite occurs in the muds, sands, and gravel sampled along the banks of India Brook. The protomylonite occurs at the edge of an allochthonous slab of Precambrian rock thrust northwest over Paleozoic rock along the Peapack-Ralston fault. The allochthonous slab was subsequently intersected by the east-west trending Flemington Fault that has placed Ordovician sedimentary rock in fault contact with protomylonitic pegmatite along the southern edge of the India Brook exposure. The combined effects of complex faulting have resulted in a friable protomylonite that is eroding along the eastern cut bank of India Brook. Erosion is carrying crocidolite in mud and in suspension as it flows south toward the Raritan River.

Environmental implications include the extent to which crocidolite has contaminated any groundwater or parkland. The crocidolite site is at the edge of the parking area of the India Brook Natural Area and is a potential contaminate of the Knollwood water wells located near the site. The Knollwood #2 well log indicates that it was drilled through 68 feet (22 m) of Bryam Granite and 257 feet (85 m) of underlying Ordovician limestone. Although the casing is 67 feet deep, infiltration of suspended crocidolite into the limestone cannot be prevented. Crocidolite contamination into the Knollwood wells was first reported by Puffer and Germine (1982). Subsequent conformation of crocidolite contamination of Knollwood well water was reported by the U.S. Environmental Protection Agency (EPA, 1984) in a report that indicated 2.201 million amphibole asbestos fibers per liter and 1.089 million chrysotile fibers per liter. Since crocidolite asbestos is the only amphibole asbestos type identified near the Knollwood wells it is presumed that the amphibole asbestos indicated by the EPA is crocidolite. The limestone and the protomylonite are therefore permeable enough to transmit suspended asbestos fibers into the water supply.

The EPA (2001) on the basis of the risk of developing benign intestinal polyps has set an enforceable maximum containment level of 7 million fibers per liter of water but has not determined if there is a cancer risk. The EPA (2000) has determined that "Several epidemiological studies have found an association between asbestos in drinking water and cancer

of the esophagus, stomach, and intestines; however confounding factors and the short follow-up time relative to the long latent period for tumor formation make it difficult to interpret the results". However once asbestos contaminated water is used for many domestic purposes such as washing carpets, sheets, pillowcases, and clothing, a potential for entry into an air supply exists. The EPA (2000) is clear about inhalation exposure of asbestos which can cause asbestosis, lung cancer, and mesothelioma and has been classified it as a Group A human carcinogen. It is also generally recognized that among the various types of asbestos, crocidolite is the most dangerous and Mossman and Gee (1989) single out the amphiboles, particularly crocidolite, as the leading cause of asbestos related disease. The American Conference of Governmental and Industrial Hygienists (ACGIH) threshold limit value to which most workers can be exposed without adverse effects is only 0.1 fibers of crocidolite compared to 2.0 fibers of chrysotile (EPA, 2000).

In addition, the asbestos exposed along the parking area of the India Brook Natural Area may be hazardous to park users. The rock is bright blue and orange and may attract attention among rock and mineral collectors. The crocidolite coatings on the rock are soft and easily rub off on contact. It may, therefore, be prudent to monitor the crocidolite content of the well water and perhaps warn park visitors with a sign posting not to disturb blue rock exposures.

INTRODUCTION

When Germine and Puffer (1981), Germine et al. (1981), and Puffer and Germine (1982) reported on the occurrence of high concentrations of crocidolite in blue friable rock exposed along the banks of the India Brook at the northern edge of the Boro of Mendham, New Jersey (Figure 1) it was assumed by both Puffer and Germine that some action would be taken by the Boro to guard against the possibility of public exposure to a know toxin, particularly since water wells had been drilled into the crocidolite bearing rock. In addition, Puffer sent a letter in 1984 to the Mendham Environmental Commission describing the results of both the Puffer and Germine (1982) data and similar data generated by the EPA (1984) although receipt of the letter was not acknowledged by any Mendham official. However, during a recent revisit (Dec. 2000) to the India Brook site, Puffer found that instead of the expected abandoned well and a somewhat inaccessible stream cut exposure, the well was still pumping and a public parking area for a nature trail had been constructed immediately adjacent to the site. A notice at the trailhead describes the blue "riebeckite" but does not advise any precautions against exposure.

The igneous and metamorphic rocks near the site are well exposed and are featured as the principal attraction for visitors to the nature trail at the India Brook Natural Area developed by the Township of Mendham. A petrographic study of the various lithologies near the site area was therefore offered as a class project to the Igneous and Metamorphic Petrology class taught at Rutgers during the spring 2001 semester. Considerable caution was advised to each of the three students that elected to study the area because of the well-known toxicity of crocidolite (Puffer, 1979, 1980). The results of the class project constitutes a portion of this report together with an update on the regulatory status of crocidolite and changes at the site during the 20 years since it was last examined as a crocidolite exposure.

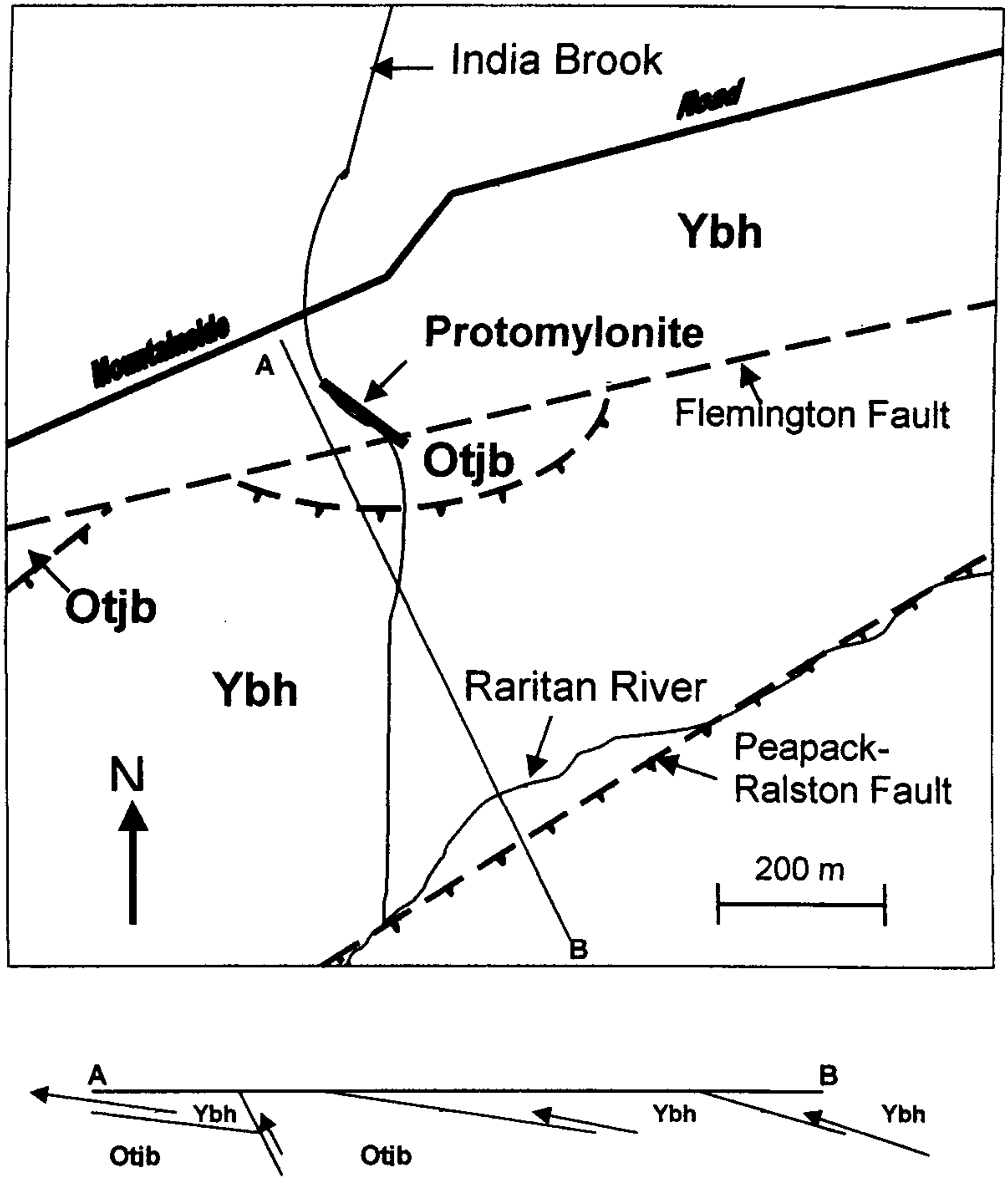

Figure 1. Geologic map based on Volkert (1988) with cross-section consistent with locally thin layer of Byram Granite (Ybh) thrust over Ordovician carbonates (Otjb) and with measured 76° southern dip of mylonitic foliation at the protomylonite exposure.

GEOLOGIC SETTING

The study area (Figure 1) is comprised of an exposure of blue crocidolite rich protomylonite (Figure 2) and the immediately surrounding area. The protomylonite is contained within the Byram Granite near its contact with sedimentary rocks of Unit B of the Jutland Klippe as mapped by Volkert (1988). The hornblende granite facies (Byram Granite) of the Byram Intrusive suite comprises most of the surface exposure in the area. The Jutland Klippe is a small geologic window exposed at the southern end of the crocidolite outcropping. Additionally, two other lithologies appear near the site. About ½ km upstream (north) from the site, the stream cuts through rocks of the quartz-oligoclaise gneiss member of the Losee Metamorphic Suite. About ½ km northeast of the site rocks of the Microperthite-Alaskite facies of the Byram Intrusive Suite are exposed.

The Byram Granite (Ybh) in the study area is a pinkish-gray to medium-buff-weathering, pinkish-white or light pinkish gray, medium-to-coarse-grained, gneissoid to indistinctly foliated granite. It is composed principally of pink microcline microperthite, clear to smoky quartz, grayish albite-oligoclaise and hornblende. On the basis of radiometric age dating the rock is 1116 +/- 41 Ma (Volkert et al., 2000). In the study area, the hornblende granite is marked by coatings of the distinctively blue crocidolite, which is found in the fracture zones along the Peapack-Ralston Fault. Coatings are typically a millimeter or less in thickness. Pegmatites are commonly found in the granite that are mineralogically the same as the granite host. Lenses of amphibolite are also common within the granite.

Unit B of the Jutland Klippe (Ojtb). The Jutland Klippe is a series of six isolated tectonic fragments of middle Ordovician sedimentary rock located east of Jutland, New Jersey and also occurs in two fragments along Peapack, New Jersey (the Peapack Klippe). Unit B (Ojtb) is a heterogeneous sequence of interbedded red, green, tan and gray shale; interlaminated dolomite and shale; interbedded fine grained greywacke, siltstone and beds or lenses of sandstone, light gray to pale pinkish gray quartzite, and occasionally, interbedded fine grained, thin bedded limestone and red and green shale. The rocks of the Jutland Klippe are exposed in a small area south of the crocidolite exposure (Figure 1).

The India Brook Proto-Mylonite – is the crocidolite-bearing portion of the Byram Granite, pegmatites, and amphibolite rock exposed along India Brook (Figure 2) that is the principal focus of this report. Although most of the crocidolite bearing rock exposed at the India Brook site is protomylonite about 15 % of the rock is mylonite. Both rock types display strong mylonitic foliation produced by syntectonic crystal – plastic processes. Proto-mylonite is distinguished from mylonite on the basis of a less than 50 % ratio of foliated fine matrix to large clasts (or megacrysts). In addition, there are common thin zones of slickensided fault gouge along the outcrop that are identified by their lack of primary cohesion. These fault gouge zones were logged in the Knollwood wells as "soft streaks" and "rotten streaks". The angular clasts within the fine matrix of the protomylonite consist largely of bright sky-blue quartz and bright orange K-feldspar with minor white plagioclase. The fine matrix is dark blue and is rich in crocidolite. The clasts are typically about 1 to 6 mm across but in many samples measure 1 to 3 cm across indicating that much of the protolith was a granite pegmatite facies of the hornblende granite. Some amphibolite exposed along the India Brook stream-cut was also retrograded to protomylonite and mylonite. The amphibolite in the New Jersey Highlands is typically composed of approximately equal amount of plagioclase and hornblende, but the protomylonitic amphibolite at India Brook is composed of approximately equal

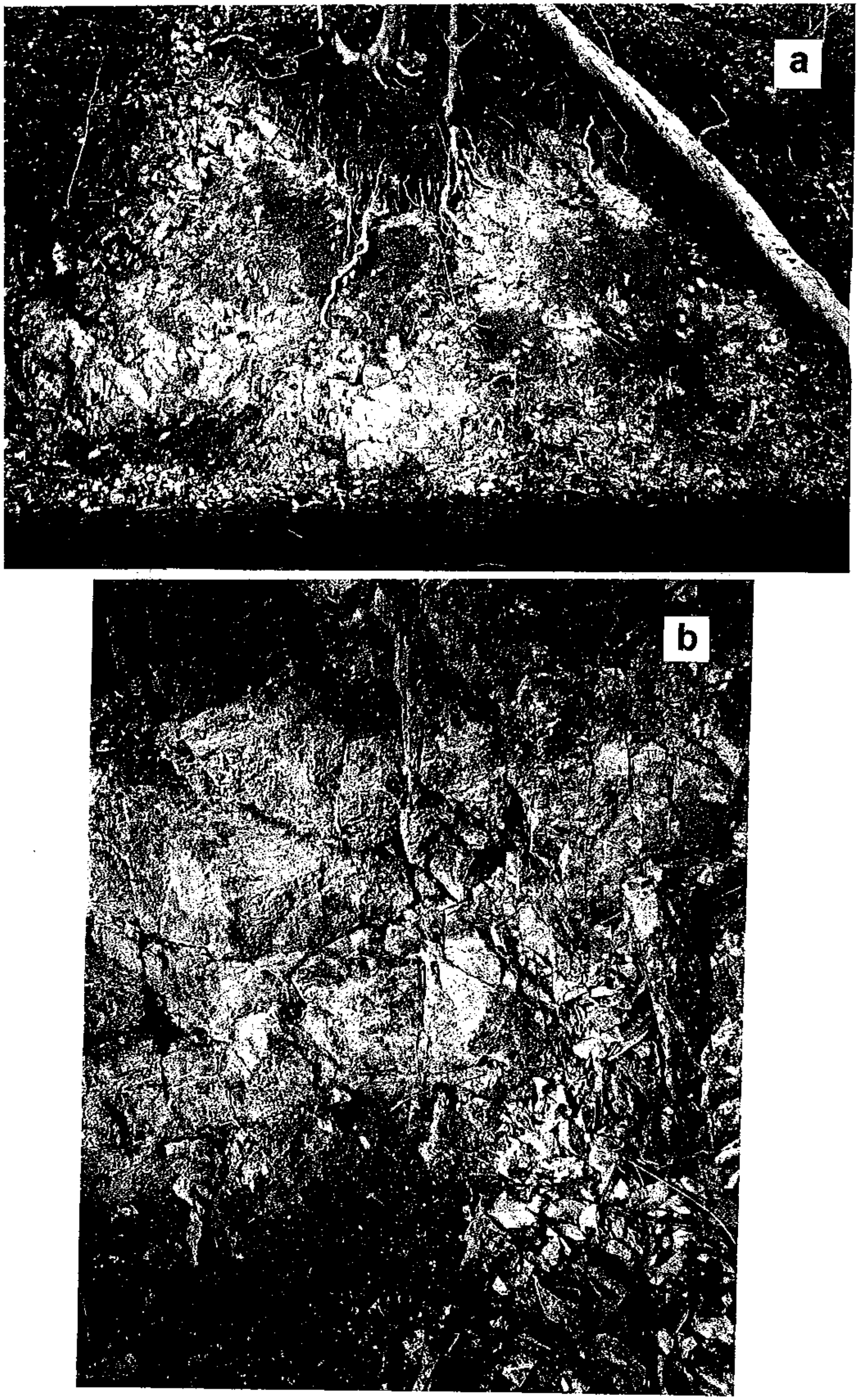

Figure 2. A. Color photograph of India Brook stream-cut. Note the blue crocidolite rich protomylonite. B. Close-up color photograph of the center of the above area near the stream.

portions of plagioclase and hornblende clasts in a fine dark blue matrix rich in crocidolite. The exposure at India Brook is approximately 70 percent protomylonitic pegmatite and 30 percent protomylonitic amphibolite. In addition some microfaults in the Byram granite exposed within Figure 1 are lined with crocidolite.

STRUCTURAL SETTING

The New Jersey Highlands have been intersected by several faults including the Flemington Fault and the Peapack-Ralston Fault (Figures 1). Precambrian wedges of Byram Granite (Ybh) have been thrust over Ordovician rocks (Otjb) within the study area (Figure 1). The mylonitic interval between rock units was generated during shearing of material during movement of the allochthonous slab and subsequent normal faulting.

The Flemington Fault, also known as the Mendham Fault, is drawn (Figure 1) as a steep normal fault oriented approximately 80 NE, and dipping 76 SW on the basis of mylonitic foliation measurements (Volkert, 1988). The Peapack-Ralston fault (Figure 1) is a low angle thrust fault, dipping 29 SE. The foliation of the granite in the study area strikes approximately E-W and dips south.

The Byram granite was intruded into the Middle Proterozoic basement complex 1116 +/- 41 Ma before the peak of the Ottawan orogenic event that marked the end of the Grenville Orogeny (Volkert et al. 2000). Subsequent Paleozoic compressional and transpressional movement of the basement rocks caused allochthonous slabs of granite to thrust over Paleozoic sediment layers. Shearing between the rock units form the mylonitic interval containing crocidolite. Evidence of overthrusting is the occurrence of Paleozoic limestone below the Precambrian slab of Byram Granite (Figure 1).

CROCIDOLITE

The amphibole fibers found along India Brook display all of the characteristics of crocidolite. Crocidolite by definition is simply the fibrous form of the amphibole riebeckite [$Na_2Fe_3^{II}Fe_2^{III}(Si_8O_{22})(OH, F)_2$], a monoclinic biaxial mineral with strong pleochroism. It has parallel extinction and, when viewed conoscopically, produces a biaxial negative figure with a large axial angle. Each of these optical and chemical characteristics of crocidolite was compared with samples from India Brook (Figures 3 and 4) to confirm its identification. In addition, the principal characteristic, a bright blue color, reinforces its identification. The color blue is rare among minerals and crocidolite is the only asbestos mineral or fibrous amphibole that is characteristically blue.

Crocidolite is one of six minerals that fall under the general heading of asbestos. Asbestos includes the minerals amosite, tremolite, actinolite, anthophyllite, crocidolite and chrysotile. Chrysotile, however, is by far the most commonly used industrial asbestos type.

Riebeckite and crocidolite are typically found in soda-rich (A-Type) granites (Collins et al, 1982, Hyndman, 1985) and related rocks (aplites, pegmatites, syenites, rhyolites, and trachytes). Additionally, crocidolite is found in some highly siliceous metamorphic rocks such as "ironstone" (Kerr, 1977). The occurrence at India Brook is consistent with the A-type composition of the Byram Granite (Volkert et al., 2000). However riebeckite and crocidolite are not common within the Byram Granite and crocidolite occurrences are rare. The crocidolite of India Brook is instead

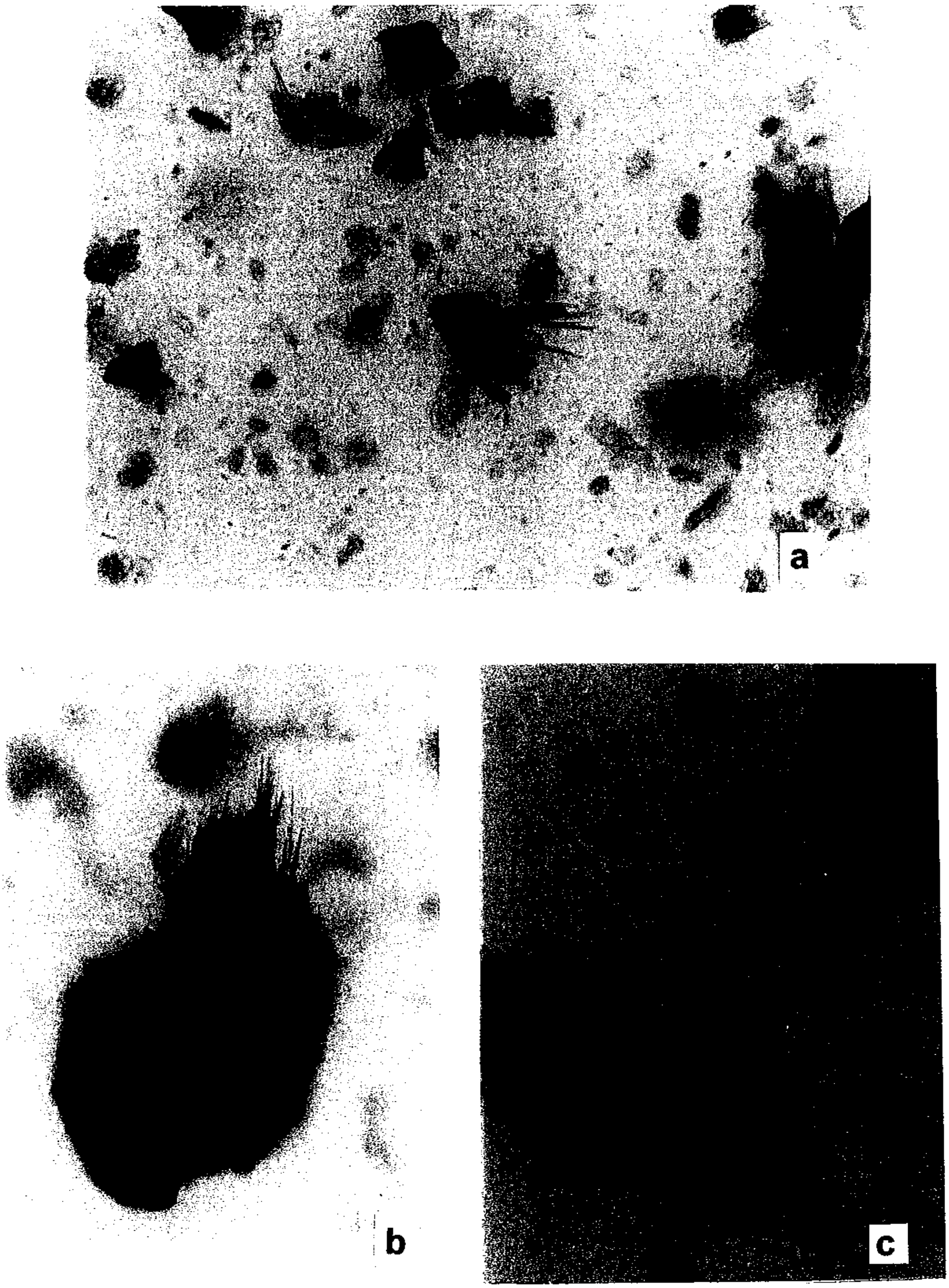

Figure 3. Photomicrographs of soft blue powder separated, without crushing or grinding, from the surface of a typical rock exposed along the banks of India Brook. A. Field of view = 0.5 mm.; B and C. = 0.1 mm.

Figure 4A. Scanning electron photomicrograph of crocidolite from Mendham; 4B. Transmission electron photomicrograph of fine-fiber crocidolite from Mendham. The longest fiber is 2.3 um X 0.07 um, with an aspect ratio of about 33 (after Puffer and Germine 1982).

highly localized to the fault zone along the base of the allochthonous slab of Byram Granite and was probably derived as a secondary alteration product of primary amphibole in the granite, pegmatite, and amphibolite. The amphibole was locally altered to mangesioriebeckite that in turn has been partially altered during retrograde cataclastic shear zone metamorphism to fibrous crocidolite.

THE CROCIDOLITE CONTENT OF THE INDIA BROOK SITE

The exposed bedrock: The crocidolite found in the protomylonite of India Brook is a fibrous magnesioriebeckite with a high titanium content (2.3%, Puffer and Germine, 1982). The area was determined by Puffer and Germine (1982) to have two varieties of fibrous magnesioriebeckite. The first variety is fine, flexible fiber with parallel extinction and is pleochroic from blue or violet blue to light blue or nearly colorless (Figure 4b). Interference colors range up to first-order yellow, but are invariably masked by the blue color. The first variety occurs as wooly aggregates of long fibers and thicker fiber bundles. The second variety is coarse fiber replacement of hornblende, and has inclined extinction ranging up to 25°. Pleochroism is pronounced from light blue or bluish green to light yellowish green or colorless, and interference colors are not masked by mineral color as in the fine-fiber crocidolite. This relatively massive crocidolite/magnesioriebeckite after hornblende is typically composed of coarse, splintery fiber.

New petrographic examinations of thin sections of samples from India Brook indicate a blue crocidolite/magnesioriebeckite content in three protomylonitic pegmatite samples of 2, 6, and 9 volume percent. The content of two protomylonitic amphibolite samples measured 18 and 29 volume percent. These data are, however, may underestimate the actual content because of loss of crocidolite during thin section preparation. Soft friable crocidolite veins contained in shear planes and joints tended to break loose during the rock cutting process leaving relatively crocidolite free but coherent chips for grinding. However, the shear planes and joints are the principal avenue for water transmission through the rock.

The well water: Two wells were drilled near the India Brook site (Knollwood #2 and #3). Both wells intersect the Flemington (Mendham) Fault and both are used for public supply purposes. According to the New Jersey Geological Survey program PSW200 (a compilation of New Jersey public supply wells updated in the early part of the year 2000) both wells remain in use. During a March 2001 inspection of the Figure 1 site the well closest to India Brook was completed as a stick-up and there was no evidence of the well's having been grouted to the surface.

Knollwood #2 permit # 25-15323, was drilled by Wm. Stothoff Co. Inc., on 11-18-69, and is operated by the New Jersey-American Water Co. for the Mendham Borough public water supply. It was logged by Wm. Stothoff Co., Inc on 8-14-70:

Formations:
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

Knollwood #2 was tested on 10-15-69 to yield 578 gallons per minute. The static water level before pumping was 15 feet below the surface, pumping level was 76 feet below the surface. After 8 hours of pumping the drawdown was 61 feet. A 12-inch casing was extended to 67 feet with no screen.

Puffer and Germine (1982) observed several crocidolite fibers filtered from well #2. One example was photographed through a transmission electron microscope that measures 0.83 um x 0.061 um with an aspect ratio of 14. In addition, an electron diffraction (SAED) pattern consistent with crocidolite was presented and an EDXS spectrum from a fiber from the Mendham Borough municipal water supply was presented consistent with a magnesioriebeckite chemical composition.

Knollwood #3 public water supply well (permit # 25-21199), was drilled by the Somerville Well Drilling Co., Inc. on 2-20-80 for the New Jersey-American Water Co. and logged by them on 7-2-80:

Formations:
0 – 86 top soil, clay, sand, fractured rock
86 – 325 limestone

Knollwood #3 was tested on 3-12-80 to yield 200 gallons per minute. The static water level before pumping was 30 feet below the surface. The pumping level was 150 feet below the surface. After 24 hours of pumping the drawdown was 50 feet. An 8-inch casing was extended to 88 feet. Puffer and Germine observed fresh cuttings at the well during their initial visit in 1981 and found crocidolite fibers in the well water.

Both of the Knollwood wells encountered bedrock in the Byram granite and bottom in Paleozoic dolomitic limestone. The principal productive zone in these wells appears to be the contact between these two rock types, which is marked by a mylonitic interval indicating that it is a fault contact.

The Mendham Borough's municipal water supply: Puffer and Germine (1982) used the analytical procedure of Anderson and Long (1980) to study samples of water from the Knollwood wells and a sample collected at the Hilltop Elementary School located near the center of the Boro. Crocidolite was found in each sample and was quantitatively reported for the municipal sample. The technique uses 25 mm diameter 0.2-micron Nuclepore polycarbonate filters and a Millipore vacuum filtration apparatus for particle filtration. Particles were deposited on parlodian membranes, 400 mesh nickel grids, and analyzed using Phillips 400 scanning-transmission electron microscopes (STEM) equipped with a field emission gun which increases analytical sensitivity. Systematic searches for fibers were conducted on particles having an aspect ratio greater than 3:1. Fibrous particles were characterized chemically by energy –dispersive x-ray spectroscopy (EDXS) and characterized structurally using selected area electron diffraction (SAED) and then photographed. Crocidolite fibers were not observed in control samples from other sources or in a blank sample of distilled, filtered water. In the municipal water sample crocidolite asbestos was measured at 4.7 million fibers per liter (MFL) +/- 2.0 MFL at a 95% confidence interval. This level of contamination greatly exceeds the 0.3 MFL proposed EPA guideline that was in affect during the Puffer and Germine (1982) investigation.

Subsequent conformation of crocidolite contamination was reported by the U.S. Environmental Protection Agency (EPA, 1984) in a report that indicated 2.201 million amphibole asbestos fibers per liter and 1.089 million chrysotile fibers per liter in Knollwood well water.

Since crocidolite asbestos is the only amphibole asbestos type identified near the Knollwood wells it is presumed that the amphibole asbestos indicated by the EPA is crocidolite.

PUBLIC HEALTH IMPLICATIONS

Crocidolite in Drinking Water

There are many conflicting studies regarding the effects of ingestion of asbestos. For example, the occurrence of pleural mesothelioma has been associated with the presence of asbestos fibers in water in a region of Turkey with very high environmental levels of naturally-occurring asbestos (CASRN, 2001). In 1981 Conforti et al. conducted a study of the San Francisco Bay area using cancer incidence data from 1969-1974. Chrysotile concentrations in drinking water ranged from non-detectable to 3.6E7 fibers per liter. Conforti et al. (1981) determined that associations between ingested asbestos and cancer of the digestive organs, esophagus, pancreas and stomach in both sexes was statistically significant. Contrarily, Marsh (1983) evaluated eight independent studies of the effects of ingested asbestos in five geographical areas and found no study, either viewed individually or in aggregate, that could establish risk levels for asbestos in drinking water. However Carter and Taylor (1980) in a study of the Duluth Minnesota area, an area of known groundwater contamination by crocidolite, found ingested crocidolite could accumulate in the liver and jejunum. They also found significantly more crocidolite in the livers of people whose drinking water supply was contaminated by crocidolite than in the livers of the control group. The EPA (1998) has concluded that, overall, epidemiological data is inadequate and that a drawback of the studies was that only short-term effects were considered and that long-term studies still need to be undertaken. In addition, Mossman and Gee (1989) reviewed numerous studies and found that "the magnitudes of the increased standardized mortality ratios (SMRs) originally reported as statistically significant [for gastrointestinal cancers]...have not been confirmed in studies of more than 30 separate cohorts."

In a document entitled "Current Drinking Water Standards," the Environmental Protection Agency (EPA) stated that the potential health effect from ingestion of asbestos in drinking water was an increased risk of developing benign intestinal polyps for fibers greater than 10 micrometers. (EPA, 2001). Based on these findings, the EPA has set maximum containment levels (MCL) for asbestos at 7 million fibers per liter of water (MFL). MCLs are an enforceable standard set by the EPA. They are based on two considerations: 1) the Maximum Containment Level Goal (MCGL) and 2) the ability of the water system to remove contaminants based on suitable treatment technologies. MCGLs are set at the highest level possible while still affording protection from potential health problems. MCGLs for asbestos are also set at 7 million fibers per liter of water. Although the EPA does not provide information on how they determined the risk, it appears to come from a 1985 study where male rats were exposed to chrysotile asbestos through their diet over the course of their lifetime. A statistically significant increase in benign intestinal polyps was observed. (CASRN, 2001).

If the risk set by the EPA is indeed based on the above study, it is in our opinion, inadequate. The EPA ignores the differences in types of asbestos. The study above exposed rats only to chrysotile asbestos. Chrysotile asbestos has been found to dissolve in the human body and, therefore, does not cause the health risks that the amphibole types of asbestos, such as crocidolite, cause. Crocidolite is composed of relatively inert needlelike fibers that lodge in the lungs. Mossman and Gee (1989) state, "...a growing body of information supports the concept that the amphiboles crocidolite, amosite, and tremolite are largely, if not entirely, the cause of malignant mesothelioma in humans." By grouping all types of asbestos together and by basing its data on the effects of chrysotile alone, the EPA does not adequately protect against the risks associated with amphibole asbestos types.

Regardless of the basis for the EPA standards, water suppliers were required by law to test for asbestos in drinking water beginning in 1993. If the asbestos was found to exceed 7 million fibers per liter, the water supplier is now required to monitor the contaminant once every three months. Further, water suppliers are required to notify the public of the excessive levels of asbestos via newspaper, radio, TV and other means.

According to an EPA Safe Drinking Water Violation Report, New Jersey-American Water Company, the water supplier for Mendham, had no health based violations for its water system since testing began in 1993 (EPA, 2001). A health-based violation is one in which the amount of contaminant exceeded safety standards (MCLs). The January 1 to December 31, 1999 Consumer Confidence Report for New Jersey-American Water Company implied that asbestos was not found in the treated water supply. It stated "those substances not listed in this table [provided] were not found in the treated water supply. The data presented here is the same data collected to comply with U.S. Environmental Protection Agency and New Jersey Department of Environmental protection monitoring and testing requirements." (NJAWC, 1999). The report does not state, however, what substances were listed in the table, so there is no way to know whether asbestos was actually tested for and not found, or if it was not tested for at all.

Inhaled Crocidolite

Even if ingestion of crocidolite in drinking water is not found to be a factor, one must still consider the problems associated with inhalation. The health effects of crocidolite when it is inhaled have far better documentation than the health effects of crocidolite when it is ingested. Potable water from Mendham's supply is not used only for drinking. It is also used for household purposes such as the washing of clothes and dishes. There is a potential for asbestos fibers to enter the air through these uses. Also, the outcrop of crocidolite at India Brook is located in a public park where crocidolite is entering the air through the normal course of weathering. General use of the park, therefore, may put park patrons at risk through inhalation. Also, because of crocidolite's bright blue color, people often collect the mineral unaware of the health risks involved.

The EPA (2001) concluded that "a large number of studies of occupationally exposed workers have conclusively demonstrated the relationship between asbestos exposure and lung cancer or mesothelioma. [Further], these results have been corroborated by animal studies using adequate numbers of animals." (CASRN, 20001). Mossman and Gee (1989) agree and go even further, singling out the amphiboles, particularly crocidolite, as the leading cause of asbestos related diseases.

Mossman and Gee (1989) found that the amphiboles are almost solely responsible for malignant mesothelioma in humans. The needlelike amphiboles lodge more readily in the lungs than do the curly chrysotile fibers, which appear in bundles. In a separate article, Mossman et.al. (1990) found that "the number of amphibole fibers (crocidolite and amosite) was significantly higher in lungs from mesothelioma patients, whereas numbers of chrysotile and non-asbestos fibers were similar in all groups. These data suggest that the lung burden of chrysotile and non-asbestos fibers bears no relation to the occurrence of these cancers." Mossman and Gee (1989) found that mortality was highest among those workers who handled amphiboles alone, followed by those who handled a mixture of amphiboles and chrysotile. Significantly, they found that the incidence of mesothelioma originally attributed to mining and milling of Canadian chrysotile was really due to contamination of the mines by tremolite, an amphibole. Further Mossman et al, 1990 found that the risk of developing malignant mesotheliomas was directly related to the ratio of tremolite to chrysotile fibers in the lungs of those affected. Malignant mesotheliomas were found, not only in workers, but also in people living in the vicinity of crocidolite mines and factories and in the family members of crocidolite workers. Mossman and Gee (1989) also found that lung cancer and asbestosis are more commonly associated with the amphiboles than with chrysotile. In general, they found that workers exposed to chrysotile alone had consistently lower rates of cancer than those workers exposed to amphibole forms of asbestos. Fiber size was found to play an extremely important role in the carcinogenic affects of asbestos (Mossman, 1990). Longer crocidolite fibers produce more risk than shorter fibers. Mossman and Gee (1989) summarize several studies that find that longer fibers produce malignancies where shorter fibers do not. Fibers more than 8 μm long and less than 0.25 μm in diameter were found to be the most potent. (Mossman, 1990).

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BADD Field Safety

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Abstract

Personal health and safety is one of the most overlooked and misunderstood job-related issues facing geoscience professionals today. Many times, employees are ignorant of and/or are not given proper training before being sent into a potentially hazardous situation. Although dangers are inherent in field work, most injuries are fairly easy to avoid. Even seemingly harmless habits, such as wearing sneakers in the field, can expose a person to puncture wounds, bites, broken bones, and a multitude of other consequences. Dangers that field personnel can face include physical, chemical and biological hazards. Physical hazards include slip, trip, fall, strenuous manual labor, heat and cold stress, hole collapse, falling objects, etc. Chemical hazards include gases, acids, and other noxious fluids and dusts. Biological hazards include insects, reptiles, rodents, mammals of the fur-bearing variety, and restless natives. Using personal Protective Equipment (PPE), following Occupational Safety and Health Administration (OSHA) guidelines, knowing about potential hazards, and employing common sense and discretion work together to keep all field hands safe.

ARSENIC AND PHOSPHOROUS RESULTS FROM THE SUBSURFACE NAVESINK FORMATION, NEW JERSEY COASTAL PLAIN

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ABSTRACT

Glauconitic formations from the coastal plain of New Jersey have recently been cited for containing higher concentrations of lithogenic heavy metals and phosphorous relative to non-glauconite formations. The citation is used for eliminating anthropogenic sources, which would require remediation actions. For this study, sediment samples were collected at one foot intervals from the subsurface along the entire 27-foot thick glauconitic Navesink Formation in the original Village of Middletown. The upper contact of the Navesink Formation occurred 14 feet below grade, shielding the sediments from potential land and atmospheric sources. Thirty-eight samples collected from the Navesink and bordering formations detected arsenic below the New Jersey Department of Environmental Protection Direct Contact Cleanup Criteria of 20 mg/kg with only one exception. Twenty-seven samples analyzed for leachable orthophosphorous found all concentrations exceeding the New Jersey Department of Environmental Protection surface water standard of 0.1 mg/l. The arsenic findings do not support the lithogenic source hypothesis and the orthophosphorous findings show a dissolved component that can enter streams.

INTRODUCTION

Analyses of soil, water, and air are performed in New Jersey by property owners as either regulatory or real estate requirements to assess the health of the sampled environment. Tests are conducted to determine the presence of chemicals that can present health risks if exceeding thresholds established by government. Sampling results that exceed thresholds are remediated with the assumption that the contamination is anthropogenic. However, in recent years, the regulated community sampling anthropogenically-contaminated sites (Barringer, et al. 1998) have detected background concentrations of contaminants which exceed regulatory cleanup criteria. The background concentrations suggest a lithogenic source that has skewed the sampling results in anthropogenically-contaminated areas. This paper focuses on potential lithogenic impacts of the Navesink Formation on environmental assessments.

In New Jersey, soil sampling in 1996 of a residential development (NJDEP, 1999) located on former agricultural land detected concentrations of pesticides and metals exceeding the soil standards of the New Jersey Department of Environmental Protection (NJDEP). Soil sampling at the Imperial Oil Company Superfund Site in Marlboro, New Jersey, detected widespread occurrence of arsenic, initially attributed to the petroleum-related contamination. However, further investigation determined that the areal occurrence of arsenic was attributable to the historic use of the site as a fruit orchard (Barringer, et al. 1998). These findings led to the sampling of agricultural land destined for residential development (N.J. Assembly Bill #1886, May 6, 1996). Recommended sampling protocols and frequency were established by the Historic Pesticide Contamination Task Force (NJDEP, 1999).

The primary concern with agricultural pesticides is the EPA-banned organochlorine compounds such as DDT, Chlordane, and Aldrin. Inorganic metals, such as arsenic and lead, are of equal concern as agricultural pesticides. Metals, banned from pesticide use since the 1980s (Welch, et al. 2000), were the primary active ingredient prior to the introduction of DDT in 1947 (Shepard, 1951). Metals are a concern because they do not readily break down and become bound into the soil. Theoretically, over time pesticides will breakdown and disappear while metals will remain concentrated in the topsoil.

Since 1996, the realization of residual pesticides in former agricultural soils of New Jersey has lead to sampling such lands by developers. The sampling includes neighboring lands not historically subject to farming contaminants for background comparison. A growing data set suggests that the background results are similar to those taken from supposed agriculturally impacted lands (NJDEP, 2000). Such findings have caused the NJDEP and the regulated community to address the lithogenic impacts on environmental sampling.

Background sampling in New Jersey has identified anthropogenic sources (Fields et al., 1993) with the study of lithogenic impacts focusing on metals. In the Coastal Plain Physiographic Province of New Jersey glauconitic soils have been recognized as a lithogenic source of metals (Barringer, et al. 1998, Dooley 1998). The Coastal Plain strata noted for being glauconite-rich are the Hornerstown, Navesink, and Marshalltown Formations (Dooley 1998).

STUDY RATIONALE

The Middletown Township Environmental Commission (MTEC) is investigating the Navesink Formation for two reasons. The Environmental Commission is assessing Township soils for residual pesticide-related metals. With the Navesink Formation outcropping in the Township, there is a need to determine its lithogenic contribution of metals to the soil. A second reason for the interest in the Navesink Formation is a recent nonpoint source water quality study which detected high total phosphorous concentrations during base flow conditions (Middletown Township Environmental Commission 1999). Rain event samples collected from the McClees Creek watershed in Middletown Township consistently detected total phosphorous concentrations above the NJDEP's surface water standard of 100 ug/l. The high concentrations were attributed to runoff. Baseline stream samples were collected during summer low-flow conditions when ground water discharge was the predominant water source for the Creek. The baseline samples also detected elevated phosphorous concentrations, which suggested a non-rainfall phosphorous source. It was recognized that the McClees Creek channel and floodplain are underlain by the Navesink Formation. The Navesink Formation is noted for its phosphatic fragments (Minard 1969) and a higher percentage of phosphorous than most of the other Coastal Plain formations (Dooley 1998).

A lithogenic phosphorous source is important when assessing surface water quality as required by the Clean Water Act. Section 303(d) of the Act requires New Jersey to develop an Impaired Waterbodies List of state waters, which do not meet water quality standards for certain parameters including phosphorous. Under Section 303(d), a Total Maximum Daily Load (TMDL) must be established for each excessive pollutant and be unique for the impaired watershed. With TMDLs established for any given watershed, the goal of the Clean Water Act is to reduce the pollutant load and reach the TMDLs by regulation of permitted discharges, nonpoint source discharges, and land development. Confirmation of a lithogenic phosphorous source would insure the establishment of a reachable phosphorous TMDL which would only address anthropogenic sources. The lithogenic phosphorous source would have to be differentiated between unmanageable ground water sources and manageable sediment-related sources such as bank erosion and poor runoff management. Remediation efforts would not be concentrated on reducing anthropogenic phosphorous sources but on lithogenic sources via stream bank stabilization and siltation basins.

STUDY SCOPE OF WORK

The Middletown Township Environmental Commission has limited its investigation to the Navesink Formation. In Middletown, the Marshalltown and Hornerstown Formations are thin, poorly exposed and do not underlie former agricultural lands or long lengths of stream channel corridors. The Navesink Formation is 25 feet thick (Minard 1969) and outcrops in topographically low areas, coinciding with several stream channels. This coincidence results in the outcropping of the Navesink Formation on the order of thousands of feet along stream channels and floodplains in Middletown Township (**Figure** 1). Such exposure allows this study to assess the Navesink Formation's potential lithogenic contribution of arsenic to surficial soils and phosphorous to surface streams via ground water flow. Although the glauconitic formations are noted for containing several metals at higher than average Coastal Plain concentrations (Dooley 1998), the study was limited to arsenic because of its low NJDEP Soil Cleanup Criteria of 20 mg/kg relative to pesticide-associated lead which has an NJDEP Soil Cleanup Criteria of 400 mg/kg. Past studies of the Navesink Formation to assess its lithogenic metal content involved random samples, mostly from surficial exposures assumed to be free of anthropogenic impacts (Barringer, et al. 1998, Dooley 1998). This study sampled the entire thickness of the Navesink Formation at 1-foot intervals from a subsurface location where it would be free from any potential anthropogenic impacts.

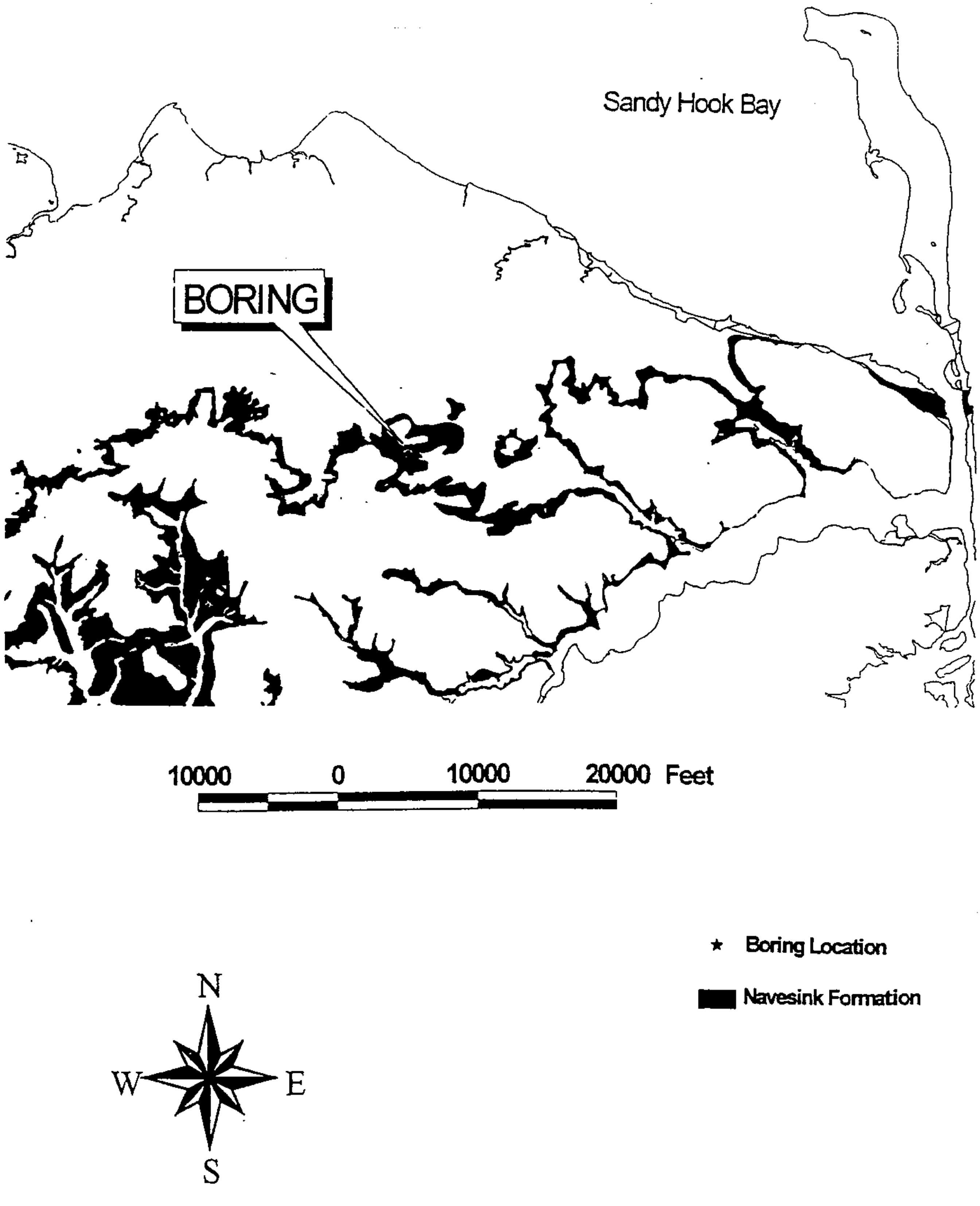
THE NAVESINK FORMATION

The Navesink Formation is Upper Cretaceous in age and is considered an outer shelf deposit due to its abundant glauconite content. The Navesink Formation is the basal unit of an upward coarsening sequence representing a transgressive shoreline (Becker et al. 1996). The unweathered formation in Middletown is a massive clayey sand with clay and silt constituting about 30 percent of the formation (Minard 1969). The sand is mostly glauconite with a small amount of quartz present in the basal portion of the formation. Pyrite clusters and phosphatic fragments are common, as well as abundant fossils in the basal portion. Hydrologically, the Navesink Formation is the basal part of a composite confining unit having low to moderate permeabilities (Zapecza 1989).

METHODOLOGY

The entire thickness of the subsurface Navesink Formation was sampled to assess its arsenic and phosphorous content. A sampling location was determined from Minard's (1969) geologic map where there was minimal coverage by the overlying Red Bank Formation and where agricultural practices were unlikely. A location was chosen in the original Village of Middletown at latitude 40°23' 36.66" N and longitude 74°07' 05.10" W (Figure 1). The sample location was initially settled in the 1600's and its land use has since remained residential.

A boring was advanced with a pneumatic push-probe drilling rig on two dates. Continuous soil samples were collected with dedicated polyethylene sampling tubes. Soil



Navesink Formation Arsenic Study Middletown Township Environmental Commission	Figure 1

samples were collected at 1-foot intervals and placed in new pre-cleaned glass jars with lined polyethylene screw caps for eventual arsenic and phosphorous analyses. Upon completion of the boring, the hole was filled with bentonite clay.

The samples were submitted to Environmental Testing Laboratories, Inc., a NJDEP-certified laboratory (NJ Cert. # 73812). The arsenic analyses were performed using EPA method 6010B, which is approved by the NJDEP. The soil samples were not directly analyzed for phosphorous. The Navesink Formation is noted for its phosphorous content yet it is believed that the phosphorous is immobile and bound to iron within the mineral vivianite (Dooley, oral commun. 1999). The interest is in whether phosphorous dissolves out of the Navesink Formation by either rainfall infiltration or ground water as suggested by previous findings (Middletown Township Environmental Commission 1999). Therefore, the soil samples were subjected to leaching using ASTM Method D3987, Standard Method Extraction for Solid Waste with Water. The leachate was analyzed for orthophosphorous using EPA Method 365.2. Six samples from the base of the Navesink Formation were initially analyzed for total phosphorous by Method SM-4500-PE contrary to the other samples' analytical methods. The six samples were eventually subjected to the leaching procedure with the leachate analyzed for orthophosphorous. However, the holding time until the leachate extraction was performed may have affected the sample quality and contributed to the lower orthophosphorous concentrations in the six samples.

RESULTS

Inspection of the retrieved soil samples identified the top of the Navesink Formation to be fourteen feet below grade. The orange-brown silty sand of the Sandy Hook Member of the Red Bank Formation was identified by its mica and quartz constituents (Minard 1969), which were distinctly absent in the underlying Navesink Formation. The Navesink Formation is an olive to black-green silty glauconitic sand. Fragments of *Belemnitella americana* were visible at the Formation's base. The contact between the Navesink Formation and underlying Mount Laurel Sand was distinct with the presence of quartz sand and pebbles and traces of mica (Minard 1969). The contact was forty-one feet below grade, making the Navesink Formation twenty-seven feet thick and close to Minard's (1969) estimated maximum thickness of twenty-five feet in the area. The water table was twenty-three feet below grade. The boring log and associated chemical analyses are presented in the accompanying **table**.

Sample analyses included samples from the overlying Sandy Hook Member and underlying Mount Laurel Sand, respectively, to assess potential cross-formation trends. The arsenic analyses revealed an overall tight range in concentrations. Concentrations initially decreased with depth through the overlying Sandy Hook Member from 19.8 mg/kg to 10.1 mg/kg. It could not be determined whether the decrease was anthropogenically related. Arsenic concentrations slightly increased toward the top of the Navesink Formation. Two feet into the Navesink was the formation-high arsenic concentration of 61.4 mg/kg. This sample was bracketed by arsenic concentrations of 10.3 mg/kg and 11.9 mg/kg. The top nine feet of the Navesink Formation had lower arsenic concentrations than the lower two-thirds with a median concentration of 9.19 mg/kg, excluding the 61.4 mg/kg concentration. The lower two-thirds of the Formation had a median arsenic concentration of 14.2 mg/kg. The basal sample had an arsenic concentration of 18.8 mg/kg and was bracketed by concentrations of 8.11 mg/kg and 8.73 mg/kg. Arsenic concentrations in the immediately underlying Mount Laurel Sand were similar to the Navesink Formation.

NAVESINK FORMATION
LITHOLOGIC and GEOCHEMICAL TABLE
Middletown, New Jersey
NJ 1983 State Plane Coordinates E 598613.8, N 568501.7

Depth Below Grade (ft)	Formation	Formation Depth (ft)	Sample	Arsenic (ppm)	Ortho-Phosphorus (ppm)	Total Phosphorus (ppm)	Lithology
1	Sandy Hook Member, Red Bank Formation	+14					dark brown silt & f-m glauconitic sand, micaceous
2		+13					
3		+12					
4		+11					orange silt & f-m sand, micaceous, greasy feel, increasing % of m-c glauconite sand with depth
5		+10					
6		+9	4	19.8	0.31		
7		+8					
8		+7	6	16.4	1.33		
9		+6					
10		+5	8	13.8	0.38		
11		+4					
12		+3	10	10.1	0.1		
13		+2	11	12.6	0.22		
14		+1	12	16.8	1.74		
15	Navesink Formation	1	13	11.9	4.04		orange & olive m-vc glauconite sand, little silt, no mica, no greasy feel
16		2	14	61.4	3.34		
17		3	15	10.3	2.78		
18		4	16	12.2	2.74		
19		5	17	14.1	1.07		
20		6	18	11.4	4.39		olive f-m glauconite sand, trace silt, Fe bands @ 19.5', 20.2', 20.5'
21		7	19	3.6	5.04		
22		8	20	2.87	29.9		black-gray f-c glauconite sand, trace silt, wet & looser @ 23'
23		9	21	7.17	28.6		
24		10	22	17.9	26.6		
25		11	23	19.8	0.41		
26		12	24	10.2	0.19		black m-vc glauconite sand, trace silt, *agerostrea* shell, Fe bands
27		13	25	11.7	36.7		
28		14	26	13.2	2.48		orange-gray m-c sand, little silt
29		15	27	15.6	1.98		black m-vc glauconite sand, trace silt
30		16	28	12.8	0.21		
31		17	29	11.3	1.07		
32		18	30	13.7	5.84		
33		19	31	14.8	1.18		black f-m glauconite sand, little silt, hard, dry, *belemnite* @ 39'
34		20	32	20.1	0.99		
35		21	33	17.3	0.33		
36		22	34	11.8	ND*	5,380	
37		23	35	16	ND*	2,630	
38		24	36	10.7	0.2*	3,320	
39		25	37	11.9	0.13*	3,560	
40		26	38	8.11	0.038*	1,860	
41		27	39	18.8	0.013*	3,950	
42	Mt Laurel Frm	1	40	8.73	0.04*	2,240	green-black f-c glauconite sand, little silt, trace < 1/4" subangular-subround quartz sand
43		2	41	10.7	0.18*	4,000	
44		3	42	18.7	0.02*	799	
45		4	43	17	0.074*	2,120	gray-black quartz sand, trace glauconite, trace mica
46		5	44	10.7	ND	2,400	dark gray m-c quartz sand, trace mica, no glauconite, looser

NOTES: * - Analysis exceeded sample holding time
ND - Not Detected

The orthophosphorous analyses revealed an overall wider range of concentrations than the arsenic concentrations. Concentrations were low (0.10 mg/kg to 1.74 mg/kg) in the overlying Sandy Hook Member and rose to 4.04 mg/kg at the top of the Navesink Formation. Orthophosphorous spikes of 29.9 mg/kg to 26.6 mg/kg occurred eight to ten feet, respectively, into the Navesink. Another spike of 36.7 mg/kg occurred thirteen feet into the Formation and was bracketed by concentrations of 0.19 mg/kg and 2.48 mg/kg. At eighteen feet into the Formation, a spike of 5.84 mg/kg was bracketed by concentrations of 1.07 mg/kg and 1.18 mg/kg. Orthophosphorous concentrations in the basal five feet of the Navesink and underlying Mount Laurel, collected on a second date, may have been impacted by laboratory analytical confusion and holding times. The orthophosphorous concentrations in the basal portion ranged from non-detect to 0.2 mg/kg.

CONCLUSIONS

The Navesink Formation is considered in New Jersey as a lithogenic source of arsenic with concentrations exceeding current NJDEP Soil Cleanup Criteria. The Formation has a higher than average total phosphorous content which is considered to be immobile. The Middletown Township Environmental Commission is currently funded by the NJDEP to determine agricultural inputs of arsenic to the soil for health reasons and is reviewing proposed NJDEP water quality limits on surface water phosphorous loads. The Middletown Township Environmental Commission needs to determine lithologic arsenic and orthophosphorous inputs when assessing anthropogenically-related inputs.

The buried 27-foot thick Navesink Formation, unaffected by anthropogenic activity, was sampled at 1-foot intervals to assess its lithogenic arsenic and orthophosphorous content. Twenty-seven soil samples from the Navesink Formation and eleven samples from the overlying Red Bank Sand and underlying Mount Laurel Sand were analyzed for arsenic and orthophosphorous. The arsenic analyses documented one sample with a concentration of 61.4 mg/kg, which exceeded the NJDEP's Residential Soil Cleanup Criteria of 20 mg/kg. Another sample's arsenic concentration of 20.1 mg/kg marginally exceeded its criteria. The remaining thirty-six arsenic concentrations were lower than 20 mg/kg although one-third of these concentrations were between 15 and 19.8 mg/kg. By itself, the lithogenic amount of arsenic in the Navesink Formation was not enough to exceed the NJDEP's Residential Soil Cleanup Criteria. However, minor amounts of anthropogenically-derived arsenic, when added to Navesink Formation sediment, may result in arsenic concentrations exceeding the NJDEP's Residential Soil Cleanup Criteria.

The phosphorous analyses detected leachable orthophosphorous in thirty-five of the thirty-eight samples. Since the concern was the potential for the orthophosphorous to enter surface streams via ground water, the concentrations were compared to the NJDEP's Fresh Water Surface Water Quality Standard of 0.1 mg/l for phosphorous. The top twenty-eight samples met or exceeded phosphorous' Fresh Water Surface Water Quality Standard (SWQS). The lowest samples' orthophosphorous did not exceed the SWQS, possibly due to laboratory error. The Navesink Formation has the potential for providing enough orthophosphorous for streams to exceed the Water Surface Water Quality Standard.

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RELATION OF GEOLOGY, HYDROLOGY, AND GEOCHEMISTRY TO DISTRIBUTION OF NATURALLY OCCURRING RADIOACTIVITY IN WATER IN FRACTURED-ROCK AQUIFERS, NEWARK BASIN, AND THE UNCONFINED KIRKWOOD-COHANSEY AQUIFER SYSTEM, NEW JERSEY COASTAL PLAIN

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Naturally occurring radionuclides are among the most frequently detected and widely dispersed contaminants in the environment that pose a risk to public health. Human bone tissue accumulates ingested radium (Ra) and uranium (U) much like it does calcium. The resulting exposure to ionizing radiation can cause tissue damage and continuous exposure may increase the risk of malignancy formation. Even after the U. S. Environmental Protection Agency (USEPA) proposed interim Maximum Contaminant Levels (MCLs) of 5 pCi/L (picocuries per liter) for the sum of radium (Ra) (defined as the sum of radium-226 (Ra-226) and radium-228 (Ra-228)) and 15 pCi/L for gross alpha-particle activity in 1976, the environmental distribution of radionuclides in natural waters was poorly understood. In the late 1980s, high concentrations of radon-222 (Rn-222) were found in indoor air in northern New Jersey, and concentrations of the sum of Ra greater than the MCL were found in drinking water in southern New Jersey. Subsequently, the N. J. Department of Environmental Protection (NJDEP) established a radon program in the State in addition to funding research designed to determine the geologic occurrence, geochemistry, and dispersal mechanisms of these radionuclides in New Jersey. The U.S. Geological Survey (USGS), in cooperation with NJDEP, conducted both regional- and local-scale studies of radionuclide occurrence in two regions of the State--the alkaline rock in the north and the acidic sands in the south. The results of the studies that were completed during 1990-2000 are summarized here.

The distribution of radionuclides in ground water is controlled largely by lithology, hydrology, and geochemistry, and differs greatly between the two regions. In continuous cores from six sites in the Newark Basin, permeable strata adjacent to much less permeable zones are highly enriched in U–in some cases by as much as two orders of magnitude relative to background levels. These strata include basal conglomerates of upward-fining sequences that overlie mudstones in the Stockton Formation, and black and white, carbonate-rich siltstone and mudstone laminae that overlie massive mudstones in the Passaic Formation. Diagenetic processes likely are responsible for this U enrichment. Water from wells that penetrate highly radioactive strata (about 5 percent of the 260 wells sampled) contained elevated concentrations of radionuclides greater than MCLs. Oxidation-reduction potential controls the solubility of U and Ra in the alkaline waters of the Newark Basin. U is more abundant in oxidizing water, whereas Ra-226 dominates the reducing water in this region. The effects of land use on ground-water chemistry there have yet to be defined. The distribution of both radioactive strata and water-bearing fractures, both of which can be nonplanar and discontinuous, varies substantially over small vertical and horizontal distances. Therefore, quantifying the dispersal of radionuclides in terms other than the frequency of recurrence of radioactive lithologies and water-bearing fractures in a given area is difficult.

In the Kirkwood-Cohansey aquifer system, immature river-bed gravels of the Bridgeton Formation and silt stringers contain only slightly more U than the quartzose sands. Concentrations of Ra exceeded those of U in all 170 water samples collected, and exceeded the MCL in 33 percent, primarily in samples from areas of intensively developed (agricultural plus residential) land, most of which is underlain by the Bridgeton Formation. Ra is mobile in the Kirkwood-Cohansey aquifer system because it is inefficiently sorbed by the quartzose matrix in the acidic environment, whereas the solubility of U is limited by the absence of carbonate alkalinity. Degradation of water quality in agricultural and residential areas by nitrification of fertilizer and leaching of the nitrate increases acidification and may enhance mobilization of Ra. The acidic recharge that dissolves the Ra disperses down gradient along ground-water flowpaths in predictable orientations.

NJDEP has produced a guide for homeowners based on the results of these studies. This information also can be used to design vulnerability assessments, mitigation programs, and water-testing warnings for owners of wells.

Public Health and Environmental Health Concerns Related to New Jersey Geology (Workshop)

David P. Harper,
New Jersey Department of Environmental Protection,
Bureau of Underground Storage Tanks, P.O. Box 433, Trenton, NJ 08625

ABSTRACT

Public and environmental health concerns related to geology may be directly related to rocks or sediments (for example from dust or soil containing naturally occurring asbestos minerals), through air or water (for example from radon released to air or radium released to ground water), or from interaction with pollutants generated by human activity (for example from mobilization of mercury under certain ground water chemistry conditions).

In this workshop, the participants will match hand samples to caption cards and to a New Jersey geologic map. Samples will include rocks which might impart radioactivity to ground water or indoor air (some New Jersey Highlands crystalline rocks, Newark Basin sedimentary rocks, Paleozoic carbonates, and coastal plain sediments), rocks which might weather to soils which exceed New Jersey's maximum contaminant levels for arsenic or beryllium (some Newark Basin sedimentary rocks and coastal plain sediments), iron sulfide minerals which can break down to acidify drainage and render stream water poisonous to fish (from some coastal plain formations), and other geologic materials related to environmental concerns. The participants will assemble these on a pegboard base to display a few of the relationships between public and environmental health and geology in New Jersey.

Field Guide and GANJ & NJ-AWRA 2001 Road Log

Pierre Lacombe and Greg Herman

with tours hosted by
Frank Marascia of Elizabethtown Water Company and
Chuck Martine of Foster Wheeler Inc.

		Trip Mileage
Courtyard Marriott to Stop 1	Rutgers Campus	16.7
Stop 1 to Stop 2	Elizabethtown Water Co. Greenbrook Well field	8.2
Stop 2 to Stop 3	Manville Village Park	10.3
Stop 3 to Stop 4	Pennington Outcrop	25.3
Stop 4 to Stop 5	Naval Air Warfare Center	7.8
Stop 5 to Courtyard Marriott		24.5
Total Mileage		92.8
		Mileage

Let's protect our earth

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

Location in New Jersey

SCALE 1:300,000

5 0 5 Miles

7 0 7 Kilometers

Starting in the Courtyard Marriott parking lot located off NJ Turnpike Exit 8A
At the intersection of Rt. 535 and Rt.32, South Brunswick, NJ.

Exit Parking Lot and turn left on Rt. 535 with immediate left onto to Rt. 32 West.	0.1
Turn Right onto Rt. 130 North	1.0
At intersection of Rt.130 and Rt. 1--- Drive Rt.1 North,	9.6
At intersection of Rt.1 and Rt.18--- Drive Rt.18 North,	12.2
Drive Rt. 18N across the Raritan River and through intersection at light with River Road onto Metlars Ln. Make first left turn on Sutphen Rd.	15.7
Right turn at intersection with Frelinghuysen Rd.	16.0
Parking lot is by a soccer field. Hill Center for the Mathematics and the Chemistry Laboratory are in the building complex on the other side of the road.	16.7

Stop 1 Chemistry Building at Rutgers University (Jean Brown Report)
Abstract from Jean Brown and Vincent dePaul, USGS Report WRIR 99-4256

Volatile Organic Compounds primarily carbon tetrachloride and tetrachloroethylene (PCE), were detected in shallow ground water near the Chemical Engineering building--also called the C-Wing building--at the Rutgers University Busch Campus in Piscataway Township Middlesex County, New Jersey. The C-Wing building overlies the Passaic Formation, which comprises a water-supply aquifer, and is about 2,500 feet north-northeast of several domestic wells.

In the area of the Busch Campus, the Passaic Formation consist of dipping layer of extensively fractured coarse-grained siltstone and sandstone alternating with layers of sparsely fractured finer grained siltstone and mudstone. Ground water is primarily stored in and transmitted through interconnected fractures in these rocks. The extensively fractured layers comprise water-bearing units; the sparsely fractured layers comprise confining units. The rock layers dip 11° to the northwest. Near land surface, the rocks are weathered. Clay and silt derived from the weathering process fills many of the fractures in the weathered zone, causing it to be less permeable than the underlying water-bearing units. Four water- bearing units, alternating with the confining units, are present in the study area. The median transmissivity of the water-bearing units and confining units, respectively, is 84 and 3.7 ft^2/day (feet squared per day). The median transmissivity of the weathered zone is 4.8 ft^2/d.

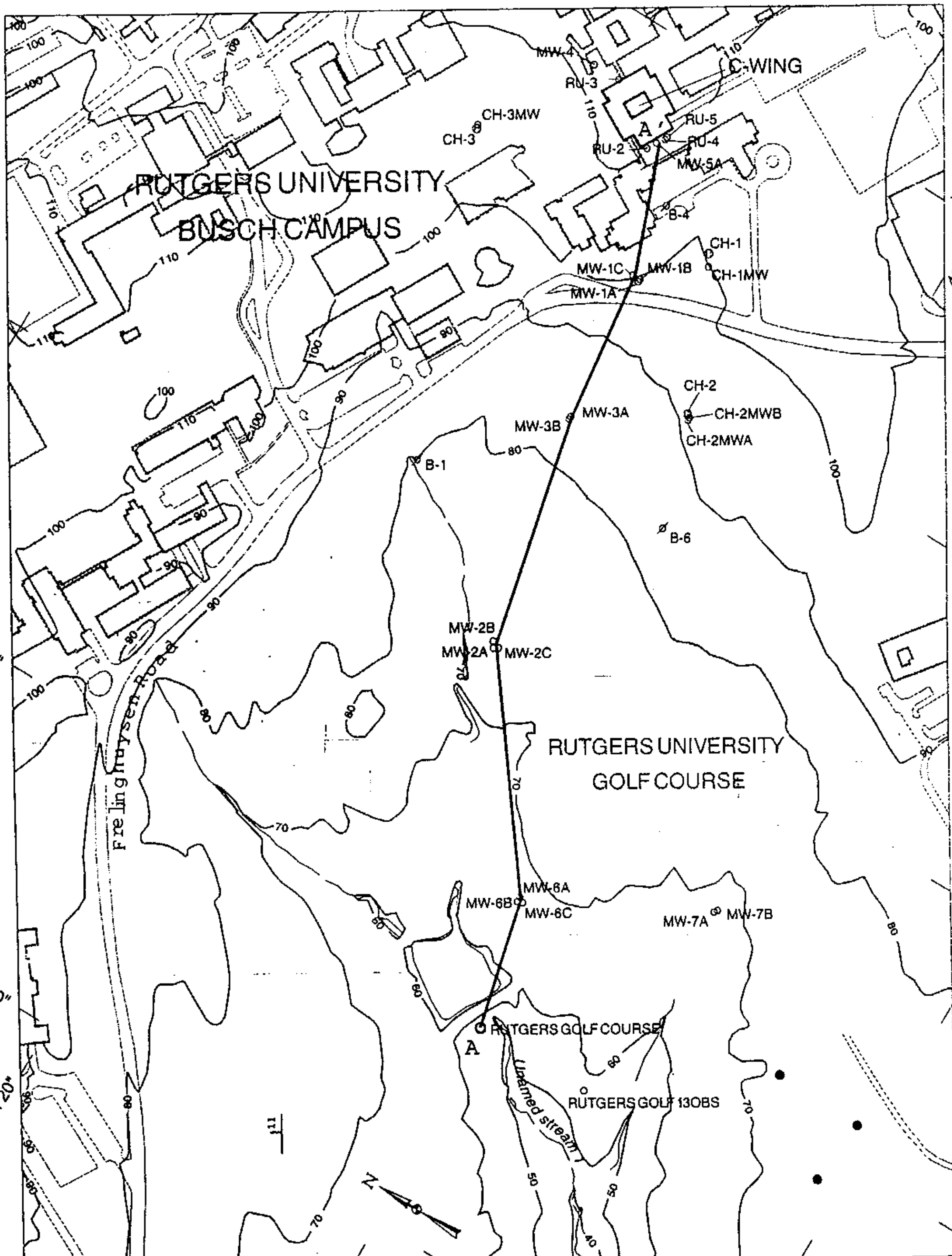
Recharge to the ground-water flow system is by downward leakage of infiltrated precipitation. The transmissivity contrasts and the dipping hydrogeologic units of the multiunit aquifer system cause large-scale anisotropic flow. Ground-water flow through the system is predominately southwest, parallel to the strike of the rock layers. Ground-water discharges predominantly to the Raritan River and its tributaries; minor amounts flow to a pumped irrigation well and several domestic wells. The northeastern half of the study area is a recharge area and the southwestern half, which is nearer to the Raritan River, is a discharge area.

A digital model was developed to simulate both steady-state and transient ground-water flow in the study area. The configuration of simulated ground-water flow paths from the vicinity of the C-Wing building are primarily horizontal in the water-bearing units and vertical in the confining units. Horizontal flow generally is parallel or subparallel to the strike of the rock layers. When the irrigation well is not being pumped, all water that passes through the vicinity of the C-Wing building discharges to the Raritan River and it tributaries. Pumping from the irrigation well causes flow lines to shift toward the well and away from the nearby domestic wells.

Water samples were collected from 25 wells in the study area at least once during the 1993-96. The spatial distribution of the two primary contaminates at Busch Campus--carbon tetrachloride and PCE--differ from each other. The carbon tetrachloride plume is localized near the C-Wing building, although trace amounts were detected in wells as far as 750 feet from the building. The occurrence of PCE, in contrast, is discontinuous. This compound was detected in concentration greater than the New Jersey maximum contaminant level of 1.0 micrograms per liter at several locations in the study area. Concentration were highest in shallow wells less than 10 feet from the C-Wing building and in the irrigation well, which is 2,370 feet from it. PCE was not detected in samples from nine wells between the C-Wing building and the irrigation well, however.

All wells in which carbon tetrachloride was detected are within the area encompassed by the simulated flow lines from the assumed carbon tetrachloride sources area at the C-Wing building, and the concentrations of carbon tetrachloride decreases along the flow lines. Therefore, the flow-path analysis supports the hypothesis that all of the carbon tetrachloride detected in the study area originated in the C-Wing building area. Some wells that contained PCE, however, are outside the area encompassed by the flow lines from the assumed PCE source area at the C-Wing building. Consequently, both the simulated flow paths and the discontinuous distribution of PCE are inconsistent with the hypothesis that all of the PCE detected in the study area originated at the broken pipe near the C-Wing building. Because actual ground-water flow paths through the fractured-rock aquifer system are undoubtedly more complex than the simulated path, however the possibility that all of the PCE originated at the broken pipe can not be conclusively ruled out.

U.S. Geological Survey in cooperation with Rutgers University investigated the ground water contamination in this area . Figure 2, 3, and 9 are from Brown and dePaul, 1999. They show the location of the wells and core holes in the study area, the generalized hydrogeologic section, and the concentration of carbon tetrachloride and simulated ground water flow path in 1995. Boxes of rock core are available for inspection of the geology and hydrogeology



Base from Rutgers University, Modified from Aerial Data Reduction Associates, 1:600, 1988, Aerial photography by Keystone Aerial Surveys, March, 1985

0 100 200 300 400 FEET

0 25 50 75 100 METERS

EXPLANATION

A —— A′	Line of hydrogeologic section	o MW-3A	Observation well location and identifier
—— 80 ——	Topographic contour--Shows altitude of land surface. Contour interval 10 feet. Datum is sea level	CH-2	Corehole location and identifier
		o	Irrigation well location
11	Average strike direction and dip angle of rock layers	●	Domestic well location
		B-6	Piezometer location and identifier

Figure 2. Location of wells and coreholes in the study area, Rutgers University Busch Campus and vicinity, Piscataway Township, New Jersey.

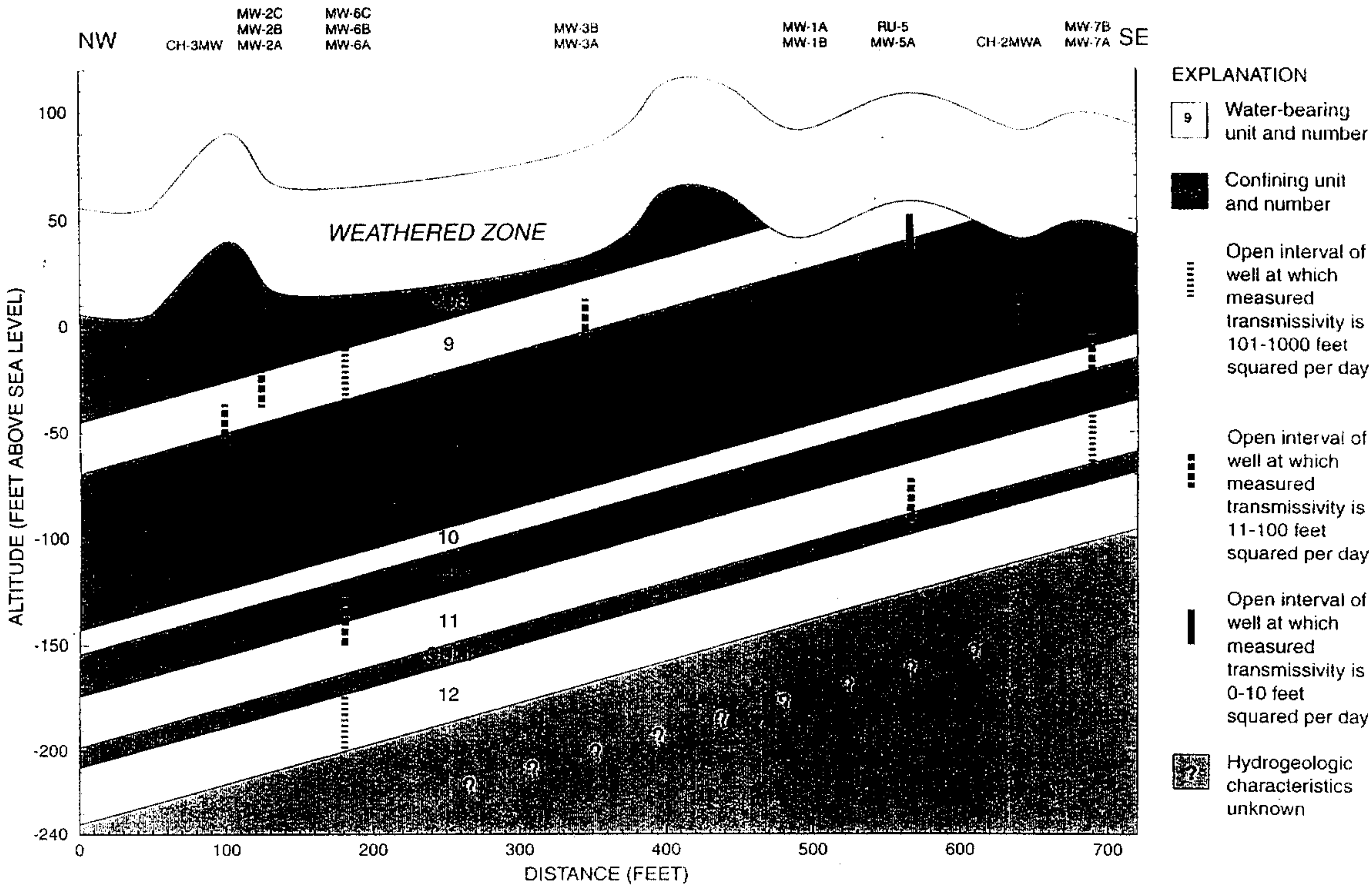
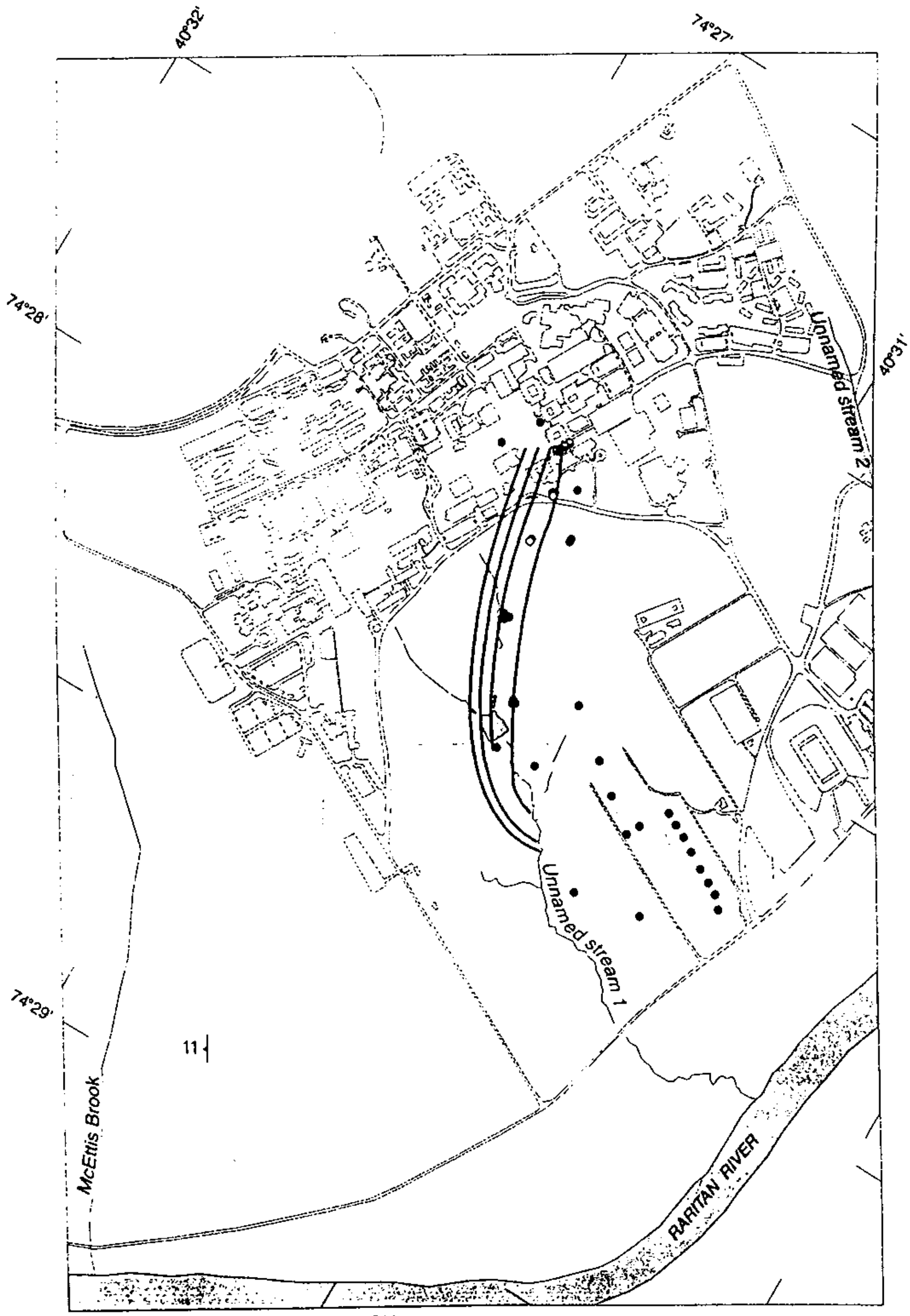


Figure 3. Generalized section along dip of bedding showing transmissivity measured at wells and interpreted location of hydrogeologic units in the study area, Rutgers University Busch Campus and vicinity, Piscataway Township, New Jersey.



EXPLANATION

— Simulated ground-water flow path

11 Strike direction and dip angle of rock layers

• Domestic well

• Well location: carbon tetrachloride not detected

○ Well location; carbon tetrachloride concentration less than 2.0 micrograms per liter

⊙ Well location; carbon tetrachloride concentration greater than 2.0 micrograms per liter

0 400 800 1,200 FEET

0 100 200 300 METERS

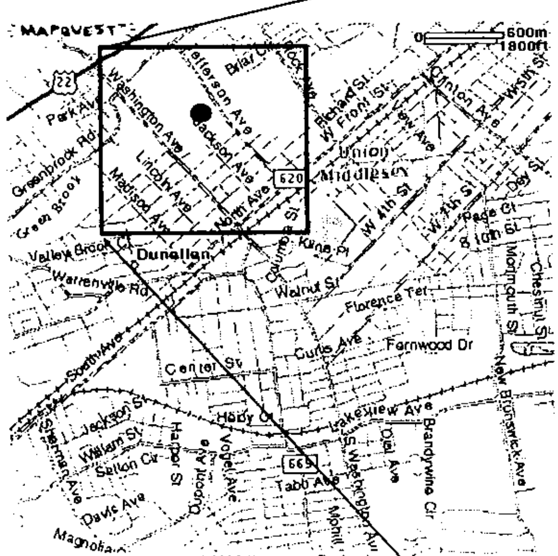
Figure 9. Concentration of carbon tetrachloride in water samples collected from wells in 1995 and simulated ground-water flow paths from the assumed carbon tetrachloride source area under steady-state conditions with no pumpage from the irrigation well, Rutgers University Busch Campus and vicinity, Piscataway Township, New Jersey.

Proceed to STOP 2-- Leave Parking lot by Math and Chemistry building complex	0
Retrace route-- Take Frelinghuysen Rd. to intersection with Sutphen Rd. Turn Left Sutphen Rd.	0.2
Drive Sutphen Rd. to Rt.609, Take Left on to Rt.609 North (aka Metlars Ln)	0.5
Drive Rt. 609 North to intersection with Rt.529, Turn left onto Rt. 529 North	2.9
Drive Rt.529 North to intersection with Green Brook Rd, Turn Right (East)	7.5
Drive Green Brook Rd to intersection with Jefferson Ave., Turn Right (South)	7.9
Drive Jefferson Ave about 0.3 miles to gravel driveway and chain-link fence at entrance to Green Brook well field.	8.2

Stop 2 Elizabethtown Water Company Green Book Well Facility: Frank Marascia

The geology that underlies the drinking water facility is Triassic age Passaic formation sandstones and shales with a strike of N151°E and a dip of 25°NW

Public Health report: This facility provides public water for nearby communities in central Somerset County. There are 10 wells with a maximum depth of about 500 ft Each well is pumped at a rate of 200 to 500gal/min. The recharge area for the wells is Grren Brook. We will visit public supply wells and an air stripper.



STOP 2 Index map and part of NJDEP DOQQ 603.jpg showing the location Public Community Water Supply Wells at the Green Brook well field (from NJ Geological Survey DGS97-1).

Proceed to STOP 3

Exit gravel road of the Green Book Well Facility, Turn Left onto Jefferson Road	0
Drive Jefferson Rd to Green Brook Road, Turn Left (West)	0.4
Drive west on Green Brook Road to Rt.529 North, Turn Right	0.8
Drive Rt.529 North to Rt. 22 West, Turn Left	0.9
Drive Rt.22 West to Exit for Manville, Turn Right, follow signs	6.7
Drive about 0.5 mi to intersection with Finderne Ave., Turn Right	7.2
Drive Finderne Ave south to strip style shopping center just after Railroad Trestle Turn Left into shopping center	9.5
Drive loop in shopping center and exit at same point of entrance	9.9
Turn Right onto Finderne Ave, drive to Rt.608 West (aka Dukes Pkwy) Turn left onto Rt.608 West	10.3
Immediately turn right into Village park Stop 3	10.3

Stop 3 Federal Creosote Site Mannington NJ.

The following passages are from the executive summary of the "Draft Final Remediation Investigation Report for Ground Water, Surface Water, and Sediment, Federal Creosote Site Remedial Investigation Feasibility Study, Manville, New Jersey", prepared for the U.S. EPA by CDM Federal, 2001.

The Federal Creosote site was formerly owned and occupied by the American/Federal Creosote Wood Treatment facility, which operated from approximately 1910 to 1957. The plant operated a wood treatment facility that used creosote as a preservative. Two unlined lagoons and an associated canal receiving creosote waste were located in the north central and southeast section of the site. Lagoon A and Canal A are is in the north central sector of the site and Lagoon B and Canal B are in the southern sector of the site. Several impoundments, standing liquid areas, and stained areas were identified northeast of the main treatment facility along the western edge of Claremont Development.

After closure of the plant, construction of the Claremont residential community began in 1962. The lagoon and the canals were reportedly filled in without removing the creosote waste. In October 1998, EPA initiated an investigation of the site to locate possible creosote contamination and determine areas that would require further study. The Federal Creosote Site was listed on the National Priority List I on January 19, 1999.

The surfacial unconsolidated overburden deposits of the site's vicinity are of glacial, interglacial, and post-glacial fluvial origin. Regionally, these deposits consist of sand and pebbly gravel with minor silt, clay, and cobbles. Total thickness in these units of up to 50 ft has been reported. However, in the are of the site these deposits are 25 to 36 feet thick.

The bedrock underlying the site and its vicinity is the Passaic Formation, part of the Newark Supergroup consisting of reddish-brown lacustrine siltstone, mudstone, shale and occasional sandstone of fluvial origin. The Passaic Formation is the thickest and most wide spread formation in the Newark Basin.

The hydrogeology of the site is divided into an over burden aquifer and a bedrock aquifer which are separated by a weathered bedrock zone of low permeability.

Groundwater in the overburden exists under both unconfined and semi-confined conditions. The water table is found approximately 20 ft below ground surface; however, shallow discontinuous silt and clay layers may cause isolated perched water-table conditions. The ground-water flow in the overburden beneath the site is predominately to the southeast toward the Millstone River. Downward hydraulic gradients dominate the majority of the site.

The bedrock aquifer is complex "leaky" multi-unit, semi-confined, aquifer system in which groundwater flow paths are along bedding partings and high angle fractures. The bedrock at the site is highly fractured and this is evidence of significant vertical flow. The vertical gradients observed in the nested wells indicate the shallow and deep aquifer zones are hydrological connected. The base of the bedrock aquifer is defined by a bedrock surface below, which all fractures have been infilled by gypsum and the bulk permeability is essentially zero. As such, the thickness of the aquifer is defined by the elevation of the gypsum in-filling.

The rock potentiometric surfaces beneath the site indicate the groundwater flow direction is generally to the southeast across the site. The effect of the bedrock strike on ground-water flow direction is expected to east-southeast. A potentiometric surface divide is present in the northwestern portion of the study area, approximately one-half mile northwest of the Claremont Development. Groundwater to the northwest of the divide, under the influence of the potentiometric surface and strike of the bedrock, flows west and northwest towards the Raritan River and the Manville municipal wells C1 and C2. The bedrock potentiometric surface beneath the site indicates the ground-water flow direction south of the divide is generally to the southeast across, toward the Millstone River. The effect of the bedrock strike on the ground-water flow will be to make ground water flow in a more easterly direction. Therefore, the actual ground-water flow direction is expected to be east-southeast.

Benzene, PCE, and TCE were detected in wells in the overburden and in the bedrock aquifer. PAH and free-phase creosote were observed beneath Lagoon A and B. Naphthalene, the primary indicator compound for site-groundwater contamination, and a major constituent of creosote was detected in ground-water samples in the immediate vicinity of Lagoon A and B area. The naphthalene and PAH results in general indicate the ground-water contamination in the over burden is limited to the primary source are at the site. Naphthalene, Dibenzofuran, phenanthrene and carbozole were detected in three bedrock wells near lagoon A, one bedrock well near Lagoon B and in off-site well MW 116I. The contamination was not detected in any of the municipal supply wells.

NJDEP Digital Orthophoto Quarter-qaud image of the Manville area showing the Raritan River and municipal water-supply wells near the Park

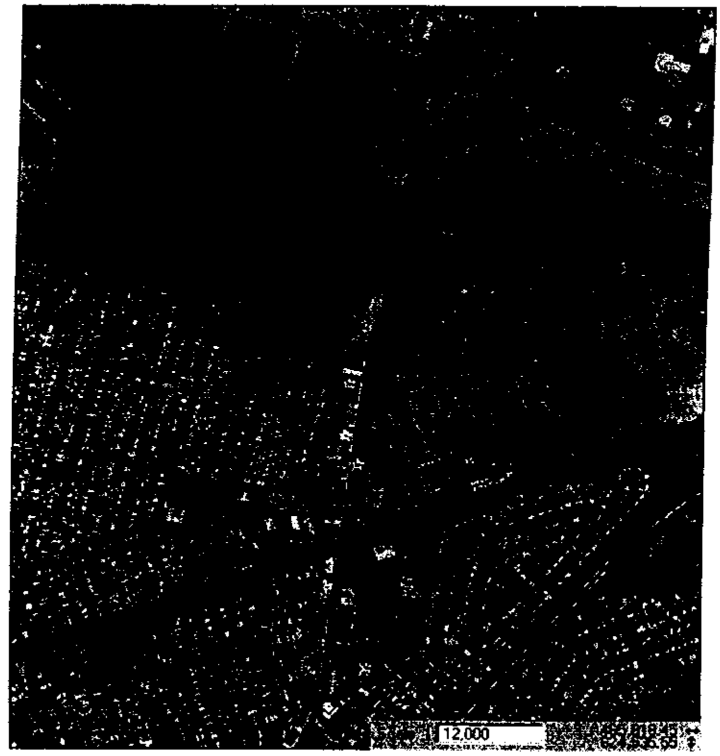
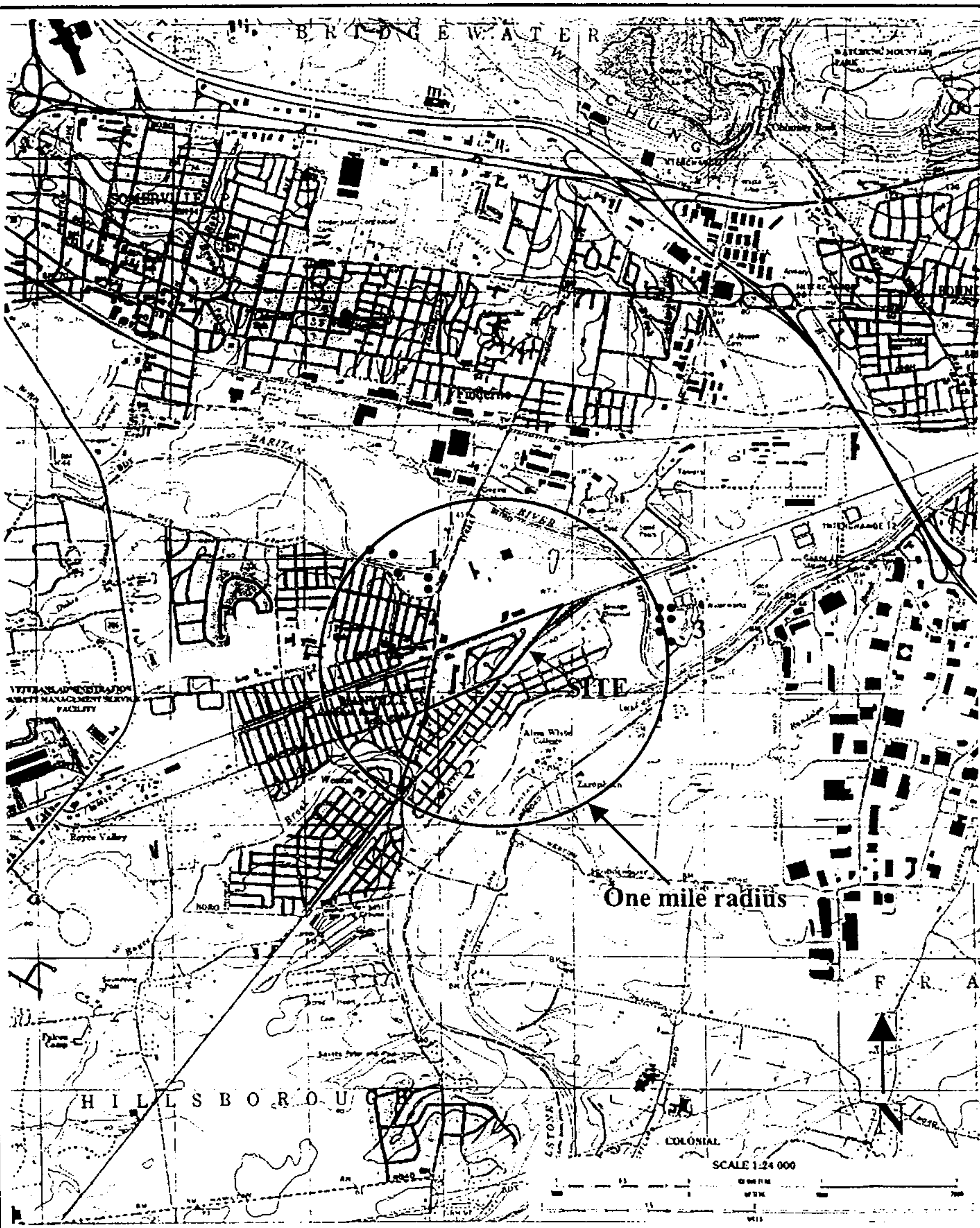


Figure 2-3 shows the location of the site and nearby permitted wells.
Figure 3-4 shows the location of sections A-A' and B-B'
Figure 3-5 shows section A-A' and includes the potentiometric surface and concentration of contamination.
Figure 3-8 shows the potentiometric surface of the overburden and
Figure 3-11 shows the potentiometric surface of the bedrock

Boxes of core are available for inspection



Basemap Source: USGS Bound Brook 7.5 Minute Topographic Map 1995

FIGURE 2-3
GROUNDWATER AND SURFACE WATER DIVERSION PERMITS

Federal Creosote Superfund Site, Manville, New Jersey
Project Number 3220-001

CDM Federal Programs Corporation

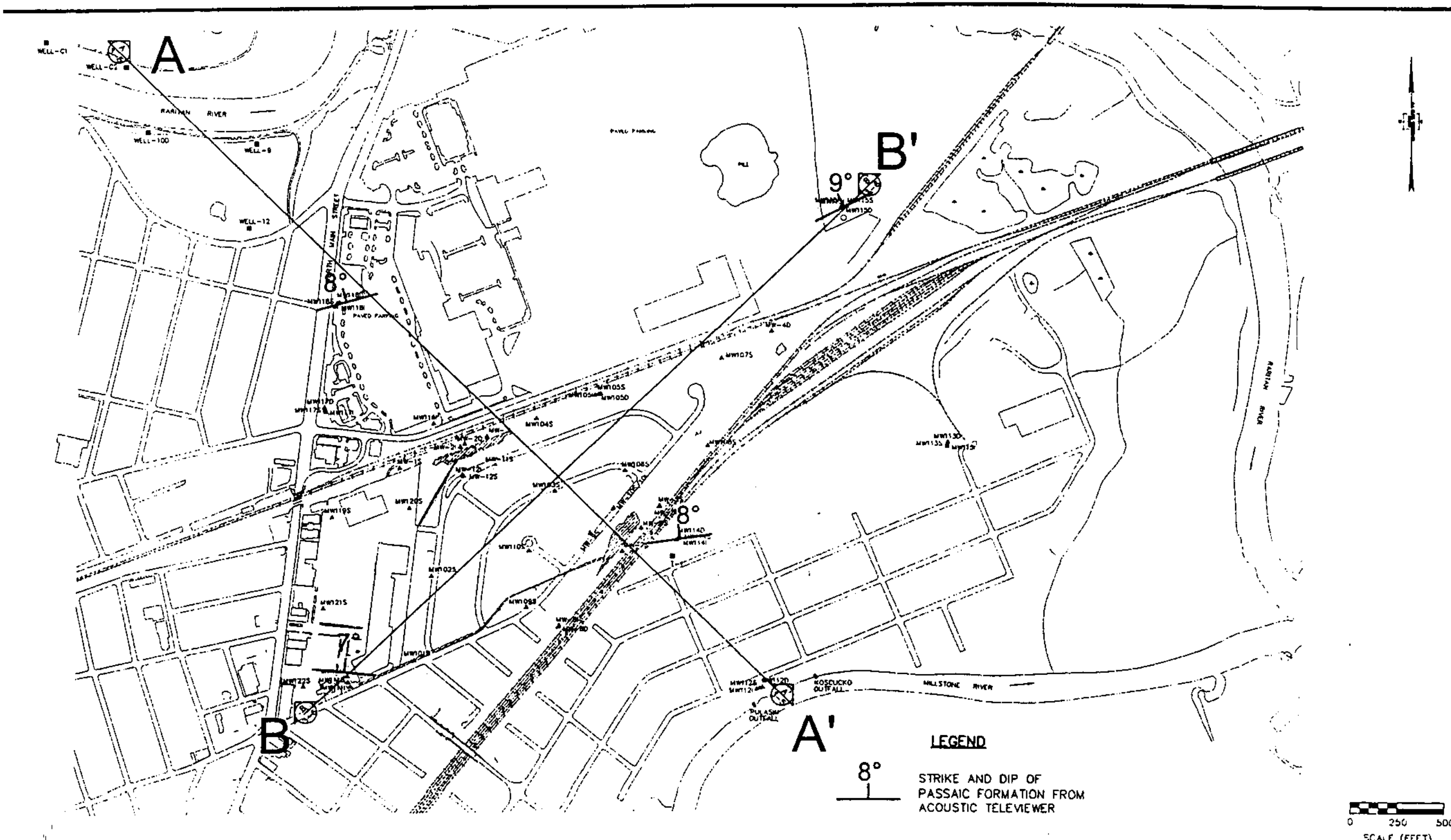
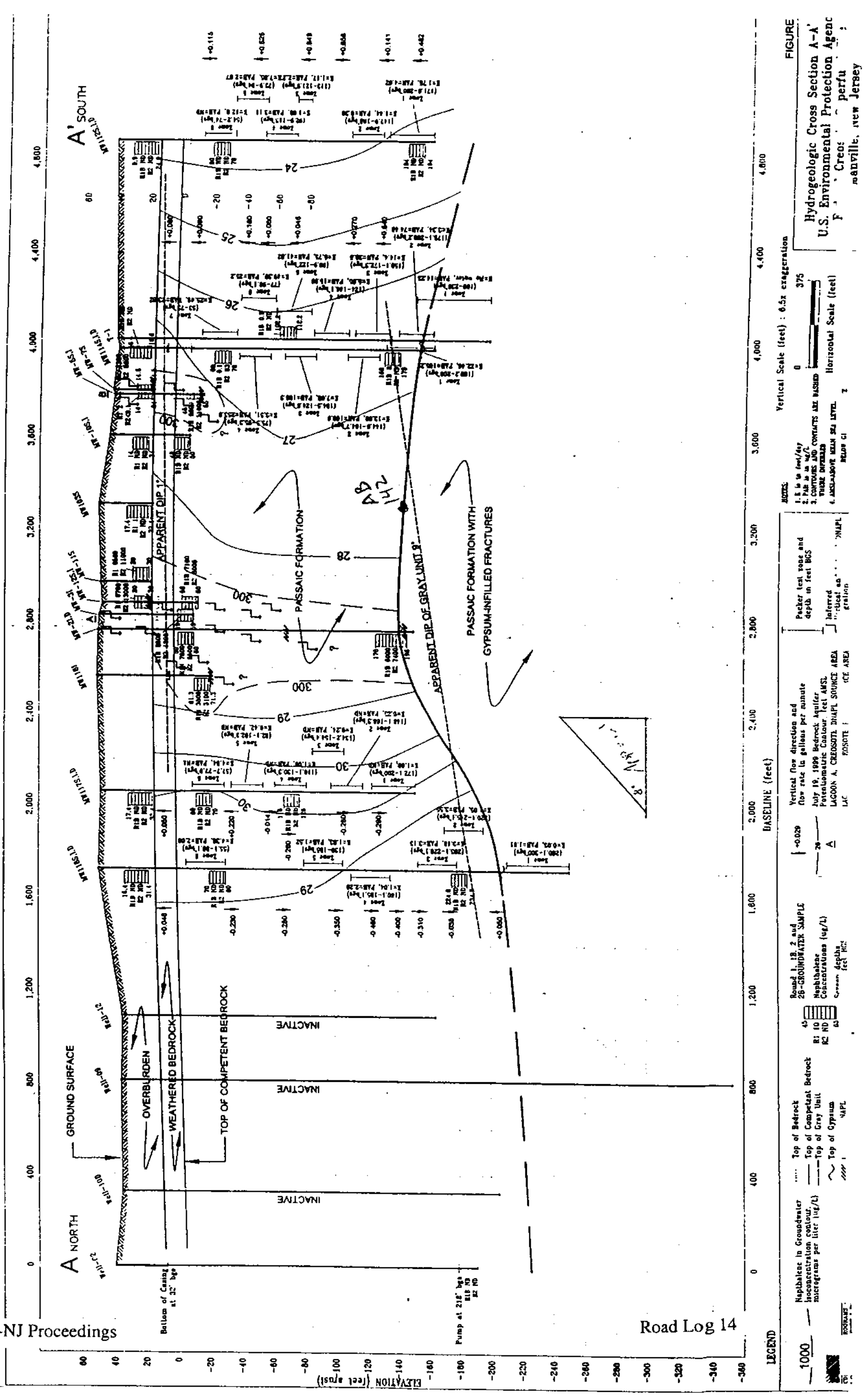


FIGURE 3-4
CROSS SECTION LOCATION MAP

FEDERAL CREOSOTE SUPERFUND SITE, MANVILLE, NEW JERSEY
PROJECT NUMBER 3220-001

CDM FEDERAL PROGRAMS CORPORATION
a subsidiary of Camp Dresser & McKee Inc.


A NORTH
A' SOUTH
GROUND SURFACE
OVERBURDEN
WEATHERED BEDROCK
TOP OF COMPETENT BEDROCK
INACTIVE
INACTIVE
INACTIVE
APPARENT DIP 1°
PASSAIC FORMATION
APPARENT DIP OF GRAY UNIT 9°
PASSAIC FORMATION WITH GYPSUM-INFILLED FRACTURES
BASELINE (feet)
ELEVATION (feet amsl)
LEGEND
FIGURE
Hydrogeologic Cross Section A-A'
U.S. Environmental Protection Agency
Vertical Scale (feet) : 6.5x exaggeration
Horizontal Scale (feet)

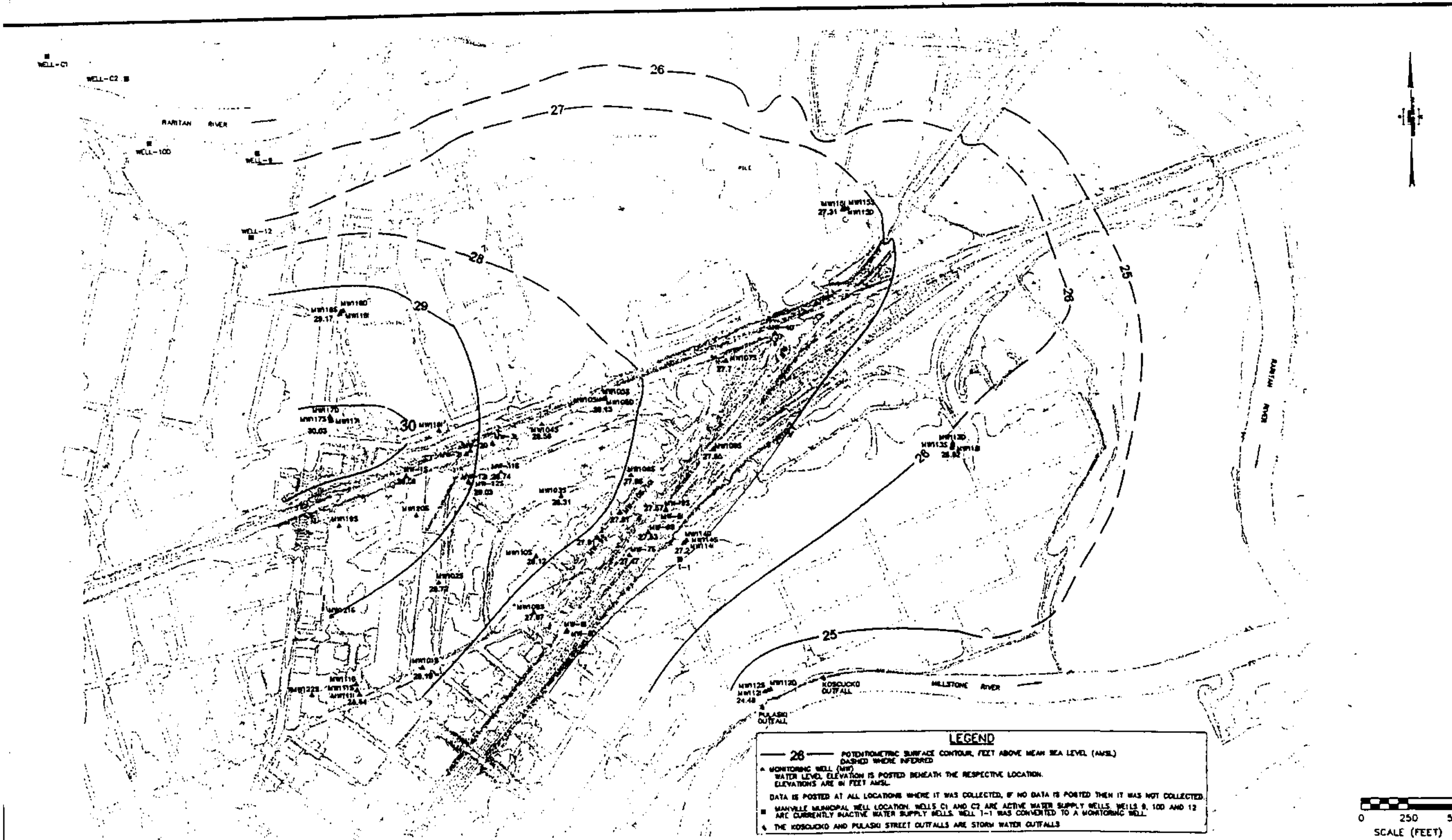


FIGURE 3-8

OVERBURDEN POTENTIOMETRIC SURFACE MAP FOR JULY 19, 1999

FEDERAL CREOSOTE SUPERFUND SITE
MANVILLE, NEW JERSEY
PROJECT NUMBER 3220-001

CDM FEDERAL PROGRAMS CORPORATION
a subsidiary of Camp Dresser & McKee Inc.

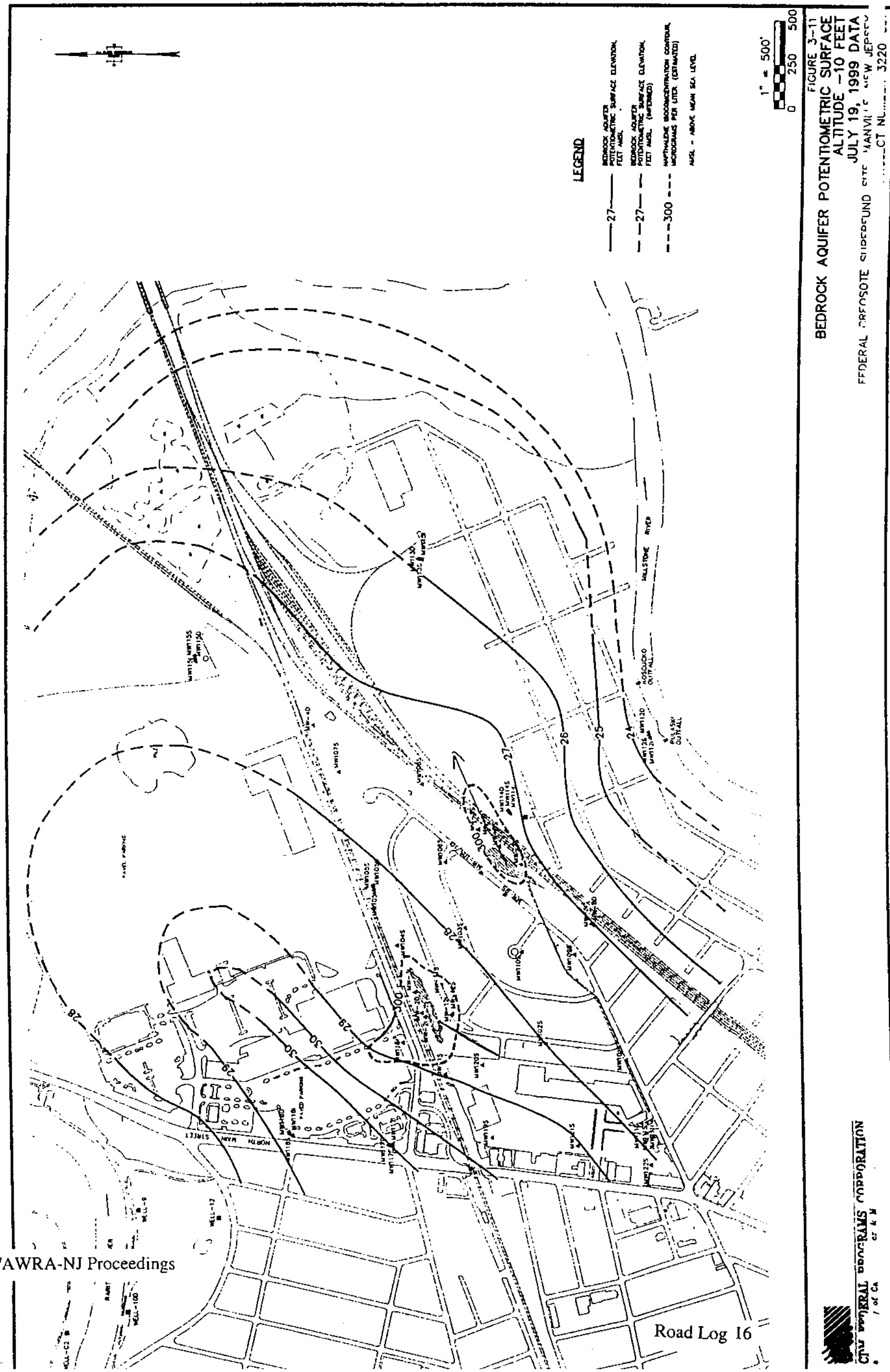


FIGURE 3-11
BEDROCK AQUIFER POTENTIOMETRIC SURFACE
ALTITUDE -10 FEET
JULY 19, 1999 DATA
LEGEND
27 BEDROCK AQUIFER POTENTIOMETRIC SURFACE ELEVATION, FEET AMSL
27 BEDROCK AQUIFER POTENTIOMETRIC SURFACE ELEVATION, FEET AMSL (INFERRED)
300 NAPTHALENE ISOCONCENTRATION CONTOUR, MICROGRAMS PER LITER (ESTIMATED)
AMSL - ABOVE MEAN SEA LEVEL
1" = 500'
0 250 500
MILLSTONE RIVER
NORTH MAIN STREET
PAVED PARKING
KOSCIUSKO OUTFALL
PULASKI OUTFALL

Proceed to STOP

Exit west end of park	0
Drive Rt.608 West (aka Dukes Pkwy) to intersection with Rt.206 South, Turn Left	1.4
Drive Rt.206 South to intersection with Rt.518 West Turn Right	14.2
Drive Rt.518 West to intersection with Rt.654, Bear Left	20.9
Driver Rt.654 West to intersection with Rt.31 South, Turn South	23.9
Drive Rt.31 South to intersection with N. Main St Pennington turn left	25.1
Drive N Main St South about 0.3 miles to parking lot on Right side of Road	25.3

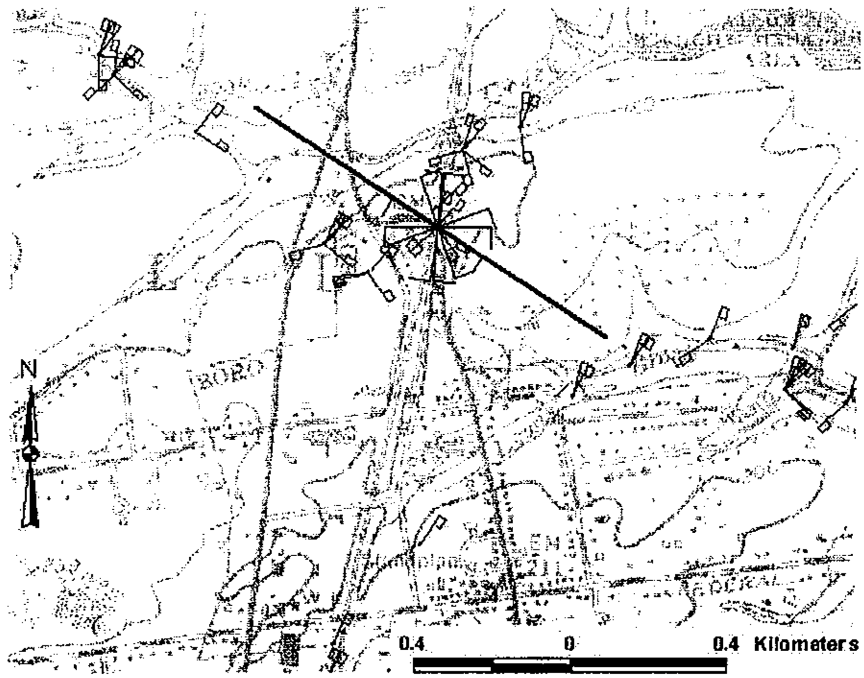
Exit buses, assemble, and wait for instructions.

STOP 4 Outcrop in Pennington by RR Tracks: Greg Herman, NJGS

Massive reddish gray mudstone crops out in both banks of the railroad cut. We focus on the eastern section just north of the bridge abutment as illustrated in the outcrop panorama below. The excavation for the railroad exposes bedrock for a few hundred feet. This cut provides a good view of the weathering profile on an alluvial terrace in the basin part of the Piedmont. The red beds are part of the Passaic (JTRp) Formation and probably are in the uppermost part of Lower Red zone of the Brunswick aquifer. A JTRp gray-bed sequence crops out at the northernmost end of the cut. Copper mineralization at the base of this gray sequence indicates the likely correlation to the base of the Kilmer Member of the Passaic Fm. This fits with having two thick gray units that crop out to the south and east that likely correspond to Neshanic and Perkasie Members. The transition from a 'red shale' into a massive mudstone occurs at about 10-12 meters below the surface. Notice how the bed partings near the surface differ from their down-dip counterpart deeper in the cut.

This location was first visited on December 21, 1995 prior to when the overpass was rebuilt. At that time, bedrock was exposed beneath the overpass, but is now cemented over as part of the abutment reconstruction. Outcrops immediately beneath the overpass contained a sub-vertical cross fault having a strike projection of 102° and showing strike-slip shear. Dominant right-lateral slip about 102° was noted. Associated shear planes were recorded, many with sub-horizontal too and groove slip lineations:

Shear planes:
070/65SE
(left lateral)
090/71SE
(right lateral)
123/83SW
074/85SE
160/87NE
008/88NW

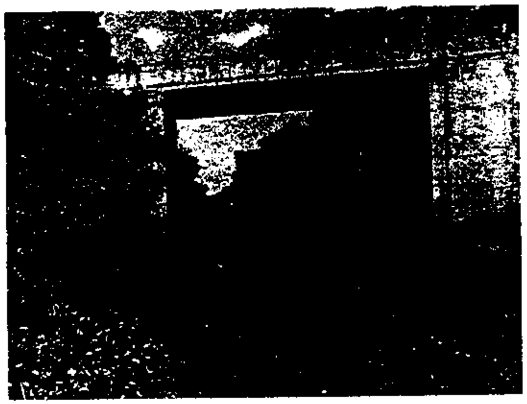


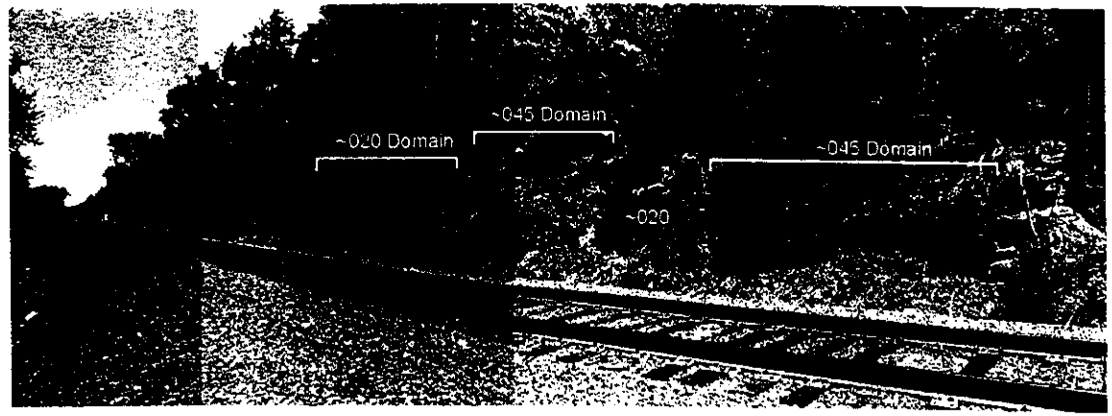
Non-bedding fractures mapped in the area of GHPN33. Flags point in the direction of dip. The cross strike fault mapped under the bridge strikes 102°. The arrays of shear planes close to the fault are shown as inclined planes with the short lines pointing the direction of dip.

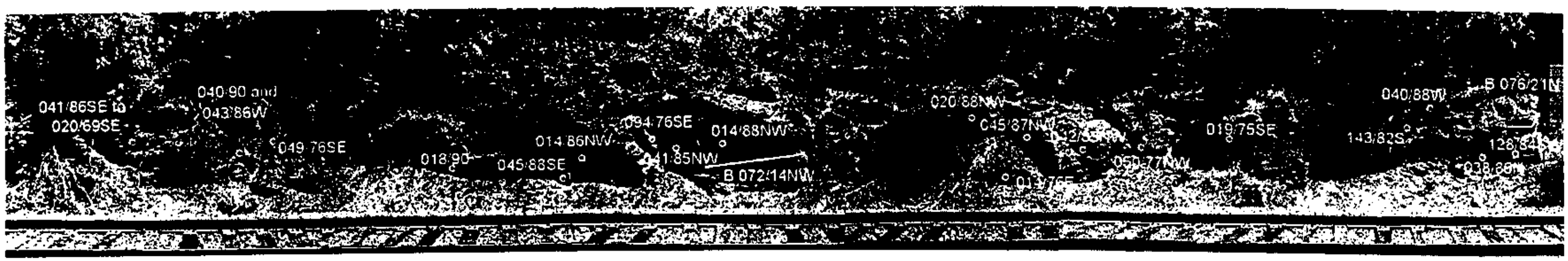
This cross fault has the same trend as another mapped in the Pennington diabase quarry immediately North (see Index map) and sits in the Hopewell fault zone structural domain (Herman, 1997). Fracture orientations measured in outcrop are summarized for the area (above) and in the outcrop panorama (below). Bedding in the train cut averages about 057/10NW but becomes 076/21NW close to the mapped fault. The clockwise rotation of bedding from drag on the fault is consistent with right-lateral slip on the fault.

Two dominant sets of systematic fractures (DECs) and the complimentary sets of cross-joints are represented here. The spatial distribution of the 020° and 045 ° fracture sets is illustrated in the lower panorama with spot measurements. Subparellel fractures of a single orientation occur in sets that locally cross or merge into other fracture sets. There are places where the 045 ° fractures twist into a 020 ° orientation, reflecting progressive counterclockwise rotation of the incremental strain field. Cross-strike fractures with a complimentary orientation also show similar twists with strikes varying from ~135 ° to ~090 °.

The outcrop is very good for illustrating the outcrop-scale geometry of fractured, massive mudstone in the central part of the basin. Systematic fracture sets of varying orientations occur in bedrock as spaced sets of fractures with variable inter-fracture spacing within sets (fracture density). Fracture domains sometimes overlap, but individual swarms of a particular fracture set exist in local isolation at the outcrop scale. Early fracture sets usually show localized extension and shear during later fracturing events, which is recorded by secondary mineral growth in veins *or dilatant en echelon cracks (DECs).* Secondary minerals commonly found in DECs include calcite, quartz, epidote, and gypsum. Calcite, quartz, and gypsum often occur with *fibrous crystal morphology (Ramsay and Huber, 1983).* The elongate, or stretched axis of the mineral crystal fibers (see examples in Guidebook) give a record of displacements and dilations of strata within tectonic fault blocks, or the *incremental strain* history. Curved fibers record systematic rotations of strata within fault blocks. The interplay between fracture sets developed in these strata, and stemming from different incremental strain events, should agree with the systematic rotation of mineral fibers and the tip-line geometry of early fractures. The structural relationships in the central part of the Newark Basin indicate incremental extension strain rotating from about the 150° to 090° azimuth during deformation of Triassic and Jurassic rocks. Fault trends in the basin appear to show a systematic relationship with age of strata (Index map), that is, earlier, border-fault trends commonly cut Triassic rocks whereas inter-basin, N-S trends affect younger Jurassic rocks. These relationships need further scrutiny.







GHPN33 JTRp Massive Mudstone

The sets of images above give three perspectives of STOP 4. The upper left image shows the outcrop on the right side through the overpass looking north from the south. The two panoramas are assembled along the same outcrop, but with different perspectives. The top right image is a splice of three shots from a single observation point located beneath the overpass on the West Side. The lower image is a composite of 6 images shot at the same distance along and across the tracks. The ~020 Domain near the left-hand side of the top right image corresponds to the left part of the lower image. The right side of both panoramic images coincides.

To proceed to STOP 5, Exit parking lot	0
Retrace route back intersection of Rt. 31 and N. Main St. turn South	0.2
Drive Rt. 31, South about to intersection with Rt. I-95 Drive onto I-95 South	3.6
Drive I-95 south to Exit 2 (West Trenton/Airport)	6.3
At end of Exit ramp take right onto Rt.579 (aka Bear Tavern Road South)	6.5
Drive Bear Tavern Road to intersection with Rt.634 (aka Parkway Ave) Turn Left	7.4
Take Rt. 634 about 0.4 miles east to Jack Stephens Way, Turn Left	7.7
Immediate Right turn into asphalt parking lot at Naval Air Warfare Center.	7.8

Stop 5 Naval Air Warfare Center Pierre Lacombe USGS

The U.S. Naval Air Warfare Center (NAWC) in West Trenton, N.J., was a jet engine testing facility for military aircraft from the mid-1950's until the late 1990's. As a result o the activities at the facility, trichloroethylene (TCE) and other chemicals have leaked onto the ground surface. TCE and the other compounds have been detected in ground water at two sites at NAWC. (figs. 1 and 2) During a remedial investigation, high concentrations of TCE, as well as its degradation products, cis-1,2-dichloroethylene (cis-DCE) and vinyl chloride (VC), and other contaminates were detected in ground water at the NAWC (International Technology Corp., 1994). Reported concentrations of TCE dissolved in ground water in a brine- handling area during 1992-93 ranged from less than 10 micrograms per liter (ug/L) to more than 20,000 ug/L the latter concentrations strongly indicate the presence of non-aqueous phase TCE At the same time, reported concentrations of TCE dissolved in ground water in a waste water lagoon and sludge disposal area ranged from less than the detection limit of 10 ug/L to 320 ug/L.

During 1993-97 the USGS, in cooperation with the U.S. Navy, conducted several studies to determine the hydrogeologic framework of the site, measure and map ground-water levels, collect samples of water-quality analysis, and map ground-water contamination plumes at the NAWC. The USGS also provided technical oversight and assistance to the U.S. Navy. During the same time, the U.S. Navy contracted EA Engineering, Science, and Technology Inc. to provide drilling services, collect water-quality samples for analysis, and measure water levels.

Geophysical, driller's and geologist logs from 48 bedrock well and the Naval Air Warfare Center in West Trenton, N.J., were examined and interpreted to prepare structure maps and sections of the hydrogeologic framework. The maps and sections show the geometry of the Stockton aquifer with 5 bedding units and Lockatong aquifer with 14 bedding units. Each bedding unit consists of water-bearing zones and semi-confining zones. An east/west-trending fault crosses the southern part of NAWC and acts as a confining unit.

A 1913 topographic map shows the West Branch of Gold Run flowed along Parkway Avenue from the west side to the east side of NAWC. A 1942 roadway construction map shows that the stream was confined in a culvert under Parkway Avenue. The stream/culvert is still active as a ground-water/surface-water discharge area.

Static water levels from the 48 wells indicated that the ground-water-flow direction in the Lockatong aquifer in along bedding strike and to the west with discharge into the West Branch of Gold Run. Drawdown water levels during three aquifer tests indicated that the Lockatong aquifer is anisotropic. The water-bearing zones in the aquifer are isotropic or nearly so in the plane of the zone. Stressed water levels from 48 bedrock wells show that the recovery well causes a local anisotropic cone of depression, which probably does not capture the whole TCE contamination plume.

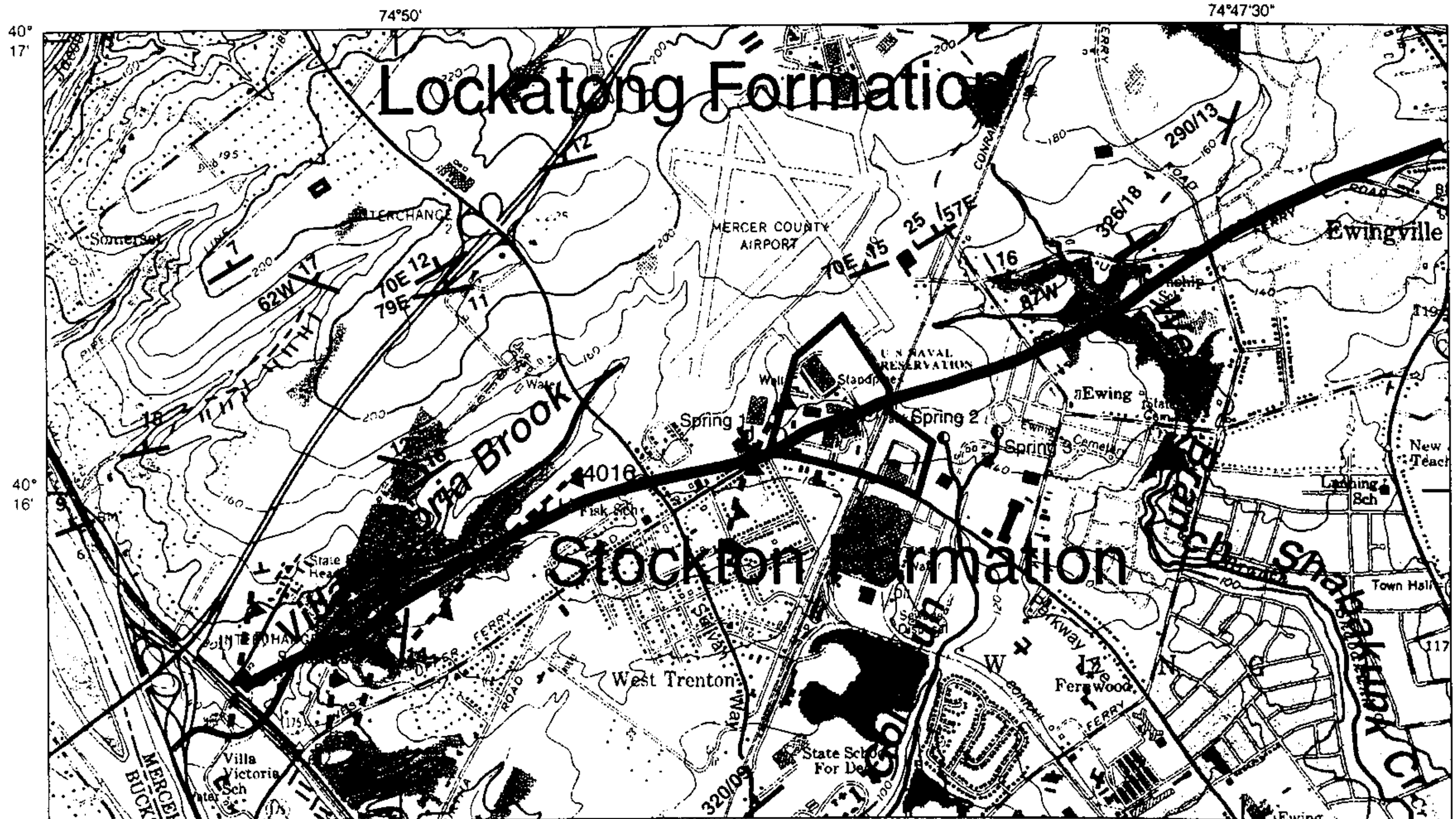
Analysis of water-quality data from the 48 wells indicates the extent of the plumes of trichloroethylene (TCE) and its degradation products cis-DCE and VC. The TCE plume emanating from a waste lagoon and a sludge-disposal area (Site 3) is moving along strike to the west along the north side of the fault. The TCE plume emanating from a brine-handling area (Site1) is interpreted for two scenarios. Scenario 1 assumes that dense non-aqueous phase liquid (DNAPL) TCE has sunk into the Lockatong aquifer to a depth of more than 200 feet. Scenario 2 assumes that the DNAPL TCE has dissolved by a depth of 100 ft below land surface. Cis-DCE and VC concentrations indicate that degradation of TCE is occurring at depths of 0 to 100 ft below land surface but that degradation is not occurring to a significant extent at greater depths. The cis-DCE and VC appear to be moving west of Site 1 as a result of ground-water flow. Centers of the cis-DCE and VC plumes are 100 and 200 ft, respectively, west of the center of the TCE plume.

Tour of Naval Air Warfare Center facility view monitoring wells, flowing wells, extraction wells, view west spring and north Parkway Ave. culverts that carry the flow of the West Branch of Gold Run.

Tour air-striping facility: Chuck Martine operator for Foster Wheeler Inc.

The U.S. Geological Survey in Cooperation with the U.S. Navy has investigated the hydrogeologic framework at NAWC Lacombe 2000

Figure 6. The outcrop geology of the area around NAWC
Table 1. The bedding units as defined by Lacombe 2000
Figure 7b. Shows the bedding units based on the gamma ray signature from well logs
Figure 8. Shows the outcrop geology and location of wells
Figure 15. section F-F' showing the structure based on gamma ray logs geologist logs and core logs
Figure 28. The static potentiometric surface at land surface
Figure 43. Section F-F', drawdown measured in wells during an aquifer test while pumping well 15BR
Figure 69. TCE concentrations projected to land surface
Figure 77b. Section view showing TCE concentrations



Base from U.S. Geological Survey digital raster graphic 1:24,000 Pennington quadrangle

Modified from H.Houghton, New Jersey Geological Survey, unpublished geologic map of the Pennington quadrangle, Novemeber, 1984

EXPLANATION

Fault contact, as defined in this report. Houghton (N.J. Department of Environmental Protection, written commun., 1984) defines this line as a bedding contact

Inclined thrust fault. 'U' is up-thrown side. 'D' is down-thrown side as defined by Houghton (written commun.,1984)

Approximate property boundary of the Naval Air Warfare Center

15 — Strike and dip of the geologic formation. Short line shows direction of dip, long line shows direction of strike

Spring

0 1,000 2,000 FEET

0 500 METERS

Figure 6. Geology in the area of the Naval Air Warfare Center, West Trenton, New Jersey.

Table 1. Bedding units at the Naval Air Warfare Center based on the natural gamma-ray logs, driller's logs, and core logs

Era	Series	Geologic units	Aquifers	Bedding unit	Predominate lithology and hydrology	Hydraulic character
Mesozoic	Upper Triassic	Lockatong Formation	Lockatong Aquifer	L-23	MUDSTONE. light to dark gray, laminated slightly calcareous, low gamma count	Not applicable
				L-22	MUDSTONE, dark gray and green-gray, low gamma count	Not applicable
				L-21	MUDSTONE, gray, platy, massive, interbedded, medium hard, low gamma zone	Not applicable
				L-20	MUDSTONE, gray, high gamma count	Semi-confining unit
				L-19	MUDSTONE, gray, hard to medium hard, with calcareous and soft brown mudstone seams low gamma zone	Not applicable
				L-18	SILTSTONE, MUDSTONE light to dark olive green or black, massive, bioturbidation, pyrite, fracture zone, some finely laminated, strongly calcareous, high gamma count	Not applicable
				L-17	MUDSTONE, red brown to green-gray brown, low gamma zone	Not applicable
				L-16	MUDSTONE, ARGILLITE, and SHALE, light green to gray and black, high gamma zone	Not applicable
				L-15	MUDSTONE, red brown and green-gray, soft, slightly broken, massive bedded, calcareous, low gamma zone	Not applicable
				L-14	MUDSTONE, dark gray to green-gray, high gamma zone	Not applicable
				L-13	MUDSTONE, dark gray, low gamma zone	Not applicable
					Stratigraphic relation unknown	Not applicable
				L-3	No data	Not applicable
				L-2	MUDSTONE, greenish gray, low gamma zone	Not applicable
				L-1	MUDSTONE, medium to dark gray, laminated, high gamma zone	Not applicable
		Stockton Formation	Stockton Aquifer	S-15	SANDSTONE, brown, medium hard	Not applicable
				S-14	SANDSTONE, gray white, medium hard	Not applicable
				S-13	MUDSTONE red, hard, massive	Not applicable
				S-12	SANDSTONE, gray white	Not applicable
				S-11	MUDSTONE, red	Not applicable

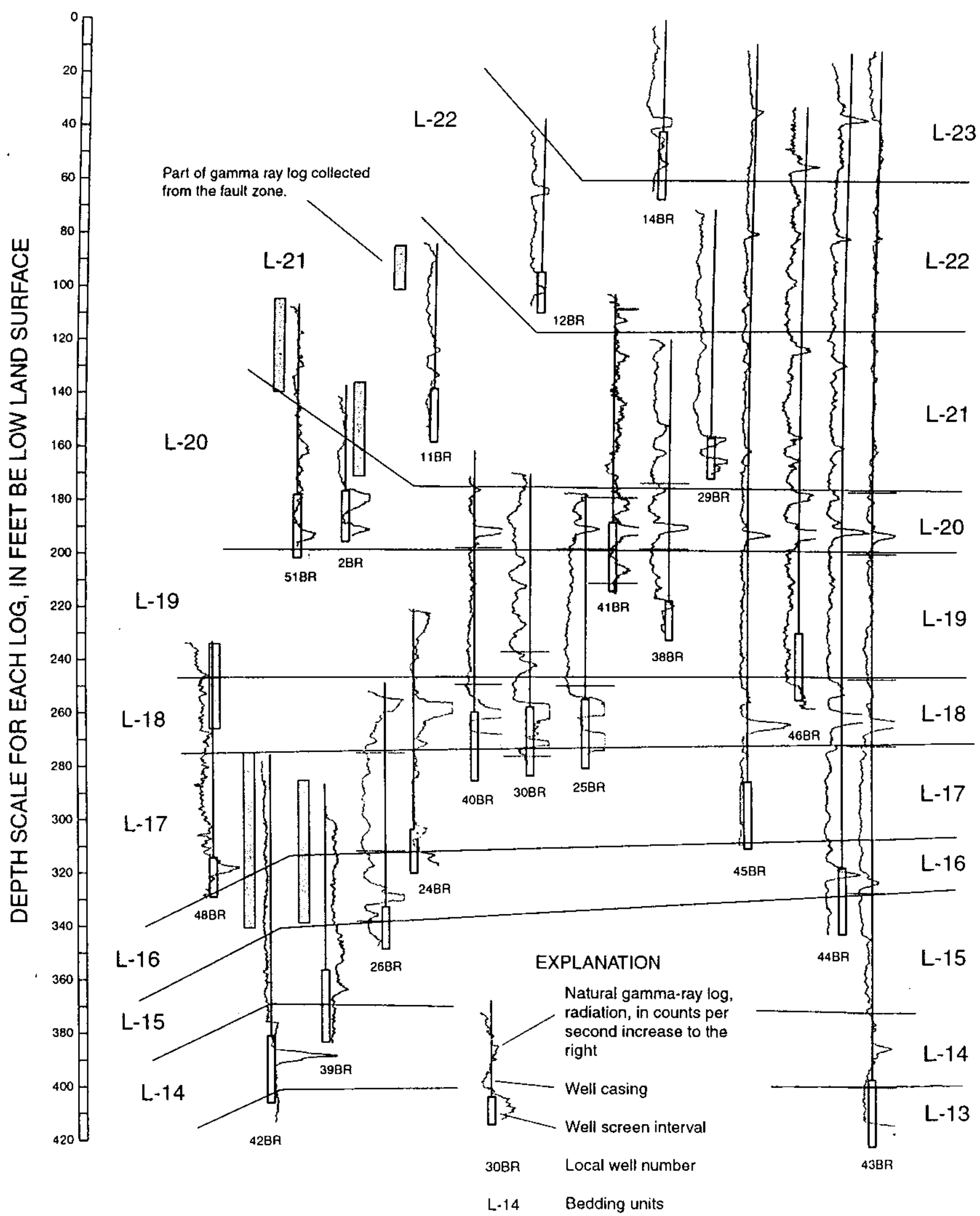


Figure 7b. Bedding units of the Lockatong Formation north of the fault, Naval Air Warfare Center, West Trenton, N.J. [Bedding units based on natural gamma-ray logs, rock type, and rock color.]

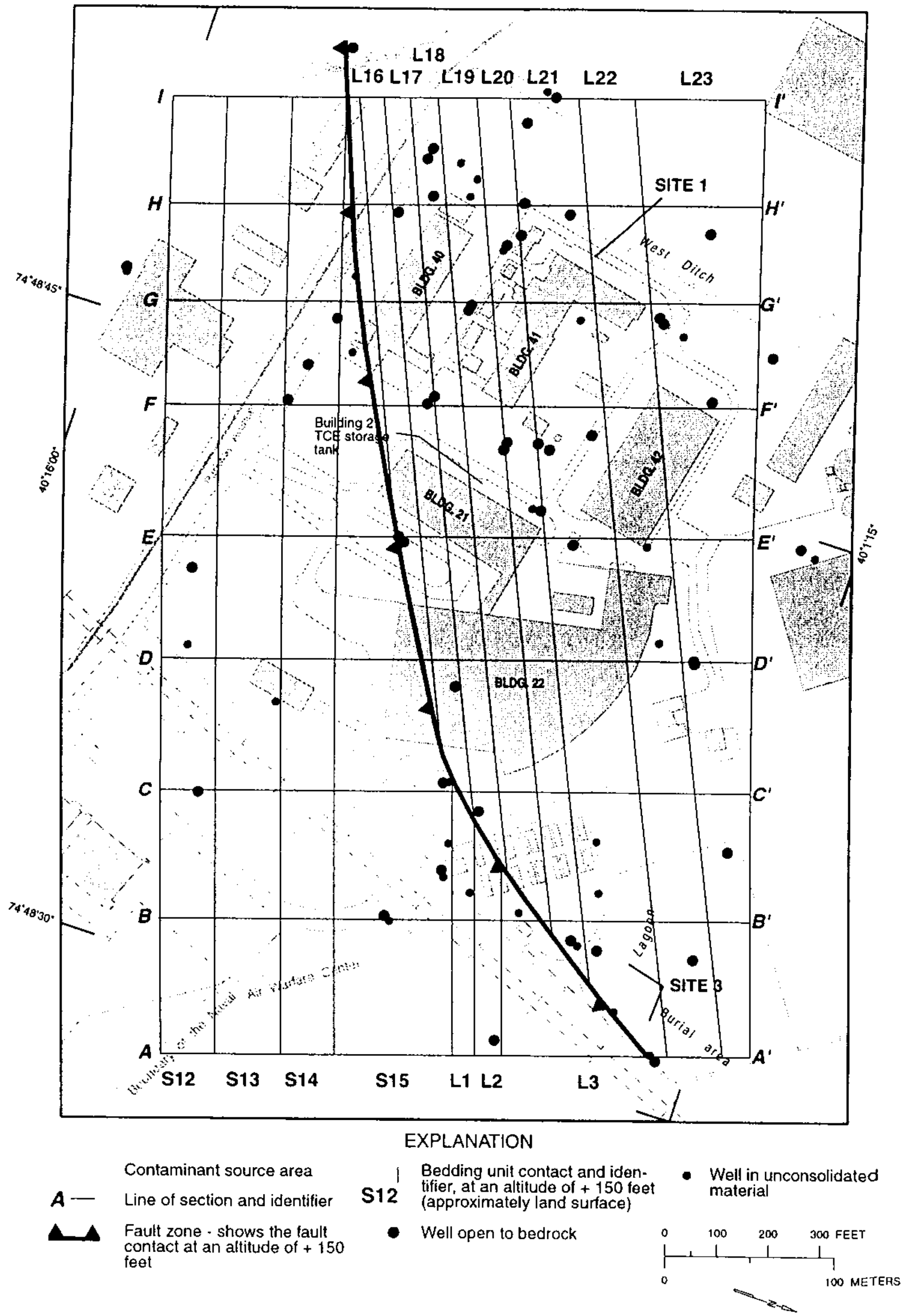


Figure 8. Bedding units and the fault trace at an altitude of + 150 feet (approximately land surface), Naval Air Warfare Center, West Trenton, N.J.

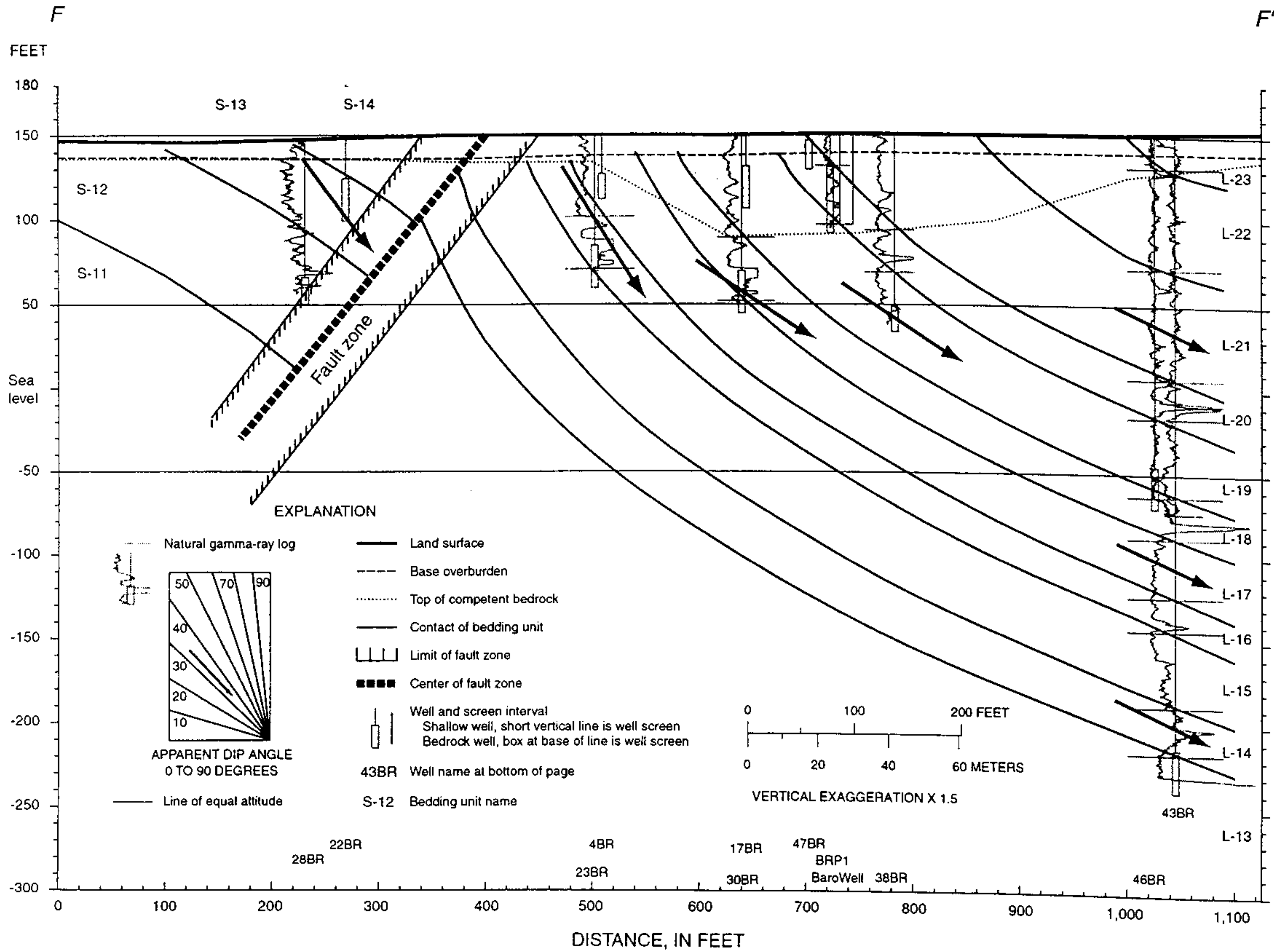
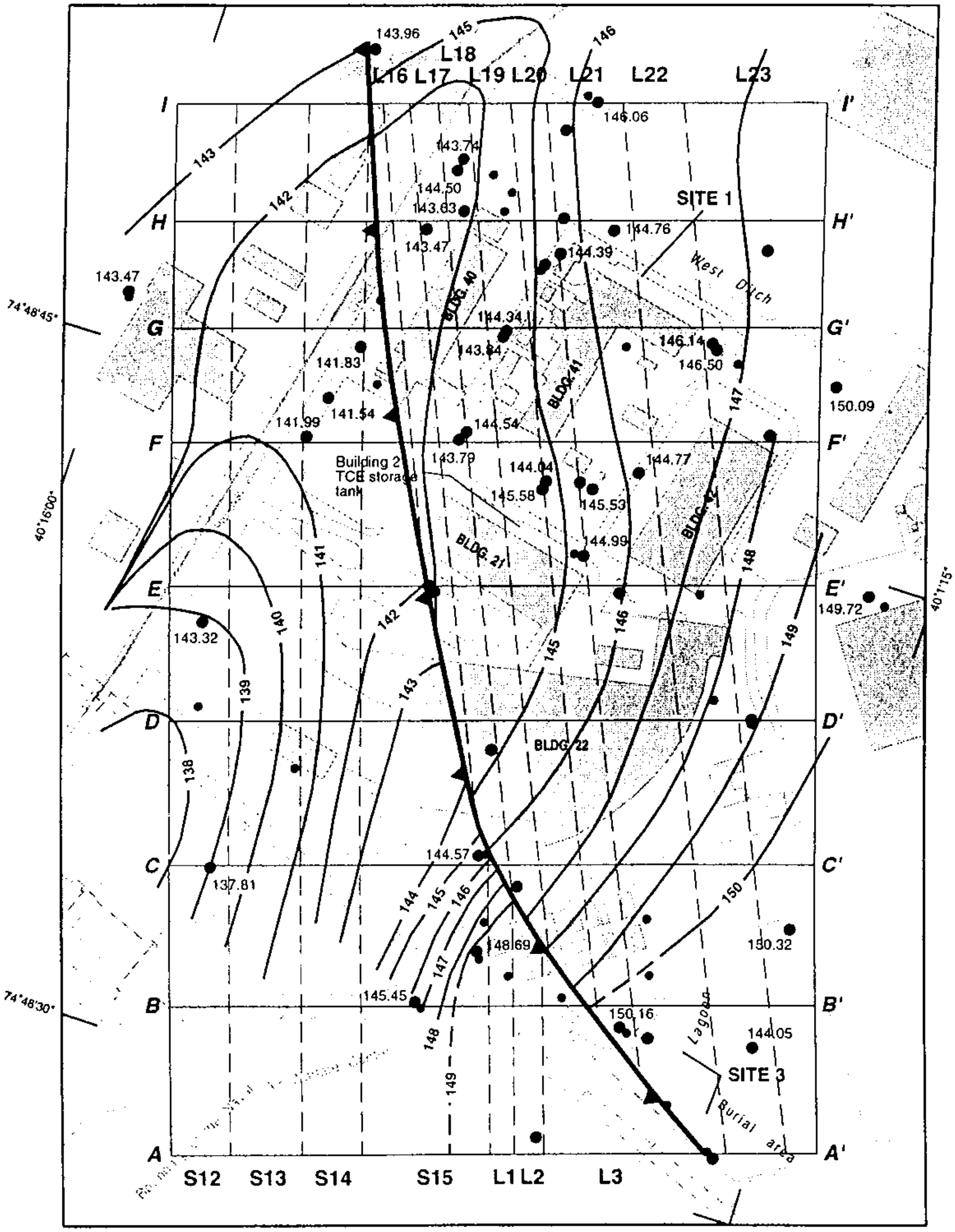


Figure 15. Section *F-F'* showing natural gamma-ray logs, dip angle from rock cores, geophysical bedding units, fault zone, and well screen placement for shallow and deep wells. Well 43BR is common to all sections for reference purposes.



EXPLANATION

Contaminant source area

A — Line of section and identifier

Fault zone - shows the fault contact at an altitude of 150 feet

S12 Bedding unit contact and identifier, at an altitude of + 150 feet (approximately land surface)

— — 147 — POTENTIOMETRIC COUNTOUR-- Shows altitude of potentiometric surface at land surface. Contour interval 1 foot. Dashed where approximate

145.45 ● Well open to bedrock. Number is altitude of water level, in feet

● Well in unconsolidated material

0 100 200 300 FEET

0 100 METERS

Figure 28. The static potentiometric surface at an altitude of + 150 feet, (approximately land surface) December 4, 1995, Naval Air Warfare Center, West Trenton, N.J.

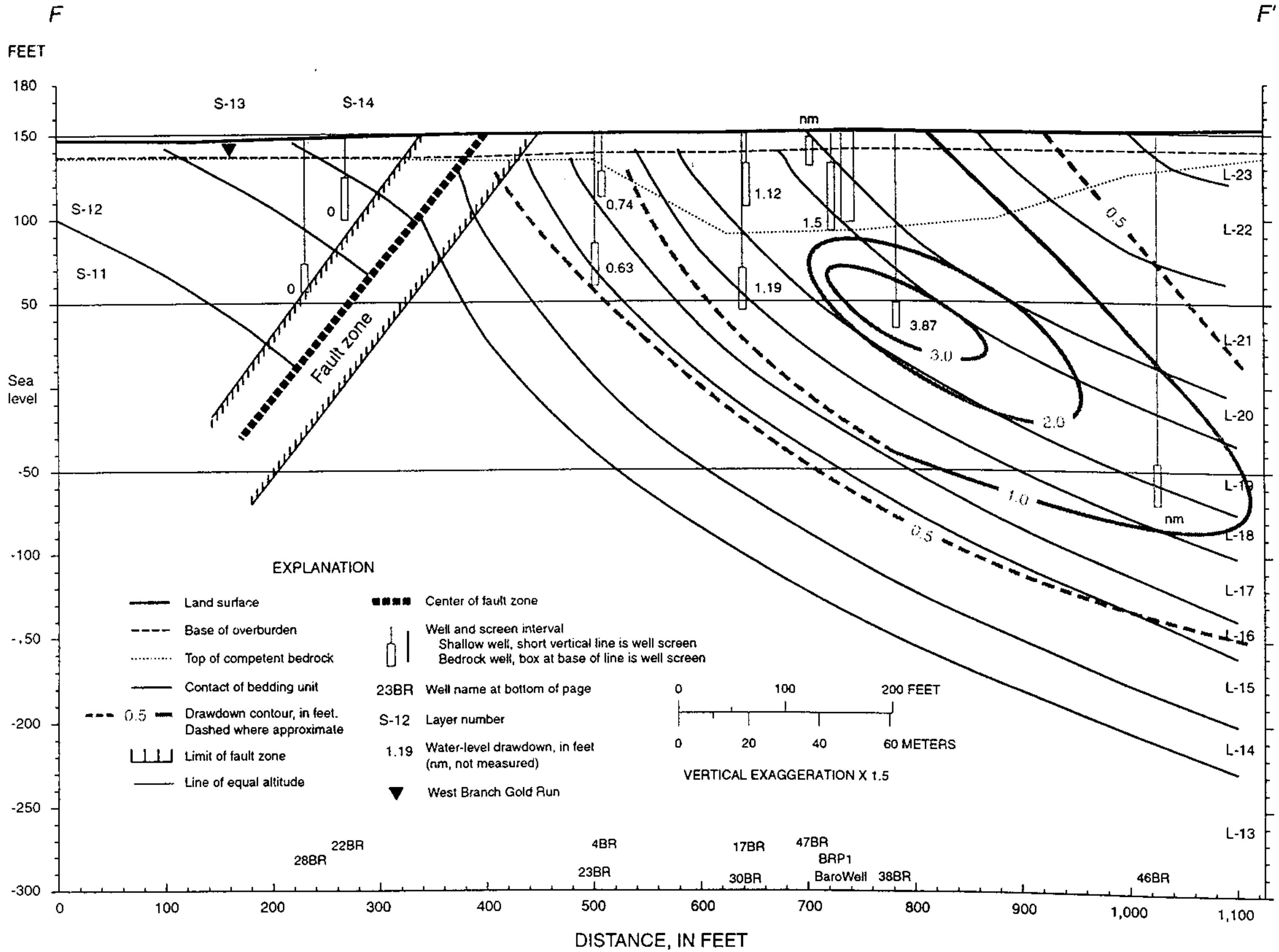
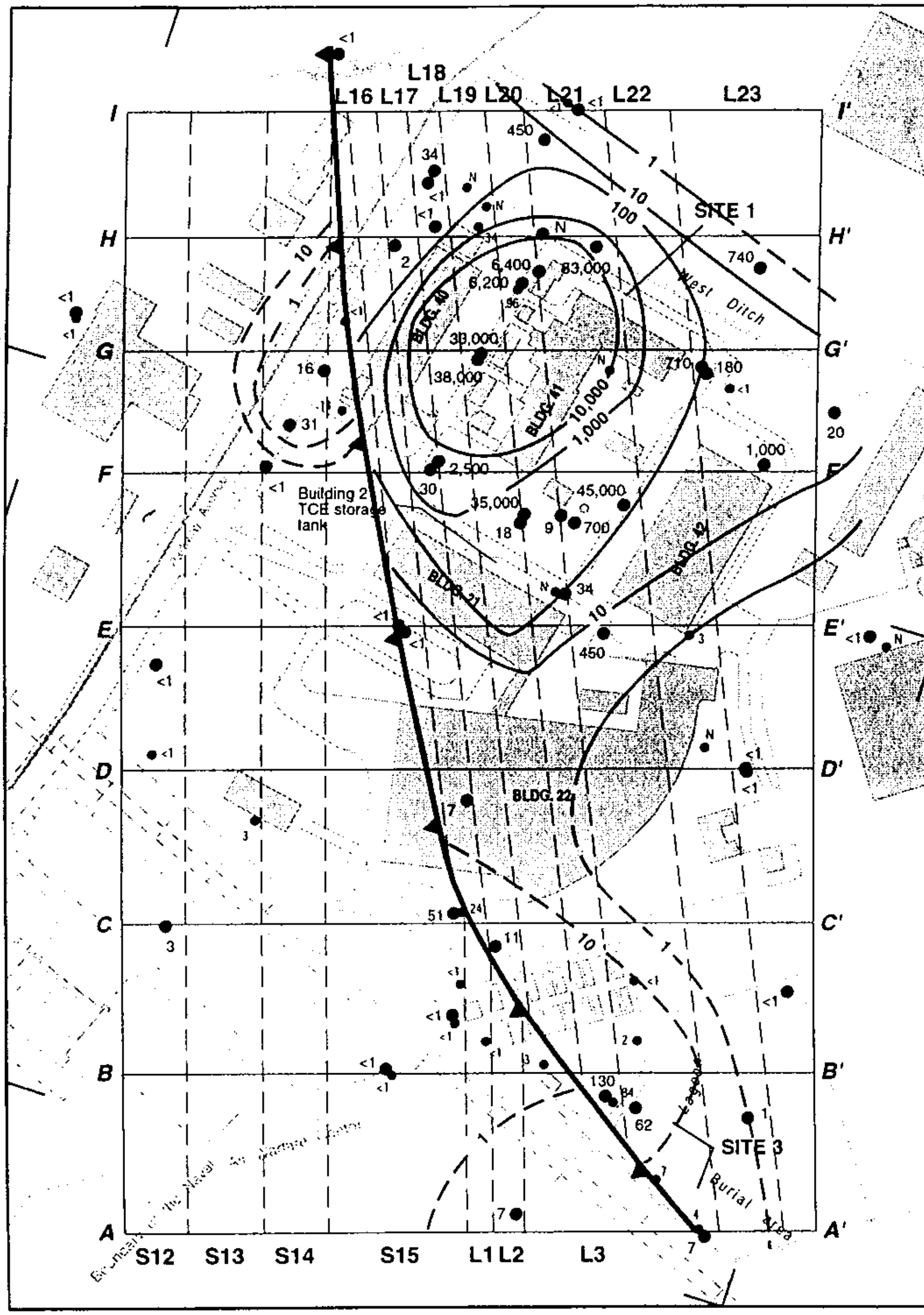


Figure 43. Water-level drawdowns measured in wells along section *F-F'* during the aquifer test while pumping well 15BR.



EXPLANATION

Contaminant source area

A — Line of section and identifier

Fault zone - shows the fault contact at an altitude of + 150 feet

S12 | Bedding unit contact and identifier, at an altitude of + 150 feet (approximately land surface)

— — 1 — LINE OF EQUAL TCE CONCENTRATION--Contour interval variable, in micrograms per liter. Dashed where approximate

<1 ● Well open to bedrock. Number is TCE concentration, in micrograms per liter (N, not sample; <, less than)

<1 ● Well in unconsolidated material. Number is TCE concentration, in micrograms per liter (N, not sample; <, less than)

0 100 200 300 FEET

0 100 METERS

Figure 69. TCE concentrations, in micrograms per liter, in water samples from bedrock and shallow wells, June 1997, and contours for top of bedrock (an altitude of + 150 feet and approximately land surface), scenario 1 and 2, Naval Air Warfare Center, West Trenton, N.J.

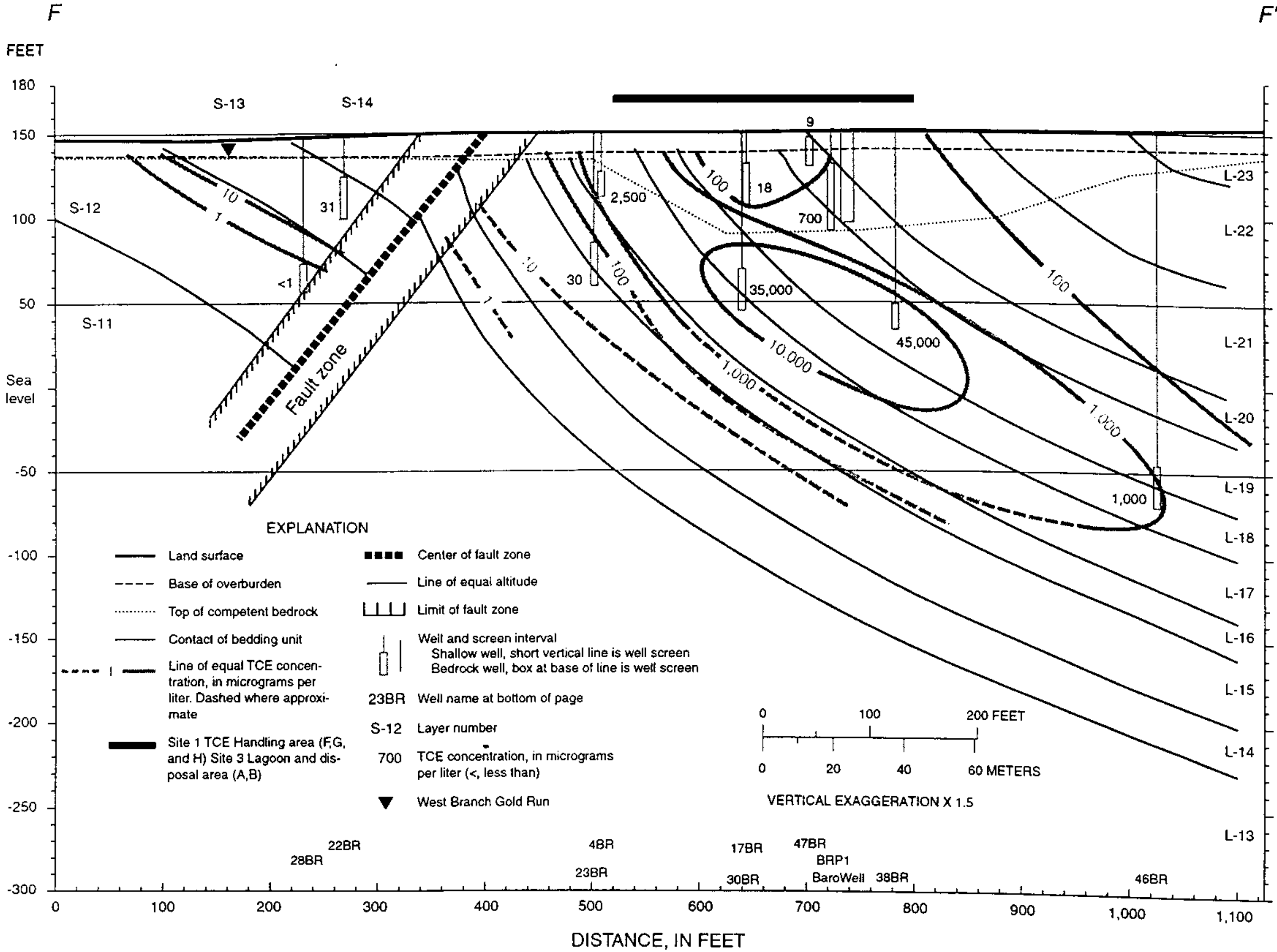


Figure 77b. Section *F-F'* showing TCE concentrations in water samples from bedrock wells, June 1997, for Scenario 2.

Return to Hotel

Exit NAWC Parking Lot and drive Parkway Ave West	0.0
Drive Parkway Ave. West to intersection with Bear Tavern Road, Turn Right	0.3
Drive Bear Tavern Road to I-95, enter ramp for I-95 North	1.1
Drive I-95 North to intersection with Rt. 1 North Drive Ramp for Rt 1 north	8.0
Drive Rt.1 North to Scudders Mill Rd, Drive onto ramp for Scudders Mill Rd.	13.2
Drive Scudders Mill Rd to intersection with Rt. 614	15.5
Drive Rt. 614 to intersection with Scotts Corner Rd., Turn Left	16.2
Drive Scotts Corner Rd. to intersection with Dey Rd, Turn Right	19.1
Drive Dey Rd to intersection with Rt 130 N, Turn Left	21.3
Drive Rt 130 North to intersection with Rt. 32 East, Turn Right	23.5
Drive Rt 32 East to Courtyard Marriott	24.5