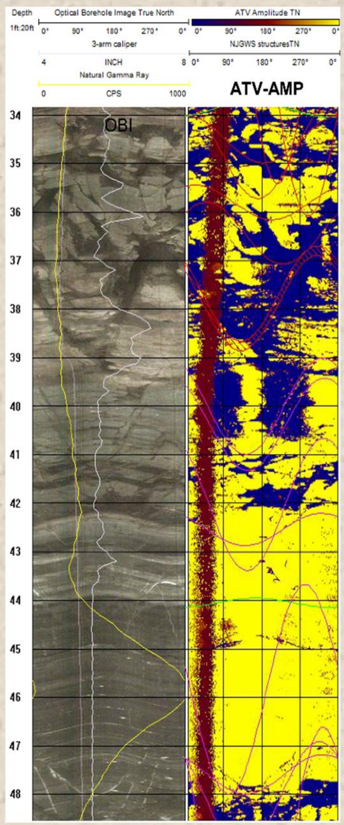


SHALLOW SUBSURFACE GEOPHYSICAL APPLICATIONS IN ENVIRONMENTAL GEOLOGY

Field Guide and Conference Proceedings

EDITED BY

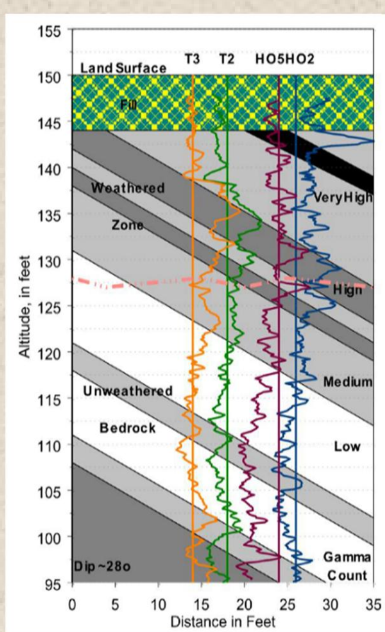
Michael P. Gagliano

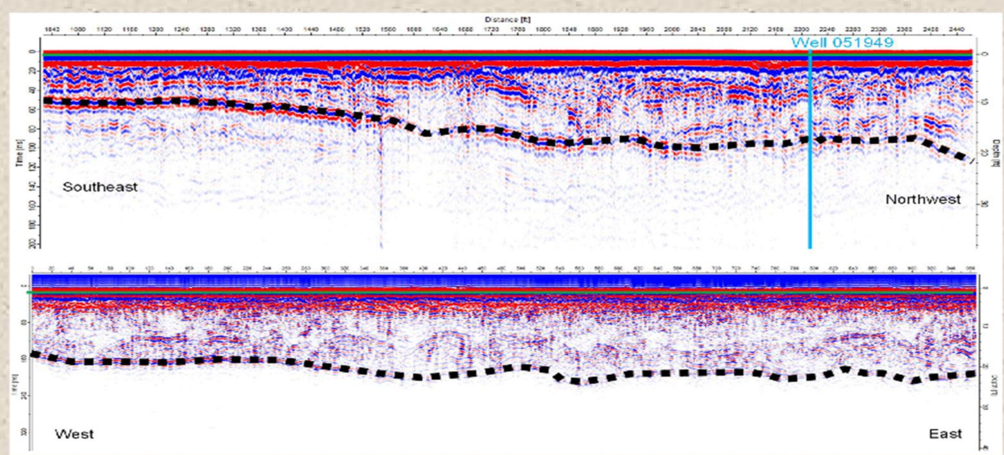
New Jersey Geological and Water Survey

and

Suzanne Macaoay Ferguson

PennJersey Environmental Consulting





THIRTY-THIRD ANNUAL MEETING OF THE GEOLOGICAL ASSOCIATION OF NEW JERSEY

OCTOBER 14-15, 2016

THE NEW JERSEY STATE MUSEUM
TRENTON, NEW JERSEY

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TEACHERS WORKSHOP

2D and 3D Fractured-bedrock characterization methods using oriented borehole imagery

Fern Beetle-Moorcroft, Gregory C. Herman, Michael P. Gagliano, Michelle E. Kuhn, and Mark A. French, NJ Geological & Water Survey, Trenton, NJ

Introduction

GANJ 33 provides an appropriate venue to share the methodology used by staff at the NJ Geological & Water Survey (NJGWS) to characterize geologically complex fractured-bedrock aquifer systems in New Jersey. The NJGWS staff utilizes a combination of subsurface geophysical log data, including optical, and surficial outcrop data in order to measure and accurately portray crosscutting geological feature relationships. This allows for the identification of permeable planes, the conduits along which groundwater flows through fractured aquifers. This workshop focuses on specific personal-computing (PC) software and the methods currently used by the NJGWS to manage and visually characterize subsurface borehole televiewer (BTV) data and outcrop data in complicated geological settings. Specifically, this workshop details the key concepts used to interpret BTV and outcrop data for establishing local hydrogeological frameworks for groundwater supply and pollution work. Prospect Park Quarry, Paterson, NJ is used as a case study to exemplify this methodology.

The first portion of the workshop serves as an introduction to 'structural-feature relative-density profiling' – a profile structural-interpretation method developed by the NJGWS staff. The process involves: 1) the delineation and characterization of visible features in BTV data in WellCAD, 2) the organization of features in Microsoft (MS) Excel, 3) the analysis of features in GeOrient 9.5, and 4) the creation of a 'structural-feature density profile' (Google Earth and MS PowerPoint). The final profile portrays the most common feature orientations in their relative proportions using apparent dip. When combined with surface-borne geological constraints, this method can be used to portray plausible and constrained profile representations of complexly fractured aquifer systems as seen in Chapter 5 (Herman, 2016).

The second portion of the workshop involves using the 'Excel to KML Formatter,' a customized, online tool, to facilitate the three-dimensional (3D) visualization of subsurface data using Google Earth (GE). This tool takes 2D and 3D geological symbols, created in Trimble Navigation's SketchUp Software, and allows the user to define the locations and orientations of features. Thus, the use of the tool and GE renders BTV data into a malleable 3D well field model that can be dynamically viewed and analyzed. As GE does not allow exploration of the subsurface, subsurface features, such as well data, must be lifted above ground for viewing. This allows for the direct comparison of features in multiple wells and visualization of common planar orientations. The concluding activity involves exploring data from Park Quarry in GE.

Prospect Park Quarry: An Ideal Case Study

Prospect Park Quarry (PPQ) is located in Prospect Park, Passaic County, New Jersey and was the first Watchung basalt trap rock quarry (Figure 1). The quarry first opened in 1901 and was fully operational until a few years ago (The Mineral Industry of New Jersey, 1910). Currently, the quarry is being filled in preparation for building a new housing development. At the present time, PPQ represents an ideal case study for fractured bedrock aquifer systems because: 1) there are three monitoring wells varying in depth in close proximity to the quarry pit, 2) the formation contact between the basalt and the sedimentary unit is present in the well records, and 3) there is ample exposed bedrock (Figure 2). The presence of multiple wells in close proximity to one another allows for data from a range of depths and greater potential for correlation of features between wells. The presence of a formation contact allows for the creation of a more accurate geologic cross section. A large amount of exposed bedrock on all sides of the quarry pit allows for documentation of a large number of features and changes in stratigraphy.

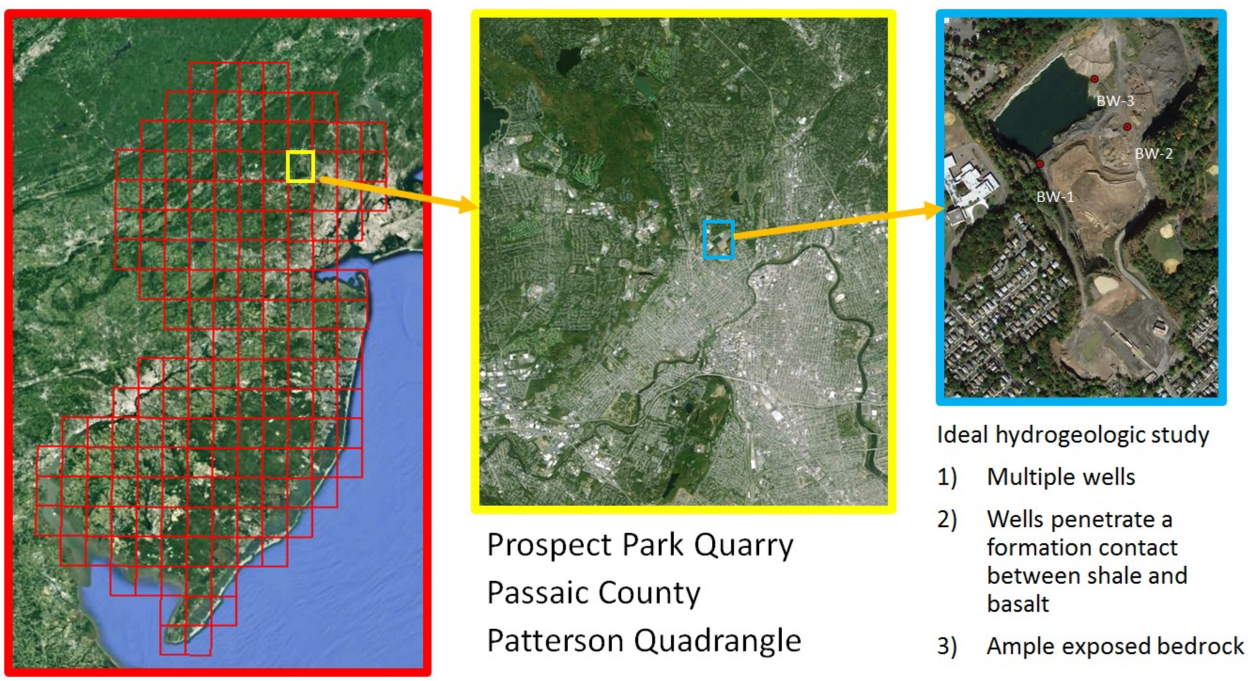


Figure 1: gives geographic context for the location of Prospect Park Quarry within the Paterson Quadrangle and the state of New Jersey.

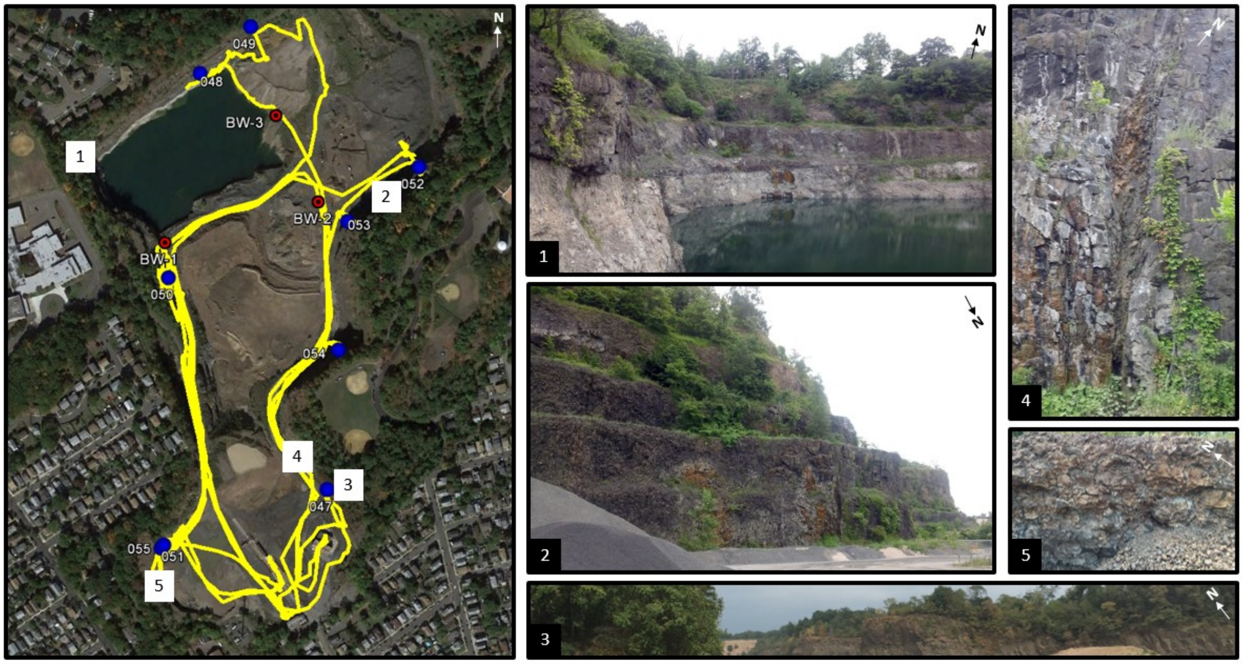


Figure 2: shows a birds-eye view of Prospect Park Quarry on the left. The yellow path is a GPS track for one site visit. The numbered boxes represent the location of each photograph taken in the quarry. 1) shows the abandoned quarry pit, which has subsequently filled in with water, 2) depicts the reddish plumose structures, 3) is a panorama along the top of the quarry, 4) shows the fault (Figure 15) from down strike, and 5) is an image of the pillow basalts.

Geological Analysis of Borehole Televiewer (BTV) Data

Borehole Televiewer Data (BTV) data provides a lens into the subsurface, as well as, access to quantifiable structural data in situ and at depth. At the NJGWS, through years of working with BTV data, we have developed a clear and concise method for transforming raw BTV data into a ‘structural-feature, relative-density profile.’ Each of these steps is outlined in detail below.

Raw BTV/OPTV Data

Borehole imaging began in the 1950’s using rigged photographic cameras and evolved into first generation optical imaging devices by the 1980’s (Lowell and others, 1999). Today, the NJGWS utilizes an optical televiewer (OPTV), which provides a continuous, orientated, detailed, color image of the borehole substrate (Figure 3A). The OPTV captures 360° stacked photographic rings in geographic alignment collected at 1mm depth intervals. Once captured, the 360° image is then unrolled in WellCAD to occupy a 2D surface, causing features to resemble ‘V’s’ where the amplitude indicates the dip and the trough shows the dip direction (Figure 3B). OPTV data is incredibly powerful and informative, but can at times be an overwhelming amount of information to analyze. Thus, it is important to break down the information using a methodical, time-tested approach such as the one described below. In order to make learning the process as simple as possible, useful shortcuts and tips are included.

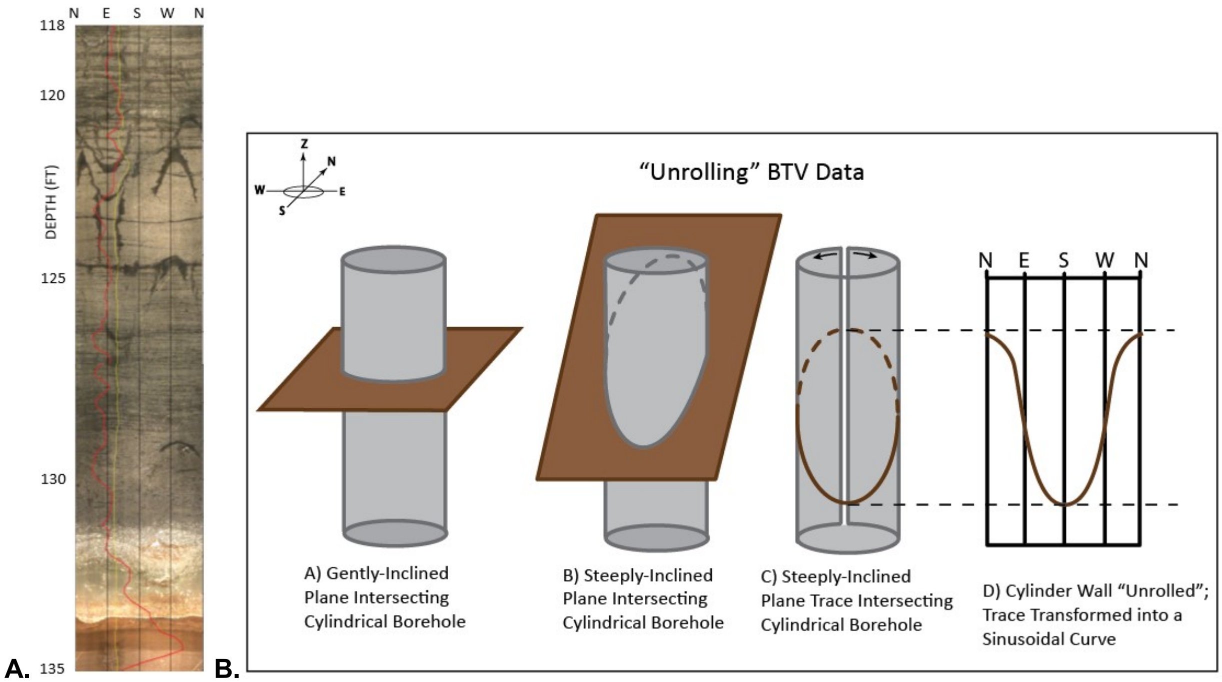


Figure 3: A) OPTV example image excerpt from Well #2 at PPQ from 118-135 ft depth. The features present resemble 'V's'. B) Schematic diagram illustrating how cylindrical BTV records are processed by 'unwrapping', flattening, and transforming borehole data. The trough of the trace (or bottom of the 'V') gives the structure dip azimuth. Higher dips correlate with sharper V's.

Pre-Analysis Corrections: Telemetry, True North, and Interpolation of Bad Traces

Prior to analyzing and quantifying features it is essential to apply a few corrections. Boreholes tend to be slightly tilted from vertical and drift more from vertical with increasing depth. Borehole telemetry is influenced by both rheological contrasts in adjacent lithologies and variations in the crustal stress regime with depth from lithostatic loading. Since feature measurements assume borehole verticality, a telemetry correction for structural measurements is needed to account for drift in boreholes generally deeper than a couple of hundred feet (Herman and Curran, 2010). The telemetry correction relies on incremental sampling of the borehole azimuth (direction) and borehole tilt (Herman et al., 2015). No example is provided here as the wells at PPQ are all less than 250 feet deep.

When captured, OPTV images are automatically oriented to magnetic north and thus, must be rotated by 12.5° counterclockwise to match true north. Additionally, 1mm increments are sometimes missing from the record and can be fixed by interpolating bad traces, which joins both sides of the image to remove small gaps.

Classification of geological structures

The creation of a detailed classification scheme is the first step in rendering BTV data into an interpretive geological cross section. At NJGWS, we categorize features in WellCAD using the geological and hydraulic variables specified in Figure 4. Features are classified first by their type (primary or secondary) and then by a series of additional characteristics (kind, sense, permeable, and altered).

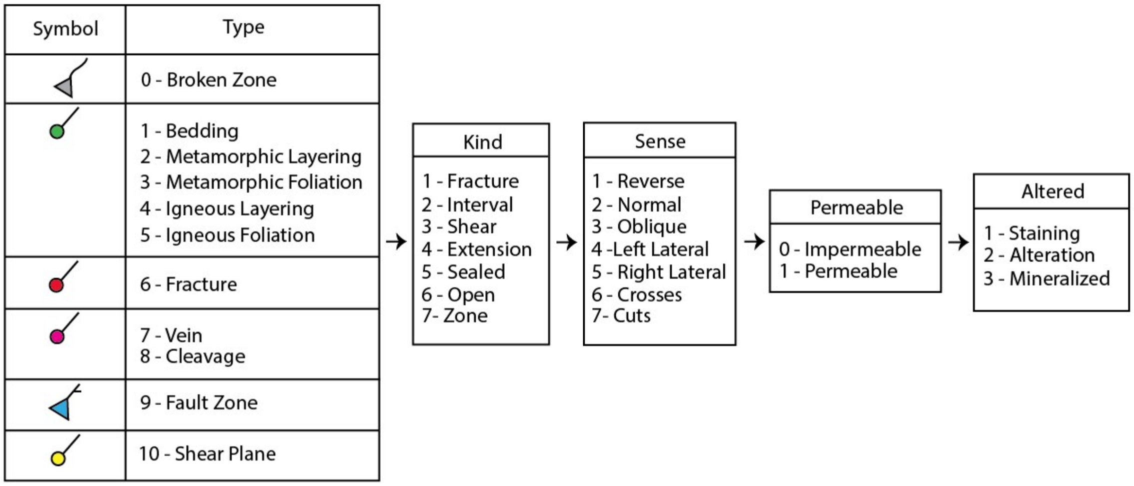


Figure 4: depicts the NJGWS Geological Classification Scheme used in WellCAD. Features are classified in the following order: type, kind, sense, permeable, and altered.

Primary features are depositional features and indicate paleohorizontal. Examples of primary features are: bedding and igneous/metamorphic layering. Secondary features are post-depositional and caused by paleo-stresses. Examples of secondary features include: 1) unhealed fractures lacking visual evidence of secondary minerals cementing fracture interstices, 2) healed fractures (i.e. veins) having cemented or partially cemented interstices, and 3) faults showing evidence of structural shear or slip (i.e. kinematic motion). Whether a fractured-bedrock aquifer behaves *isotropically*, equivalent to porous media, or with layer-controlled hydraulic anisotropy depends on the bulk heterogeneity. The identification and classification of features assists with determining the bulk heterogeneity.

Additional characteristics are organized into the categories of kind, sense, permeable, and altered (Figure 4). Kind is a descriptor for the type and mainly assists with describing secondary features. E.g. a fracture can be given kind: interval, shear, extension, or open to describe the state of stress of its formation. Similarly, a fracture in the orientation of bedding (i.e. a reactivated bedding plane) can be given type: bedding and kind: fracture. Sense relates to fault type (e.g. reverse, normal) and movement (oblique, right lateral, left lateral). Permeable provides the opportunity to note if a particular feature is permeable. Altered relates to hydrothermal alteration of the protolith (i.e. staining, mineralization).

Figure 5 provides example features present in the OPTV record from BW #1 at PPQ and shows how they were classified. The first feature in green is an example of a reactivated, impermeable, igneous layering plane. The second feature in red is an open, impermeable, fracture. Once all of the features are marked and classified, the data is exported as a comma separated values (csv) file.

The csv file is then opened in MS Excel and sorted A-Z by type. The csv file uses the number values above in Figures 4 and 5 to define the type (i.e. bedding =1; igneous layering =4; fracture=6) and additional characteristics. At NJGWS, we change the numbered categories to descriptions (e.g. change type: 1 to type: bedding) for record keeping purposes. Once we have edited the structural data in MS Excel, we import it back into WellCAD as a comments log. This allows a reader looking at the log to see the analytical description of each feature. We also copy the feature orientation data into text files for each unit, separating primary features (i.e. bedding, igneous/metamorphic layering, and igneous/metamorphic foliations) and secondary features (e.g. fractures, veins, cleavage, fault zone, and shear plane) for ease of analysis in GEOrient 9.5.

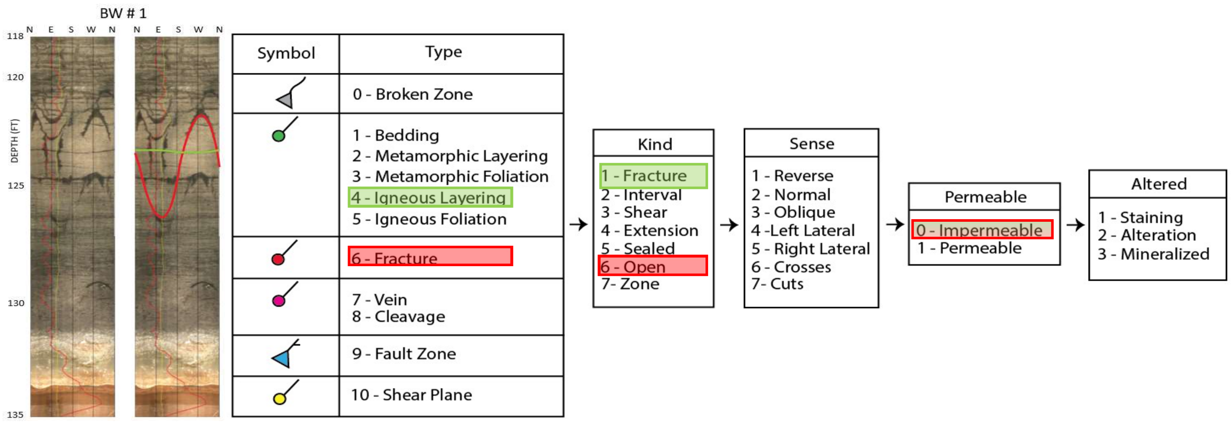


Figure 5: shows two features chosen in WellCAD along with their classifications.

Structural analysis using GEOrient 9.5 stereographic and histogram plots

Now that we have delineated and precisely characterized all of the features present in the BTV record, we begin our next level of analysis – determining the frequency of each type of feature orientation. Software that includes stereographic and histogram plots is ideal for this type of analysis. At NJGWS, we use GEOrient 9.5 to create a rose diagram (circular data frequency dip azimuth histogram) and equal-angle, lower-hemisphere stereonet projections – contour plots and cyclographic plots to analyze structural trends (Holcombe, 2011). Each plot is created separately for primary and secondary features in each rock unit (Figures 6 and 7). Specifically, these plots are used to determine the mean orientation(s) of primary features and the five most common secondary feature orientations. Rose diagrams show the relative dominance of each planar feature and provide a mean resultant direction (dip azimuth), which is particularly useful for discriminating between features having similar strike, but opposing dips (Figure 6A). This is pertinent for understanding the patterns of cross bedding seen in alluvial systems (see Chapter 5) or borehole-scale folding of the geological layers. Contour diagrams show polar lines contoured based upon the density/frequency of similar measurements and are used for determining the relative percentages of bedding and fracture orientations. These density/frequency maxima can then be manually selected to define up to five great circles – the five most representative planes (Figure 6B). Cyclographic plots depict the composite set of measurements of great circle traces (Figure 6C). The cyclographic plot is ideal for checking the other two plots. The most common planar orientations should match the maxima on the contour diagram the mean resultant direction from the rose diagram.

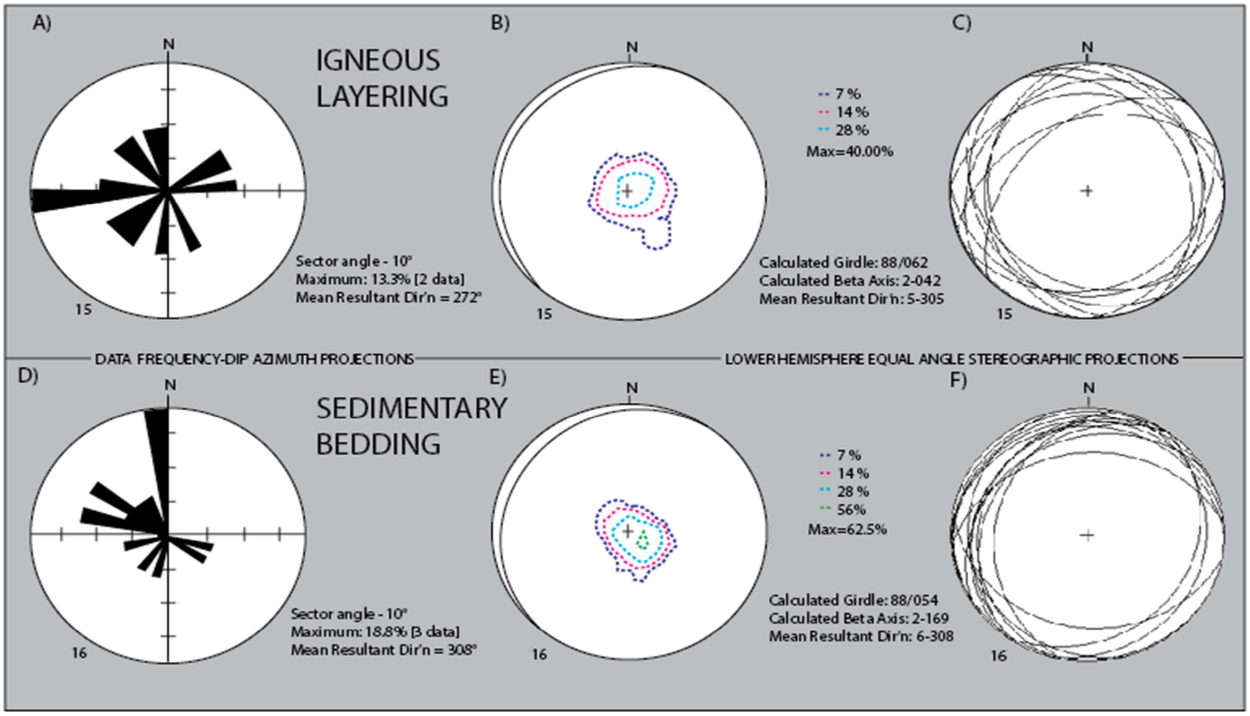


Figure 6: Stereographic and histogram plots for layering/bedding features; diagrams A, B, and C show igneous layering in the basalt unit and diagrams D, E, and F show bedding in the sedimentary unit. There is cross-bedding present in the sedimentary unit and evidence of change in the flow direction of the basalt unit. The majority of the features are shallow dipping.

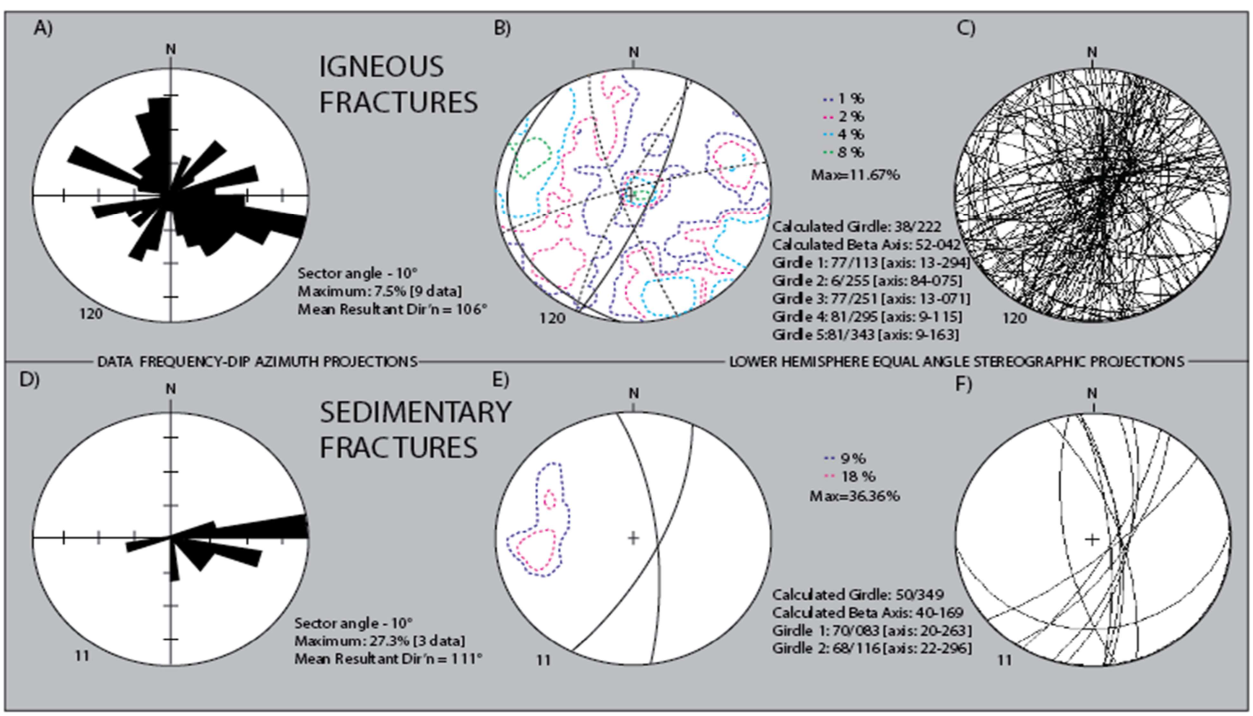


Figure 7: depicts stereographic and histogram plots for secondary features (i.e. fractures); diagrams A, B, and C show secondary features in the basalt unit and diagrams D, E, and F show secondary features in the sedimentary unit. The basalt unit is highly fractured with five main orientations present. There are fewer data points for the sedimentary unit and only two main orientations present.

Structural analysis using Prospect Park as an example

Figures 6 and 7 use data from Prospect Park Quarry to provide an example of the complexities associated with stereonet analysis and the importance of comparing multiple visual representations. Looking at the rose diagrams (Figure 6A and 6D), igneous layering has a due west maximum and sedimentary bedding has a due north maximum. This information alone suggests that the intersection of bedding/layering from the two units would be nearly orthogonal. However, the mean resultant directions of the two units are 272° and 308° respectively. This lends itself to the interpretation that there is cross-bedding present in the sedimentary unit and variance in flow direction in the basalt unit. The rose diagram provides no information about the dip of the units, whereas, the contour diagram looks at both the dominant dip and dip azimuth. Diagrams 6B and 6E have very similar dip and dip azimuths, suggesting little structural change between the deposition of the two units. The planes diagram provides the opportunity to check that the resultant planes are dominant. In this case, the mean resultant planes from the contour diagrams are dominant, but only slightly as a result of the cross-bedding.

Structural-Feature Density Profiling

Creation of the 'structural-feature density profile' is the next step in displaying subsurface structural trends. This process is used to develop geologic profiles including the orientations of the most representative structural planes. This approach can be used for outcrop and/or BTV data and utilizes the apparent dips of each representative plane determined from stereonet analysis. The first step involves choosing an ideal cross section location. The profile trace should be normal to stratigraphic layering and in close proximity to collected data points (Figure 8A). This allows stratigraphic dips to be portrayed in their true orientation and data points to be easily projected onto the cross section. Once the location of the profile trace is chosen it must be drawn in GE using the ruler tool and saved as a named feature, in this case 'Prospect Park Profile'. The elevation profile is then generated by right clicking the feature in the table of contents and selecting 'show elevation profile'. A screen shot can be taken using the 'snipping tool' and pasted into MS PowerPoint (PP). In PP, the profile is traced using the second 'curve tool' and the amount of vertical exaggeration is determined (7B). Using the example of Prospect Park, the true ground distance represented is 3,690' and the actual profile line length is 4.68". In order to remove the vertical exaggeration, the total height of the profile is divided by 9.6 in the 'size and position setting'. The 1:1 scaling created Figure 8C, the true profile.

After the profile line is scaled, wells not located directly on a profile line must be orthogonally projected onto the profile at their correct elevation, not the land surface of the profile. BW#1 lies on the cross section and thus does not need to be projected. BW#2 and BW#3 do not lie on the cross section and are orthogonally projected onto the cross section from ~ 700 ft to the NE of the cross section at their appropriate elevations (Figure 9A). From the BTV analysis (Figure 10), we know that the contact separates the igneous unit above and the sedimentary unit below and is dipping 5° NW, a much gentler dip than depicted in Figure 9A. The 'Raw Geologic Cross Section does not take into account the location of the well within the stratigraphic sequence. From the data, we know that BW#2 is down dip from the cross section. The ‘Refined Geologic Cross Section’ takes this into consideration and places BW#2 at its correct place in the sequence (Figure 9B). BW#3 record is cloudy and the contact cannot be noted, so the actual location of BW#3 in the section is unknown.

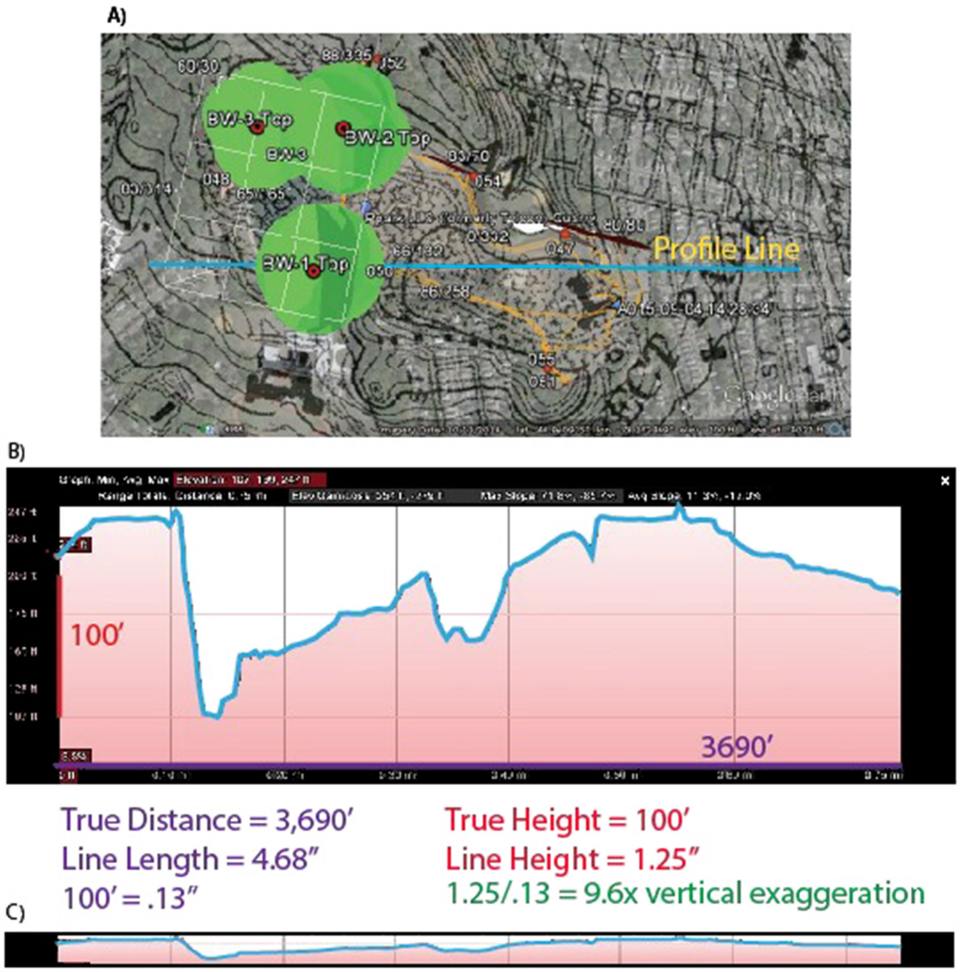
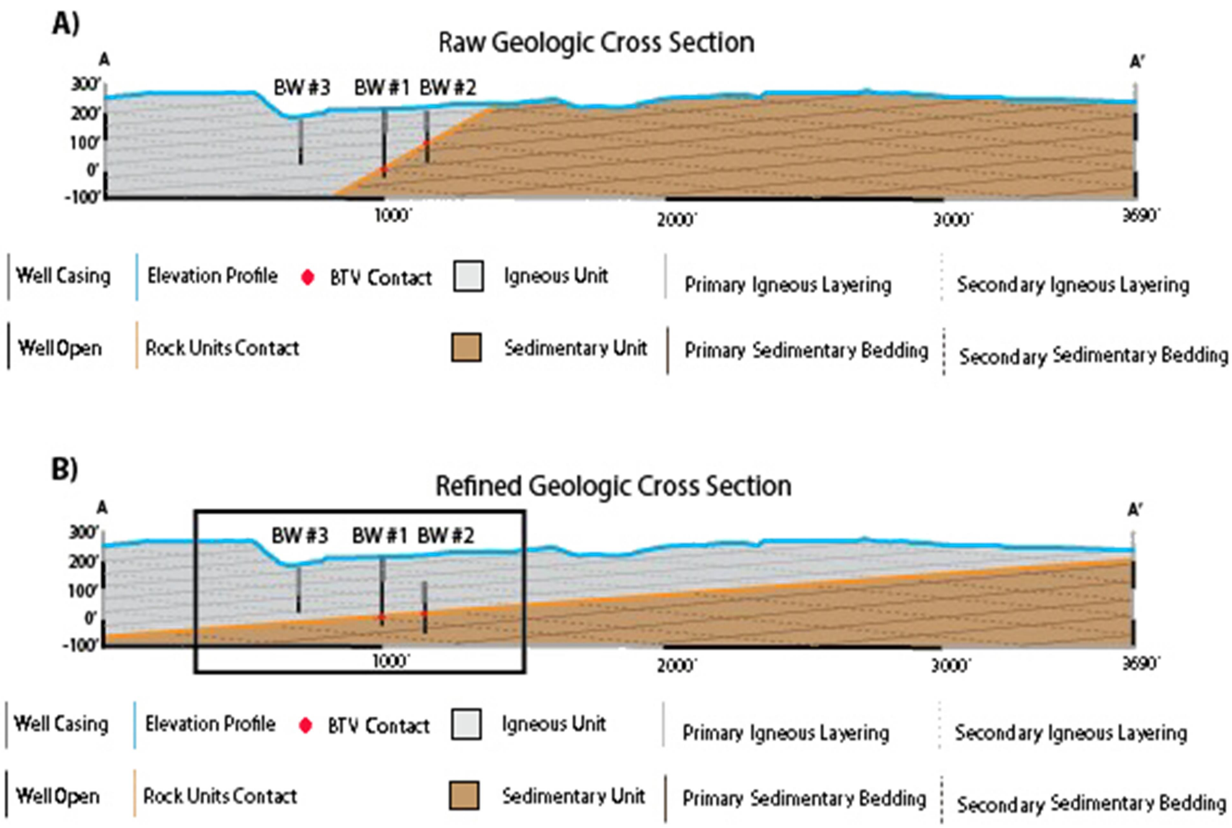


Figure 8: depicts the process of generating an elevation profile in GE and removing vertical exaggeration to create a 1-1 profile. A) shows the location of the profile line for Prospect Park, which runs through BW#1 and is located near to BW#2 and BW#3. B) depicts the cross-section generated in GE C) shows the 1-1 profile. This 1-1 profile is used later on for the geologic cross section (Figure 8) and the ‘Structural-Feature Relative Density Profile’ (Figure 10E).

Once the contact and wells have been placed on the cross section, the bedding and layering orientations – primary and secondary – must be added. These orientations are taken from the stereonet analysis (Figure 6) and apparent dip is calculated. We use this apparent dip calculator, www.impacttectonics.org/geoTools/appdipcalc.html - which uses the true dip and the deviation angle between a measured planes dip direction (azimuth) and the trend of the profile trace to calculate the apparent dip (Figure 11). For PPQ, the primary igneous layering has an apparent dip of 4° NW and the secondary igneous layering has a dip of -4° SE; the primary sedimentary bedding had a dip of 5° NW and the secondary sedimentary bedding has a dip pf -5° SE. Both units are dominated by shallow dipping



primary features and include cross-bedded features (Figure 9).

Figure 9: depicts geologic cross sections for the elevation profile shown above in Figure 7. Cross section A) is a raw geologic cross section meaning that the wells are projected onto the cross section at their approximate elevations, but structural effects are not accounted for; whereas, cross section B) is a refined cross section and accounts for the structural impact of each wells' actual location.

Once the framework of the geologic profile is complete, we generate a base unit for bedding/layering and fracture geometry. These base units include all bedding and fracture orientations in their relative abundance as determined by the stereonets and histograms. The primary and secondary bedding/layering orientations are taken from Figure 9. The fracture orientations are taken from the dominant planes determined by the contour diagrams (Figure 12A and 12B). There are effectively four dominant secondary feature orientations in the basalt unit. Three of the dominant planes each account for 8% of features and one accounts for 4% (Figure 12A). There are two dominant secondary feature planes in the sedimentary unit. Each accounts for 18% of features (Figure 12B). Figures 12C and 12D show the base units for the igneous and sedimentary units respectively. Once the base units are complete, they are transposed onto the profile and indicate relative flow pathways (Figure 12E). A higher abundance of horizontal or slightly dipping fractures indicates more bedding plane movement, whereas, a higher abundance of vertical or steeply dipping fractures indicates a greater likelihood of vertical movement and thus, greater potential contamination at depth.

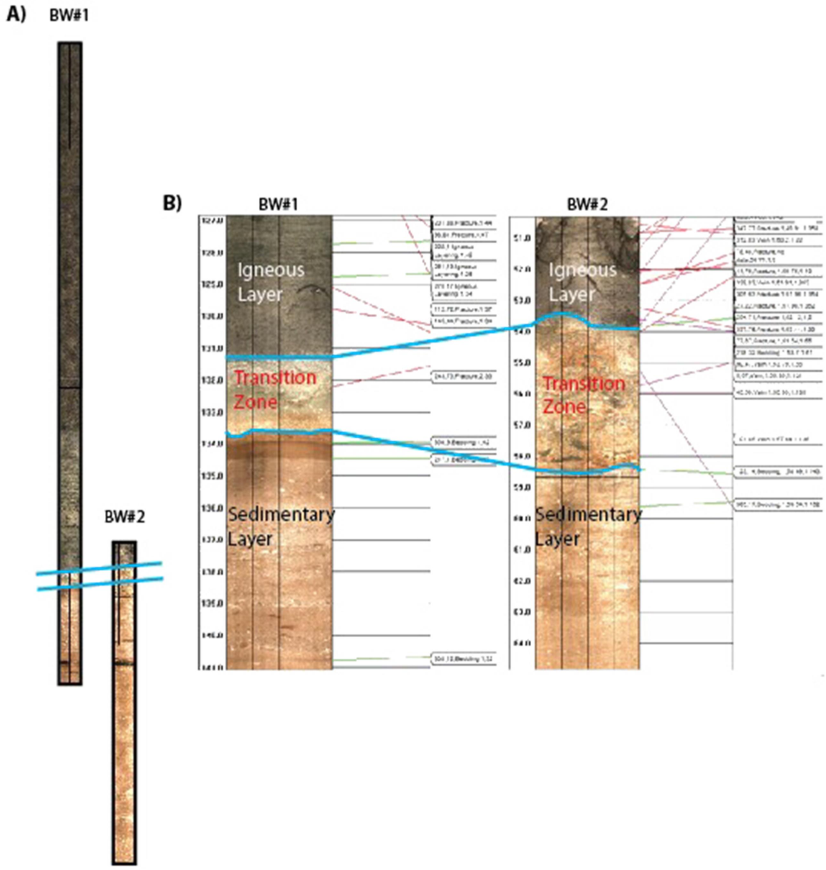


Figure 10: displays the BTV images, copied from WellCAD, for BW#1 and BW#2; BW#3 is omitted because the record is too cloudy. A) shows the full BTV record and B) shows a close up of the contact. The contact separates the dark grey igneous unit from the light orange sedimentary unit. A) shows the slope of the contact as 5°, the average apparent dip of layering and bedding in the two units. B) outlines the transition zone and shows that the same unit may not appear exactly the same.

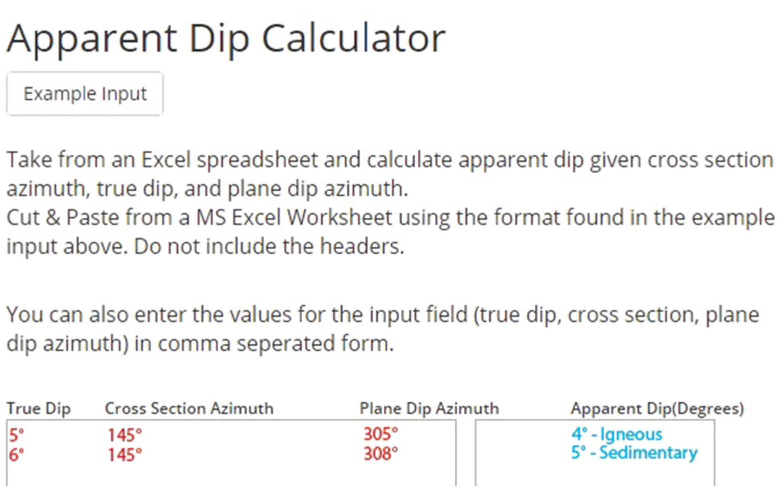
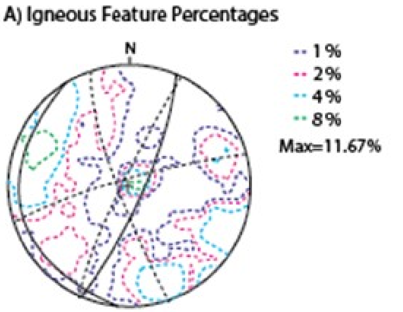
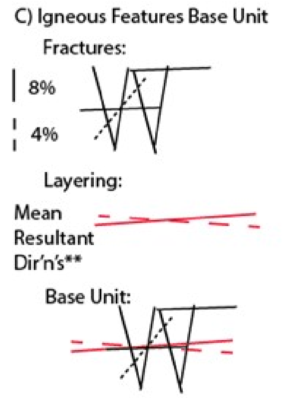
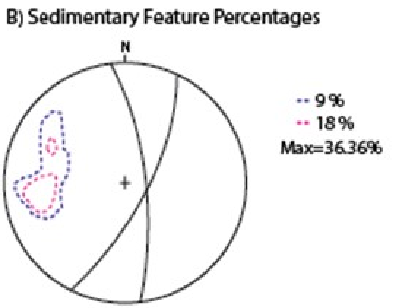


Figure 11: depicts the online apparent dip calculator used to calculate the apparent dips for the cross sections.



Girdle Maximum	Apparent Dip	Percentage
77/113	75	8
6/255	2	8
77/251	50	4
81/295	80	4*
81/343	81	4*





Girdle Maximum	Apparent Dip	Percentage
70/083	52	18
68/116	65	18

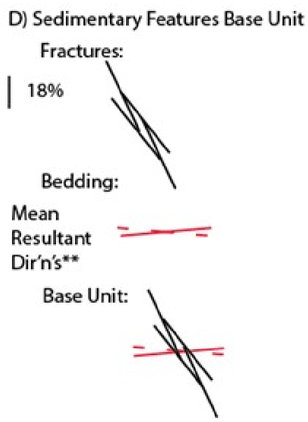
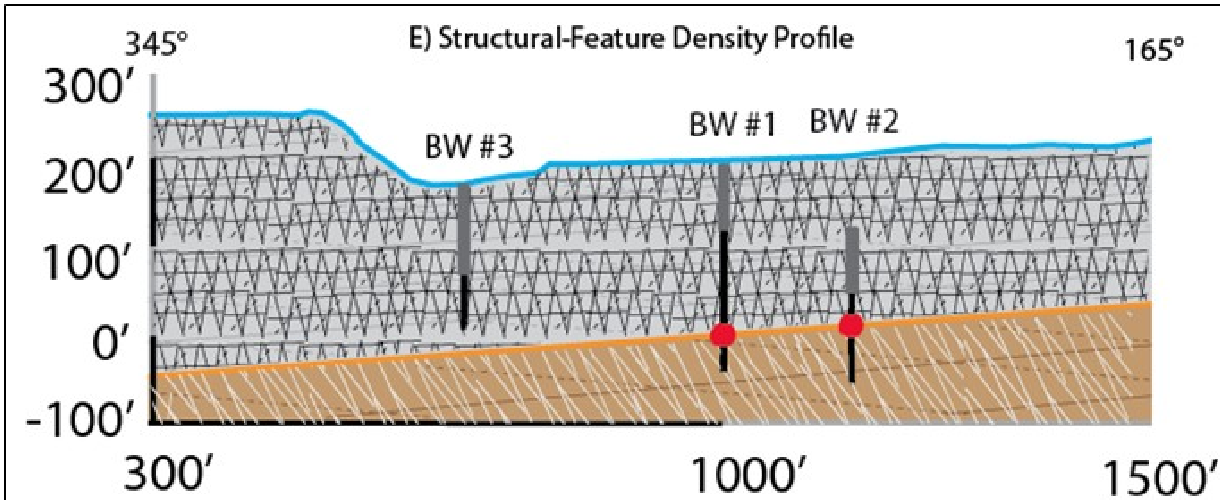


Figure 12: shows the creation of the 'Structural-Feature Relative-Density Profile'. A) and C) focus on the igneous unit and B) and D) look at the sedimentary unit. A) and B) show the stereographic contour diagrams used to determine the most common orientations. C) and D) show the base units for each rock unit. E) shows the final 'structural-feature relative-density profile'



* Girdle Maxima 3 and 4 differ in apparent dip by 1°, so these two 4% maxima were combined to create a single 8% maxima at a dip of 80.5°

** The mean resultant direction for layering and bedding were calculated using the primary features stereonet

Google Earth (GE) 2D and 3D Geological analyses

In order to aid in the understanding of geologic feature orientations and to compare features in adjacent wells or well and bedrock data, we have created 2D geologic symbols and 3D geologic models that can be placed at specified coordinates (latitude-longitude) and elevations in GE (Herman, 2013; De Paor and Whitmeyer, 2011). The 2D symbols are structural-geological symbols (i.e. strike/dip, dip/dip-azimuth, etc.) and the 3D models contain circles/ellipses with tilt that mimic the planar orientation of bedrock and/or feature data (Figure 13). The symbols are already generated in SketchUp and can be manipulated in any orientation using the online 'Excel to Kml Formatter' which can be found at http://www.impacttectonics.org/geoTools/exceltoKML.html (Figure 14).

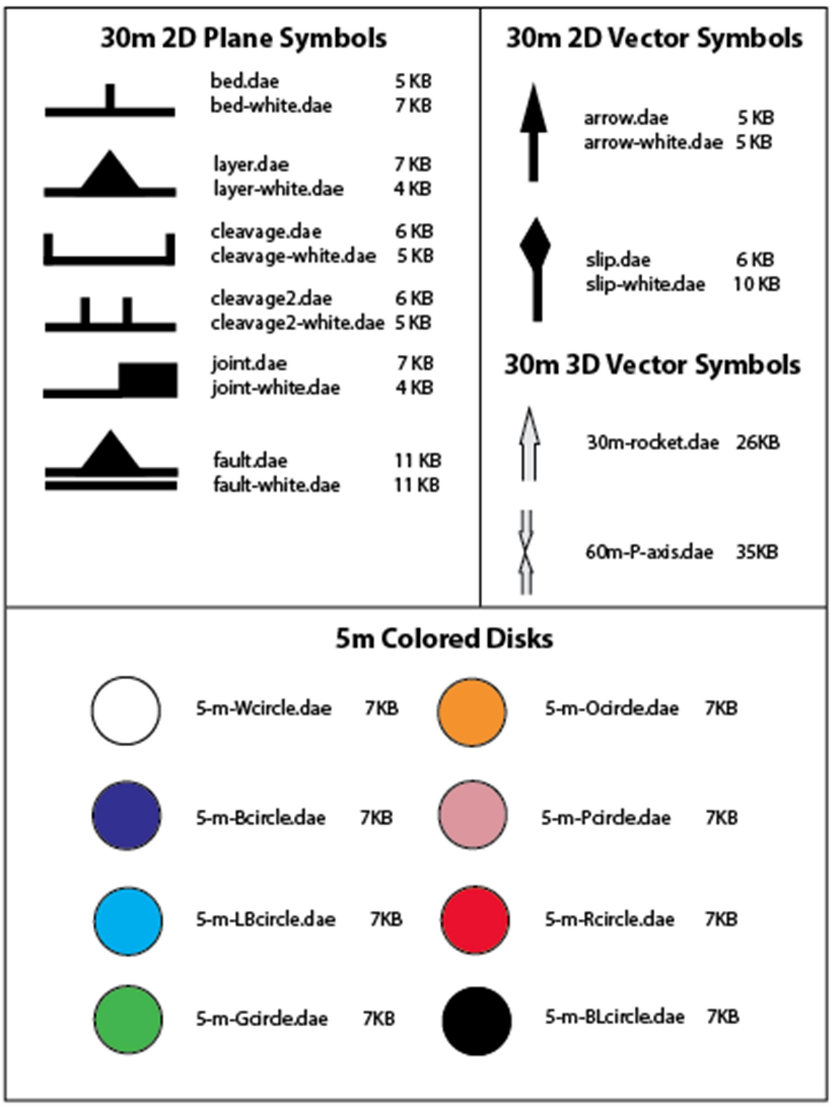


Figure 13: portrays the 2D and 3D symbols generated by the NJGWS staff in Trimble Navigation's SketchUp software for use in GE.

Before generating the symbols, it is necessary to project the subsurface data above ground (Figure 15) and to correct for telemetry (page 4). We use the following criteria to pick an appropriate high point for the model: all wells in the well field must be entirely above ground, planar features in the well should be mostly above ground (important to account for steeply dipping features near the base of the well), and wells must be placed at their accurate relative elevation (reflecting ground elevation). Outcrop feature data must be placed at the elevation of the outcrop – this can be determined using the elevation of the site as found in GE. Once these necessary corrections have been completed, the features can be generated using the MS Excel to kml tool (Figure 14). It is easiest to enter the required information in an Excel file and then copy the data into the tool. This preserves the required spacing. We typically use

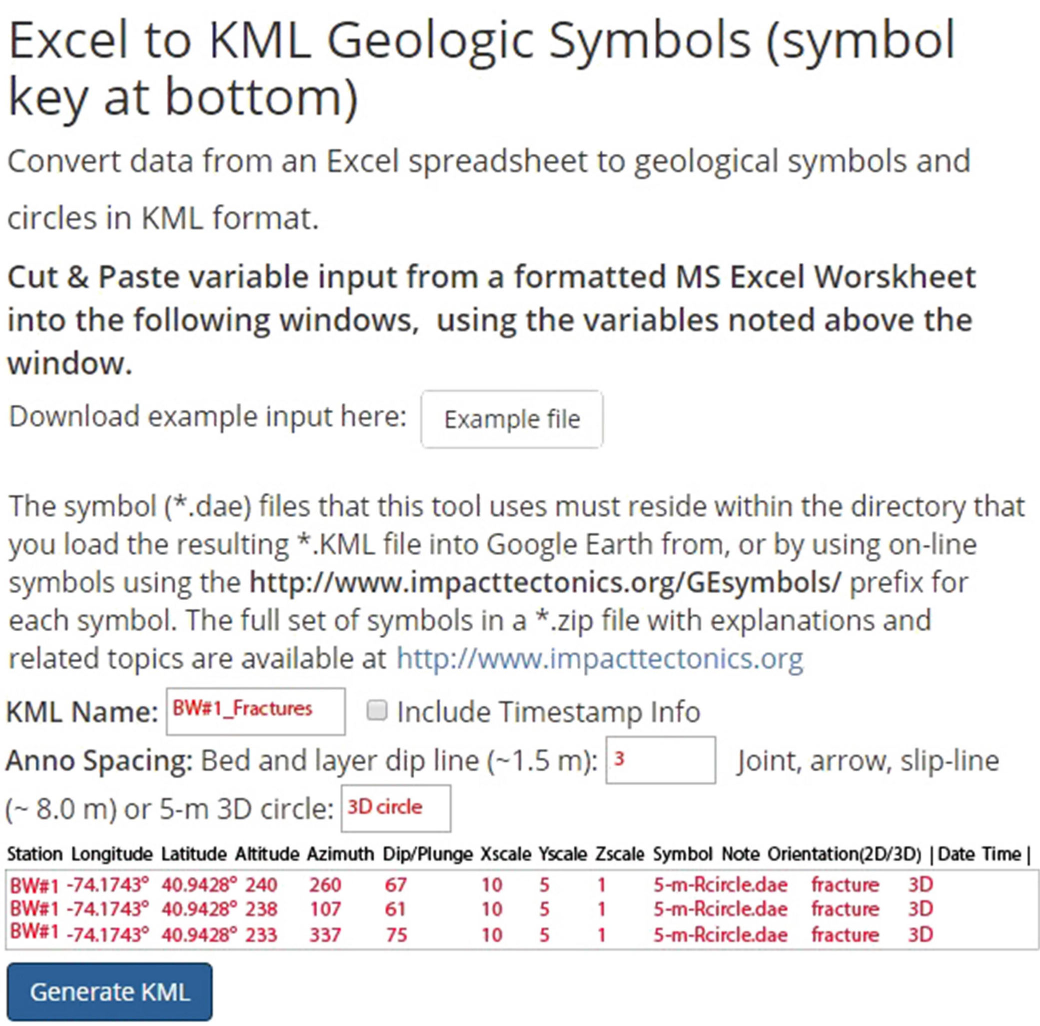


Figure 14: displays the Excel to KML tool, which converts structural data into planes in GE. The tool requires data to be input in an excel file, with each category in its own row (station, longitude, latitude, etc.) and in the proper order as shown in the diagram. The information regarding the symbol names can be downloaded from the website shown. It is important that the symbols are linked to a saved place in your directory or linked to the web using the link shown. Once all of the information is compiled it must be copied and pasted into the tool. Avoid inserting any extra spaces as this will prevent the tool from functioning properly. Finally, the "generate KML" button creates a KML file, which is automatically saved to downloads. The file is now ready for use and can be opened in GE.

different colored symbols to differentiate between bedding and secondary feature data and use the following scale for the x, y, and z dimensions – 10, 5, and 1 respectively. Sometimes, it is helpful to add additional categories to highlight a specific plane. For Prospect Park Quarry, there are two different rock units which have been coded in different colors. When working on a pollution study, it can be helpful to highlight potential fractures responsible for transmitting contaminants. To edit already generated symbols, right click on an individual plane (make sure to select the feature and not the annotations) and select properties. This opens a window with a field called “link” which lists the color of the symbol in text. Simply edit the text in the link to change the color of the desired feature. Figure 16 shows the finished floating well field for Prospect Park Quarry as an example.

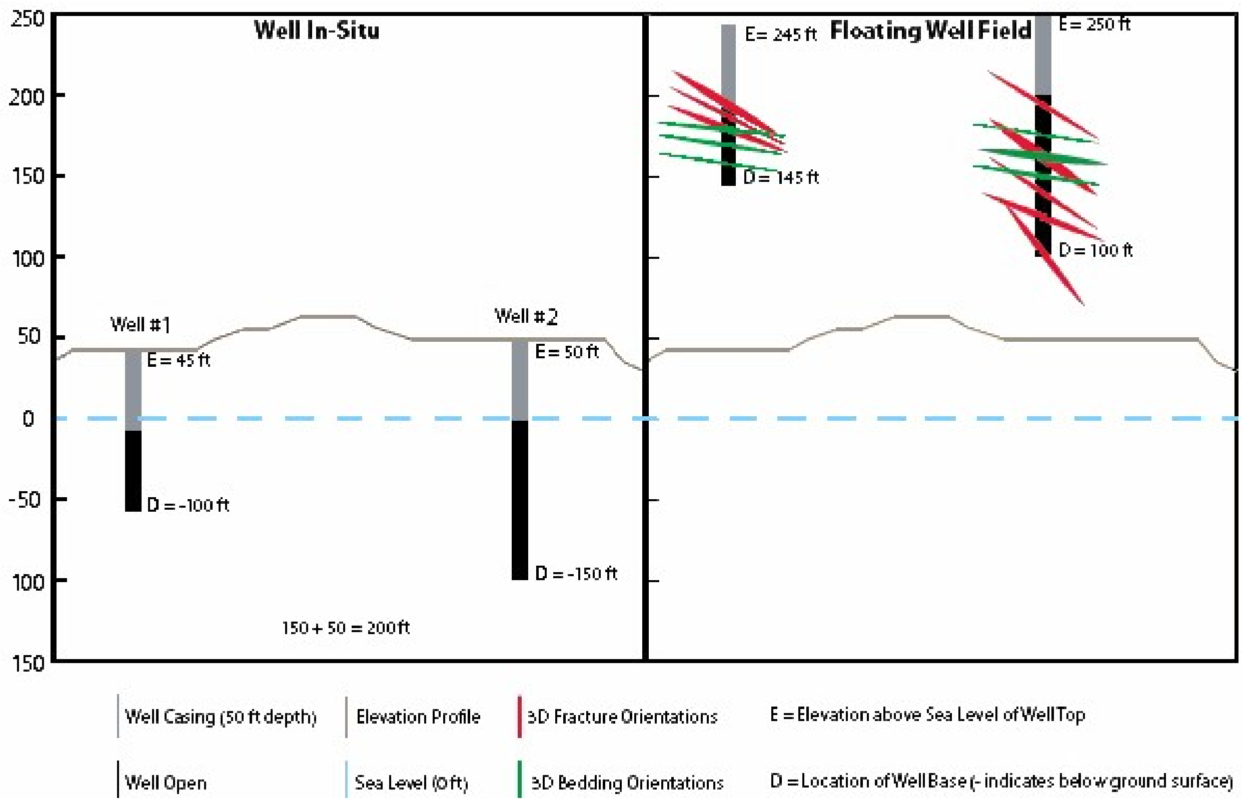


Figure 15: makes clear the translation of well data taken in situ and at depth to a floating well field model. The initial elevation and depth of well #1 are 45ft and -55ft respectively. This translated to an elevation of 245ft and a depth of 145ft for the floating well field. Well #2 had an initial elevation of 50ft and a depth of -150ft. The model for Well #2 has an elevation of 250ft and a depth of 50ft. This floating well field meets the aforementioned criteria.

Altitude Options in GE

GE Provides five options for altitude: relative to ground, relative to sea floor, absolute, clamped to ground, and clamped to sea floor. When a newly generated kml file is opened in GE; features are automatically placed relative to ground. The relative options measure from the chosen surface (meaning GE views the chosen surface as 0 ft), ground and seafloor respectively; thus, if the ground surface is 75 ft and a plane

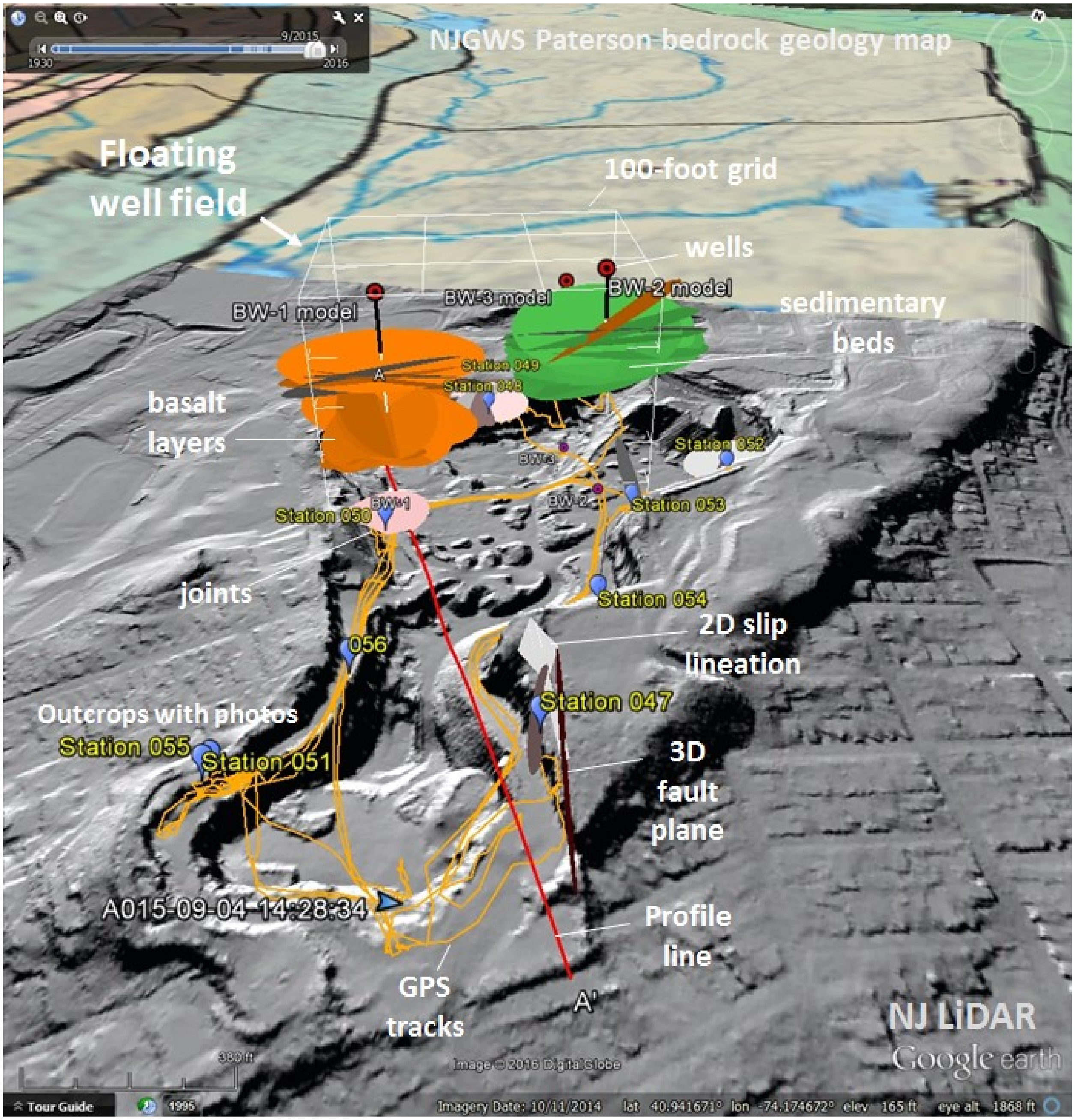


Figure 16: GE display of the NJGWS outcrop and BTV data for Prospect Park Quarry. Basalt layering is shown in orange and sedimentary bedding is in green. The cross-cutting bedding planes represents cross bedding in the sedimentary unit and multidirectional flows in the basalt. Note the offset of the bedrock ridge along the 3D fault plane, and the mismatch of layering and bedding across the projected fault zone.

is given an altitude of 25 ft, the plane will be placed at 100 total ft and 25 ft above the ground surface. The absolute option measures directly from sea level; so, if the ground elevation is 25 ft and a plane is given an altitude of 35 ft, the plane will be placed 10 ft above the ground. As our elevation profiles represent a range of ground elevations, we typically think of elevation in terms of absolute for well and/or other subsurface measurements. The clamped to ground/seafloor options place the center of the feature at ground/seafloor level. This is useful for outcrop data, where measurements are typically taken at the ground surface.

In addition to creating planes for bedding/layering and features present in well data, the Excel to Kml Tool is also useful for modeling outcrop data. Planes are generated the same way, except instead of giving the planes an absolute altitude, the planes can be clamped to the ground. Outcrop data can provide information regarding general bedding trends, unit contacts, faults, and common fracture planes. Being able to visualize this information in GE aids in quarry prospecting, in determining the extent of potential contamination, and in a more complete understanding of the area's subsurface geology.

Exercise using outcrop and BTV data to render features in Google Earth (GE)

For this conference, we have posted the outcrop and BTV data for Prospect Park Trap Rock Quarry for free download: www.ganj.org/2016/2016data.html. This data includes a GE kmz file containing: 1) a GPS track of data collection, 2) waypoints marking outcrops where structural data was collected, and 3) BTV data including Optical Borehole Imaging (OBI) for the three monitoring wells. Also included is a MS PowerPoint File, which shows the structural interpretation methods outlined above.

The goal of this exercise is to utilize MS Excel, MS PowerPoint, and GE kmz data on your laptop to practice the discussed methodology. We will present the methods used and demonstrate ways of inserting and manipulating graphics in both 2D and 3D perspectives.

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