Report as of FY2006 for 2006NJ98B: "Advancing the characterization of fractured bedrock aquifers using electrical geophysical methods: application to water resources evaluation in the New Jersey Highlands"

Publications

- Conference Proceedings:
  - Wishart, D. N. and L. D. Slater. 2007. Advancements in Fracture anisotropy characterization of the New Jersey Highlands bedrock using Azimuthal Geoelectric Methods. American Geophysical Union, Spring Meeting 2007, Acapulco, Mexico, May 22-25, 2007 (Oral presentation). Eos. Trans. AGU, 88(23), Jt. Assem. Suppl., Abstract NS53A-07.
  - Wishart, D. N., L. D. Slater, and A. E. Gates. 2006. Azimuthal geoelectric characterization of fracture flow in the New Jersey Highlands bedrock. Geological Society of America 2006 Philadelphia Annual Meeting, October 22 25, 2006 (Oral presentation). GSA Abstracts with Programs, 38(7):26.
  - Wishart, D. N. and L. D. Slater. 2006. Hydraulic and electric anisotropy characterization of the New Jersey Highlands fractured bedrock in: Environmental Geology of the Highlands, Field Guide and Proceedings, S. Macaoay and W. Montgomery (Eds). Geological Association of New Jersey, XXIII Annual Conference and Field Trip, October 13 -14, 2006, Ramapo College, New Jersey. (Oral presentation)
  - Wishart, D. N. and L. D. Slater. 2006. Geoelectric characterization of fracture flow in the North and Central New Jersey Highlands bedrock. Pennsylvania Water Resources Symposium, Camp Hill, Pennsylvania, October 11, 2006.
  - Wishart, D. N. and L. D. Slater. 2006. Geoelectric characterization of fracture flow in the New Jersey Highlands bedrock. 18th Annual Electromagnetic Induction (EMI) Workshop, University of Barcelona, El Vendrell, Spain, September 17 23, 2006. (Poster presentation)
  - Slater, L. D. and D. N. Wishart. 2006. Geoelectric characterization of hydraulic anisotropy in fractured rock aquifer model: the advantages of natural (self) potential over induced electric potentials. Society of Exploration Geophysicists (SEG) Hydrogeophysics Workshop, Vancouver, British Columbia, July 31August 2, 2006.
  - Wishart, D., L. D. Slater, and A. G. Bolden. 2005. An integrated geoelectric assessment of fracture and anisotropy characterization of the North New Jersey Highlands bedrock. American Geophysical Union Fall 2005 Meeting, San Francisco, California, December 59, 2005. (Poster presentation)
- Articles in Refereed Scientific Journals:
  - Wishart, D.N., L.D. Slater, and A.E. Gates. 2006. Self potential improves characterization of hydraulically-active fractures from azimuthal geoelectrical measurements. Geophysics Research Letters, 33: L17314, doi:1029/2006GL027092.
- Dissertations:
  - Wishart, D. N. Anisotropy Characterization of fracture-dominated media using azimuthal geoelectric methods. Ph.D. Dissertation. Rutgers, The State University of New Jersey, Newark, NJ. 250 p. (In prep)

Report Follows

Problem Statement

Global population growth and increasing demand for new, viable groundwater resources has necessitated the exploration and development of fractured-rock aquifers. Groundwater pollution from paint sludge and gas stations impacts Ringwood, one of the communities in the north New Jersey Highlands. This poses a serious threat to the region's most important watershed. State authorities fear the contamination will work its way into the drinking water supply of 2.5 million people in Bergen, Passaic, and Essex counties.[1] The Federal Government aims to preserve environmentally sensitive areas of the New Jersey Highlands[2] that include highly fractured rocks. The recently enacted New Jersey Highlands Water Protection and Planning Act (2004) aimed at preventing urban sprawl in the North Jersey Highlands is also in accordance with the New Jersey Department of Environmental Protection (NJDEP) water quality initiative to protect water resources in these areas.[3,4] Fractures serving some communities as the principal sources of clean groundwater also act as hydraulic conductors that form potential pathways for transport of contaminants in the groundwater system or, if mineralized, may act as barriers that prevent fluid flow. Groundwater flow through a fracture network is strongly influenced by the geometry of fractures, thus impacting the transport of contaminants and the design of groundwater remediation efforts. The potential exists for contaminants to migrate at high velocities in these fractures. Information on the presence, extent, intensity, and direction of fracturing is vital to the design of groundwater remediation strategies. Importantly, increasing our understanding of the properties influencing groundwater flow through fractured-rock aquifers has great implications for our world today and in the future. Geophysical techniques applied to fracture characterization and fluid flow analysis may be used to locate, identify, and predict the behavior of hydraulically-significant fractures in the subsurface.

Geophysical methods provide rapid, helpful, and cost-effective techniques that are increasingly used to non-invasively investigate water resources and water quality.[11, 12, 16, 18, 19] Azimuthal electrical measurements have aided in the hydrogeologic characterization of fractured rock aquifers for over three decades.[6, 20] Electrical current and groundwater are both channeled through fractures in rock (the rock itself is electrically insulating and impermeable to flow of water) such that it is assumed that the principal direction of groundwater flow may be inferred from the measured electrical anisotropy under favorable conditions.[23] The direction of maximum apparent resistivity measured with collinear azimuthal resistivity arrays is parallel to the principal fracture strike orientation. [14, 20, 21, 22] Unfortunately, the resistivity measurement is not a unique proxy measure of a water bearing fracture as other features, particularly clay minerals, are also electrically conductive.[7, 17] The method therefore can fail when geological features other than fractures cause the subsurface to exhibit anisotropy and/or heterogeneity.

Project Research Objectives

This project initiates hydrogeophysical research in the New Jersey Highlands directed towards improving water resources management and reducing aquifer vulnerability in the region. Rather than relying solely on traditional collinear (symmetric) azimuthal resistivity surveys alone to characterize fracture anisotropy as was done in previous investigations, asymmetric azimuthal arrays of ASP and ARS measurements are coupled with hydrologic measurements to characterize fractures at the laboratory and extended to the field scale. Two-thirds of the research completed has allows us to (1) improve the effectiveness of electrical geophysical methods in the hydrogeologic characterization of fractured bedrock aquifers, (2) devise a method to delineate hydraulically-active fractures, (3) extend bench-scale laboratory research to the field sites, and (4) apply methods to improve understanding of fracture geometry in the north New Jersey Highlands

(NJH). The complex fracture geometry in the bedrock of the NJH region encourages the application of such integrated geophysical methods that are sensitive to hydraulic anisotropy, the direction of groundwater flow, and heterogeneity. Interestingly, the program of research investigates how integrated geoelectric measurements can be used to distinguish hydraulically-conductive fractures and to infer direction (and possibly rates) of groundwater flow based on the electrokinetic phenomena associated with "streaming' or self potential (SP), illustrated in Figure 1. The third and final experiment for the completion of the project will involve the use of electric geophysical methods used in earlier experiments to characterize fractures created in a clay formation by the Pneumatic Fracturing Technology® (an engineering application) that serves two principal functions: (1) to enhance fluid flow and (2) reduce transport limitations that are inherent at many remediation sites. The Pneumatic Fracturing Technology® patented in 1992 (*Schuring*, 1992) has emerged as one of the most cost effective methods for enhanced remediation of contaminated groundwater and soils over the last decade. The objective of this study is to investigate the relationship between fracture propagation pressure and the simultaneous injection of a liquid by capitalizing on the *in situ* electrokinetics to increase the capability to detect the advance of injectate/contaminant through hydraulically-conductive fractures.

A successful demonstration of the concepts outlined here to a real-world problem (water resources and water quality in the NJ Highlands) will pave the way for submission of a research proposal to the Hydrologic Sciences Division of the National Science Foundation. The proceeds of the New Jersey Water Resources Research Institute (NJWRRI) have provided a remarkable opportunity to collect significant data to justify the NSF proposal. There is ample scope to expand this work into an NSF proposal as the next logical step is to model and interpret the integrated geophysical signals in terms of the physical and chemical characteristics of the fractures (aperture width; fracture surface chemistry; hydraulic gradient; flow velocity, etc.).

METHODOLOGY

Electric geophysical investigations were undertaken to characterize hydraulic and electric anisotropy in the laboratory on (1) a fracture block model and (2) pneumatic-fractured compressed clay sediments, and (3) above fractured crystalline bedrock at field sites throughout the north New Jersey Highlands Province. We examined the potential for geophysical characterization of fractured rock anisotropy by combining asymmetric configurations of azimuthal self potential (ASP) and azimuthal resistivity surveys (ARS).

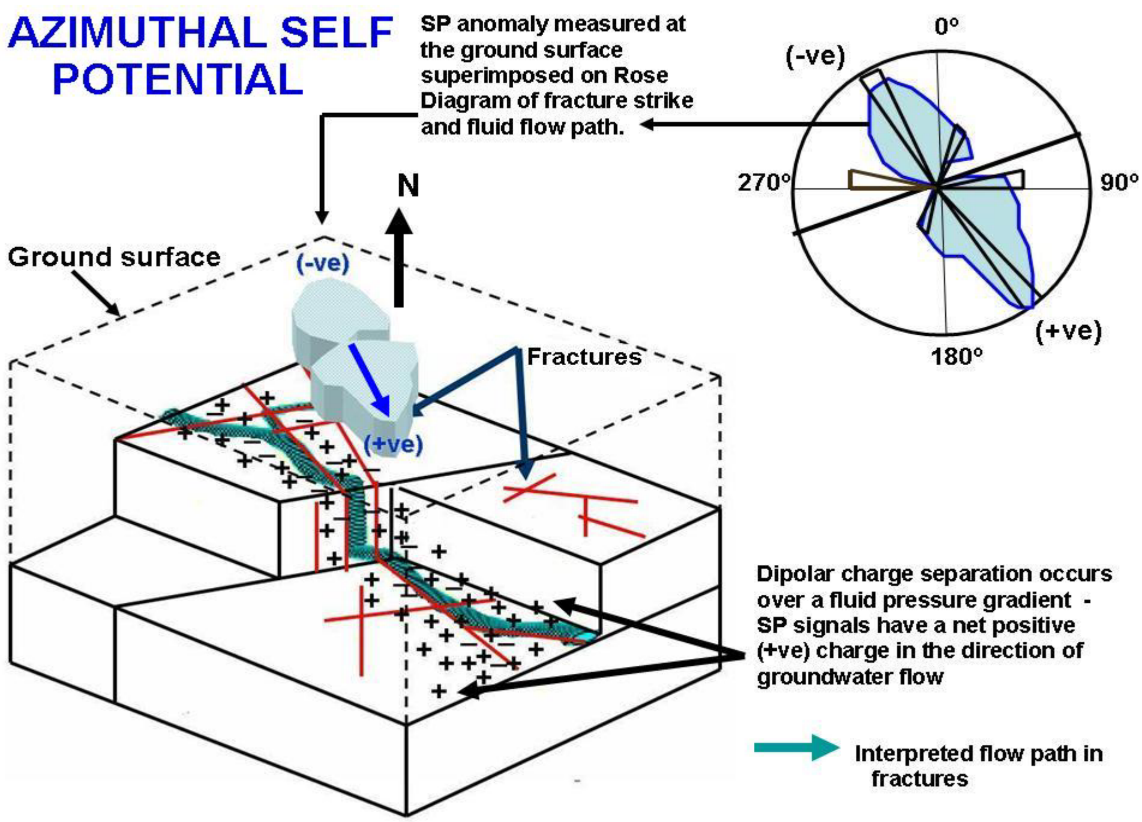


Figure 1. Schematic of the streaming potentials (electrokinetic effect) during flow along interconnected (dense) fractures over a hydraulic-pressure gradient in the bedrock.

Laboratory Investigations

Fractured Aquifer System (FAS)

ASP and ARS measurements were performed on a Plexiglas® fracture block model (50.0 cm long x 39.0 cm wide) cemented to the base of a sand-filled rectangular glass tank 91.5 cm x 61.0 cm x 30.5 cm, shown in Figures 2(a) – (b). The fracture block is a replica of the *Wisconsin Niagaran Dolomite Formation* fracture study.[9] The fracture block is considered an anisotropic medium due to the preferential alignment of fractures of varying lengths and widths along three azimuths. In order to establish a uniform surface with good electrical contact, the FAS was filled with Ottawa Sand to a level 3 cm above the block (i.e. 10 cm deep in the surrounding area). The tank was then saturated with a 0.01 M NaCl electrolytic solution. A steady-state flow through the FAS was established using variable flow pumps connected to the inflow and outflow chamber via a single tube at each end of the glass tank (Figure 2). Azimuthal self potential and azimuthal resistivity measurements were made using asymmetric arrays so that anisotropy and heterogeneity could be distinguished.[6] A mobile asymmetric dipole method was used to acquire ASP measurements with two custom-made non-polarizable PbCl-$PbCl_2$ miniature electrodes[6] constructed in our laboratory were kept at a fixed distance from each other and rotated simultaneously at 20º degree segments to record electric potential *(φ)* as a function of azimuth. Electrodes were connected to a precision multimeter (input impedance >10 MOhm). SP values were recorded for no-flow conditions and at five flow rates: Q = 0.50 mL/min, 0.65 mL/min, 0.80 mL/min, 1.20 mL/min, and 1.40 mL/min.

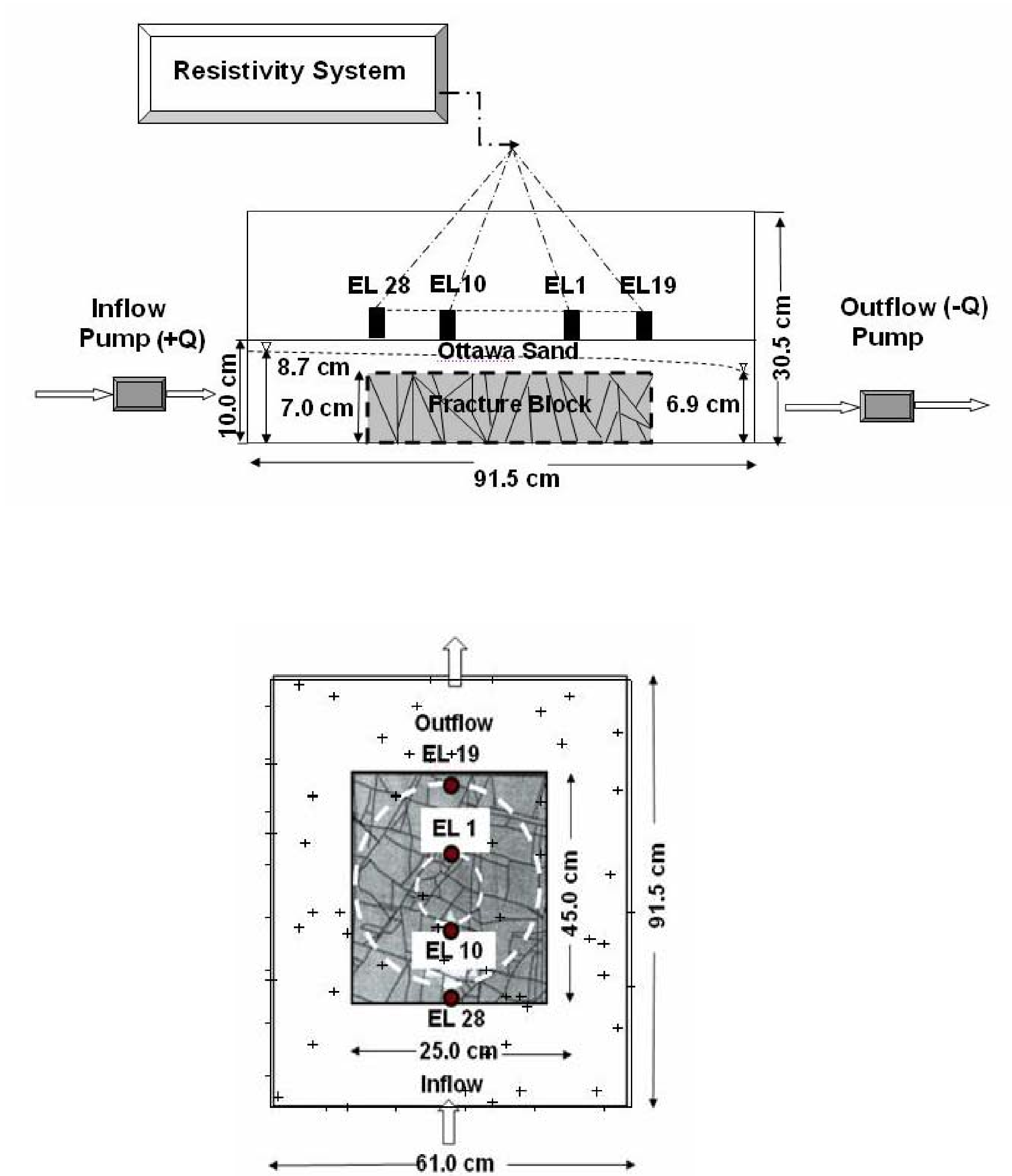


FIGURE 2(a): Schematic side view of the experimental tank holding the FAS and a fracture block which is a replica of the Wisconsin Niagaran Dolomite Formation fracture study[9] (1985) (EL defines electrode) and (**b**) Plan view with black crosses indicating the locations where hydraulic head was measured at flow rate of 1.40 ml/min. White circles indicate circumferences of inner and outer electrode rings making up asymmetric azimuthal self potential and azimuthal resistivity arrays.

Pneumatic-Fractured Aquifer System (PFAS)

The Pneumatically Fractured Aquifer System (PFAS) consists of a 1.0 m x 1.0 m x 1.0 m clay-filled, square, bullet–resistant glass tank, illustrated in Figure 3. The tank is being packed with clay and compressed to a level 0.9 m and sealed by 0.1 m thick layer of bentonite. A 3.0 inch diameter clear *Lexan®* tube inserted in the center of the tank and connected to a sealable portal in the base of the tank facilitates optical imaging of the pneumatic-induced fractures propagated in the formation. Compressed nitrogen (N_2) gas is to be supplied from two cylinders with a flow rate of 5 psi and injected into the formation through two 0.50 inch diameter Schedule 40 PVC tubes, each attached to nozzles situated to the depth of the anticipated fracture interval at 0.25 m (indicated by dashed line in Figure 3). Both injector tubes are positioned at 71.0 cm diameter from the optical imaging port along a diagonal length of the tank. The parameters associated with fracture propagation and deformation (fracture initiation pressure and maintenance pressures) will be measured and recorded digitally. Eight electronic biaxial tiltmeters will be placed on the soil surface to (1) assure intimate contact with the tamped ground surface, (2) sense the surface deformation caused by fracturing (heave), and (3) measure change in angular deformation with changes in ground surface movements (i.e. heave or differential tilt) during the injection and history of fracture propagation. Any digital tilt values recorded during injection will be curve-fitted to generate the deformation surface using a computer program, and the deformation surface is converted to a contour plot of ground surface heave. Azimuthal self potential (ASP) and azimuthal resistivity, (ARS) measurements will be acquired for fracture characterization using miniature electrodes. Self potential sampling and electrokinetic (EKE) information will be downloaded every 0.5 seconds during injection using a data logger connected to a common electronic network (controlled by laptop). Detailed structural analyses will be conducted by

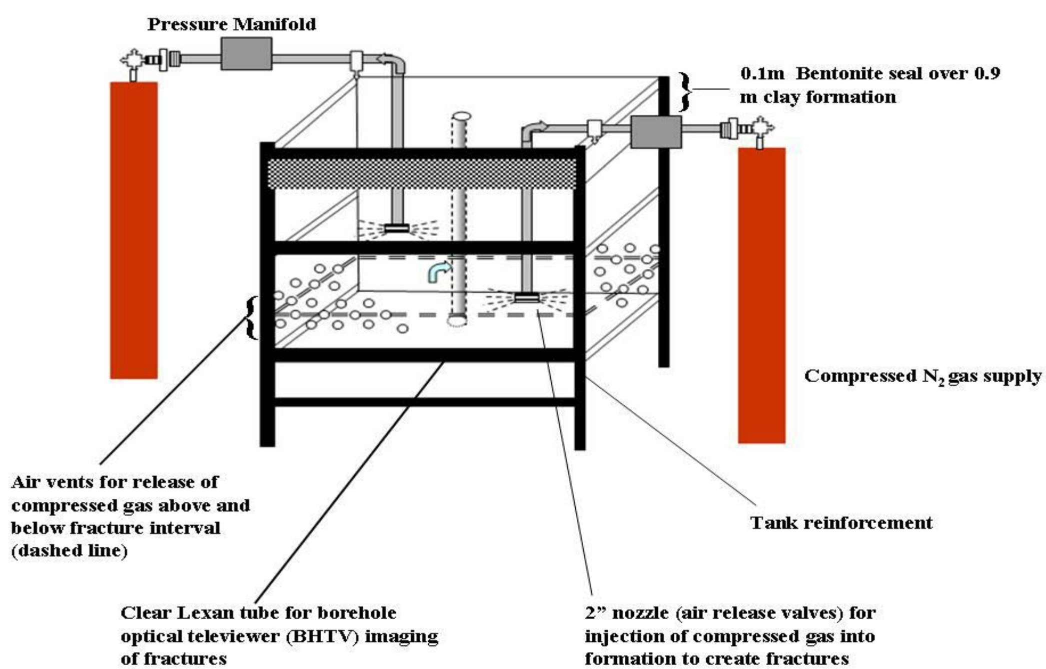


Figure 3. Schematic of experimental tank facility and set up of pneumatic fracturing of the clay formation using the injection of compressed nitrogen gas.

optical imaging (360º) of the pneumatic fractures from a centrally located borehole using a borehole Televiewer (BHV) and a physical density characterization. This final experiment is set to be performed on June 25, 2007 and the results submitted to a peer review journal (Engineering Geophysics) for publication.

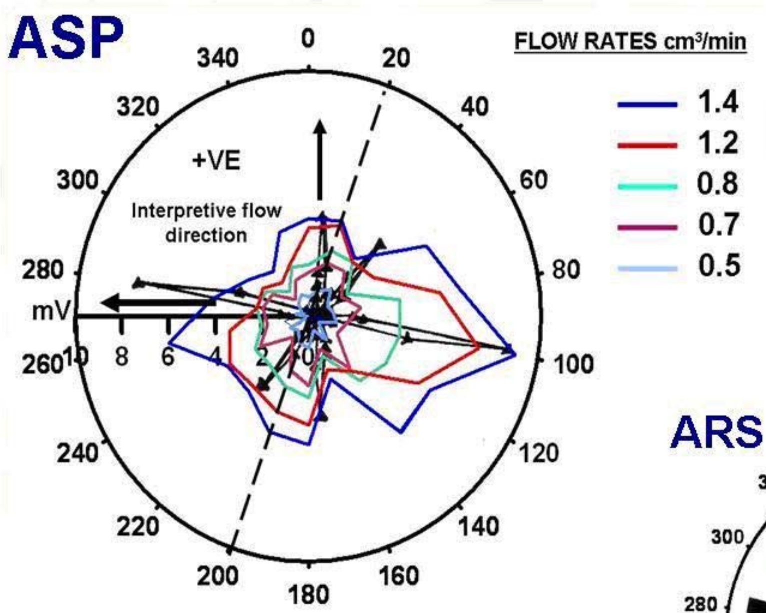
Field Investigations

Azimuthal asymmetric arrays of SP measurements were employed to delineate hydraulic (flow) anisotropy at a total of 16 field sites located in the New Jersey Highlands. We examined the potential for geophysical characterization of fractured rock anisotropy by combining asymmetric configurations of azimuthal self potential (ASP) and azimuthal resistivity surveys (ARS), as previously demonstrated in the laboratory, at the field sites in the New Jersey Highlands (NJH) Province. Detailed, site-specific structural analyses were conducted and extrapolated to outcrops exposed on or near the target area at four of the sixteen field sites. A mobile dipole method was used to acquire ASP measurements with two custom-made, non-polarizable PbCl-$PbCl_2$ electrodes[13] kept at a fixed distance from each other and rotated simultaneously at 20º steps through 360º to record electric potential (φ) as a function of azimuth. The radius of the electrode ring used in the site surveys was 21 m. Electrodes were connected to a precision multimeter (input impedance >10 MOhm). Additional processing of ASP measurements involved the transformation of electric potential (SP) signals (φ) with variation in azimuth (a 'time' series) into a frequency domain [the SP signal is a periodic function with a discrete spectrum]. The frequency is the inverse of the signal period defined by the number of degrees of array rotation required to repeat a waveform. The time to frequency conversion of the periodic functions contained in data-transformed peaks of 'odd' and 'even' harmonics were used to derive *f(t)*-the Discrete Fourier Transform (DFT) of the SP signals using a *Fourier* series representation. The characterization of 'fluid flow' as anisotropic or heterogeneous was quantified by calculating an *O/E* ratio (odd to even harmonics) or *K* value for comparison of the magnitudes of the odd and even harmonics of SP spectra for each dataset.

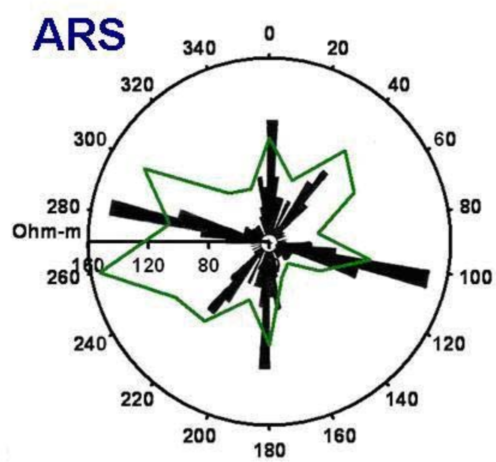
PRINCIPAL FINDINGS AND SIGNIFICANCE

The results of recent laboratory investigations suggest that azimuthal self potential measurements can potentially advance the geoelectrical characterization of hydraulic anisotropy in fractured rocks. Laboratory ASP surveys on a fracture block model show that ASP measurements are capable of distinguishing hydraulically-active fractures from electrically-conductive fractures, and are diagnostic of flow direction and flow rates in fractures (Figure 4a). In contrast, electrical resistivity measurements that are sensitive to the anisotropy in electrical current flow through fractures may not necessarily be equivalent to groundwater flow as previously indicated in earlier authors (Figure 4b). Both ASP and ARS measurements are influenced by anisotropy (due to the strike of major fracture sets) and heterogeneity (due to variable fracture density) of the block model. The existence of the positive polarity of the self potential defines the flow direction and the self potential magnitude within a single fracture set was observed to increase with flow rate. Whereas the ARS anisotropy is primarily controlled by fracture density/connectivity (and hence presumably hydraulic conductivity), ASP anisotropy appears diagnostic of (1) hydraulic gradient driving flow within fracture sets, and (2) fracture density, presumably controlling the strength of the streaming potential coefficient (Figures 1 and 4a).

Preliminary field data from the New Jersey Highlands illustrated that ASP surveys can define hydraulic anisotropy in fractured rock environments. A striking correlation was observed to exist



(a)



(b)

FIGURE 4 (a): Polar plot of the azimuthal self potential superimposed on fracture length rosette of the fracture block in the FAS as a function of flow rate and **(b)** plot of apparent resistivity (ρ_a) anisotropy superimposed on rosette of fracture strike orientation.

between ASP measurements and fracture strike orientations at three of four sites investigated (Figures 5a, 5c, 6a, 6c, and 7). The characteristic anisotropicity at the fourth site is controlled by a master structure; the NE-SW trending Lake Inez Fault Zone (LIFZ) that strikes at N10ºE (Figure 6a). The flow directions appear to be conformable with the regional northwest and northeast fracture trend of the NJH (Figures 5a and 5e). ARS (electrical) data suggest three sites are overall heterogeneous and the fourth is anisotropic (Figures 5b, 5d, 6c, 6d, and 8a – 8d).

Quantitative analysis of the magnitude of the energy observed in the odd and even coefficients of the power spectra of self potential (SP) datasets analyzed using a *Fourier* series was useful for characterizing anisotropic or heterogeneous flow in the fracture network. For anisotropic flow, the odd coefficients (harmonics) were close to zero, whereas heterogeneous flow resulted in significant energy in the odd coefficients. The employment of asymmetric geoelectric arrays has allowed this quantitative distinction between anisotropy and heterogeneity in fractured bedrock. Conversely, Figure 9 and Table 1, SP measurements show anisotropic behavior at three of four sites and flow anisotropy corresponds with the occurrence of high fracture density.

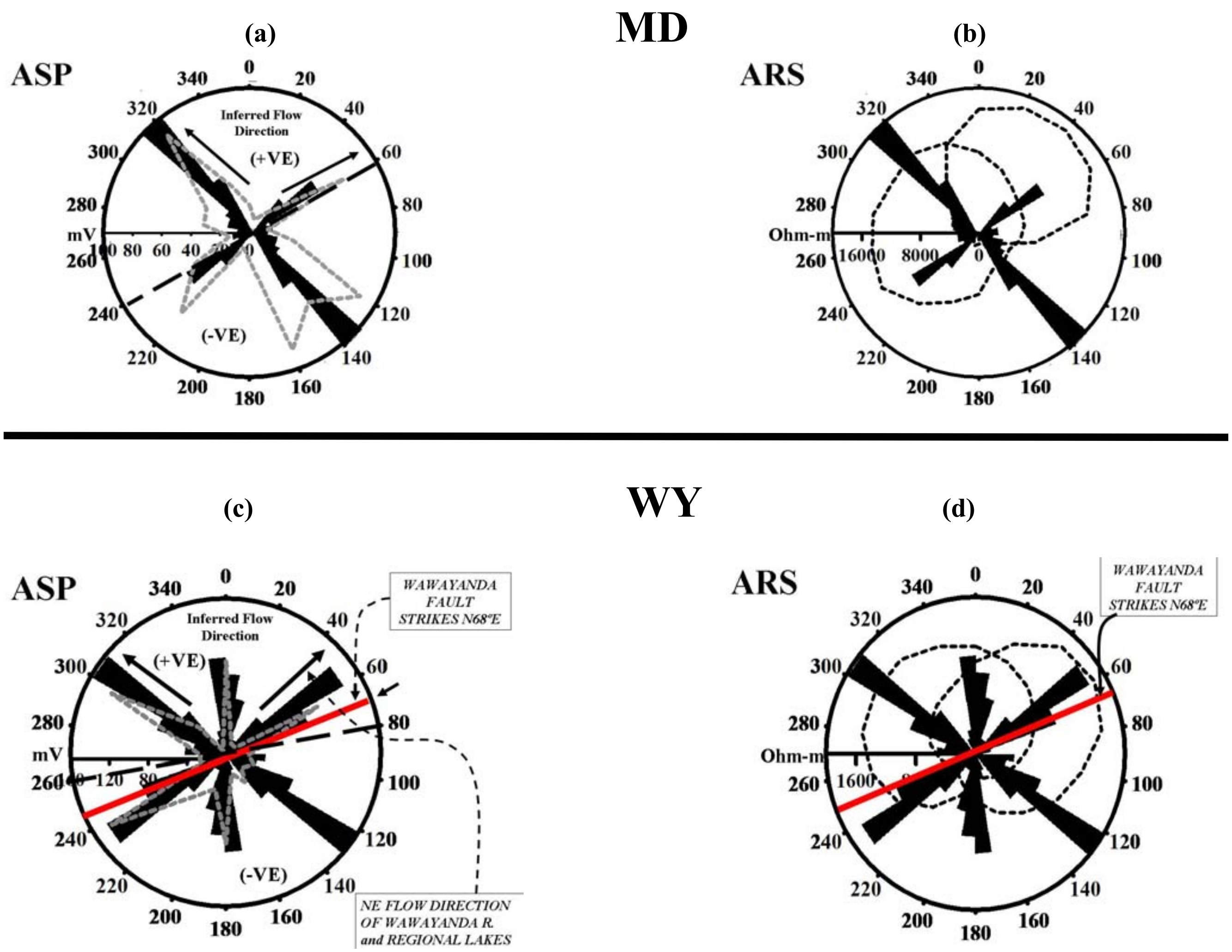


FIGURE 5. Polar plots of self potential anomalies and apparent resistivity (electrical anisotropy) for **(a-b)** MD, Lake Hopatcong, and **(c-d)** WY, Vernon sites in the New Jersey Highlands.

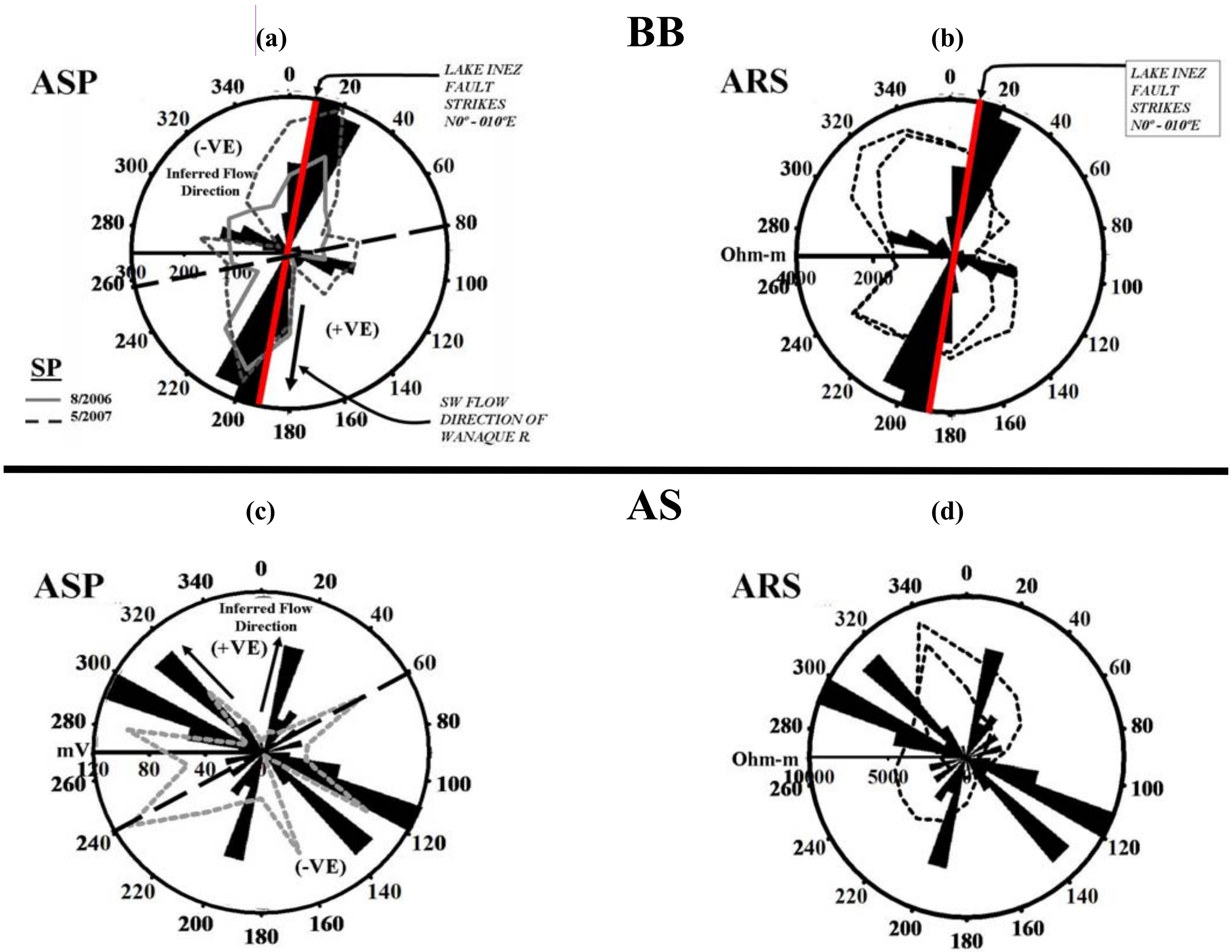


FIGURE 6. Polar plots of self potential anomalies and apparent resistivity (electrical anisotropy) for the **(a-b)** BB, Wanaque and **(c-d)** AS, Wharton sites in the New Jersey Highlands.

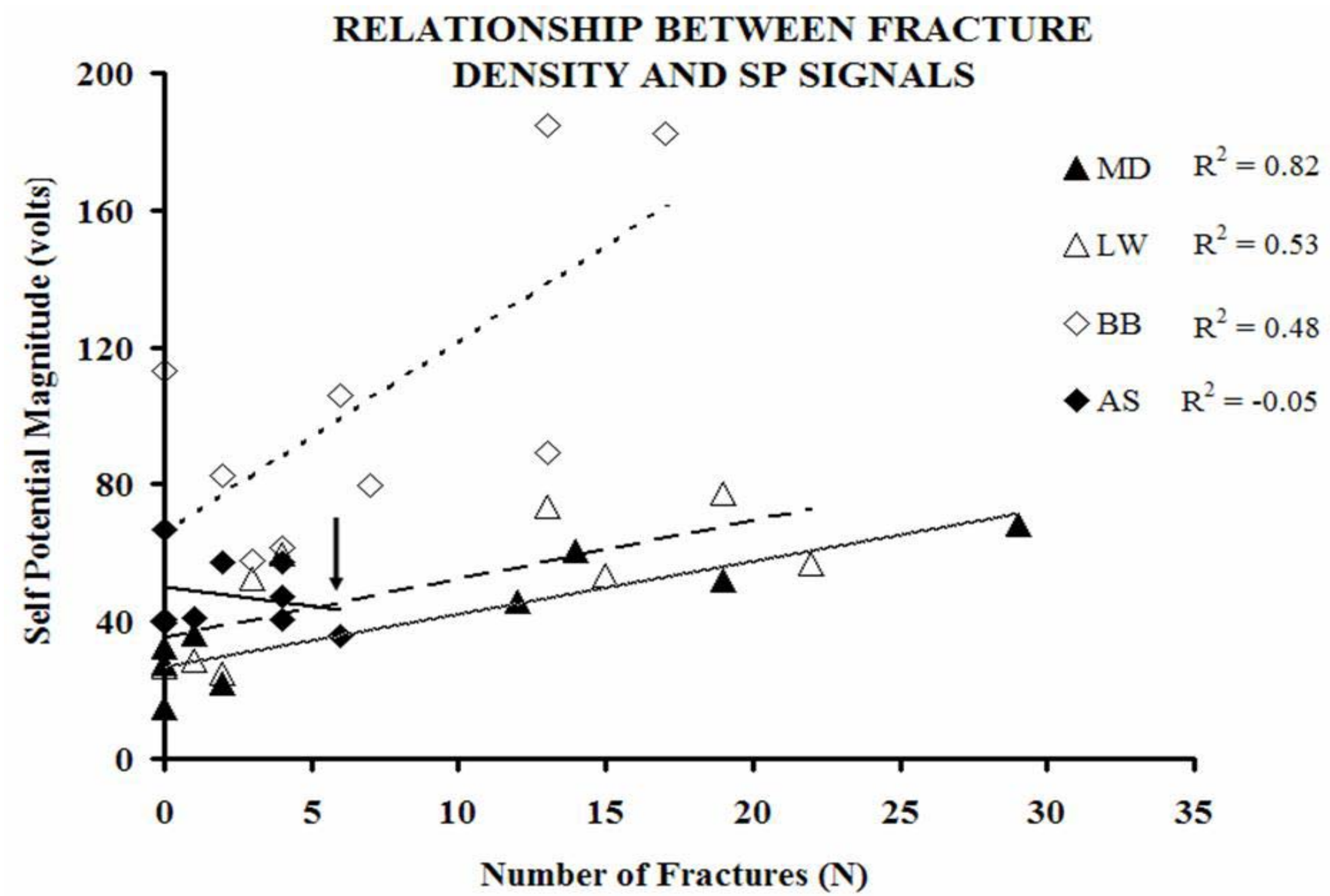
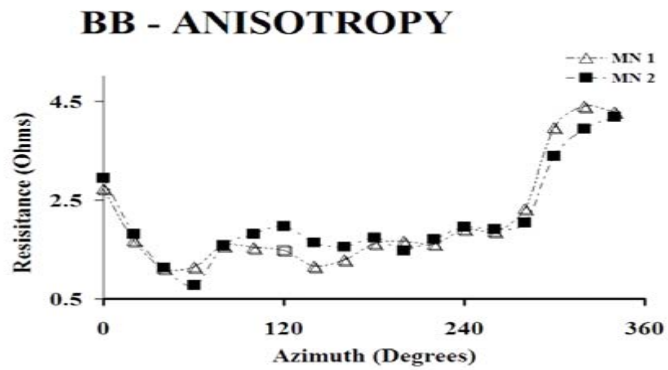
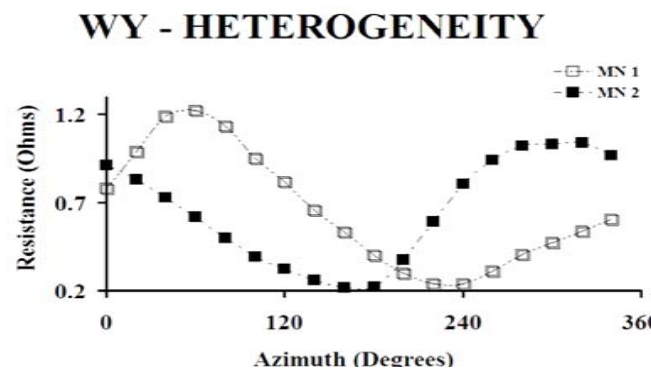


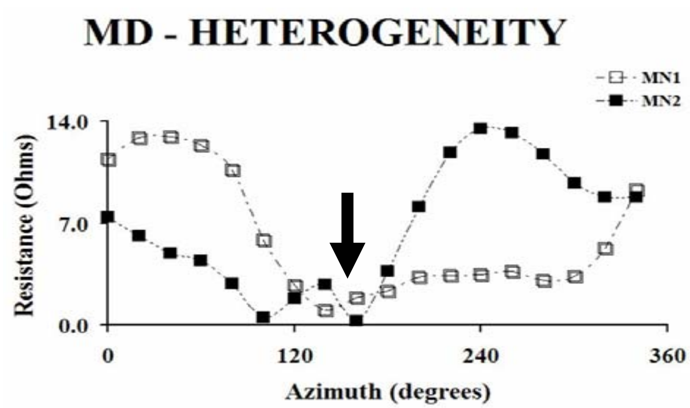
FIGURE 7. Linear relationships between the number of fractures and the intensity and direction of the SP signal at the MD, WY, BB, and AS sites. Higher R^2 values are observed for the sites where fractures outcrops are extended onto or close to the targeted field sites.

(a) **(b)**





(c) **(d)**



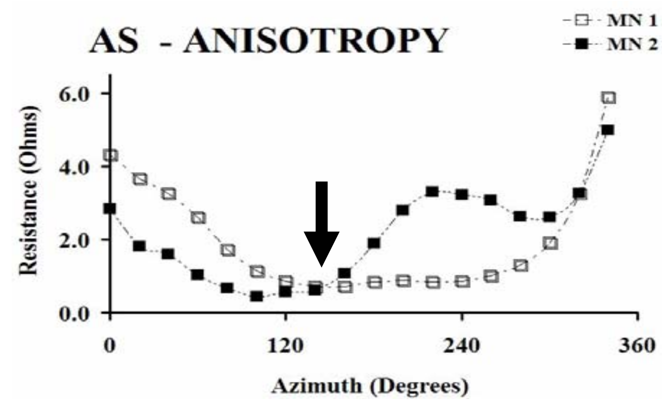


FIGURE 8. Graphs illustrating quantitative distinction of **(a)** electrical anisotropy at the BB site, and **(b-d)** electrical heterogeneity at the MD, WY, and AS sites by comparing the values of electrical resistance measured at both MN pairs for each current injection at 20º steps throughout 360º azimuth. [Anisotropy causes similarity in both resistance (MN) curves, whereas disparity in the MN curves signifies heterogeneity].

(a) **(b)**

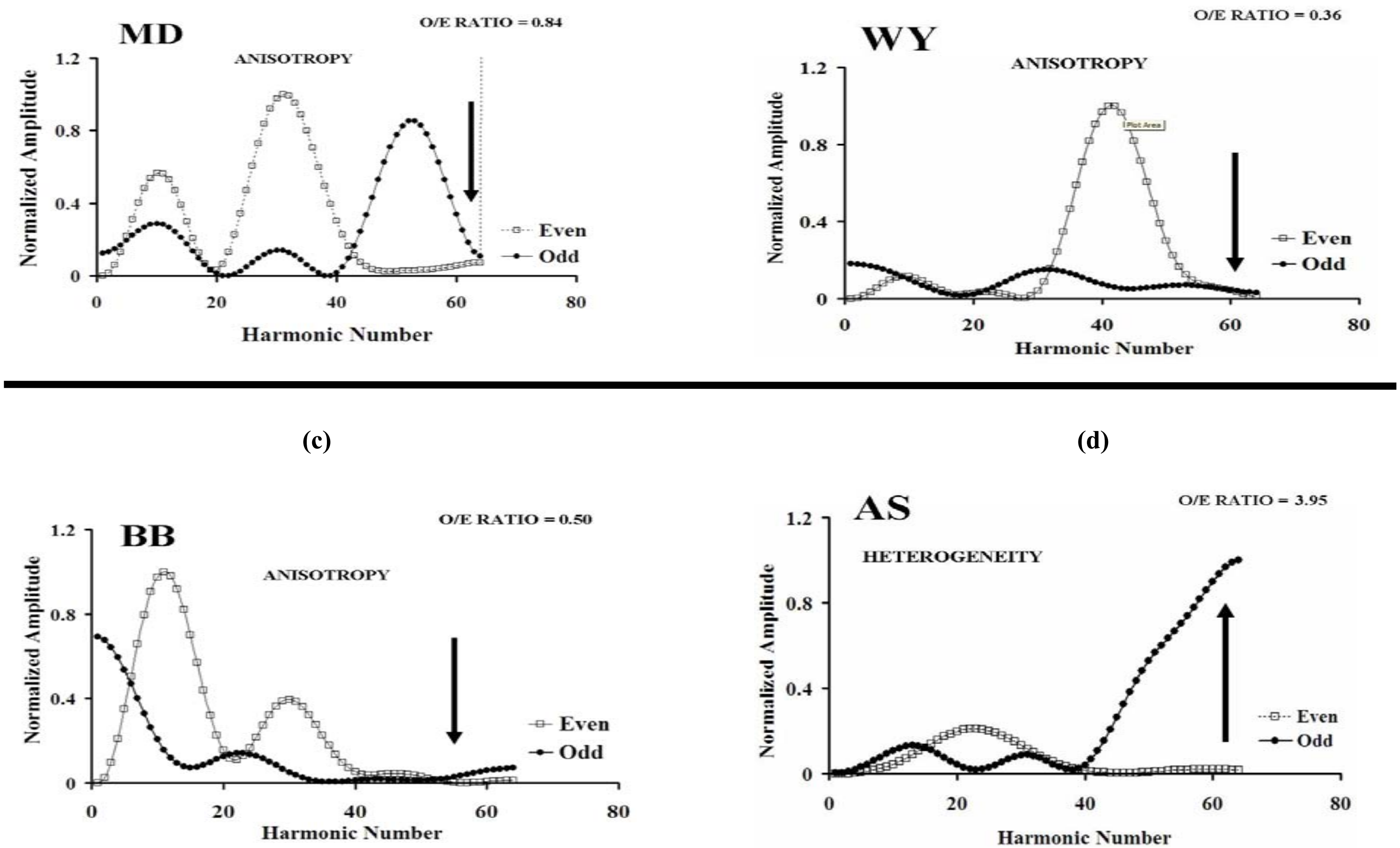


FIGURE 9. Graphs illustrating quantitative distinction of **(a-c)** hydraulic anisotropy at the MD, WY, and BB sites, and **(d)** hydraulic heterogeneity at the AS sites from transformation of the SP data using a Fourier series. An O/E ratio < 1.0 indicates anisotropic flow and an O/E ratio > 1.0 indicates heterogeneous flow at the field site. [Upward pointing arrow shows the increase in the energy of the odd harmonics.]

TABLE 1. Electrical and hydraulic anisotropy characterization of bedrock fractures at four field sites in the New Jersey Highlands (NJH) Province.

Site	Fracture Orientation (Azimuth)	Fracture Density[2] (fractures/meter)	O/E Ratio (K[1])	Flow[3] Characterization (Hydraulic)	Resistivity[4] Characterization (Electrical)
BB	010º - 030º 280º - 290º	6.0	0.50	Anisotropic	Anisotropic
WY	300º - 310º 350º - 010º 050º - 060º	3.0	0.36	Anisotropic	Heterogeneous
MD	310º -320º 050º -060º	12.0	0.84	Anisotropic	Heterogeneous
AS	290º - 300º 310º - 320º 010º - 020º	2.0	3.95	Heterogeneous	Heterogeneous

[1] O/E ratio determined from Discrete Fourier Transform (DFT) analysis of the 'odd and even harmonics' of the energy spectra associated with SP data sets.
[2] Fracture density based on 60 cm counting grid placed over fracture outcrops at field sites.
[3] Site hydraulic anisotropy characterization based on the energy spectra for SP data sets.
[4] Site electrical resistivity anisotropy characterization based on comparison resistance curves measured between potential electrodes $MN_1 – MN_2$.

Recent laboratory data shows that the polarity of the SP anomaly associated with a fracture set indicates the direction of groundwater flow within the fracture set.[24] Limited data obtained from these sites (primarily surface water flow directions) is consistent with this being borne out at these field sites, which is a very exciting result. These data suggest simple field-scale electrical measurements can define not just hydraulic anisotropy, but delineate the direction of groundwater flow. These results show the distinct differences between ARS and ASP surveys and highlight apparent advantages of ASP. ARS is strongly impacted by heterogeneity and it is interesting to note that this may be related to structures that also impart anisotropy (e.g. fault zone at the anisotropic site). Based on observance of a strong correlation between the fracture network and presumed hydraulic anisotropy, ASP appears more intimately connected to hydrogeology than ARS. In conclusion, preliminary field measurements in a fractured rock environment suggest that this work could improve the characterization of fracture systems in bedrock aquifers and promote understanding of regional groundwater resources in fracture-dominated systems required for the design of groundwater remediation strategies.

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