Evaluation of Drill Cuttings for Determination of Formation Change using Particle-Size Analysis in a Water Test Well, San Diego, California

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Abstract:

The Municipality of San Diego is reliant on imported water and is in need of control over future water supplies. Outside factors affecting imported supply are of growing concern; drought, periodic cutbacks and the potential for price increases are just some of the realities that have fueled the need for the exploration of new sources. Thus, in an effort to become less reliant on imported water, the U.S. Geological Survey in cooperation with the City of San Diego has sought to investigate the feasibility of using groundwater aquifers, in particular the San Diego Formation and its overlying and underlying units as possible sources of groundwater. This study focuses on a quantitative approach to delineate these subsurface formations using drill cuttings. The analysis was conducted using digital image processing to determine grain-size distributions of samples taken at various depths in a single water test well. The data were then analyzed and correlated to asses formation changes in the subsurface. These quantitative data delineated formations that were consistent with the geophysical logs, thereby aiding in the effort to better understand the hydrogeology of subsurface San Diego. The data are consistent with the six known subsurface formations: San Diego Formation, Stadium Conglomerate, Mission Valley Formation, Poway Conglomerate, Otay Formation, and Friars Formation. Because the drill cuttings lack formation clay and silt, the sediment-size analysis is skewed to providing useful information only about the sand, granule, and pebble components of these formations.

INTRODUCTION

In 1997, the City of San Diego developed a Strategic Plan for Water Supply, in which the City concluded that it needed to become involved in the planning and development of its own water resources, primarily with the aim of reducing its reliance on imported water (Adrian et al, 2002). However, at that time, the focus was on capital improvements to existing infrastructure and not in developing its own supplies. Consequently, the City's Water Department worked to develop a water supply plan, which resulted in the creation of the Long-Range Water Resources Plan. Unanimously adopted by the City Council on December 9, 2002, the Long-Range Water Resources Plan identified water conservation, water recycling, groundwater desalination, groundwater storage, ocean desalination, marine transport, water transfers, and imported supply from the current wholesale suppliers as potential near-term and long-term supplies (San Diego County Water Authority, 2011). Currently the City uses imported water, local surface water, recycled water, and a small amount of groundwater as its supply sources (San Diego County Water Authority, 2011). The Long-Range Water Resources Plan states that groundwater resources present the potential for a promising local supply. To solve this, a broad geologic and hydrologic study of the San Diego area was needed.

USGS Hydrogeology Drilling Project

Without a study of that scope and nature, the ability for state and Federal agencies, water purveyors and consultants to develop groundwater resources would be challenging. In 2003, the U.S. Geological Survey (USGS) was approached by the City with the intention of partnering on such an endeavor. Thus, the partnership between the City of San Diego and the USGS created the San Diego Hydrologeology Project (Figure 1). The project's primary objectives are to develop an integrated, comprehensive understanding of the geology and hydrology of the San Diego area, focusing on the San Diego Formation and the overlying alluvial deposits and to use this understanding to evaluate and expand the use of the alluvial deposits and the San Diego Formation for recharge and extraction (Danskin, et al, 2012).

USGS San Diego Home and Federal Water Test Well

The USGS San Diego Home and Federal (SDHF) well is located at N 32°43'08.16", W 117°06'35.81" at the intersection of Home and Federal Avenues, San Diego, California. It is within the Pueblo Watershed (Figure 2 and Figure 3). The well site is one of many that the USGS selected for the installation of multi-depth monitoring wells (Figure 1).

Previous work on the SDHF well and its cuttings and cores have been conducted by Wesley R. Danskin, Anthony N. Brown, Adam Kjos, Eleanora I. Robbins, and other members of the U.S. Geological Survey. Paleontologist Scott Rugh analyzed invertebrate fossils to help determine the depth ranges for the San Diego Formation. Based on the available evidence, Rugh placed the range of the Upper San Diego Formation at 60 to 240 ft, and the Lower San Diego Formation at approximately 240 to 620 ft where the bottom of the Lower San Diego Formation comes into contact with the top of the cream -colored Otay sediments (S. Rugh, written comm. to U.S. Geological Survey, 2011).Wes Danskin provided the initial information regarding the specific formations and their relative depths (Figure 4). Hydrological technician and site supervisor, Anthony Brown, and hydrological technician Adam Kjos described the extraction process for sample types and provided initial guidance regarding the well construction and geophysical logs (Figure 5).

Purpose of this Research

The purpose of this report is to further the understanding of the subsurface by conducting a grain size analysis on drill cuttings and shoe samples from the SDHF well. Evaluation of the drill cuttings will be used to provide data to help establish the depths at which formation change occurs. Drill cuttings are numerous and readily available, although imperfect by definition. Their inherent imperfection comes from the drilling extraction process, which is described further in the Methods section. Although flawed, the samples allow for the addition of quantifiable evidence to be added to the well's geophysical logs. Furthermore, by comparing the drill cuttings to the shoe samples, which are less corrupted by the extraction process, the analysis should produce useful and more accurate results to aid in developing the broad geologic and hydrologic understanding required to establish groundwater resources for the City and potentially its associated cities.

MATERIALS AND METHODS

Materials and Extraction Process

The SDHF well was drilled with a USGS truck-mounted mud rotary drill rig, and completed using 2-in. diameter, schedule 80, threaded flush-joint (TFJ) polyvinyl chloride (PVC) casing in 20ft sections and screened in accordance with USGS protocols (Lapham et al., 1995). During drilling, a viscous drilling fluid, mostly comprised of bentonite drilling mud, is pumped down the center of the drilling rod, which circulates back up the borehole annulus transporting the cuttings into a pick-up pit at the surface. The drilling fluid is continuously pumped from the pit using a pick-up pump to the drilling fluid recycling system. Drill cuttings are collected throughout 20 ft. intervals from the returning drilling fluid. However, in certain cases these samples were collected at specific depths. Drill cuttings collected at specific depths are termed point samples (PS). The initial phase of the drilling fluid recycling process sieves the returning mud through a 20 mesh (841 µm) medium sand shaker screen (A. Kjos, written comm., 2012). Samples are then collected from the shaker screen and placed into 5-gallon buckets from which the study samples were taken. The fluid then continues to a secondary cleaning process referred to as "cones" where centrifugal force is used to remove the fine grained component and is then recirculated back down the center of the drill rod (A. Kjos, written comm., 2012).

When collecting shoe samples, a Christensen 94 mm wire-line coring system is used (A. Brown, written comm., 2012). A 5 ft core barrel is loaded onto the system with a plastic liner and then lowered to depth. Drilling continues for a core interval of 5 ft, and the core is retrieved. Shoe samples are collected at the very bottom of core barrels. The shoe samples are then collected for particle processing (A. Brown, written comm., 2012). The shoe is sampled from outside the liner and consequently is degraded by drilling mud. However, the drilling mud only penetrates the outside of the shoe for a few millimeters. Prior to grain size analysis, the outside of the shoe samples were scraped off in order to remove the contaminated portion.

Methods

Drill cuttings were then dehydrated and disaggregated to analyze by a digital image processing instrument, the Retsch CAMSIZER. Samples were individually fed in from the feed chute so that all particles fell individually through the measurement field. During the measurement procedure, two digital cameras simultaneously took photos of the particles as they fall. Each camera has a separate task. The basic camera (CCD-B) records large particles, while the zoom camera (CCD-Z) records the small ones (Retsch, 2004). The particle images are optically recorded, digitized and processed in the attached workstation. The resolution capability of the CAMSIZER is to the micrometer range. Specifically, the bottom range is 31 micrometers, which is in the range of medium silt. This means that detailed studies can be undertaken even on very fine or multimodal particle size distributions (Retsch, 2004).

The computer attached to the CAMSIZER outputs a spreadsheet in which data are grouped into grain size classes thereby providing detailed information about percent sediment retained and percent passing. The exact number of grains in each class is not counted; rather the weight percent of the sample within each class is recorded. Each of the drill cuttings was run twice in order to ensure random sampling. The whole sample was run first. The second run was composed of a portion of the obtained sample divided by a Retsch Sample Divider model number PT 100. The composition of each fraction of the sample is thought to correspond to that of the original bulk sample (Retsch, 2004).

In this study, the standard method of displaying sediment data was used, i.e. semi -log grain size distribution (GSD) curves were plotted. Graphs were created in Microsoft Excel. The GSD curves were then compared to each other in order to assess formation change

Using the statistics generated from the GSD curves, values related to the median grain diameter (D50) and sorting coefficient (D60+D10/2) were used to help assess formation change (Table 1). The median value, or D50, is the value where half of the grain size distribution resides above and half resides below this point (Hajek et al., 2010). The sorting coefficient was defined by McLeish (1986). A well sorted sediment is one in which the grains are all about the same size. In terms of the GSD curves, well sorted samples would exhibit vertical trend lines. In contrast, poorly sorted sediment contains a variety of particle sizes, a mixture of large, intermediate and small grains, which would exhibit sloping trend lines in the GSD curves. Numerical values for both parameters are assigned directly from the GSD curves (Zhou, 2006). By assigning numerical values to such shape parameters, it becomes possible to compare grain-size distribution curves for the different depths.

Once the drill cuttings were compared to one another and preliminarily divided into groups that may or may not represent formations, the depth-related shoe samples were compared against them. A major problem with the chosen technique is that shoe samples and cuttings samples are only somewhat comparable. Shoe samples contain the fines (silt and clays) that are lacking in the drill cutting samples, so that the samples that are being described statistically are likely skewed to the coarser size fraction.

The shoe samples data were then statistically manipulated using GRADISTAT version 8. GRADISTAT was written for the rapid analysis of grain size statistics from any of the standard measuring techniques, in this case digital imaging processing (Blott and Pye, 2001). Mean, mode, sorting, skewness and other statistics were calculated arithmetically and geometrically (in metric units) and logarithmically (in phi units) using moment and Folk and Ward graphical methods (Blott and Pye, 2001). The statistical data for a single shoe that is most analogous of the GSD curves of the drill cuttings were then used to identify and add descriptive information about the formations.

RESULTS

The grain size analysis was determined for the 84 drill cuttings and 15 shoe samples. The material is representative of the entire well, from 0 ft to TD at 1640 ft.

Shoe Sample Graphs & Analysis

The CAMSIZER's output data were used to create 15 shoe sample graphs (Figure 6). These CAMSIZER data are grouped into grain size distribution (GSD) curves by their grain size classes that are represented in the horizontal axis of the GSD graphs. The vertical axis denotes the percent passing by weight. The shape of the curves described in geometric terms differentiates the individual samples from one another. For example, the trend of the sample 40-42.5 ft is linear with slight concavity between 0.1 mm to 1 mm denoting a greater degree of sand-sized particles than coarse silt or fine gravel. Shoe sample 42.5-45 ft is anomalous due to the amount of sample available for processing; this shoe sample was not used. Shoe sample 45-50 ft has a Gaussian distribution, which means that it has an even distribution of particles from coarse silt to fine gravel. Shoe sample 180-185 ft climbs steeply from 0.1 - 0.4 mm, having a large amount of fine to medium sands. Shoe samples below 180-185 ft exhibit more linear trends with varying concavities from fine to coarse sand (Figure 6).

Shoe samples were manually sieved to contrast the content of fines as measured by manual sieving in comparison to those measured analytically by the CAMSIZER. The percent fines in the shoe samples, as calculated by the CAMSIZER and by manual sieve, exhibit a large variation (Table 2). This means that fines in the shoe samples as computed by the CAMSIZER are underrepresented as the analysis proceeds. This is not unanticipated because, as previously noted, the CAMSIZER can only measure fines larger than 31 µm. Furthermore, an additional error in grain sizes is introduced because fine particles clump as they pass the measurement field (Retsch, 2004). The CAMSIZER calibration reticle illustrates how particle clumping could cause error (Figure 7).

Drill Cutting Graphs

The CAMSIZER's output data were used to create 84 drill cutting graphs (Figure 8). CAMSIZER data are grouped into grain sizes classes. Grain size class data are based on the weight percent of the sample within each size class. Thus, the graphed data are weight percent passing on the vertical axis and grain sizes on the horizontal axis. Samples labeled as 100% represent the entire sample as it was collected. Samples labeled as partial represent the second run composed of a portion of the sample, which is considered to be statistically representative of the whole sample. Numerical values for both parameters are assigned directly from these GSD curves (Zhou, 2006). The values are the effective grain size (D10), the median grain size (D50) and the ratio of the grain size that is 60 % finer by weight (D60).

Drill Cutting and Shoe Sample Correlations

The grain size distribution (GSD) graphs for the shoe samples and drill cuttings were then compared according to depth relationship. The GSD curve for drill cutting sample labeled 0-20 ft, from Figure 8, stands out with its own distinct curvature (Figure 9). Thus, it will be considered as its own group, Group 1. The GSD curve turns concave as it coarsens from fine to coarse sand with a D50 value at 0.9 mm or fine sand (Table 1). No shoe samples were collected by the drillers at this range. Therefore, no comparison can be done.

Group 2 is represented by the graphs between 20 and 200 ft depth. It is being assigned based on the visual trends of the GSD curves to the Upper San Diego Formation. Most samples between 20-200 ft below ground surface have a distinct, somewhat Gaussian distribution, or non-linear trend (Figure 8). The exceptions to the curvature are the point samples, which have far more linear trends an example of this is the point sample 80 ft (Figure 10). Its trend is linear with a slight curve as it coarsens from coarse sand to fine gravel. At that depth, coarse sand is the dominant particle size, which is consistent with the D50 value at 1.7 mm. In comparison, the GSD curves of the drill cuttings and the shoe samples show a certain degree of correspondence to one another (Figure 10). It is important to reiterate that the drill cuttings have been pre-filtered for fines thus they should be coarser than the shoe samples. Nevertheless, the GSD curves for the drill cutting sample 20 -40 ft is highly analogous to the shoe curve for sample 45-50 ft. The slight offset between the curves is due to the greater amount of fines in the shoe sample. The shoe sample 40-42.5 ft is clearly coarser than the drill cutting over this interval. Ultimately, this is an expected outcome. The shoe samples cover a smaller sampled interval, which is collected every 5 ft and have not been sieved to remove their fines; the drill cuttings are typically sampled over a 20 foot range (A. Brown, written comm., 2012).

Group 3 is represented by the graphs between 200 and 620 ft below ground surface, and was assigned to the Lower San Diego Formation. All of the samples throughout this interval have similar GSD curves, as most of the interval samples between 200 and 620 ft below ground surface have distinct linear trends with relatively little curvature (Figure 8). Notably, there is a great deal of variability that appears to be gradational through the unit (Figure 11). In comparison, the drill and shoe samples show a great deal of contrast, with none of the GSD curves of the shoe samples demonstrate analogous curvature to the drill cuttings. However, drill cutting 460-480 ft follows the trend of the shoe samples as it coarsens from coarse sand to fine gravel (Figure 11). This outcome is consistent with the limitation of the analysis, in that the drill cuttings have been filtered for fines and that the depth range of the samples does not represent the entire grouping in either the drill cuttings or the shoe samples.

Group 4, correlates with the Otay Formation, represented by graphs labeled 623.5-640 ft through 740-760 ft, and is bound by virtually identical drill cutting GSD curves (Figure 8). In comparison, the drill cuttings are clearly coarser than each of the shoe samples. However, the trends between the two samples are fairly consistent with each other as they coarsen from coarse sand to fine gravel (Figure 12).

Group 5 exists between 760 and 820 ft below ground surface and was assigned to the Pomerado Conglomerate (Figure 13). The GSD curve for this interval is distinctly more linear than the adjacent groupings and stands out significantly. From the GSD graphs the formations begins with sample 760-780 ft and ending in sample 800-820 ft (Figure 8). No shoe samples were taken at this depth, so no comparison can be made.

Group 6 encompasses 820-960 ft below ground surface and was correlated to the Mission Valley Formation (Figure 14). This interval fines from a gravely sand to sand at its base (Figure 8). A comparison of the shoe and drill cutting samples yields highly analogous GSD curves in the coarser portions, from 1mm to 10mm, with the expected variation caused by the differential loss of fines.

Group 7 occurs between 960 and1040 ft below ground surface and was correlated to the Stadium Conglomerate (Figure 15). The GSD curve for this interval is distinctly more linear than the adjacent groupings and stands out significantly. From the graphs, it is clear that this unit is much coarser than the adjacent units as the trend of the samples increase at 0.5 mm and trends sharply into the fine gravel range. Furthermore, the D50 values for the interval are all greater than 1 mm, or coarse sand. No shoe samples were taken at this depth, so no comparison can be made.

Group 8 begins at 1140 ft and goes to total depth of the well. It encompasses samples from 1140-1640 ft. (Figure 16). This group was associated to the Friars Formation. From the graph, it is clear that this unit is much finer than the adjacent unit. This is noticeably observed by the (D50) value which is within the medium sand range for most of the drill cuttings and shoe samples. In comparison, the shoe and drill cuttings in this formation are highly analogous to one another in the size ranges from 1 to 10 mm and the expected variations in the finer sizes (Figure 16).

From the GSD curves, values related to the grain diameter estimated as the effective grain size (D10), the median grain size (D50) and the ratio of the grain size that is 60 % finer by weight (D60) are gathered to create parameters values from which interpretation will be based (Figure 17, Figure 18).

Data Manipulation of Drill Cuttings

In order to compare the grain size diameter (GSD) curves to the geophysical logs, parameters median grain size (D50) and the Sorting Coefficient were calculated (Table 1). These are graphically depicted on a bar graph with sample names on the vertical axis depicting the depths alongside the parameters (Figure 17, Figure 18). Noticeably, the graphs expose patterns that help to define the depths at which individual formations may be interpreted.

The sorting and median grain size (D50) graphs show distinct patterns. Both illustrate that the upper part of the well has distinctly coarser sediment. The bottom of the well, starting at 1140 ft below ground surface is much finer grained. Many intervals show pulses of coarser sediment input, such as 80ft, 900ft to 920ft, 1000ft to 1100ft and 1580ft to 1600ft.

Data Manipulation with Stratigraphic Information

To further illustrate the relationship between the depth ranges of the formations and the D50 values, the depth ranges determined by the GSD curve graph associations are emphasized (Figure 19).The median grain size class (D50) strikingly delineates the different formations. The most diagnostic are the distinct patterns for the Friars Formation and the Stadium Conglomerate.

Statistical Description and Textural Analysis of Formations

The emerging pattern of the correlation between the drill cuttings and the shoe samples is thereby clear. The shaker truck is undoubtedly performing as it should, removing the majority of fines. The emerging development of some significance is that the shoe samples and drill cuttings on the coarser end are highly analogous in almost all cases, an important outcome because it shows that the error that can be created by sample preparation and analysis may not be the cause of the variability produced in the comparisons. However, the result of the comparison has also shown that there is a great deal of gradational variability within the formations, though the trends are highly analogous to each other (Figure 8).

As identified by the U.S. Geological Survey there are six known subsurface formations: San Diego Formation, Stadium Conglomerate, Mission Valley Formation, Pomerado Conglomerate, Otay Formation, and the Friars Formation (W. Danskin, written comm., 2012). Of the 84 drill cutting samples collected, one sample represents alluvial fill and 35 samples represent the upper and lower members of the San Diego Formation. Additionally three of the drill cuttings represent the Otay Formation, three represent the Pomerado Conglomerate, seven represent the Mission Valley Formation, nine represent the Stadium Conglomerate, and finally 24 represent the Friars Formation.

In order to tighten the correlations, this analysis includes GRADISTAT statistics for the shoe samples that are most analogous to the GSD curves of the drill cuttings that compose the formations. Formations that lacked shoe samples had their sample statistics calculated based on the finest D50 sample within the interval.

The single sample that represents fill is sample Group 1 (Figure 9).The sample statistics and logarithmic frequency plot showing grain size distribution as calculated by GRADISTAT (Figure 20). The statistics related to the 0-20 ft samples classifies it as medium gravely coarse sand, which texturally classifies it as gravelly sand with 25.7 % gravel and 74.3 % sand. Unfortunately, a geophysical comparison cannot be done due to the presence of noise at this depth range.

The San Diego Formation, an early Pleistocene and late Pliocene transitional marine and nonmarine pebble and cobble conglomerate was identified onsite at the time of drilling by Scott Rugh (Figure 10, Figure 11). Based on the available evidence, Rugh placed the range of the Upper San Diego Formation at 60-240 ft, and the Lower San Diego Formation at approximately 240-620 ft (S. Rugh, written comm., to U.S. Geological Survey, 2011). In contrast, this investigation placed the Upper San Diego Formation at between 20 and 200 ft below ground surface due to the abrupt change in the grain size distribution curves at the 200 ft depth (Figure 8). The sample statistics and logarithmic frequency plot showing grain size distribution for the Upper San Diego Formation are based on shoe sample 45-50 ft, as the shoe sample for this member of the San Diego Formation is most similar to the GSD curves of the drill cuttings (Figure 21 and Figure 10).

The Lower San Diego Formation, according to this analysis, begins at 200 ft below ground surface. Both paleontological evidence and this analysis agree that the formation ends at 620 ft below ground surface. The sample statistics and logarithmic frequency plot showing grain size distribution are based on shoe sample 483-485 ft because this sample is the most analogous to the curves of the drill cuttings (Figure 22 and Figure 11).

From the GRADISTAT sample statistics, it becomes clear that the San Diego Formation in its upper member is coarser than in the lower portion, coarsening from very fine gravelly coarse sand to very fine gravely fine sand. Both members were textually defined as gravelly sands by GRADISTAT, with the upper containing 11 % gravel and 88.7 % sand and the lower containing 15 % gravel and 83.5 % sand. Although the upper member has greater sand percentage, the sand contained within it is far coarser than in the lower member.

The sandstone portion of the Otay Formation is a late Eocene deposit and is thought to have been deposited in river channels or floodplains (Demere and Walsh, 1991). The sample statistics and logarithmic frequency plot showing grain size distribution for this formation are created from shoe sample 663-668 ft. The GSD curves for the shoes are highly analogous. Thus, the shoe sample 663-668 ft was chosen as the most representative because its D50 is slightly finer than the others (Figure 23). GRADISTAT statistics for the Otay Formation show that it is polymodel and poorly sorted. Furthermore, it classified as very fine gravelly fine sand, which places it in the textural group of gravelly sand with 9.1 % gravel and 89.4 % sand (Figure 23).

The Pomerado Conglomerate is late Eocene in age and is a massive cobble conglomerate lithologically identical to the Stadium Conglomerate (Peterson and Kennedy, 1974). Moreover, it is occasionally characterized by thin beds, lenses, and tongues of light brown medium-grained sandstone (Peterson and Kennedy, 1974). Sample statistics and logarithmic frequency plot show grain size distributions were calculated only for the drill cutting sample labeled 800-820 ft because shoe samples were not available for the formation (Figure 24). However, the 800-820 ft sample adequately represents the distribution of sediments throughout the unit (Figure 13). GRADISTAT statistics for the Pomerado Conglomerate show that it is polymodel and poorly sorted. Moreover, it can be classified as very fine gravelly very coarse sand, which places it in the textural group of gravelly sand with 29.3 % gravel and 70.7 % sand (Figure 24).

The contact between the Mission Valley Formation and Pomerado Conglomerate is conformable and gradational (Peterson and Kennedy, 1974). The Eocene age Mission Valley Formation is composed of marine, lagoonal, and nonmarine sandstone (Hanna, 1926). Sample statistics are based on shoe sample labeled 865-870 ft because its sediment distribution is more closely similar to the drill cuttings for this unit (Figure 14). GRADISTAT statistics and logarithmic frequency plot showing grain size distribution for the Mission Valley Formation show that it is polymodel and poorly sorted. Furthermore, it can be classified as very fine gravelly medium sand, which places it in the textural group of gravelly sand with 18.5 % gravel and 81.4 % sand (Figure 25).

The Stadium Conglomerate lies conformably beneath the Mission Valley Formation and is lithologically identical to the Pomerado Conglomerate (Hanna, 1926). Consequently, the expectation is that the two conglomerates will have similar arithmetic and statistical values. Sample statistics are based on the drill cutting sample labeled 1120-1140 ft because shoe samples were not available for the formation. However, the drill cutting1120-1140 ft sample adequately represents the distribution of particles throughout the unit. GRADISTAT statistics and logarithmic frequency plots showing grain size distribution for the Stadium Conglomerate indicate that the conglomerate is polymodel and poorly sorted. It can be classified as very fine gravelly very coarse sand, which places it in the textural group of gravelly sand with 45.1 % gravel and 54.9 % sand (Figure 26). This result is unexpected because the Pomerado Conglomerate is very fine gravelly very coarse sand which contains 29.3 % gravel and 70.7 % sand. A possible explanation for the difference is explained by Peterson and Kennedy's 1974 portrayal of the Pomerado as having thin beds, lenses, and tongues of light-brown medium-grained sandstone.

The Friars Formation is middle to late Eocene in age and is predominantly a nonmarine and nearshore marine sandstone (Hanna, 1926). Sample statistics and logarithmic frequency plots are based on shoe sample labeled 1340-1345 ft because its GSD curve is more closely analogous to the drill cuttings and appears to represent a greater fraction of the fines that are encountered through the section (Figure 16). GRADISTAT statistics for the Friars show that the formation is polymodel and poorly sorted. Furthermore, it can be classified as very fine gravelly medium sand, which places it in the textural group of gravelly sand with 12.3 % gravel and 86.8 % sand (Figure 27).

GRADISTAT also produces ternary diagrams that effectively summarize the textural grouping of the samples chosen to represent the formations in the SDHF well. Fill (yellow) with 25.7 % gravel and 74.3 % sand, both members of the San Diego Formation (Tsd) with the upper (dark green) containing 11 % gravel and 88.7 % sand and the lower (light green) containing 15 % gravel and 83.5 % sand. The Otay Formation (To) (dark brown) containing 9.1 % gravel and 89.4 % sand. The Pomerado Conglomerate (blue) contains 29.3 % gravel and 70.7 % sand. The Mission Valley Formation (light brown) contains 18.5 % gravel and 81.4 % sand. The Stadium Conglomerate (pink) contains 45.1 % gravel and 54.9 % sand. The Friars Formation (gold) containing 12.3 % gravel and 86.8 % sand (Figure 28).

DISCUSSION

The distribution of grain sizes in sedimentary systems is largely a function of the distribution of available sediment and energy within the system that drives the sediment-transport processes, which ultimately sorts and redistributes particles (Hajek et al., 2010). In terms of this study, the particle-size distributions were reduced to the median value of the percentile grain diameter, D50, in order to correlate grain size to the resistivity logs (Figure 17, Figure 19). Furthermore, the sorting coefficient was used to relate the depositional environment to the D50. The generalization is that as the D50 increases, the formation's sediment coarsens and the value of the Sorting Coefficient increases. The larger the sorting values, the poorer the sorting; thus poorly sorted correlates to coarser sediments and lower sorting values correlate to finer sediments, relative to the drill cutting samples (Figure 29).

The geophysical logs for the San Diego Formation illustrate the gradational difference between the upper and lower members of the formation. Specifically, both resistivity logs show that the upper member has a lower resistivity (greater conductance) than that of the lower member (Figure 5). The corresponding D50 value for the Upper San Diego Formation shows a coarsening to 80 ft below ground surface, which agrees to the upper members' lower resistivity (Figure 29). However, the D50 then becomes inconsistent, a tendency reflected by the sorting in the lower member. Undoubtedly, this inconsistency is based on the error associated to the fine sediments. Although lacking fines, it is clear that sorting and D50 are in agreement and that as the Lower San Diego Formation coarsens at 460 ft below ground surface, the resistivity decreases. The implication is that as pore space increases, the formation gains more capacity to contain groundwater. It is likely that at 460 ft below ground surface, the depositional environment has migrated to a nearshore environment from its formerly subtidal environment (Abbott, 1999).

The Otay Formation's geophysical logs show a small spike in the gamma log and a jump to the left where the Otay begins at approximately 620 ft below ground surface in both resistivity logs (Figure 5). The logs show relative stability until 760 ft below ground surface, marking the bottom of the Otay Formation. The parameter values stay relatively constant throughout the unit with D50 at medium sand and consistent sorting values. The unit has a low resistivity thereby exhibiting abundant pore space for groundwater. Moreover, because the depositional environment was a river channel or floodplain (Demere and Walsh, 1991), the expectation would be sorted sand hence the 9.1 % gravel and 89.4 % sand. The exception to the above analysis occurs at the 680 ft depth. The assumption would be that some event occurred that increased the stream power of the river, which would allow for larger-sized sediments to be deposited, thus decreasing the sorting (Figure 29).

The Pomerado Conglomerate's resistivity increases markedly showing the initiation of conglomerate deposition (Figure 29). This is presumably due to a low permeability layer at approximately 780 ft below ground surface. The resistivity fluctuates slightly until another spike to the right at 820 ft below ground surface. This marks the end of the Pomerado Conglomerate. The depositional environment must have shifted from fluvial to coastal plain (Abbott, 1999), hence the drastic decrease in D50 and increase in sorting.

The Mission Valley Formation has low resistivity (high conductivity) for the entire unit, which is supported by the D50 values of medium sand and corresponding sorting values (Figure 29). The depositional environment was fluvial and marginal marine (Abbott, 1999), hence 18.5 % gravel and 81.4 % sand.

The Stadium Conglomerate fluctuates repeatedly down the unit at a moderate resistivity beginning at 940 ft below ground surface and ending at 1040 ft below ground surface. The depositional environment was fluvial-braid delta, which is supported by the parameters D50 and sorting; as the unit coarsens, the sorting decreases (S. Rugh, written comm., 2012). The unit is fairly coarse, 45.1 % gravel and 54.9 % sand (Figure 29). This could mean that the river was gaining power, peaking at the time that sample 1060 ft below ground surface was deposited and then slowly tapering off.

The Friars Formation resistivity is low over the entire unit. The depositional environment is marginal marine (Abbott, 1999); the parameter values correspond to that type of deposition. The D50 is of medium sand with a consistent sorting relative to the D50 values. It is possible that this was a beach at one time and the energy that produced this type of sorting was from wave action, thus producing 12.3 % gravel and 86.8 % sand (Figure 29).

CONCLUSIONS

Drill cuttings and shoe samples were analyzed for grain size distributions, median grain size diameters and sorting coefficients. These data were used to help identify the presence of different formations in subsurface San Diego. In total, six formations were recognized and described using GRADISTAT arithmetic methods. However, the sediment-size analysis is skewed to providing useful information about sand, granule, and pebble components because the drill cuttings lack formation clay and silt. In order to try to account for the lack of silts and clays, shoe samples were used for comparison. The use of shoe samples only partially corrects for the loss of the fines because of the errors associated with sample preparation and the limitations of the CAMSIZER. The error that occurs during sample preparation is difficult to quantify. In contrast to the drill cuttings, there is still more data in the rare and expensive shoe samples which were ultimately used to add descriptive terminology to the formations.

In summary:

(1) The statistics related to the Fill (0-20 ft) classifies it as medium gravely coarse sand, which texturally identifies it as gravelly sand with 25.7 % gravel and 74.3 % sand.

(2) The San Diego Formation in its upper member (20-200 ft) is coarser than in the lower member (200-620 ft), fining from very fine gravelly coarse sand to very fine gravely fine sand. Both members were textually identified as gravelly sands by GRADISTAT, with the upper containing 11 % gravel and 88.7 % sand and the lower containing 15 % gravel and 83.5 % sand.

(3) The Otay Formation (620-760 ft) classifies as very fine gravelly fine sand, which places it in the textural group of gravelly sand with 9.1 % gravel and 89.4 % sand.

(4) The Pomerado Conglomerate (760-820 ft) classifies as very fine gravelly very coarse sand, which places it in the textural group of gravelly sand with 29.3 % gravel and 70.7 % sand.

(5) The Mission Valley Formation (820-960 ft) classifies as very fine gravelly medium sand, which places it in the textural group of gravelly sand with 18.5 % gravel and 81.4 % sand.

(6) The Stadium Conglomerate (960-1140 ft) classifies as very fine gravelly very coarse sand, which places it in the textural group of gravelly sand with 45.1 % gravel and 54.9 % sand.

(7) The Friars Formation (1140 ft- to total depth) classifies as very fine gravelly medium sand, which places it in the textural group of gravelly sand with 12.3 % gravel and 86.8 % sand.

Drill cuttings therefore can be used to show quantitatively the depths at which formation change occurs. Initially, the plots or grain size distribution curves could be successfully associated to each other through visual trends and compared to show at which depths formation change occurs. Accompanied by the parameters values (D50 and Sorting Coefficient), which were gathered from the grain size distribution curves, direct comparison to the geophysical logs was feasible.

The purpose of this research was to apply a new technique (CAMSIZER analysis) to help determine formations in the San Diego subsurface. The CAMSIZER has a serious limitation in that it does not record the presence of silt and clay. Those two grain sizes are important because their presence exerts a great deal of control over the flow of water in the subsurface. Therefore, a different technique should be tested to measure silt and clay. In order to measure the smaller particles I would recommend separating the samples into two parts, sediments coarser than 0.075 mm and sediments finer than 0.075 mm, or the fraction considered fines (Fetter, 2001). Sample fines could then be measured by a Horiba LA-300 laser particle-size analyzer (LPSA), which has the ability to quantity the fine-grained fraction of the sediment samples (Hajek et al., 2010). However, the CAMSIZER provides important sedimentological information about the coarser sediment fraction and could still be used. Nevertheless, there is still a certain degree of error that will have to be accepted when analyzing sediments of this type. Drilling fluid will still introduce clay into drill cuttings and sample preparation will still require desegregating the samples. Thus, the presence of error will persist. Still, modeling for formation change using grain size distribution can be useful when the grain size distributions are reduced to one or two characteristic parameter values in order to directly compare the curves to the geophysical logs. Programs such as GRADISTAT can be used on shoe or drill cutting samples to further assemble information about formations and should be used in the future to help standardize an analytical method for drill cuttings that can add valuable information to the quest for understanding the subsurface.

ACKNOWLEDGMENTS

This research was supported by my immediate family, Harry and Gregoria Polis, my brothers Dimitris and Nickolas Polis whose love, support and patience with me is never ending, and the Pell grant and State University Grant (SUG) for enabling me to continue my education. I also would like to thank Dr. Eleanora Robbins (USGS-retired; SDSU) for her help, which was nothing short of miraculous, Wes Danskin for providing me access to his staff Adam Kjos, Anthony Brown and the support and materials that came along with them. I thank Anthony Carrasco and Joan Kimbrough for showing me how to use the machines at San Diego State University, associate professor Dr. Kathy Thorbjarnarson for initiating this research, and to my colleagues especially Anthony Norton for all comradery and assistance.

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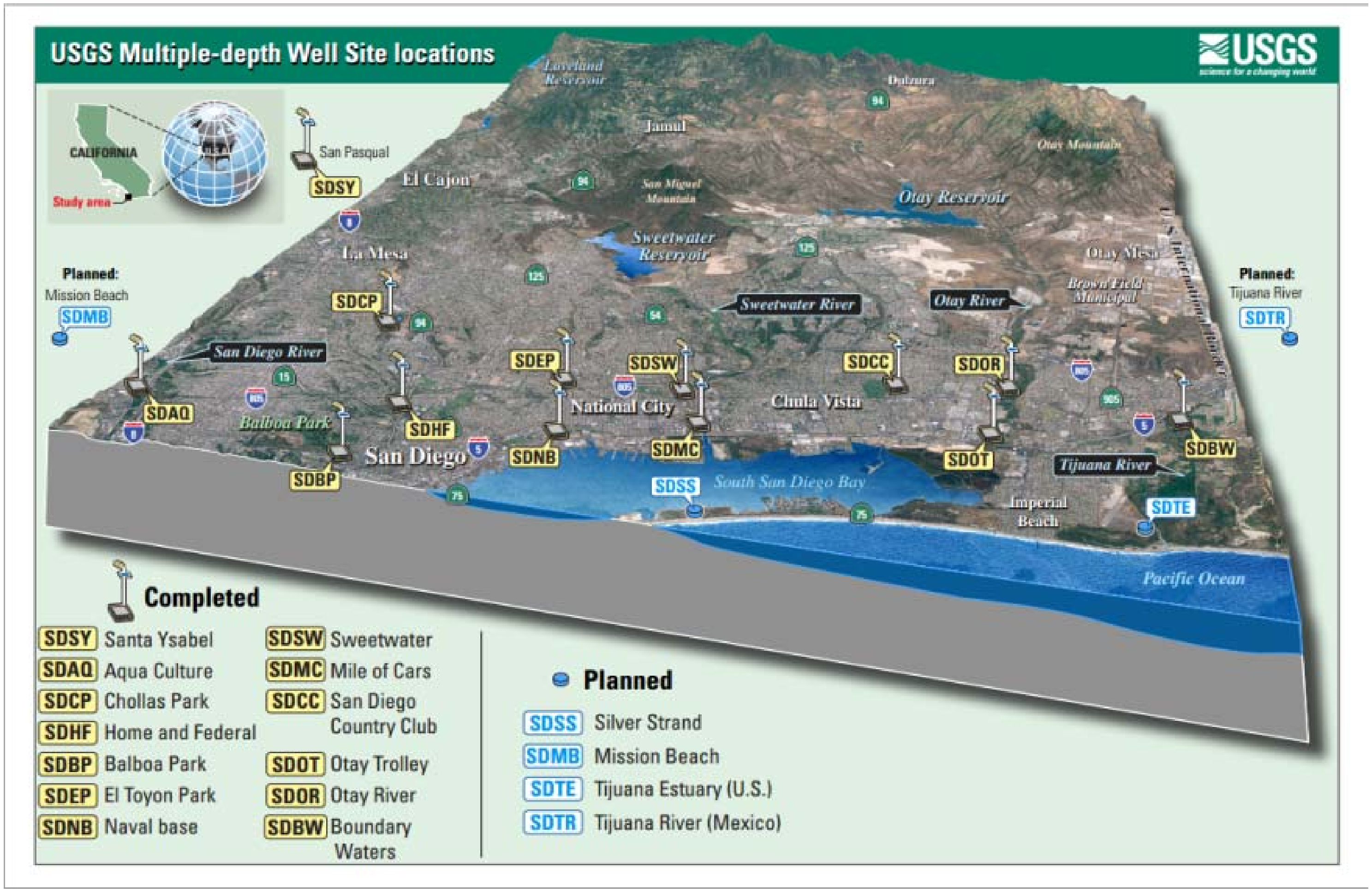


Figure 1. USGS multi-depth well site locations. Project site is labeled SDHF (San Diego Home and Federal) test well (from Danskin et al., 2011).

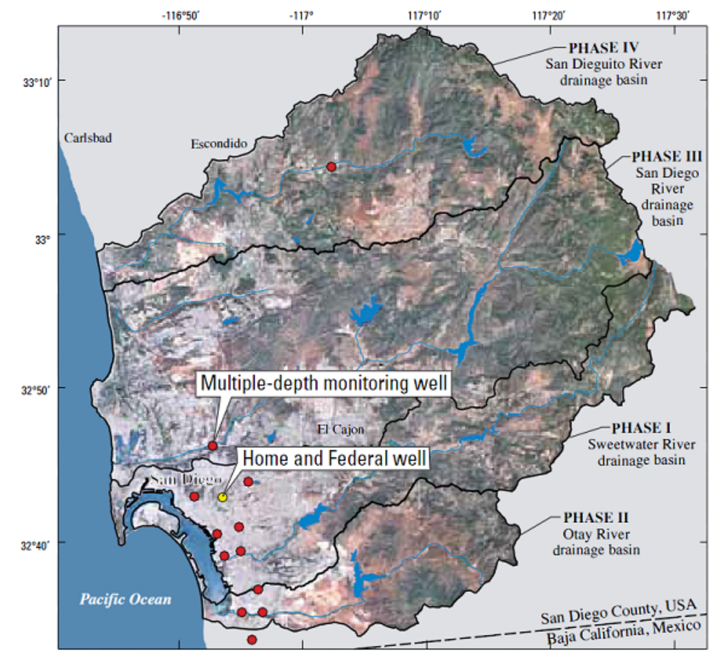


Figure 2. Map view of SDHF well site (from Danskin et al., 2011)

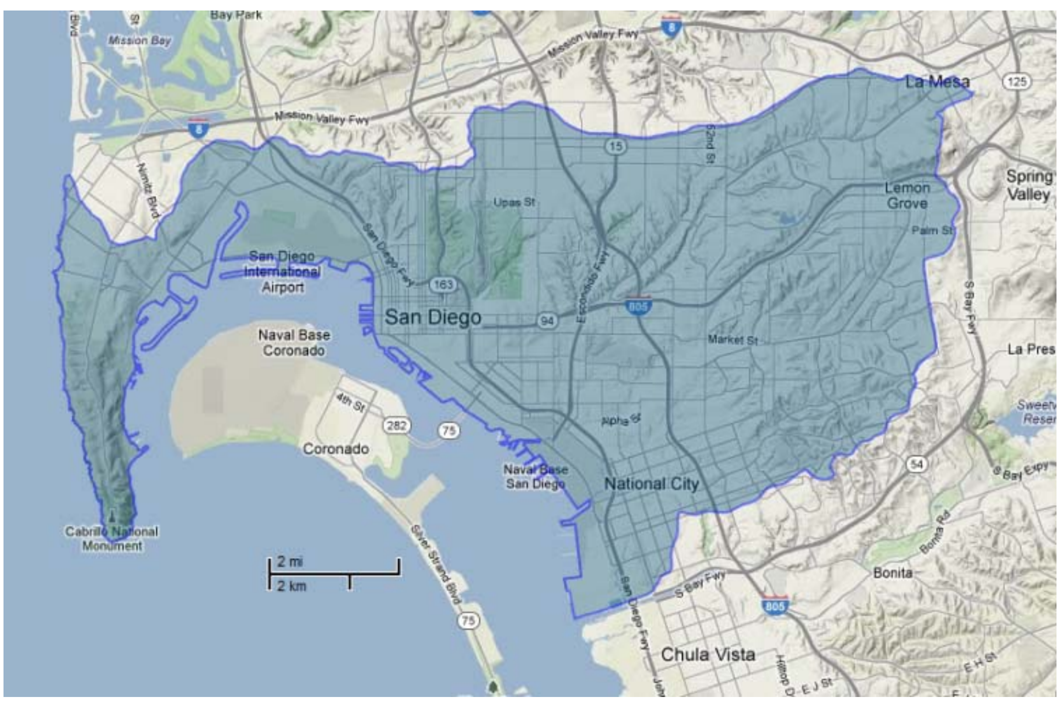


Figure 3. Map view of Pueblo Watershed, San Diego CA. The watershed is smallest and most populated in the region, encompassing Lemon Grove, La Mesa, National City, downtown San Diego and Point Loma (from San Diego Coastkeeper, 2001).

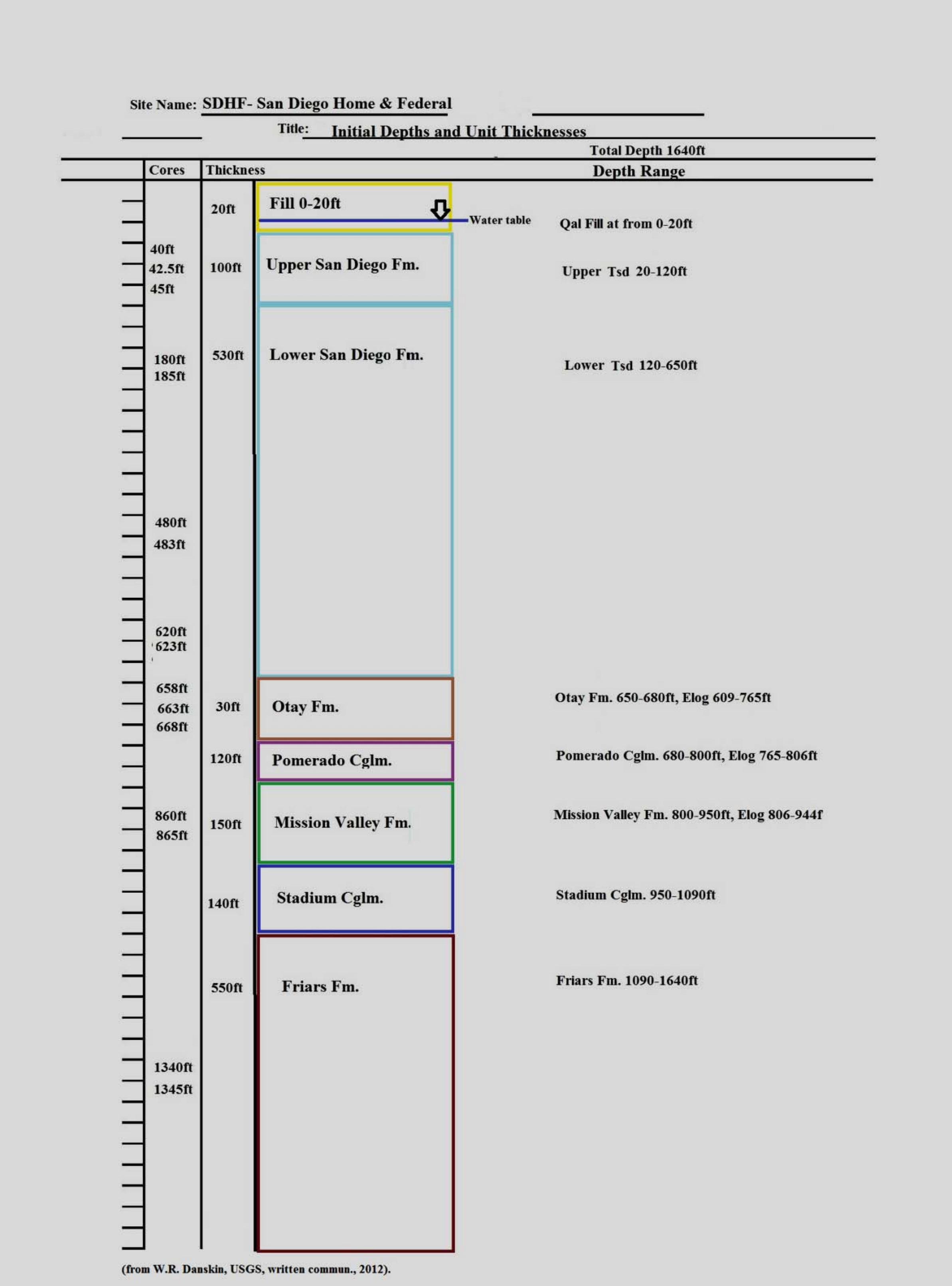


Figure 4. Preliminary stratigraphic column from SDHF well showing formations and formation depths (from W.R. Danskin, USGS, written commun., 2012).

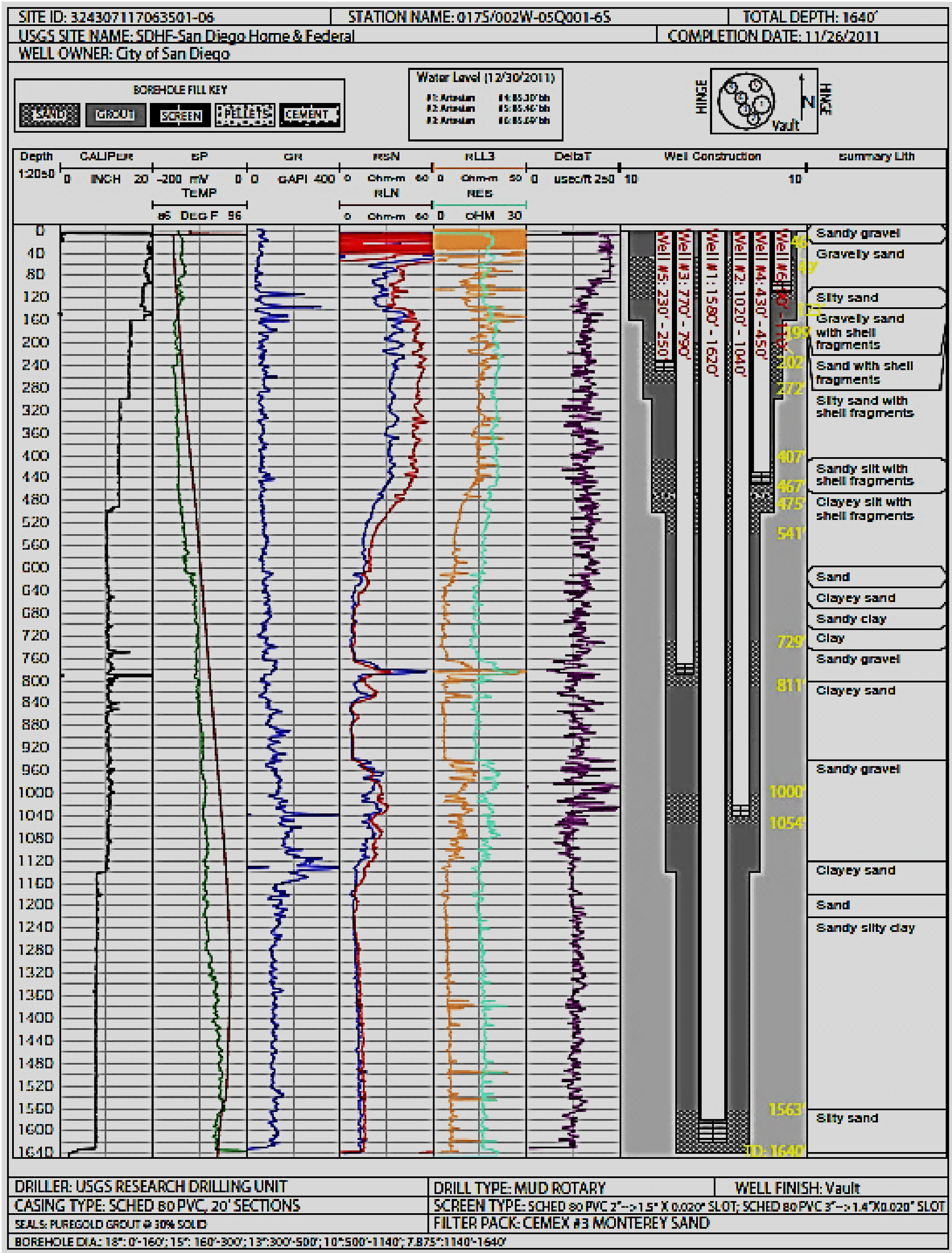


Figure 5. Geophysical logs showing caliper, spontaneous potential, gamma ray, resistivity short normal, resistivity long normal, interval transit time (deltaT), well construction with piezometers, and summary lithology in USGS SDHF test well (from A. Brown and A. Kjos, USGS, written commun., 2012).

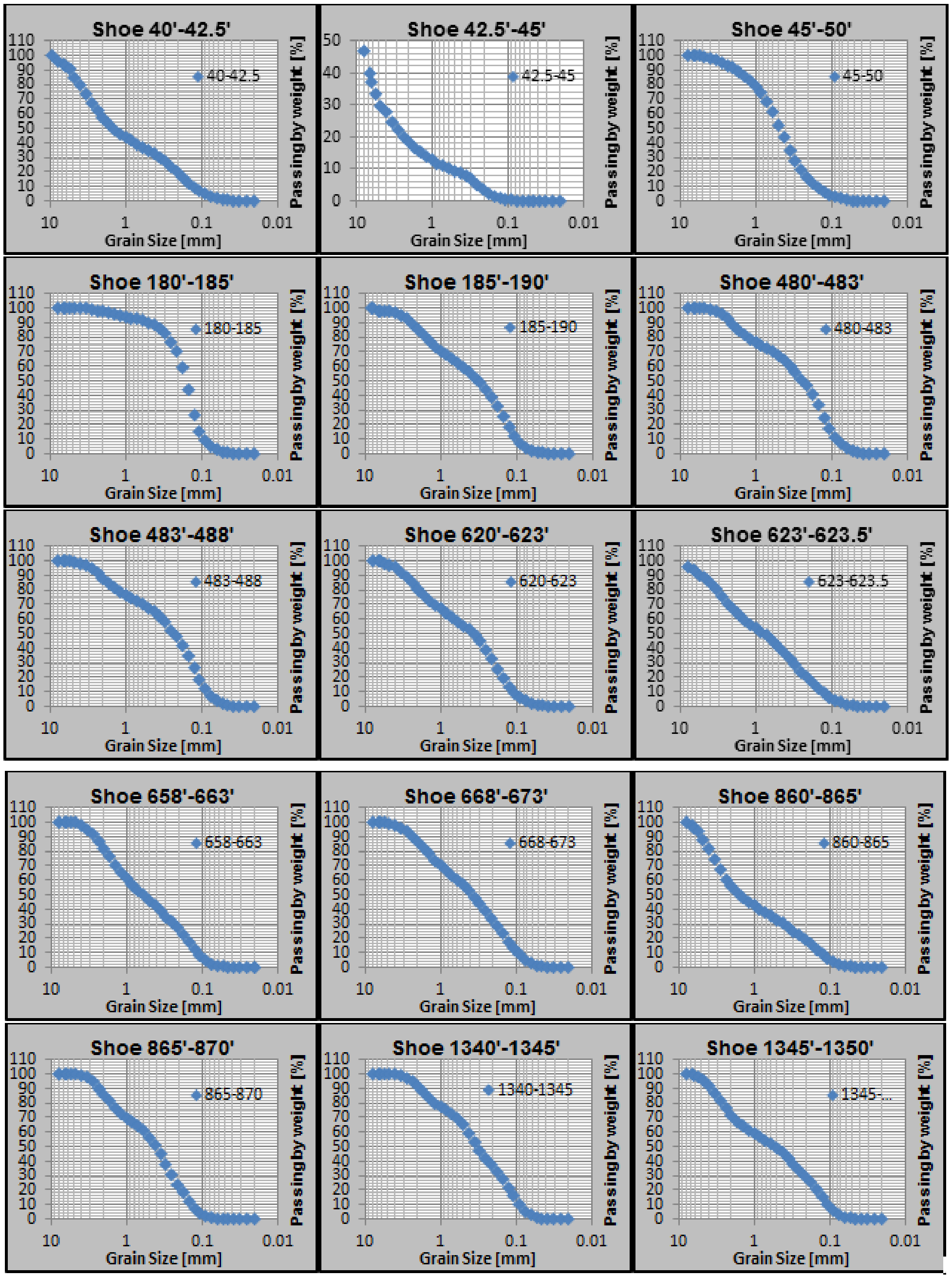
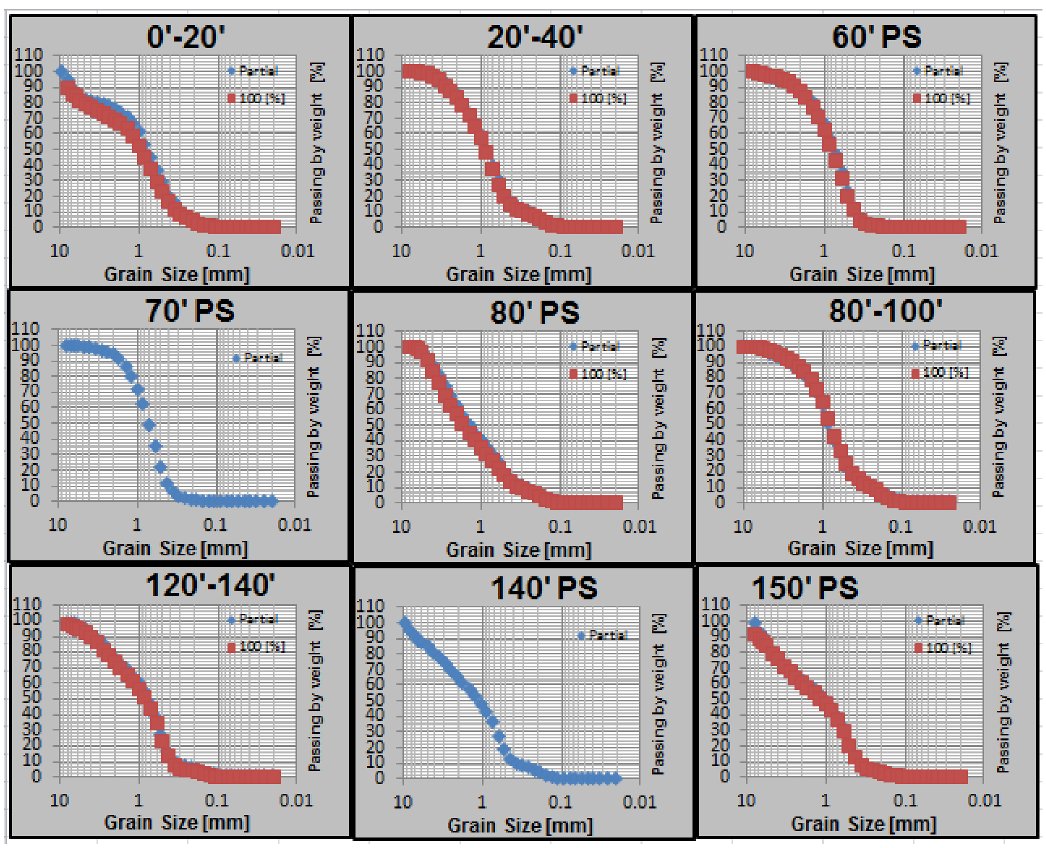
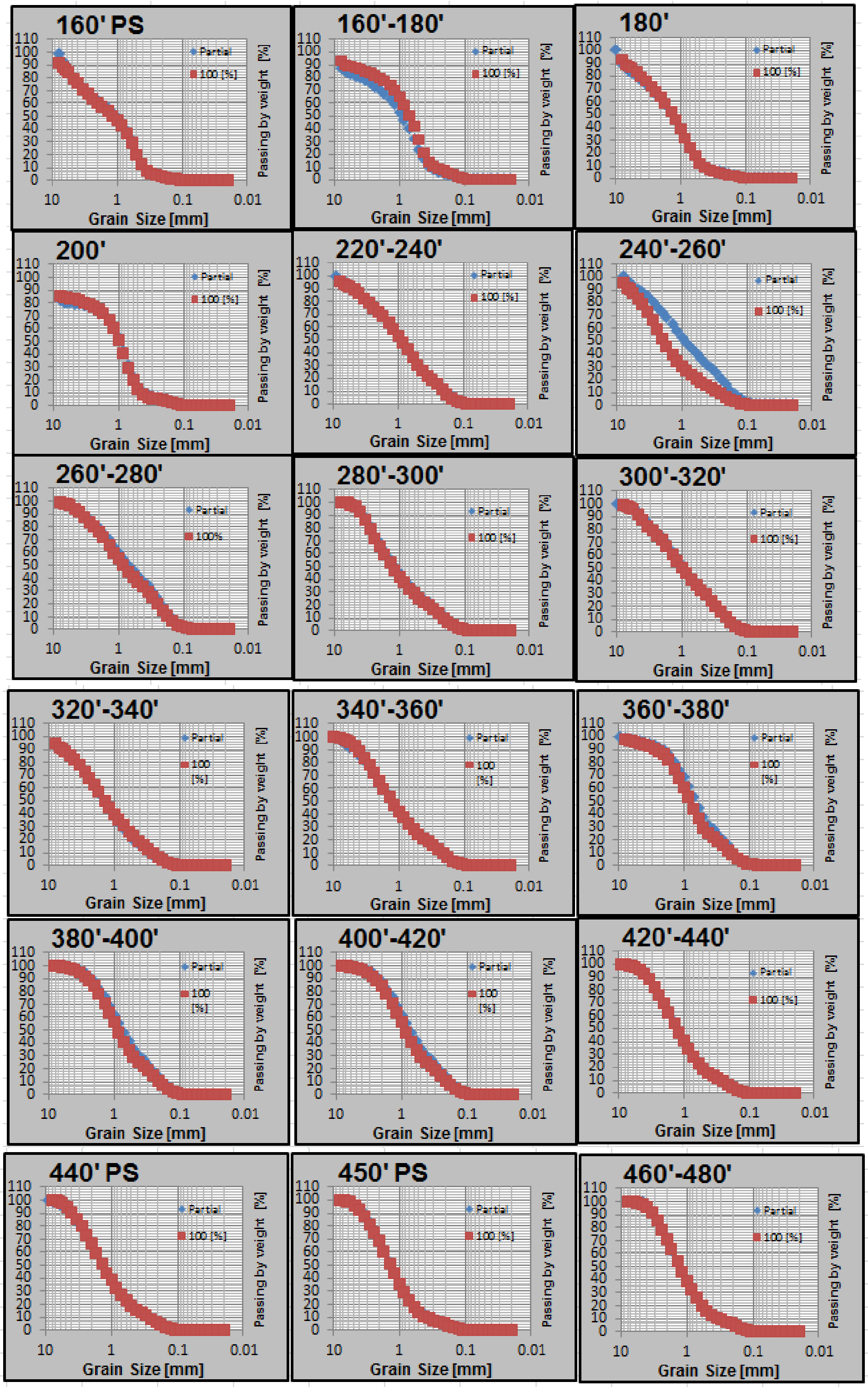
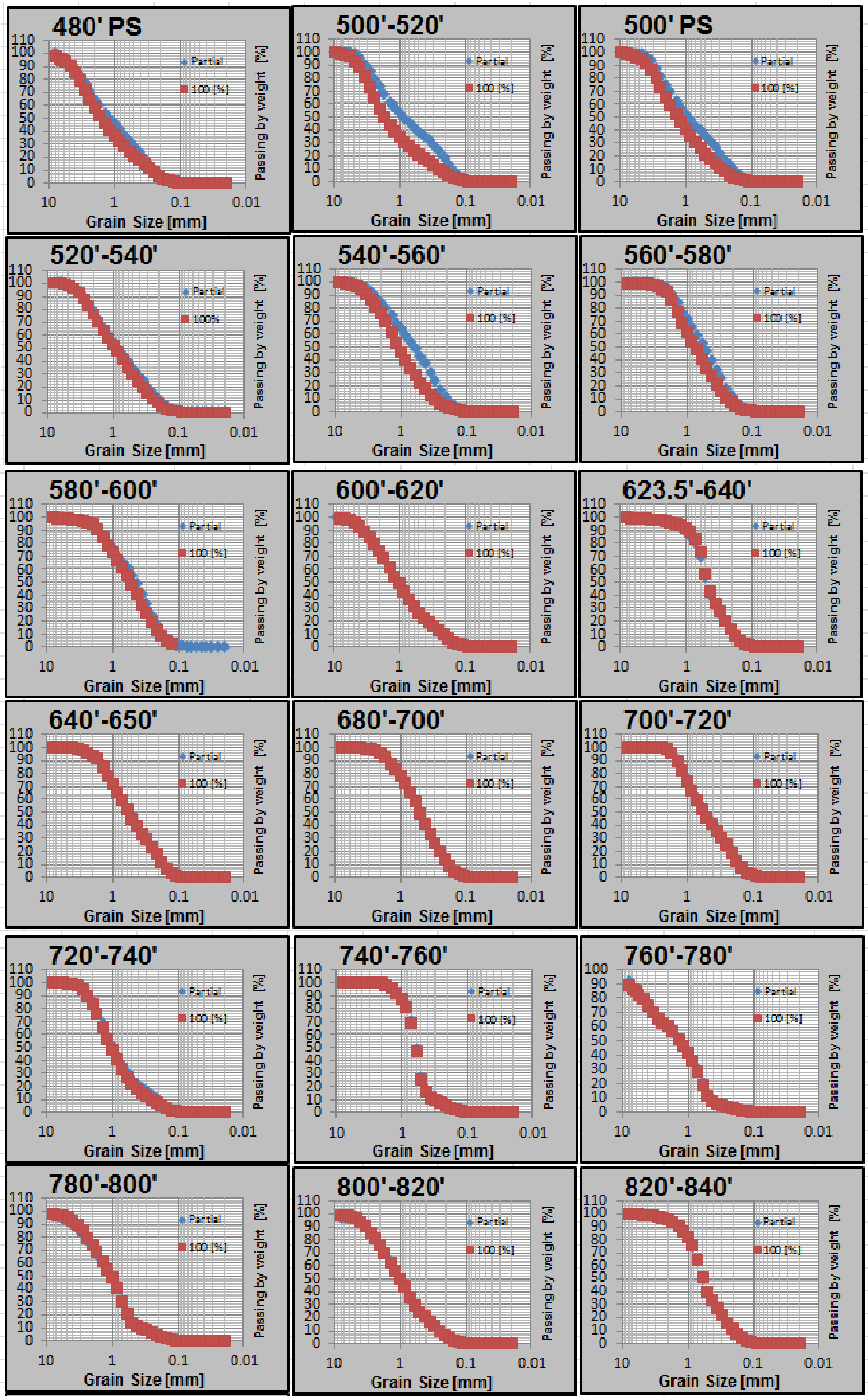


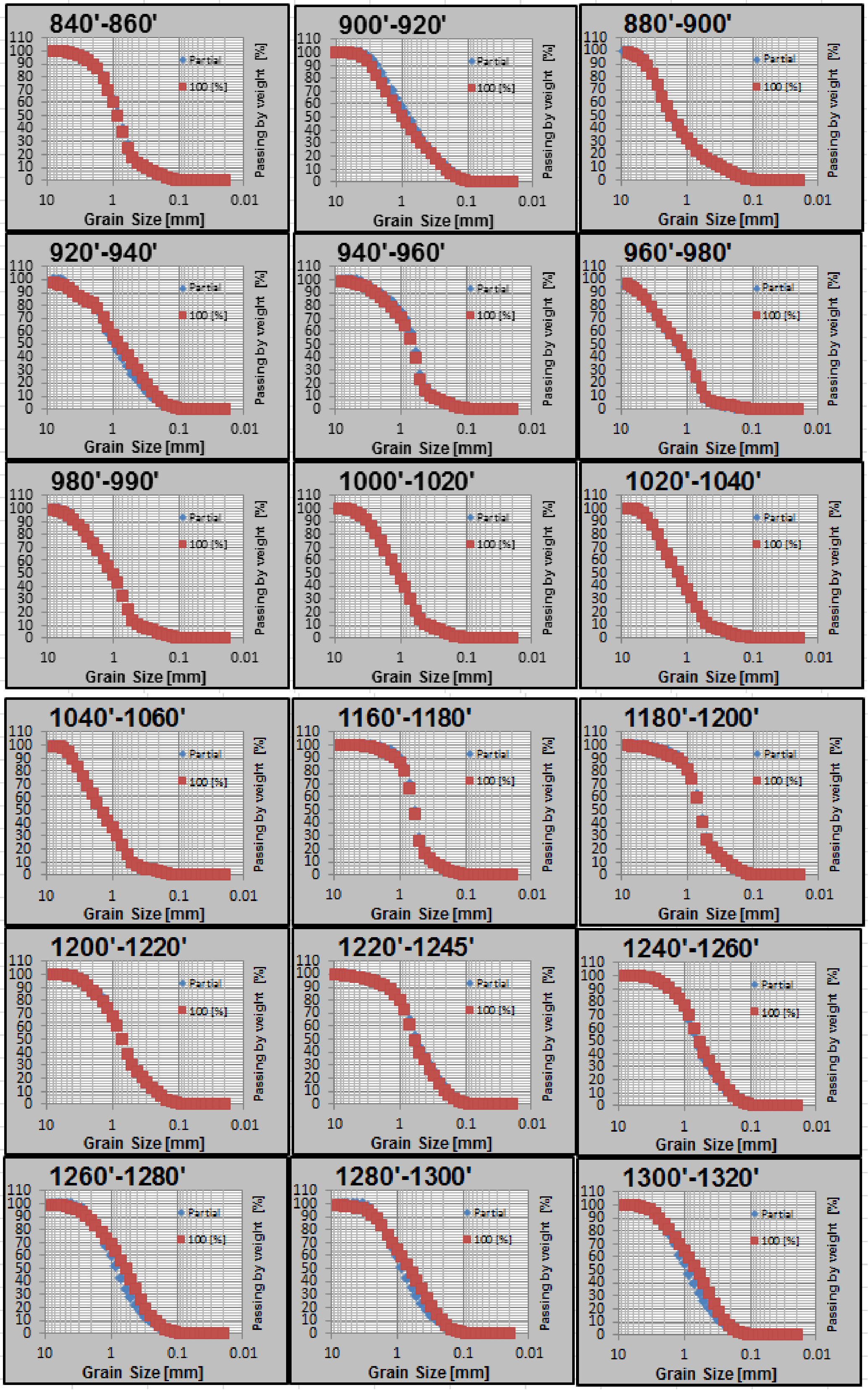
Figure 6**.** Grain size distribution graphs for shoe samples from the SDHF well site. Graph titles are also the sample names. Percent of sediment passing by weight on the vertical axis and grain size in millimeters on the horizontal axis.

Figure 7. CAMSIZER calibration reticle showing sediment dispersal (from Retsch, 2004).




160' PS
160'-180'
180'
200'
220'-240'
240'-260'
260'-280'
280'-300'
300'-320'
320'-340'
340'-360'
360'-380'
380'-400'
400'-420'
420'-440'
440' PS
450' PS
460'-480'
Partial
100 [%]
100%
Grain Size [mm]
Passing by weight [%]


480' PS
500'-520'
500' PS
520'-540'
540'-560'
560'-580'
580'-600'
600'-620'
623.5'-640'
640'-650'
680'-700'
700'-720'
720'-740'
740'-760'
760'-780'
780'-800'
800'-820'
820'-840'
Partial
100 [%]
100%
Grain Size [mm]
Passing by weight [%]


840'-860'
900'-920'
880'-900'
920'-940'
940'-960'
960'-980'
980'-990'
1000'-1020'
1020'-1040'
1040'-1060'
1160'-1180'
1180'-1200'
1200'-1220'
1220'-1245'
1240'-1260'
1260'-1280'
1280'-1300'
1300'-1320'
Partial
100 [%]
Passing by weight [%]
Grain Size [mm]

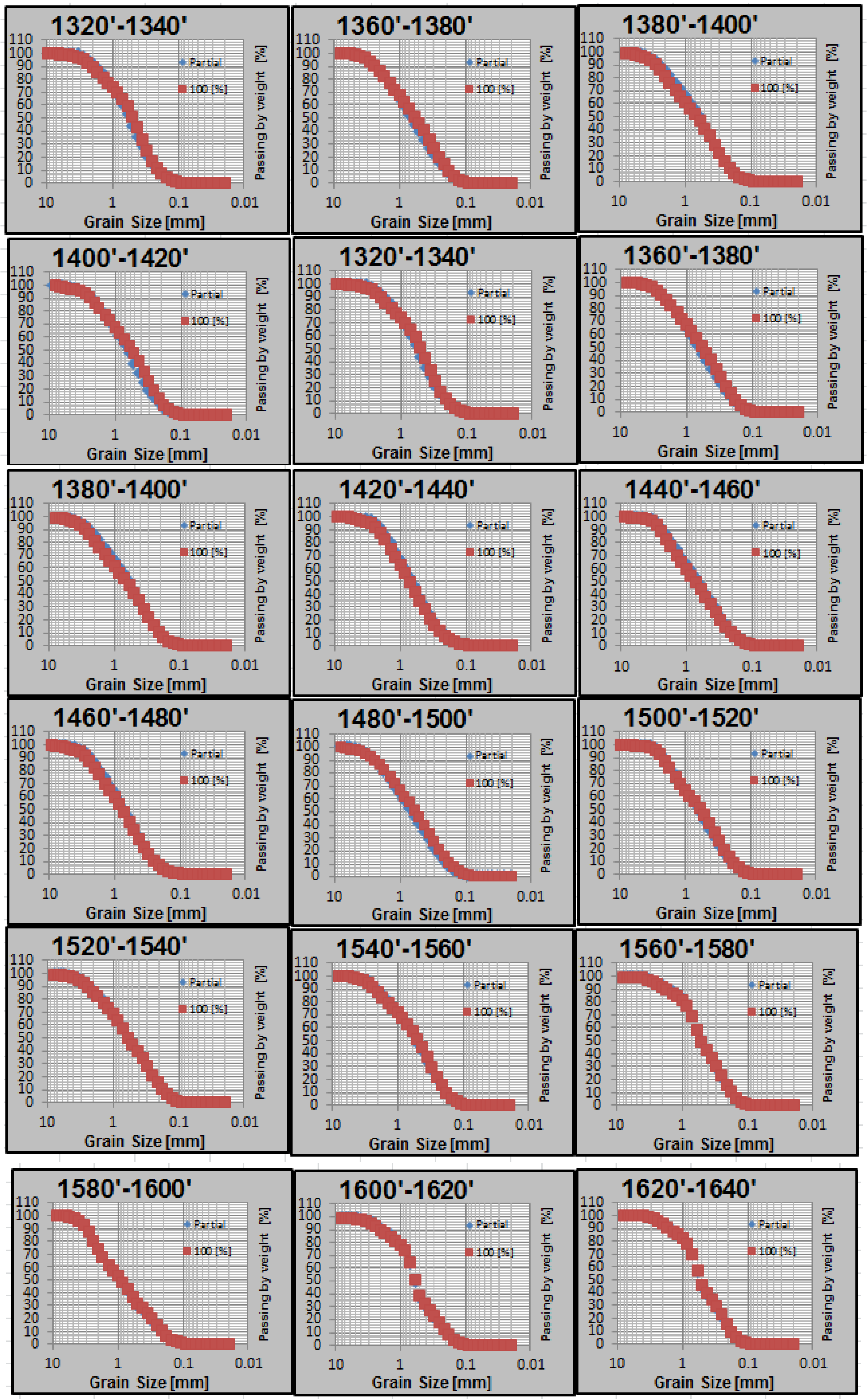


Figure 8. Grain size distribution graphs for drill cuttings from the SDHF well site. Graphs depict both partial and whole sample (100%) curves.

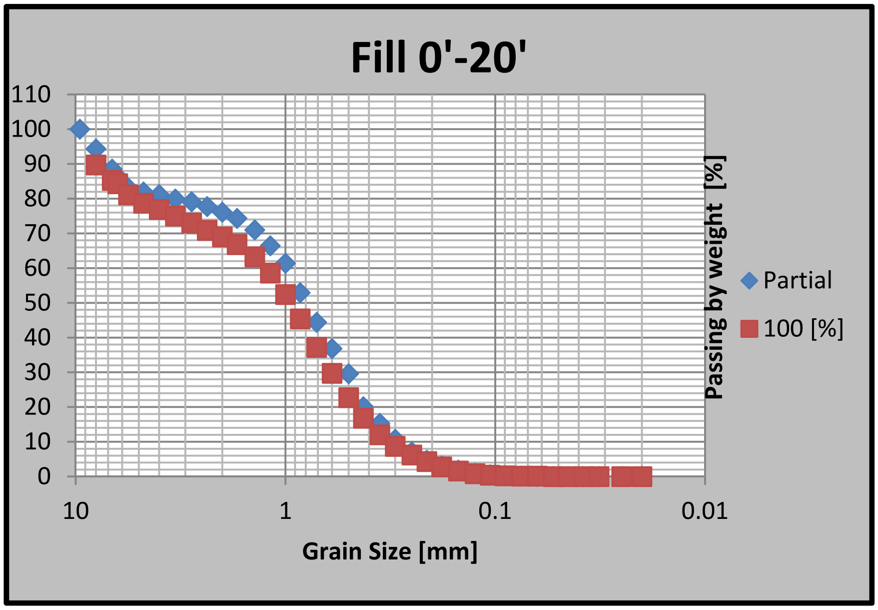


Figure 9. Grain size distribution curve for Fill (0-20 ft). Red line represents whole sample, blue line represents partial sample.

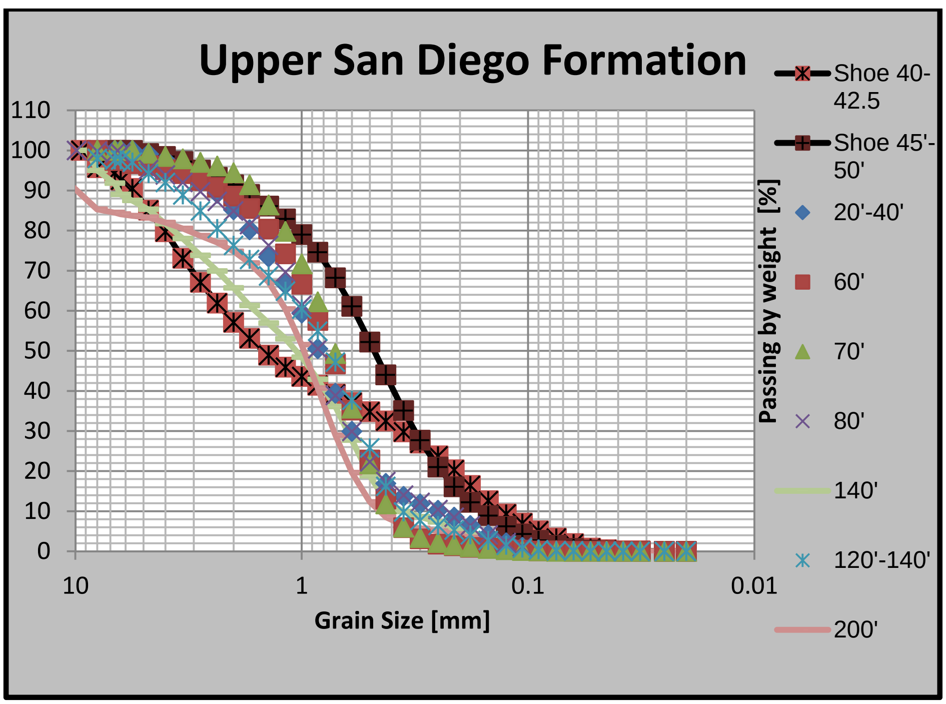


Figure 10**.** Grain size distribution curves of the upper member of the San Diego Formation (20-200 ft) showing drill cuttings and shoe samples at different depths.

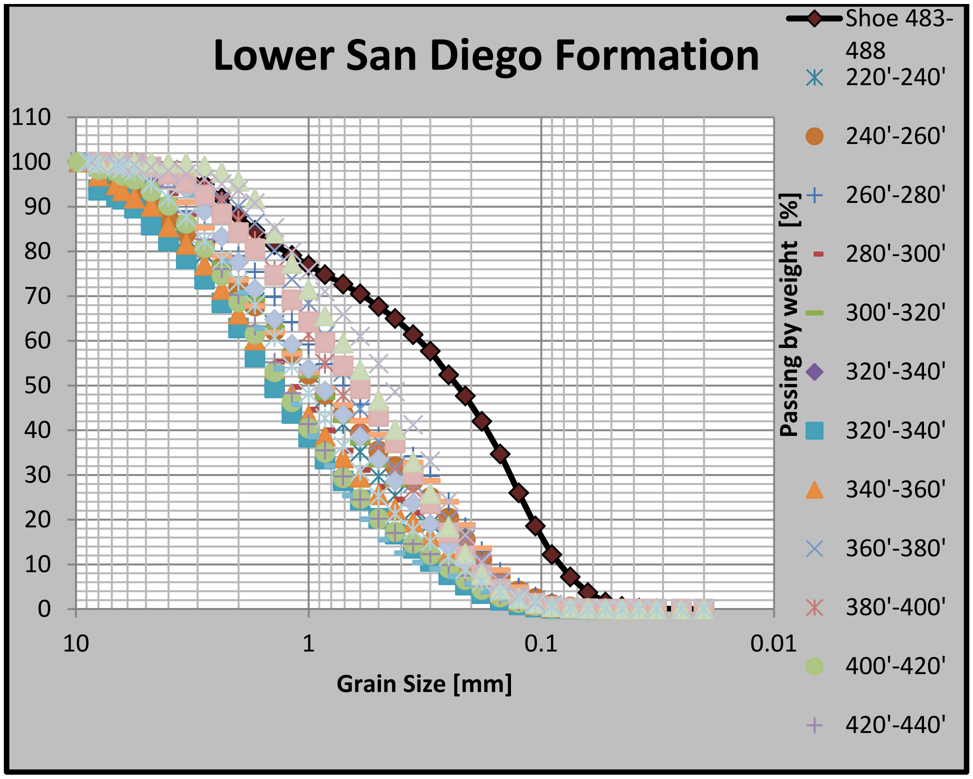


Figure 11**:** Grain size distribution curves of the lower member of the San Diego Formation (200-620 ft) showing drill cuttings and shoe samples at different depths.

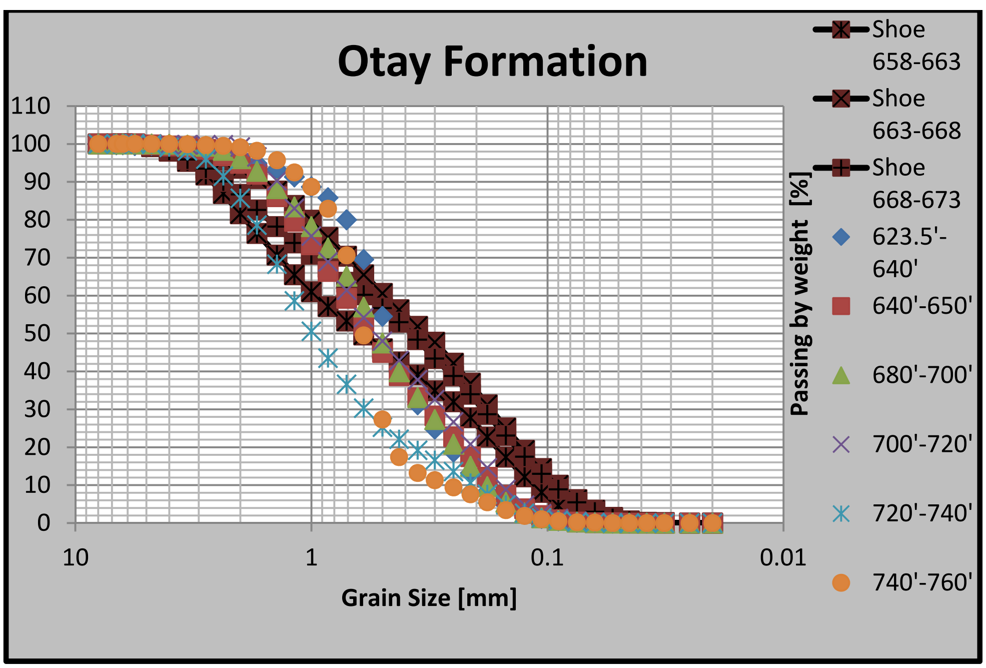


Figure 12. Grain size distribution curves of the Otay Formation (620ft-760ft) showing drill cuttings and shoe samples at different depths.

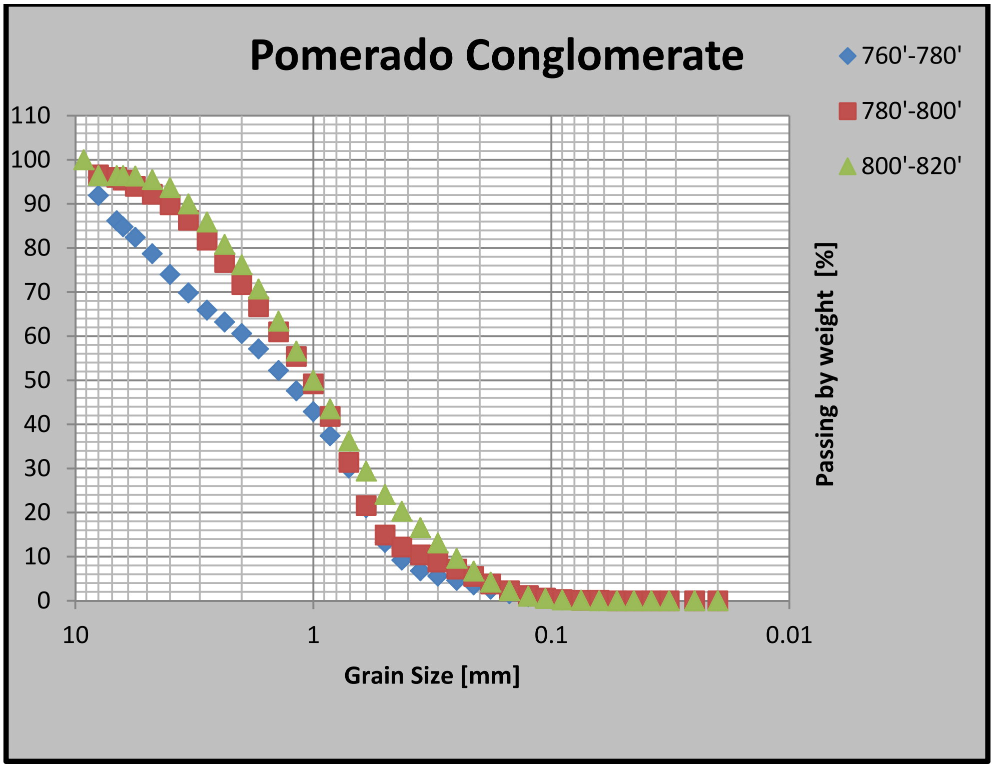


Figure 13. Grain size distribution curves of the Pomerado Conglomerate (760-820 ft) showing drill cuttings from different depths.

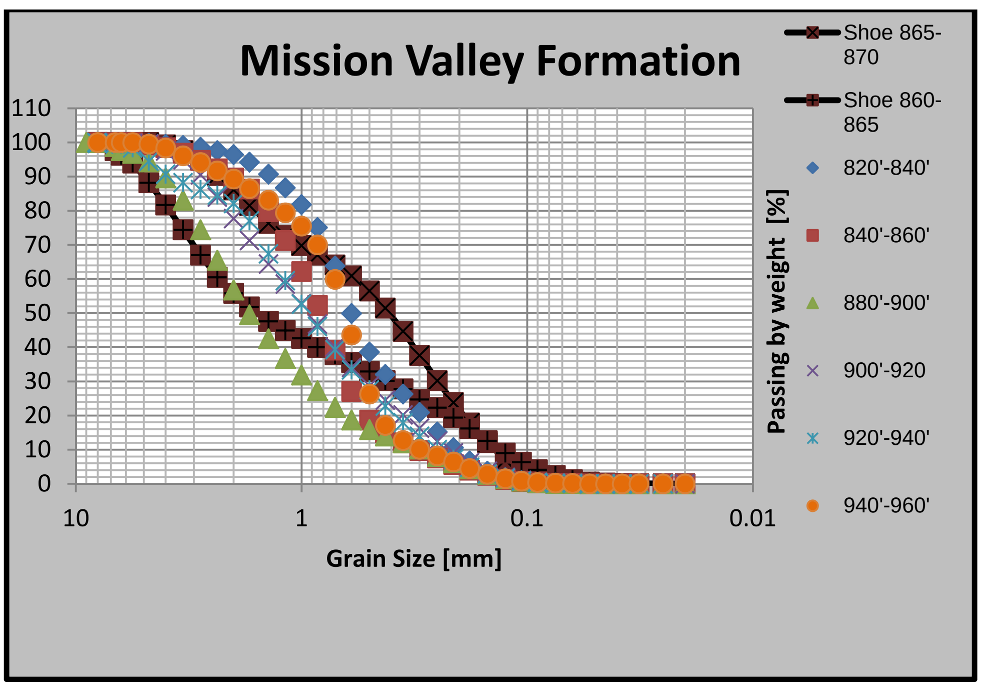


Figure 14. Grain size distribution curves for the Mission Valley Formation (820-960 ft) depicting drill cuttings and shoe samples from different depths.

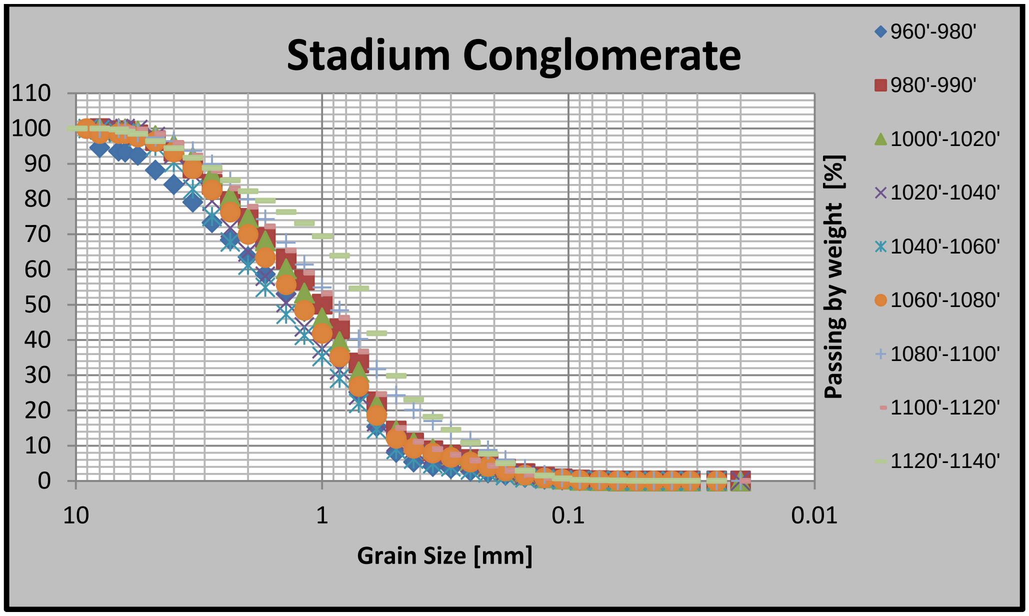


Figure 15**.** Grain size distribution curves of the Stadium Conglomerate (960-1140 ft) showing drill cuttings from different depths.

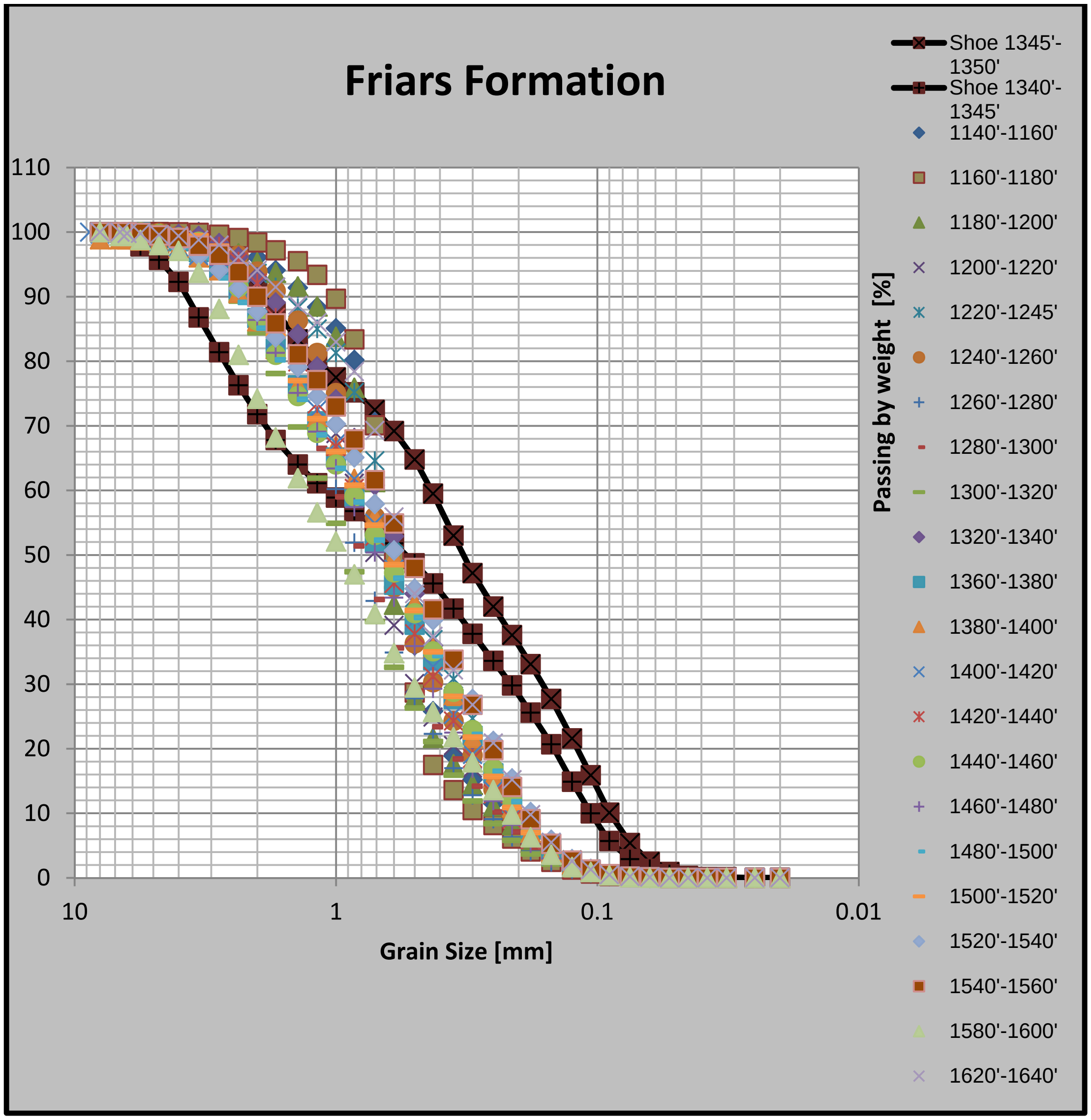


Figure 16. Grain size distribution curves for the Friars Formation (1140ft-TD) showing drill cuttings and shoe samples at different depths.

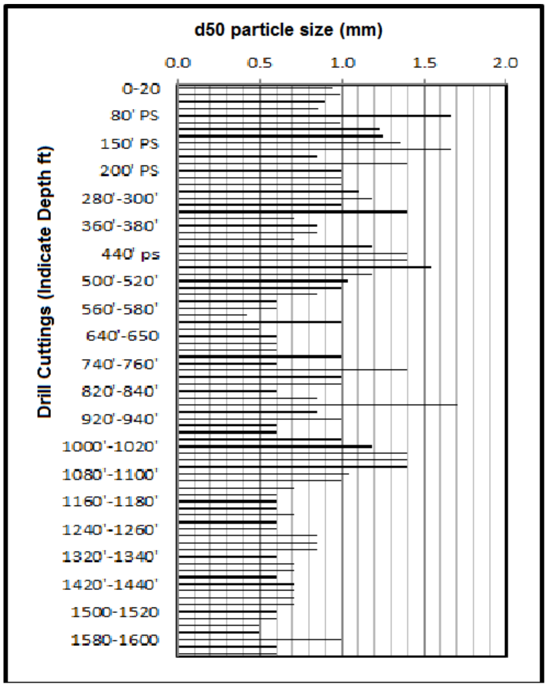


Figure 17. Bar graphs of SDHF drill cuttings showing median grain size (D50) values

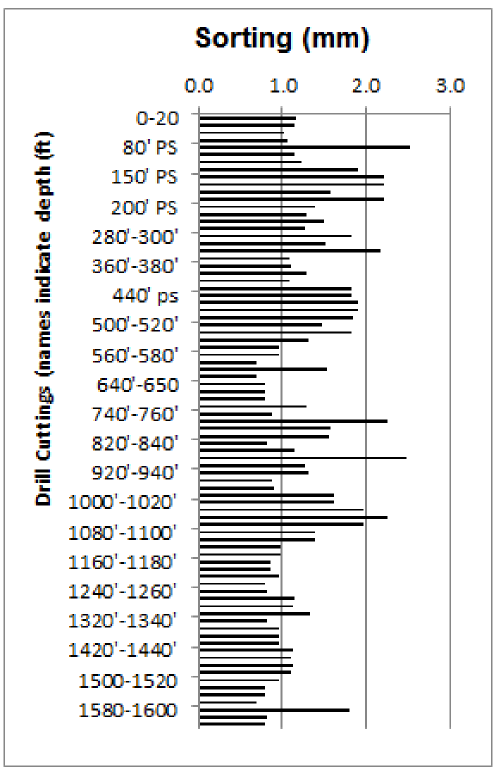


Figure 18. Bar graphs of SDHF drill cuttings showing sorting coefficient values.

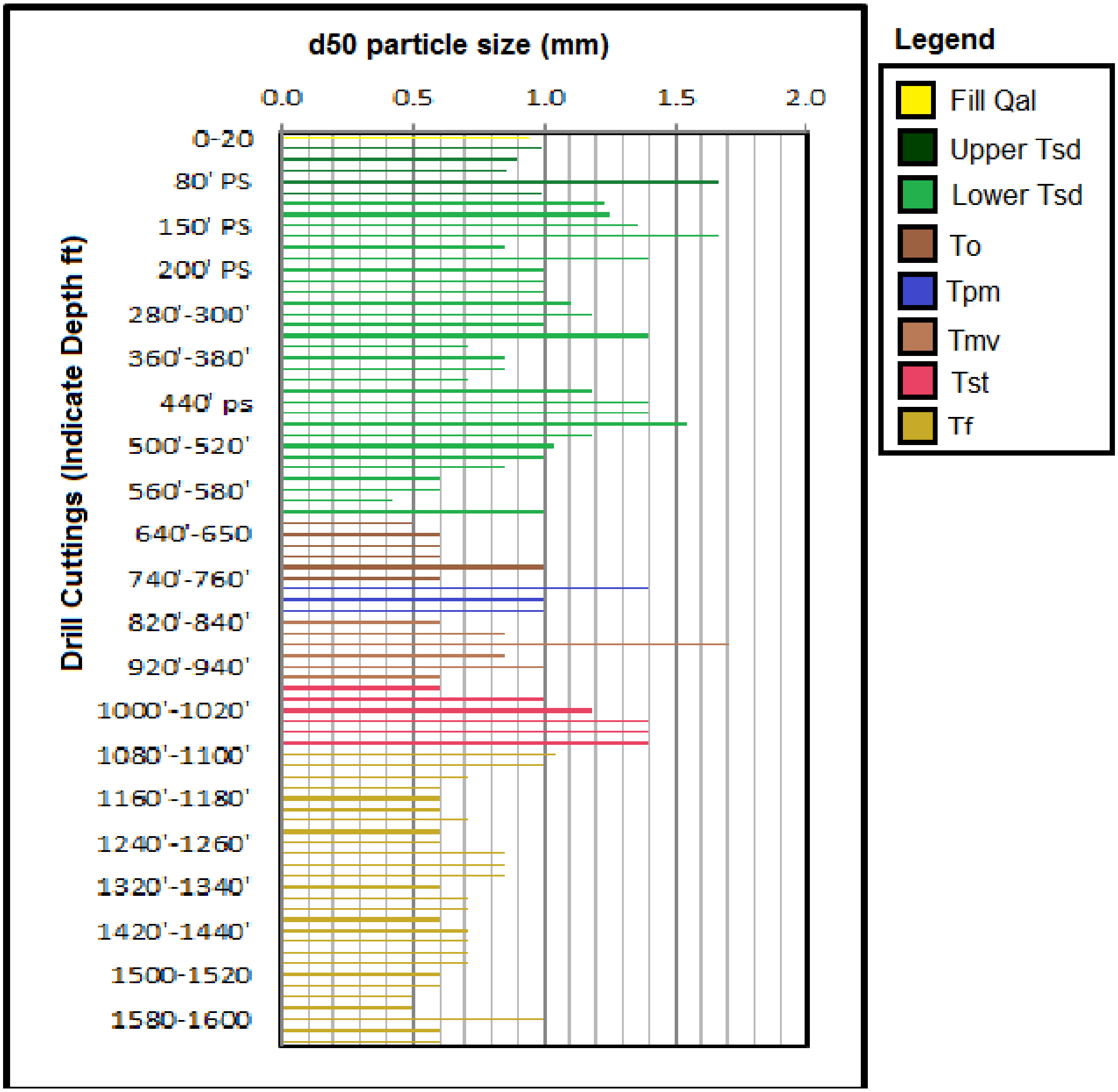


Figure 19**.** Bar graph of SDHF drill cuttings showing the correlation between median grain size values (D50) and analyzed formations.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Fill 0'-20'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Medium Gravelly Coarse Sand

	μm	ϕ
MODE 1:	6500.0	-2.700
MODE 2:	925.0	0.117
MODE 3:	550.0	0.868
D_{10}:	343.6	-3.066
MEDIAN or D_{50}:	946.1	0.080
D_{90}:	8375.2	1.541
(D_{90} / D_{10}):	24.38	-0.503
(D_{90} - D_{10}):	8031.6	4.607
(D_{75} / D_{25}):	3.883	-0.791
(D_{75} - D_{25}):	1583.7	1.957

GRAIN SIZE DISTRIBUTION			
GRAVEL:	25.7%	COARSE SAND:	32.8%
SAND:	74.3%	MEDIUM SAND:	15.4%
MUD:	0.0%	FINE SAND:	4.2%
		V FINE SAND:	0.5%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.0%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	11.5%	MEDIUM SILT:	0.0%
FINE GRAVEL:	8.6%	FINE SILT:	0.0%
V FINE GRAVEL:	5.6%	V FINE SILT:	0.0%
V COARSE SAND:	21.4%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	1790.9	709.3	-0.072	1382.6	-0.467	Very Coarse Sand
SORTING (σ):	2389.8	6.647	1.431	3.252	1.701	Poorly Sorted
SKEWNESS (Sk):	1.975	-2.105	-0.613	0.320	-0.320	Very Coarse Skewed
KURTOSIS (K):	5.587	8.588	2.936	1.010	1.010	Mesokurtic

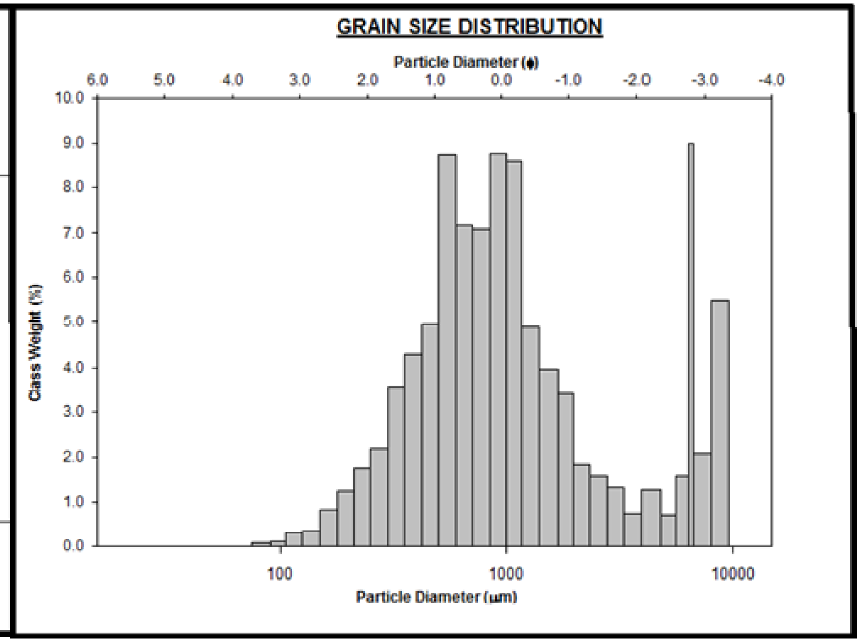


Figure 20. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for Fill based on drill cuttings sample 0-20 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Shoe 45'-50'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Coarse Sand

	µm	φ
MODE 1:	462.5	1.117
MODE 2:	655.0	0.616
MODE 3:	1850.0	-0.883
D_{10}:	190.1	-1.099
MEDIAN or D_{50}:	571.4	0.808
D_{90}:	2142.8	2.395
(D_{90} / D_{10}):	11.27	-2.178
$(D_{90} - D_{10})$:	1952.7	3.495
(D_{75} / D_{25}):	3.060	-73.336
$(D_{75} - D_{25})$:	683.4	1.614

GRAIN SIZE DISTRIBUTION

GRAVEL:	11.0%	COARSE SAND:	30.6%
SAND:	88.7%	MEDIUM SAND:	27.9%
MUD:	0.3%	FINE SAND:	11.8%
		V FINE SAND:	4.0%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.3%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
FINE GRAVEL:	2.8%	FINE SILT:	0.0%
V FINE GRAVEL:	8.2%	V FINE SILT:	0.0%
V COARSE SAND:	14.4%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic µm	Geometric µm	Logarithmic φ	Geometric µm	Logarithmic φ	Description
MEAN ($\bar{x}$):	926.2	598.3	0.741	597.1	0.744	Coarse Sand
SORTING (σ):	1027.8	2.491	1.317	2.547	1.349	Poorly Sorted
SKEWNESS (Sk):	2.523	0.198	-0.198	0.085	-0.085	Symmetrical
KURTOSIS (K):	9.958	2.900	2.900	1.177	1.177	Leptokurtic

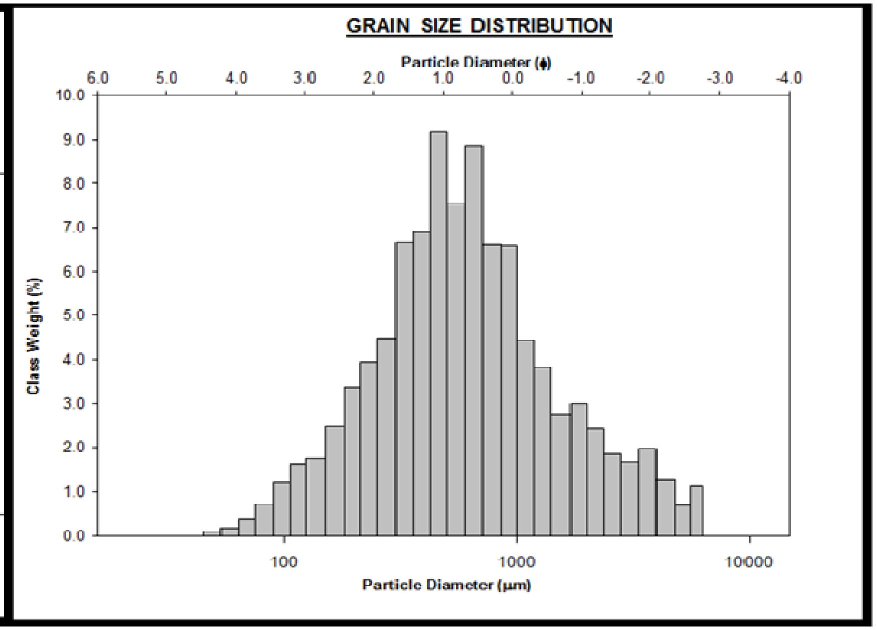


Figure 21. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for Upper Sane Diego Formation based on shoe sample 45-50 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Shoe 483-485** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Fine Sand

	μm	ϕ
MODE 1:	165.0	2.605
MODE 2:	462.5	1.117
MODE 3:	327.5	1.616
D_{10}:	101.8	-1.293
MEDIAN or D_{50}:	285.2	1.810
D_{90}:	2450.2	3.297
(D_{90} / D_{10}):	24.08	-2.550
$(D_{90} - D_{10})$:	2348.5	4.590
(D_{75} / D_{25}):	6.984	-29.197
$(D_{75} - D_{25})$:	913.8	2.804

GRAIN SIZE DISTRIBUTION

GRAVEL:	15.0%	COARSE SAND:	9.7%
SAND:	83.5%	MEDIUM SAND:	18.0%
MUD:	1.5%	FINE SAND:	29.7%
		V FINE SAND:	15.4%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	1.5%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
FINE GRAVEL:	2.4%	FINE SILT:	0.0%
V FINE GRAVEL:	12.6%	V FINE SILT:	0.0%
V COARSE SAND:	10.7%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	818.9	389.3	1.361	405.3	1.303	Medium Sand
SORTING (σ):	1078.2	3.298	1.722	3.456	1.789	Poorly Sorted
SKEWNESS (Sk):	1.936	0.491	-0.491	0.348	-0.348	Very Coarse Skewed
KURTOSIS (K):	6.465	2.067	2.067	0.767	0.767	Platykurtic

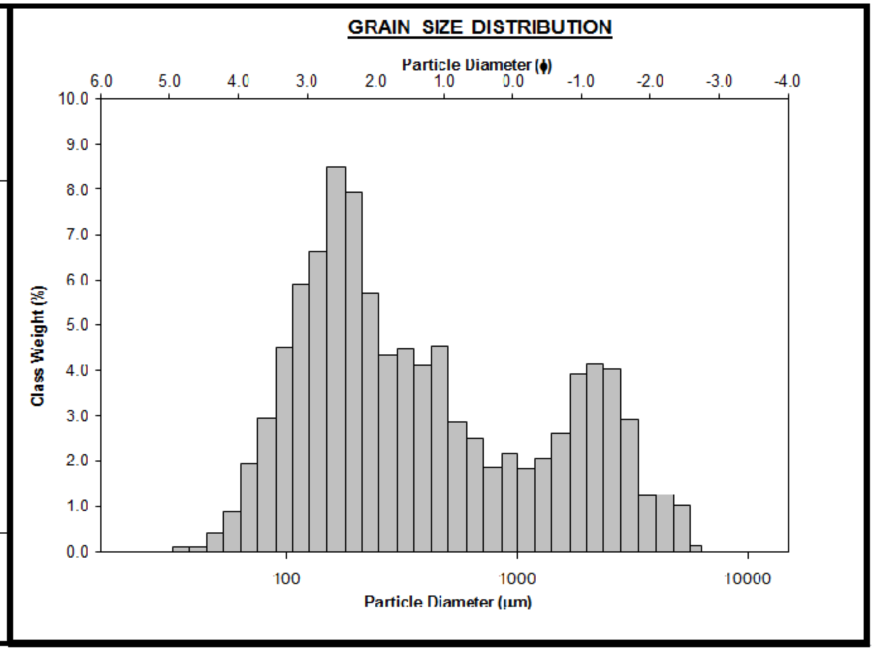


Figure 22**.** Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Lower San Diego Formation based on shoe sample 483-485 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Shoe 663-668** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Fine Sand

	μm	φ
MODE 1:	196.0	2.356
MODE 2:	327.5	1.616
MODE 3:	655.0	0.616
D_{10}:	106.0	-0.936
MEDIAN or D_{50}:	391.8	1.352
D_{90}:	1913.3	3.238
(D_{90} / D_{10}):	18.05	-3.459
$(D_{90} - D_{10})$:	1807.3	4.174
(D_{75} / D_{25}):	5.501	132.1
$(D_{75} - D_{25})$:	807.6	2.460

GRAIN SIZE DISTRIBUTION			
GRAVEL:	9.1%	COARSE SAND:	19.1%
SAND:	89.4%	MEDIUM SAND:	19.4%
MUD:	1.5%	FINE SAND:	22.5%
		V FINE SAND:	12.9%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	1.5%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
FINE GRAVEL:	1.6%	FINE SILT:	0.0%
V FINE GRAVEL:	7.5%	V FINE SILT:	0.0%
V COARSE SAND:	15.5%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	762.7	426.0	1.231	419.1	1.255	Medium Sand
SORTING (σ):	907.9	2.960	1.566	3.051	1.609	Poorly Sorted
SKEWNESS (Sk):	2.371	0.186	-0.186	0.095	-0.095	Symmetrical
KURTOSIS (K):	9.834	2.159	2.159	0.831	0.831	Platykurtic

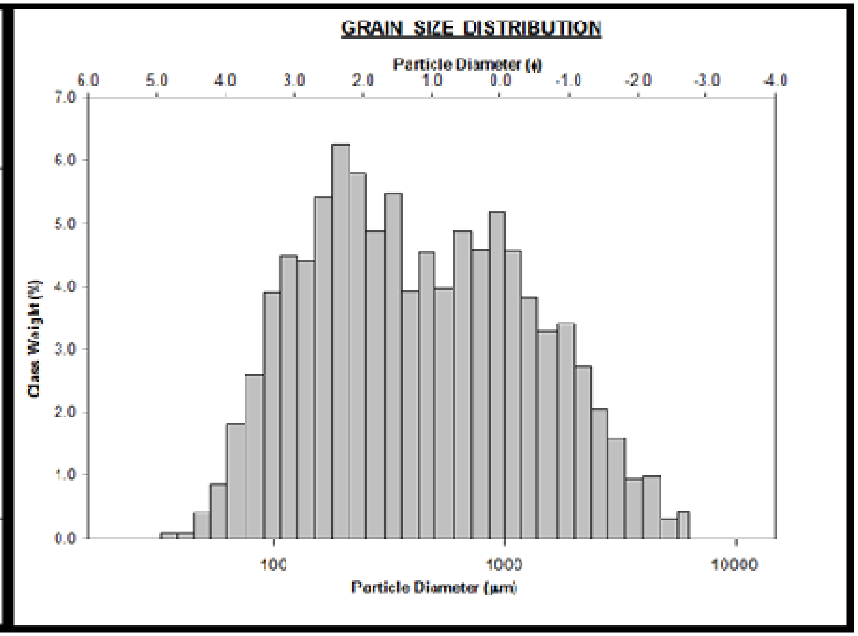


Figure 23. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Otay Formation based on shoe sample 663-688 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Drill Cutting 800'-820'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Very Coarse Sand

	μm	φ
MODE 1:	925.0	0.117
MODE 2:	3075.0	-1.615
MODE 3:	462.5	1.117
D_{10}:	305.8	-2.000
MEDIAN or D_{50}:	1180.0	-0.239
D_{90}:	4000.0	1.709
(D_{90} / D_{10}):	13.08	-0.855
$(D_{90} - D_{10})$:	3694.2	3.709
(D_{75} / D_{25}):	3.687	-0.586
$(D_{75} - D_{25})$:	1658.9	1.882

GRAIN SIZE DISTRIBUTION			
GRAVEL:	29.3%	COARSE SAND:	23.2%
SAND:	70.7%	MEDIUM SAND:	13.6%
MUD:	0.0%	FINE SAND:	6.2%
		V FINE SAND:	0.5%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.0%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	3.6%	MEDIUM SILT:	0.0%
FINE GRAVEL:	6.4%	FINE SILT:	0.0%
V FINE GRAVEL:	19.3%	V FINE SILT:	0.0%
V COARSE SAND:	27.2%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	1490.9	838.9	-0.105	1150.7	-0.203	Very Coarse Sand
SORTING (σ):	1287.1	4.804	1.266	2.687	1.426	Poorly Sorted
SKEWNESS (Sk):	1.298	-2.736	0.266	-0.043	0.043	Symmetrical
KURTOSIS (K):	4.253	12.45	2.487	0.997	0.997	Mesokurtic

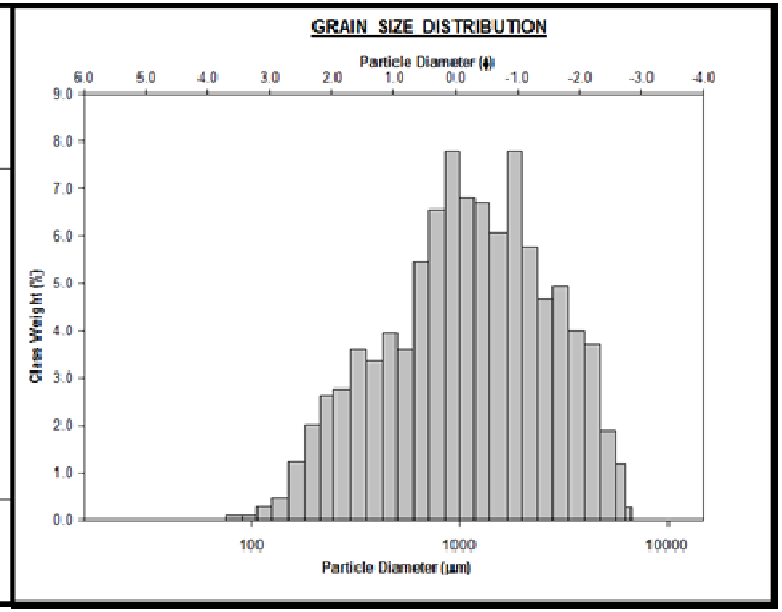


Figure 24. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Pomerado Conglomerate based on drill cuttings sample 800-820 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Shoe 865'-870'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Medium Sand

	μm	ϕ
MODE 1:	327.5	1.616
MODE 2:	462.5	1.117
MODE 3:	231.0	2.119
D_{10}:	167.2	-1.468
MEDIAN or D_{50}:	482.4	1.052
D_{90}:	2766.0	2.580
(D_{90} / D_{10}):	16.54	-1.758
$(D_{90} - D_{10})$:	2598.8	4.048
(D_{75} / D_{25}):	6.127	-2.936
$(D_{75} - D_{25})$:	1326.2	2.615

GRAIN SIZE DISTRIBUTION

GRAVEL:	18.5%	COARSE SAND:	15.5%
SAND:	81.4%	MEDIUM SAND:	27.7%
MUD:	0.1%	FINE SAND:	20.2%
		V FINE SAND:	3.5%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.1%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
FINE GRAVEL:	2.4%	FINE SILT:	0.0%
V FINE GRAVEL:	16.1%	V FINE SILT:	0.0%
V COARSE SAND:	14.5%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	1031.4	599.4	0.738	596.8	0.745	Coarse Sand
SORTING (σ):	1105.0	2.843	1.508	2.959	1.565	Poorly Sorted
SKEWNESS (Sk):	1.520	0.271	-0.271	0.239	-0.239	Coarse Skewed
KURTOSIS (K):	4.614	1.947	1.947	0.729	0.729	Platykurtic

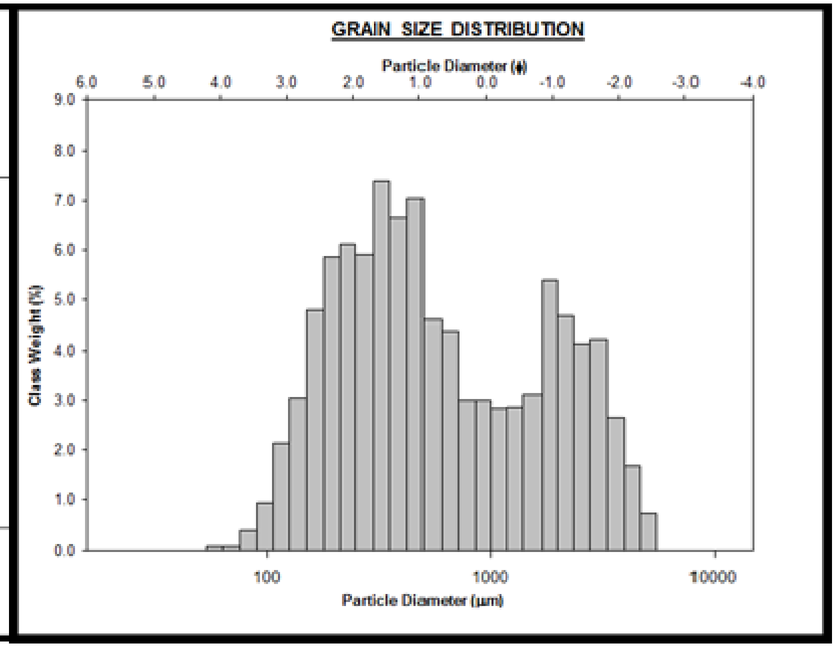


Figure 25. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Mission Valley Formation based on shoe sample 865-870 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Drill Cut 1120'-1140'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ
MODE 1:	1850.0	-0.883
MODE 2:	3675.0	-1.872
MODE 3:	925.0	0.117
D_{10}:	619.5	-2.238
MEDIAN or D_{50}:	1801.0	-0.849
D_{90}:	4717.5	0.691
(D_{90} / D_{10}):	7.615	-0.309
$(D_{90} - D_{10})$:	4098.0	2.929
(D_{75} / D_{25}):	3.680	-0.078
$(D_{75} - D_{25})$:	2439.6	1.880

GRAIN SIZE DISTRIBUTION

GRAVEL: 45.1%	COARSE SAND: 22.9%
SAND: 54.9%	MEDIUM SAND: 3.9%
MUD: 0.0%	FINE SAND: 2.0%
	V FINE SAND: 0.3%
V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
MEDIUM GRAVEL: 1.2%	MEDIUM SILT: 0.0%
FINE GRAVEL: 16.0%	FINE SILT: 0.0%
V FINE GRAVEL: 27.9%	V FINE SILT: 0.0%
V COARSE SAND: 25.8%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2261.9	1628.9	-0.744	1757.5	-0.814	Very Coarse Sand
SORTING (σ):	1671.1	2.585	1.192	2.272	1.184	Poorly Sorted
SKEWNESS (Sk):	1.038	-2.107	0.431	-0.078	0.078	Symmetrical
KURTOSIS (K):	3.657	16.32	2.845	0.809	0.809	Platykurtic

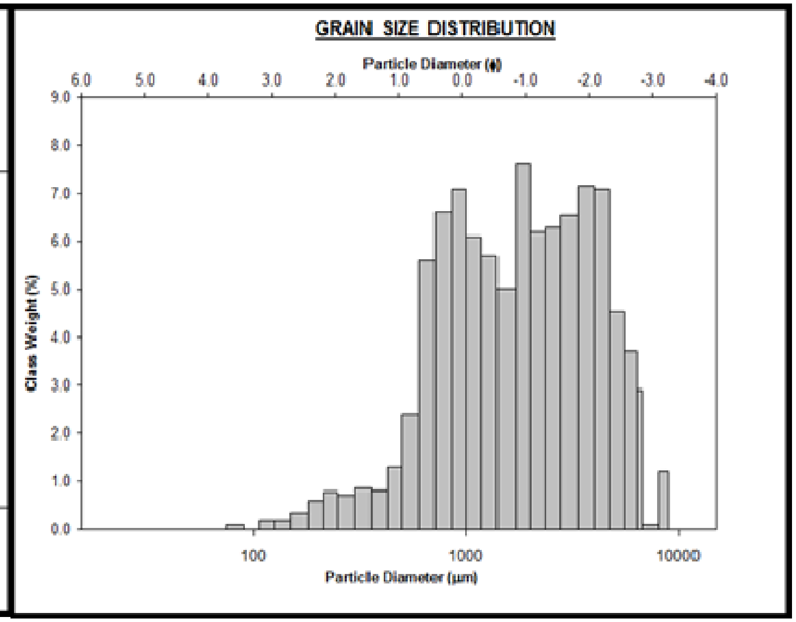


Figure 26. Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Stadium Conglomerate based on drill cutting sample 1120-1140 ft.

SAMPLE STATISTICS

SAMPLE IDENTITY: **Shoe 1340'-1345'** ANALYST & DATE: Polis, 2012

SAMPLE TYPE: Polymodal, Poorly Sorted TEXTURAL GROUP: Gravelly Sand

SEDIMENT NAME: Very Fine Gravelly Medium Sand

	μm	ϕ	GRAIN SIZE DISTRIBUTION			
MODE 1:	462.5	1.117	GRAVEL:	12.3%	COARSE SAND:	15.7%
MODE 2:	115.5	3.119	SAND:	86.8%	MEDIUM SAND:	21.9%
MODE 3:	165.0	2.605	MUD:	0.9%	FINE SAND:	21.7%
D_{10}:	105.6	-1.145			V FINE SAND:	15.0%
MEDIAN or D_{50}:	387.2	1.369	V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.9%
D_{90}:	2210.7	3.243	COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
(D_{90} / D_{10}):	20.93	-2.833	MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
$(D_{90} - D_{10})$:	2105.1	4.387	FINE GRAVEL:	1.1%	FINE SILT:	0.0%
(D_{75} / D_{25}):	5.950	149.1	V FINE GRAVEL:	11.2%	V FINE SILT:	0.0%
$(D_{75} - D_{25})$:	822.0	2.573	V COARSE SAND:	12.5%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	786.0	422.6	1.243	438.7	1.189	Medium Sand
SORTING (σ):	932.9	3.045	1.606	3.261	1.705	Poorly Sorted
SKEWNESS (Sk):	1.870	0.286	-0.286	0.143	-0.143	Coarse Skewed
KURTOSIS (K):	6.272	2.055	2.055	0.796	0.796	Platykurtic

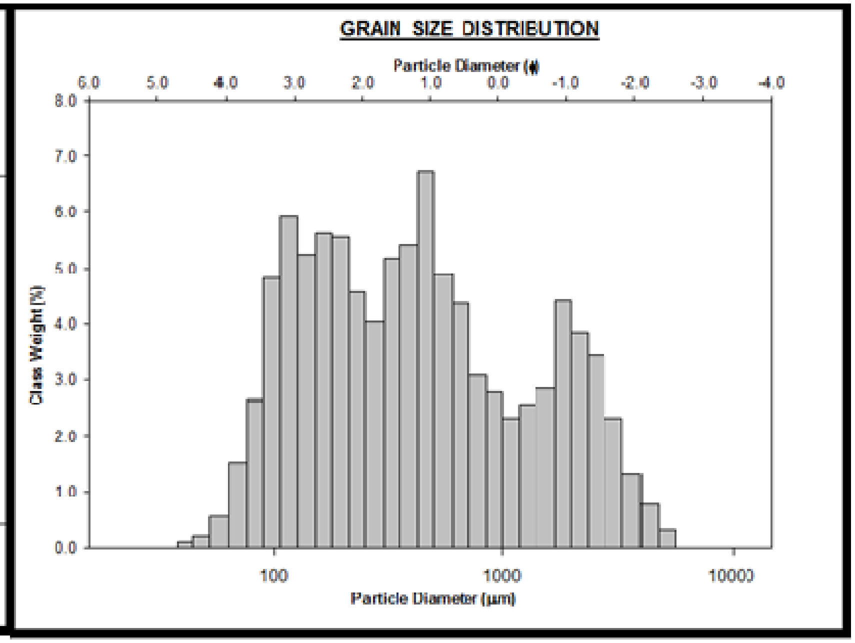


Figure 27**.** Statistical calculations (left) and logarithmic frequency plot (right) showing grain size distribution from GRADISTAT program for the Friars Formation based on shoe samples 1340-1345 ft.

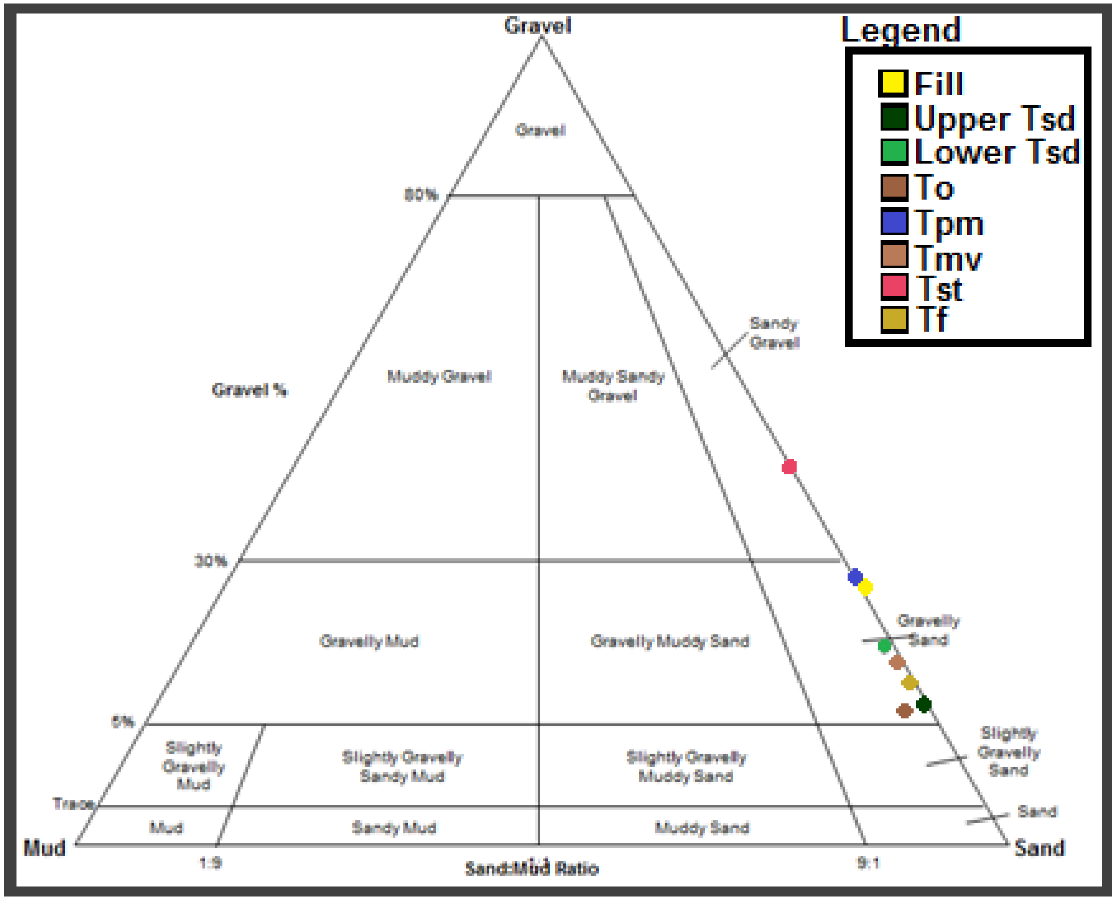


Figure 28. Ternary diagram illustrating the textural grouping of the formations encountered in the SDHF well. Fill (yellow) containing 25.7 % gravel and 74.3 % sand. San Diego Formation (Tsd) upper member (dark green) containing 11 % gravel and 88.7 % sand, Lower San Diego Formation (light green) containing 15 % gravel and 83.5 % sand. Otay Formation (To) (dark brown) containing 9.1 % gravel and 89.4 % sand. The Pomerado Conglomerate (Tpm) (blue) contains 29.3 % gravel and 70.7 % sand. The Mission Valley Formation (Tmv) (light brown) contains 18.5 % gravel and 81.4 % sand. The Stadium Conglomerate (Tst) (pink) contains 45.1 % gravel and 54.9 % sand. The Friars Formation (Tf) (gold) contains 12.3 % gravel and 86.8 % sand.

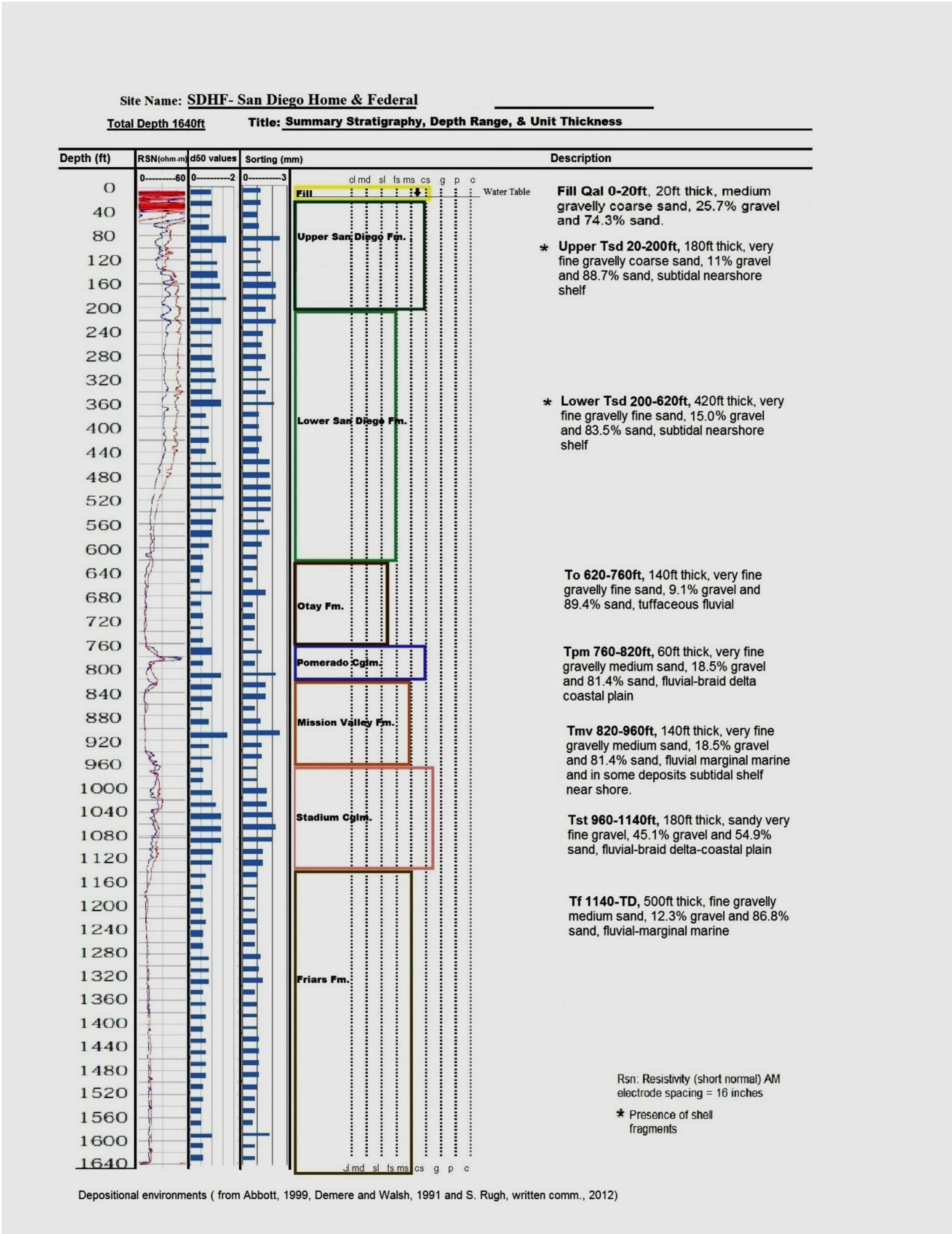


Figure 29. Stratigraphic column for SDHF well based on drill cuttings and shoe sample analysis. Figure compares resistivity, median grain size (D50) and sorting coefficients**.** (Sediment size abbreviations; c-cobble, cg-coarse grained sand, cl-clay, fg-fine grained sand, g-granule, md-mud, mg- medium grained sand, p-pebble, sl-silt)

TABLES

Table 1. Drill cutting grain size distribution parameter values. (Abbreviations: effective porosity, D10; median grain size, D50; the ratio of the grain size that is 60 % finer by weight, D60; and Sorting Coefficient)

Depth (ft)	D10 mm	Median Grain Size (D50) mm	D60 mm	Sorting Coefficent (D10+D60/2)
0-20	0.3	0.946	1.0	1.2
20-40	0.3	0.993	1.0	1.1
60 PS	0.4	0.893	0.9	1.0
70 PS	0.4	0.858	0.9	1.1
80' PS	0.3	1.669	2.4	2.5
80-100	0.3	0.993	1.0	1.1
120-140	0.5	1.234	1.0	1.2
140 PS	0.4	1.252	1.7	1.9
150' PS	0.4	1.365	2.0	2.2
160' PS	0.4	1.667	2.0	2.2
160'-180'	0.4	0.850	1.4	1.6
180' PS	0.4	1.400	2.0	2.2
200' PS	0.4	1.000	1.2	1.4
220'-240'	0.2	1.000	1.2	1.3
240'-260'	0.2	1.000	1.4	1.5
260'-280'	0.2	1.100	1.2	1.3
280'-300'	0.2	1.180	1.7	1.8
300'-320'	0.2	1.000	1.4	1.5
320'-340'	0.3	1.400	2.0	2.2
340'-360'	0.2	0.710	1.0	1.1
360'-380'	0.2	0.850	1.0	1.1
380'-400'	0.2	0.850	1.2	1.3
400'-420'	0.2	0.710	1.0	1.1
420'-440'	0.3	1.180	1.7	1.8
440' ps	0.3	1.400	1.7	1.8
450' ps	0.4	1.400	1.7	1.9
460'-480'	0.4	1.550	1.7	1.9
480' ps	0.3	1.180	1.7	1.9
500'-520'	0.2	1.033	1.4	1.5
500' ps	0.3	1.000	1.7	1.8
520'-540'	0.3	0.850	1.2	1.3
540'-560'	0.2	0.600	0.9	1.0
560'-580'	0.2	0.600	0.9	1.0
580'-600'	0.2	0.425	0.6	0.7
600'-620'	0.3	1.000	1.4	1.5
623.5'-640'	0.2	0.500	0.6	0.7
640'-650	0.2	0.600	0.7	0.8
680'-700'	0.2	0.600	0.7	0.8
700'-720'	0.2	0.600	0.7	0.8
720'-740'	0.2	1.000	1.2	1.3
740'-760'	0.3	0.600	0.7	0.9

Table 1 (cont'd.) Drill cutting GSD curve parameter values.

Depth (ft)	D10 mm	Median Grain Size (D50) mm	D60 mm	Sorting Coefficent (D10+D60/2)
760'-780'	0.5	1.400	2.0	2.3
780'-800'	0.4	1.000	1.4	1.6
800'-820'	0.3	1.000	1.4	1.6
820'-840'	0.2	0.600	0.7	0.8
840'-860'	0.3	0.850	1.0	1.2
880'-900'	0.3	1.700	2.3	2.5
900'-920'	0.2	0.850	1.2	1.3
920'-940'	0.3	1.000	1.2	1.3
940'-960'	0.4	0.600	0.7	0.9
960'-980'	0.4	0.600	0.7	0.9
980'-990'	0.4	1.000	1.4	1.6
1000'-1020'	0.4	1.180	1.4	1.6
1020'-1040'	0.5	1.400	1.7	2.0
1040'-1060'	0.5	1.400	2.0	2.3
1060'-1080'	0.5	1.400	1.7	2.0
1080'-1100'	0.4	1.042	1.2	1.4
1100'-1120'	0.4	1.000	1.2	1.4
1120'-1140'	0.3	0.710	0.9	1.0
1140'-1160'	0.3	0.600	0.9	1.0
1160'-1180'	0.3	0.600	0.7	0.9
1180'-1200'	0.3	0.600	0.7	0.9
1200'-1220'	0.2	0.710	0.9	1.0
1220'-1245'	0.2	0.600	0.7	0.8
1240'-1260'	0.2	0.600	0.7	0.8
1260'-1280'	0.3	0.850	1.0	1.2
1280'-1300'	0.3	0.850	1.0	1.1
1300'-1320'	0.3	0.850	1.2	1.3
1320'-1340'	0.2	0.600	0.7	0.8
1360'-1380'	0.2	0.710	0.9	1.0
1380'-1400'	0.2	0.710	0.9	1.0
1400'-1420'	0.2	0.600	0.9	1.0
1420'-1440'	0.3	0.710	1.0	1.1
1440'-1460	0.2	0.710	1.0	1.1
1460-1480	0.3	0.710	1.0	1.1
1480-1500	0.2	0.710	1.0	1.1
1500-1520	0.2	0.600	0.9	1.0
1520-1540	0.2	0.600	0.7	0.8
1540-1560	0.2	0.500	0.7	0.8
1560-1580	0.2	0.500	0.6	0.7
1580-1600	0.2	1.000	1.7	1.8
1600-1620	0.2	0.600	0.7	0.8
1620-1640	0.2	0.600	0.7	0.8

Table 2. Comparison of shoe sample grain size distribution curve parameter values, weights of manually sieved fines in samples, and CAMSIZER calculated fines in samples. Fines defined as sediment finer than the No. 200 sieve, 0.075 mm.

Depth (ft)	D10 mm	D50 mm	D60 mm	Sieved Weight % Fines	Camsizer Calculated % Fines
40-42.5	0.1	1.4	2.4	8.27	6.6
42.5-45	0.7	8		1.63	0.2
45-50	0.2	0.5	0.6	6.15	2.6
180-185	0.1	0.2	0.2	9.34	10.2
185-190	0.1	0.4	0.6	7.21	8.1
480-483	0.1	0.3	0.4	28.35	12.6
483-488	0.1	0.3	0.4	25.14	13.4
620-623	0.1	0.4	0.7	7.60	7.4
623-623.5	0.2	0.9	1.4	7.38	4.8
658-663	0.1	0.7	1.2	6.71	3.8
663-668	0.1	0.4	0.6	6.60	12
668-673	0.1	0.4	0.7	12.97	10.7
860-865	0.2	1.7	2.4	5.16	4.4
865-870	0.1	0.4	0.7	8.10	0.9
1340-1345	0.1	0.3	0.4	27.89	9.2
1345-1350	0.1	0.7	1.4	12.19	5.3