Characterization of anisotropic aquifer behavior in the Pen Argyl Member of the Martinsburg Formation, Pennsylvania

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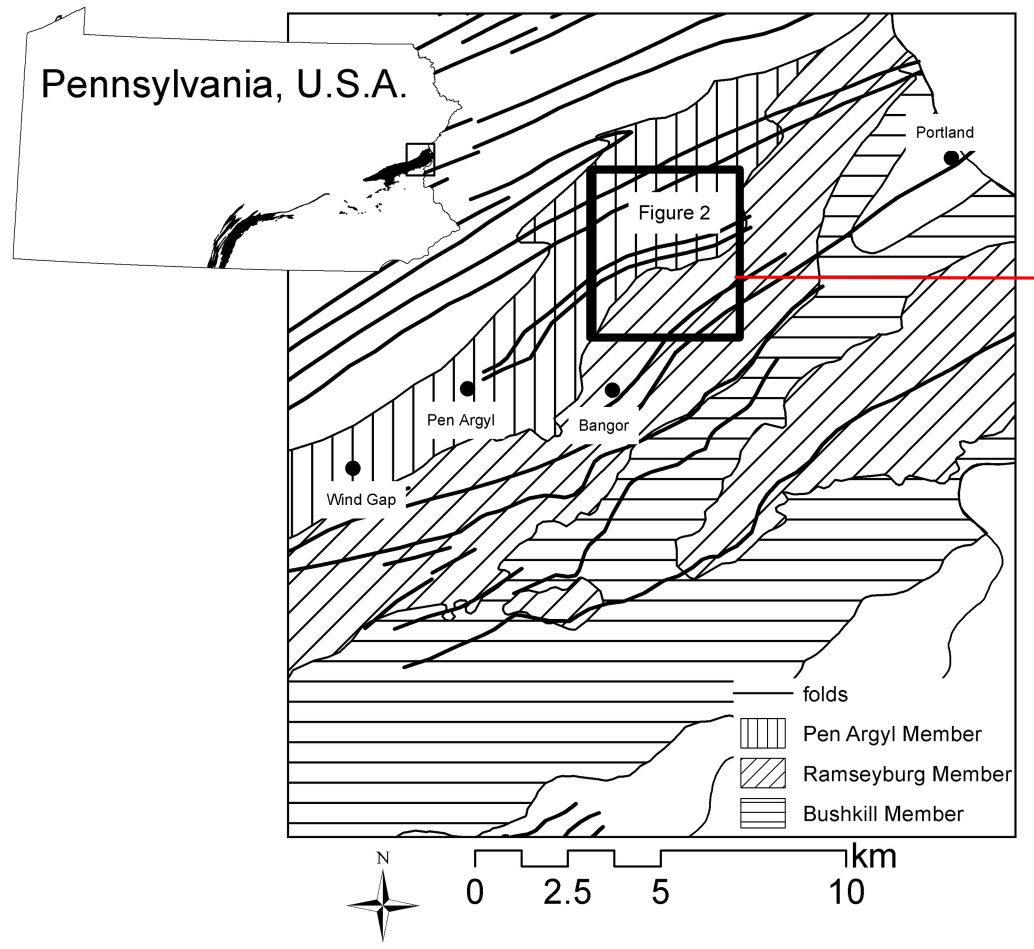
ABSTRACT

Horizontal anisotropy in aquifer properties is common in deformed terrains. When structural fabrics and resulting secondary porosity are controlled by regional tectonics, principle transmissivity tensor (T_α) orientation (θ) may be similar over a wide area. Lithologic variability within a terrain may affect fracture characteristics and thus the magnitude of T_α may vary. Recognition of domains with similar orientation and magnitude of transmissivity tensors is important for effective groundwater management.

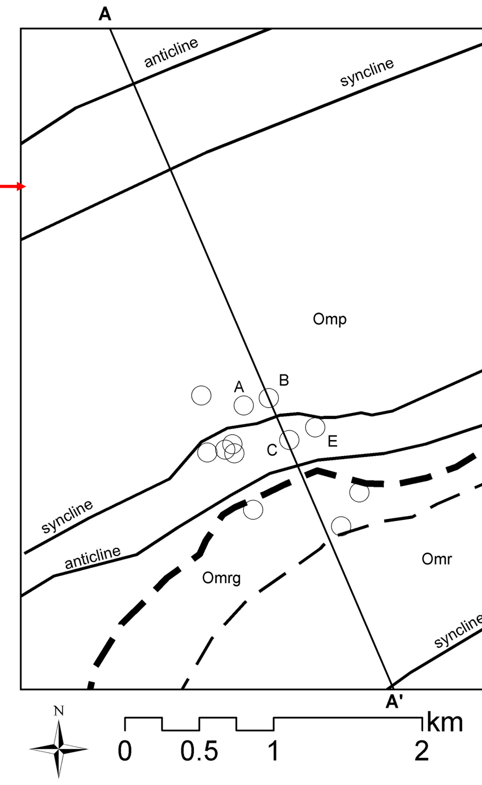
The Pen Argyl Member of the Martinsburg Formation is a thick sequence of claystone slate with subordinate intercalated quartzose slate and subgraywacke. Time-drawdown data from four aquifer tests in the Pen Argyl Member exhibited anisotropic behavior at a scale of at least 600 m. The horizontal anisotropic properties were determined using analytical models and the results were statistically characterized allowing for uncertainty estimation and testing for differences. The uncertainties quantify deviation of the real aquifer from the idealized model aquifer and arise from aquifer heterogeneity, deviation from radial flow conditions with likely extended well behavior, and the presence of multiple dipping fracture zones as well as measurement error.

Principle transmissivity tensor orientation for four pumping tests within the Pen Argyl Member of the Martinsburg Formation were statistically indistinguishable (mean θ_α = 41.5±8.8(3σ)) and aligned parallel to the strike of bedding, axial planar cleavage, and a joint set. Faults were prominent water-bearing zones in the wells. The fault orientations in the wells are unknown but it is likely that they represent bedding plane faults evident in a nearby quarry and identified as important groundwater flow paths in the member. An example of results from a single test show the aquifer is anisotropic (H_0: $T_\alpha=T_\beta$ rejected at P<0.005) with θ=47.7±19.0(2σ), T_α/T_β=7.9±5.5(2σ), T_α=218 ±441(2σ) m^2/d, and T_β=27±53(2σ) m^2/d. The study is a step toward delineation of hydrostructural/hydrogeologic units in the Martinsburg Formation.

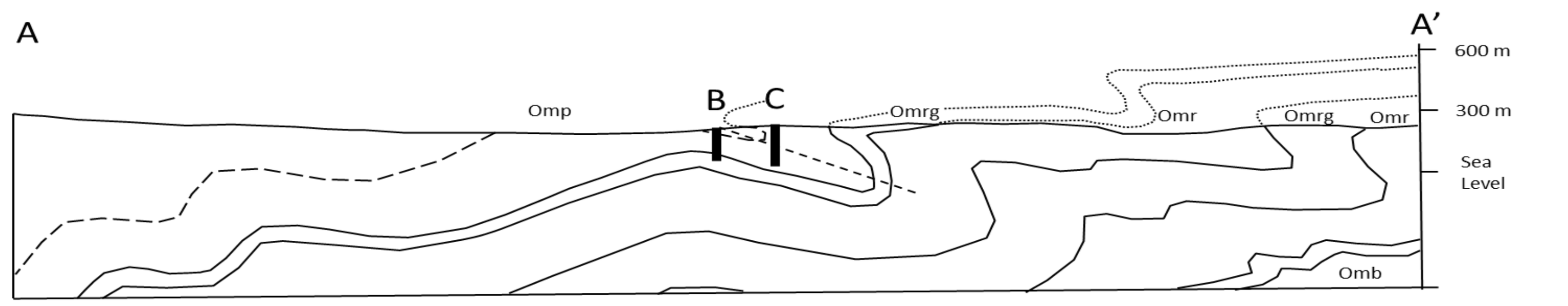
SITE LOCATION, STRATIGRAPHY, AND STRUCTURE



Maps of outcrop belt of Martinsburg Formation in Pennsylvania (inset; Berg and others, 1980) and distribution of formation members in eastern Pennsylvania with outline (black rectangle) of the study area shown in Figure 2. Fold axial traces from Faill (2011).

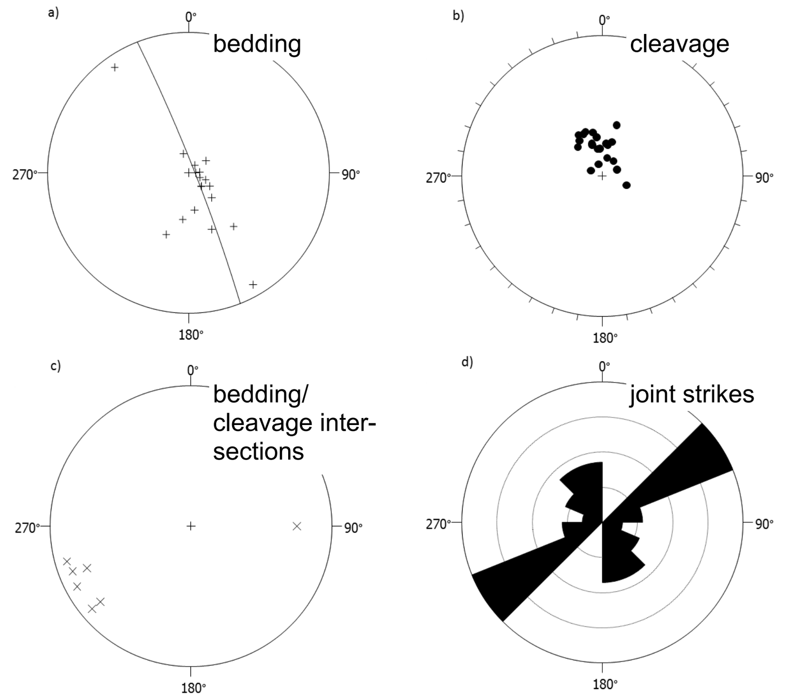


Portion of the Stroudsburg, Pennsylvania 7.5 minute quadrangle with structural features, lithologic boundaries (after Epstein, 1973) and locations of wells monitoring during this study. Omp = Pen Argyl Member, Omrg = greywacke-rich portion of the Ramseyburg Member, Omr = Ramseyburg Member. A-A' is line of cross-section shown in Figure 3.

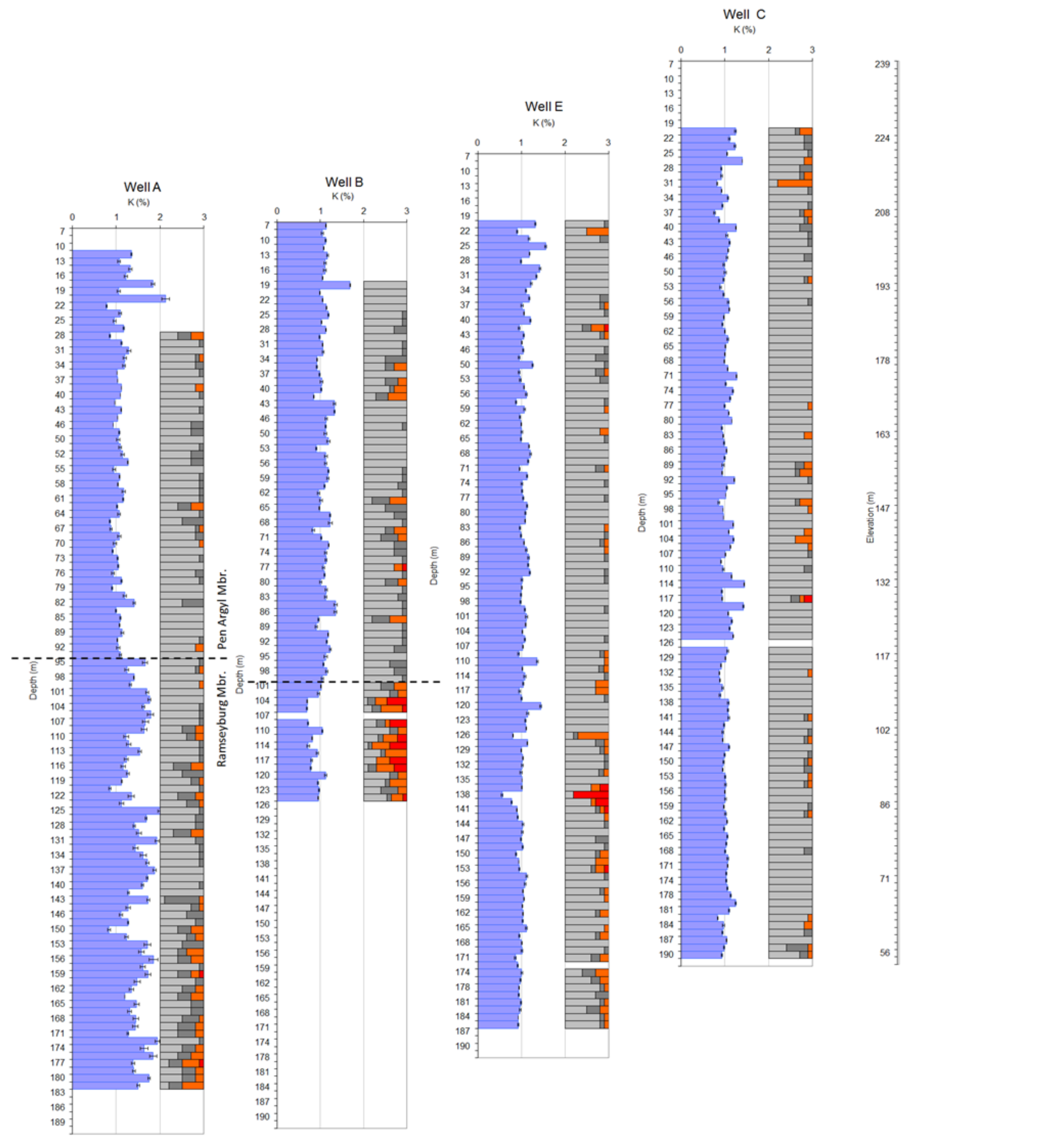


Geologic cross-section A-A' (modified from Epstein (1973)) showing locations of wells B and C.

Photograph of an outcrop located near Well C. Note the more steeply dipping, wider spaced cleavage in the quartzose lower portions of the finning upward beds.

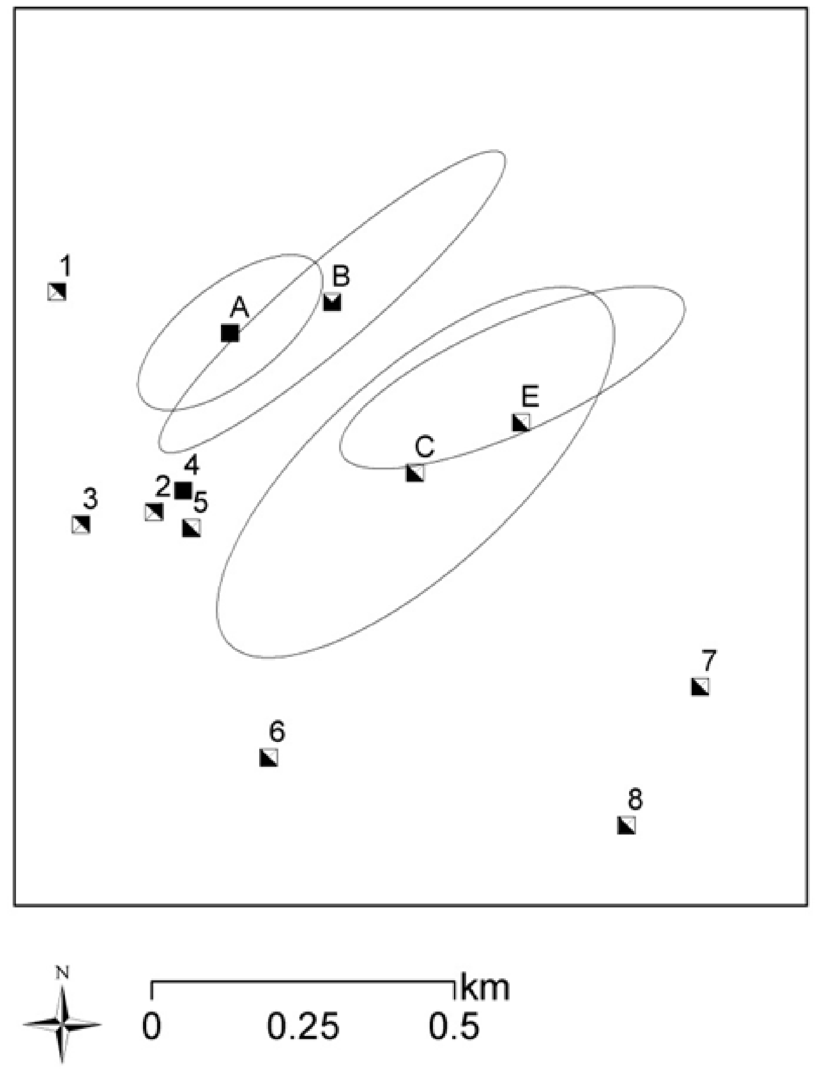


Equal angle lower hemisphere projections of structural features. Data from Epstein, 1973 and 1974; this study.

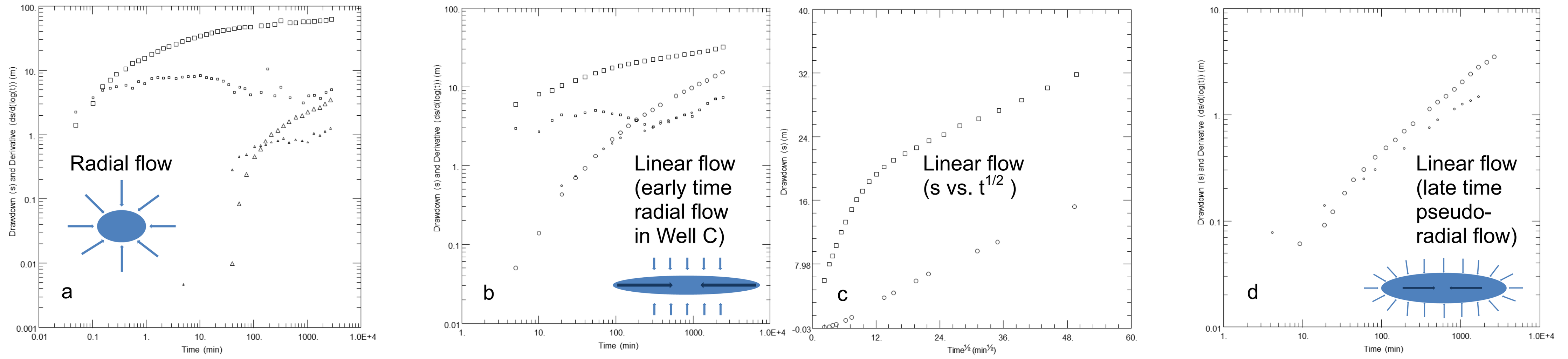


Lithologic logs (light gray = mudstone, dark gray = siltstone, orange = fine sandstone, red = medium sandstone) and spectral gamma ray logs (blue bars = percent potassium) for test wells A, B, C, and E.

AQUIFER ANALYSIS



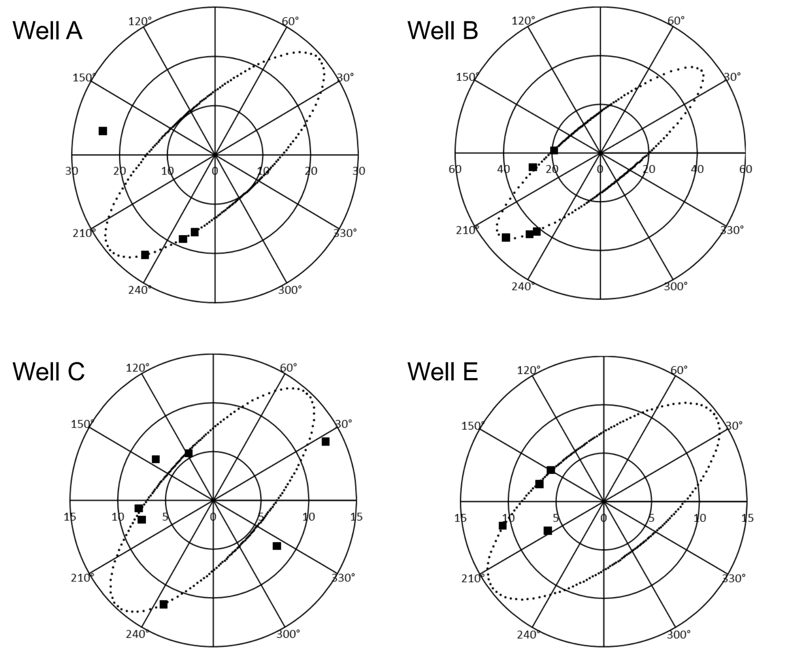
Pumping and monitoring well location map. Blackened N, E, S, or W quadrants of well symbols indicate monitoring during testing of wells A, B, C, and E, respectively. Ellipses show estimated 6 m drawdown contours after 2 days of pumping.



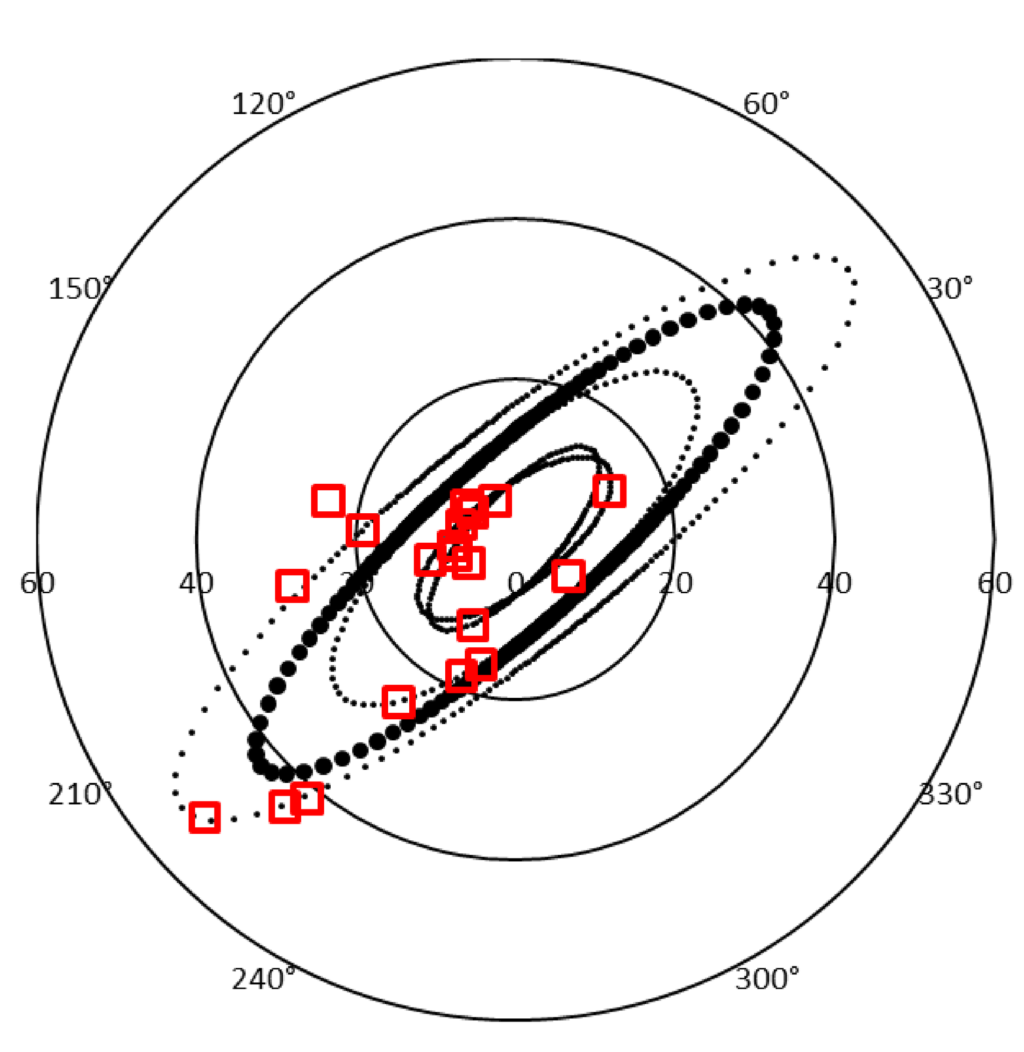
Diagnostic plots of drawdown data. Large symbols are drawdown data and small symbols are derivative data, a) squares = pumping well B, triangles=observation well 2, b and c) squares = pumping well C, circles = observation well E, d) drawdown response of well C during pumping of well E.

CHARACTERIZATION OF AQUIFER ANISOTROPY

The equation for unsteady drawdown induced in a confined aquifer that is anisotropic on the horizontal plane was derived by Papadopulos (1965). Neuman and others (1984) extended the model to include a linear least squares approach to the simultaneous analysis of test data to determination of anisotropy axes orientations and magnitudes. Kern and Dobson (1998) extended the least squares method of Neuman and others (1984) to include statistical tests for anisotropy and methods for constructing variance formulas for the principle axes of transmissivity and confidence intervals for the angles of orientation. We applied the method of Kern and Dobson (1998) to the pumping test data and the results are summarized in Table 1. Variances were estimated for pumping test B, C, and E and for a combination of all four pumping tests. These statistics are a measure of the quality of fit between the theoretical transmissivity ellipse and the estimated radial transmissivity values from monitoring wells.



Comparison of theoretical transmissivity ellipses calculated using the method of Kern and Dobson (1998) and estimated radial transmissivity for observation wells (squares). The square root of T (m^2/d) is plotted. Average storage coefficients (S) for each test (A=2.14x10^{-4}, B=9.12x10^{-4}, C=4.05x10^{-4}, E=5.72x10^{-4}) were used to calculate the directional transmissivity.



Theoretical transmissivity ellipse for all tests combined (large circles), ellipses from all individual well tests (small circles), and estimated radial transmissivity for observation wells (red squares). The square root of T (m^2/d) is plotted

TABLE 1: Summary of horizontal anisotropy in transmissivity and quantification of uncertainty in parameter estimates

Pumping well(s):	B	E	A	C	ABCE***
eigenvalue	2.94870E-08	2.47589E-07	2.32857E-07	1.72439E-07	5.70560E-08
eigenvalue	4.81961E-07	1.52648E-06	1.94914E-06	1.36710E-06	9.75922E-07
θ_α (degrees)	38.8	37.9	41.5	47.7	41.6
θ_α ±95%CI*	3.43	17.4	nd**	19.0	16.1
z_1	12.603149	1.677148	nd	3.266967	2.124772
z_2	12.805201	0.300969	nd	2.444748	0.507885
$Pr(Z>z_1)$‡	<0.001	0.047	nd	0.005	0.017
$Pr(Z>z_2)$‡‡	<0.001	0.382	nd	0.007	0.306
T_α (m^2/d)	2,874	215	855	217	1,812
T_β (m^2/d)	176	35	102	28	106
±95%CI T_α	11,705	1633	nd	441	7,719
±95%CI T_β	716	48	nd	53	241
T_α/T_β	16.3	6.2	8.4	7.9	17.1
±95%CI T_α/T_β	2.3	33.6	nd	5.5	61.9
N	5	4	3	5	20

*CI = confidence interval

**nd = not determined

***All test data combined

‡$Pr(Z>z_1)$ = probability of observing test statistic as extreme as z_1 for the null hypothesis H_0: $T_\alpha=T_\beta$

‡‡$Pr(Z>z_2)$ = probability of observing test statistic as extreme as z_2 for the null hypothesis H_0: $T_\alpha/T_\beta=1.0$

REFERENCES:**1.** Berg, T. M., Edmunds, W. E., Geyer, A. R., and others, (Compilers), 1980, *Geologic map of Pennsylvania (2nd ed..).*Pa Geol. Surv., 4th ser., Map 1, scale 1:250,000. **2.** Epstein, J.B., 1973, *Geologic map of the Stroudsburg quadrangle, Pennsylvania-New Jersey*.U.S. Geol. Surv. Quad. Map GQ-1047.**3.** Epstein, J.B., 1974, Map showing slate quarries and dumps in the Stroudsburg quadrangle, Pennsylvania-New Jersey, with a discussion of their environmental significance. Pa Topo. Geol. Surv., Misc. Field Studies, Map MF-578 A, 2 sheets. **4.** Faill, R. T., (Compiler), 2011, Folds of Pennsylvania—GIS data and map: Pa Geol. Surv., 4th ser., OFR OFGG 11–01.0, scale 1:500,000. **5.** Kern, J.W., and Dobson, C.W., 1998, Determination of variances for maximum and minimum transmissivities of anisotropic aquifers from multiple pumping test data: Ground Water, Vol. 36, No. 3, pp. 457-464. **5.** Neuman, S.P., Walter, G.R., Bentley, H.W., Ward, J.J., and Gonzalez, D.D., 1984, Determination of horizontal aquifer anisotropy with three wells: Ground Water, Vol. 22, No. 1, pp. 66-72. **6.** Papadopulos, I.S., 1965, Nonsteady flow to a well in an infinite anisotropic aquifer: Proceedings of the Dubrovnik Symposium on the Hydrology of Fractured Rocks, International Association of Scientific Hydrology, p. 21-31.

CONCLUSIONS:

1. Principle transmissivity tensor orientation for four pumping tests within the Pen Argyl Member of the Martinsburg Formation were statistically indistinguishable (mean θ_α = 41.5±8.8(2σ)) and aligned parallel to the strike of bedding, axial planar cleavage, and a joint set. Fractured, mineralized zones in the test wells are inferred to be faults. The fault orientations in the wells are unknown but it is likely that they represent bedding plane faults evident in a nearby quarry and identified as important groundwater flow paths in the member.

2. The best estimate for the ratio T_α/T_β was 16.3±2.3(2σ).

3. Principle transmissivities, T_α and T_β, had geometric means of 582 m^2/d and 65 m^2/d, respectively and have high variances.

4. The tests showed that the Pen Argyl Member exhibits anisotropic behavior at scales up to at least 600 m and that both radial and linear flow regimes formed in response to pumping.