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

Gregory C. Herman, New Jersey Geological Survey

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 sedimentalogical, 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 km2 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

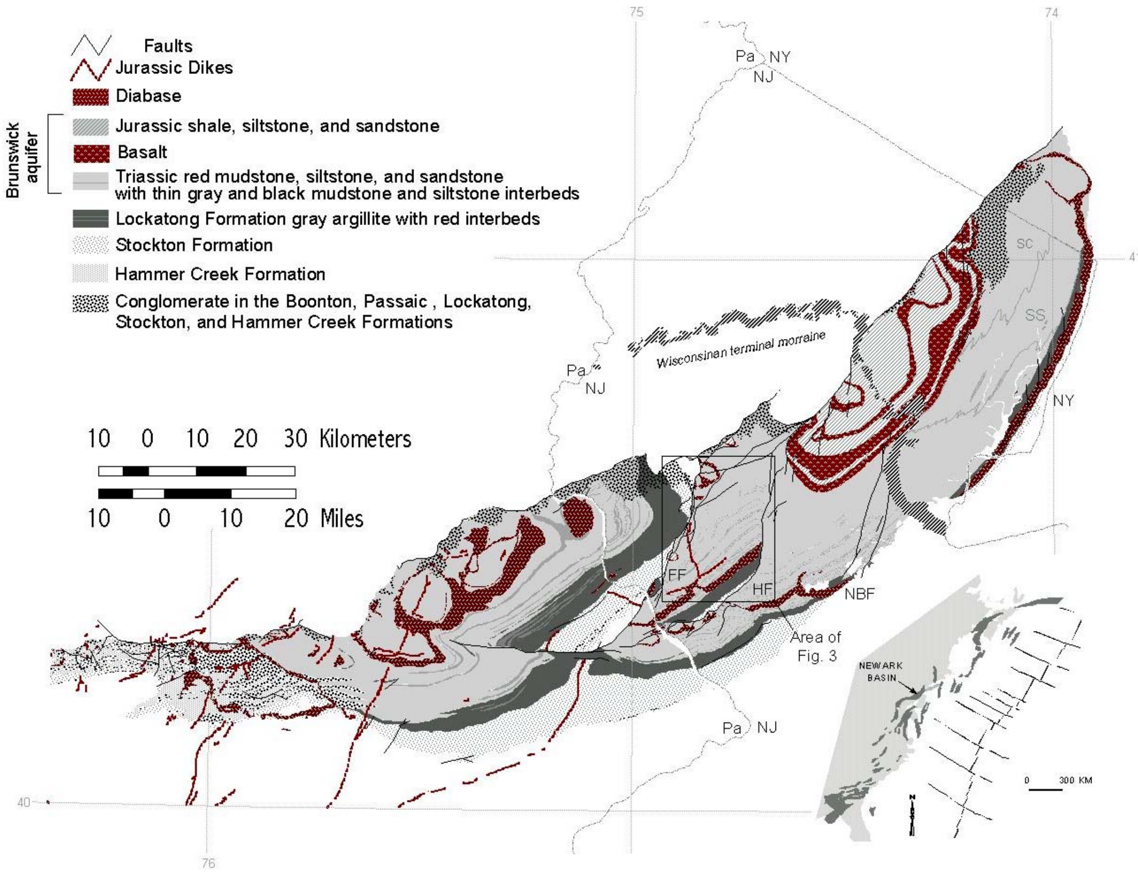


Figure 1. Generalized bedrock geology map of the Newark Basin with location of faults, Jurassic dikes, and sedimentary facies correlated to aquifer zones. Map compiled from geographic information system coverage for New Jersey (1:100,000 scale, NJ Geological Survey, 2000), New York (1:250,000 scale, 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).

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 lakebed 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 Newark Basin as buried valleys, till plains, upland surfaces, and fluvial terraces and scarps (Stanford, 2000; Stanford and others, 2001).

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 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^{o} x 2^{o} 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

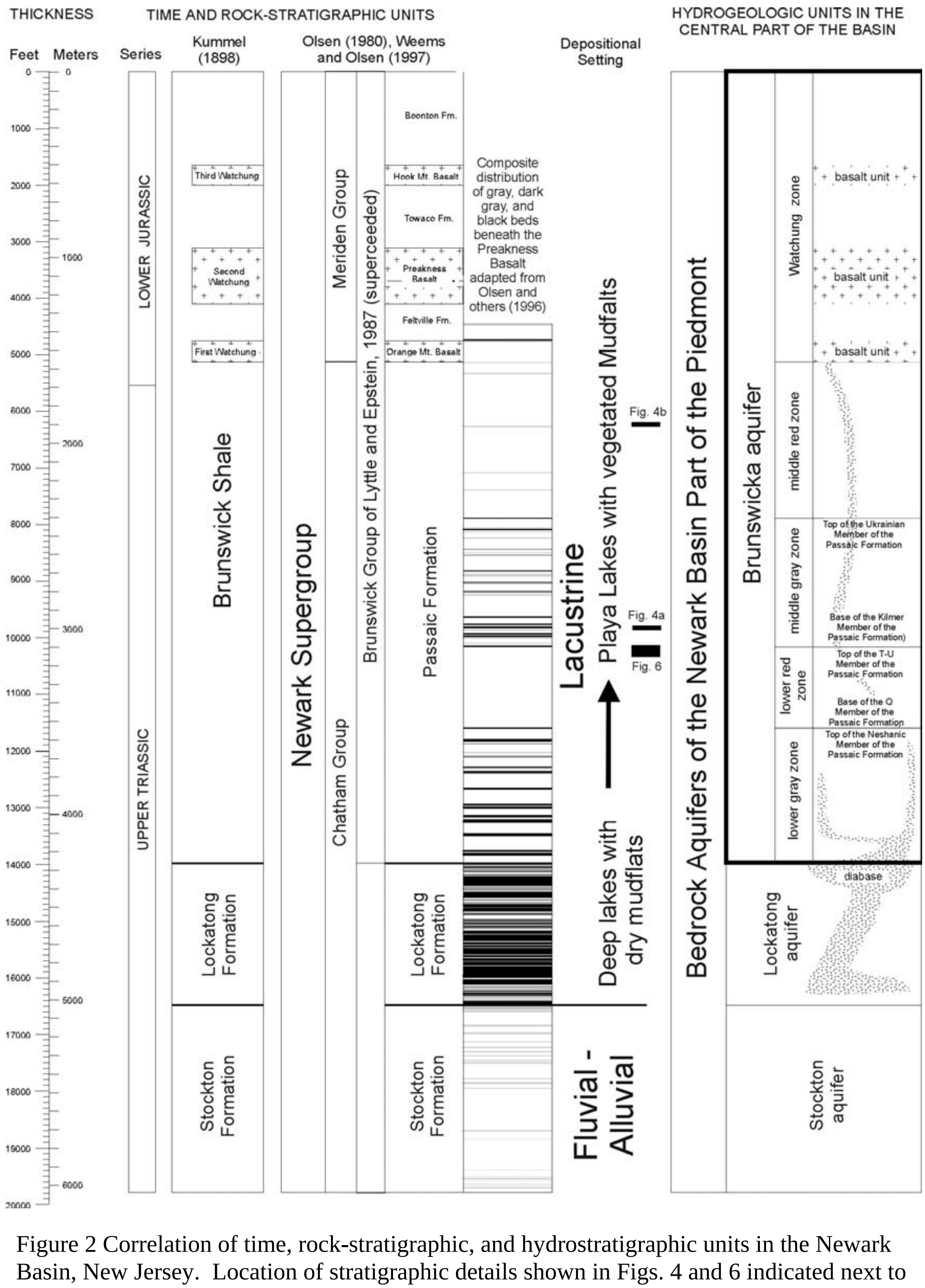


Figure 2 Correlation of time, rock-stratigraphic, and hydrostratigraphic units in the Newark Basin, New Jersey. Location of stratigraphic details shown in Figs. 4 and 6 indicated next to the left of the hydrogeological-units column.

‘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.

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).

Bedrock maps show many lateral and vertical facies changes for sedimentary rocks comprising the Brunswick aquifer (Drake and others, 1996;Olsen and others, 1998). Five primary lithologies include shale, 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. According to Smoot and Olsen (1988), the term ‘massive’ 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". 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.

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			
Shale	X	X	X
Mudstone	X	X	
Siltstone	X	X	
Sandstone	X	X	
Conglomerate	X	X	

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. This model is used for 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

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.

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.

Cylostratigraphy 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 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

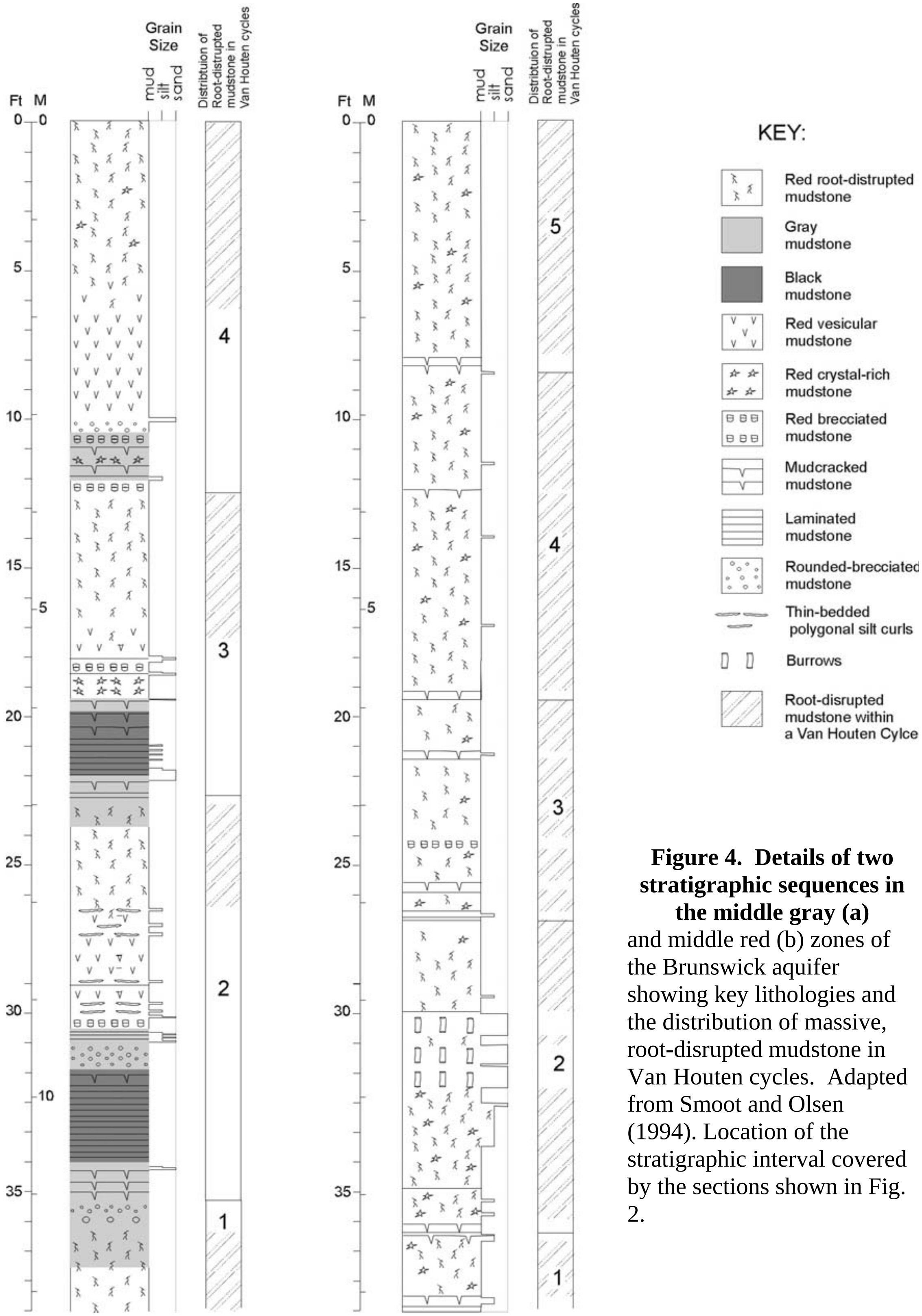


Figure 4. Details of two stratigraphic sequences in the middle gray (a) and middle red (b) zones of the Brunswick aquifer showing key lithologies and the distribution of massive, root-disrupted mudstone in Van Houten cycles. Adapted from Smoot and Olsen (1994). Location of the stratigraphic interval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

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 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 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 NJ 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.

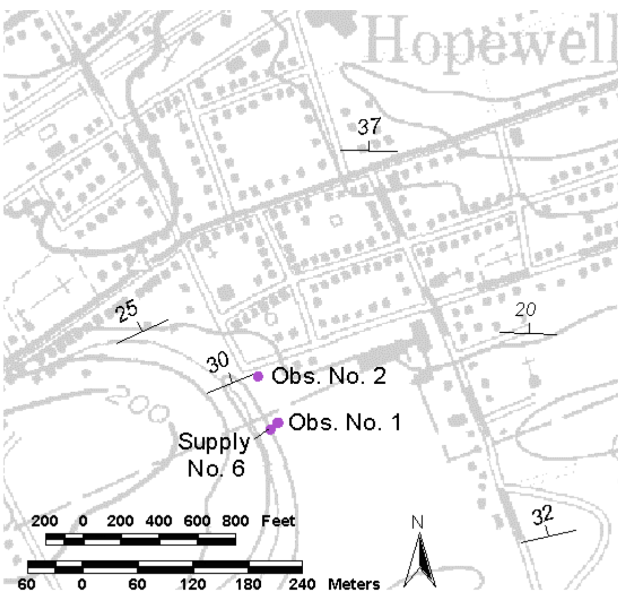


Figure 5a. Location of the Hopewell Borough hydrogeological investigation of water supply Well No. 6. Well No. 6 is shown in relation to nearby observation wells and stratigraphic bedding orientations on a 7-1/2' topographic base.

Figure 5b. Figure 5b shows the drilling of core HBCH-1 in between wells No.6 and Obs-1.

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 1o 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,

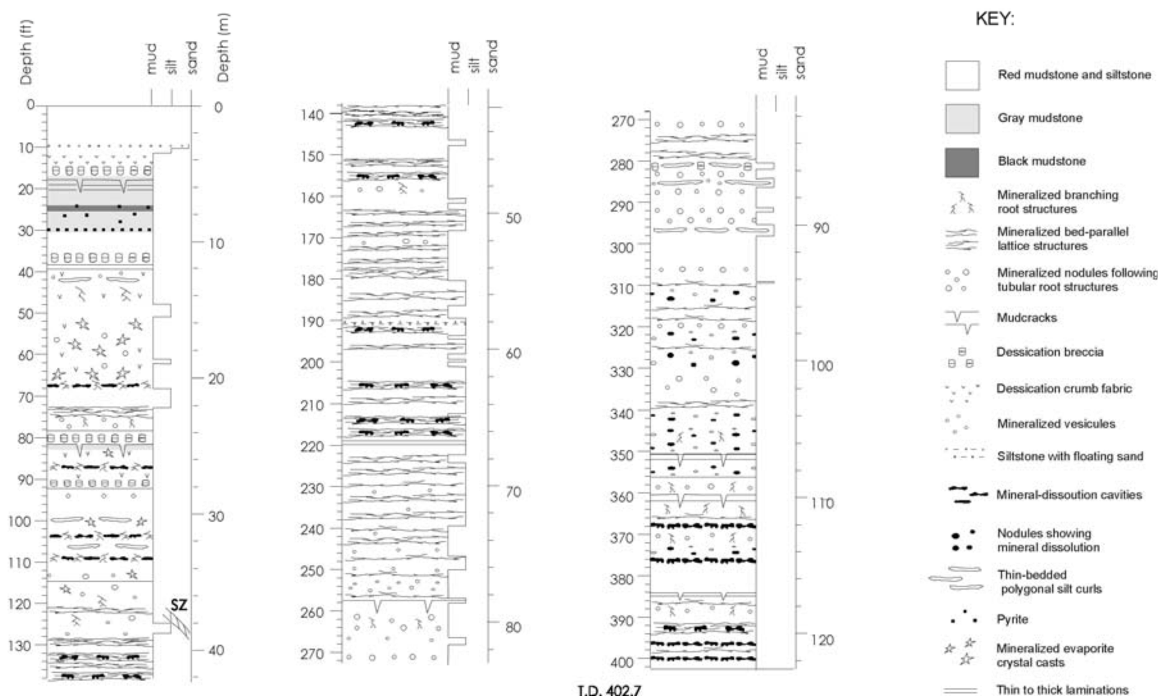


Figure 6. Detailed geological log of core holeHBCH-1 near Hopewell Borough Well No. 6. Location of the stratigraphic interval covered by the core hole shown in Fig. 2. sz – shear zone, T.D. – total depth

negative temperature anomalies (Fig. 10). 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 below.

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

Figure 7a
HBCH-1 @

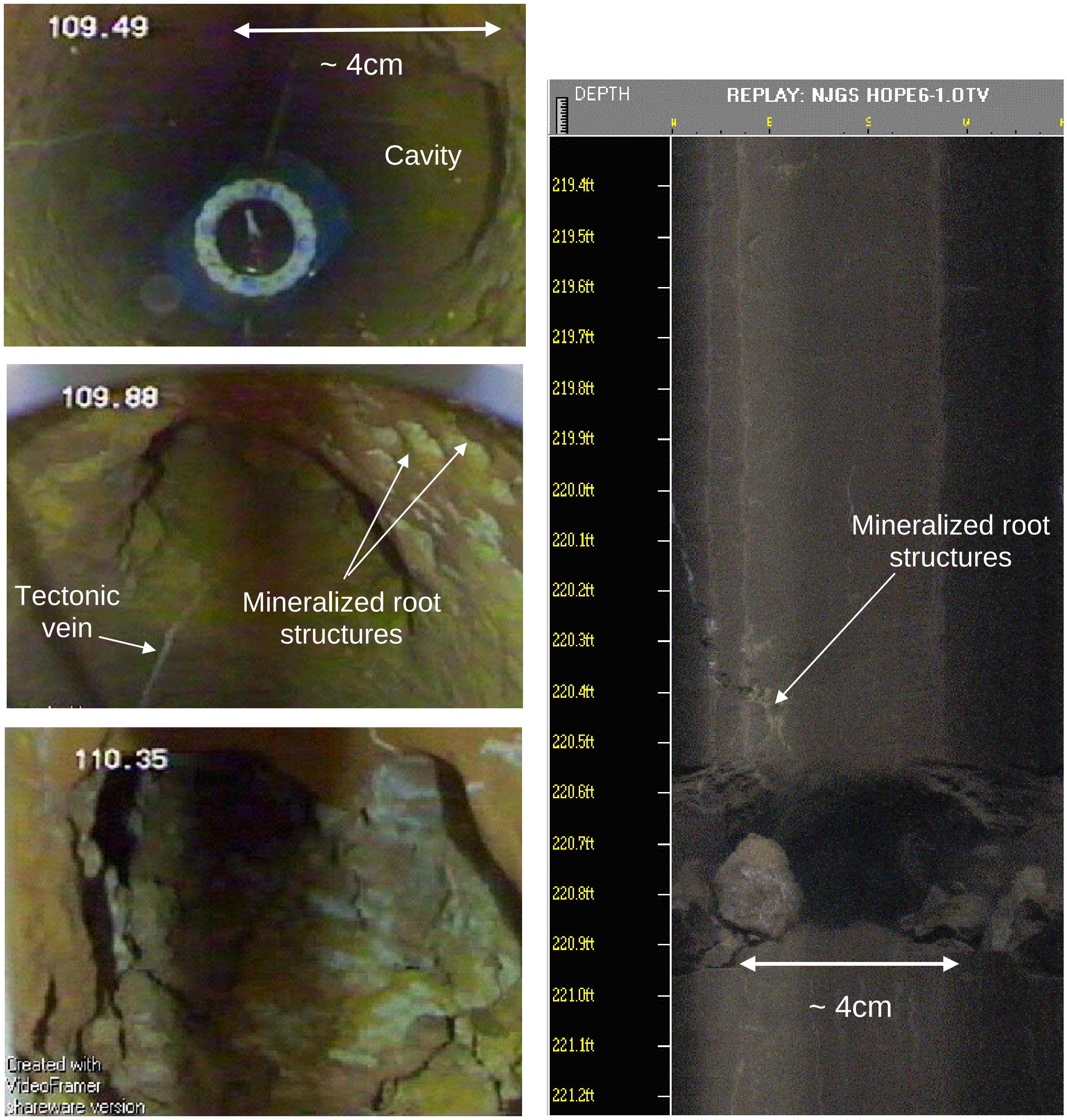
Figure 7b
HBCH-1 @ 99

Figure 7c
HBCH-1 @ 77m

Figure 7d
HBCH-1 @ 40m

Figure 7. Images of core HBCH-1 from the Hopewell hydrogeological investigation 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 features profiled in Figure 6.

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 m2/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 m2/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.



8a **8b**

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^{o} perspective of the borehole with a diameter of about 7.6-cm (3 in).

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?

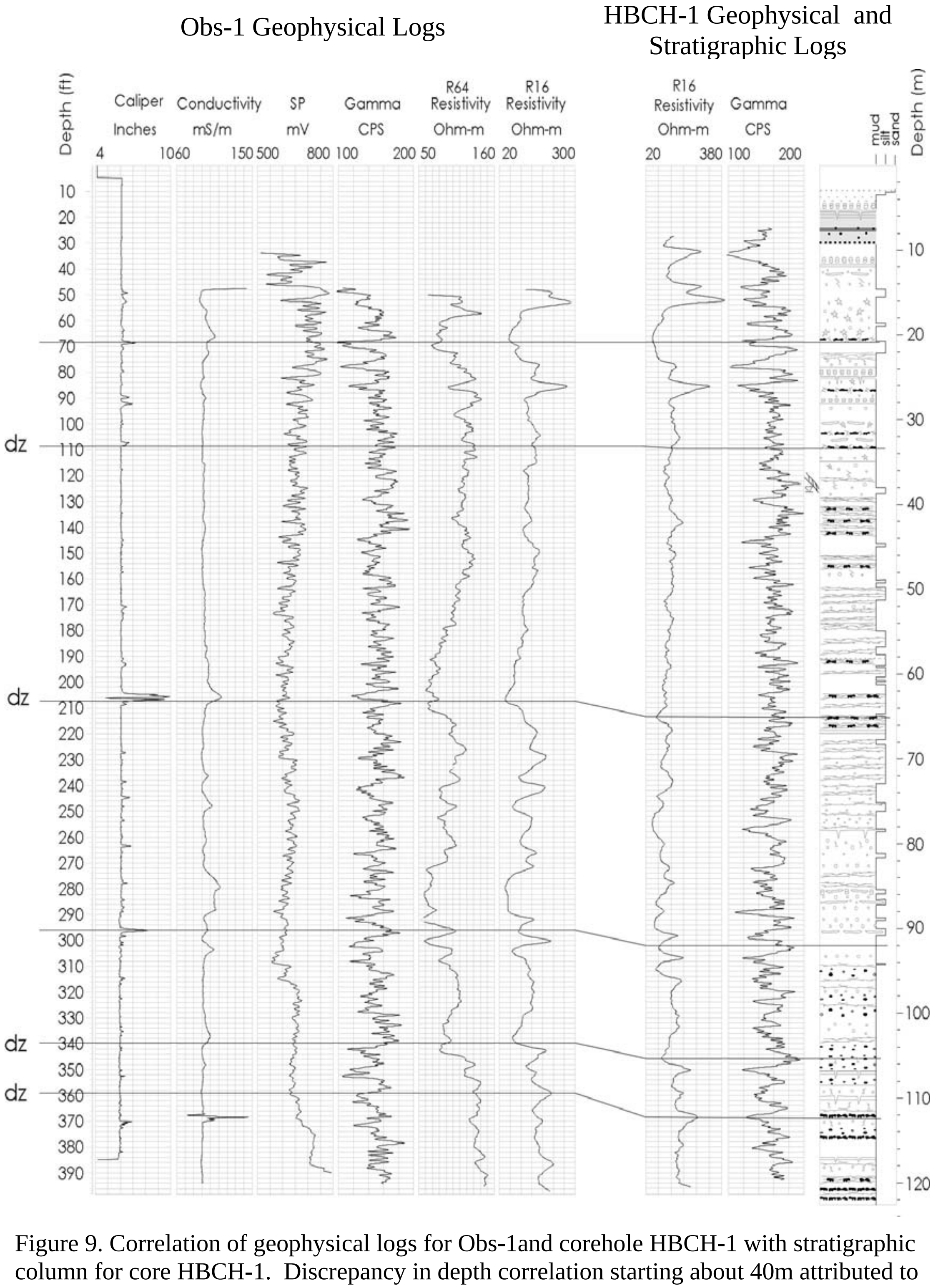


Figure 9. Correlation of geophysical logs for Obs-1and corehole HBCH-1 with stratigraphic column for core HBCH-1. Discrepancy in depth correlation starting about 40m attributed to sub-vertical drift of the core hole and localized dip-slip faulting along small shear zone (sz). Note the correlation between enlarged borehole intervals in the caliper log and the location of mineral dissolution zones (dz) mapped in the core. Stratigraphic details and key to symbols are the same as for Figure 6.

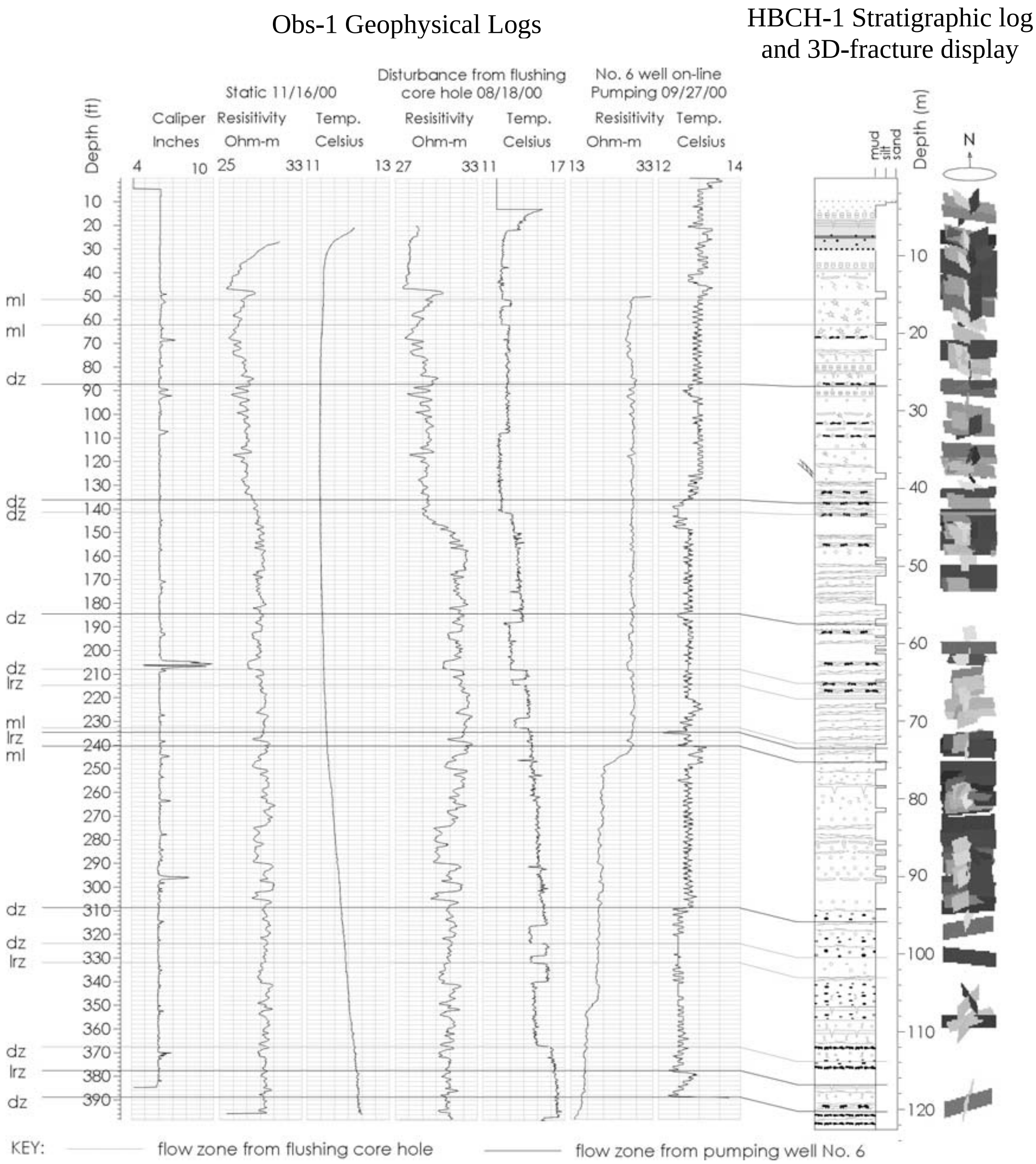
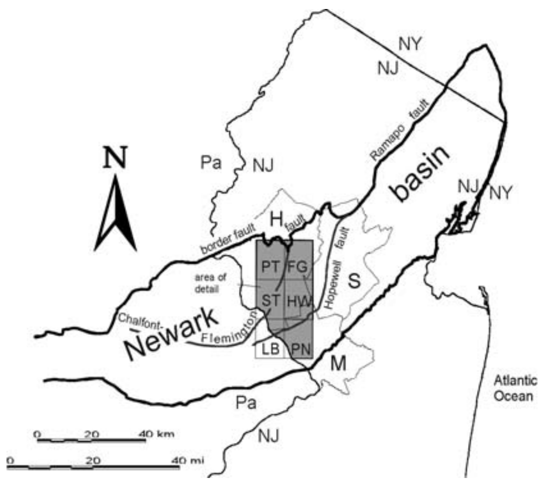


Figure 10. Comparison of fluid temperature and fluid resistivity logs for well Obs-1 during static and pumping conditions with stratigraphic and fracture logs for core HBCH-1. Fluid temperature anomalies recorded in Obs-1 stem from flushing water in the nearby core hole and pumping well No. 6. A good 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 same as for 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 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 dipping, systematic fracture sets occurs here (Fig. 11).



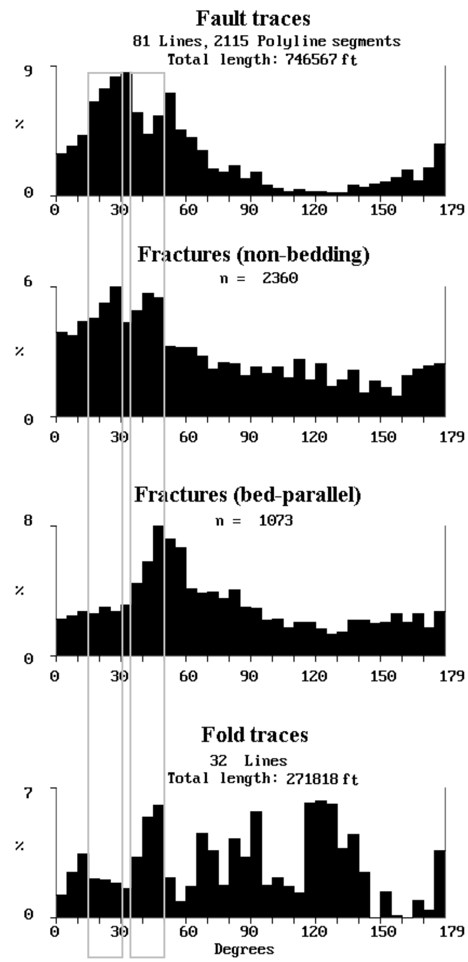
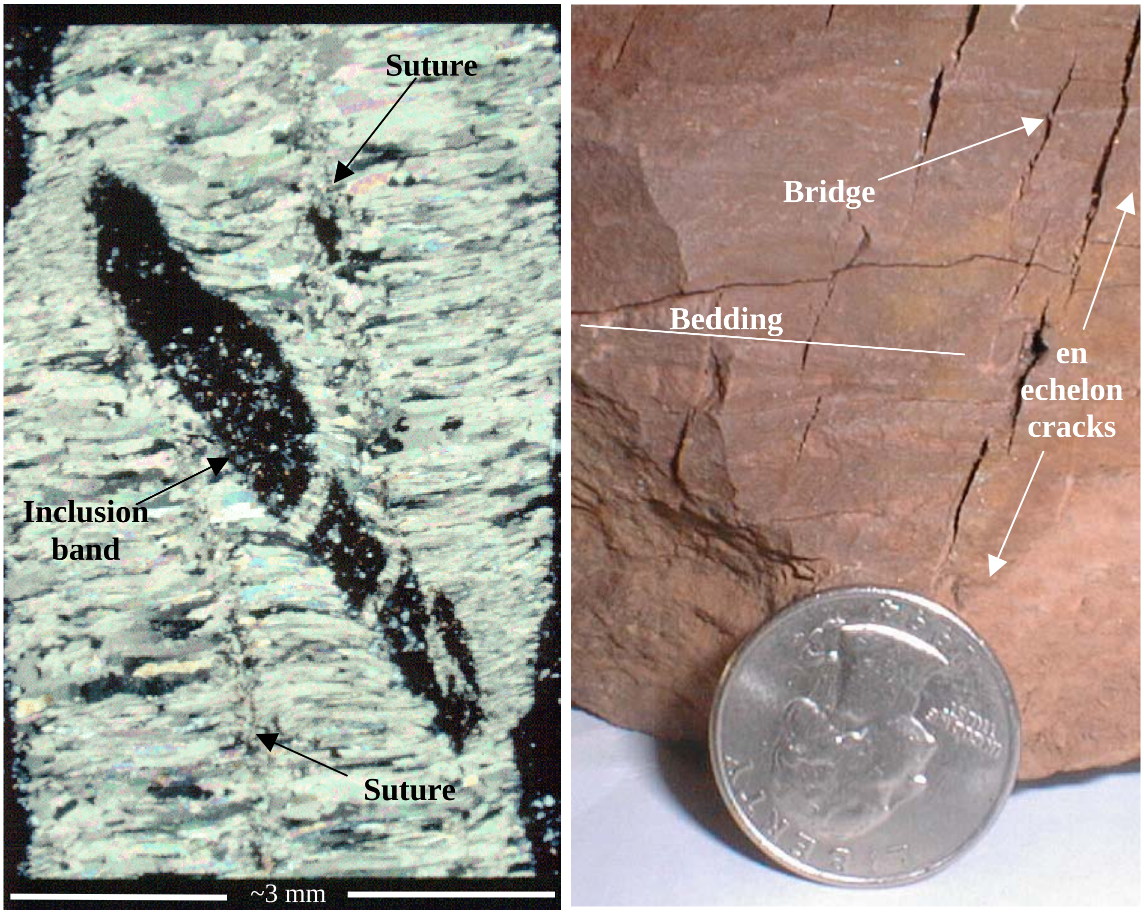


Figure 11. Index map (above) shows the location of a detailed fracture study (shaded area), major faults, 7.5-minute quadrangles, and counties. Quadrangle abbreviations include PT (Pittstown), FG (Flemington), ST (Stockton), HW (Hopewell), LB (Lambertville), and PN (Pennington). County abbreviations 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 two dominant sets of non-bedding fractures to facilitate comparisons. Adapted from Herman (1997).

The two most frequent sets strike subparallel to border faults along the basin's northwest margin (about N35oE to N50o E, Fig. 1) and to intra-basin faults and regional dike swarms (about N15o to N30 o 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

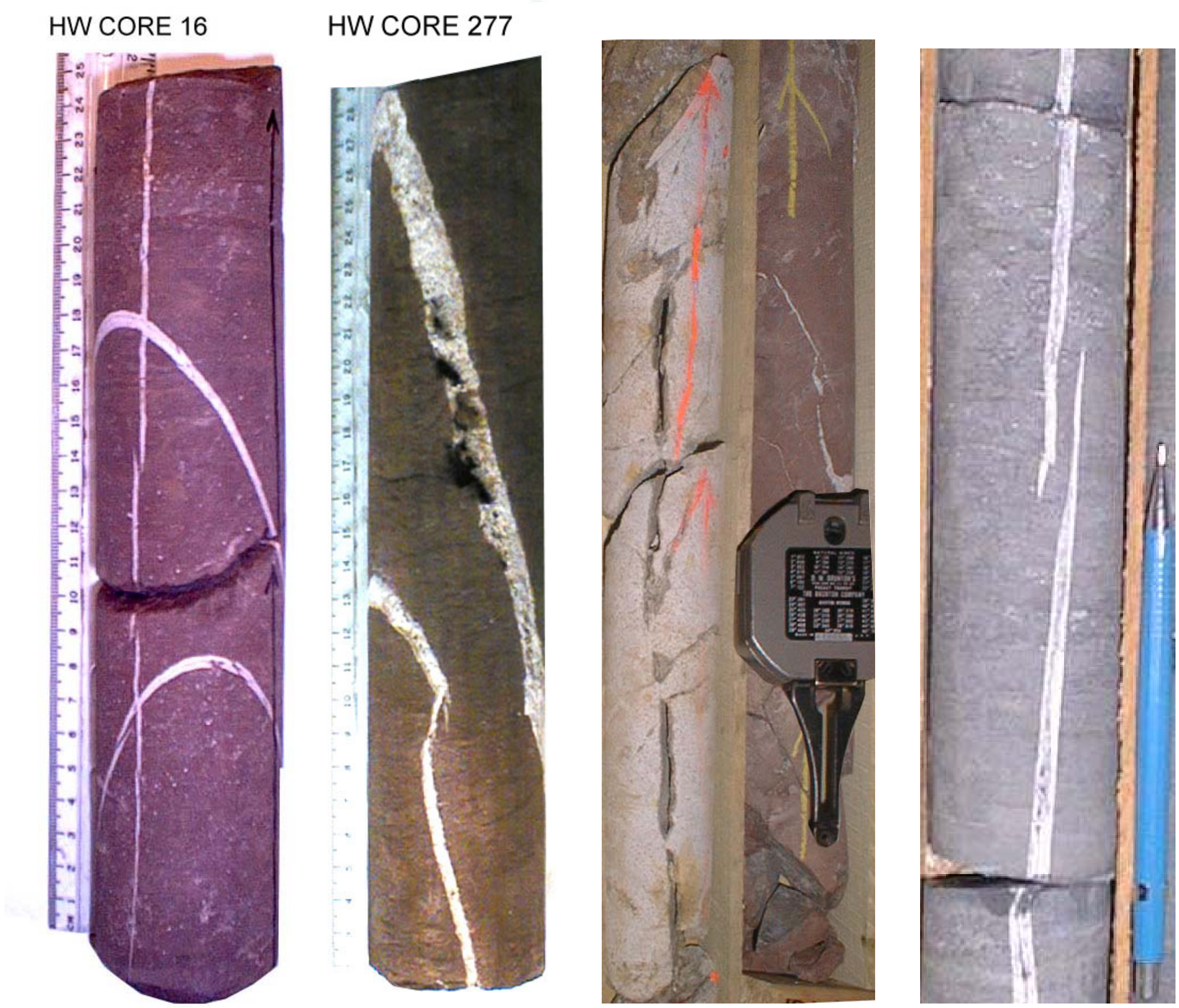


12a **12b**

Figure 12. Morphology of diltatant en echelon cracks (DECs). 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.

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



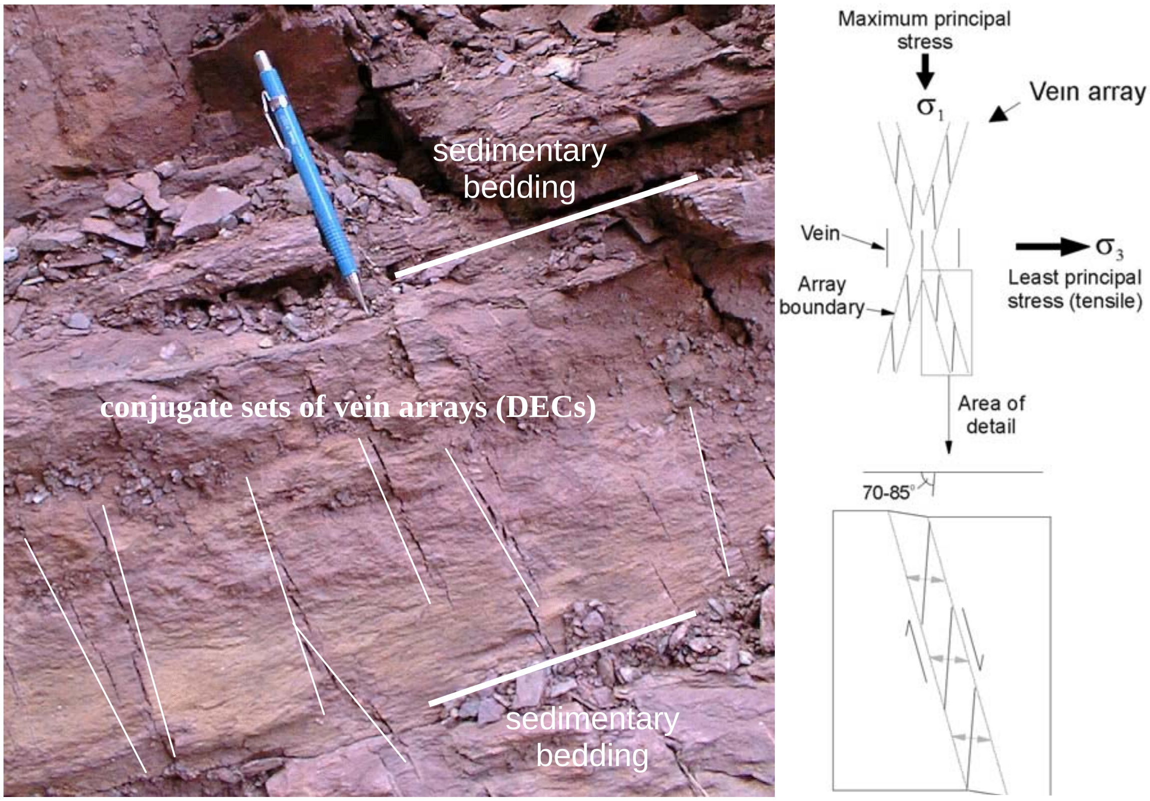
13a **13b** **13c** **13d**

Figure 13. Samples of DECs in rock core. Figure. 13a shows a DEC set oriented 170/86E that crosscut 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.

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^{o}E to N30^{o}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^{o}) directly agrees with the angle of inclined-shear failure (~70^{o}) 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



14a **14b**

Figure 14. Dilatant Echelon Cracks (DECs) occur in conjugate arrays that dip at steep angles normal to bedding (14a). 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. 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).

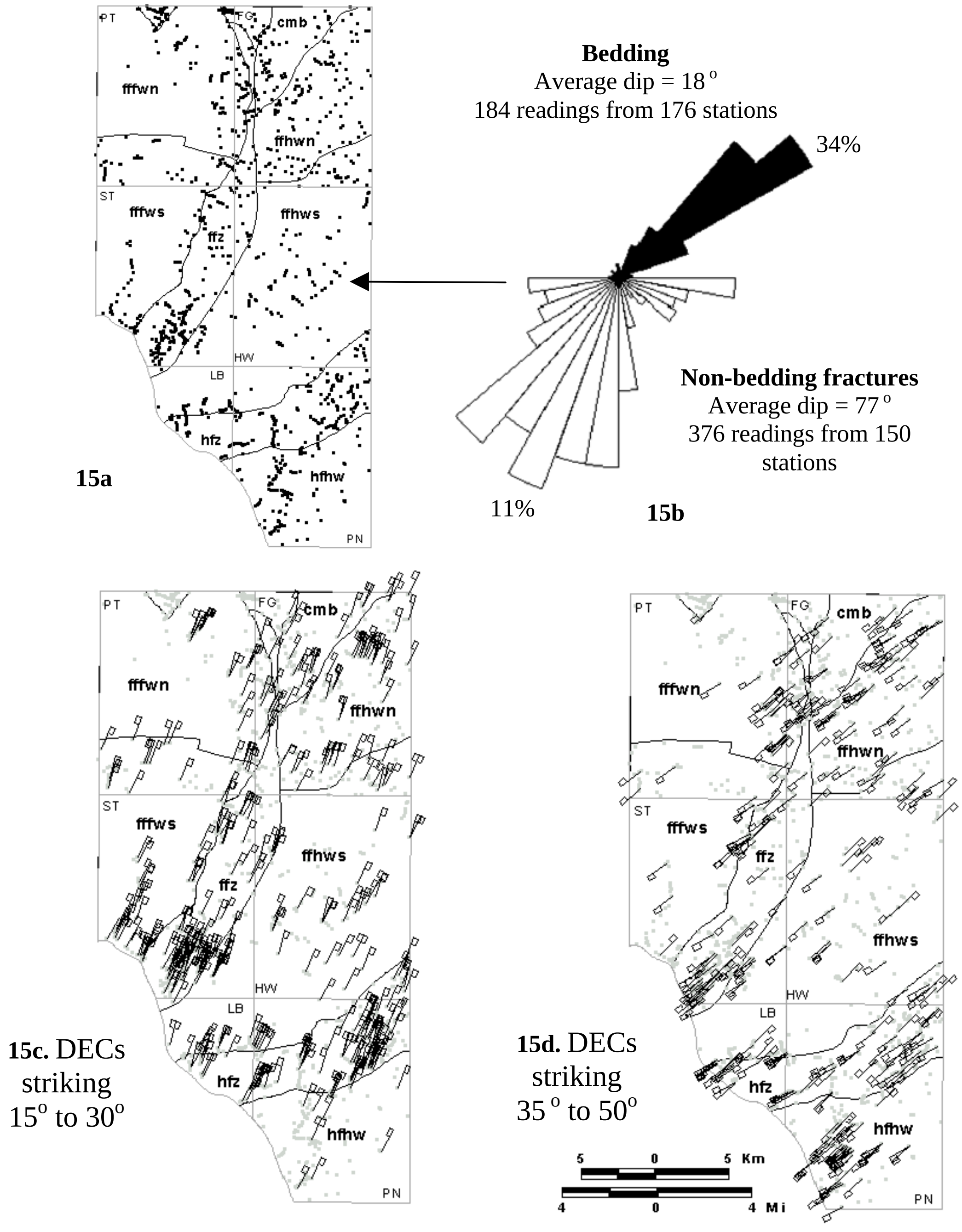
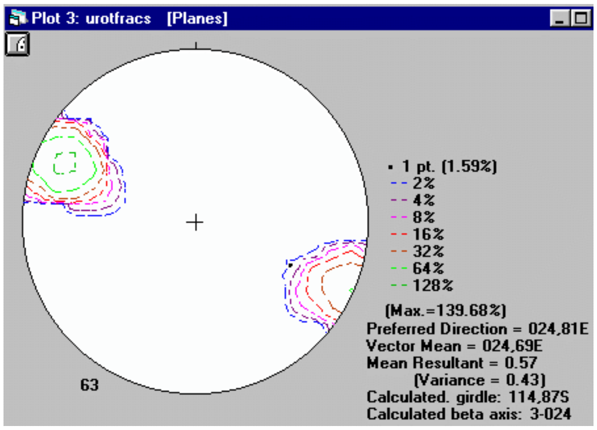
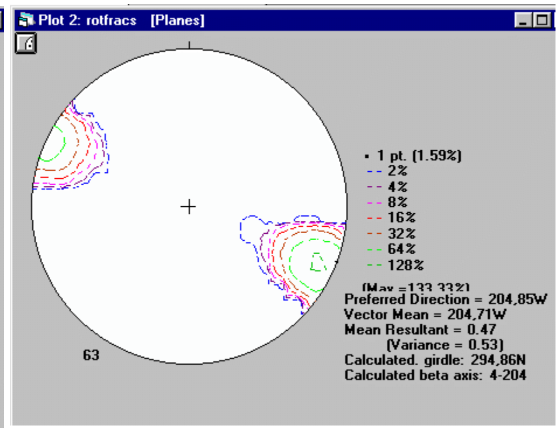


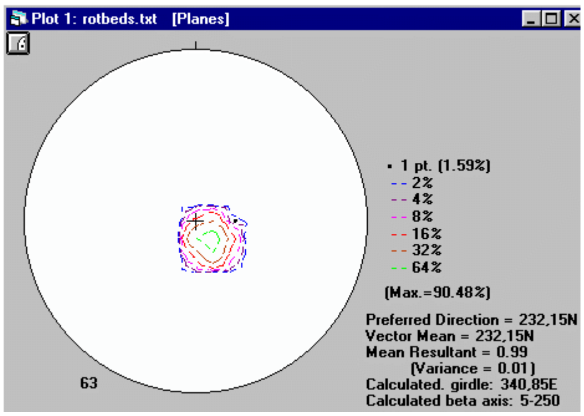
Figure 15a shows field stations and structural domains for a six-quadrangle area in the central part of the Newark Basin (Herman, 1997). Area corresponds to that shown figure 11. Figure 15b is a circular histogram summary of bed-parallel and non-bedding fractures mapped in the **ffhws** structural domain. 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 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. Quadrangle abbreviations same as those in figure 11.



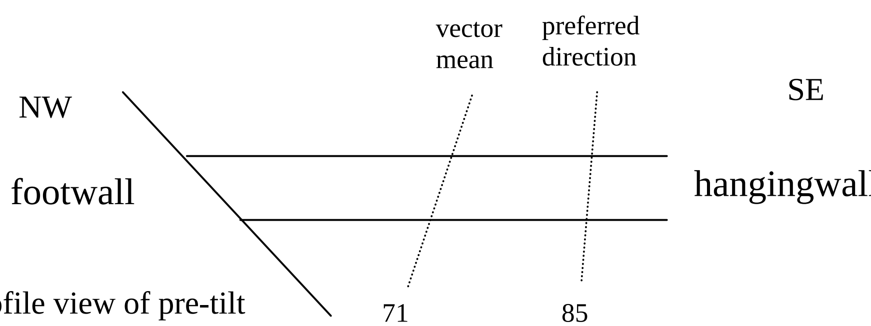
16 a. Current DEC orientations



16c. Pre-tilt DEC Orientations

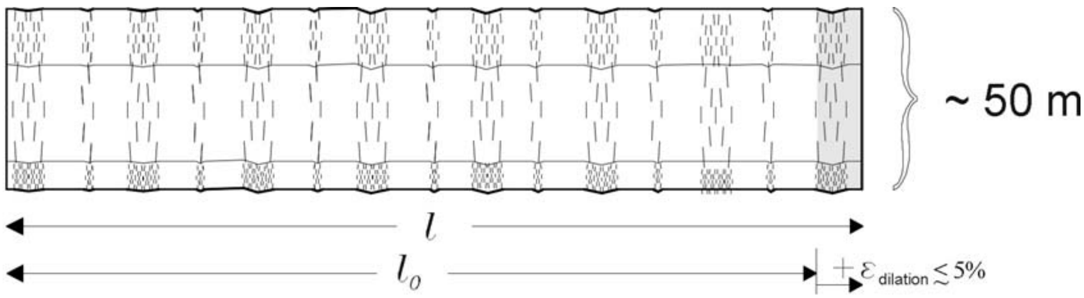


16b. Current Bedding Orientation

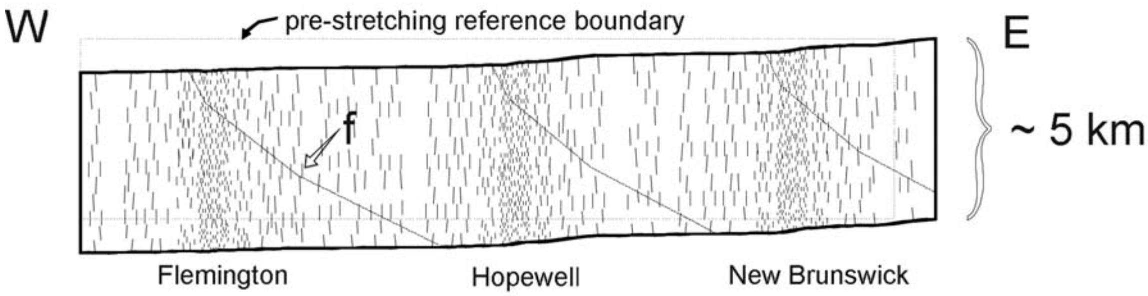


16d. Profile view of pre-tilt DEC orientations

Figure 16. A geometric exercise conducted on the systematic set of DECs striking 15^{o} to 30^{o} 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 using GEOrient software (v. 7.2, by Dr. R.J. Holcombe). DECs mostly dip southeast in their current orientation (Fig. 16a) and bedding dips northwest in the ffhws structural domain (Fig 15). Pre-tilt DEC orientations (Fig. 16c) are derived by restoring bedding to horizontal using methods described in the text. The preferred direction for the pre-tilt DECs is 85^{o} W with a vector mean (average direction) of 71^{o} W (Fig. 16d).



17a



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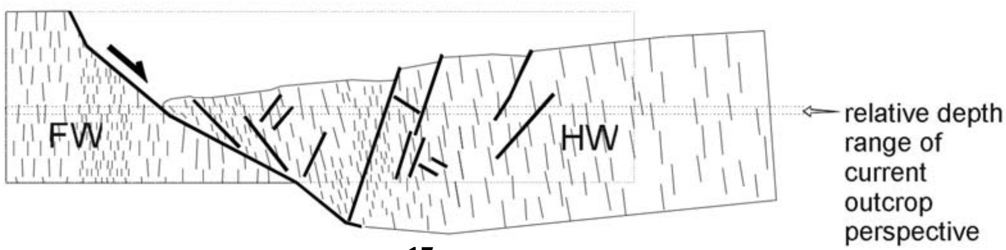


17c

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 hanging wall of faults from their pre-tilt orientation.

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^{o} 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).

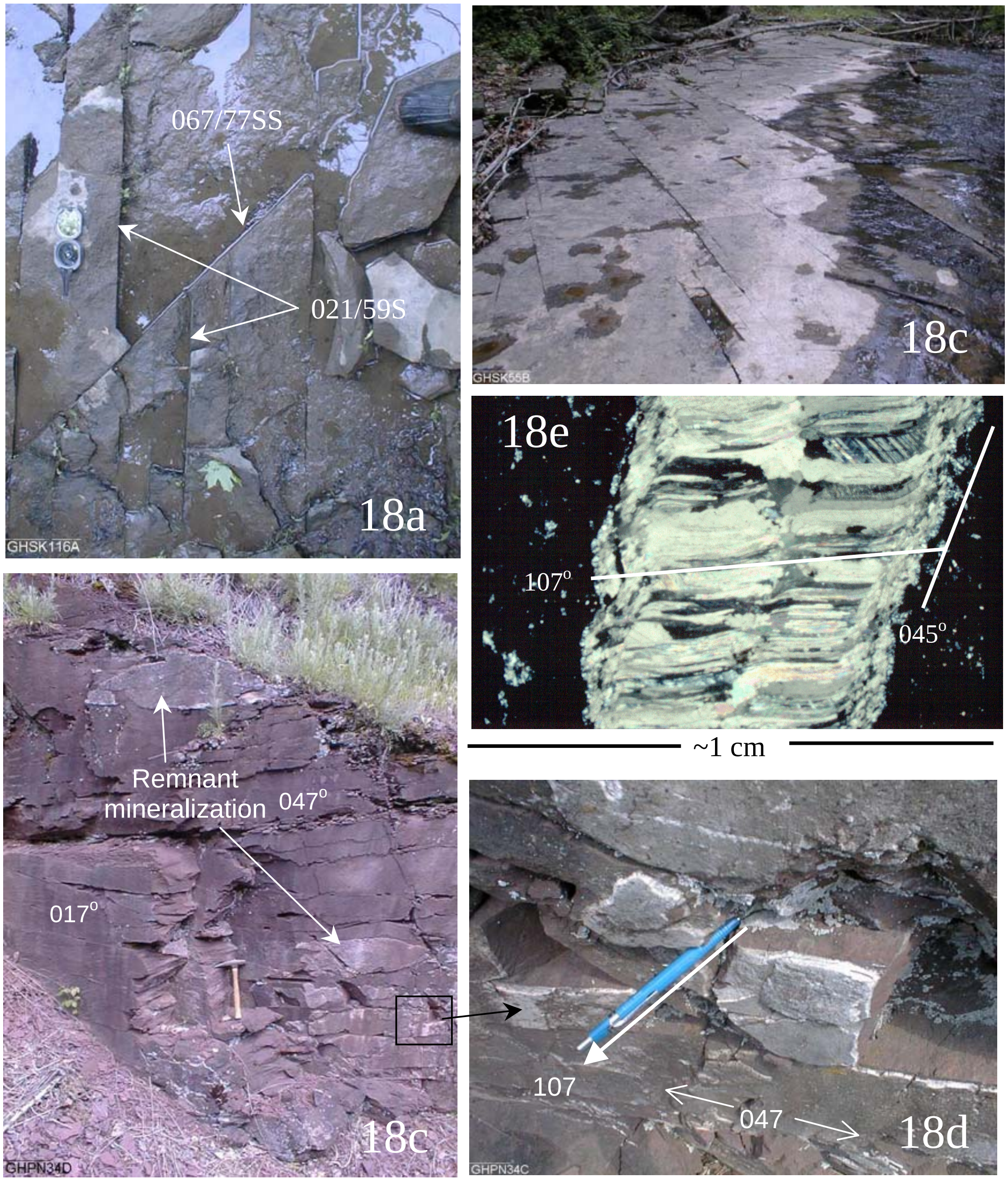


Figure 18. DEC walls commonly appear as ordinary ‘joints’ in outcrop because secondary minerals that once filled DECs are usually dissolved from weathering. Figure 8a shows DECs within an outcrop of gray mudstone of the Passaic Formation; the set striking subparallel to the intra-basin faults are locally 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^o) locally grew normal to the later (017^o) set, further illustrating that DECs of the border fault trend predate the intra-basin fracture trend.

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.

MODIFICATIONS TO THE LMAS

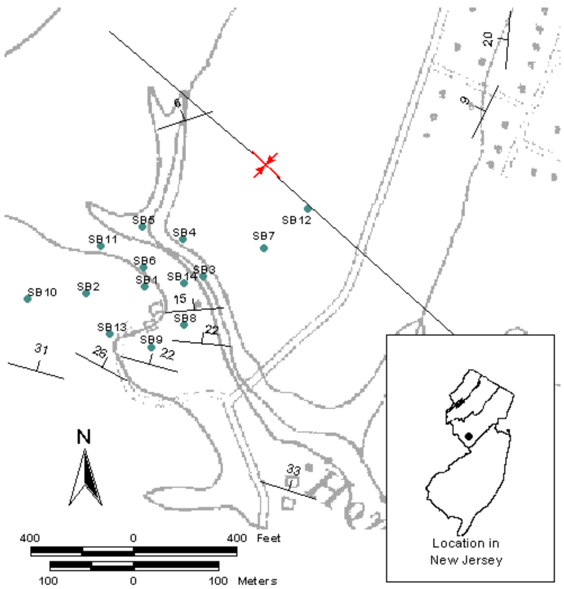
The hydrogeologic framework of fine-grained sedimentary bedrock the Newark Basin where unconsolidated sediment is generally thin (< 5m) includes shallow, intermediate, and deep intervals having variable hydraulic properties (Fig. 19). The shallow interval correlates to 'overburden' and includes unconsolidated 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.

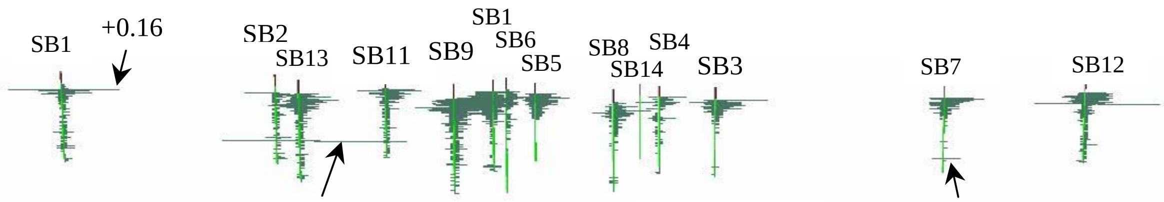
In summary, ground water exhibits complex flow behavior in bedrock aquifers of the Newark Basin. Complexities arise from sedimentalogical and structural variations in the aquifer framework that affect both water table and confined-flow conditions. Ground water is reportedly stored and transmitted along 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) 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.



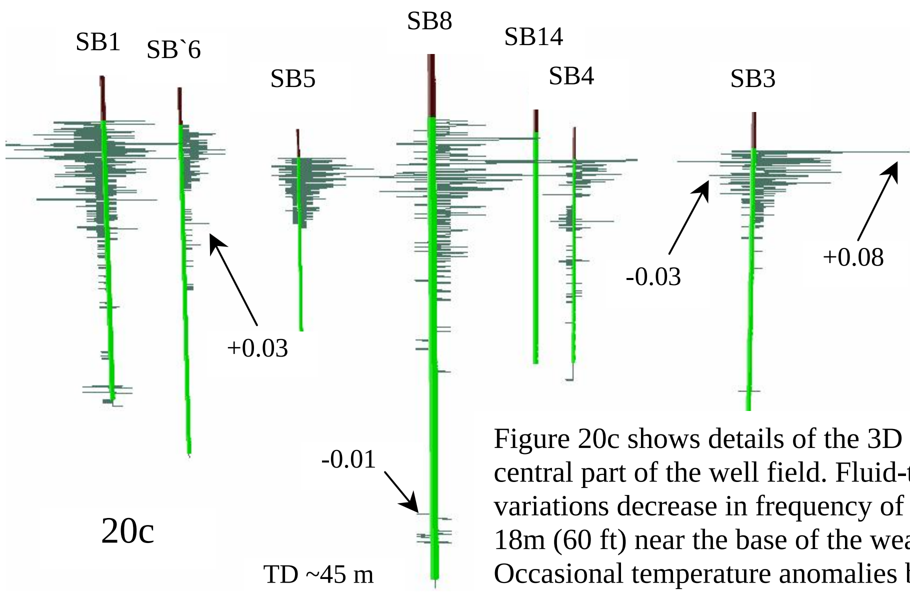
20a

Figure 20a shows the bedrock orientation and well locations at the Stonybrook-Millstone Watershed Association (SMWA) preserve near Pennington, New Jersey.

Figure 20b. A three-dimensional (3D) profile looking northwest through the well field shows fluid-temperature differentials (^{o}F) below casing under non-pumping conditions. Differentials are calculated by subtracting successive fluid-temperature log readings every 2.1-cm (0.1-ft). The vertical distribution of temperature changes provides insight into the depth of the weathered zone for mudstone and siltstone of the Brunswick aquifer in unglaciated areas. The depth of each well is about 45 m (150 ft) with 6 m (20 ft) of casing.



20b



20c

Figure 20c shows details of the 3D profile for the central part of the well field. Fluid-temperature variations decrease in frequency of occurrence to 18m (60 ft) near the base of the weathered zone. Occasional temperature anomalies below this depth probably correspond to isolated flow zones in deep bedrock. Well data and fluid-temperature logs provided courtesy of Glen Carleton, U.S. Geological Survey

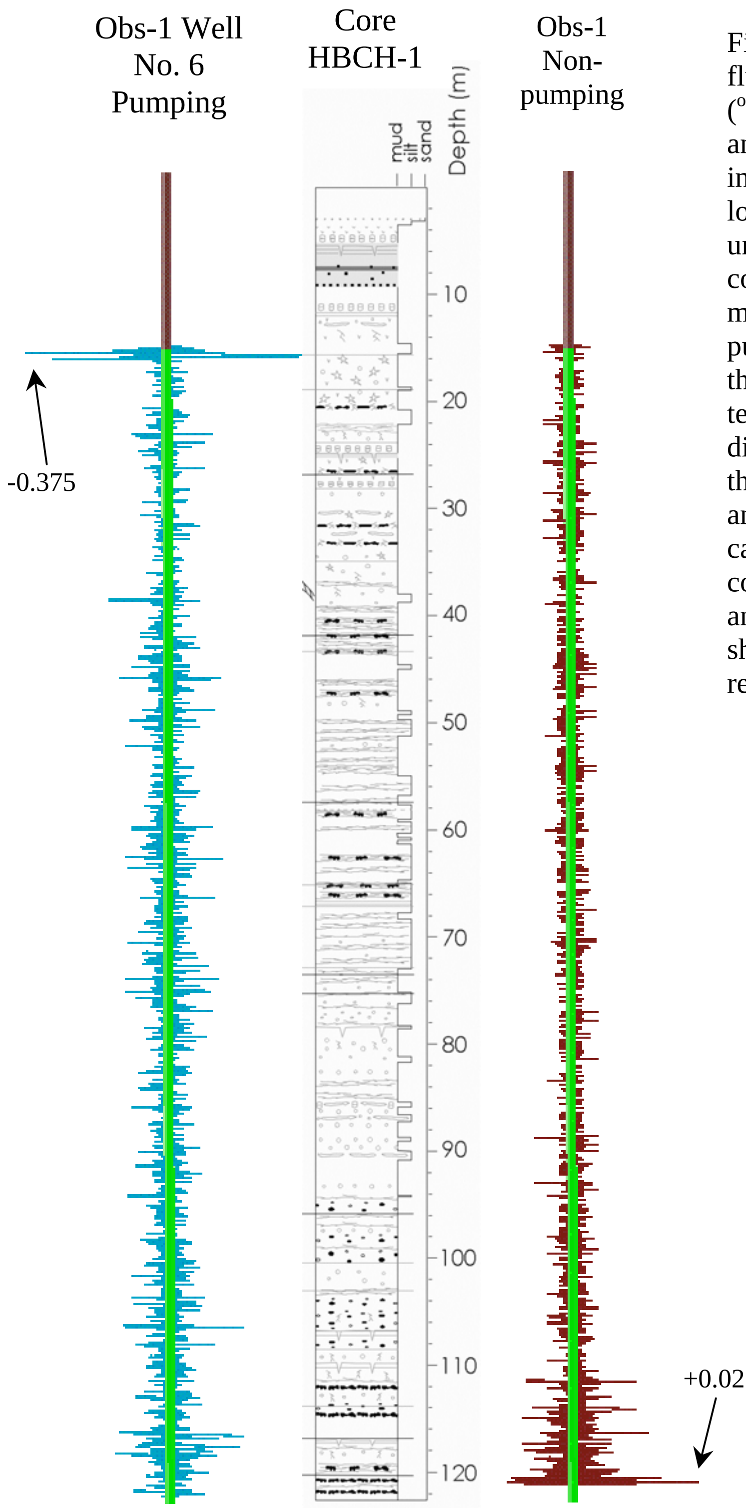


Figure 21. Comparison of fluid-temperature differentials (^oF) in Obs-1 under pumping and non-pumping conditions in relation to the nearby core log. Differential readings under non-pumping conditions are two orders of magnitude lower than for the pumping conditions. Note the correlation between temperature 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.

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.

The NJ 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 NJ 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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