



Development of a Hydrologic Characterization Technology for Fault Zones

—Phase II 2nd Report —

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March 2011

NUMO-LBNL Collaborative Research Project Report

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Executive Summary

This is the 2nd report on the three-year program of the 2nd phase of the NUMO-LBNL collaborative project: Development of Hydrologic Characterization Technology for Fault Zones under NUMO-DOE/LBNL collaboration agreement. As such, this report is a compendium of the results by Kiho et al. (2011) and those by LBNL.

An electric resistivity tomography (ERT) study, ER-4 was conducted on the survey line in the upper East Canyon area of Lawrence Berkeley National Laboratory roughly parallel to the line that connects the WF-1, WF-2, and WF-3 boreholes. ER-4 is the fourth ERT survey under this project. An excellent data set with considerably less noise compared to the past surveys was obtained, and a subsequent inversion analysis revealed two well-defined low resistivity anomalies. These anomalies can be interpreted as fault gouges or damaged zones with high groundwater content. However, the location of the eastern anomaly is somewhat unexpected: ~35 m west of where the Wildcat Fault had been anticipated, based on previous studies. This discrepancy will be addressed in future studies.

Two additional boreholes, WF-3 (~150 m) and WF-4 (~210 m) were core-drilled to further define the location and extent of the Wildcat Fault zone in the East Canyon area. A vertical borehole, WF-3, was drilled ~85 m to the west of WF-2, and a slanted borehole, WF-4, was drilled ~50 m to the south of WF-2. The drilling and coring of WF-3 was difficult, as with the first two boreholes. The Orinda formation kept caving in, and it was necessary to put a casing down to ~40 m before conducting the borehole logging. Drilling and coring in the Claremont formation was very slow and difficult: A new drill bit with large, impregnated carbonado crystals was used with limited success. The drilling of WF-4 was also very troublesome, mainly because it is a slanted borehole, and there were many fault zones within which no cores were recovered, particularly in the last 100 ft.

However, the drilling of WF-4 brought many interesting discoveries: We found that the Wildcat Fault zone has multiple fault planes and that the main fault plane may be still too young to have gouges. There was strong hydraulic communication between the bottoms of WF-1 and WF-4, parallel to the direction of the Wildcat. The head at the bottom of WF-4 is higher than the elevation at the top of the hole, i.e., indicating that WF-4 is an artesian well.

Borehole geophysical logs were conducted in these boreholes, including logs for caliper, natural gamma, electrical resistivity, SP, televiewer, sonic, and fluid conductivity. In general, no apparent correlations were found between the results of the geophysical logs and the hydrologic properties, except for the fluid conductivity logs.

The cores from the boreholes were carefully examined and logged. Microscopic analysis of the thin sections and x-ray diffraction (XRD) analysis were conducted, as was isotopic analysis of the carbonates in the samples taken from the cores of the four boreholes. An additional (and extensive) surface geologic mapping was performed as well. Based on these data, a comprehensive structural analysis of the fault zone was carried out, and probable conceptual models of the fault zone structure were proposed. There still remains an ambiguity as to where/if the main fault plane exists.

After we gathered the borehole geophysical logs, the boreholes were washed and developed. In WF-3, a bailer was used to develop the hole. In WF-4, because of its artesian nature, washing was somewhat inadvertently accomplished as it flowed naturally. The WF-3 turned out to have the lowest permeability of the four boreholes; consequently, hydraulic tests in WF-3 were conducted mostly by water slug and slug rod injection and withdrawal. In WF-4, one short and one long (3 day) pumping test were conducted. The bottom 30 m of WF-4 was found to be hydraulically very well connected to the bottom section of WF-1; similarly, the middle section of WF-4 appeared to be connected to the same section in WF-2. These indicate that the preferential flow direction is from north to south, along the projected direction of the Wildcat Fault. More hydraulic tests are planned in the immediate future.

Our investigative team also constructed a preliminary 3-dimensional geologic model. This model was used for visualization of the existing data, as well as for conducting investigation into possible abutment relations within the buried formations offset by the fault(s). The 3D model was useful in conducting ‘what if’ scenario testing to aid the selection of additional borehole drilling locations and configurations. Once we have enough confidence in the geologic/structural model, it will be merged into a hydrogeological model. Meanwhile, a hydrogeological model is being constructed in parallel. In addition,

simulations were conducted to examine the extent to which topography and fault permeability influence groundwater flow. It was found that a low permeability planar feature could help match the heads observed in WF-1~3 Data from the pumping well, SSL-1 near the top of the hill turned out to be very useful in constraining the model. Even with coarse discretization, the preliminary model incorporated the majority of the features of the study site and discharge conditions were successfully matched to observed data using inversion analysis.

Our team also conducted geochemical analysis of the waters sampled from pre-existing and new boreholes. The observed tritium concentrations suggest that the waters from the bottom of WF-1 and WF-2 are of similar ages, while ICP-MS analyses suggest that the dissolved metal composition is vastly different between the two waters. These findings suggest that the waters travel a similar distance, probably recharged at the top of the Berkeley Hills, but are traveling in two separate paths, and thus through different rocks, probably along opposite sides of the presumed Wildcat Fault. This is plausible because the geology on the immediate east side of the fault, (the Claremont chert/mudstone formation) differs from the geology on the west side (the Moraga formation).

Finally, the lessons learned from conducting field investigations thus far are listed in our Conclusions (Section 8). Noteworthy among these conclusions is that investigators should not rely on existing information too heavily. Geologic maps are constructed from extrapolating/interpolating available *surface* outcrops and opportunistically obtained data, and are two dimensional. The geology at depth may be quite different, as we discovered here. Another noteworthy lesson is the need to prepare for Murphy's Law. Of course, all necessary and reasonable measures should be taken to prevent mishaps, but one should nonetheless assume that things will go wrong in the field. Thus, backup equipment and schedules should be in place beforehand. It is envisaged that these lessons will be valuable pieces of information for NUMO when it conducts its own preliminary investigations at yet-to-be selected candidate sites in Japan.

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1 Introduction

The Nuclear Waste Management Organization of Japan (NUMO) and the Department of Energy of the United States of America (DOE) established a cooperative agreement in the field of radioactive waste management on July 10, 2002. In May 2005, NUMO and the Regents of the University of California, as the DOE Management and Operating Contractor for the Ernest Orlando Lawrence Berkeley National Laboratory (LBNL), entered into an agreement to collaborate, and for LBNL to conduct work, under the auspices of the bilateral agreement.

In 2006, ANRE (Agency for Natural Resources and Energy), jointly with JAEA (Japan Atomic Energy Agency), identified outstanding technological issues and needs regarding the research and development for geologic disposal of high-level radioactive waste (HLW) subsequent to the publication of the Second Progress Report by JNC (Japan Nuclear Cycle Development Institute) in 1999. Research organizations in Japan as well as NUMO have been conducting investigations on these issues and needs. In the area of groundwater hydrology, four R&D needs were identified and are currently being investigated: (1) improvement of groundwater flow characterization technology, (2) development of testing and characterization technology in coastal areas, (3) development of testing equipment and technology, and (4) field application of testing and characterization technology. NUMO has been incorporating the results of the outcome of these R&Ds as they become available and are deemed appropriate, and is in the process of systematizing the testing and characterization technology to form a solid technical foundation for selecting the sites for detailed investigation.

The first NUMO-LBNL collaborative project, entitled “Feature Detection, Characterization and Confirmation Methodology,” was designed to further develop radioactive waste management technologies related to an investigation strategy and technology for detection, characterization, and confirmation of key geologic features at possible nuclear waste repository sites. The project was carried out from May 2005 through March 2007. Among other important findings, the study has identified the hydrologic

properties of fault zones as one of the most important parameters that need to be evaluated during the preliminary investigation stage. Based on the lessons learned at the Mizunami and Horonobe URLs, as well as at numerous mines, dams, and tunnels—and given the geologic environment of the Japanese Islands—faults are likely to exist almost ubiquitously, which need to be assessed both at the preliminary and the detailed investigation stage (the length scale of the faults of interest would range from several kilometers in the former down to several hundred meters in the latter). However, none of the four R&D activities mentioned above sufficiently addresses the development of systematized hydrologic characterization technology specifically tailored for fault zones. At present, it is necessary to use perhaps overly conservative values for the hydrologic parameters of fault zones for the design and performance assessment of a repository. Therefore, development of a more efficient and reliable fault-zone characterization technology is highly desirable. —The geologic properties of faults and the relationships among their geometry, type, fault parameters, and internal structures are being investigated mostly overseas. Hydrologic investigation of faults of various sizes are also being conducted at foreign as well as at domestic characterization sites. However, the relationship between the geologic and hydrologic properties of faults is not yet studied sufficiently.

In light of the above recognition, NUMO and LBNL entered an agreement for LBNL to conduct a three-year study entitled “Development of Hydrologic Characterization Technology of Fault Zones” in August 2007. For FY2007, the objectives of the study were to organize the information available from overseas to ultimately establish an efficient and systematized methodology for hydrologic investigation and characterization of faults at the scale of interest *during the preliminary investigation stage*, for more practical design and performance assessment. LBNL’s study (Karasaki et al, 2008) concluded that while there is very little available in the literature that relates the geologic structure of faults to hydrology, that it still may be feasible to classify faults based on geologic attributes to predict their hydrologic characteristics, and that it is critical to establish a field investigation technology for fault zone hydrology. In July 2008, NUMO and LBNL agreed to continue the project and develop a field site to study fault zone hydrology.

As part of the first phase of the field study program, a literature survey was conducted, which concluded that it may be possible to classify faults by indicators based on various geometric and geologic attributes that may indirectly relate to the hydrologic property of faults. The Wildcat Fault, which is a predominantly strike-slip fault and a member of the Hayward Fault system, was chosen to be the target fault of the field study. The Wildcat Fault runs through the LBNL property, within and around which surface-based investigations were conducted from September of 2008 through March 2011.

Three trenches were excavated and at least one fault was encountered in all three trenches. Some intriguing and puzzling discoveries were made that may contradict past published work. Predictions were made regarding the hydrologic properties of the Wildcat Fault based on the analysis of fault structure. Preliminary conceptual models of the Wildcat Fault were proposed. The Wildcat Fault appears to have multiple splays, and some low-angled faults may be part of a flower structure. Surface geophysical investigations were conducted using electrical resistivity survey and seismic reflection profiling along three survey lines north and south of the LBNL site. One interpretation suggests that the Wildcat Fault is westerly dipping; however, due to the complex geology of the Berkeley Hills, multiple interpretations of the geophysical surveys were possible. The findings are summarized in Karasaki et al (2009).

The second phase of the investigation program started in August 2009. Two more trenches were cut along the ridge of the hill that lies south of LBNL where surface geophysical surveys were conducted. The trenches encountered multiple faults. Two 150 m deep boreholes, WF-1 and WF-2, were core drilled on each side of the projected trace of the Wildcat Fault, in the East Canyon area of LBNL, during the period from December 2009 through March 2010. It was observed that the rocks were extensively sheared and fractured; gouges were observed at several depths, and a thick cataclastic zone was also observed. While confirming some earlier published conclusions from shallow observations about Wildcat, we made some unexpected findings. Preliminary analysis indicated that Wildcat near the field site consists of multiple faults. The hydraulic test data suggested that

the hydrologic structure of the fault zone had two distinct properties. The summary of the findings can be found in Karasaki et al (2010).

The present report summarizes the findings of the investigations conducted from April 2010 through March 2011. This report is conducted as a collaborative study between NUMO and USDOE/LBNL. As such, the report integrates the findings by Kiho et al (2011).

It should be possible to apply/transfer the results and findings obtained in the present report, conducted at a site on the U.S. West Coast whose tectonic environment is just as active as that in Japan, to the Japanese repository program. It is expected that those results and findings would also be beneficial to the future U.S. program.

1.1 References

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2 Geophysical Surveys

2.1 Introduction

One of the challenges of conducting geophysical surveys is finding the optimum places (lines) for conducting surveys. As noted in Kiho et al. (2011), ideally the survey lines should be located near the drilling site. It is of course best to conduct all characterization activity in one location, but it is often impractical to do so. Nonetheless, as much as possible, survey lines should adhere to the following criteria. They should be:

1. Close to the site of interest
2. Straight
3. Perpendicular to the fault
4. Free of anthropogenic noises
5. Long enough to cover the depth of interest

In 2008, during the first phase of the field investigation project, surface geophysical surveys, specifically electrical resistivity and seismic reflection surveys, were conducted along the three lines shown in Figure 2-1. These lines satisfied Criteria 2 through 5 above. In addition, the intent was to bracket the fault in the north and south. We then decided to drill WF holes in the East Canyon area of LBNL. Thus, the 1st criterion in the list above was not met, for the following reasons (as noted in Karasaki et al. (2009):

1. The location of the Wildcat shown in the literature was believed to be accurate.
2. The truck-mounted source for the reflection surveys could not be used in the steep terrain near the WF boreholes.
3. Potential anthropogenic noise sources that may affect electrical surveys, including high voltage power lines, guard rails, and buried conduits and cables, are present along WF wells.

The results of the electrical resistivity survey are shown in Figure 2-2, and the results of the seismic reflection survey are shown in Figure 2-5. As noted in the previous report

(Karasaki et al, 2009), multiple interpretations of the survey data are possible, mainly because of the highly complex geology and the inherent nature of geophysical surveys.

As part of the activities in the second phase of the project (Karasaki et al, 2010), the geophysical survey data from 2008 were reanalyzed. The reanalysis of the electrical conductivity surveys was done by two parties (Figure 2-3 and Figure 2-4), both of which showed better definition of the resistivity structure; however, there were no drastically new findings. The reanalysis of the seismic reflection data was performed by using only first-arrival data, effectively treating them as refraction survey data. The SR-2 data revealed strong evidence of a west dipping velocity discontinuity, corroborating the original analysis (Figure 2-6).

In this 2nd year of Phase II, we conducted an electrical resistivity survey in the East Canyon, which we call ER-4. The survey line is the closest ever to the WF borehole complex, marginally satisfying Criterion 1 as well as the rest of the criteria listed above. In the next section, we will describe ER-4 survey in detail.

2.2 Electrical Resistivity Survey (ER-4)

We laid out a surface electrical resistivity tomography (ERT) profile across the area of interest to image the subsurface and identify a possible fault. The profile (location as shown in Figure 2-7) was 350 m long with 6 m electrode spacing.

ERT methods use four electrodes to make each measurement: a known current is injected between two electrodes and the potential difference is measured across the other two electrodes. Electrical properties of the Earth's subsurface are related to rock types, the presence or movement of water or other fluids, or to changes in temperature and salinity. We used a combination of dipole-dipole, Wenner and Schlumberger arrays and an AGI SuperSting R8/IP system for data acquisition. The ERT dataset contained about 5,000 measurements. Data quality was very good—Figure 2-9(a) and Figure 2-9(b) show scattered plots of the injected current and measured voltage, respectively. For the interpretation, measurements that were below specified minimum voltage and current were removed.

ERT data sets were inverted for resistivity variation as a function of location using an AGI inversion code (LaBrecque and Yang, 2001). Figure 2-10(a) and Figure 2-10(b) show two inversion results that fit measured data equally well. Figure 2-11 and Figure 2-12 show comparisons of calculated and measured field data for inversion results in Figure 2-10(a) and Figure 2-10(b), respectively. The warm colors indicate areas of high resistivity, while cool colors indicate areas of low resistivity. As can be seen from the figures, the measured and calculated data match very closely.

The ER-4 results appeared to show the clearest image of the subsurface structure thus far. The data were collected overnight, a relatively long time and much longer time than ER-1 through ER-3. The ER-4 data have much less noise than the previous three surveys. Furthermore, the survey line is much closer to the WF borehole complex and thus more easily relatable to the features encountered in these boreholes.

Figure 2-10 indicates that there are two discontinuities with low resistivity, at ~150 m and ~250 m from the east end of the profile. It also appears that there is a horizontal low-resistivity zone between the two vertical zones. One interpretation is that the discontinuity at 150 m is the Wildcat Fault, while the other discontinuity at 250 m could be the East Canyon Fault, whose existence has been disputed in the past. These inferred fault traces are indicated by the blue broken lines in Figure 2-7. The horizontal low resistivity zone can be interpreted as the damaged zone (with a high-water content) between the two faults.

2.3 Summary

We conducted an electrical resistivity survey parallel to and ~110 m north of the line that connects WF boreholes. Excellent quality data were obtained, and two low-resistivity anomalies were imaged (Figure 2-7 and Figure 2-10), which may indicate the location of faults. The anomaly in the west roughly coincides with the location of the East Canyon Fault, whereas the one in the east does not quite match with the suspected location of the Wildcat, which had been thought to be further east. This discrepancy needs to be addressed by the investigation in the following year.

2.4 References

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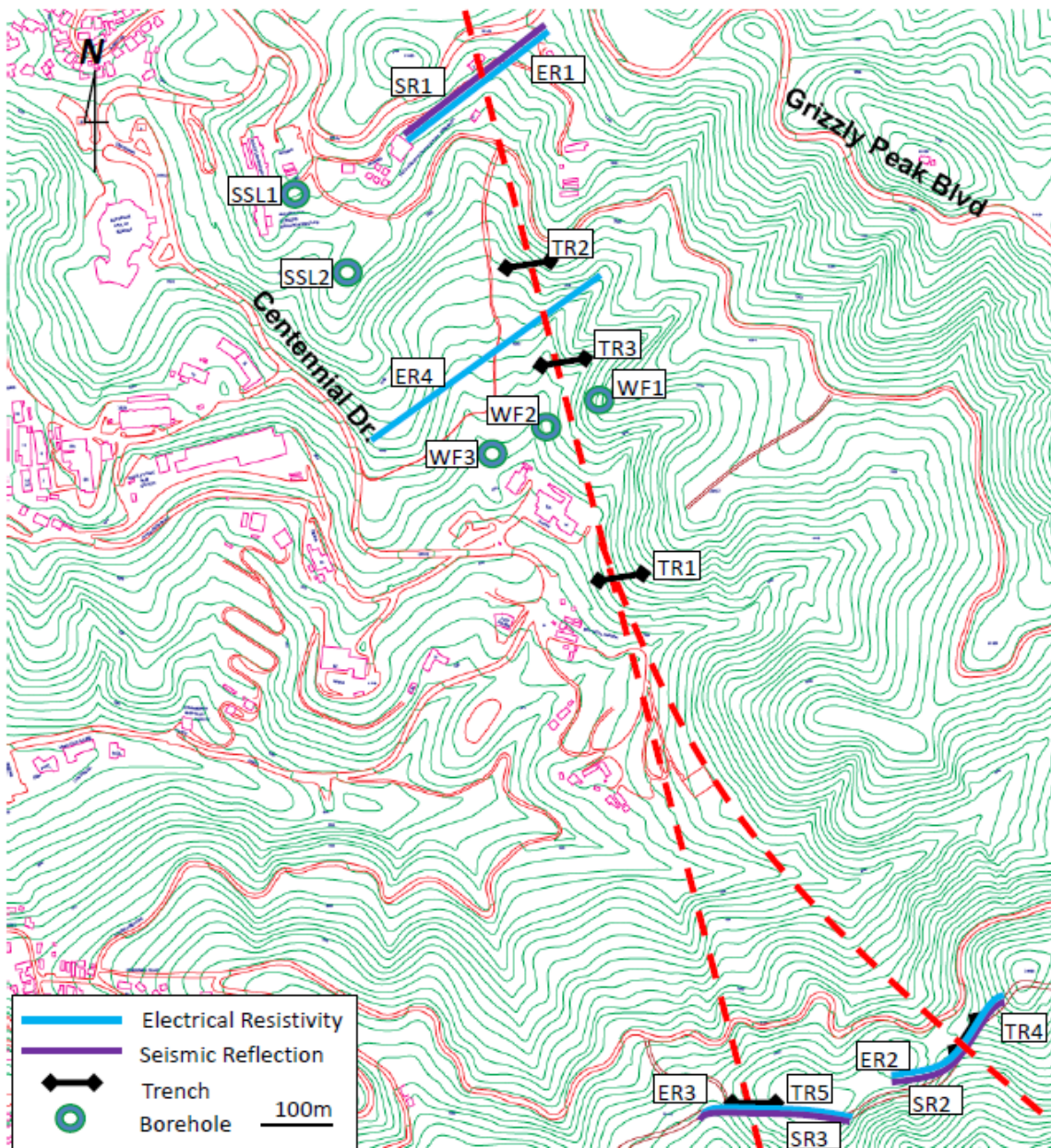


Figure 2-1. Map showing the location of surface geophysical survey lines, trenches, boreholes and inferred trace of the Wildcat Fault (red broken lines).

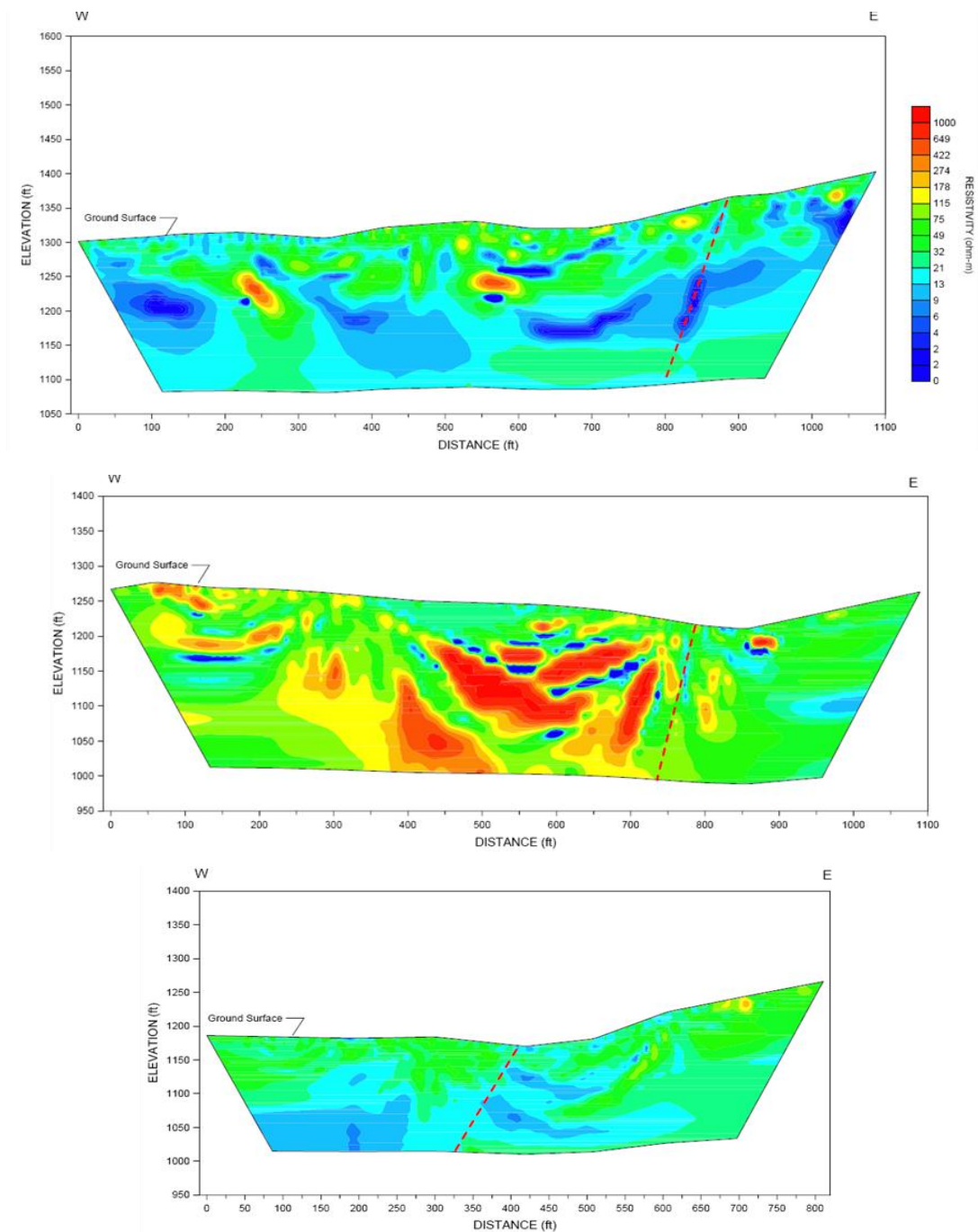


Figure 2-2 Original electrical resistivity survey interpretation for ER-1(top), ER-2 (middle) and ER-3 (bottom).

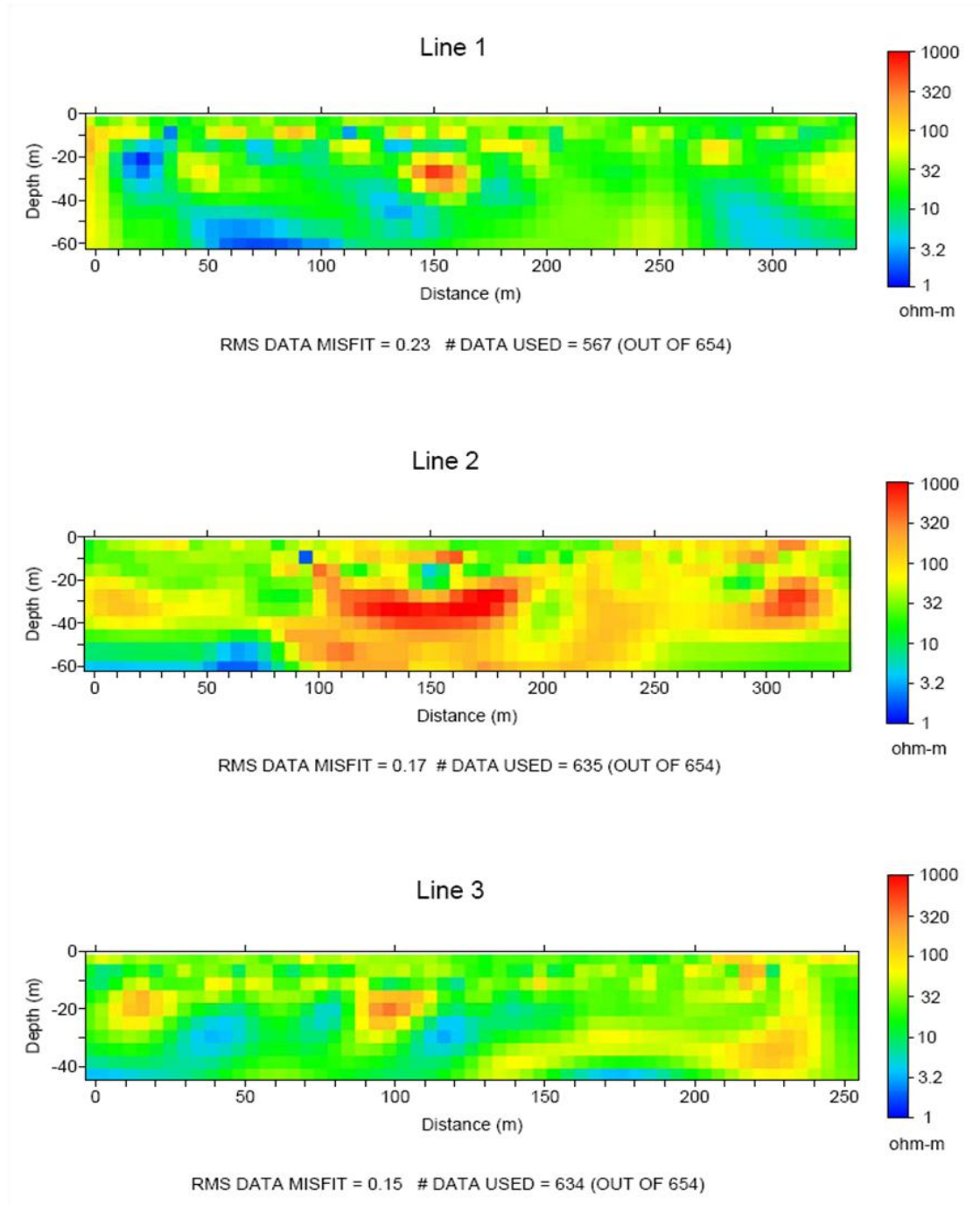


Figure 2-3. Reanalysis results of the resistivity data by Sasaki (2009).

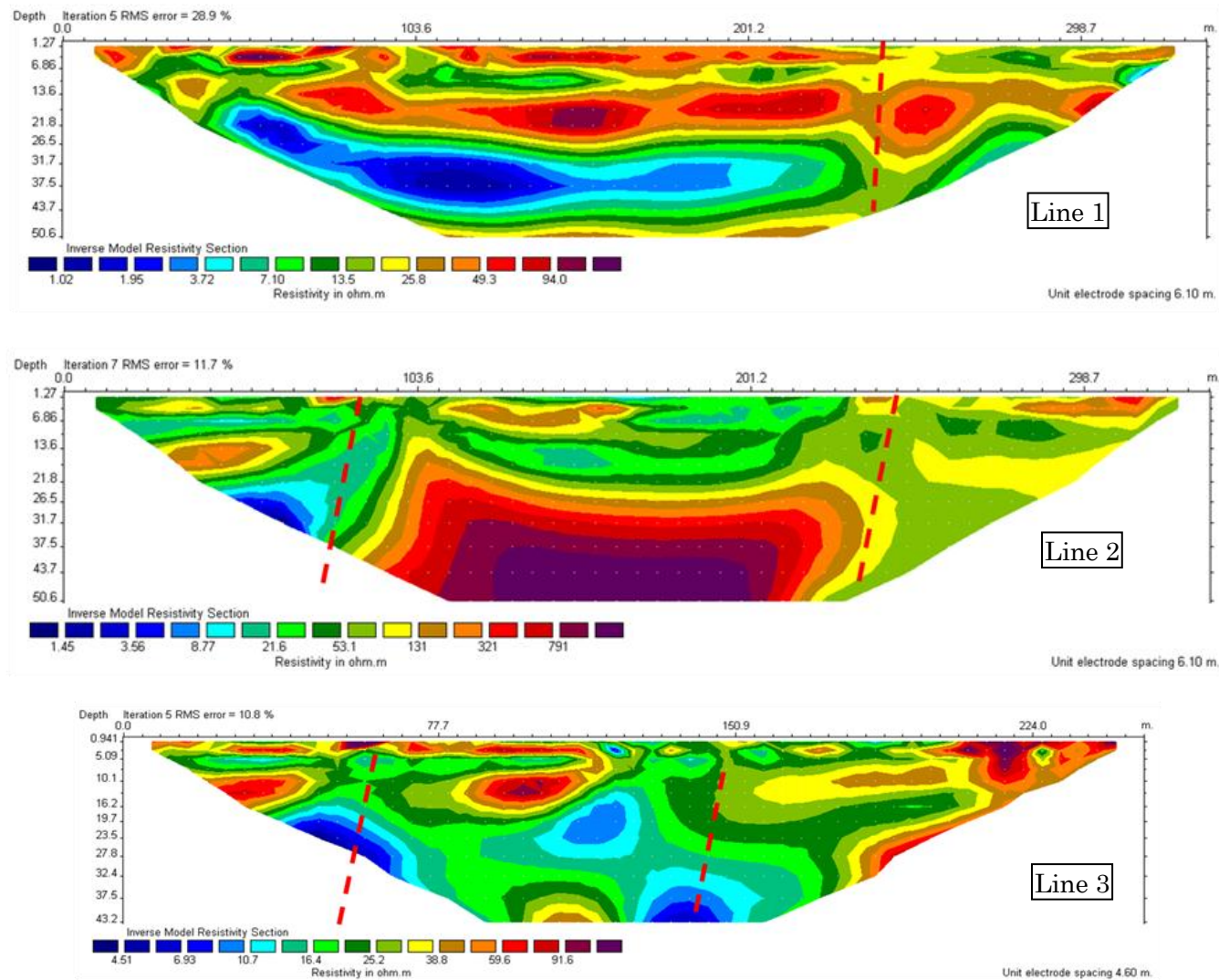


Figure 2-4. Resistivity reanalysis results by Korkealaakso (2009).

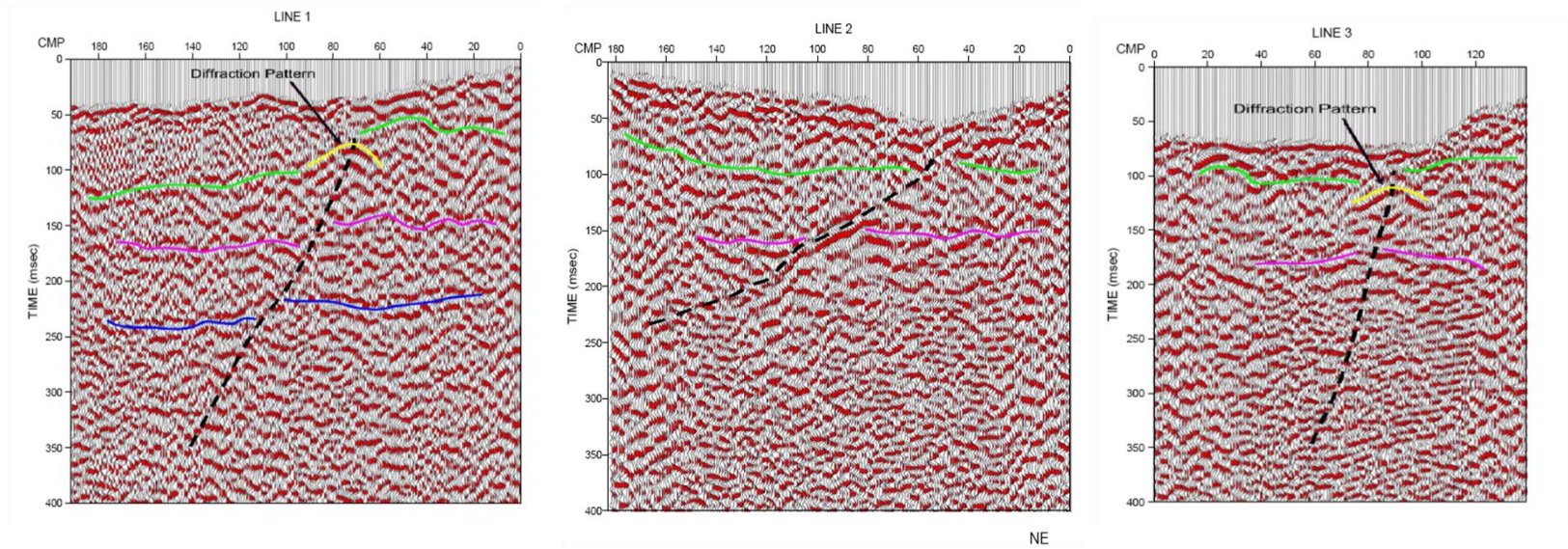


Figure 2-5: Original seismic reflection survey interpretation for SR-1(left), SR-2 (middle) and SR-3 (right).

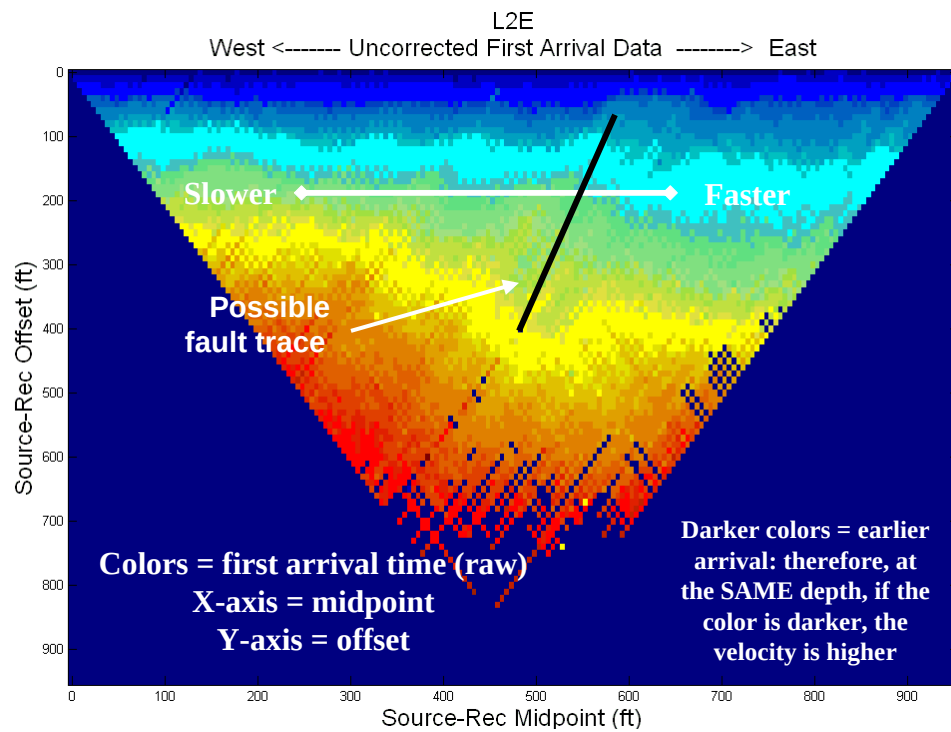


Figure 2-6: Arrival time analysis of SR-2 data. The apparent velocity is faster to the east.



Figure 2-7: Location of ER-4 profile. The blue broken lines indicate potential fault trace identified in the ERT inversion. The red broken line is the previously suspected trace of the Wildcat Fault.



(a)



(b)



(c)



(d)

Figure 2-8: (a) the AGI SupeSting resistivity imaging system, (b) looking the resistivity cable laid on the ground toward the east, (c) cable laid over asphalt road, and (d) the electrode drilled into the asphalt.

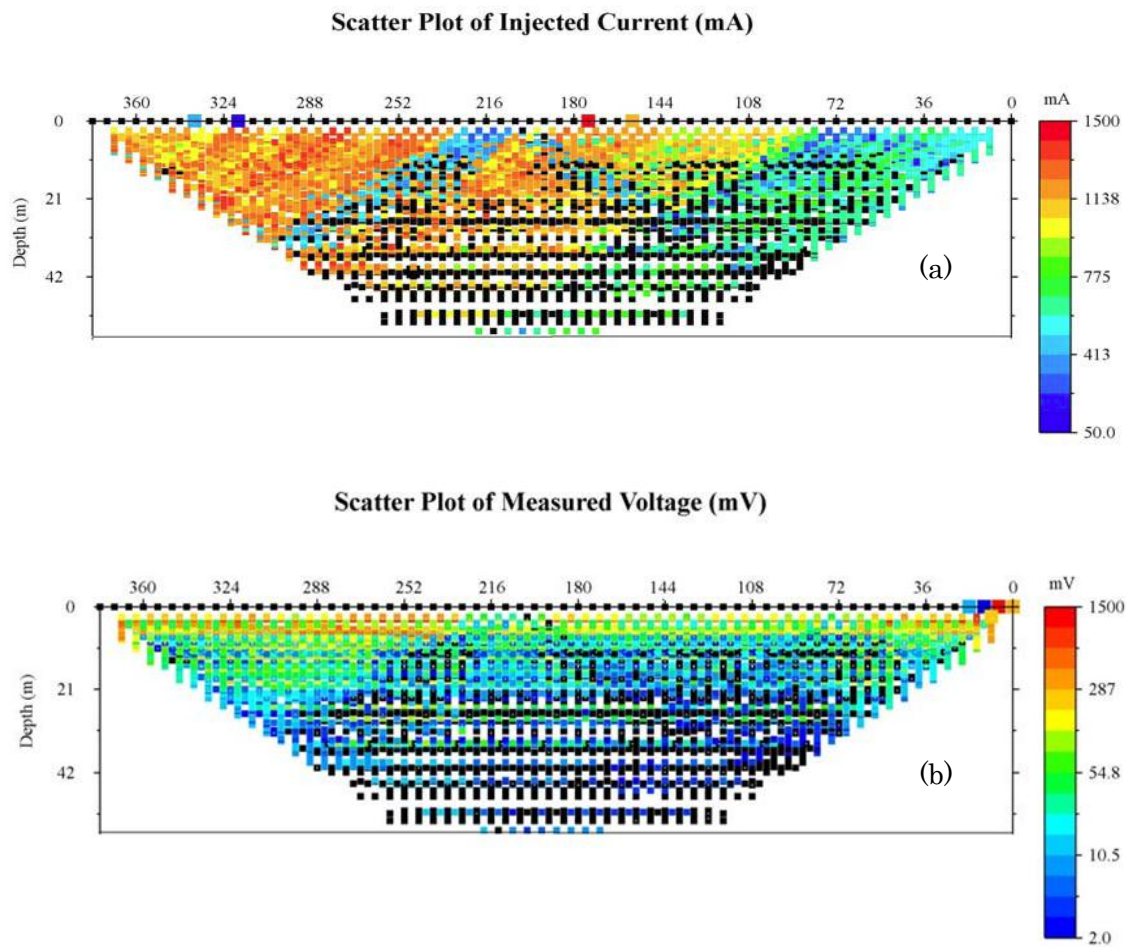


Figure 2-9: (a) Scattered plot of injected current, (b) scattered plot of measured voltage.

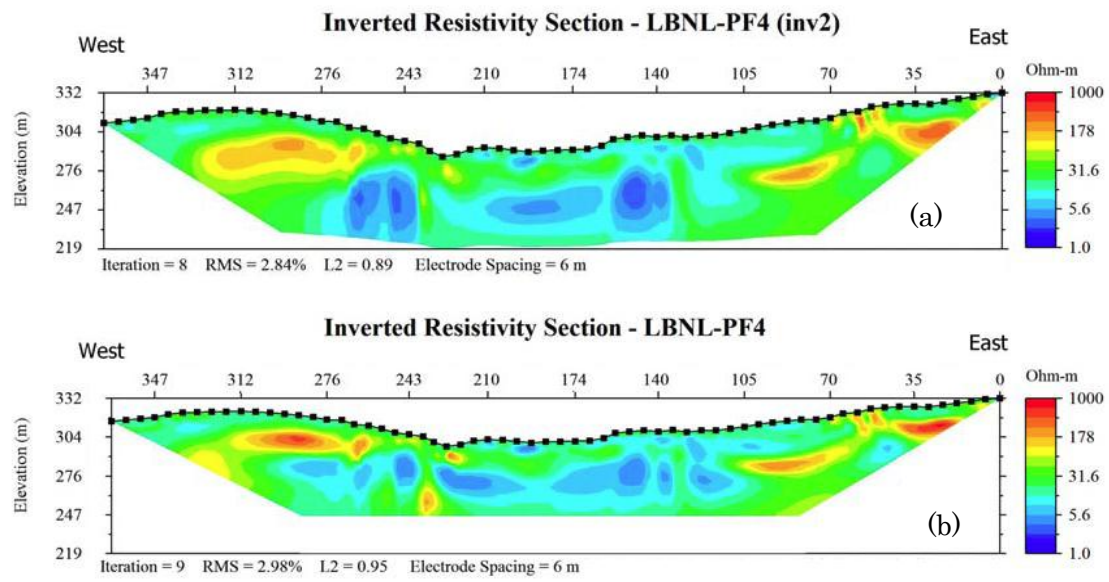


Figure 2-10: Two equally good resistivity inversion results, (a) and (b).

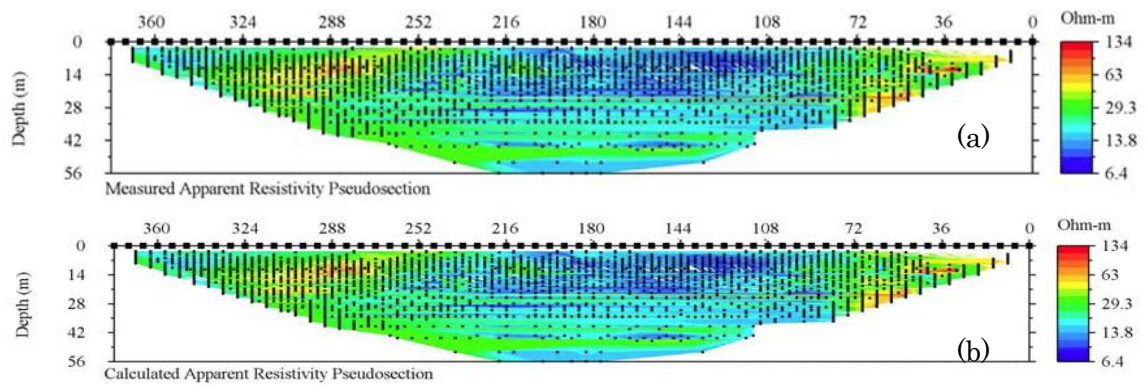


Figure 2-11: Comparison of (a) measured and (b) calculated data for the inversion model in Figure 2-10 (a).

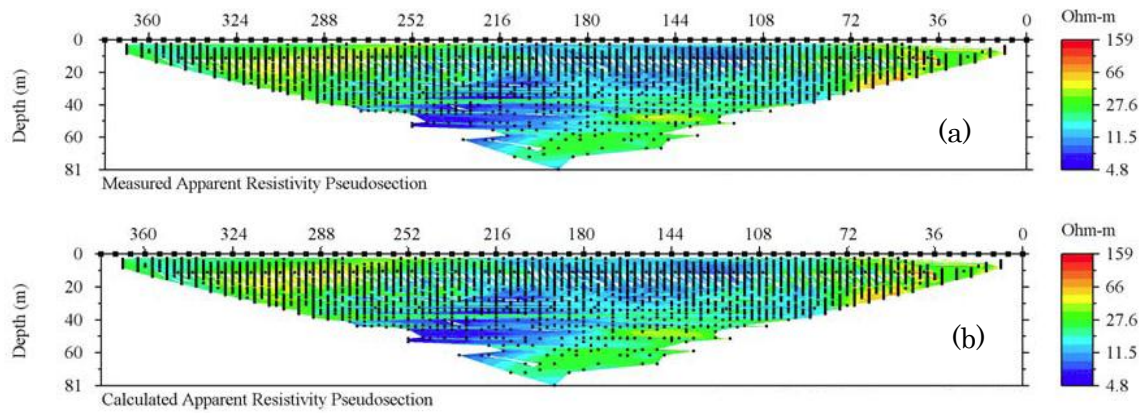


Figure 2-12: Comparison of (a) measured and (b) calculated data for the inversion model in Figure 2 8 (b).

3 Drilling Investigations

3.1 Introduction

In the first year of Phase II within the Fracture Zone Hydrology project, we drilled two approximately 150 m deep vertical boreholes (Karasaki et al, 2010). In the first hole, WF-1, we encountered the geology as expected, based on then-available literature: the Claremont formation with interbeds of chert/mudstone and shale (T_{CC} and T_{CS}), and thick formations of sandstone, whose thicknesses (up to 100 ft) were to some extent unexpected. Available information included numerous LBNL geotechnical investigation reports (ex: HLA 1974, 1977, 1980, 1982; Converse Consultants, 1994; WLA, 2008). According to the reports and other literature, the Wildcat Fault defines the geologic boundary between T_{CC}/T_{CS} and the San Pablo (T_{SP})/Orinda (T_{OR}) formations. Based on this concept, WF-2 was drilled on the west side of the Wildcat Fault, where we fully expected to encounter T_{SP} and/or T_{OR} . As discussed in Karasaki et al. (2010) after a mere 18 m thick T_{OR} formation, the WF-2 borehole encountered T_{CC}/T_{CS} from 18 m to the bottom of the hole, to 154 m.

3.2 WF-3

3.2.1 Drilling

The fact that we encountered the Claremont Formation at a very shallow depth in WF-2 made us wonder if we had missed the Wildcat Fault to the west. Thus, in FY2010, we decided to drill WF-3 at a location 86 m west of WF-2 (Figure 3-1 and Figure 3-2). Figure 3-3 shows the picture of the drill-rig setup. The location of WF-3 was chosen to ensure that the borehole would be on the west side of the Wildcat Fault, thus would have enabled us to bracket the western extent of the Claremont formation. We fully expected that we would not encounter the Claremont.

WF-3 was drilled down to 156 m. As can be seen in Figure 3-4, we initially encountered T_{OR} and T_{SP} , as expected. However, at ~100 m depth, the Claremont Formation (T_{CS}) emerged, which was totally unexpected. T_{OR} appeared again near the bottom of the hole at ~150 m. These findings are quite contrary to the expectations based

on the existing literature, which locate the Wildcat at the geologic boundary between Orinda/San Pablo and Claremont. (The detailed log of the cores from WF-3 and their analysis is given in Chapter 4, the Geology Section.) After WF-3 was drilled down to a depth of 156 m, slightly deeper than originally planned, the borehole was washed by fresh water. Subsequently, a bailer was used to develop the well by drawing down the water level in the borehole to more than 50 m below ground level.

Figure 3-5 shows the drilling speed as a function of depth. As can be seen from the figure, the drilling speed is generally well correlated with the geology: Orinda silt stones and San Pablo sandstones are relatively easier and faster to drill than Claremont mudstones. Of course, as the hole gets deeper, the speed generally decreases because core retrieval trips are longer. The drilling speed significantly slows down when the pipes need to be pulled out, such as when replacing drill bits.

3.2.2 Borehole Coordinates

The global coordinate location of WF-3 is shown in Table 3-1, as well as other WF boreholes, specifically WF-1, 2, and 4. The coordinates were surveyed by laser survey equipment, whose accuracy is better than 2.5 mm.

3.2.3 Borehole Logging in WF-3

Borehole logging of WF-3 was attempted immediately after the completion of the drilling. However, the caliper probe, usually the first of the suit of logs to be conducted because of its relatively slim size and it being the least expensive of probes, could not get past the depth of 50 m (165 ft) because of an obstruction. It was suspected that debris or rock fragments fell from somewhere at above 80 ft, where the rock is the weak Orinda siltstone. The driller was called back and the hole was drilled through once again. To prevent more sloughs from falling and blocking the hole, a 4" casing was set down initially to a 30 m depth and later deepened to a 42 m depth.

3.2.3.1 Caliper log

The results of the caliper log are shown in Figure 3-6. Caliper log anomalies correlate well with the location of faults, where the rock is generally soft, so that the borehole diameter is enlarged. The caliper log is thus very useful when deciding where to set packers. The upper portion of WF-3 has several locations where the borehole diameter is quite large. A fault was suspected in the first 30 m portion (Kiho et al., 2011). Drill pipes vibrate and damage the hole where rock is weak, such as at the Orinda siltstone formation. Frequent pulling up and lowering down of drill pipes can damage the hole. At the end of each day, the drill string was pulled out to prevent it from freezing in the hole due to a cave-in. This was a lesson learned from the first hole, in which the drill string was caught by a fault gouge zone and had to be overcored to release it, which significantly delayed the project and added costs.

Particularly notable is the fault at ~150 m, where the borehole is enlarged over a span of 2 m, indicating the potential magnitude of the damage due to faulting. Kiho et al. (2011) named the fault Fc.

3.2.3.2 Electric logs (ELOG)

The so-called ELOG probe measures the rock resistivity with three different offsets, as well as measuring the level of natural gamma and self-potential (SP). A section of the ELOG results conducted in WF-3 is shown in Figure 3-7. (The entire log is shown in Appendix A.) ELOGs were conducted in **in [within? for?]** all the holes drilled thus far; However, we have not been able to correlate any significant geologic or hydrologic features to the ELOG anomalies, with the possible exception of the bleached lithified chert breccia found at several depths in WF-1 and WF-2, as well as at a depth of 450 ft in WF-3. All of these do occur near a suspected fault, signified by opposite kicks in natural gamma (low) and resistivity (high), as shown in Figure 3-19.

3.2.3.3 Borehole Televiewer (BTV) log

Borehole televiewer (BTV) logs have been conducted in all the boreholes thus far. They have been an effective tool for determining the bedding and fracture orientations in

boreholes, particularly when the water in the borehole is not clear. All WF boreholes have been drilled using a mud rotary rig. Drilling in the Orinda silt and Claremont mudstone formation produce fine particles, as do the fault gouges that get suspended in water even after a good washing. The use of optical viewers has not been possible.

Figure 3-8 shows the borehole televiewer images from a depth of ~74–77.4 m (243–254 ft), where the largest inflow was observed by an FFEC log in the San Pablo sandstone, and at a depth of 148.7–151.7 m (488–498 ft), where a large fault is suspected. The former image is very clear, and fractures can be easily identified. The latter is not so clear. Due to the presence of a fault, the borehole is enlarged and the rock is soft, so that acoustic waves reflect strongly back to the receiver. The existence of a fault is suspected, but the orientation of it is difficult to determine. The dip and orientation for the top and bottom boundaries of the darkened zone are used (with some uncertainty) to determine the orientation. Geologic analysis by combining the results of the BTV images and core observations is discussed in Chapter 4. The complete BTV images of WF-3 and WF-4 can be found in Appendix A and B, respectively.

3.2.3.4 Sonic log

Along with other borehole logs, sonic logs were conducted in all the boreholes, including WF-3. Sonic borehole logs can be used to estimate the P-wave velocity of the rock as a function of depth. The data from sonic logs were originally intended to help analyze the data of the seismic reflection surveys and future borehole seismic tomography. However, the reflection surveys revealed that the data are too noisy to be effective in the Berkeley Hills. The Claremont chert/mudstone formations are immensely folded, fractured and faulted, not like a layer cake geology, in which reflection surveys are successfully used.

Figure 3-9 shows a section (30–90 m) of the sonic log results conducted in WF-3. (The entire plot of the log can be found in Appendix A.) As can be seen from the figure, the interval from 240–270 ft (73–82.3 m) shows high sonic velocity, indicating a higher density rock. At the same time, the interval has a high resistivity. This interval corresponds to San Pablo sandstone with many sea-shell fossils. At the same time, this zone includes the

largest FFEC anomaly. However, we cannot draw the general conclusion that high sonic velocity and high resistivity signifies a flow zone. As shown in Figure 3-10, the highest flow zone at 450 ft (137 m) in WF-2 has a low-velocity (high transit time) anomaly, which is quite the opposite of what is seen here.

3.2.3.5 Flowing Fluid Conductivity (FFEL) log

FFEC logs were conducted in boreholes WF-1 and WF-2 (Karasaki et al., 2010) and proved to be effective in pinpointing the location of flowing features. When conducting FFEC logs, it is ideal to replace the borehole water with deionized water for maximum sensitivity, however, we used tap water from a nearby fire hydrant for convenience and cost saving—there is enough contrast in conductivity between the water from the fire hydrant and the formation water, FFEC logs worked reasonably well in WF-3. Figure 3-11 shows the FFEC log results from WF-3, where two round trips (from top to the bottom and back to the top) of the conductivity sensor were made. Inflow points can be identified by the growing conductivity and kinks in temperature profile. As can be seen in the figure, three points can be identified, 75 m, ~100 m, and ~110 m; by far the most dominant is the feature at 75 m. Figure 3-11 also shows the picture of the core from the same depth. The rock is San Pablo sandstone with many sea-shell fossils. It appears that the fracture at the end of the core is the flowing fracture, based on the comparison to the BTV image shown in Figure 3-8.

Table 3-1 Global coordinates of WF Borehole tops

	Northing		Easting		Elevation (m)
	Degrees and minutes	Decimal	Degrees and minutes	Decimal	
WF-1	37° 52' 41.554"	37.87820944	-122° 14' 19.902"	-122.2388631	285.8
WF-2	37° 52' 40.341"	37.8778725	-122° 14' 21.984"	-122.23944	278.1
WF-3	37° 52' 38.905"	37.87747361	-122° 14' 25.003"	-122.2402786	270.2
WF-4	37° 52' 38.874"	37.877465	-122° 14' 22.358"	-122.2395439	265.1

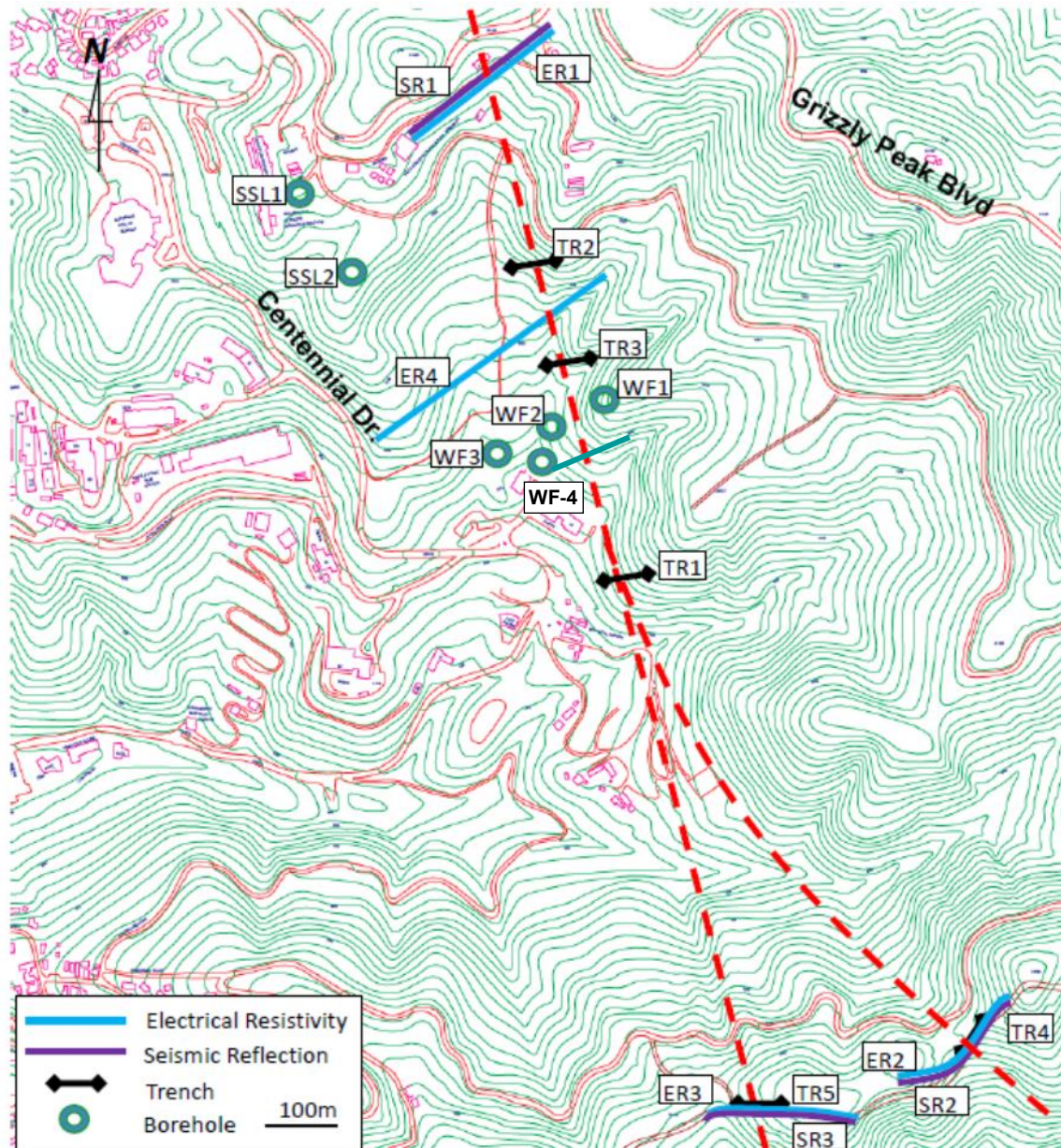


Figure 3-1. Map showing the location of surface geophysical survey lines, trenches, boreholes and inferred trace of the Wildcat Fault (red broken lines).



Figure 3-2. Satellite view of the WF borehole locations compiled using Google Earth.



Figure 3-3. Drilling of WF-3. A truck mounted drill-rig with a 30ft mast is used. The truck behind it is the support water truck with drill pipes.

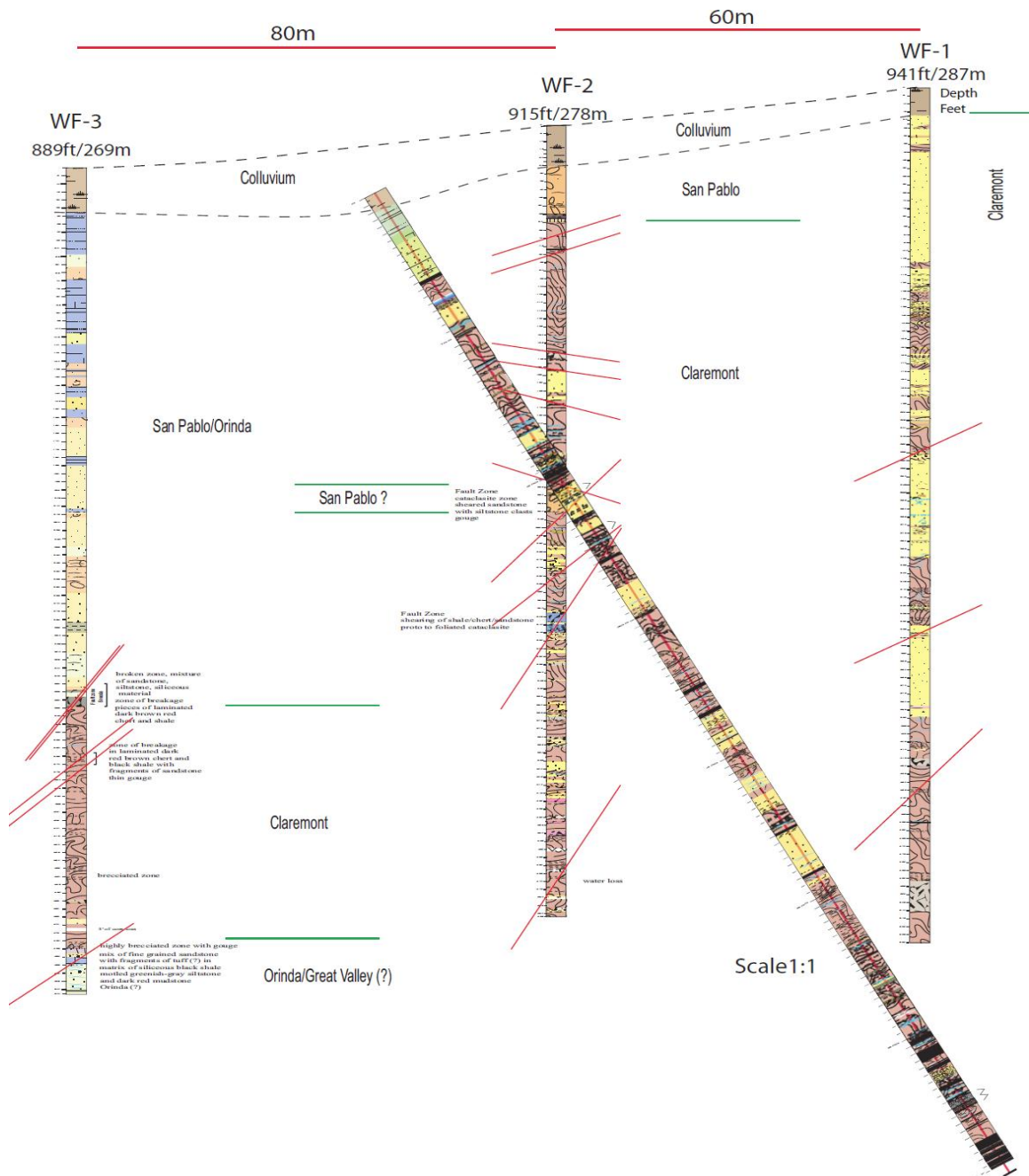


Figure 3-4. Geologic columns and fault traces in WF boreholes.

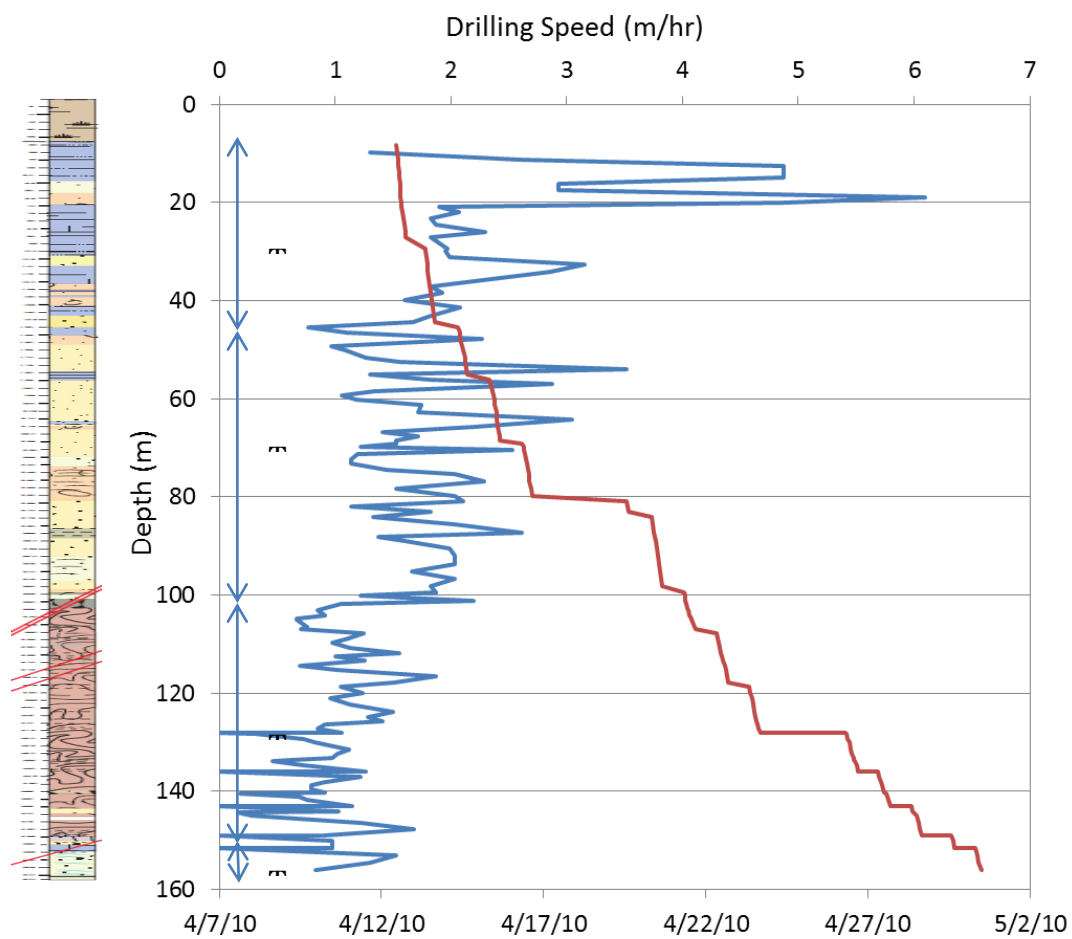


Figure 3-5. Drilling speed as a function of depth and lithology. Note that the drilling speed reduced dramatically in chert.

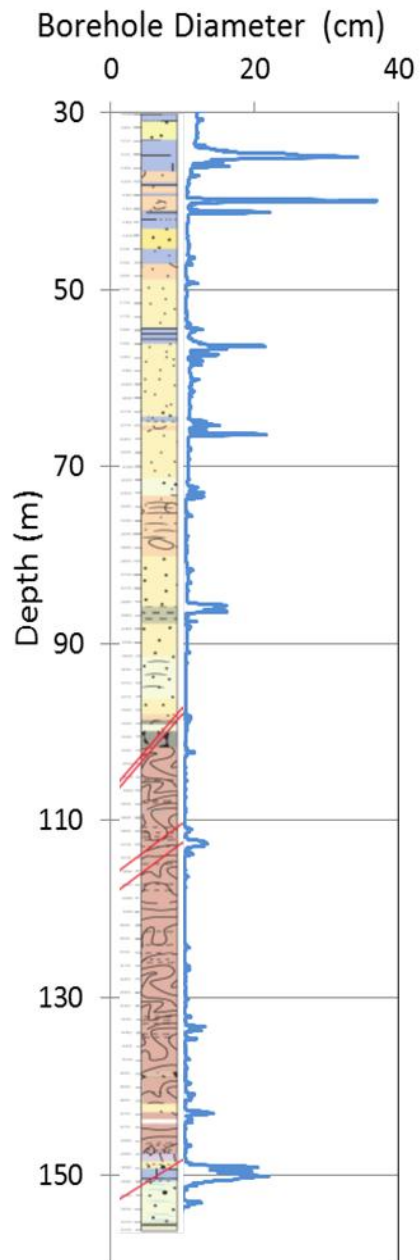


Figure 3-6. Borehole caliper log superimposed with the core log of WF-3. All identified faults (red lines) correlate well with the enlarged borehole diameter. In addition, the Orinda siltstone/sandstone formation is very weak and gets enlarged by drillpipes.

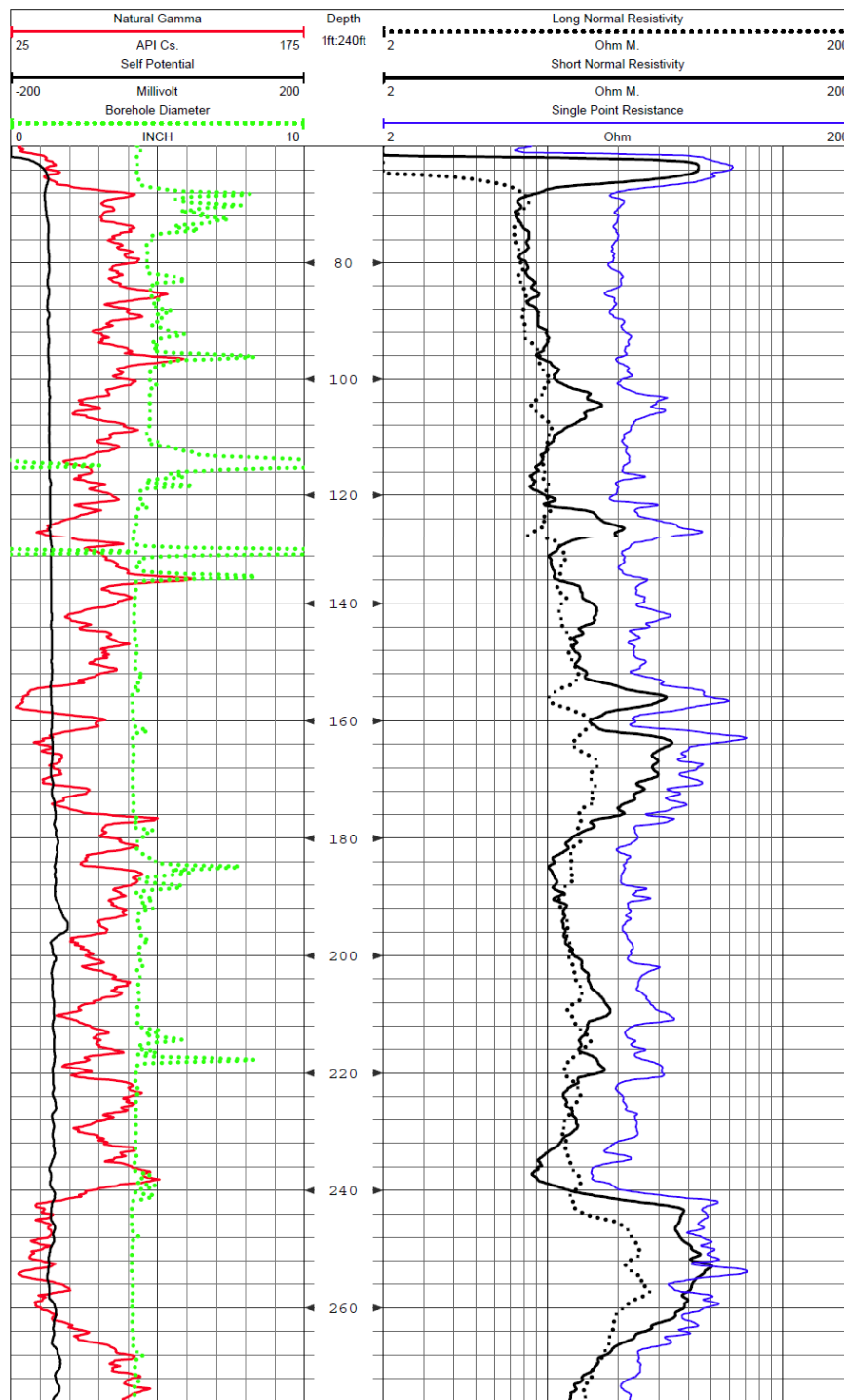


Figure 3-7. Example plot of ELOG survey by a Robertson Geologging tool from WF-3.

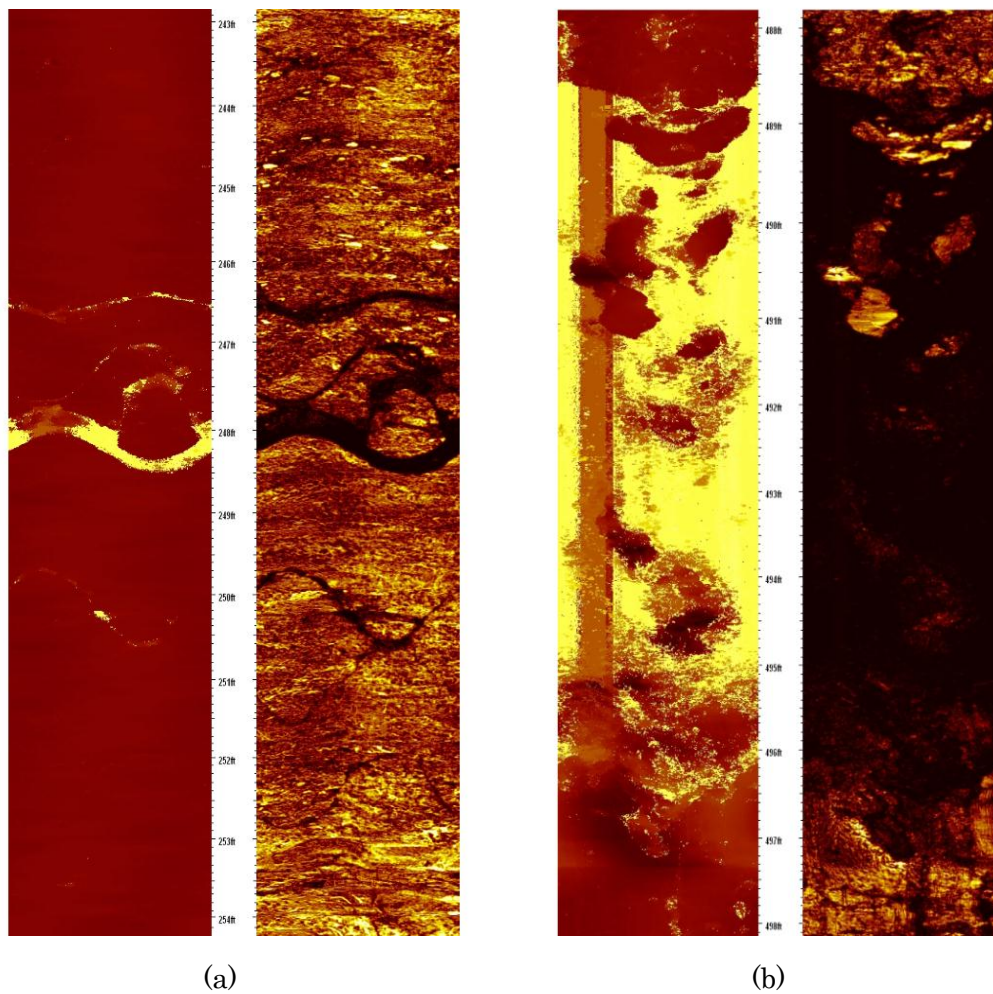


Figure 3-8. Borehole televiwer images from (a) 74~77.4m (243-254ft), where the largest inflow was observed by a FFEC log. (b) 148.7~151.7m (488~498ft), where a large fault is suspected.

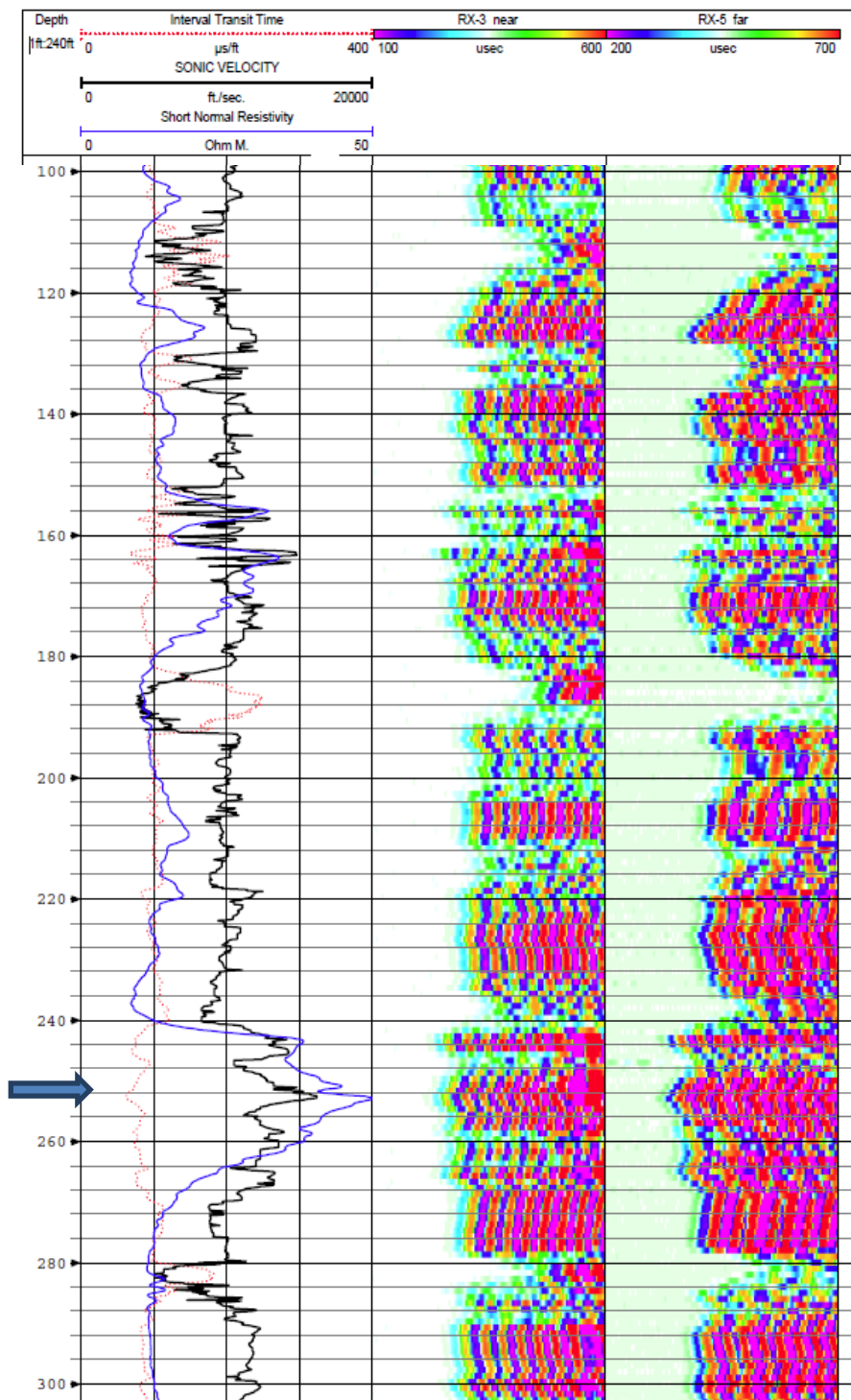


Figure 3-9. Sonic log plots from the interval of 30~90m (100~300ft) in WF-3. Note that FFEC log revealed a strong inflow point at 246 ft (75 m).

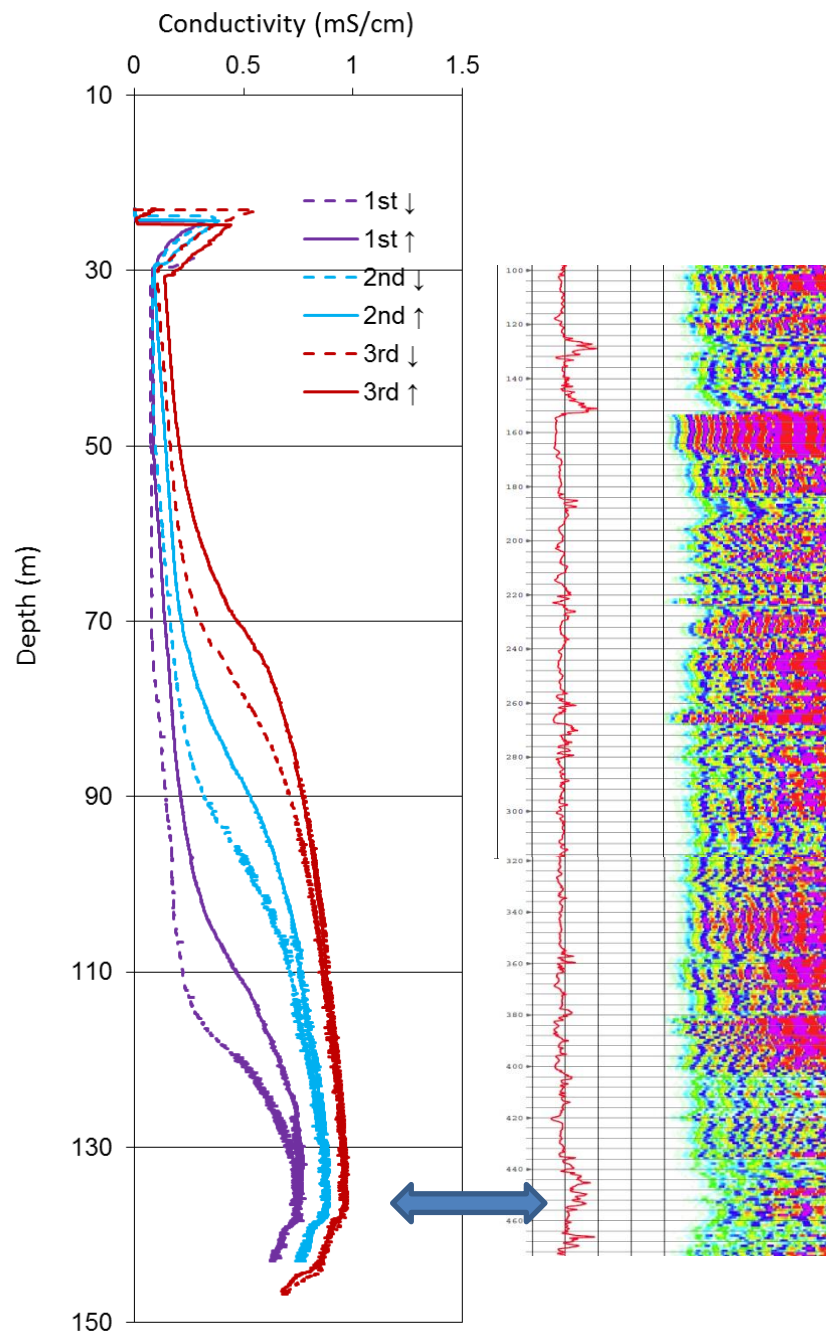


Figure 3-10. FFEC log of WF-2 showing a strong inflow point at 137m (451ft), where the sonic log shows low velocity (high transit time).

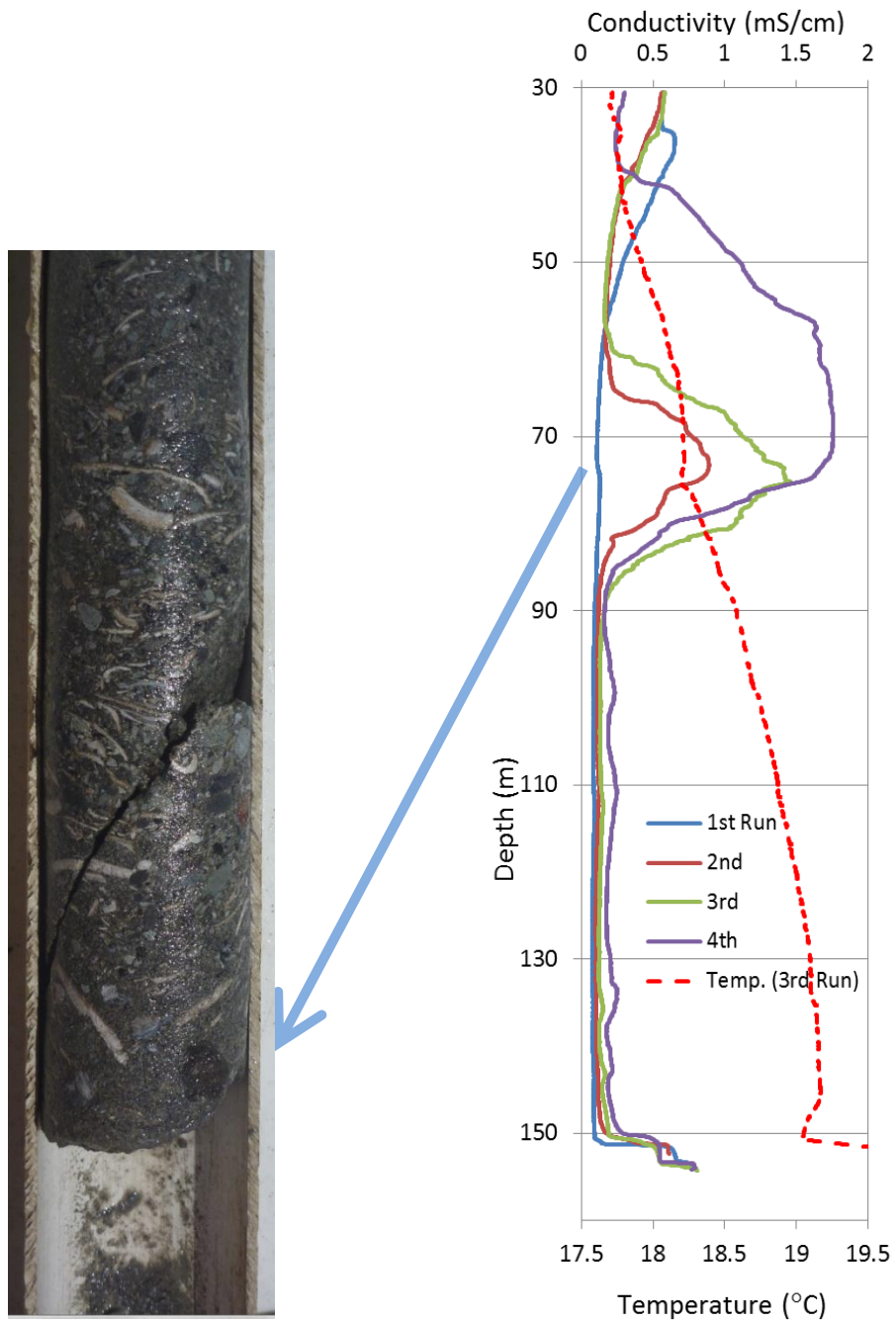


Figure 3-11. FFEC (Flowing fluid electric conductivity) log results in WF-3 showing one fracture near 75m suspected to be responsible for the large inflow point.

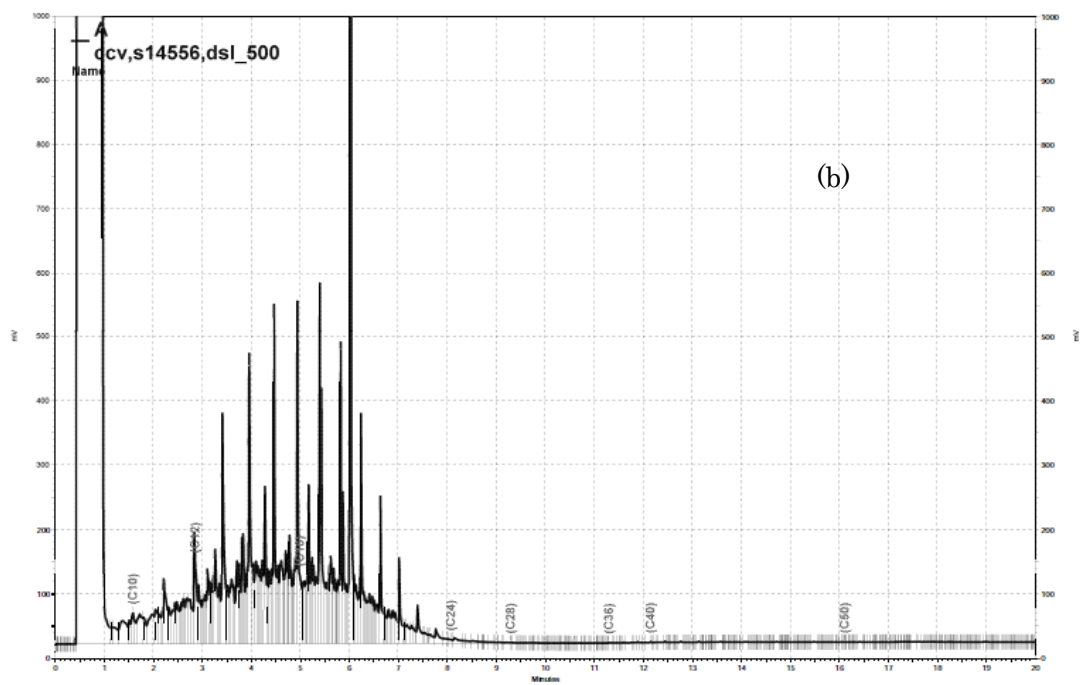
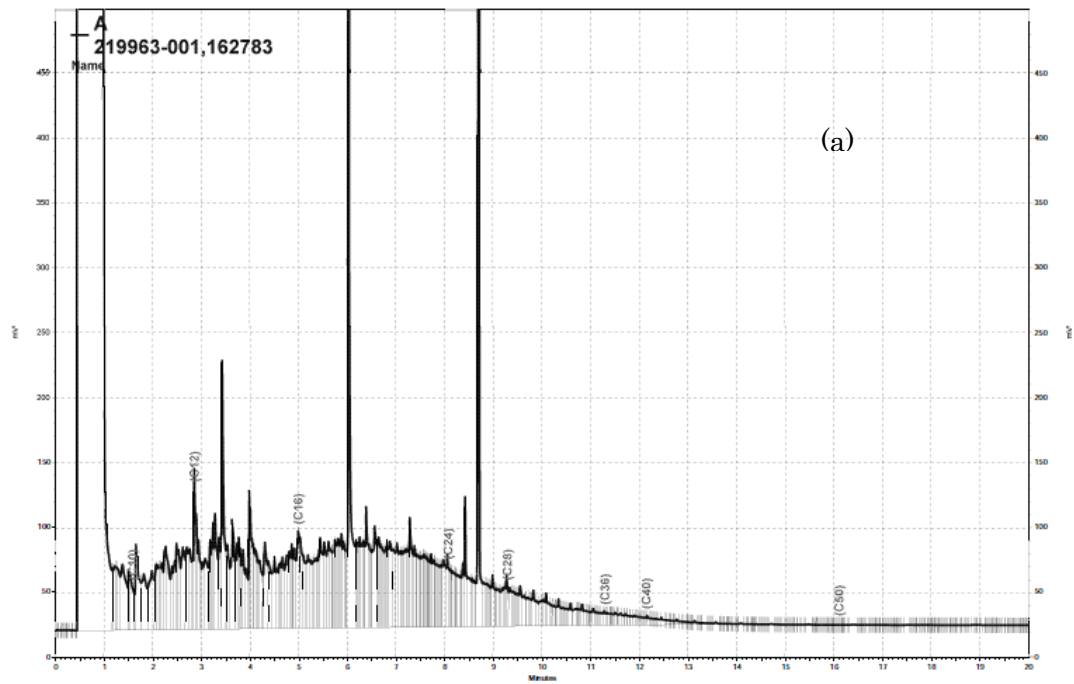
3.2.4 Hydrocarbon Contamination

While drilling the WF-3 borehole, we noticed a strong diesel-like smell from the cores. The smell was particularly noticeable from 48 m to 70 m depth. Subsequent to the completion of the drilling, samples of water in the borehole and rock samples from cores were taken and analyzed. Figure 3-12(a) is the water from WF-3 and (b), (c) and (d) are the diesel, motor oil, and crude oil standard results, respectively. As can be seen from the figure, the hydrocarbon composition in the water from WF-3 appears to be a mixture of diesel and motor oil. One alternative interpretation is that the signature is similar to that of natural crude oil. We could not pursue the issue to find the actual source of the hydrocarbon or to determine if it is natural or anthropogenic—such investigation is outside our work scope, particularly when resources are limited. This is unfortunate, because it is incumbent upon us conducting science to do our best when it comes to long-term safety and protection of the environment. This incident did affect the project in several ways, and we have learned some important lessons, which will be described in the Lessons Learned Section.

If the hydrocarbons have an anthropogenic origin, one possibility is that the contamination may have traveled from the Corporate Yard area of LBNL, where such chemicals were used in the past, through the tensile transverse “New Fault” postulated by Lennert and Associates (1979). Figure 3-13 shows the postulated trace of the “New Fault” and the Wildcat Fault and their location relative to the WF complex. Note that the existence of the “New Fault” has been disputed by Converse Consultants (1984), who argue that Lennert and Associates used only anecdotal evidence in their findings.

The “contaminated” water, drilling mud, and drill cuttings had to be disposed of properly. Usually, the drilling fluids and mud are temporarily stored in large bins to be trucked off to a landfill. When the bins became full, some drill spoils were dumped at the borrow pit at LBNL. After it was found that the rock was contaminated with hydrocarbons, the spill site had to be decontaminated. The water produced during pumping tests, ordinarily uncontaminated groundwater, can be run off on the hillside and infiltrate back

into the ground. This was the case for the pumping tests in WF-1 and WF-2. However, in the case of WF-3, we had to store the water in tanks and had to be properly disposed of.



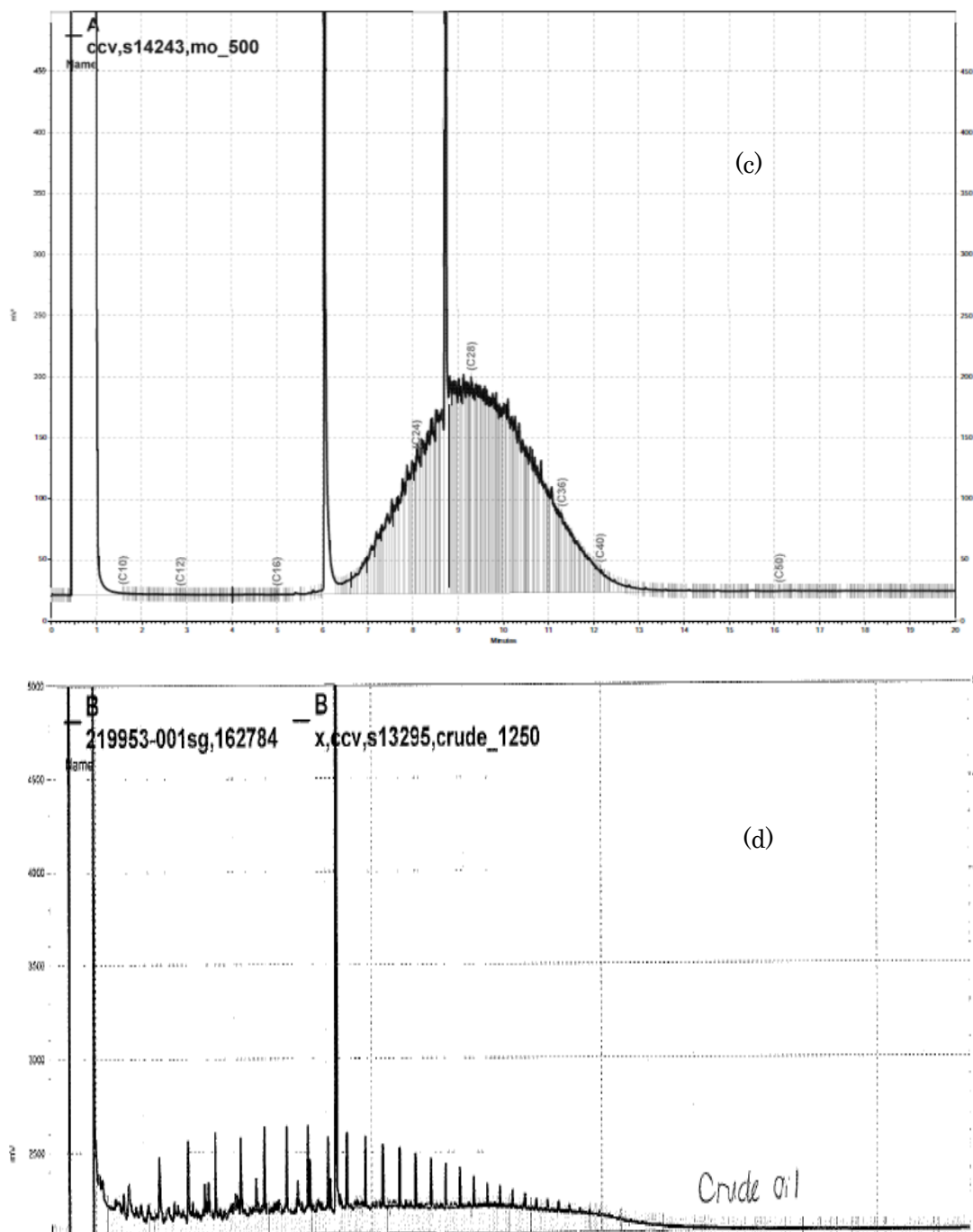


Figure 3-12. Chromatographic analysis of hydrocarbons in (a) the WF-3 water sample, (b) diesel standard (c) motor oil standard, and (d) crude oil standard.



Figure 3-13. “New Fault” identified by Lennert and Associates (1979) and its relation to WF-3 and the Wildcat Fault.

3.3 WF-4

3.3.1 Drilling

During and after the drilling of WF-3, the cores from WF-3 were examined, as well as those from WF-1 and 2. It was concluded that the main fault plane of the Wildcat Fault would probably lie between WF-1 and WF-2 after all. Thus, we decided to drill an inclined borehole from the west toward the postulated location of the fault, starting from the parking lot situated to the south west of WF-2. See Figure 3-1 and Figure 3-2 for the exact location of WF-4 and its relation to the other boreholes.

WF-4 was drilled in the direction of 59NE with a dip angle of 59 degrees. The direction was intended to be parallel to the line that connects WF-1 and WF-2. It turned out that the casual measurement of the direction by a hand-held compass was not very accurate and was in fact off by several degrees: the actual heading of the line connecting WF-2 to WF-1 is ~53 degrees. This difference caused some inconvenience when we tried to correlate the features in each borehole. The deviation log data during the drilling of WF-4 are shown in Table 3-2. As can be seen in the table, the hole was drilled relatively straight— only slightly corkscrewing.

Figure 3-14 shows the drilling speed and core recovery ratio as a function of depth (drilling length). The drilling speed decreased as the hole got deeper, particularly after 150 m. Also note that there are four bands of red lines between 100 m and 200 m, indicating heavy core losses. It is possible to interpret the location of the bands as fault zones. It was unfortunate that the cores were not recovered in those zones, which made the geologic analysis difficult when correlating the lithology among the boreholes. The fact that the cores were not recovered suggests that there was little to no clay gouge in the zones. Clay gouges are usually recovered successfully, which was the case in WF-1, where a ~30 cm long core of clay was recovered. In WF-4, several cores with a couple-of-inches-thick gouges were recovered. However, in those core-loss zones, not even small cuttings were caught in the strainer positioned at the mud return. This strongly suggests that the fault planes of the Wildcat are too young, and/or some geochemical/hydrothermal conditions are

missing, to produce gouges. These zones are suspected to be filled with pulverized rock powders instead of solid clay.

Figure 3-15 shows the water-level changes as the drilling progressed. As can be seen from the figure, the water level rose as the hole got deeper. In fact, at ~650 ft, the hole became artesian. Although, for multiple reasons, the water level during the drilling period may not accurately reflect the head at the corresponding depth, it is nonetheless a piece of information that may be indicative of the state of hydrology in the formation.

The drilling was initially terminated at the depth of 650 ft (198 m), close to the original target depth of 200 m. Immediately after that, a suite of borehole geophysical logs were conducted. After examining the results of the logs and the cores, we decided that we were still in the middle of a fault zone, and that we needed to go deeper—we thought we should drill until the hole had passed the Wildcat to assess the extent of its damage zone. The extended drilling lasted three more days and reached a final depth of 693.7 ft (211.4 m). It was very difficult to decide when to actually stop drilling, because each time we thought we were through a fault zone, another zone appeared with damaged cores or an entire core loss. The decision to stopping the drilling was made based on time and money constraints.

Figure 3-4 shows the geologic column of WF-4 and other WF holes. As can be seen from the figure, there were many sections with core loss below 600 ft (180 m). A detailed analysis of the WF-4 cores can be found in Chapter 4, Geologic Investigation and Analysis.

Note that while drilling WF-4 near the depth of 76 m (250 ft), three monitoring intervals in WF-2 responded. These were upticks in the pressure probably caused by the high circulation pressure in WF-4, indicating a hydraulic connection between the middle of WF-3 and WF-4. More notable is the responses observed in the WF-1 intervals when the drilling depth of WF-4 passed 183 m (600 ft). More discussion on this can be found in Chapter 5, Hydrologic Investigations.

Drilling inclined boreholes has some advantages and some drawbacks. Compared to vertical holes, they cover more horizontal distances and can penetrate a fault, which was the

intent of WF-4. However, they can also be costly and, depending on the competency of the rock, holes can collapse and redrillings may become necessary, which was the case with WF-4. By penetrating a fault, boreholes can mix the groundwater together on either side of the fault, causing some challenges for geochemical analysis. In WF-4, the bottom 30 m (100 ft) had a higher head than the surface, by about 5 m. The water may have been entering into the hole near the bottom and exiting somewhere in the shallower zone, even when the hole was plugged at the top.

3.3.2 Feature near 180 m (591 ft)

On September 13th, as soon as the drilling started at a depth of 178 m (584 ft), the drill pipe dropped ~1.5 m (5'). This first core run recovered only a 1 feet 2 inches long core out of 5 ft. The driller initially thought that he miscounted the number of pipes 5' short to add up to the total length. The drill pipes were pulled up and disconnected at the end of each day and re-connected first thing on the next day of drilling, in order to avoid the pipes getting caught in a collapsed hole. The driller believed that the 5' drop resulted from the drill bit being 5' above the bottom of the hole when he had started drilling that morning. At the end of the day, the pipes were recounted; it turned out that we were indeed at 178 m (584 ft) and that there was a zone of ~5 ft that had little resistance to drilling. On the following day, the pressure in the bottommost #5 zone in WF-1 started to respond to the drilling activities, indicating that there could be a strong hydraulic connection between the bottom of WF-1 and WF-4. This will be further discussed in Chapter 5.

3.3.3 Borehole Coordinates and Inclination

The coordinates of the top of WF-4 at the ground level can be found in Table 3-1. Because it was an inclined drilling, a deviation survey was necessary. A survey probe was then run roughly every 40 ft of drilling depth. The probe was lowered using the wireline after the HQ pipes were connected to the bottom before starting the day's drilling. Table 3-2 shows the survey data. As can be seen from the table, the hole deviated very little. As expected, it slightly corkscrewed in the direction of the drill-bit rotation.

3.3.4 Borehole logging in WF-4

Borehole geophysical logging in WF-4 was attempted several times. Because the hole is inclined and has several fault zones, from which debris can fall off, blockages occurred that prevented the geophysical probe's passage. The first attempt, a successful one, was conducted immediately after the borehole was drilled to 650 ft (198 m) deep. The surface casing at the time was set to 30 ft. Thus, the logs from 30–650 ft (9 m–198 m) were obtained. After the hole was extended to 693.7 ft (211.4 m) we set the surface casing down to 75 ft (23 m). We first attempted to conduct a caliper log, which is the smallest and least expensive probe of all, but the hole had a blockage at 625 ft (190 m). We initially tried to push the obstacle down with 10 ft long one-inch-diameter plastic pipes, but were unsuccessful in clearing the blockage. We then redrilled the hole and connected the HQ drill pipes down to ~640 ft (195 m) for smooth lowering of the probes. Consequently, the hole was open only from 640 ft to the bottom, within which only a caliper log and BTV log were conducted.

3.3.4.1 *Caliper log*

For the reasons mentioned above, caliper logs were conducted three times (with some overlaps). Figure 3-18 shows the caliper log from WF-4. The caliper tool had three dependent arms, meaning that the diameter logged is the minimum diameter registered between two arms. The first log was done from 30–650 ft (9 m–198 m). The second run was done after the hole was extended from 650 ft (198 m) to 693.7 ft (211.4 m), but could only reach to 188 m because of a blockage. The third run logged only the bottom part of the hole, from 640 ft (195 m) to 687.6 ft (209.6 m). Note that the bottom 20 m is highly enlarged, which made us suspect that it is the major fault zone. Also of interest is that some locations of the borehole became larger between the first and second run, most significantly at 180 m and 183 m. The existence of a fault is suspected at these locations. The cores from these locations were not fully recovered, either.

As noted before, the caliper log has been most useful in estimating the location of faults, which often cause the borehole diameter to enlarge. An HQ drilling would otherwise

create a smooth wall of ~4.5 inches (11 cm) in diameter. In fact, the decision to deepen the hole was made mainly after examining the first caliper log, which showed that the borehole wall was significantly larger and rough near the bottom.

3.3.4.2 Electric logs (ELOG)

As was discussed in the WF-3 section, ELOG data did not correlate very well with rock types or hydrologic features except for the bleached, lithified chert breccia, which seems to occur often (but not always) near a fault. Figure 3-19 shows a portion of the plot of the ELOG conducted in WF-4. Blue arrows indicate the location of opposite kicks of natural gamma and resistivity anomalies, where bleached chert breccia are observed. A complete plot of the ELOG survey conducted from 30–650 ft (9 m–198 m) in WF-4 can be found in Appendix B. ELOG was not performed after WF-4 was extended.

3.3.4.3 Borehole televiewer (BTV) log

BTV logs are quite useful for orienting cores and obtaining some information about the rock when cores are not recovered. In WF-4, BTV logs were conducted twice, first from 30–650 ft (9–198 m) and for a second time from 640 ft (195 m) to 687.6 ft (209.6 m) after the hole was extended. The complete set of combined BTV images can be found in Appendix B.

A good example of the effective use of BTV is shown in Figure 3-20, which shows the BTV image from 681–684 ft (207.5 m–208.5 m). Also shown is the picture of the core from the same interval, most of which is not recovered. Note the very grainy image of the BTV where the core-loss occurred, indicating the rock has been pulverized to grains.

3.3.4.4 Sonic log

Sonic velocity is a function of rock density and stiffness. Thus, sonic logs can be used to identify rock types and faults where the rock is expected to be soft, thus yielding a slower sonic velocity. The Claremont formation appears to have large contrast in rock density due to fracturing/faulting superimposed on interlayering of chert/mudstone/shale as well as sandstone. We have conducted sonic logs in all the WF holes, but had been unable

to effectively correlate low/high velocity signatures to features of interest. Figure 3-20 shows one example of potential correlation between slow sonic velocity and a fault at 370 ft (112.7 m). However, this is not the case for all the faults. We found several faults below 600 ft (180 m), but the sonic log showed no distinctive anomalies (though it did show numerous moderate lows and highs that appeared noisy, which in turn may be interpreted as multiple faults).

3.3.4.5 FEC log

Figure 3-22 shows the results of the FFEC log conducted in WF-4 before the hole was extended to 211.4 m (693.7 ft), showing the conductivity and temperature profile along the length of the borehole. The FEC log was run only once because of time constraints and because the formation water quickly saturated the conductivity profile (the hole is artesian). Note that there is a dominant inflow point at 185 m (604 ft). An expanded plot can be found in Appendix B.

Table 3-2 Borehole inclination survey data of WF-4

Depth		Dip	Orientation (deg)	
(m)	(ft)	(deg)	Magnetic	True
11.9	39	58.4	45.9	60.05
24.8	81.4	58.5	45.8	59.95
39.2	128.5	58.6	47	61.15
50.7	166.5	58.7	46.6	60.75
63.2	207.3	58.7	47.1	61.25
75.9	249	59.1	47.1	61.25
99.4	326	59.4	46.9	61.05
109.4	359	59.5	47.2	61.35
121.3	398	59.5	47.6	61.75
134.8	442.4	59.5	47.6	61.75
147.5	484	59.4	47.8	61.95
158.0	518.4	59.6	47.5	61.65
169.5	556.2	59.8	47.3	61.45
187.0	613.5	59.8	47	61.15

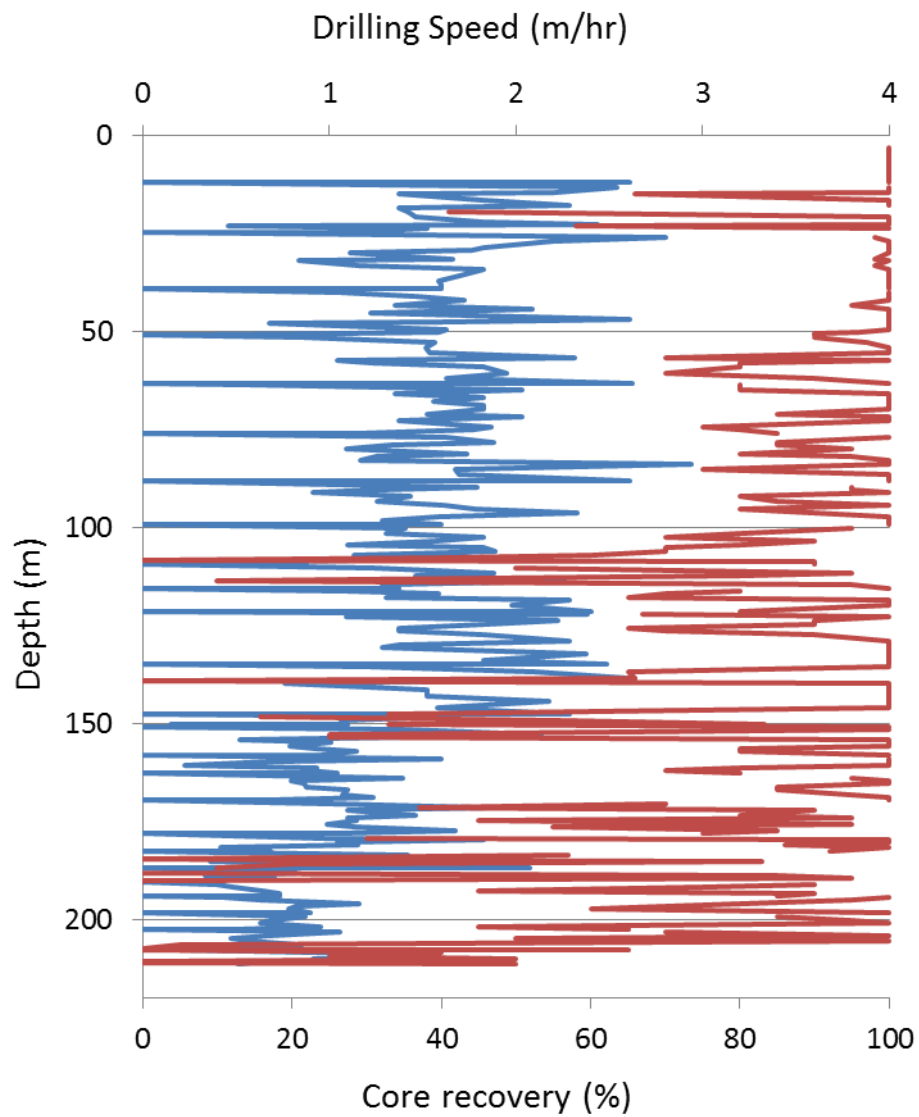


Figure 3-14. Drilling speed and core recovery percentage of WF-4 drilling. Note there are four distinct core loss zones, where faults are likely to exist without gouges.

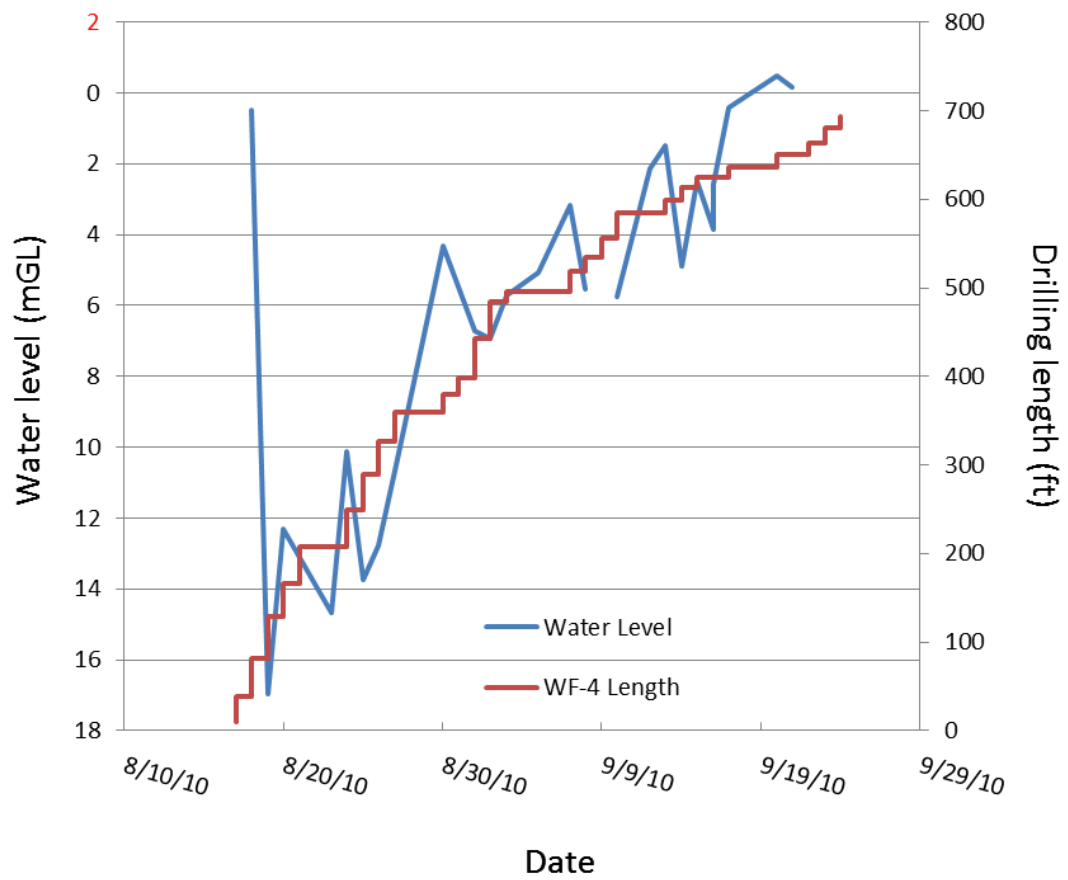


Figure 3-15. Progression of drilling and water-level change in WF-4.



Figure 3-16. Drilling of WF-4. Note that it is a 60° inclined drilling.



Figure 3-17. Borehole inclination survey equipment, with sensor probe enlarged. The 5 ft brass bar is the sensor housing that fastens to the 15 ft silver aluminum rod. An aluminum rod is attached to the wireline. The probe protrudes from the drill bit at enough distance away from the magnetically susceptible drill string.

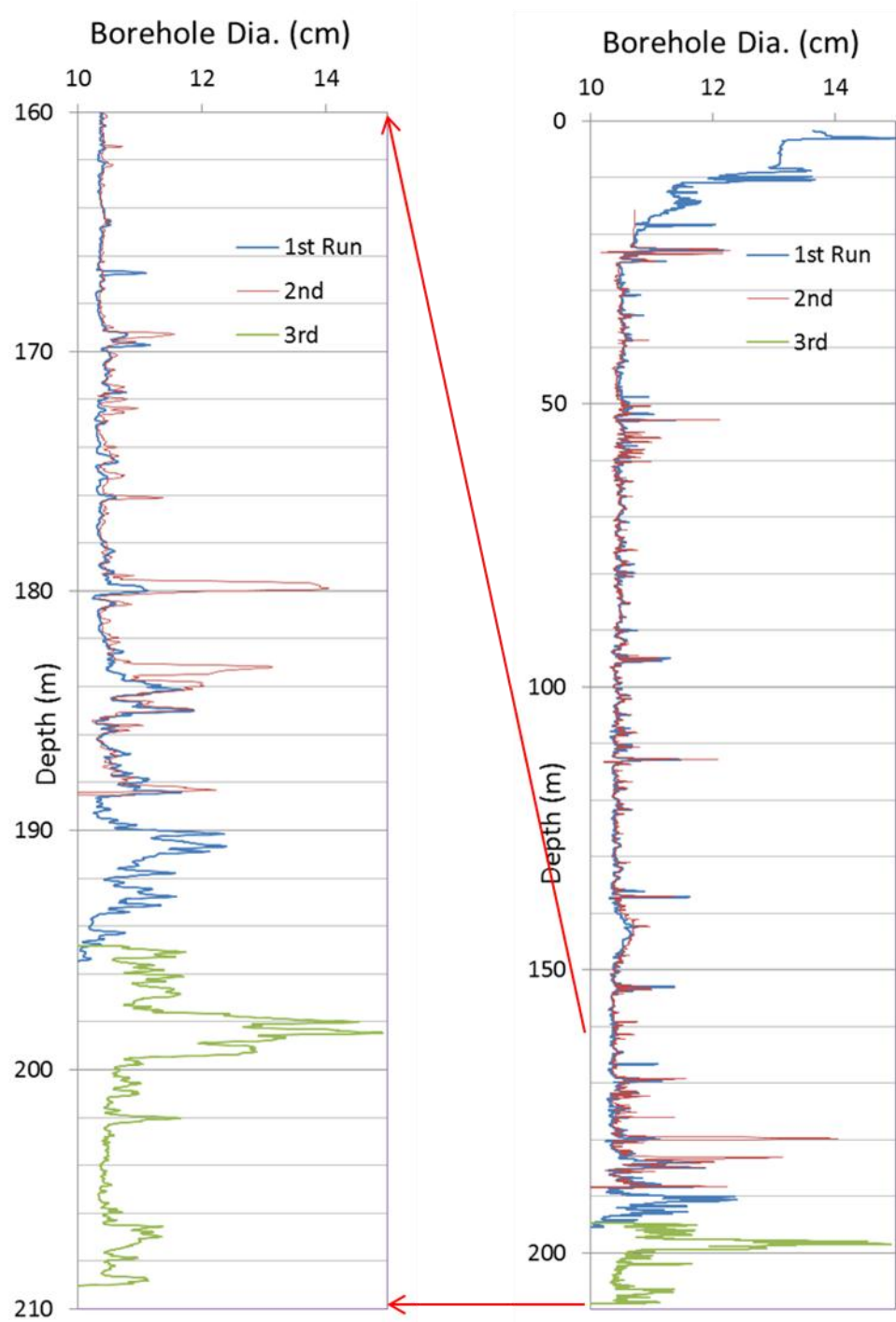


Figure 3-18. Caliper logs in WF-4. The left plot is a magnified portion of the plot on the right. Note that the borehole became larger after the first run.

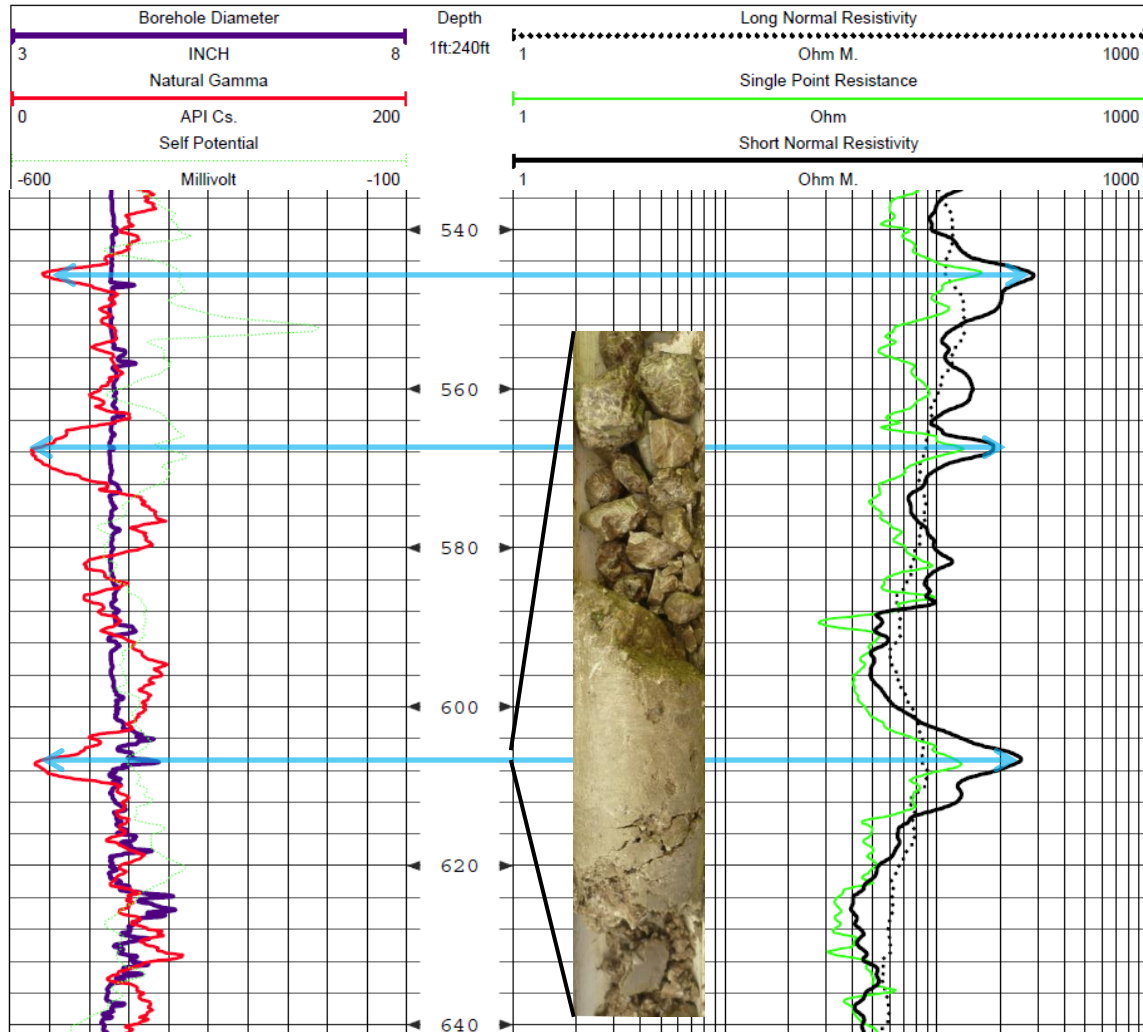


Figure 3-19. Excerpt of the ELOG results from WF-4, showing the oppsite kicks of the natural gamma and resistivity locations, marked by the blue arrows corresponding to bleached lithified brecciated chert. A picture of the core of such rock from 607 ft (185 m) is also shown.

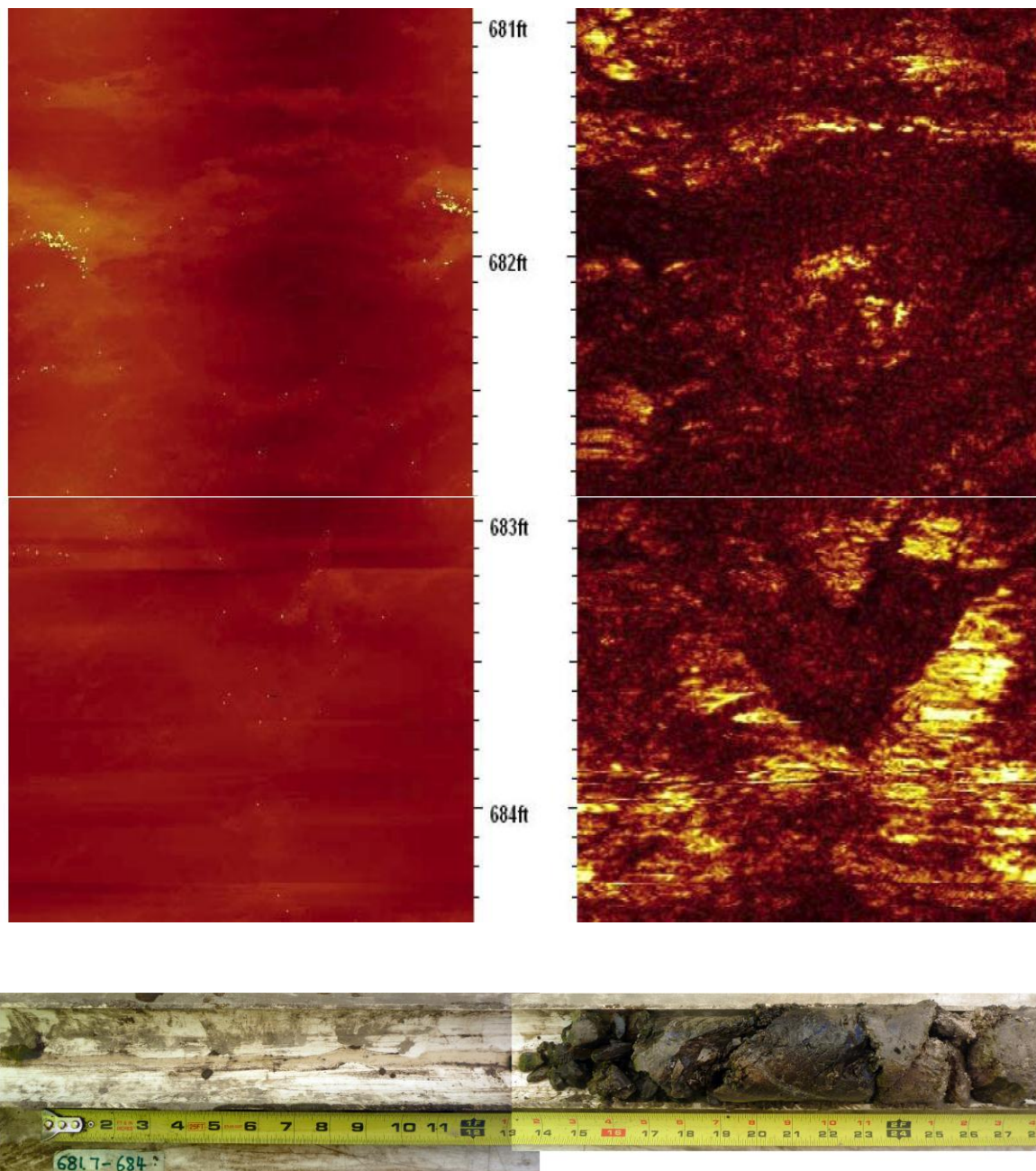


Figure 3-20. The BTV image from 681–684 ft (207.5 m–208.5 m). Also shown is the picture of the core from the same interval, most of which is not recovered. Note the very grainy image of the BTV, indicating that the rock is pulverized.

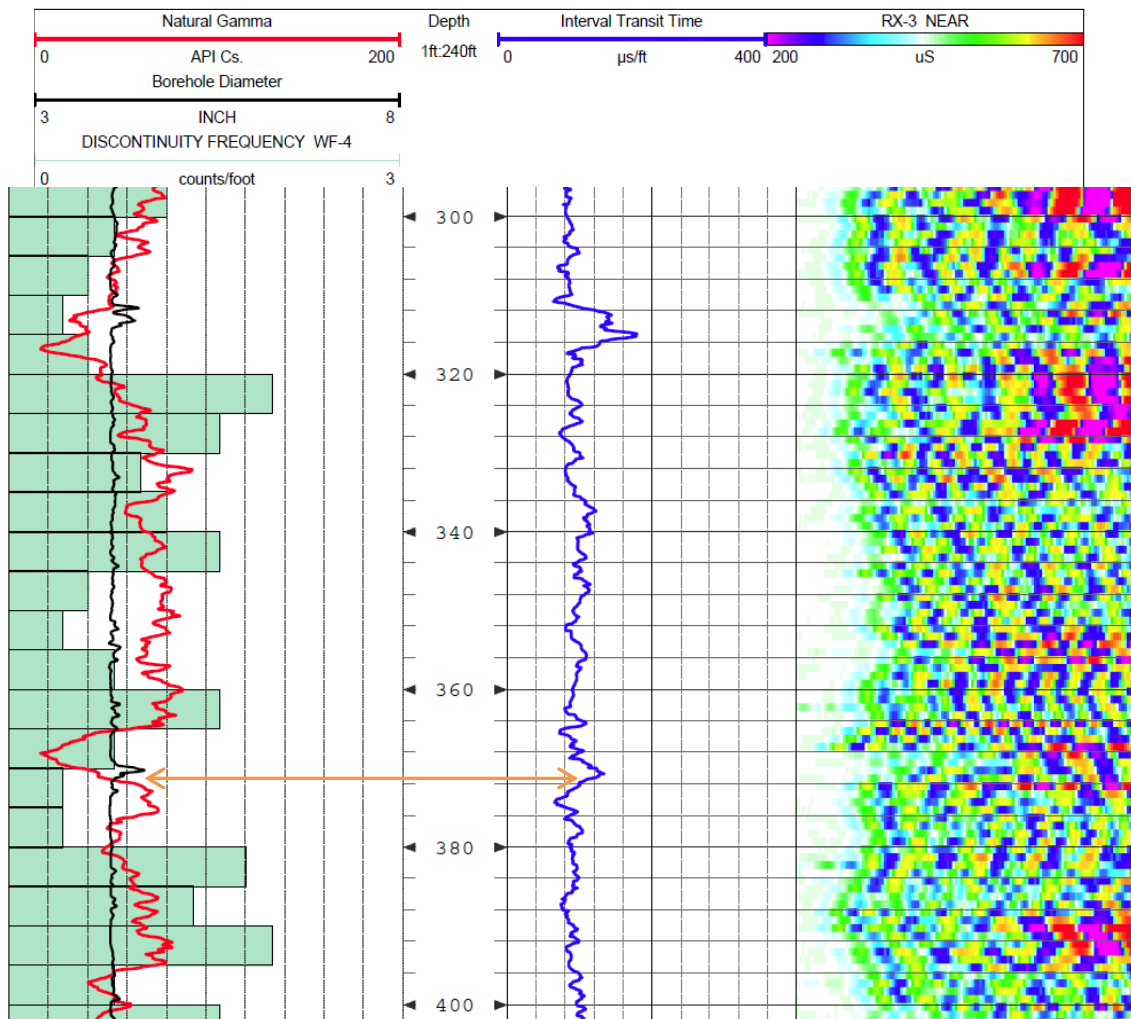


Figure 3-21. A composite plot of natural gamma (red) caliper (black), discontinuity counts (green bar), sonic transit time (blue) and the full wave sonic log (far right). The orange arrow indicates the location of a fault that has an enlarged hole diameter and slow velocity.

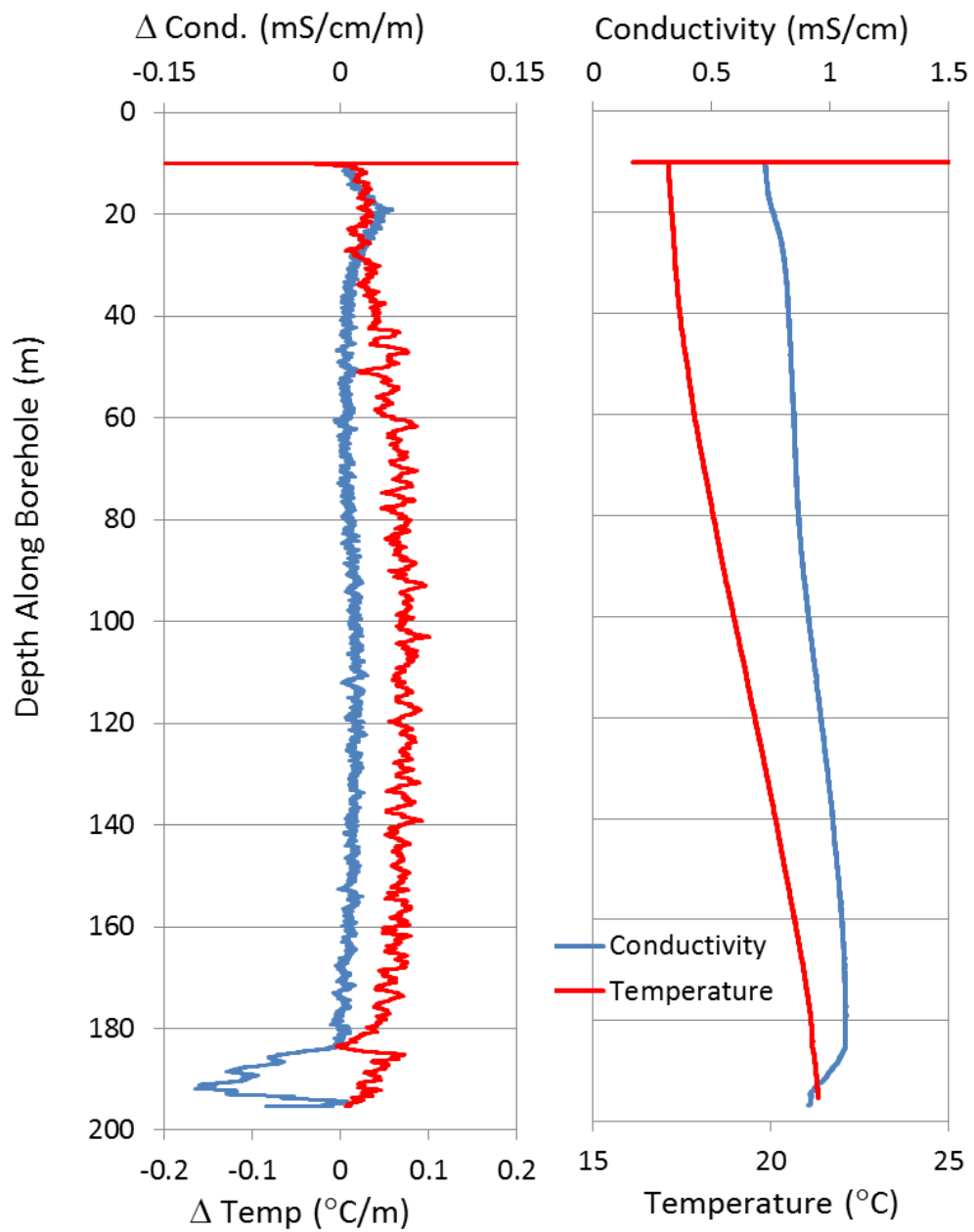


Figure 3-22. FFEC log in WF-4. Only one run was conducted. Note the strong inflow point at 185 m (604 ft).

3.4 References

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4 Geologic Investigation and Analysis

4.1 Introduction

In FY 2010, as part of our investigation of the Wildcat Canyon Fault geologic, geophysics, and drilling investigations were conducted across the trace of the Wildcat Fault at the eastern end of the Lawrence-Berkeley National Laboratory property. Kiho et al. (2011) conducted additional geological mapping of the Berkeley Hills and the Tilden Park area. Following the FY 2009 Annual Report entitled “Development of Hydrologic Characterization Technology of Fault Zones” (Karasaki et al., 2010), two more boreholes were drilled on the western side of Wildcat fault near Calvin Road. WF3 is a vertical borehole located 80 m west of WF2, near the Building 85 entrance. This borehole, about 156 m (512 ft) deep, was drilled in order to bracket the westernmost location of the Wildcat fault, since 90 percent of WF2 encountered the Claremont formation and not Orinda formation/ San Pablo Group, as expected from surface geologic mapping. The WF4 borehole is an inclined borehole of 60 degrees dip and oriented N60E, and was intended to be aligned with the other three boreholes. However, it turned out that the orientation of the line connecting WF-2 and WF-1 is actually N53E, off by several degrees. The total length of the borehole is 211.4 m (693.7 ft). This borehole was designed to cross the main trace of Wildcat fault. Not only did it encounter the contact between the Orinda Formation/San Pablo Group and the Claremont formation, it also encountered several zones of brecciation, gouges, and a major active fault zone starting from 152.4 m (500 ft) depth and extending to the end of the borehole.

Selected samples from the boreholes were collected and examined for petrographic analysis, whole rock x-Ray diffraction, and isotope analysis of carbonate veins. In parallel, Kiho et al. (2011) conducted a core analysis and structural analysis as well.

Based on fault zones encountered during drilling and data from borehole geophysics, a selected number of fault projections were constructed to develop a 3D geologic and structural model, using Earth Vision.

4.2 Geologic Mapping

Kiho et al. (2011) conducted additional geologic mapping in the Berkeley Hills and Tilden Park area, as shown in Figure 4-1. They fine-tuned the previous maps by Graymer (2000) and Onishi (2009).

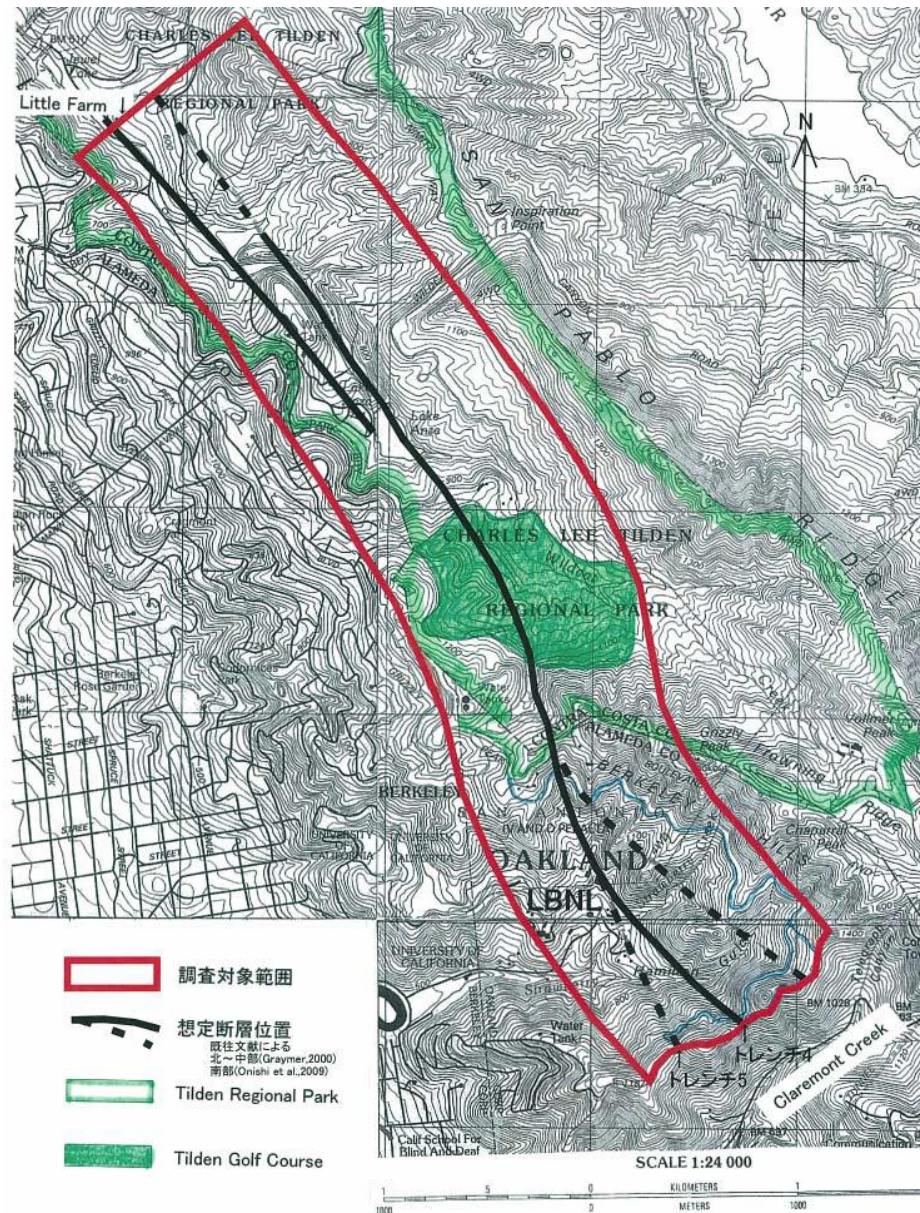


Figure 4-1. Area of additional geologic mapping conducted in FY2011 (Kiho et al., 2011).

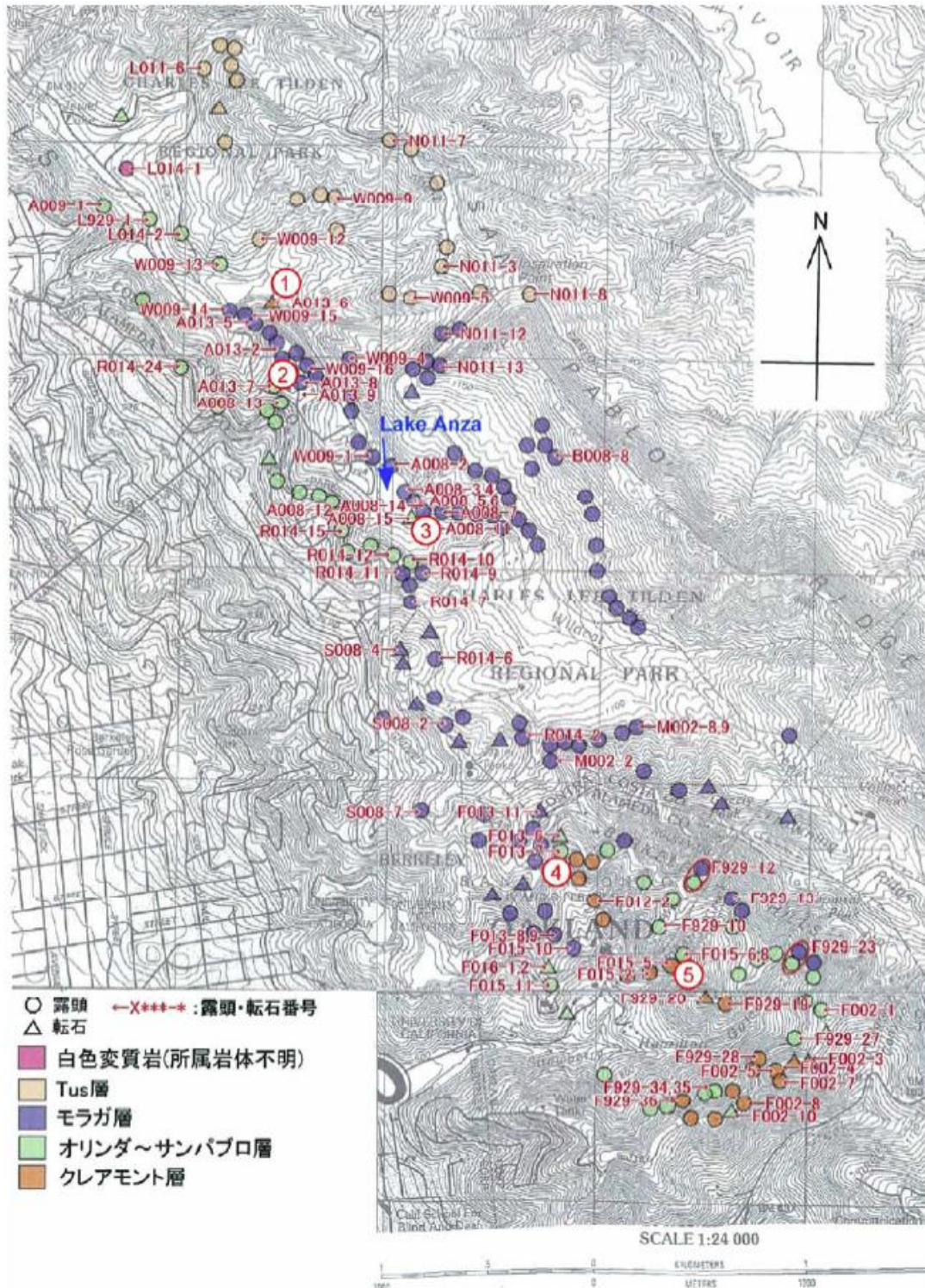


Figure 4-2. The locations of the outcrops and bounding rocks mapped by Kiho et al. (2011)

Figure 4-2 show the locations of the outcrops and bounding rocks mapped by Kiho et al. (2011). They proposed a new geologic map with finer definition of geologic boundaries and new suspected faults, as shown in Figure 4-3.

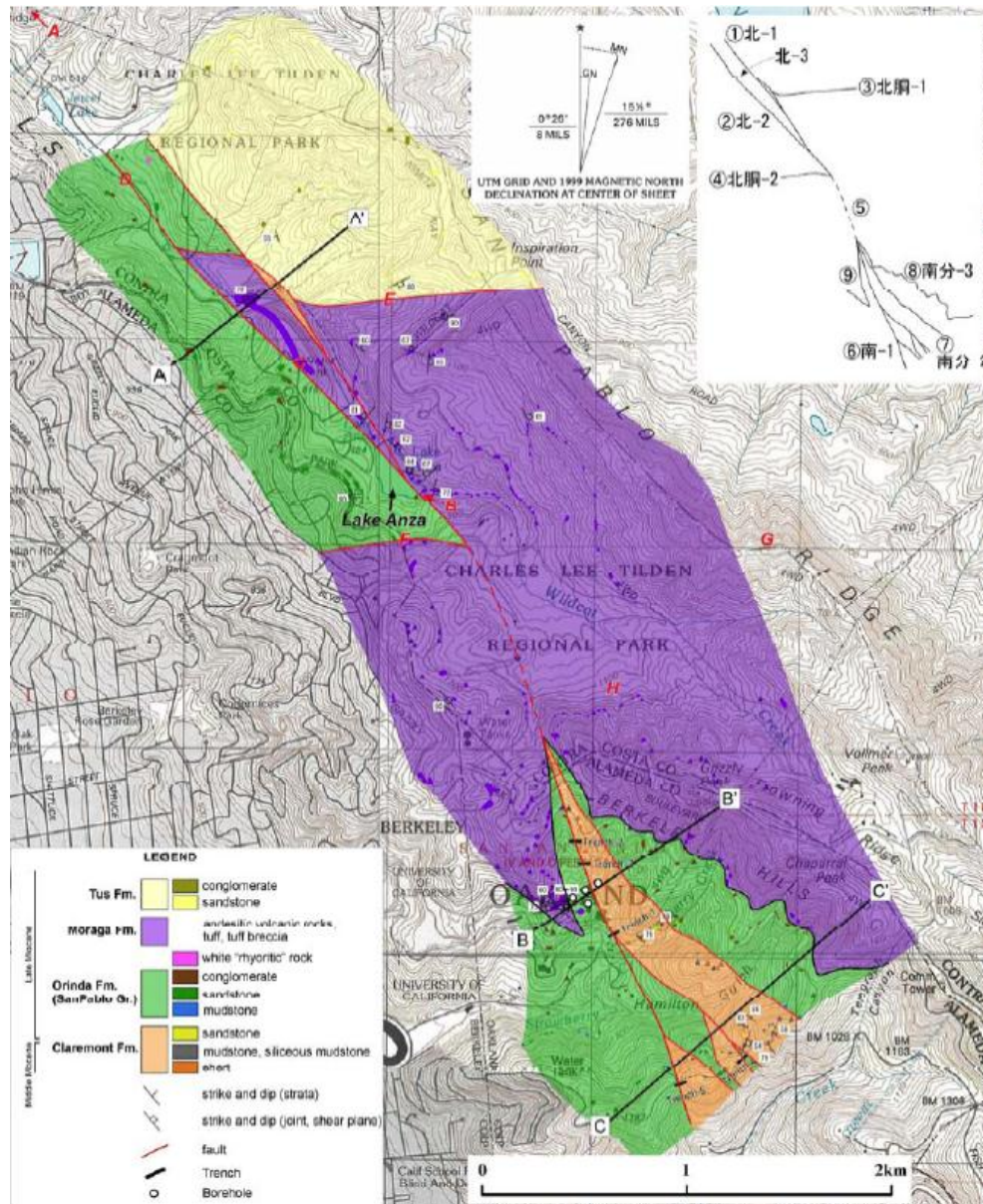


Figure 4-3. Geologic map proposed by Kiho et al. (2011)

4.3 Drilling

Drilling commenced on April 12, 2010, for borehole WF-3 and August 17, 2010, for borehole WF-4. The drilling sites were selected based on the location of previous WF boreholes. WF3 was located along Calvin Road near LBNL Building 85; WF4 was an inclined borehole (60 degrees) primarily intended to be oriented parallel to the direction of the other three boreholes (i.e., at N46E); however, a misorientation of six to seven degrees was found. WF4 was drilled within the parking lot in front of Building 84. Figure 4-4 shows the locations of WF-3 and WF-4. Core images are shown in Appendix 1 and 2 for WF3 and WF4, respectively.

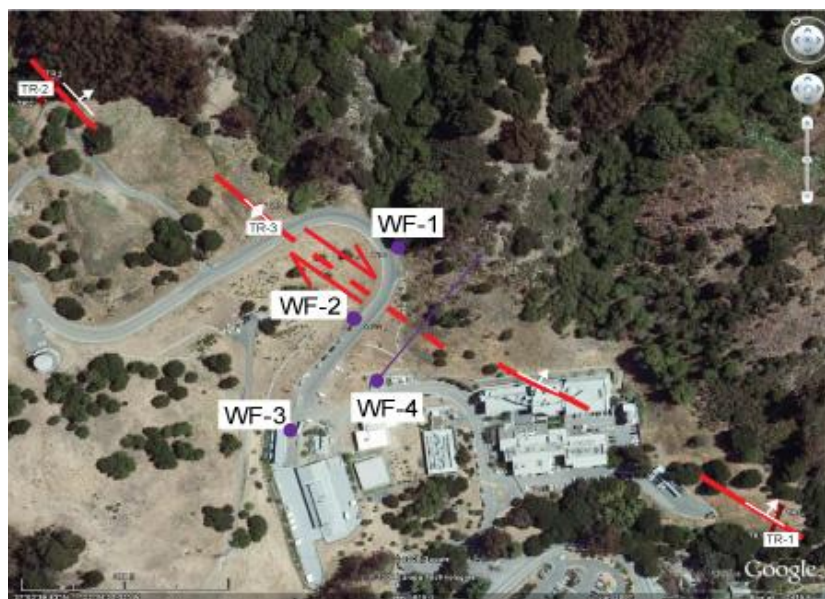


Figure 4-4. Location of the boreholes WF3 and WF4 in relation to WF1 and WF2 (drilled in 2009) and the trace of the Wildcat fault.

4.4 WF-3 Core Logging and Description

WF3 was drilled on the eastern side of the fault, on the edge of building 85A, along Calvin Road, at latitude $37^{\circ} 52' 38.905''\text{N}$ and longitude $-122^{\circ} 14' 25.003''\text{E}$. A picture of the drilling is shown in Figure 4-5.



Figure 4-5. Drilling of WF3 along the edge of Calvin Road and Building 85A

Drilling of WF-3 started at 270.2 m above sea level and encountered 8.38 m of colluvium. The total length of the borehole is 156 m (512 ft). Approximately 60% of the core is of sedimentary rock from Orinda Fm. and San Pablo Gr. The rock is mainly fine to coarse sandstone locally rich in fragments of marine fossils and interbedded with siltstone and mudstone. Minor faults with gouges in the sandy siltstone between 21–22.2 m (69–74 ft) are described by Kiho et al. (2010). A fault along the contact between Orinda Fm. and San Pablo Gr. with Claremont chert and shale is logged at 99 m (324 ft) depth. The fault is characterized by a zone of brecciation as well as a mixture of sediments from both formations. The average fault orientation is $324/47^{\circ}$ and $207/67^{\circ}$. A second fault zone, logged at 146 m (480 ft) depth, oriented $216/38^{\circ}$, and running along the lithological contact between Claremont Fm. and possibly Orinda Fm., is characterized by a gouge and a zone of brecciation.

Orinda Formation (in the Berkeley Hills) is part of the Contra Costa Group and includes alluvial-fluvial sequences and lacustrine sequences (Graham, et al., 1984). Doell (1930) describes the Orinda Formation as composed of fine-to-coarse well-rounded conglomerate, sand, and sandy clay. All those units vary greatly in color and degree of

sorting. The descriptions of Orinda formation from borehole data, geotechnical reports, and previous trenches within the LBNL property include:

- Mottled brown claystone to mottled yellow/orange brown an light gray-brown silty and pebbly sandstone (Subsurface Consultants, 1994);
- Yellowish-brown to gray shale, gray-green sandy siltstone, red-brown claystone to siltstone, gray-green siltstone, mottled yellow-brown sandstone, mottled red-brown & green claystone, gray fine sandstone to blue-gray silty sandstone (HLA, 1977 and 1980);
- Gray to green-gray fine grained siltstone, red-brown to purple brown siltstone, gray sandstone interbedded with siltstone and shale, red-brown silty clay, purple-gray siltstone-claystone (Converse Consultants, 1983);
- Dark gray to light gray-brown siltstone, mottled light blue and gray clay sand gravel, gray-brown clayey sandy gravel, green silty sandstone (Kleinfelder, 2001),
- Blue-gray sandstone, gray-brown siltstone to sandy siltstone (Geo/Resources Consultants, 1994).
- Massive with fine-grained sand and stringers of clay and silt (AKA, 2008 in WLA, 2008)
- Mottled grayish green to dark reddish brown, fine grained silty sand (WLA, 2008)

The bluish-gray fine grained sandstone to siltstone in WF-3 appeared below the colluvium at 8.38 m (27 ft). It changes to coarse sandstone to conglomerate rich in marine fossils (Figure 4-6). Large zones of mottled green-blue sandstone to fine siltstone and dark red mudstone are shown in Figure 4-7.



Figure 4-6. Coarse sandstone to conglomerate rich in marine fossils



Figure 4-7. Typical mottled greenish-blue to fine sandstone and dark red mudstone (131-136ft)

4.4.1 Orinda Fm/San Pablo Gr.-Claremont Fm. contact at fault zone 322-332ft

The contact between Orinda Fm./San Pablo Gr. and Claremont Fm. was recorded by a zone of brecciation and mixing of silicified conglomerate, sandstone, and siltstone, as shown in Figure 4-8.



Figure 4-8 Zone of deformation characterized along the contact between Orinda Fm/San Pablo Gr. and Claremont Fm.

4.4.2 Claremont Fm.- Orinda Fm./San Pablo Gr. contact at 484.6–489 ft—gouge

A second contact between chert and shale of the Claremont Fm. and sandy-siltstone of the Orinda Fm. is recorded at 147.8 m (484.6–489 ft), as shown in Figure 4-9. The contact includes a zone with mixtures of tuffaceous and carbonate material, followed by a gouge with a well-defined shear zone and strips of black shale. A second zone with mixtures of fine-grained sandstone and black shale resembles a zone of damage. Also found was a transition to a mottled greenish-gray siltstone and dark red mudstone typical of the Orinda Fm.. Shearing is noted in the mottled greenish-gray siltstone to dark red mudstone, the same material encountered up to the end of the core at 156 m (512 ft).

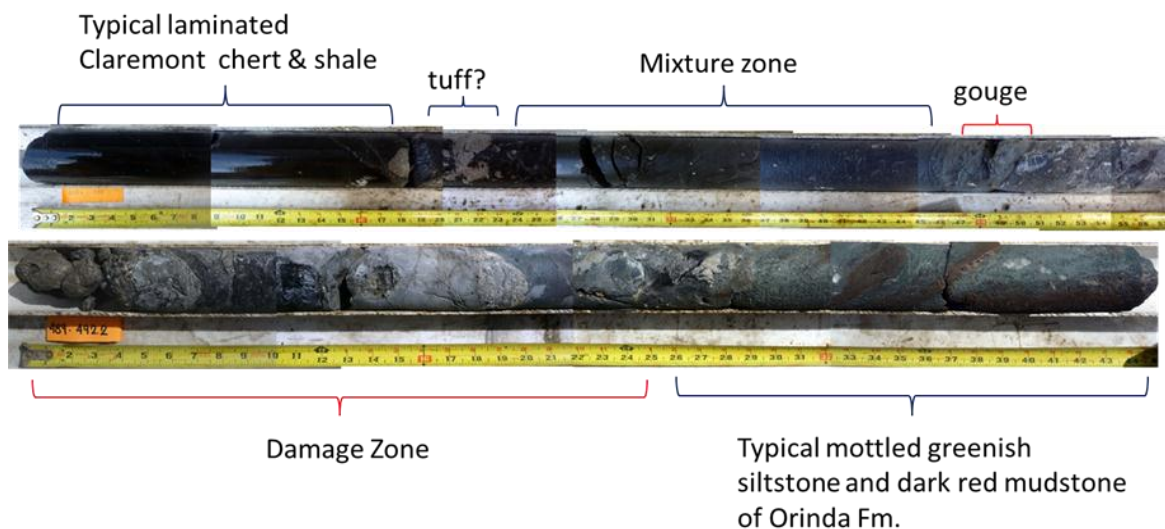
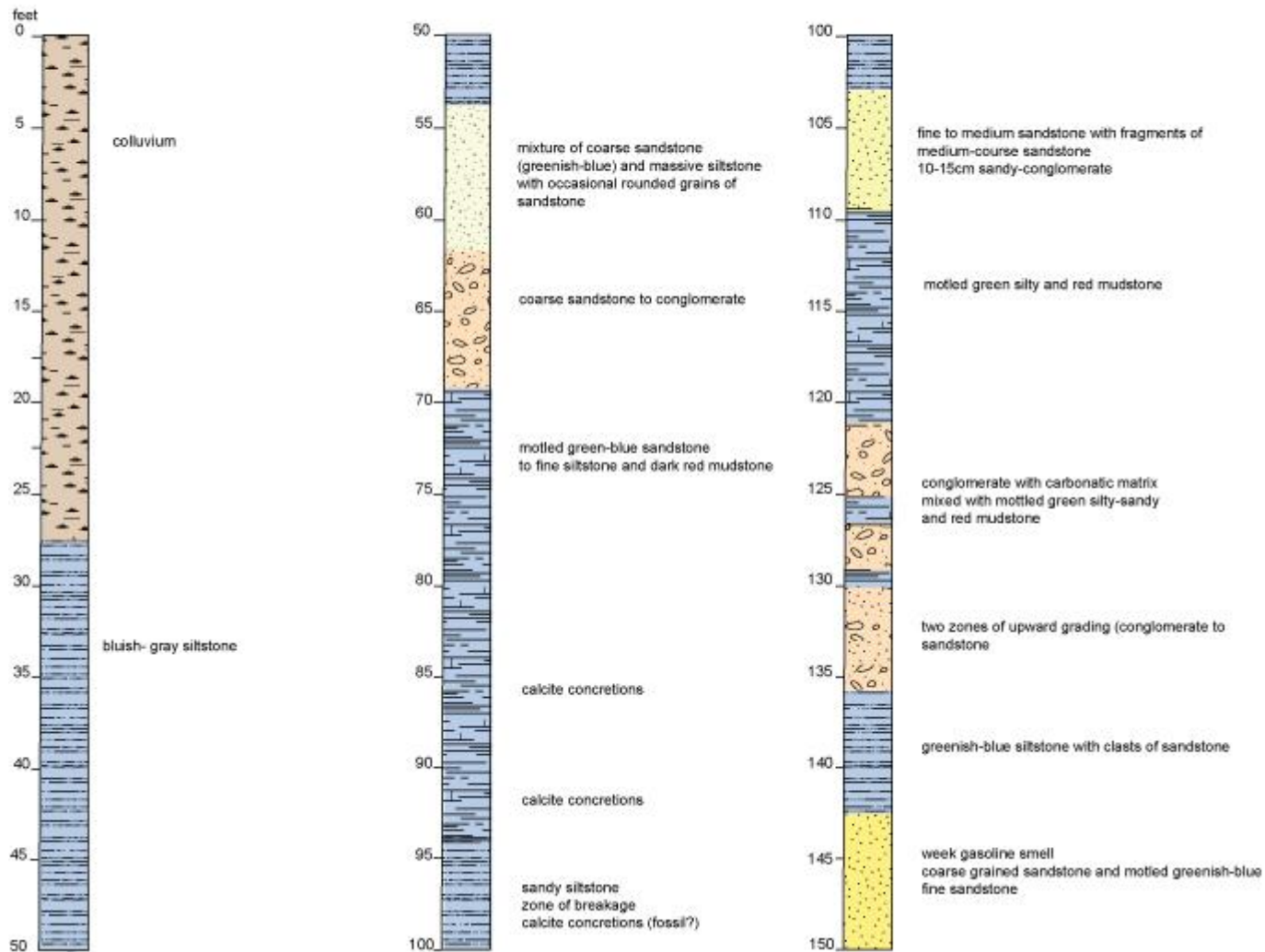


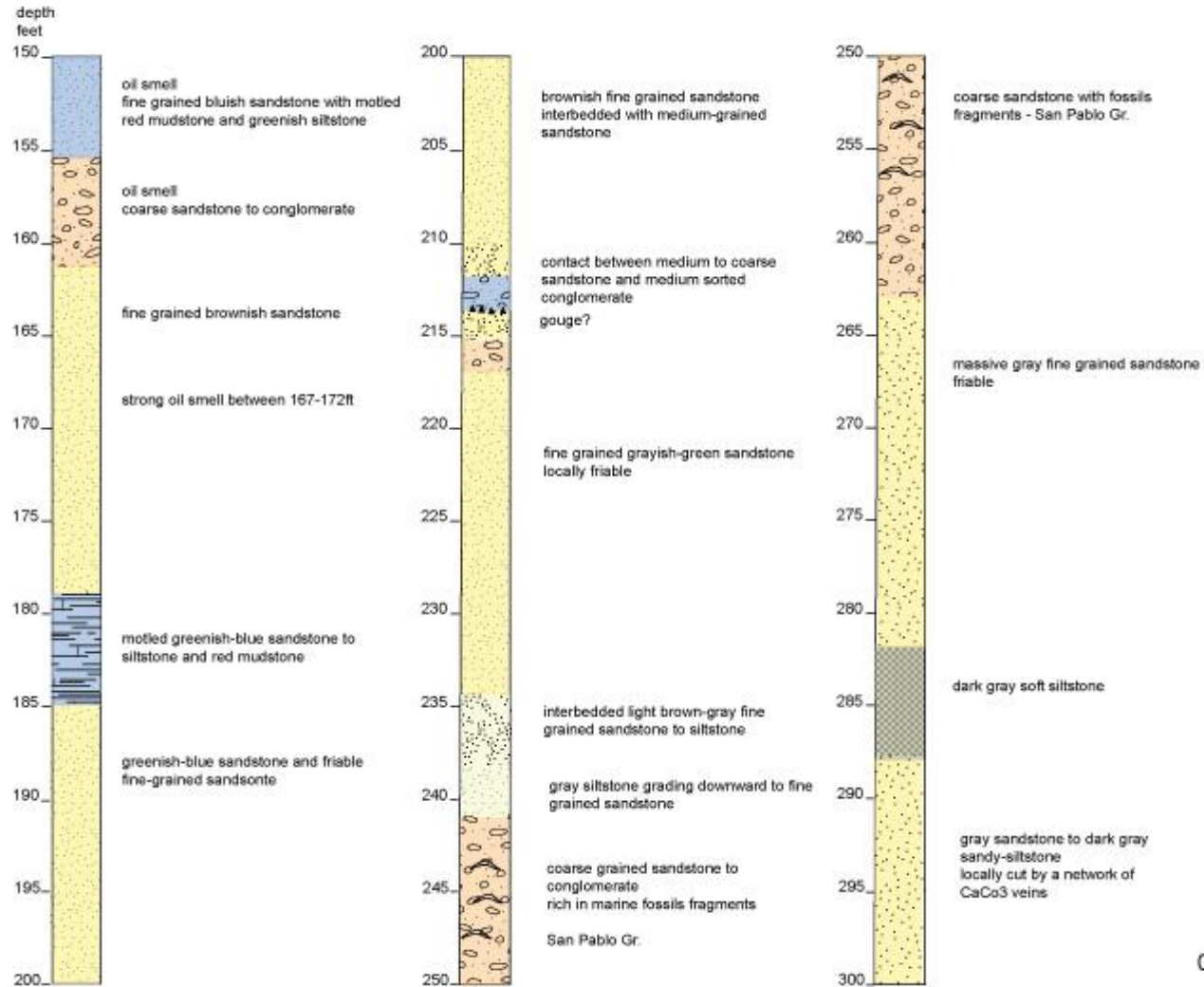
Figure 4-9. Picture of core showing the change from Claremont Fm to Orinda Fm.

A summary of core logging is illustrated in Figure 4-10.

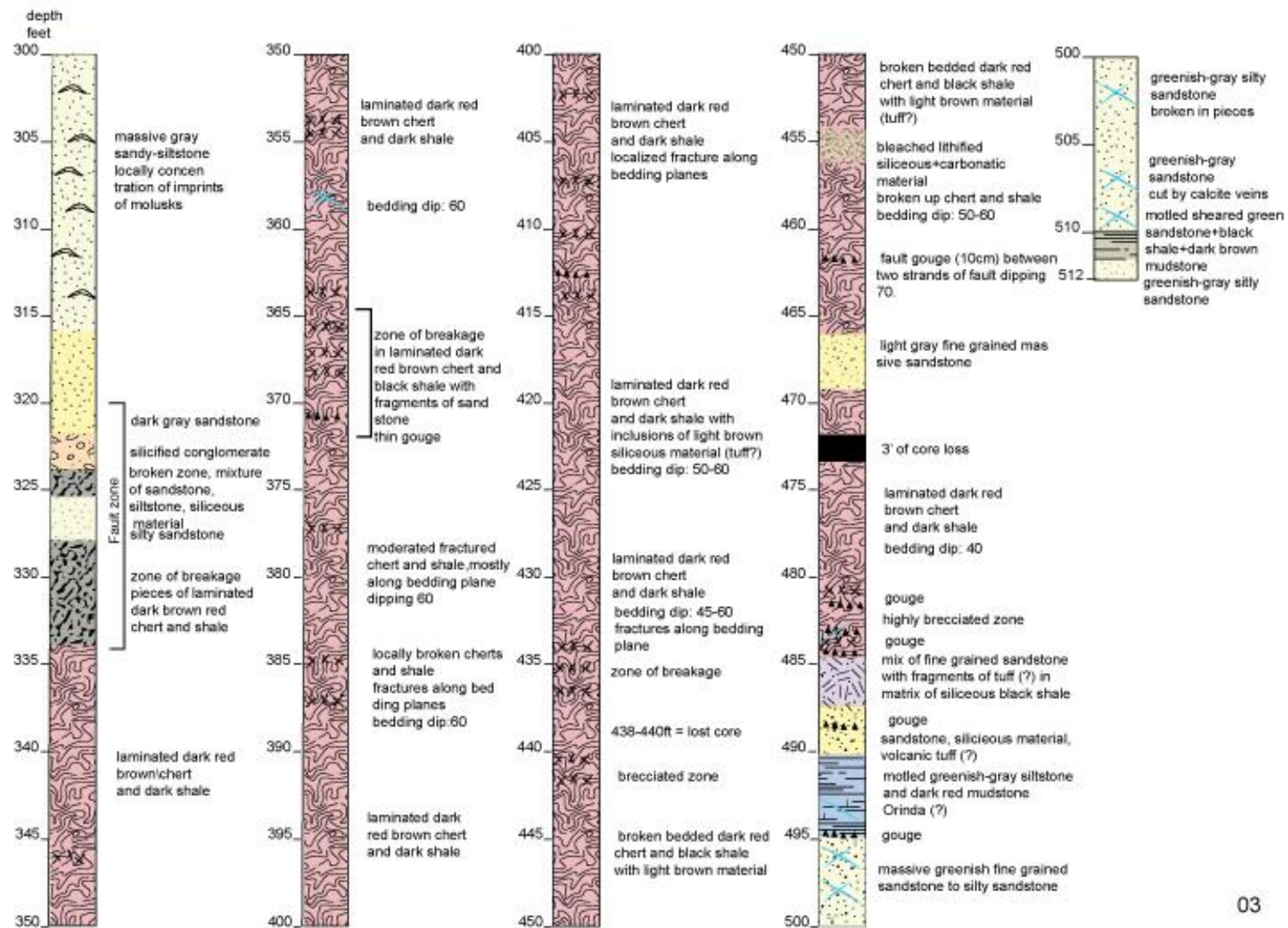
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Figure 4-10. Logging summary for WF-3

4.5 WF-4 Core Logging and Description

WF-4 was drilled at latitude $37^{\circ} 52' 38.874''\text{N}$ and longitude $-122^{\circ} 14' 22.358''\text{E}$. The location of the drilling is shown in Figure 4-11.



Figure 4-11 WF-4 drilling site, by parking lot at Calvin Road, in front of Building 83

Drilling of WF-4 commenced on August 17, 2010, and ended on September 22, 2010. The drilling started at 265.1 m above sea level. Total core length was 211.44 m (693.7 ft). The site was chosen to line up with previous boreholes oriented at N53E, but WF-4 is off by 6–7 degrees with an N60E orientation. The inclination is 60 degrees. In this report, the depth of core described refers to the logged depth (liner length) and has not been converted to vertical depth. The borehole encountered 3.2 m (10.5 ft) of colluviums, followed by 15.1 m (49.5 ft) of mottled greenish-gray silt-sandstone to fine grained silt-sandstone, with carbonate concretions of the Orinda Fm. /San Pablo Gr.. Below 18.3 m (60 ft) the core is essentially that of the Claremont Fm..

Core and water losses were encountered along the contact between Orinda Fm/San Pablo Gr. and the Claremont Fm. at 18.3 m (60 ft), suggesting the presence of a fault. No conglomerate

or any other type of faulting material was observed at contact. Gouge and brecciation are observed throughout the core at various depths (73 m, 95 m, 106–112 m, 139–142 m, and 153 m). Over thirty-one core losses have been described; among them, as many as fourteen were below 183 m (600 ft). The large ones, up to 1.5 m, might be related to the most recent faulting, since they are also zones of large fluid flow.

Down to 70.7 m (232 ft), eight zones of carbonate rich siltstone to carbonate concretion are observed. Below 70.7 m (232 ft), there is no evidence of carbonate concretion; instead, there are only zones of bleached brecciated calcareous material.

The Claremont Formation is part of the Middle Miocene Monterey Group. It consists of well-consolidated, moderately weathered, light yellow siliceous shale and bedded chert, interbedded with thin layers of siltstone. The Claremont Formation is regionally and locally folded and commonly overturned; bedding dip varies from northeast to southwest. Compared to surrounding bedrock, cherts are generally weather-resistant, forming some of the steeply sloped hills in the area (Ultermman, 1935; Page, 1950; Graham et al, 1984).

As with WF-1 and WF-2, sandstone in WF-4 is observed as a minor component in the interbedded shale and chert of the Claremont Formation. The sandstone is cored as a massive; macroscopically, it does not show any sedimentary texture such as sorting or grading. The grains are fine and angular to subangular. The structures observed with the naked eye in the sandstones are several millimetric dark seams, localized brecciation, and irregular contact with black shale and chert.

4.5.1 Main features within WF-4

4.5.1.1 Orinda/San Pablo-Claremont Contact at 18.8 m (60 ft) depth

The contact consisting of Orinda/San Pablo-Claremont chert at about 18.8 m (60 ft) depth is marked by core loss of about one meter. It is also a zone of water loss, suggesting the possibility of faulting along this contact.

The Orinda Fm/San Pablo Gr. above the contact is marked by greenish-gray silty-sandstone to claystone and by dark gray, fine-grained silty-sandstone rich in carbonatic concretions, as shown in Figure 4-12.



Figure 4-12 Greenish-gray silty-sandstone above the contact with the Claremont Fm.

4.5.1.2 Carbonate concretions from 23–71 m (75 to 234 ft)

One of the features that has not been described in previous core boreholes is the presence of carbonate concretions. In WF-4, ten zones rich in carbonate were found and are here described. They are usually light to dark color, massive to vug-like structures, very hard, and fizzes with HCl. They were found at 22.8 m (75 ft), 28.6 m (94 ft), 37 m (122 ft), 47.5 m (156 ft), 51 m (166 ft), 57 m (187 ft), 59 m (195 ft), 67 m (220 ft), 70 m (230 ft) and 70.7 m (232 ft). Some of them occur near a zone of brecciation—one example is shown in Figure 4-13.



Figure 4-13. Example of carbonate concretions at WF4_23m (75ft)

4.5.1.3 Zones of bleached laminated to brecciated siliceous material

Apart from the carbonate concretion, there are several zones of bleached brecciated siliceous material. They preserve the lamination but are internally broken and lithified. They are very hard, siliceous, but react with HCl. They are illustrated in Figure 4-14. A thick zone varying from 1.5 to 2.4 m (5 to 18 ft). The same material is found in WF-1 and described by Karasaki et al. (2010).

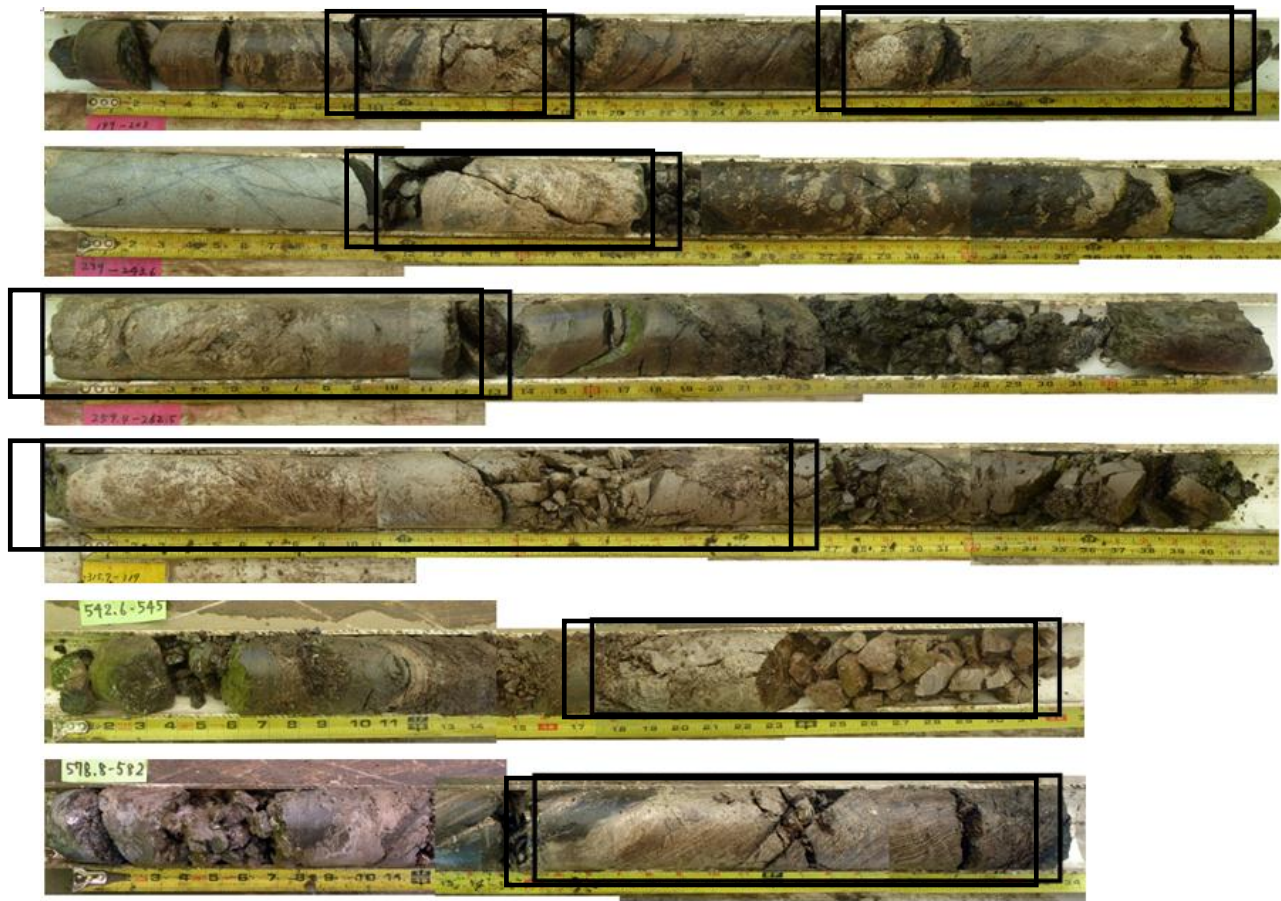


Figure 4-14. Framed areas show bleached laminated-to-brecciated siliceous material

4.5.1.4 Characteristic Fault Zones in WF-4

WF-4 encountered several minor fault zones showing localized deformation, specifically brecciation and gouge. Large intervals of rocks are found to be broken within a zone of brecciation, and there are localized zones where the rock is crushed. One example is shown in Figure 4-15.

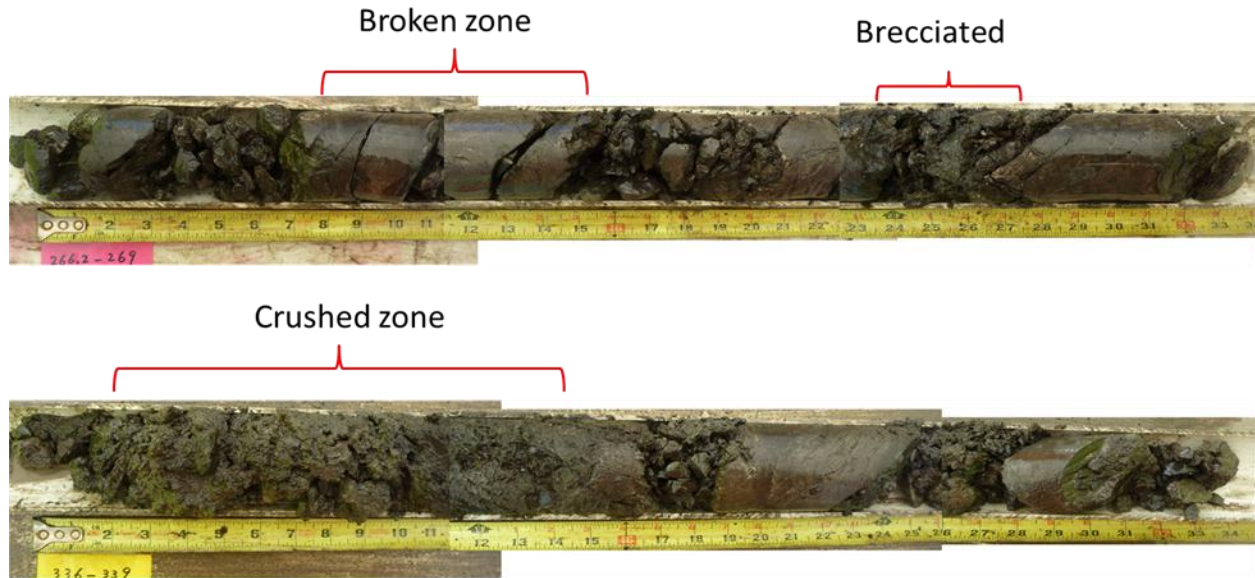


Figure 4-15. Example of deformation encountered in WF4

An example of cataclasite, found at 73.5 m (241 ft), is illustrated in Figure 4-16. The cataclasite, which is almost 0.6 m (2 ft) long, was observed between siliceous carbonate and broken up shale, chert, and sandstone. It is characterized by a cohesive random fabric of clasts and fragments of chert, bleached calcareous siliceous material, sandstone, and siltstone, or possibly tuffaceous material in a matrix of black shale.



Figure 4-16 Zone of cataclasite in WF4

Another example of cataclasite is the gouge found at 154 m (505 ft). It is an ~3 inch wide clay rich with fragments of chert and shale, oriented along the shear plane (Figure 4-17).

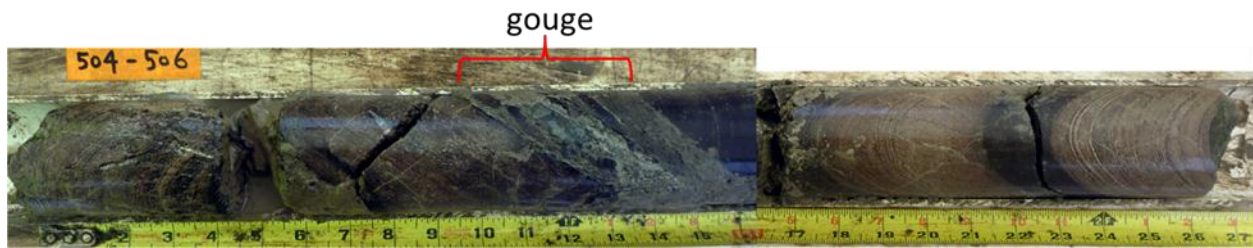


Figure 4-17. Three inch long gouge in WF4

At 192–192.6 m (629-632 ft), we observed a protocataclasite such as that shown in Figure 4-18. This is one of the intact fault rocks comprising angular to subangular clasts of light-gray fine-grained sandstone, floating in a matrix of fine-grained material of the same composition. Along the contact, there is a zone of dark brown gouge. Surrounding the breccia are zones of highly deformed material and core loss, indicating zones of high strain. Kiho et al. (2010) have described and analyzed this protocataclasite under CT scan.



Figure 4-18. Sandstone protocataclasite at 629-632ft depth from WF4

4.5.1.5 Major faults and core losses

The cores recovered from WF-4 were more damaged than those of the other three boreholes. Gouge and breccias occurred frequently, as did core losses: these locations are likely zones of high strain. The contact between Orinda Fm./San Pablo Gr. and Claremont Fm. is characterized by core loss, as described previously. The same contact in WF-2 and WF-3 is marked by coarse material that under the microscope resembles more sedimentary than tectonic breccia, although zones of brecciation are observed under the microscope. See a detailed description under “Petrographic Analysis” in Section 4.6.

Between 56 and 61 m (185 ft and 200 ft) depth, three zones of core losses are described that are closely related to zones rich in carbonate. The same is noted in two core losses at 74 m (243 ft) and 75 m (246 ft). However, between 182 m (600 ft) and 211 m (693.7 ft), there are fourteen zones of core losses, the largest one over 1.5 m (5 feet) long, as described in the Core

Logging section and shown in Figure 4-19. This zone is considered the zone of most recent faulting, as they are also related to zones of high fluid flow, evidenced by the development of calcite veins that increase towards the end of the core (see Section 4.6 for more detail).

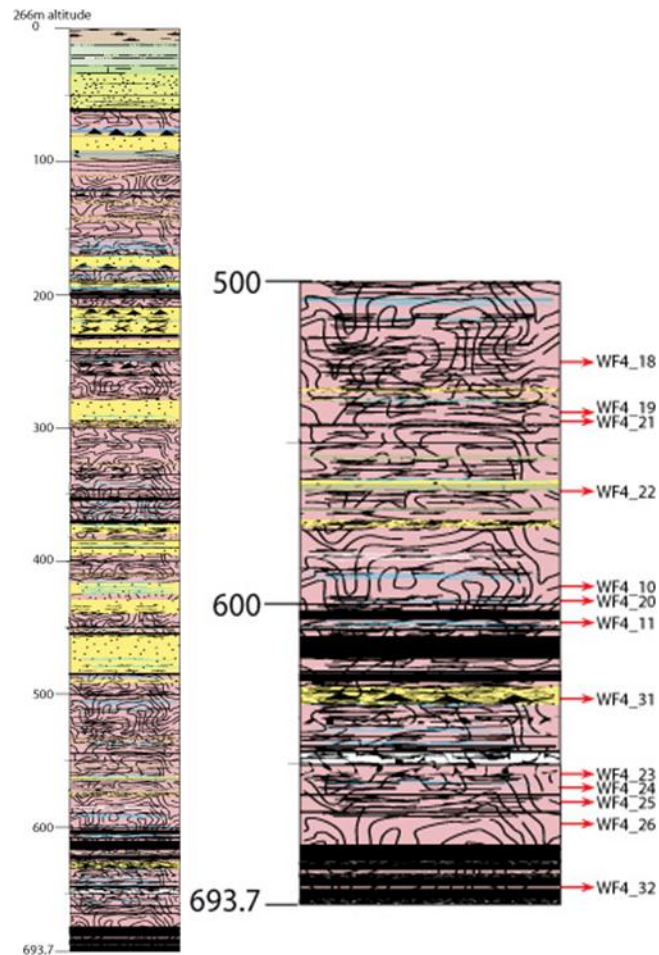
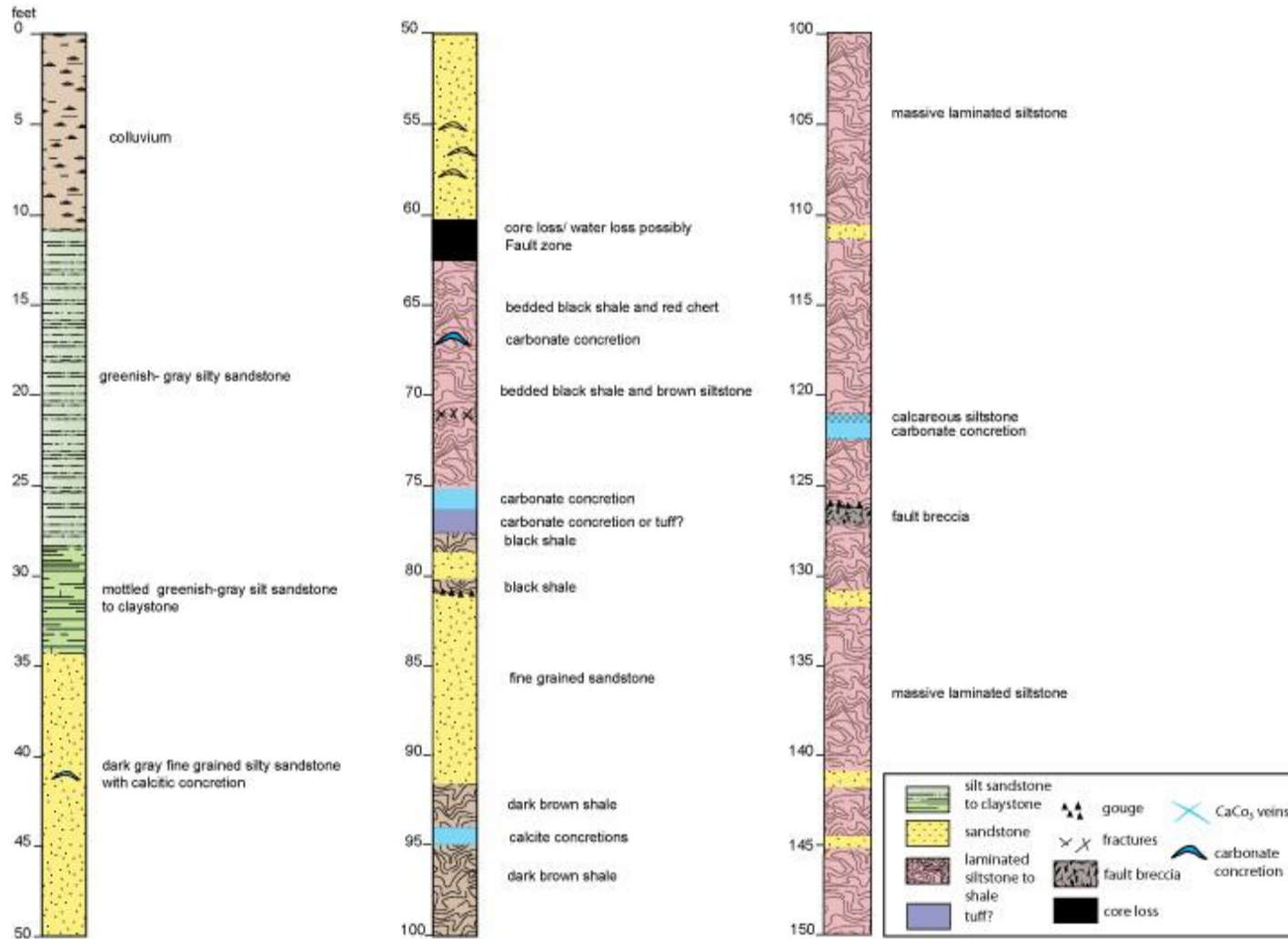


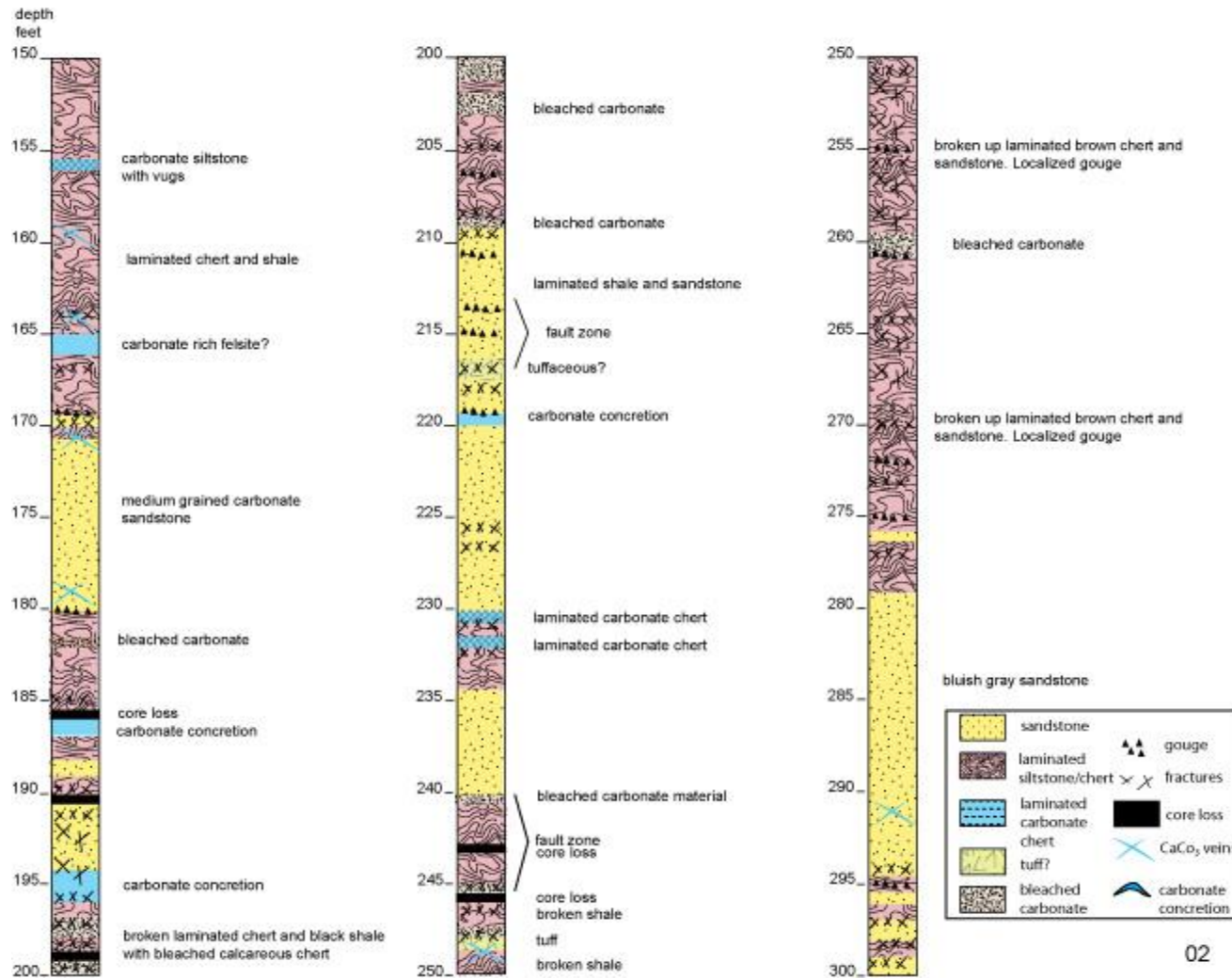
Figure 4-19 Zone of massive core losses (182 m–211 m) .

A summary of core logging is illustrated in Figure 4-20 below.

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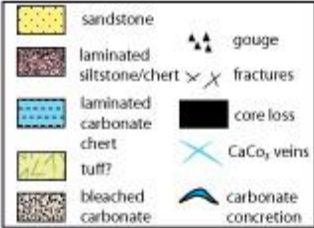


Wildcat Fault - Hole WF-4
Project: NUMO-LBNL-CRIEPI

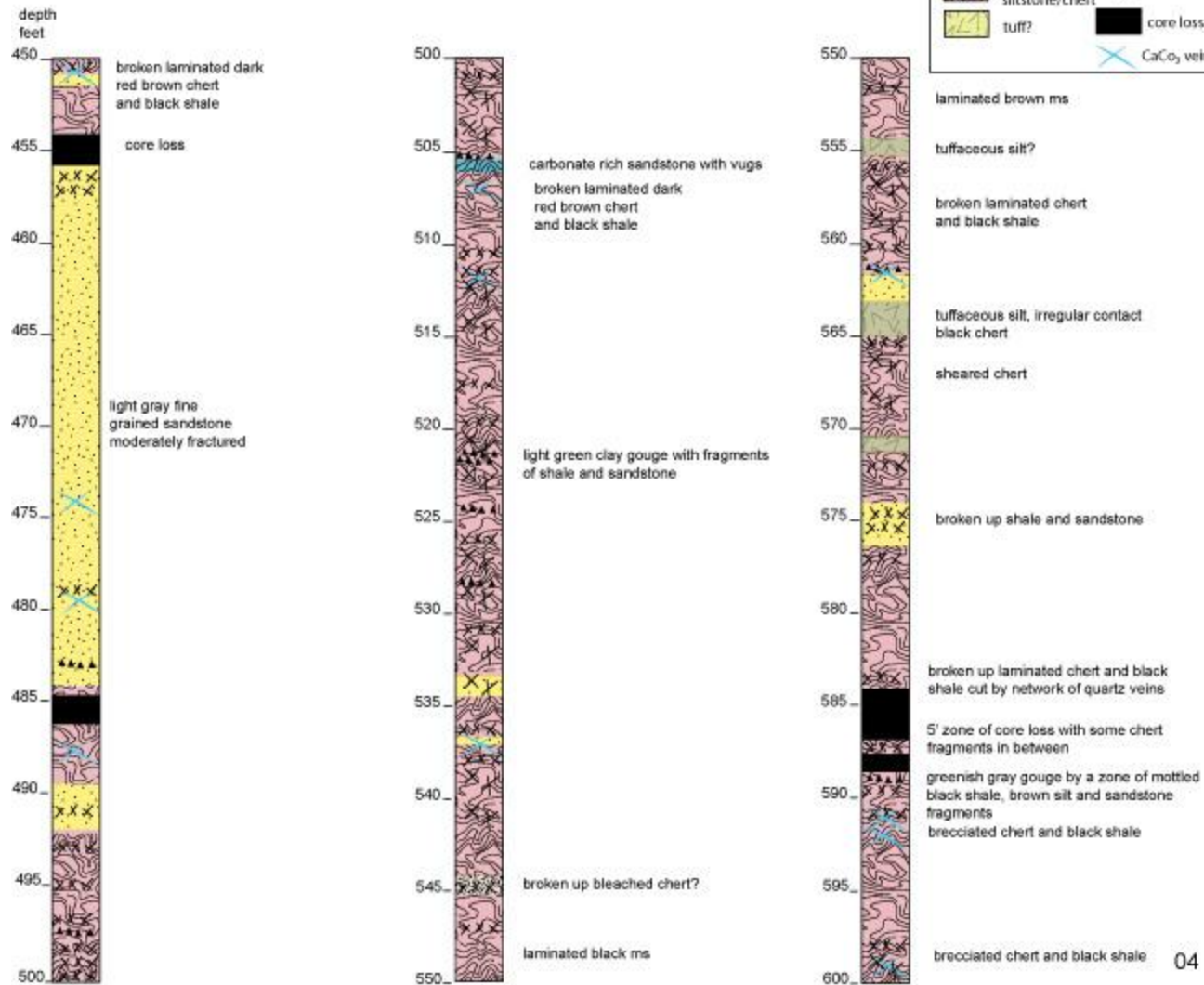


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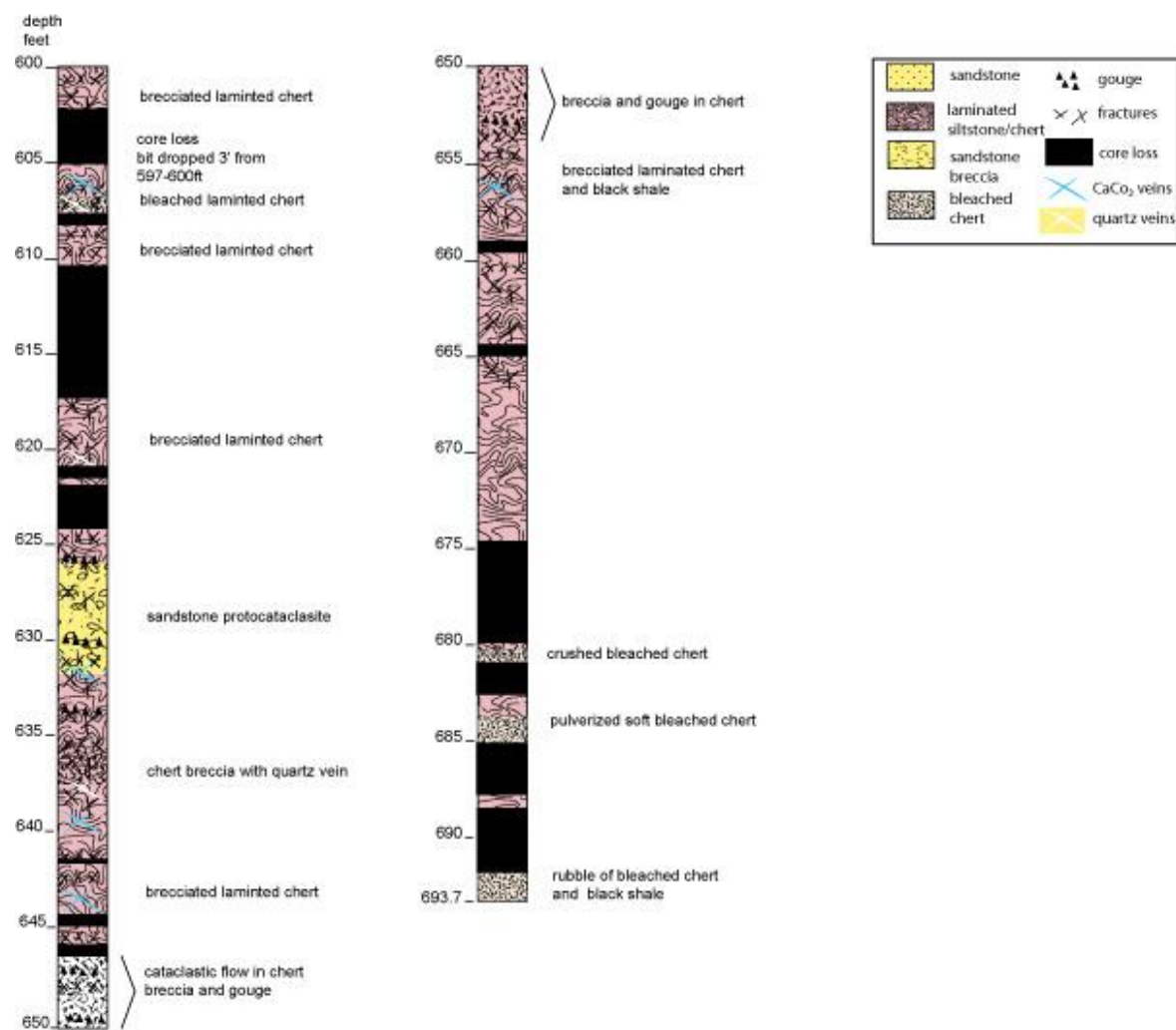
Wildcat Fault - Hole WF-4
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Wildcat Fault - Hole WF-4
Project: NUMO-LBNL-CRIEPI



Wildcat Fault - Hole WF-4
Project: NUMO-LBNL-CRIEPI



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Figure 4-20. Logging summary for WF-4.

4.6 Petrographic Analysis

About fifty thin sections were examined for petrographic analysis, sampled from all the WF boreholes. The main objectives for optical petrography were to (1) correlate chert mineralogy from macro to micro scale, (2) differentiate macroscopically described sandstone from Claremont Fm. and Orinda Fm, (3) correlate and characterize faults, and (4) examine carbonate veins for isotopes and relate them to fluid flow.

Graymer (2000) describes the Claremont Formation in the Berkeley Hills macroscopically as laminated and bedded chert, minor brown shale, and white sandstone. Untermann (1934) was one of the few to describe them petrographically, although all of his samples were from outcrop, and therefore weathered.

The advantage of using core samples for petrographic analysis is the unweathered state of the rock, which is useful for mineral identification, chemical analysis, and spacial correlation of stratigraphy.

Bulk-rock XRD analysis was conducted as an auxiliary tool for petrographic analysis. XRD analysis allows investigators to identify the crystallographic structure and chemical composition of fine-grained minerals, which are not possible to identify optically. Selected samples were analyzed under x-ray diffraction at LAMIR (Laboratorio de Analises de Minerais e Rochas) at University of Parana State in Brazil. The unabridged analysis can be found in Appendix 3. In addition, Kiho et al. (2011) conducted thin-section analysis, XRD analysis, and U-Pb analysis of zircon found in cores.

4.6.1 Claremont Fm. chert and shale mineralogy

The Claremont Formation is part of the Miocene Monterey Group, which extends along the coast of California from Santa Barbara to Point Reyes. According to Barron (1986) the Monterey Group is not homogeneous. It consists of varying amounts of biogenic calcite (calcareous nanofossils and foraminifers) and biogenic silica (diatoms and radiolarians) deposited in laminated beds and in thick, massive beds. These Monterey rocks were apparently deposited at depths of 1,000 to 1,500 m in the sea, within silled anaerobic basins (Ingle, 1981).

Isaacs (1983, 1984) argue that fluctuations in the strength of upwelling through the Miocene were largely responsible for the varying proportions of the biogenic components, with

the diatoms being the most abundant during times of increased upwelling. These upwellings were related to major polar cooling during the Middle Miocene, causing intensification of a pole-to-equator thermal gradient (Ingle, 1981; Pisciotta and Garrison, 1981; Woodruff et al, 1981). Other characteristic of the Monterey Group is its lower rate of terrigenous accumulation compared to rocks above and below (Isaacs, 1983, 1984).

Graymer (2000) describes the Claremont chert as late to middle Miocene. It consists of laminated and bedded chert, minor brown shale, and white sandstone. In the Berkeley Hills, the chert is distinctively black and laminated. Lawson (1914) and Graymer (2004) use the Claremont shale as coeval with this unit. Other lithologies mapped in the Berkeley Hills include the Miocene unnamed sandstone, Early Miocene unnamed gray mudstone, and Miocene to Oligocene unnamed glauconite mudstone, mapped by Radbruch (1969) as including interbedded sandstone and unnamed green and maroon foraminifer-rich Eocene mudstone.

Karasaki et al. (2010) describe the Claremont Formation in the Berkeley Hills as:

- Laminated, hard to moderately hard, dark gray/white/yellow/black banded/laminated/silicified chert and moderately to deeply weathered (Subsurface Consultants, 1994);
- Brown shale, dark brown siliceous shale, thinly bedded (HLA, 1980);
- Light brown and black Claremont shale (Kleinfelder, 2001).
- Beds of chert separated by sandy to silty shale interbeds. Claremont chert derived dense sandy gravel matrix with angular to subrounded chert clasts, locally reddish-brown, clay-rich weathering zone (WLA, 2008)

Under the microscope, the laminae are distinguished by a change in composition. For instance, there are levels rich in microcrystalline quartz, levels rich in clay minerals, and others rich in carbonate. Overall, they are dark brown, with a dirty feel, due a considerable amount of iron oxide. Since they are too fine to be identified under microscope, even at high magnification, some samples were analyzed under x-ray diffraction. An example of rich laminated microcrystalline quartz levels combined with rich brown clay rich levels is shown in Figure 4-21.

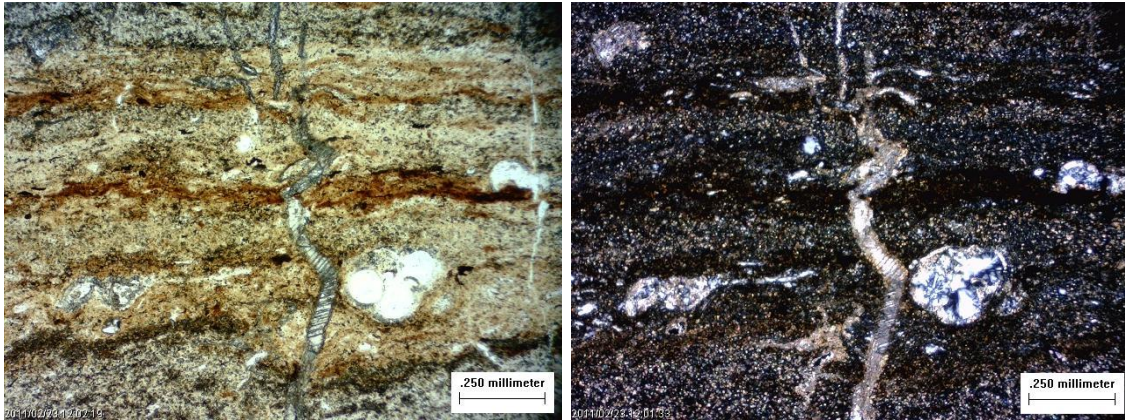


Figure 4-21. Typical Claremont chert. Note the laminae and microfossils. Sampled from WF-1—133 m (437 ft)

Another example of laminated microcrystalline quartz and carbonate rich is shown in Figure 4-22. XRD analysis indicates the presence of quartz, calcite, dolomite, siderite, and kaolinite. Note that the laminae is cut and displaced by fine-grained carbonate-rich material.

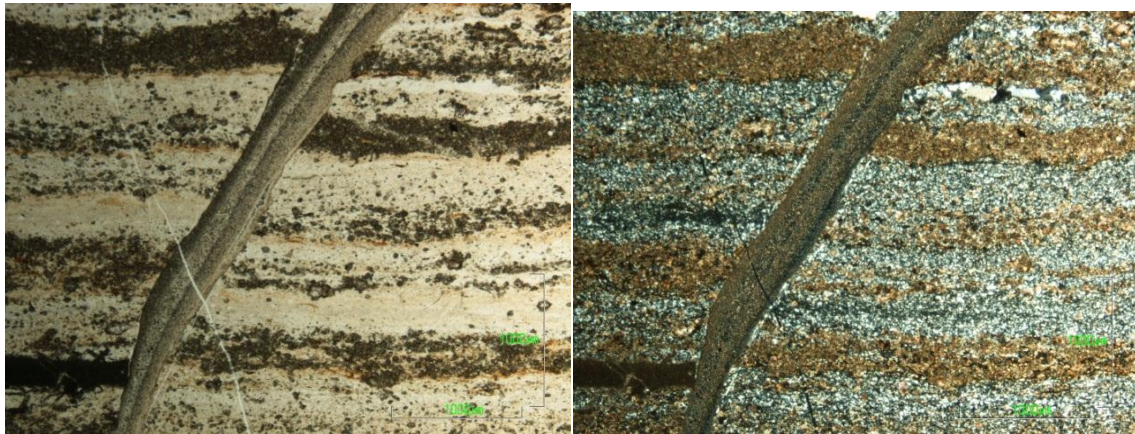


Figure 4-22. Laminated carbonate-rich, microcrystalline quartz from WF-4—185 m (606ft)

4.6.2 Microfossils

There is a dearth of publications related to microfossils of the Claremont Formation. The amount of bioclast (marine fossils) is quite high in the silt as well, and the formation is clay-rich and carbonate-rich. Microbiologists Mary McGall and Charles Powell from the US Geological Survey conducted a quick analysis of pictures taken from the thin sections and concluded that they are heavy in foraminifera, with some gastropode, fragments of oyster shells, and possibly radiolaria (McGall and Powell, personal communication, 2011). Both were surprised by the amount, diversity, and good preservation of the microfossils. Similar microfossils were found in

the layers of the Orinda Fm. in WF-3. Macroscale imprints of mollusks and shells observed in WF-2 indicate a shallow marine environment (Powell, personal communication, 2010). According to Charles Powell (personal communication, 2011), at the contact between Orinda Fm. and Claremont Fm. in WF-3 at 98 m (321 ft), there are heavy amounts of oyster shell fragments in the conglomerate. Below are some of the examples of marine fossils found within the Claremont Formation in WF-1, WF-2, and WF-4, and in the Orinda Formation in WF3

Examples of microfossils in the Claremont Fm. are illustrated in **Error! Not a valid bookmark self-reference., Error! Not a valid bookmark self-reference.,** Figure 4-25, and in the Orinda Fm in Figure 4-26. All pictures are taken in plane-polarized light.

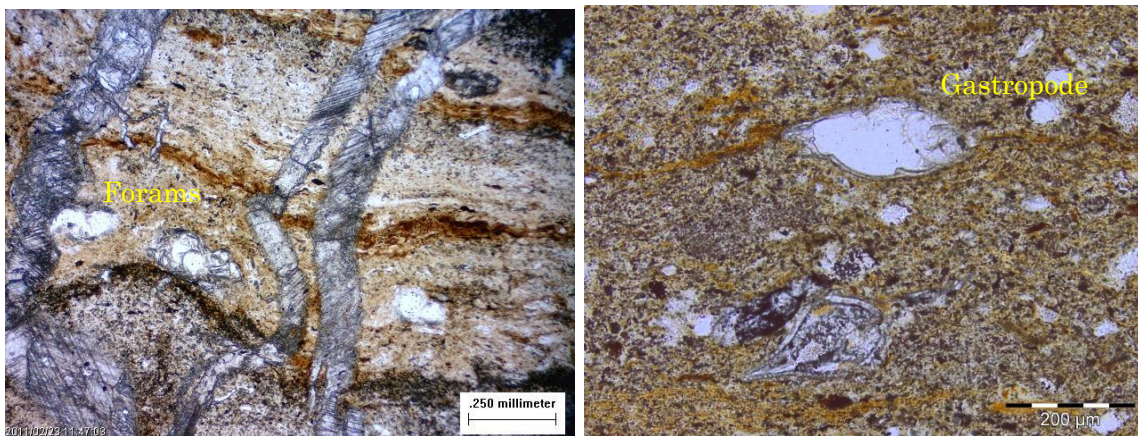


Figure 4-23. Microfossils (foraminiferas and gastropode) in the Claremont Fm. WF-1—133 m (437.5 ft) and in WF-4—165 m (541 ft)

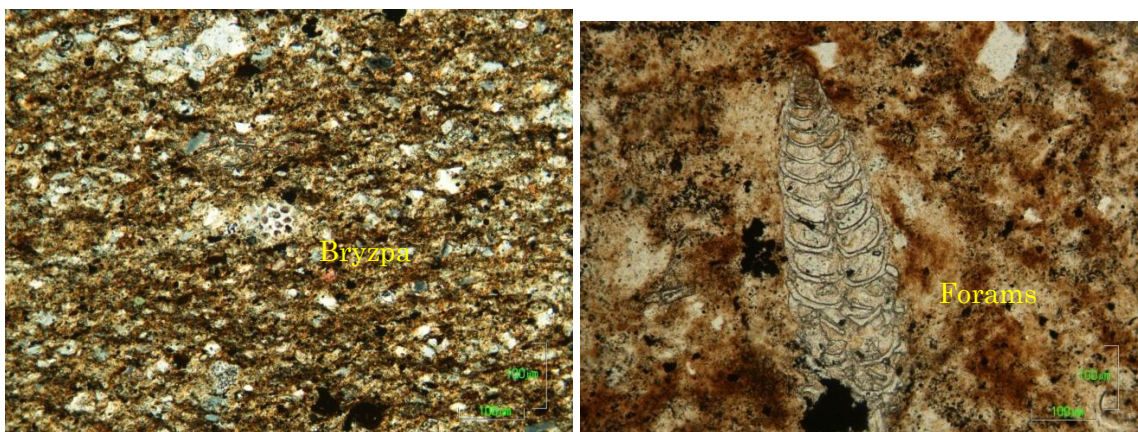


Figure 4-24. Examples of Bryzoa and Foraminifera from WF-2—18 m (58.3 ft) and WF2—61 m (200 ft) in Claremont Fm.

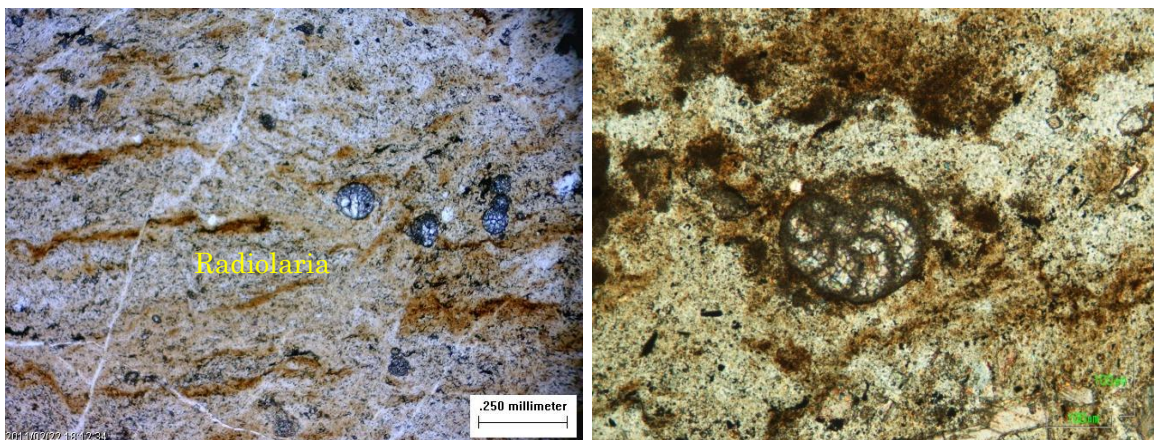


Figure 4-25. Example of radiolaria from WF2—92 m (300.8 ft) and from WF-1—124 m (406 ft) in Claremont Fm.

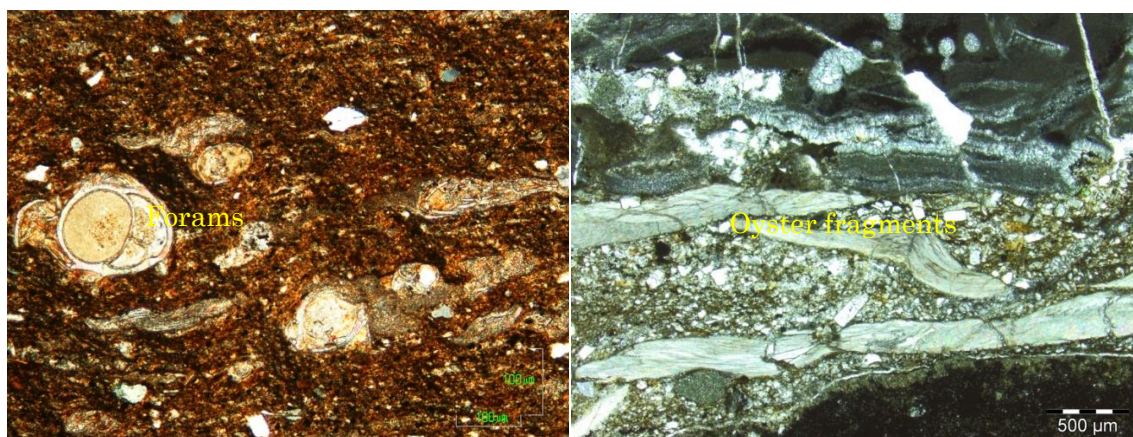


Figure 4-26. Siltstone rich in foraminifera from WF-3—66 m (216 ft) and oyster fragments from WF-3—98 m (321 ft) in Orinda Fm.

4.6.3 Orinda Fm. and Claremont Fm. sandstone

4.6.3.1 Claremont Sandstone

In core logs, sandstone from the Claremont Fm. is described as light gray to bluish fine-grained and homogeneous sandstone. Under the microscope, they are more heterogeneous. The grains are poorly sorted, angular to subangular, and composed mostly of quartz grains (including chalcedony, microcrystalline, and metamorphic grains), plagioclase, K-feldspar, lithic fragments, carbonate, opaque (mainly pyrite), zircon, glauconite, white mica, and clay minerals. The matrix is made up of very finely mixed grains of quartz, feldspars, clay minerals and carbonate. It is texturally immature. The amount of glauconite zircon varies, as well as the amount of fine mica and carbonates. However, the large percentage (over 20%) of feldspar, the presence of glauconite, and the angularity and sorting of the sediment suggest a deposition in the shallow marine environment (Figure 4-27).

The mineral most characteristic of the deposition environment is glauconite, a green grained, hydrous potassium iron alumino-silicate mineral that forms exclusively in marine environments, usually in fairly shallow waters (Adams et al., 1984). Glauconite was found in Claremont Fm., Orinda Fm. and San Pablo Gr. samples. According to Mackenzie (2005) present-day glauconite is found in low-depositional-rate environments, such as in the shallow water of the continental shelf, at depths between 50 and 1000 m (Selley, 2000). Glauconites are commonly found with phosphates (Fountain and McClellan, 2000 in Mackenzie, 2005).

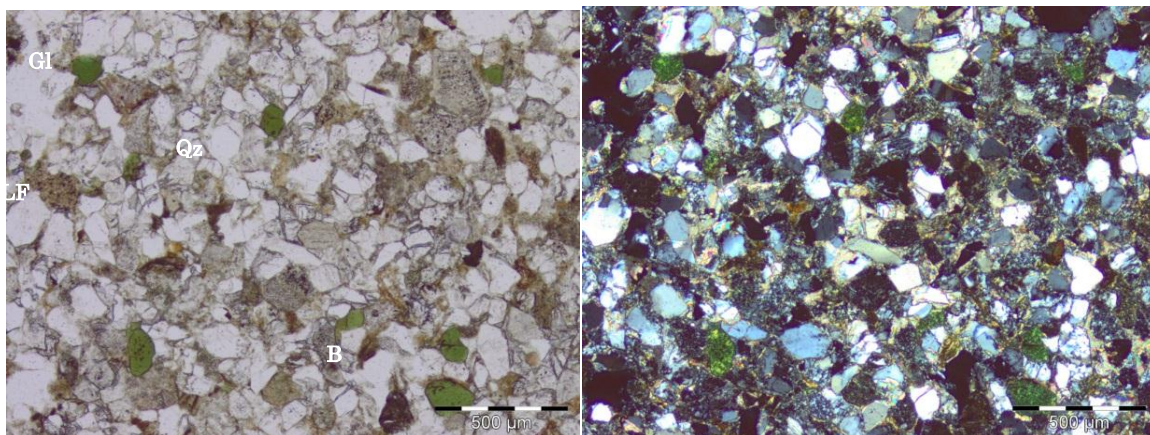


Figure 4-27 Poorly sorted sandstone rich in glauconite (Gl), Quartz (Qz), Plagioclase (Pl), lithic fragment (LF), biotite (B). Plane-polarized light and crossed polarizers views of WF1—154 m (504 ft).

Besides glauconite, the matrix also contained carbonate, noted as a large recrystallized rock mixed with fine-grain material. Results from XRD analysis indicate the presence of quartz, plagioclase (albite), glauconite, clay mineral (nacrile from kaolinite group), piroxene (diopside), possibly aerinite, and muscovite in WF1—154 m (504 ft); and quartz, albite, and possibly nantronite. Nantronite is an iron-rich member of the smectite group of clay minerals in WF4—119 m (390 ft) (see Appendix 3). Pictures of thin sections are shown in Figure 4-28.

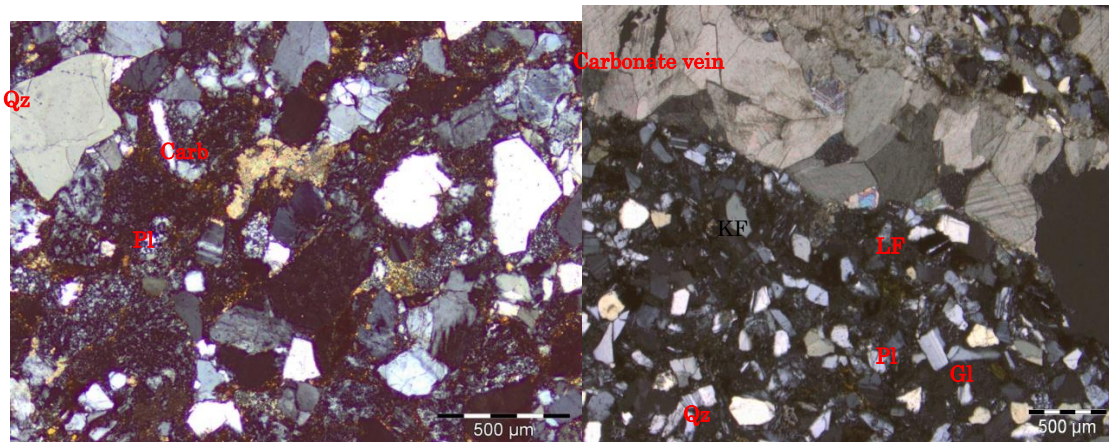


Figure 4-28 Recrystallized carbonate and fine grained in the matrix. Crossed polarizers views of WF1_108m (353ft) and WF4_119m (390ft). Quartz (Qz), plagioclase (Pl), K-feldspar (KF), glauconite (Gl), lithic fragments (LF) and carbonate in matrix (Carb) in cross polarized views.

In one particular poorly sorted sandstone, a heavy amount of zircon grains (tiny grains with high relief under plane-polarized light) were observed mixed with angular to subangular grains such as quartz, plagioclase, K-feldspar, glauconite, lithic fragments (

Figure 4-29).

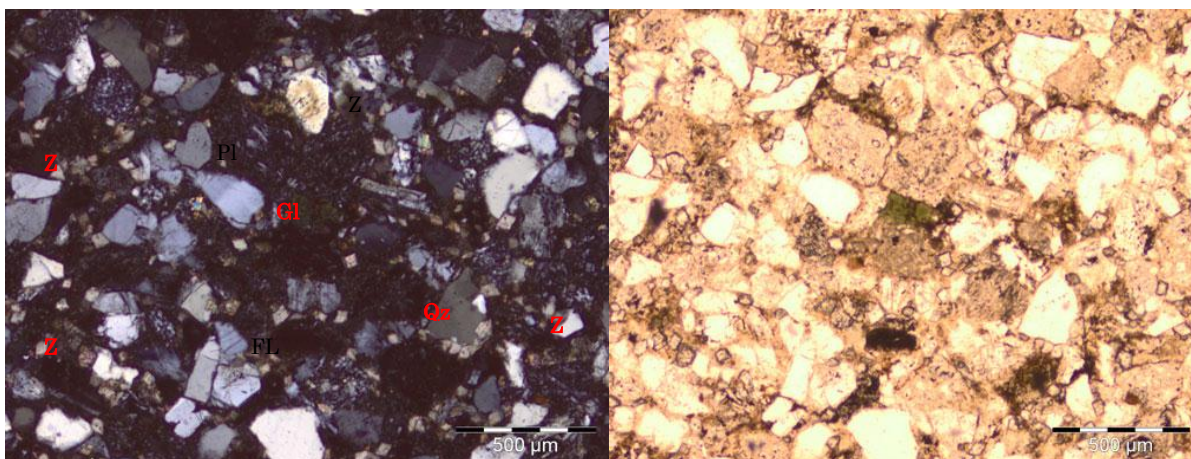


Figure 4-29. Besides glauconite (Gl), quartz (Qz), plagioclase (Pl), lithic fragments (LF), this sample from WF4—129 m (424 ft) has a high concentration of zircon (Z) grains—Plane-polarized light and crossed polarized views.

Sandstone next to the fault zone, such as observed in WF2—68 m (224.6 ft) (Figure 4-30) shows white mica (muscovite) oriented along two sets of preferential orientation. However, the grains do not show any kind of deformation (fracturing or brecciation). Under XRD, the main bulk mineralogy is quartz, dolomite, pyrite, plagioclase, and clay minerals. (See Appendix 3.)

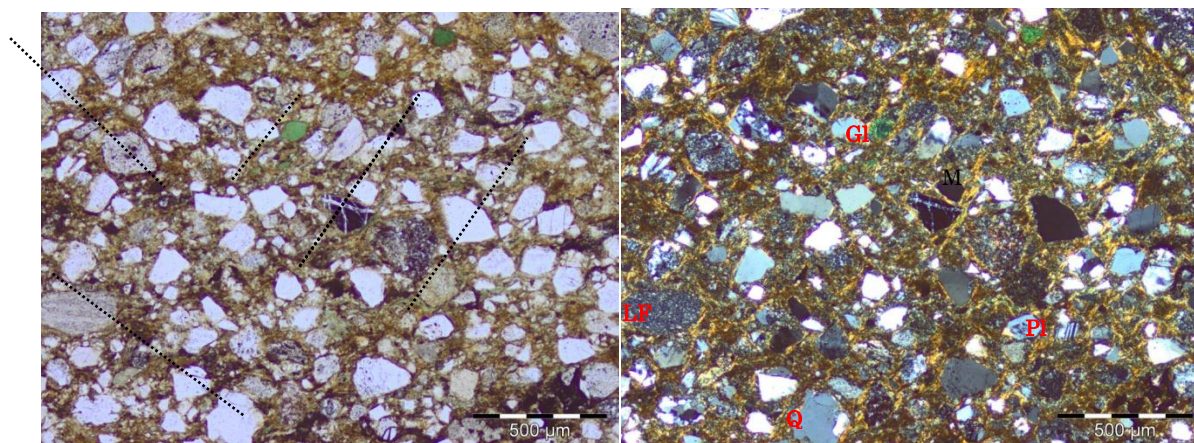


Figure 4-30. Sandstone next to a fault zone from WF-2—68 m.

4.6.3.2 Orinda Sandstone

Sandstone from the Orinda Fm. at macro scale is less cohesive than the sandstone from the Claremont Fm. It has finer grain size, a silty component, and is green in color. The greenish

color possibly results from the amount of green minerals within it, such as chlorite and glauconite. Under the microscope, the sample from WF-3—497ft (Figure 4-31) shows very similar composition to the Claremont Fm. It is fine grained and composed of poorly sorted angular-to-subangular grains of quartz, feldspars, lithic fragments, mica, biotite, pyrite, clay minerals, glauconite and possibly serpentine. An XRD analysis of this sample indicated the presence of quartz, albite, lizardite, and ankerite. The presence of lizardite (serpentine group) was detected under XRD, which needs to be confirmed by more samples. Another sandstone with glauconite, shown in Figure 4-32, again shows angular-to-subangular grains similar to the Claremont sandstone. Other than the presence of serpentine, there is a lack of fine mica and carbonate in the matrix when compared with Claremont sandstone, but this observation needs to be confirmed by more samples.

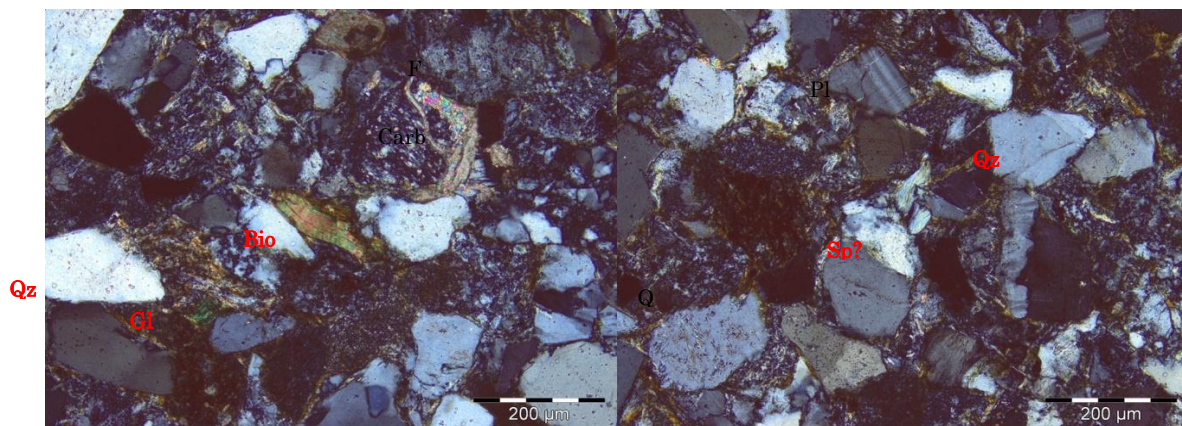


Figure 4-31. Fragment of biotite and possible serpentine under cross-polarized view in poorly sorted sandstone, sample WF3—151 m (497 ft)

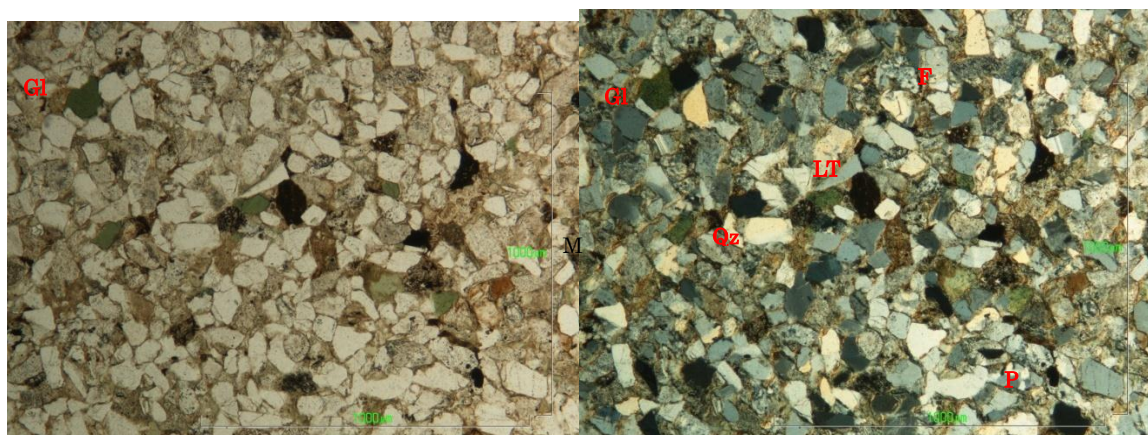


Figure 4-32. Plane-polarized and cross-polarized view of fine-grained, poorly sorted sandstone with glauconite from WF3—154 m (506 ft)

4.6.3.3 San Pablo Sandstone

At the macroscopic scale, sediments from the San Pablo Group are basically described as coarse, immature sandstone rich in shell fragments. Under the microscope, shell (oyster) fragments are clearly observed in a matrix very similar to the Orinda sandstone (Figure 4-33). The presence of glauconite is often observed within this group. Below is a sample from WF3—80 m (262 ft).

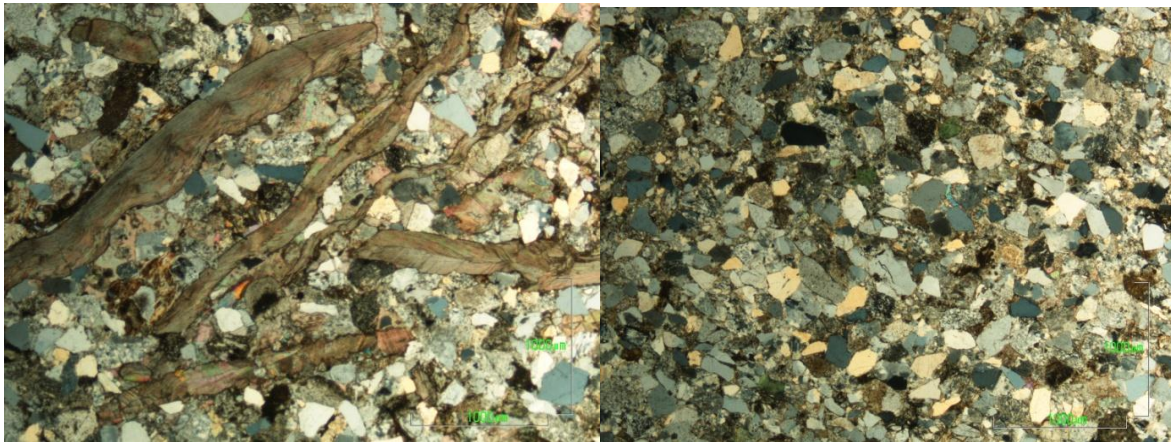


Figure 4-33. Shell fragments and immature sandstone of San Pablo Group. Cross-polarized views

4.6.4 Bleached, brecciated and lithified siliceous carbonate rocks

First described in the discussion of WF-1, these bleached, brecciated, lithified siliceous, often-laminated rocks are found interbedded with Claremont shale and chert (and less often with sandstone). Their thickness is variable. In WF-1, a highly fractured zone of 5.4 m (18 ft) in length was found (Karasaki et al., 2010). In WF-2, they are widespread, and their thickness varies from 0.3—0.9 m (1–3 ft). In WF-4, these calcareous concretions, rich in vugs and bleached siliceous and carbonate rocks, are often found near fault zones. An example is shown in Figure 4-34.

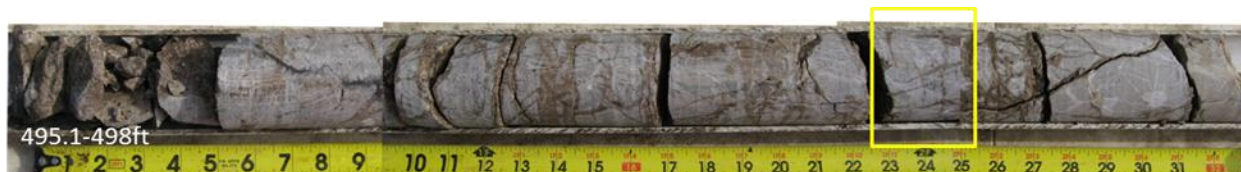


Figure 4-34 Example of bleached brecciated lithified siliceous carbonate material

Under the microscope, the sample from WF-1—151 m (497 ft), as shown in Figure 4-35, is characterized by two stages of carbonate. The finely laminated carbonate and clay-rich (carbonate 1) is disrupted and displaced by a chaotic network of quartz (possibly chalcedony) veins; carbonate 2 is granular and rich in marine fossils, such as foraminifera. A bulk XRD test confirmed the presence of quartz, calcite, plagioclase, dolomite and clay minerals. But because it was a bulk analysis, it was not possible to distinguish between the calcite and dolomite carbonate.

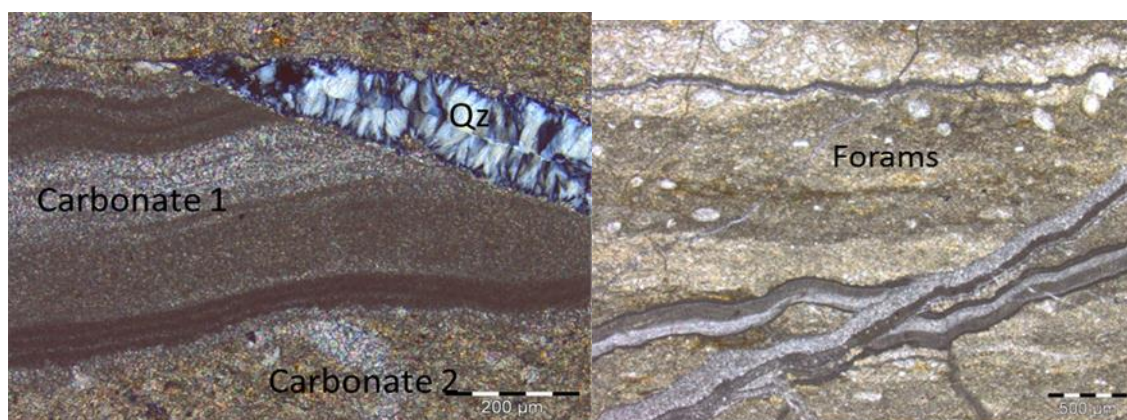


Figure 4-35 Cross-polarized views of two stages of carbonate, quartz veins and microfossils

Another sample from WF4—112 m (368.2 ft) shows a very similar texture, as illustrated in Figure 4-36. Two distinct carbonates are observed. One carbonate is finely laminated; the other is coarse and granular—and both are disrupted and displaced by quartz veins. Under XRD analysis, the main compositions are found to be quartz, dolomite, and plagioclase.

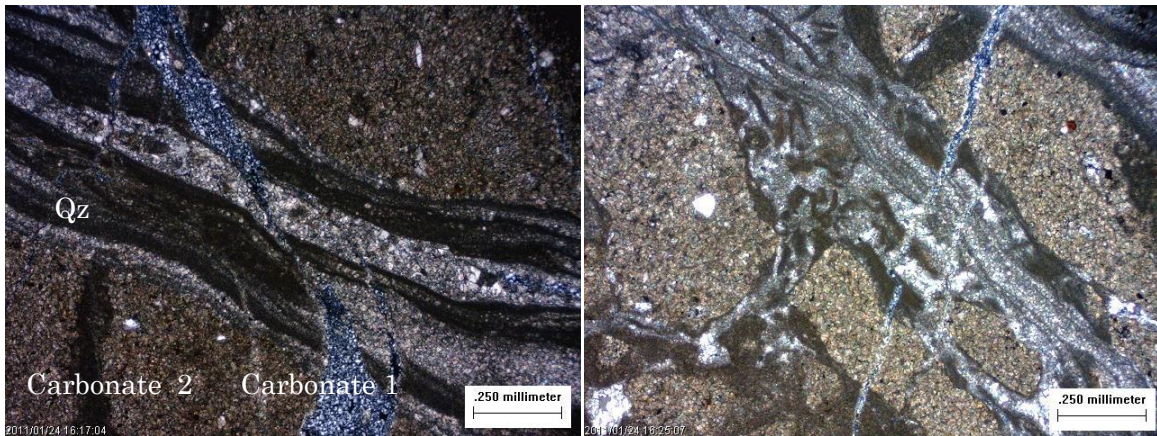


Figure 4-36. Cross-polarized views of two carbonates (laminated and granular), quartz veins and microfossils

4.6.5 Unconformity and/or Fault zone: Orinda Fm/San Pablo Gr. and Claremont Fm.

During the drilling of WF-2, WF-3 and WF-4, the contact between Orinda Fm/San Pablo Gr and Claremont Fm is crossed. Macroscopic descriptions of WF2 suggest a sharp contact at 16.76 m (55 ft) depth made up of a dense material that resembles coarse, homogeneous conglomerate or a lithified gouge (Karasaki et al., 2010). Under the microscope (Figure 4-37, Figure 4-38, and Figure 4-39), this material is characterized by round clasts of various sizes and shapes. The clasts are composed of laminated to massive carbonate-rich material, often also rich in microfossils. Most of the clasts show internal deformation characterized by calcite and quartz veins. Some clasts have concentrations of tiny grains of opaques, possibly pyrite, along the rim. The matrix is made of fine-grained carbonate material, fine grains of quartz, feldspars, and lithic fragments. Localized zones of brecciation are observed; fragments are angular, but there is no indication of shearing. This suggests an unconformity made of a brecciated carbonate conglomerate. Page (1950) describes conglomerates along the contact between Orinda Fm. and Claremont Fm, along the Broadway Tunnel. In the Broadway Tunnel, this basal conglomerate ranges from 0–5 ft thick and fills erosional depressions in the underlying Claremont Fm. Page (1950) also records angular unconformity with some slippage.



Figure 4-37. Thin section of WF2—16.8 m (55.3 ft), along the contact between Orinda Fm/San Pablo Gr. and Claremont Fm.

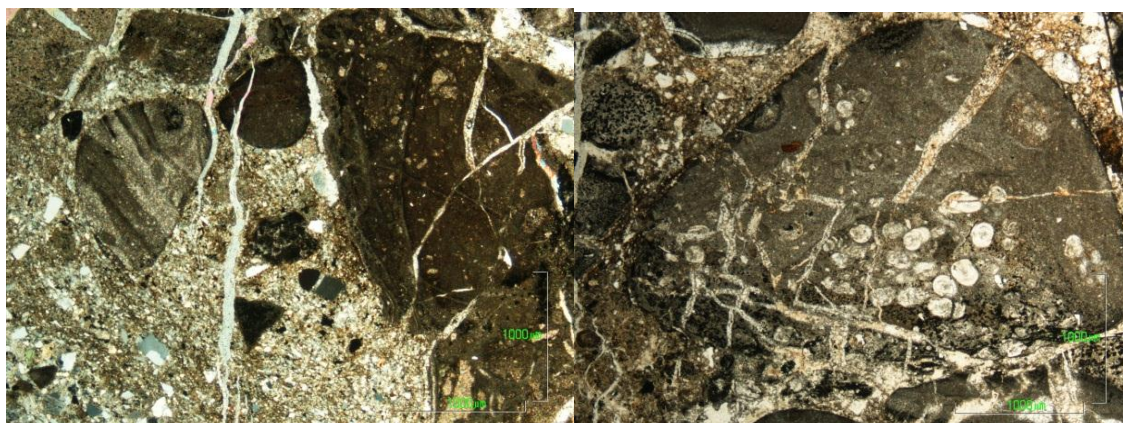


Figure 4-38. Clasts and matrix of WF2—16.8 m (55.3 ft). Some rich in bioclasts in cross-polarized views.

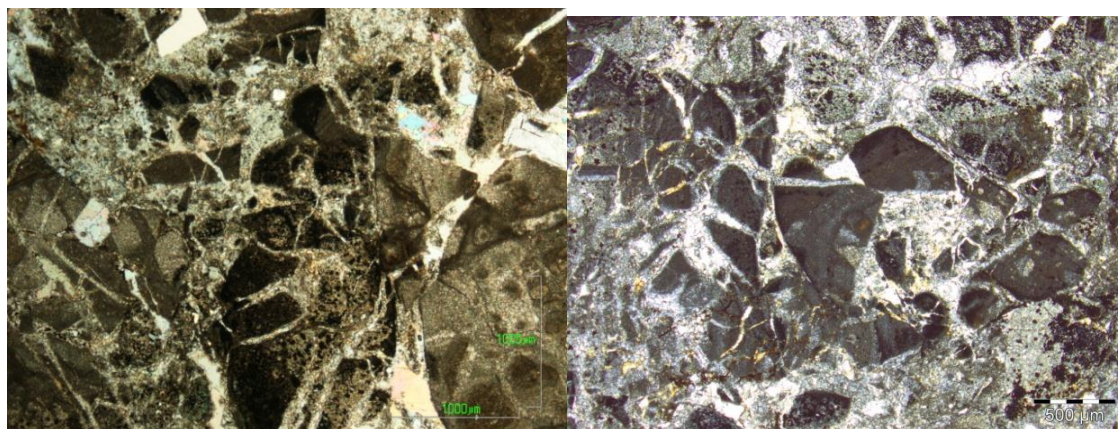


Figure 4-39. Localized brecciation, no shearing in WF2—16.8 m (55.3 ft) in cross-polarized views

In WF-3, the contact is observed at about 98.75 m (321.9 ft) and at 147.8 m (485 ft). The first contact is characterized macroscopically by a zone of brecciation, including a mixture of sandstone, siltstone, and calcareous material; and the second contact (with the Orinda Fm) was observed as a thin gouge (described in Section 4.4.2). The first contact is illustrated in Figure 4-40.



Figure 4-40. Thin section of WF3—98.75 m (321.9 ft) along the contact between the Orinda Fm/San Pablo Gr. and the Claremont Fm.

Under the microscope, the first contact has similar composition, as previously described in the findings for WF-2. XRD results indicate the presence of quartz, dolomite, pyrite, calcite, plagioclase, mica, and clay minerals (see Appendix 3). The sample has a heterogeneous texture, with some clast sizes being large enough to cover the entire thin section (Figure 4-41). The clasts are laminated and carbonatic, and rich in fossils. The matrix is composed of angular grains of quartz, feldspars, glauconite, lithic fragments and fine-grained carbonate. Compositionally and texturally, the rock is very similar to that described in the core log of WF-2—16.8 m (55.3 ft). The main difference is that in this sample (1) the clasts rim has a thicker zone of concentration, consisting possibly of pyrite minerals, (2) some clasts have an irregular shape, which suggest dissolution, and (3) the presence of large oyster fragments, showing a foliated internal structure (Powell and McGall, personal communication, 2011).

This sample brecciation is not as clear as those in WF-2—16.8 m (55.3 ft), although there are angular fragments scattered within the matrix. Analysis of this rock and its similarity with WF2—16.8 m (55.3 ft) suggest that they are related.

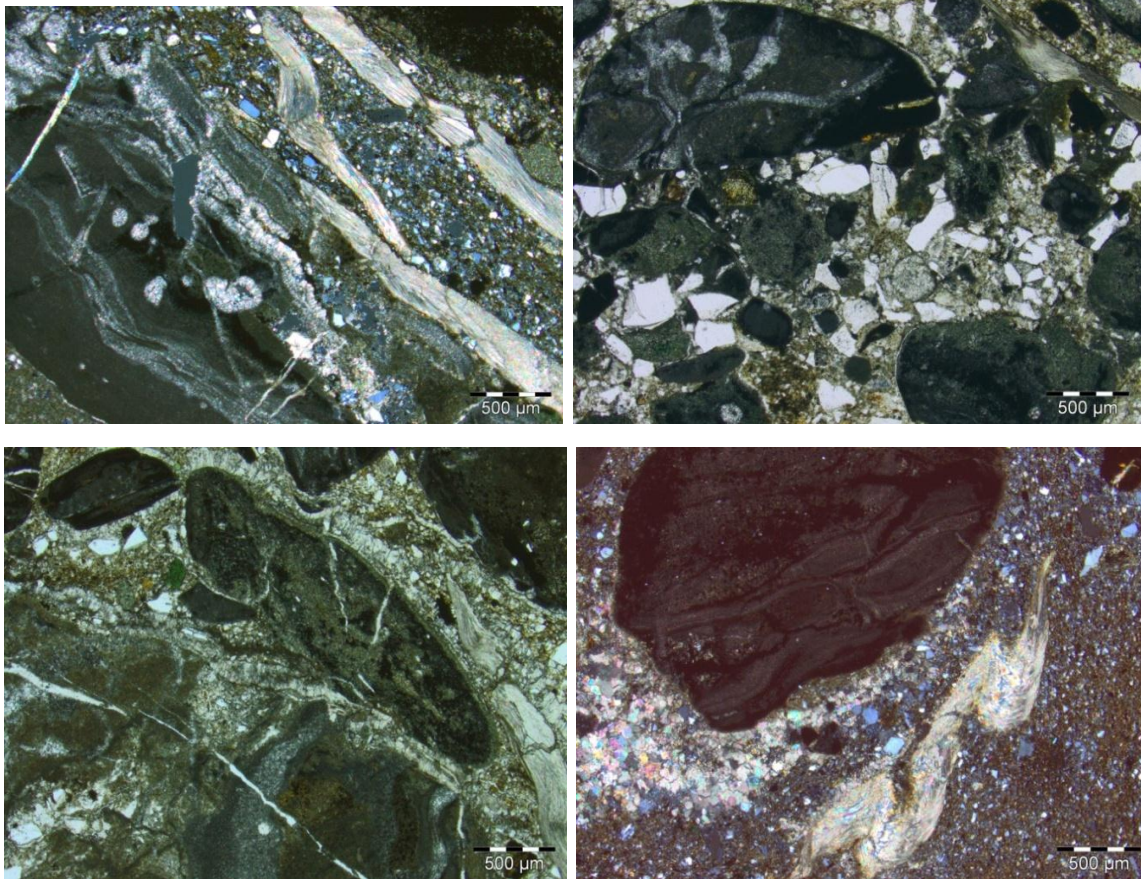
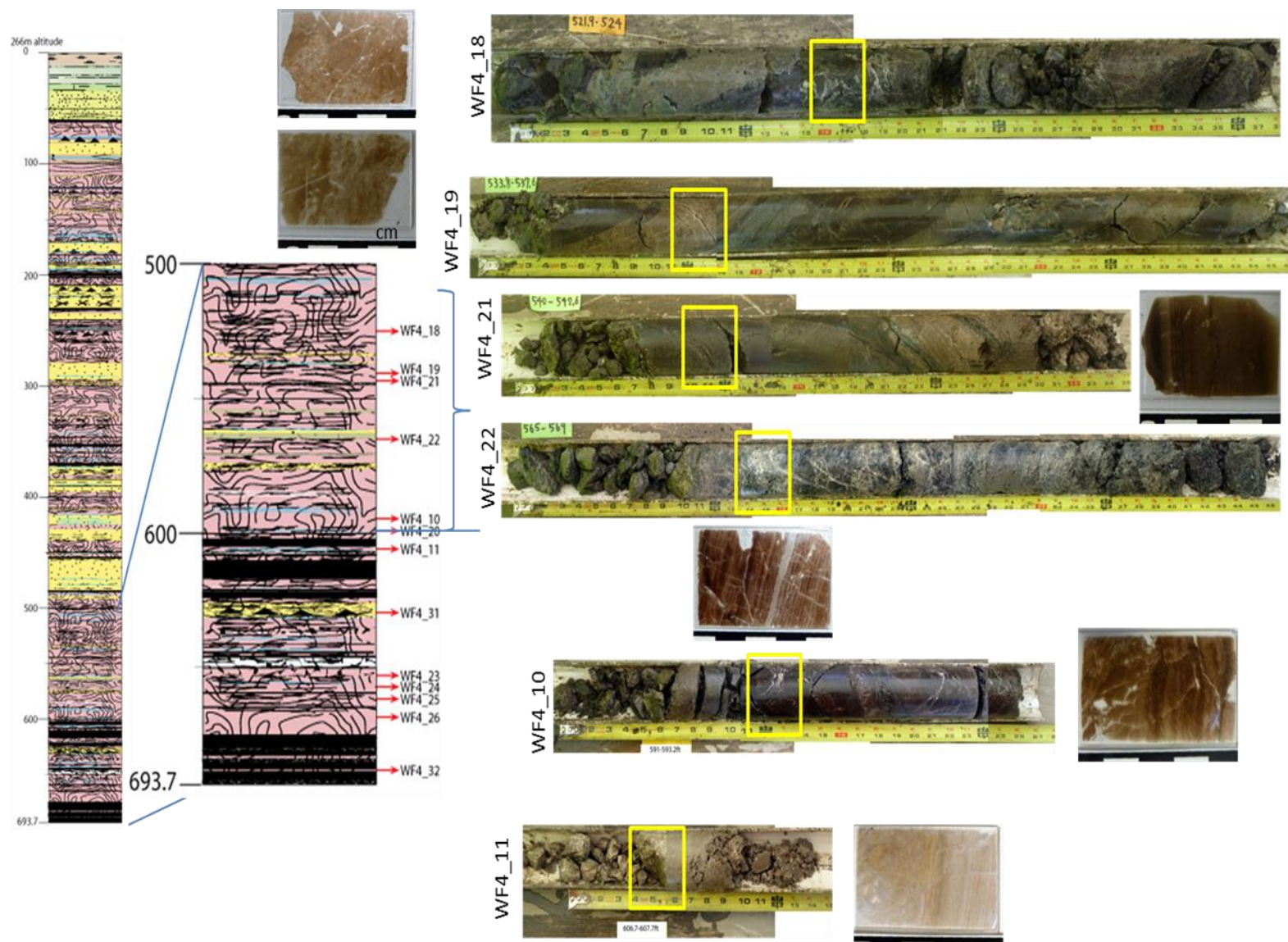


Figure 4-41. Cross-polarized views of WF3_98.75m (321.9ft)

In WF-4, the contact between Orinda Fm and Claremont Fm. is characterized by a core loss of about 1 m (3 ft) at 60.5 ft depth. Besides the lack of cores, geophysical logging does not show a significant anomaly that could be compared with the same contact in WF-2 or WF-3. It is possible that the contact is a fault.

4.7 Major fault zones in WF-4

Although there were several localized zones of deformation in WF4, the major fault seems to be located below 183 m (600 ft). This supposition is not only based on the large amounts of core loss but also on the progressive deformation found towards the end of the core. Several thin sections were analyzed, along with carbon isotope analysis. We found increased carbon-vein deformation and density towards the end of the core. The progressive increase in carbonate veins is illustrated in Figure 4-42. From 152.4–183 m (500 to 600 ft), detailed microscopic analyses were conducted to analyze the increased deformation.



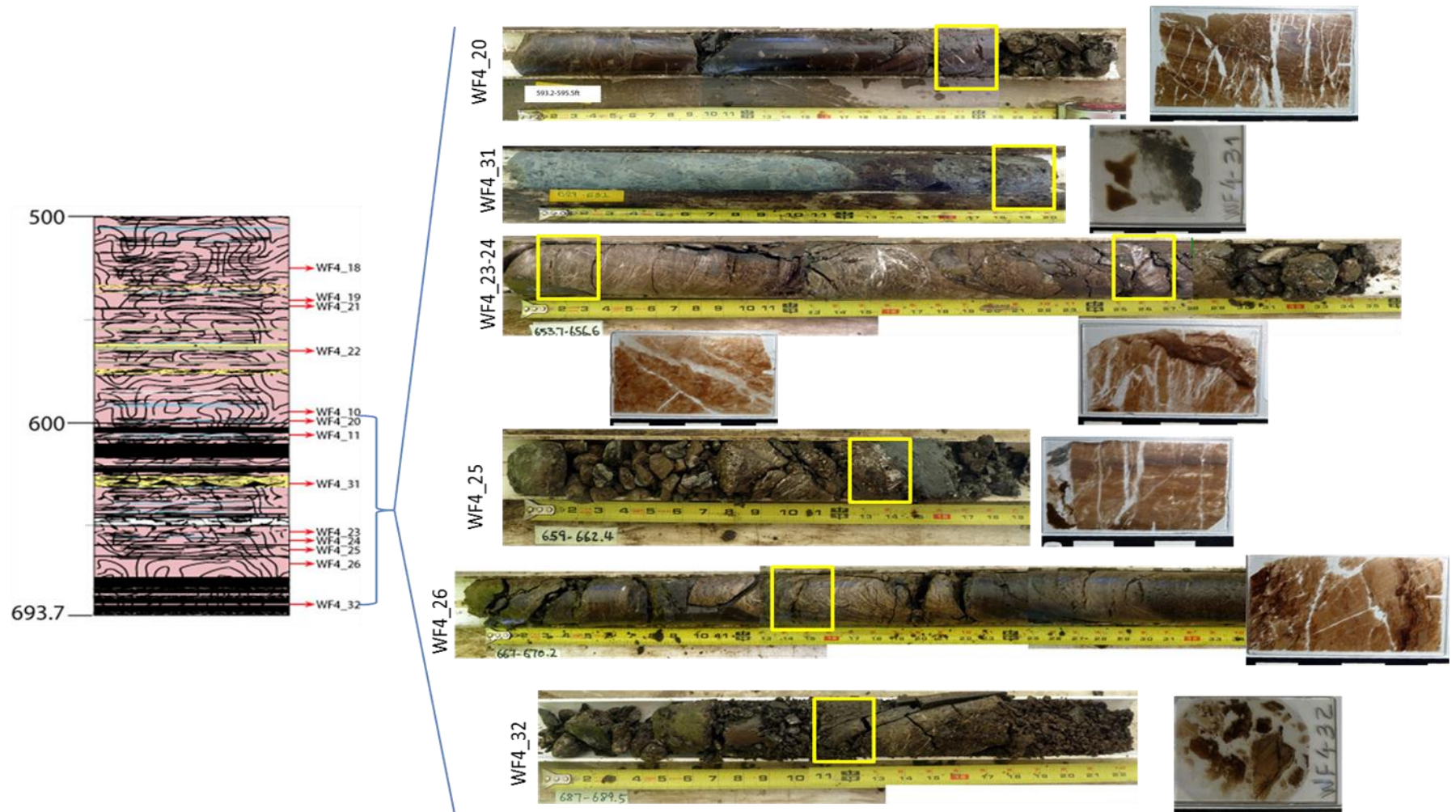


Figure 4-42. Progressive deformation in WF4.

Thin sections were analyzed under the microscope and using x-ray diffraction, to correlate with carbonate isotope samples. Below are the descriptions for each thin section of the major fault zone in WF-4.

4.7.1 WF-4_18(159m/522.5ft)

In the core from this depth, we found very fine grained, brownish clay rich in microfossil (possibly lime mudstone) mixed with aggregates of fine quartz and carbonate. The clay and quartz rich rocks were originally layered, but were afterwards disturbed and convoluted. The microfossils have been replaced by microcrystalline quartz. In the thin section, it is possible to distinguish between a zone rich with carbonate veins and a zone dominated with mud. They are both cut by carbonate veins (Figure 4-43).

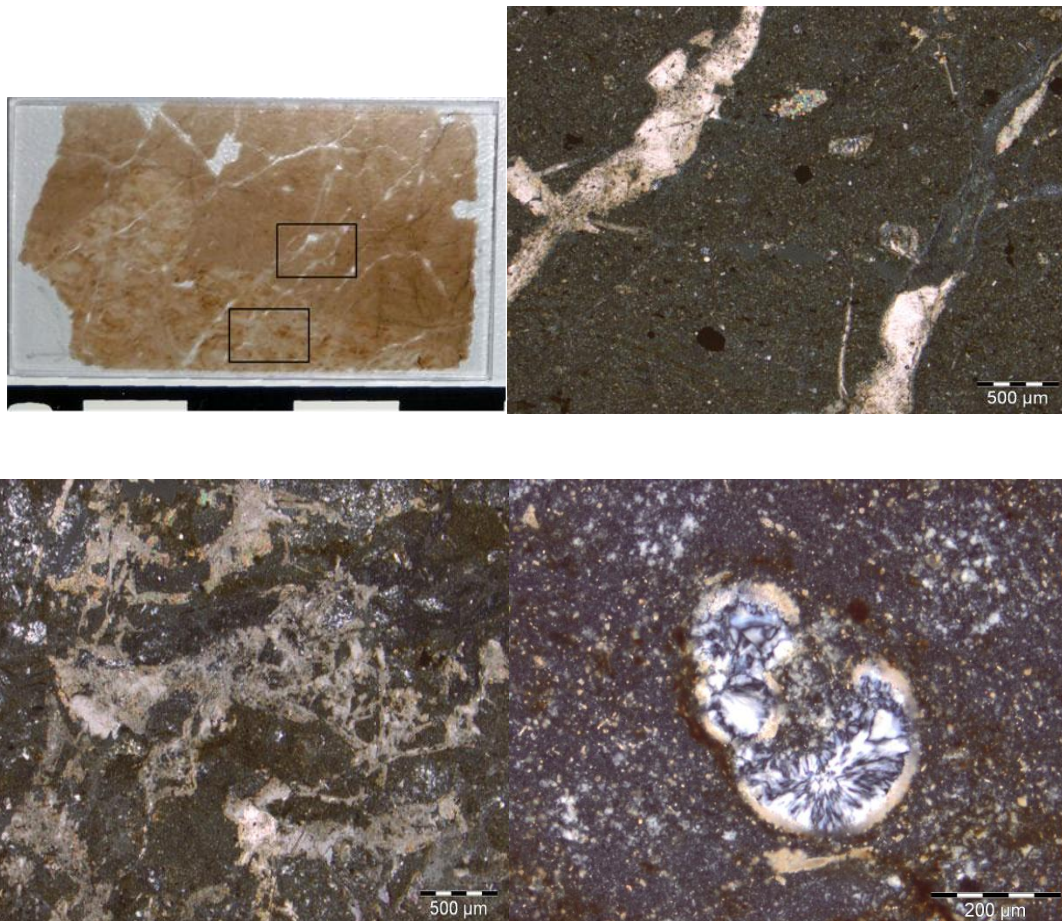


Figure 4-43. Clay rich with microfossils and cut by carbonate veins (top right). Irregular carbonate (bottom left) and quartz (calcedony) replaced microfossils with a carbonate rim (bottom right). All cross-polarized views

4.7.2 WF-4_19 (534.8 ft)

In this sample, chaotic mixtures of aggregates of very fine quartz-rich and dark brown clay-rich materials are observed, cut by a network of carbonate veins. Relict of microfossils are filled by microcrystalline quartz. Deformation seems to have taken place under soft sediment conditions. There is a mix of recrystallized quartz and carbonate veins Figure 4-44).

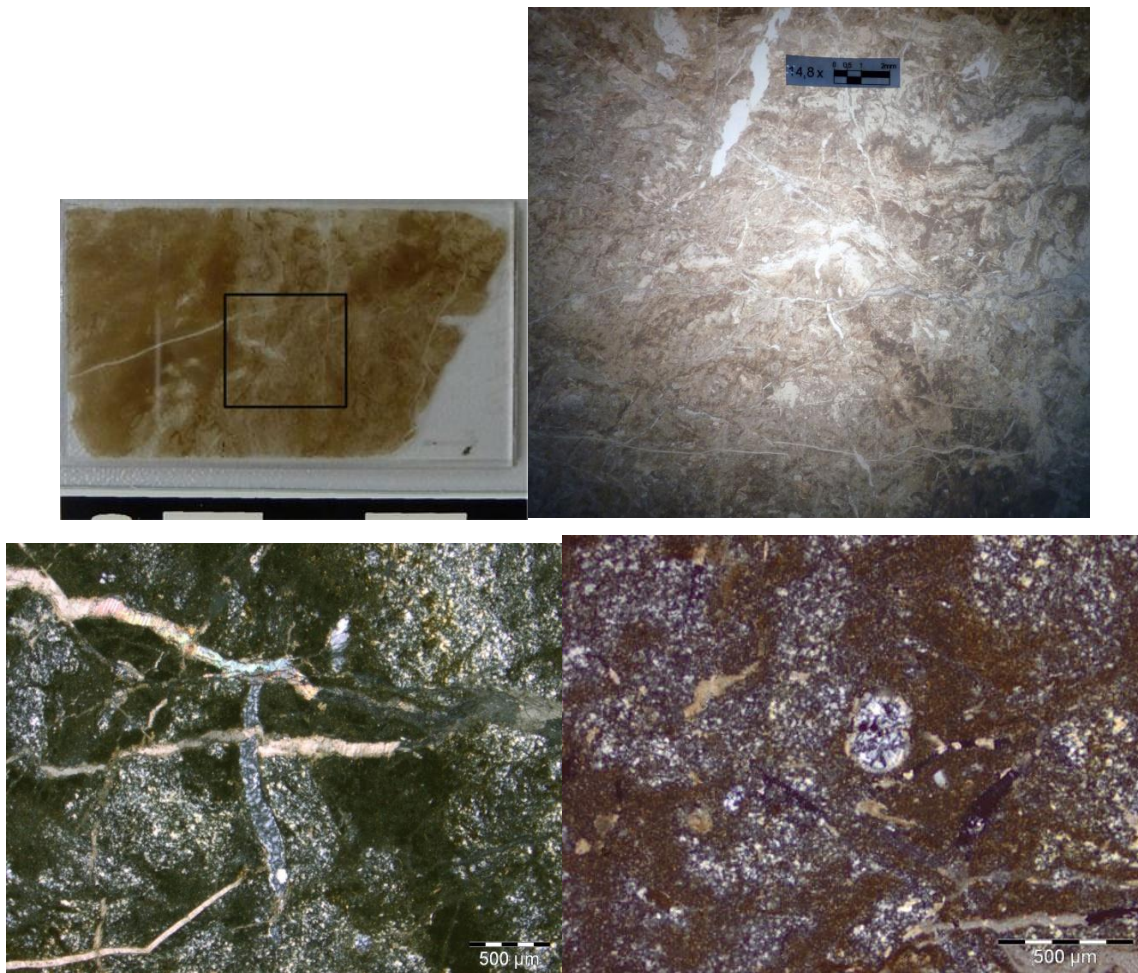


Figure 4-44. General view of WF-4_19 thin section. Plane polarized view of broad area. Close-up of the chaos (bottom left) and microfossil recrystallized with quartz, (bottom right). Cross-polarized views.

4.7.3 WF4_21 (541ft)

At this level, we found dark brown, laminated, very-fine-grained material —silt to mud. Lamination is marked by dark stylolites, and the matrix is rich in microfossils. Microfossils are round and are replaced by microcrystalline quartz. Thin fine-grained quartz veins occur

sporadically, with the thicker ones being carbonate veins (Figure 4-45). The XRD analysis indicates the presence of quartz, calcite, plagioclase, pyrite, and clay minerals (see Appendix 3).

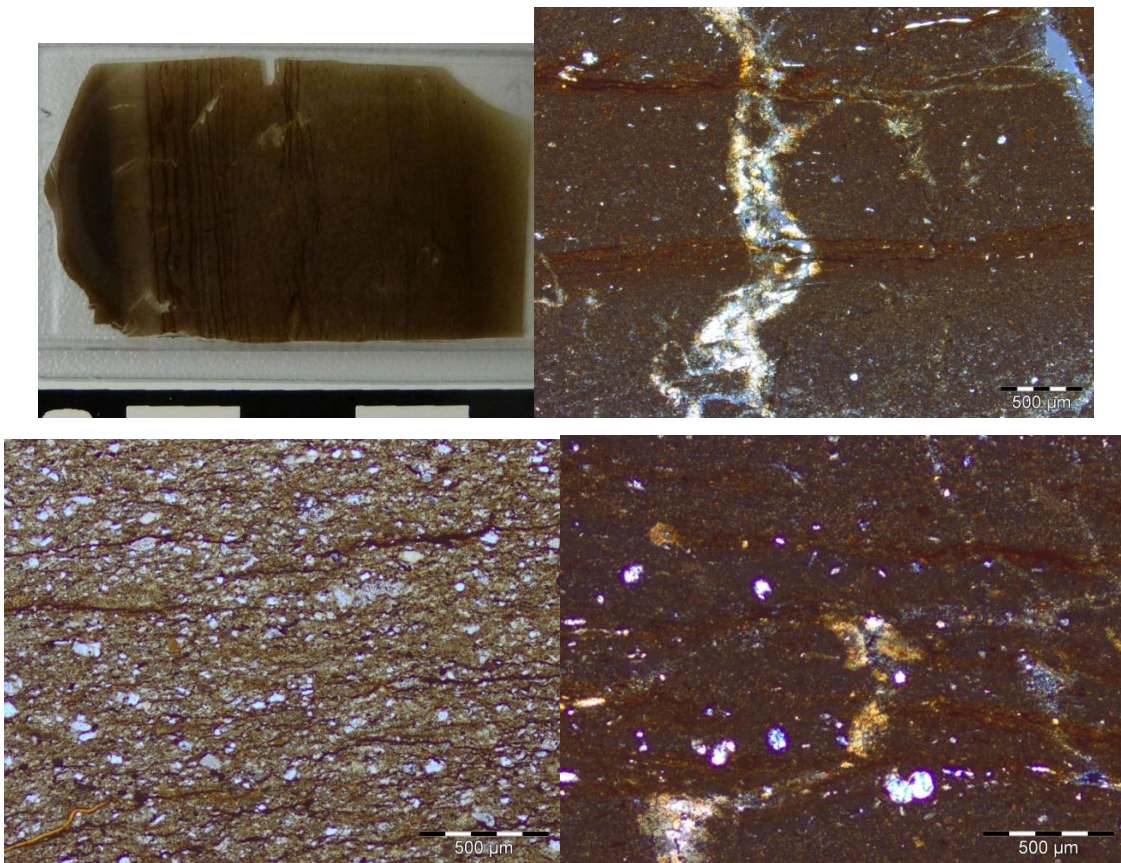


Figure 4-45 Laminated silt and clay rich in microfossils and cut by carbonate vein

4.7.4 WF-4_22 (566.3 ft)

This sample has finely laminated dark-to-light-brown carbonate-rich material interbedded with very finely laminated carbonatic mud (possibly lime mud, dark gray) cut by a network of carbonate veins. This lime mud shows brecciation on one side and crystallized carbonate (possibly calcite) on the other (Figure 4-46).

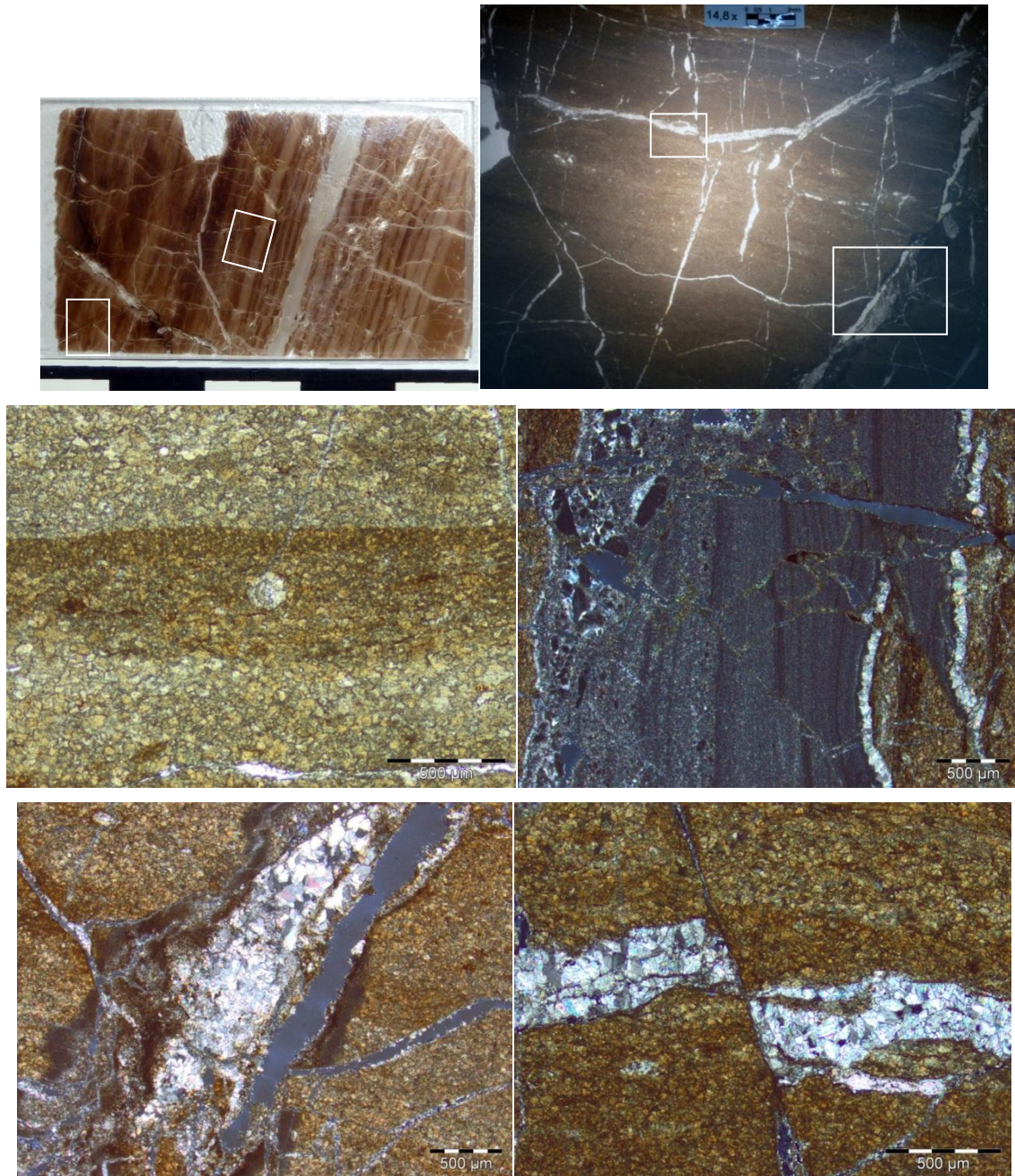


Figure 4-46. Two types of carbonates in cross-polarized views

4.7.5 WF-4_10 (593.5ft)

This sample is a finely laminated, dark-brown clay and silt rich in microfossils. Lamination is regular to irregular, and it is locally disrupted and locally displaced by carbonate veins (Figure 4-47).

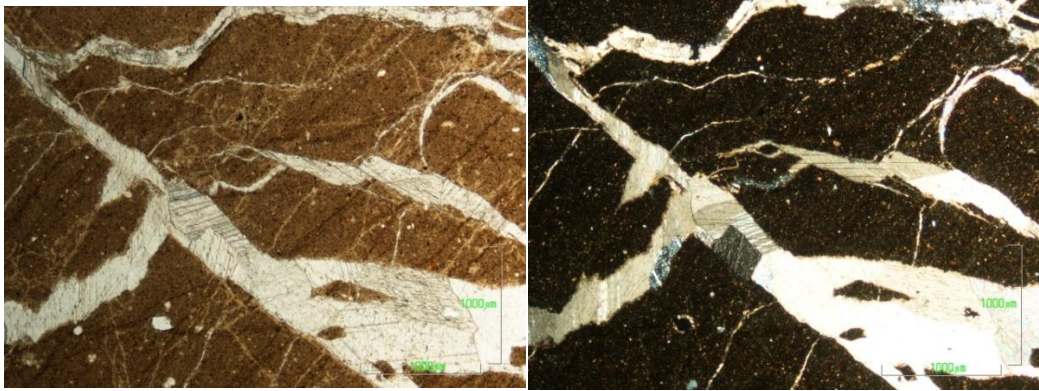


Figure 4-47 Large carbonate veins cutting the lamination. Plane polarized and cross polarized views.

4.7.6 WF-4_20 (595.5ft)

At this level, we found laminated, dark-brown, clay-rich rock and light-brown quartz-rich rock that was also rich in bioclast. The entire sample is cut by thick carbonate veins that displace the lamination (Figure 4-48). The XRD analysis indicates the presence of quartz, calcite, plagioclase, pyrite, dolomite, and clay minerals (see Appendix 3).

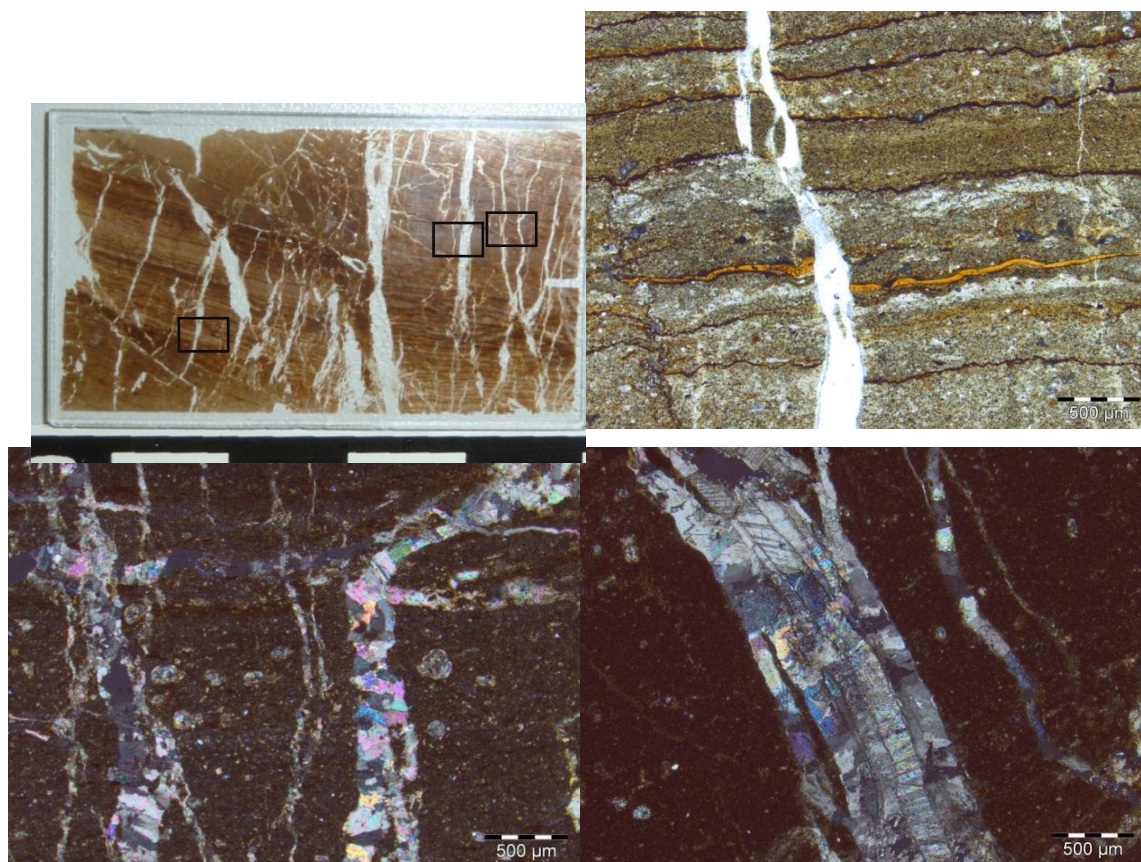


Figure 4-48. Lamination and carbonate veins in cross-polarized views

4.7.7 WF-4_31 (631.6 ft)

The rock sample at this level was friable, and the thin section was conducted with small pieces of crumbled material from the same core of sandstone protocataclasite described in Section 4.5.1.4. Under the microscope, deformation was clearly visible, evidenced by fragments of quartz, pyrite, and feldspar, in a matrix of recrystallized fine micas and pockets of sandstone surrounded by concentrated zones of micas, as shown in Figure 4-49.

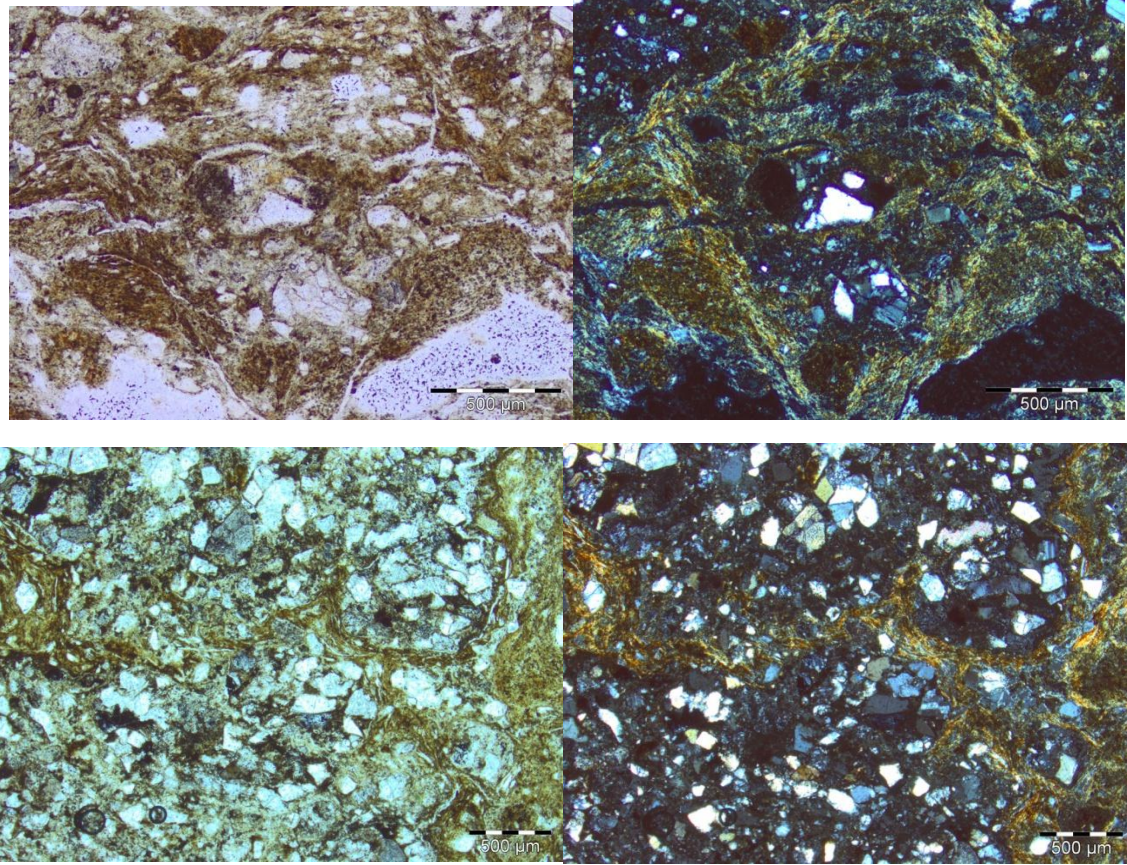


Figure 4-49. Deformed sandstone. Note shearing along recrystallized mica. Plane polarized and cross-polarized views

4.7.8 WF-4_23 (653.7 ft)

This sample shows a dark brown, microfossil-rich mud (clay material) to light brown, microcrystalline quartz (siliciclastic material) cut by thick carbonate veins. No lamination is observed. Shearing is concentrated along the carbonate veins and clay-rich material. Microfossils have been replaced by microcrystalline quartz (Figure 4-50). XRD analysis indicates that quartz, magnesian calcite, and dolomite are dominant minerals (see Appendix 3).

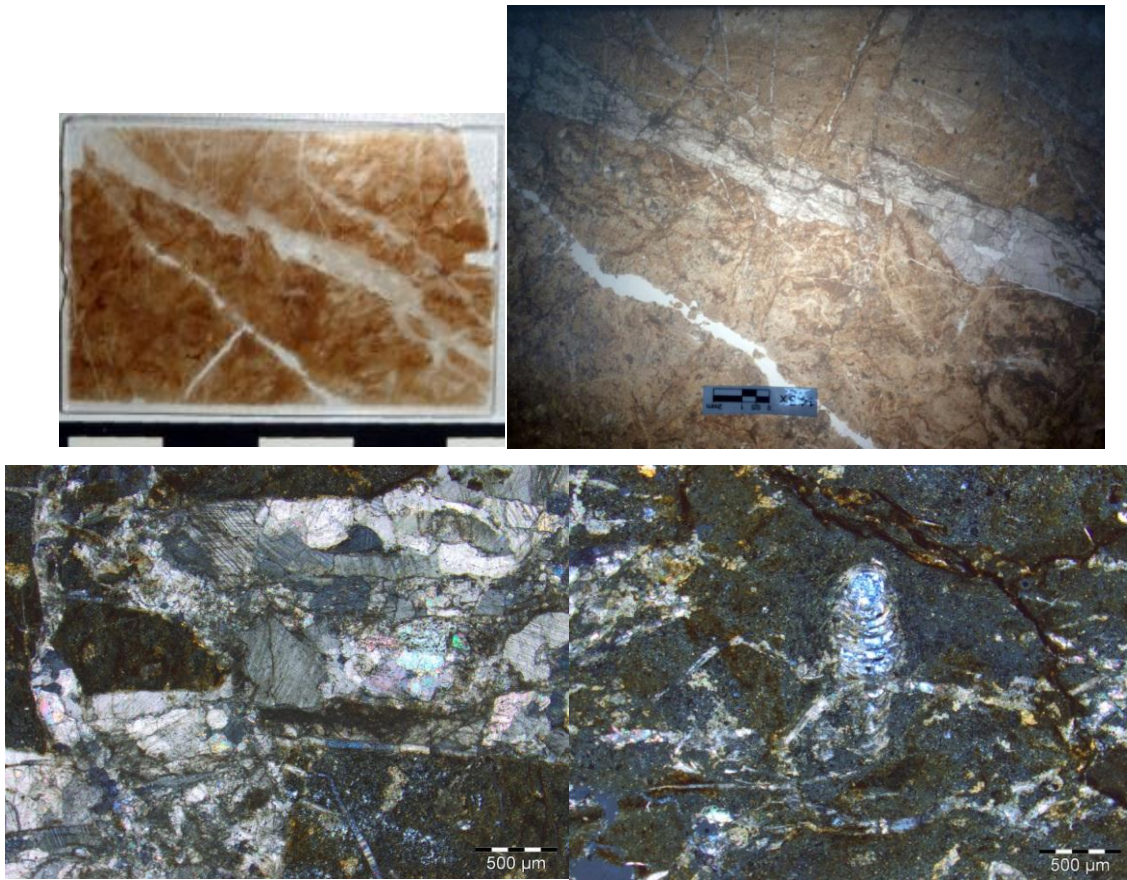


Figure 4-50. Thick veins of carbonate in deformed clay- and quartz-rich material. Cross-polarized views

4.7.9 WF-4_24 (655.8 ft)

In this sample, deformation was concentrated in the dark brown, clay-rich material where cataclastic flow was observed. Shearing, s-c structure, and fine white mica were found in the deformation band. This deformation seems to postdate the stage of carbonate veins (Figure 4-51).

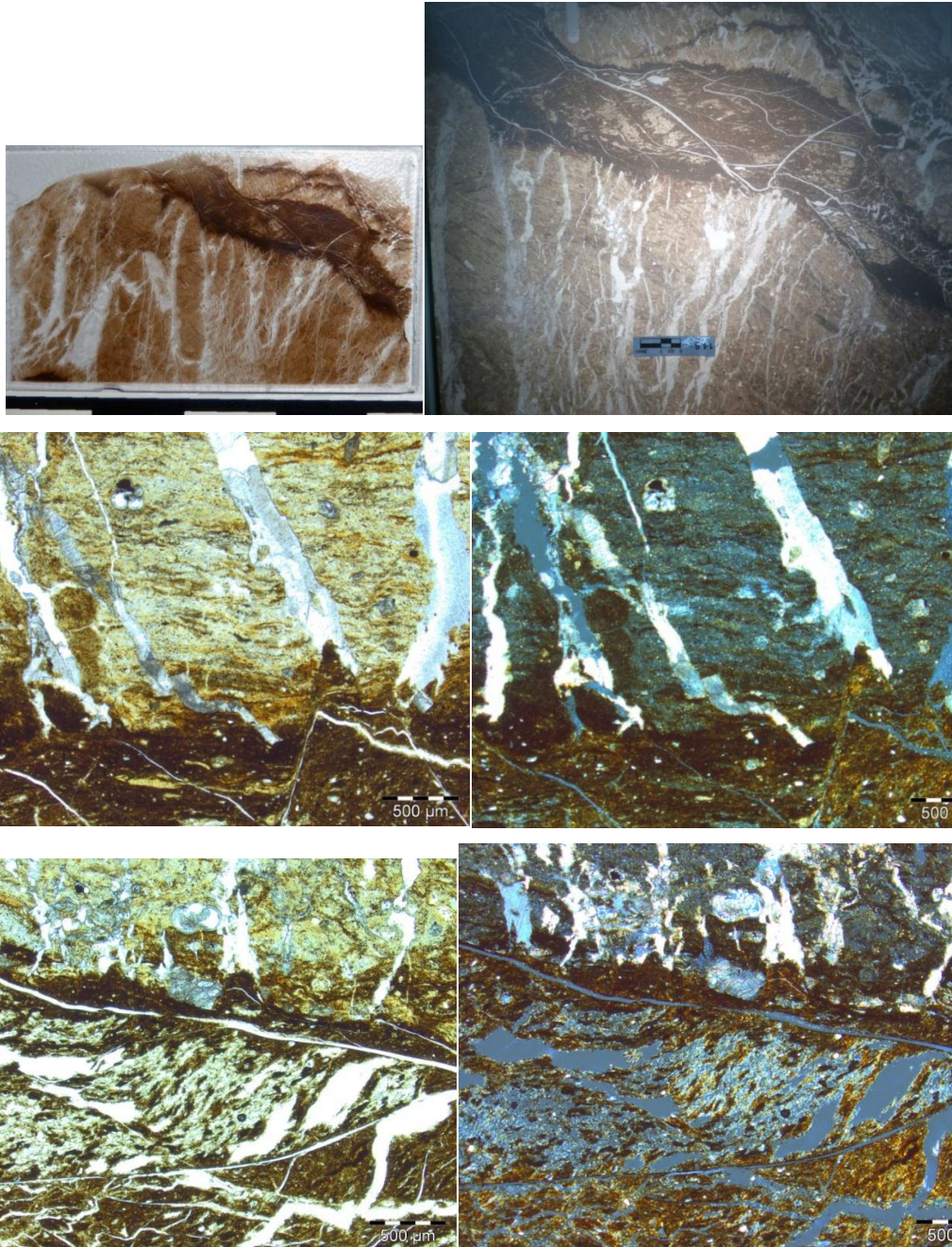


Figure 4-51. Cataclastic flow along the dark brown zone and distribution of carbonate veins and s-c structure. Cross-polarized views.

4.7.10 WF-4_25 (660.2ft)

The enlarged plane-polarized view of Figure 4-52 illustrates the overall deformation in the rock. It apparently preserved the lamination but were disrupted and displaced by carbonate veins. The deformation seems to have taken place during the unconsolidated stage, because

layers of quartz seem to be ruptured instead of broken-up. There are also zones of higher strain where fragments are floating in a matrix of very fine clay-rich material. A sample of the carbonate veins were taken for isotope analysis.



Figure 4-52 Picture of entire thin section and enlarged area showing the overall deformation

4.7.11 WF-4_26

In this sample, lamination is marked by zones of a concentration of dark material, possibly oxide. Lamination is convoluted and displaced by shear fracture and carbonate veins. The matrix is made of very fine carbonate material and clay rich in microfossils. Localized cataclasite with fragments of matrix is observed near thick veins (Figure 4-53).

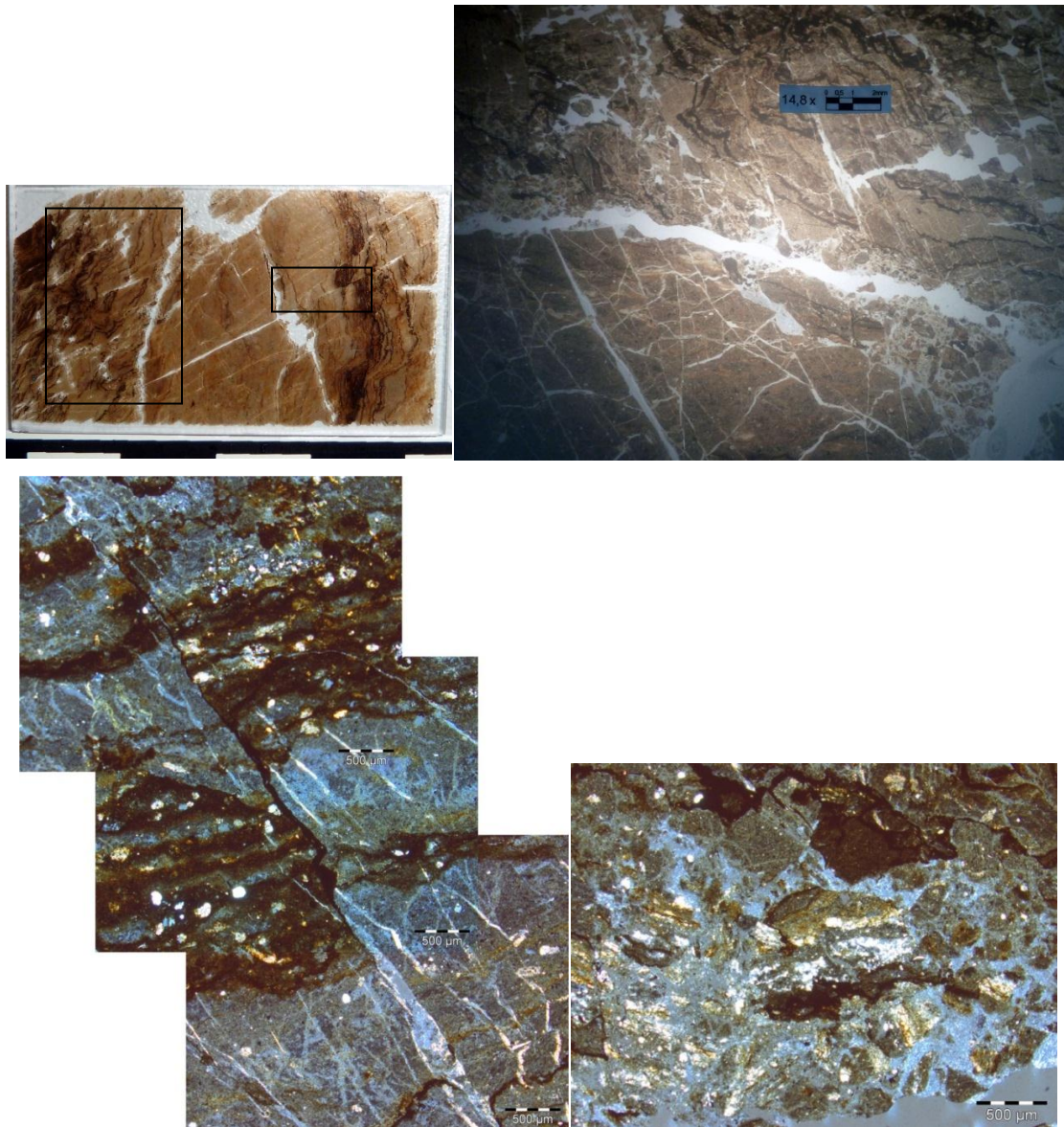


Figure 4-53. Cataclastic deformation and network of carbonate veins. Shear fracture displacing lamination and a close-up on the cataclastic flow. Cross-polarized views.

4.8 Structural Data

Data from borehole logging (BTV images) were used to determine the orientation of faults and fractures in all four wells. Data were plotted in a lower hemisphere projection using the SteroWin program and represented by diagrams located near the depth of the data set, as shown in Figure 4-54.

In WF1, three zones of primary deformation were observed. A zone of brecciation at 36.6 to 42.7 m (120-140 ft), a zone of fracture and gouge at 96.6 to 99.7 m (318–327 ft) and a large

zone of brecciation, including highly fractured bleached, brecciated, and lithified siliceous material at 143–160 m (470–525 ft). The plot of fractures from this zones resulted in the main orientation trending to NE dipping to NW, and a secondary orientation to NW dipping to NE.

In WF2, there were four main zones of deformation. The first one was the contact between Orinda/San Pablo with Claremont siliceous shale at 18 m (60 ft) and described in Section 4.6.5. The second one consists of cataclasite encountered at 68–73 m (224.6 to 240 ft) and described in Karasaki et al. (2010). The third one was a zone of foliated cataclasite at depth of 91.7–98 m (301 to 322 ft), which has also been described in detail in Karasaki et al. (2010). The fourth deformation zone consisted of brecciation and water loss encountered at 133–141 m (436 to 463 ft). Except for the cataclasite, all deformation was observed mainly in the Claremont Formation. The overall deformation is oriented NE dipping to NW, with a possibility of having conjugate fracture sets. A NW-oriented fracture set was observed only in the fourth zone of deformation.

In WF3, the first zone of deformation was observed in the core of Orinda siltstone and sandstone at 8.2– 15.8 m (27-52 ft). They are described in detail by Kiho et al. (2010). The second deformation is observed at the contact between the Orinda/San Pablo and Claremont Formation at 98–99.3 m (321–326 ft). A similar type of rock was found in the contact between those two formations in WF2 (see Section 4.6.5). A second contact between the Claremont and Orinda Fm was observed at 146–148.7 m (480–488 ft). Both deformation zones were characterized by NE and NW orientation of fracture planes, although in the second contact, the NE orientation is more dominant.

Borehole WF-4 had the most deformation zones compared to other boreholes, characterized by brecciation, cataclasis, gouge, and core loss. As described previously, WF4 has over thirty core-loss sections, most of them concentrated in the last 46 m (150 ft) of the borehole. A total of six deformation zones were identified, described in descending order: (1) core loss at 18 m (60 ft) along the contact between the Orinda and Claremont Fm—although there was core loss, a fracture orientation was picked from the BTV log; (2) cataclasite at 65 m (241 ft) and described in Section 4.5.1.4; (3) a zone of brecciation and comminuted chert, possibly tuff and carbonate material at 95–96 m (312–315 ft); (4) a brecciated zone at 106-113 m (347–370 ft); (5) a 3-inch fault gouge described in Section 4.5.1.4; and (6) a wide zone of deformation including

brecciation, gouge, and protocataclasite. The combined structural analysis included depths of 158 to 197.5 m (520 to 648 ft), which was the end of the fracture and BTV logging. Besides the Orinda Fm-Claremont Fm contact and the gouge at 153 m (501 ft), which were oriented NE, the overall fracture orientation had two sets: NE orientation and dipping to NW, and NW orientation dipping to NE. The two fracture sets strongly suggest that they are conjugate sets of fractures. These conjugate sets of fractures might reflect a secondary fault structure, such as Riedel shear, and might not be the orientation of the main fault as observed by Hickman (personal communication, 2011). According to Hickman, who has experience in logging fault zones including the San Andreas Fault, the main fault is often missed during borehole logging, so that only the secondary structures are retrieved.

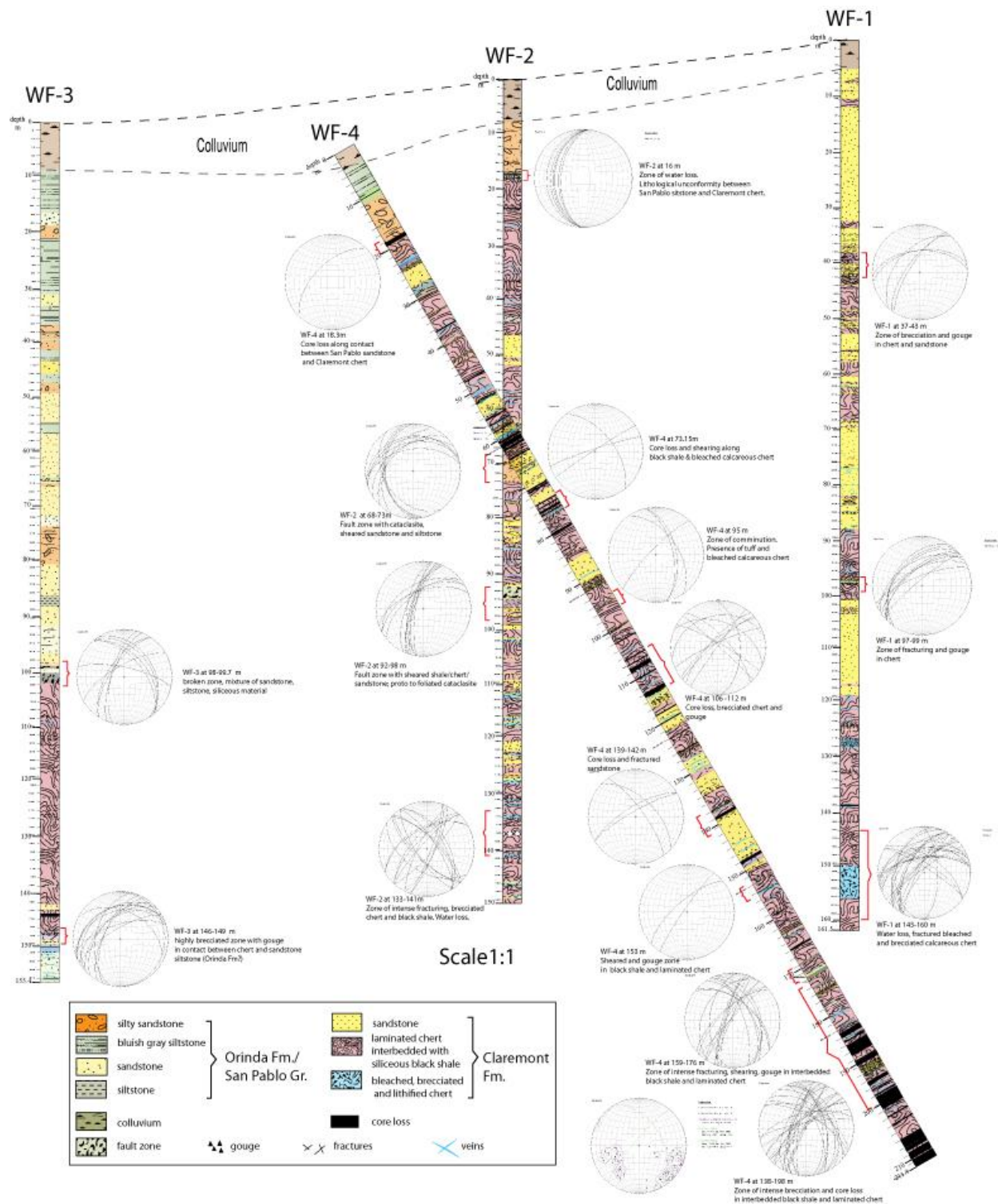


Figure 4-54. Summary of core log and structural data. Lower hemisphere projection of fractures in main zones of deformation.

4.9 3D Geologic Model

A 3D structural model was constructed using the Earth Vision software. Two models were constructed, a regional and a local area model. Input for the geologic model was based on data from previous geologic mapping by Graymer (2000), geologic surveys, trenching studies, BTV combined with field surveys, cores from deep drilling, and additional well data from previous geotechnical reports produced at LBNL. Fault data were based on projections of surface data from core logs (WF1, WF2, WF3 and WF4), trenching (Karasaki et al., 2010; WLA, 2008) and previous geologic maps (HLA, 2004; Graymer, 2000).

A 10 m resolution digital elevation model (DEM) and an ARC/INFO digital coverage were imported into Earth Vision to construct the regional and local geologic model. Earth Vision is a software that calculates a data grid based on 3D data points. The 2D grid for the regional area ranged from 4194000 to 4190500 NS and 566400 to 569000 EW, providing an area of ~3.5 by 2.6 km. The area included the hills on the East, North and South and to the West, and the Contact Fault was also included. The 2D grid for the well area ranged from 4192340 to 4192745 NS and 566490 to 567224 EW, with a grid size of 302.165.

The geologic contact and fault data obtained from boreholes and surface data points were interpolated using a 2-D minimum tension gridding technique. In the case of one data point, vector gridding was used based on strike and dip. Once the gridding was completed, the faults were imported to the model and a fault tree was built manually, based on the fault hierarchy.

Earth Vision uses faults to subdivide the study volume area into fault blocks. Faults in this model included the two traces of the Wildcat fault, the contact fault between the Great Valley Sequence and the Orinda Formation to the west of the main study area, and the contact fault between the Claremont and Orinda Formation and the Orinda Formation and Moraga volcanic to the East. This model included the contact between Orinda Fm/San Pablo Gr and Claremont Fm from WF2, WF3, and WF4, as well as two fracture sets from WF4 from the last 200 ft of cores. The model resulted in ten fault blocks. Each fault block was further subdivided into stratigraphic units with depositional surfaces. The only depositional contact was between Orinda/San Pablo and Moraga volcanic; all other contacts were modeled as unconformities. Faults were the only structure used in this model; although the area has folded, no fold information was used.

Figure 4-55 and Figure 4-56 illustrate the regional model and its slice. The modeling result shows the distribution of the main lithologies: Great Valley Sequence, Claremont Formation, Orinda Formation and Moraga Volcanics. The geologic block model includes nine faults, separating ten major blocks.

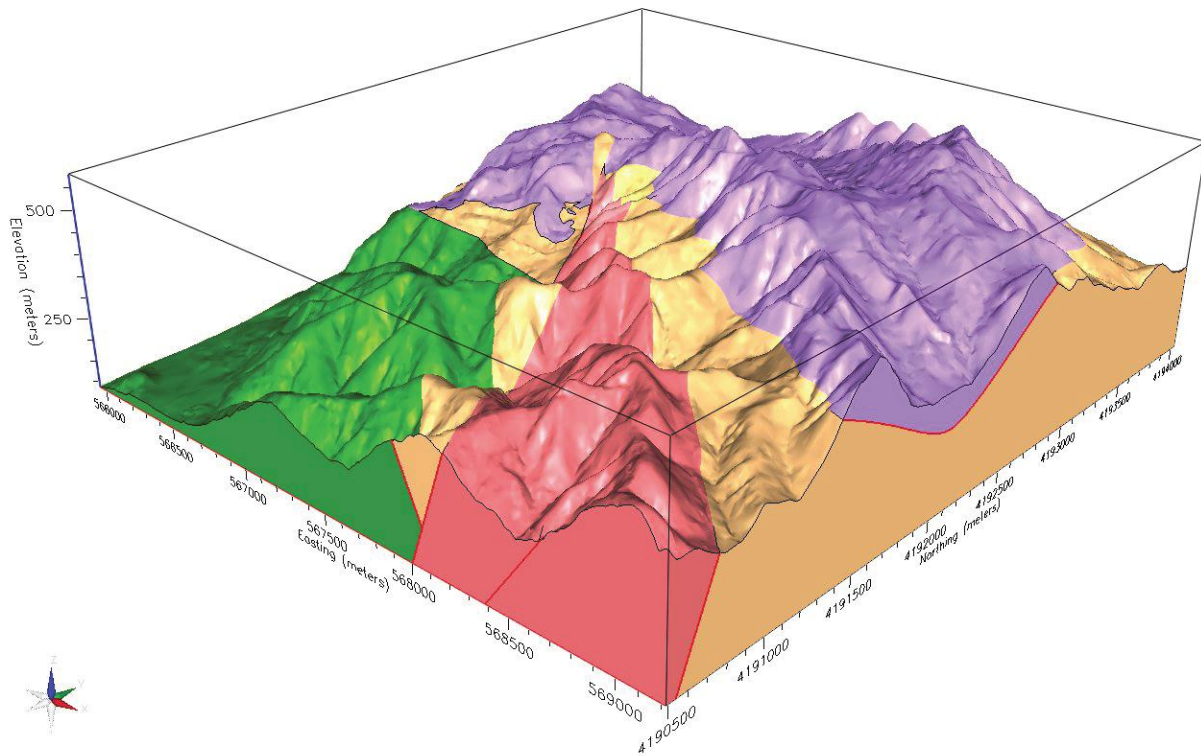


Figure 4-55. Regional 3D geologic model illustrating the main faults

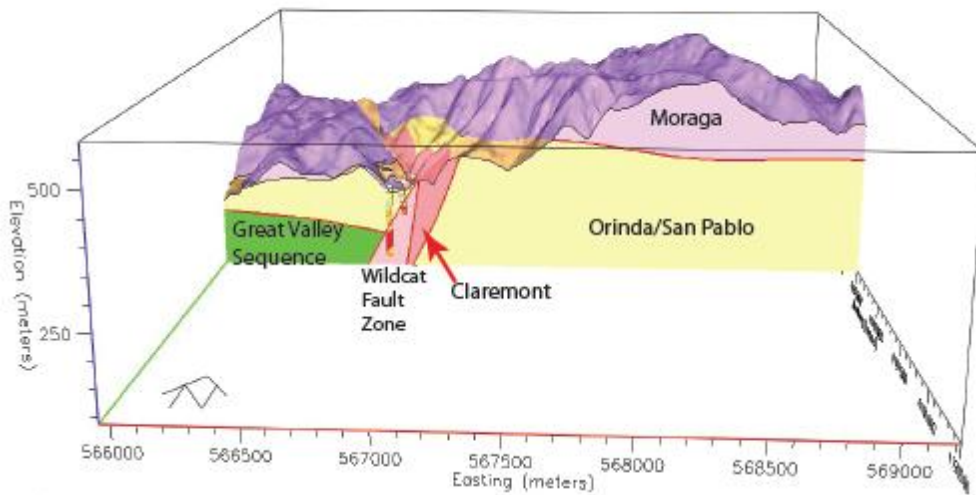


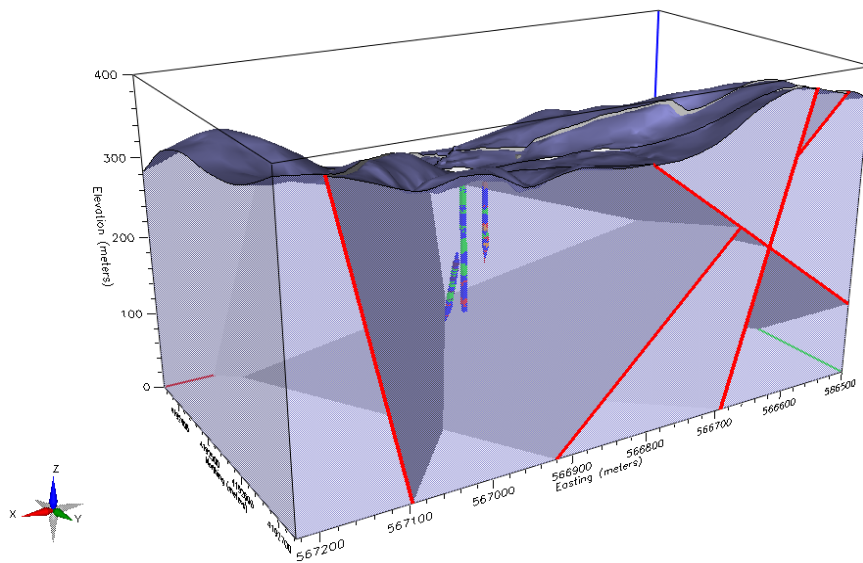
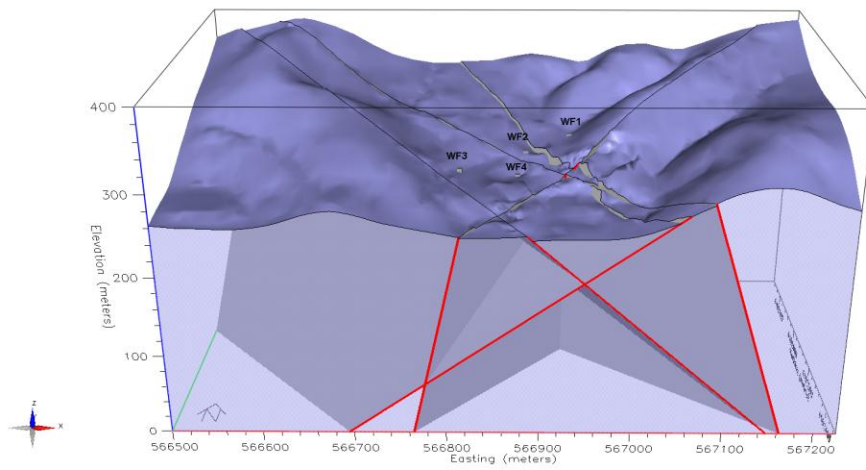
Figure 4-56. Sliced view of regional model showing the location of the wells

To capture the local 3D structure within the model, several scenarios of faulting were considered. The first step was to identify major faults and then project the planes into the model. At this stage, about nine faults and their conjugate sets were used. During the fault projection, each one was evaluated separately and checked if it would intercept a zone of deformation along the plane in other wells. This exercise proved that most of the projected planes did not intercept a fault plane or the zone of brecciation in other wells. The fact that within a short distance (>200 m between wells), the stratigraphy cannot be correlated, suggests that in fact, we are in a zone of broad deformation, surrounded by faults that had juxtaposed small slivers of rocks. As a test for a simplified model, two models were run:

Model A: Fault information used:

1. The fault plane along the contact between Orinda Fm./San Pablo Gr and Claremont Fm. from WF2, WF3 and WF4.
2. A fault plane that intercepted WF4 at 106 m (347 ft) and WF2 at 93 m (305 ft)
3. Two sets of fractures in WF4 from 168–197 m (552 to 648 ft) depth. The average orientation is 220/81N and 330/48N. The NW-oriented fracture plane projected west of WF3.

The results of modeling are shown in Figure 4-57 with various projections and slices.



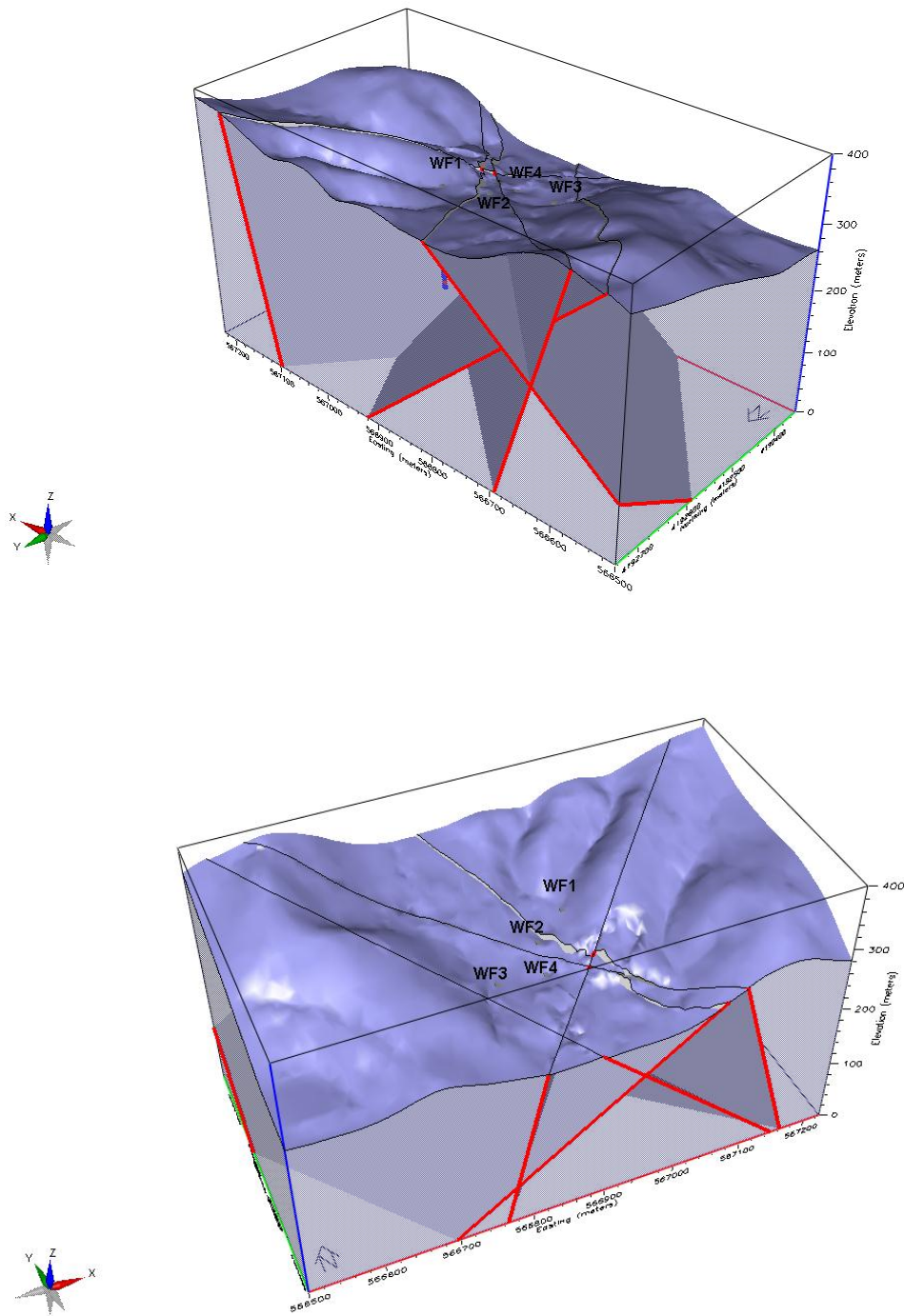
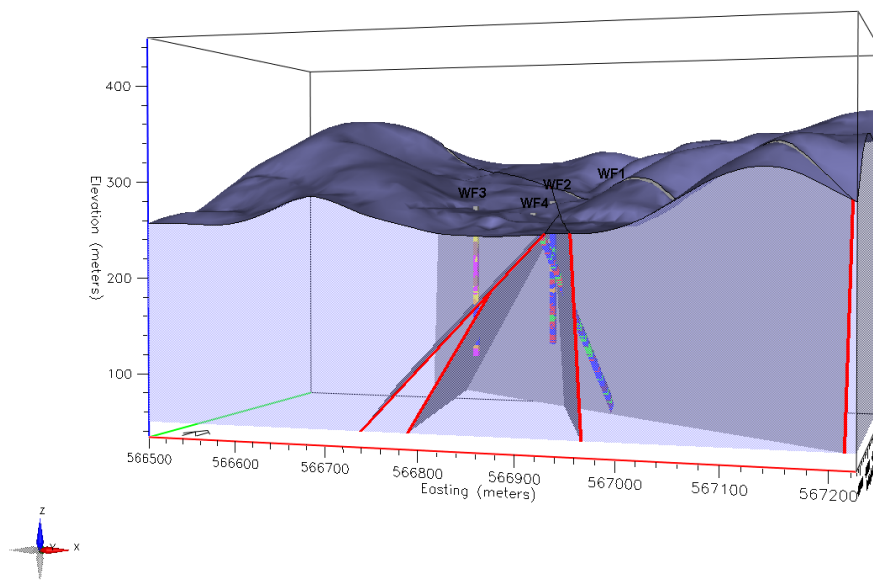


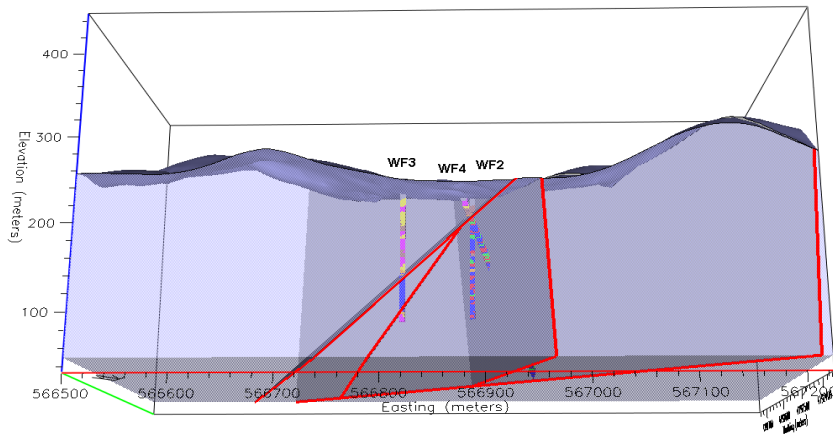
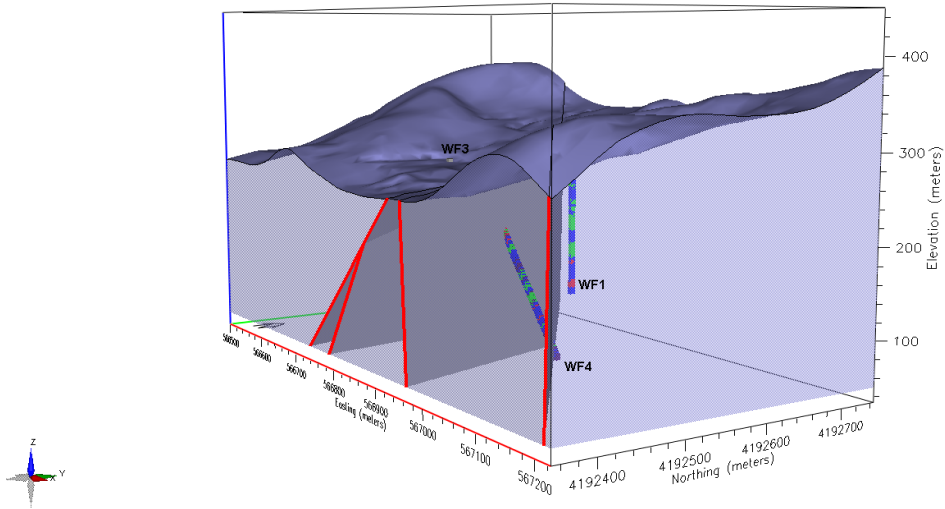
Figure 4-57. Model A: Local area 3D model illustrating the interaction of the main faults with the wells.

Model B: The major fault zone at the end of WF4 suggested that there must be a fault between WF1 and WF2. In this model, a fault plane with the same orientation as the Hayward fault (N36W/89W) is used as the major fault plane cutting the end of WF4. Conjugate fault planes were not included in this model. Therefore, the model was built using:

1. The fault plane along the contact between Orinda Fm./San Pablo Gr and Claremont Fm. in WF2, WF3 and WF4.
2. A fault contact of Claremont Fm. and Orinda Fm. in WF3
3. A fault plane that intercepted WF4 at 73.15 m (240 ft)—cataclasite
4. A fault plane between WF1 and WF2 using the orientation of the Hayward fault

The result of modeling is shown in Figure 4-58.





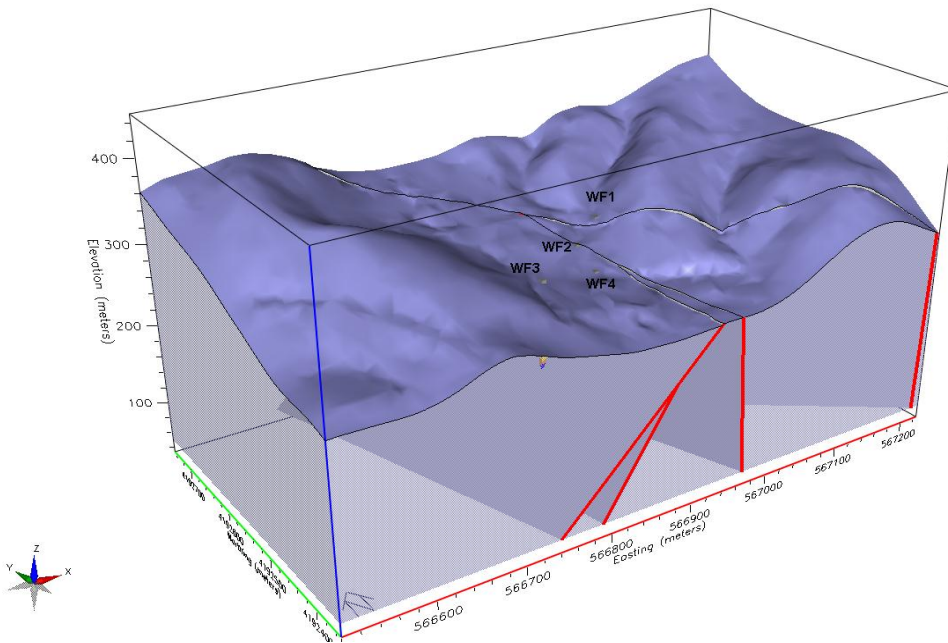


Figure 4-58. Model B: Local area 3D model illustrating the interaction of the main faults with the wells.

4.10 Summary

1. Although the core logs were from boreholes less than 100 m apart from each other, no stratigraphic correlation was possible. The thickness of siliceous shale, poorly sorted sandstone, brecciation and gouge zones, and carbonate-rich concretions to bleached and lithified carbonates were found at different depths in each of the boreholes.
2. In WF3, over 62% of the core was represented by sediments from Orinda Fm and San Pablo Gr., while in WF4, less than 9% (the top 60ft) was Orinda Fm/San Pablo Gr; the rest was Claremont Fm.
3. Marine fossils were widely distributed in the Orinda Fm., San Pablo Gr., and Claremont Fm. Large fragments of shells were observed mainly in the San Pablo Gr., while microfossils like foraminifera, gastropode, bryzoa and possibly radiolarian were found in Orinda siltstone and mudstone, and Claremont shale and chert.
4. High concentrations of carbonates were found in shales and cherts of the Claremont Fm. Not only by the amount of microfossils, but a large amount of carbonates were

disseminated in the matrix.

5. Observed siliceous shale and chert were rich with carbonate and marine microfossils, suggesting possible deposition along the transition zone between carbonate compensation depth (CCD) and silica deposition.
6. Although lamination in the Claremont Fm. was well preserved, many of them were deformed in a convoluted way, suggesting soft sediment deformation.
7. Similar rock types, a locally brecciated conglomerate, were found in the contacts between Orinda Fm/ San Pablo Gr and the Claremont Fm. in WF2 and at in the first contact in WF3. The similarities in the rock types and the degree of core loss suggested an unconformity and a possible fault.
8. Cores retrieved from WF4 showed the heaviest damage compared to the three other wells. These cores were intensely brecciated with gouge and recorded 31 core-loss intervals. At least seven significant fault zones were identified in WF4. They included brecciated material, gouge, and cataclasite. The main fault zone, considered the most recent zone of deformation, starts from 152 m (500 ft) to the end of the hole. This zone was characterized by an increase in deformation, density of carbonate veins, and large core losses.
9. Sandstone from Orinda and Claremont were compositionally and texturally similar. The grains in both were angular to subangular, poorly sorted, with a high percentage of feldspar, and containing glauconite. Glauconite is only formed in shallow marine environments. The high percentage of feldspar was more characteristic of arkose. It is not clear if the presence of serpentine found in one of Orinda samples could be used to differentiate both sandstones.
10. Kiho et al. (2011) concluded, through U-Pb age dating analysis, that the formation found at the bottom of WF-3 was not the Great Valley Fm.
11. Structural analysis of faults and fractures from borehole logging suggested two main sets of fractures, one oriented NE dipping to NW, and the other NW dipping to NE.
12. The regional 3D geologic model incorporated faults and lithologic contacts from trenches, boreholes and literature, including major NW faults, including the Wildcat and a NW/NE conjugate sets of fractures, from the fault zone in WF-4.
13. Two scenarios of local 3D structural were modeled. In one of them, conjugate faults

intercepted in WF4 were modeled, with the faults running in NW and NE directions. It illustrated the main faults such as the boundary between Orinda Fm/San Pablo Gr. and Claremont Fm. Our structural model was in essence similar to the ones proposed by Kiho et al. (2011).

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5 Hydrologic Investigations

5.1 Introduction

Hydraulic tests are the only direct method by which to evaluate the hydrologic properties of rocks *in situ*. Various geophysical, geological and geochemical tools have been proposed to correlate nonhydrologic parameters to hydrologic properties. However, except for layer-cake sedimentary formations, such efforts have yielded mixed results at best. Especially in fractured and faulted rocks, such tools have never been effective. For example, the borehole geophysical loggings conducted in the WF boreholes in our investigation of the Wildcat Fault did not correlate well with the flow zones. In this chapter, we discuss the results of hydraulic tests conducted in the WF-3 and WF-4 boreholes, as well as monitoring results from other WF boreholes and SSL-1 and 2. The locations of these boreholes are shown in Figure 5-1.

5.2 Slug tests in WF-3

In WF-3, as discussed in the Geologic Analysis section, the top one third (~50 m) is the Orinda sandy silt formation, followed by the San Pablo sandstone to a depth of 85 m, then the Claremont mudstone formation to a depth of 150 m, where the Orinda formation reappears and continues to the bottom of the borehole. That the bottom formation is Orinda has not yet been definitely confirmed; there is the possibility that it is the Tertiary Sobrante formation, older than the Claremont. Kiho et al. (2011) determined that it was Orinda based on its appearance and the zirconium dating, which showed that it was not as old as the Cretaceous Great Valley Formation.

The top ~36 m (120 ft) of the Orinda formation kept on sloughing in, with the falling debris blocking the hole multiple times. Once, the geophysical borehole logging tool could not be lowered passed 30 m. The driller was called back and the hole was chased with a HQ drill bit once again. This gave us no choice but to set down a steel casing to prevent further collapsing. Consequently a 4" casing was inserted down to 41.7 m (137 ft) after a suite of geophysical borehole logging was completed. This left us with only from 41.7 m to the bottom of the hole to conduct hydraulic tests.

Falling-head slug tests had been routinely conducted overnight after a day's drilling, with the tests stopping before the start of the next day's drilling. The data were not amenable to rigorous analysis, because the initial conditions were not controlled right after drilling and because the borehole wall most likely had been coated with thick drilling fluid, with added

polymer and silt coming from the formation. We found that the recovery was very slow, indicating that the hole has very low permeability. In fact the permeability was too low for pumping tests to produce meaningful results with the available equipment and time. Another indication that the permeability was very low is that the water level in the well fluctuated more than 10 m during drilling (Figure 5-2).

As discussed in the Drilling Investigation Section, the FFEC log in WF-3 indicated that there is only one significant inflow zone at 137 m (451 ft). Consequently, we decided to set a packer at 43.4 m (142.5 ft) just 2 m below the bottom of the casing at 41.7 m. We initially conducted slug injection and withdrawal tests. We then tried to conduct pumping tests by lowering a Grundfos submersible pump in the 2" pipe connected to the zone below the packer. After several attempts to pump, the testing method was abandoned, and we switched to slug tests. Slug injection tests were conducted either by pouring water in the pipe or dropping a rod. Slug withdrawal tests were conducted after a slug rod injection test had stabilized. In all, more than 10 tests were conducted in the lower ~112 m section.

Figure 5-3 shows the time series of slug tests conducted in WF-3. A spike in the water level indicates the start of each slug test. An uptick spike in temperature occurred when the device was polled and should be considered as noise. Downward spikes in temperature concurrent with the water level spikes indicate that colder water had been injected into the pipe.

Figure 5-4 shows normalized slug test transients with selected slug tests superimposed. They were all conducted in the same interval, albeit with different heights for the slugs and some withdrawals, which in theory should plot on top of each other if the process is linear. None of them plot on top of each other. However, they lie within a band of one order of magnitude in dimensionless time. They all show a very long tail at late time, which indicates that the permeability at some distance from the borehole is lower than that of the borehole's immediate vicinity. This may be a plausible scenario, because the flow was most likely through the feature identified by the FFEC log at 137 m. Examination of the core reveals that it is a fracture in the San Pablo Formation. The fracture may not be very extensive, and thus the permeability away from the borehole may be smaller.

Figure 5-5 shows the type-curve match of the water slug tests conducted on May 9th and May 17th to the Cooper et al. (1967) solution. As can be seen from the figure, the data from the

two tests plot on top of each other. The time shift is about three folds. The first test yielded a transmissivity of $6.5 \times 10^{-6} \text{ m}^2/\text{s}$, and the second was $2.3 \times 10^{-6} \text{ m}^2/\text{s}$ when matched to $\alpha=10^{-3}$. The matches are only reasonable for the first 50% fall of the slug. For the latter 50%, the match is far off. As can be seen in the figure, the data closely follow the curve of the 1-D solution. The flow geometry may not be that of a 1-D conduit, but it is equivalent to a flow restriction of some kind. There could simply be low-permeability rock beyond the end of the fracture. Nonetheless, the permeable fracture at 137 m is probably not very extensive.

Permeabilities from WF holes and SS-1 are listed in Table 5-1. The numbers are based on the pump tests using radial flow solutions. The low permeability number for WF-3 is based on the match to the late time data of the second water slug test from May 17th to 20th, whereas the high permeability number was obtained using the match to the early half of the first water slug test on May 9th.

5.3 Pump tests in WF-4

WF-4 is an inclined borehole, with which there have been many challenges. The drilling itself took longer than the vertical WF holes because WF-4 intersected several faults, which made core recovery difficult. In order not to lose cores by tumbling and grinding them in the core barrel, core retrieval trips were done frequently by halting the drilling, which slows down advancement. The hole was continually collapsing and sloughing off. The shape of the borehole cross section was most likely not a perfect circle, because the drill-pipes tended to drag on the bottom; the borehole might have in fact been more or less egg-shaped, which made packer seating difficult. Even worse were the fracture zones, where the hole was enlarged due to the weakened rock. Thus, we could not set packers at the locations at will. The caliper log was indeed useful in determining the location of packers.

While drilling in WF-4 at ~183 m, the zones in WF-1 responded to the lowering and rising of the fluid level in WF-4, indicating that there was strong hydraulic communication between them. Lowering and rising fluid level occur when the core barrel is retrieved or pipes are pulled or inserted. Toward the end of the drilling, we noticed that WF-4 had become artesian. Based on these observations, we expected that the pump tests would be better suited to test the hole rather than slug tests, which were the only choice in WF-3.

5.3.1 Packer configuration

Because WF-4 is deeper than other holes and has rougher walls, we decided to use larger-diameter packers with higher pressure ratings. We also decided to use double packer strings instead of single. We used two sets of double packers to isolate three zones from each other. Figure 5-6 compares the single packer string used in WF-1–3 holes and the double packer system newly acquired and used in WF-4. The double packer configuration gives extra protection from unwanted hydraulic communications between isolated zones.

Efforts to install packers suffered many setbacks. The packers leaked several times: one time it was a cross threaded fitting, other times no direct cause was found, but packers were replaced. The fact that WF-4 is an artesian posed more challenges as well. It is unlawful to discharge groundwater to storm drains. However, accidental discharges occurred several times. Leaks happened once due to deflation of packers, and other times from the failed plug at the well head. The pumping zone is made open to the surface through the packers and pipes. We use 2” pipes to the top set of packers to allow for the use of a Grundfos pump. When divided into three zones, the bottom zone has a roughly 5 m higher head than the surface elevation. Thus, when the plug of the pipe that is open to the bottom zone fails, water flows out.

The initial packer configuration was the following: the top shoulder of the upper double packer string was set at 68 m (223 ft) and that of the lower string was set at 163 m (535 ft). Thus, the #1, #2, and #3 zones are 0–68 m, 70.4–163 m, 165.4–211.4 m (BHL), respectively.

5.3.2 Packer Seating

Figure 5-7 shows three different packer placements relative to a fault in a borehole. If the fault has a low permeability core and associated damaged zones with higher permeability on either sides of the fault, an open borehole would short-circuit the zones. To test the permeability of the zone on either sides or the core, we must take care in placing the packers. If the packer is not set right over the core, as shown in Figure 5-7(c), the two zones may stay hydraulically connected through the borehole, as shown in Figure 5-7(a) and (b). However, in WF-4, we were not certain if and where the fault core was, towing to numerous core-loss locations. Even when the location of the fault core was determined, in practice it was difficult or unfeasible to set a packer at the exact location, because the borehole wall might be too rough to set a packer without damaging it, or for a packer to properly seal the borehole.

5.3.3 Gas Buildup

As noted in the previous section, a plug at the top of the pipe was necessary to prevent the groundwater from discharging. We had been using an inflatable plug for this. However, the plug got unseated several times due to gas buildup in the pipe, the cause of which has yet to be unequivocally determined. The primary suspect is the nitrogen that leaked out of the packers/lines. **Error! Not a valid bookmark self-reference.** shows the results of mass spectrometer analysis of the gases collected at two different times. They are close to air but have less oxygen and a little elevated nitrogen. The first sample has traces of hydrocarbons—note that hydrocarbon contamination was a huge problem when drilling and testing in WF-3. Other possibilities include the groundwater containing dissolved air that de-gasses due to lowering of pressure and some bio-chemical reactions that produce nitrogen.

As can be seen in Figure 5-9, there were pressure spikes on Dec 16 and Dec. 21 in the bottom zone (#3), resulting from the gas buildup in WF-4#3. The first spike was above 275 m, over 10 m above the ground level at WF-4. Such pressure buildups can dislodge the plug, from which unwanted discharge could result. To prevent gas-pressure buildup in the pipe, a float valve was fabricated and used in combination with the inflatable plug. A float valve is made of a float that opens the tubing that is vented to the outside when gas builds up and when there is no gas the float pushes the valve closed. In this way, gas would always be vented out and the correct water pressure can be measured.

In the future, we plan to use argon gas in place of nitrogen for packer inflation to see if the gas buildup ceases or if the nitrogen content would decrease. Although argon gas is more expensive than nitrogen, it has the added benefit of its molecule being larger than the nitrogen molecule, and thus less permeable through the packer's rubber member.

5.3.4 Pump Test on 1/21/2011

Figure 5-9 shows the head transients in three packed-off zones of WF-4 between 12/16/2010 and 2/14/2011, during which a preparatory free-flow test was conducted (on January 17th) and a three-day pump test was performed (January 22–24) followed by a recovery period of about one week. The WF-4 was packed off into three zones, whose intervals were #1: 0–68 m, #2: 70.4–163 m, and #3 165.4–211.4 m (BHL). Aside from the sudden increases due to the gas buildup, the head in WF-4#3 gradually increased, from the middle of December through the

middle of January, due to rain fall events. This underscores the importance of finding the right timing to conduct long-term pump tests by establishing the baseline trend of the groundwater pressures. Otherwise, it would be difficult to differentiate between the pressure changes due to pumping or pressure changes due to natural events. The January pump test was thus planned and conducted based on the preceding period of dry days and the same forecast for the following extended period. January is usually a very wet month in the Bay Area.

In the first test, the valve of the pipe connected to the #3 zone was opened, and the flow took place because of the artesian nature. It was meant to test the plumbing, flow, and pressure sensors. All the equipment worked, and the flow rate decreased to zero after about forty minutes—which was expected because it was essentially a constant head test and there was backpressure due to the plumbing. It was considered that the flow duration was too short, and thus the volume of the affected rock was too small, to conduct an analysis of flow-rate transients.

In the second test, water was extracted from the #3 zone at a constant rate of 14 liters/min from January 21st for ~3.5 days. We analyzed the recovery portion of the head transient data from WF-4#3, the pumping zone. In general, the recovery analysis was much more robust, because the skin and wellbore storage effects cancel out in the analysis. In addition, the combined time duration of pumping and recovery periods means that it is essentially a longer test than the pump test alone. In this case, it would be the equivalent of conducting almost a two-week pumping test. Figure 5-11 shows the Horner plot and the asymptotic straight lines. The straight-line fit to the late time (smaller Horner time) yields a transmissivity of 2.3 m²/s, whereas the fit to the medium time yields 1.2 m²/s, roughly one half of the former. Although it is difficult to imagine that the flow is radial and horizontal, the numbers are somewhat reasonable when compared to those obtained in the other WF boreholes, as shown in Table 5-1.

The head transients in WF-1#5, WF-2#5, and the three WF-4 zones during the three-day pump and the recovery test are shown in Figure 5-10. In Figure 5-12, head responses in all the zones in WF-1 are shown. As can be seen from the figure, WF-1#5 responds quite markedly. The degree of interference lessens with the number of observation zones. The #1 zone does not seem to have responded at all; the #2 response is almost unnoticeable—this zone is the one that seemed to have responded to the drilling of WF-4 at 650 ft (more later) when the head in #2 dropped [to?] ~2.5 m. We still do not know if this is indeed real. The drop was over a one-day

period, not a sudden shift, and the sensor seems to track the #3 head since then. Both these findings indicate that the sensor was functioning normally. Except for the steep drop, the head in #2 responds less than #3~#5, which indicates that the zone is hydraulically a further distance away (lower permeability) than #3~#5 zones.

Because the flow geometry is unknown, the interference responses are not amenable to the standard analysis technique, where a horizontal and radial flow is assumed. One perhaps feasible way is to conduct numerical inversion to match the responses by varying the permeability structure, and thus the flow geometry of the subsurface surrounding WF-1 and WF-4.

If the Wildcat Fault were semi-vertical with an extensive low-permeability core, and if the packers were successfully isolating the zones, we would have seen no change in the head in WF-4#2. However, the head decreased by more than 2 m in response to the pumping in WF-4#3, as can be seen in Figure 5-9. This could mean one or more of the following possibilities:

- (a) The packers are not sealing the borehole very well due to the rough wall.
- (b) There is no extensive low-permeability fault core with gouges; thus, the rock is permeable from east to west across the fault.
- (c) The packer is not properly separating the east and west side of the fault, as illustrated in Figure 5-7(a) or (b).

Possibility (a) seems somewhat unlikely, because we carefully selected the location and because double packers were used with a high inflation pressure of 300 psi.

The WF-2#4 and #5 responded to the pumping as well. The heads decreased ~0.5 m—as expected, because the nonpumping zone WF-4#2 had a decrease of 2.5 m and there was a response in these zones when WF-4 was being drilled at ~250 ft, indicating a hydraulic connection between the middle of WF-4 and WF-2.

5.3.5 2nd Pump Test

In order to address the issues above, on February 2nd, 2011 we raised the bottom packers from 163 m (535 ft) to 144 m (472 ft) to prepare for a second pump test. The installation seemed to have gone successfully, but it was followed by a massive nitrogen gas leak and the entire packer string had to be pulled up. Figure 5-13 shows the large pressure increase in WF-4#2 zone and WF-2 zones due to the leak. Interestingly, WF-2#2 and #3 responded to this increase, but not WF-2#4 or #5, as can be seen from the figure. Nitrogen gas must have accumulated in the top

portion of the #2 interval and may even have migrated upward to WF-2#2 and 3. Interestingly, the latter two zones did respond to the pressure decrease in WF-4#2 during the pumping in WF-4#3, but not WF-2#2 or #3. These facts indicate that there are two hydraulic connections between the interval of WF-4#2 (70.4–163 m) and WF-2. These connections may be through the faults identified by Kiho et al. (2011). The upper connection is through the “Fc” feature and the bottom communication may be through the unnamed feature at the bottom of WF-2, as seen in Figure 5-14 .

Initially, leaky packers were suspected as the cause of the leak, and new packers were acquired. It later turned out that the leak was from a cross-threaded fitting of the packer inflation line. Nevertheless, the packers, inflation lines, and fitting were replaced. This time, the bottom packer was placed at 175 m (574 ft). We had intended to place the packer 10’ deeper at 584 ft, just above the massive deformation zone. However, there was an obstruction near 177 m (582 ft), and the deepest we could set the bottom packers was at 175 m (574 ft). A second pump test is now being planned for the bottom zone (#3) of this configuration.

5.4 Pressure Monitoring

5.4.1 WF Boreholes

Figure 5-15, Figure 5-16, and Figure 5-17 show the head transients observed in WF-1, WF-2 and WF-3, respectively, since the installation of each borehole. Also shown in the right axis of Figure 5-15 and Figure 5-16 are the drilling advancement (linear footage) of WF-4 and the daily rainfall amount. Careful analysis of these figures leads to several interesting observations:

1. The effects of the rainfall intensity and amount of rainfall on the observed pressures vary hole by hole. The pressures in WF-2 appear to increase and diminish sharply in response to each rain event, whereas those in WF-3 are the least affected. On the other hand, the magnitude of the seasonal changes is greatest in WF-1 and least in WF-3. This is probably because the total recharge on the east side of the Wildcat is greater than the west side. These facts point to the possibility that WF-1, WF-2, and WF-3 are hydraulically disconnected, potentially by one or more faults. However, so far only about one year’s worth of data is available, and longer-duration data and analysis are necessary to make definitive conclusions.

2. The head of the topmost zone in all of the holes is higher than the rest of the zones in the same hole. The top zones in WF-2 and WF-3 do not respond to the rainfall events as much as the top zone in WF-1. There may be a perched zone in WF-2 and WF-3, where the lithology near the surface is low permeability Orinda siltstone.
3. The drilling of WF-4 did not affect WF-3. When the depth was near 250 ft, the #3, #4 and #5 monitoring intervals in WF-2 responded. These were upticks in the pressure, probably due to the high circulation pressure in WF-4. More notable are the responses observed in the WF-1 intervals, particularly in #5, where the drilling depth passed 183 m (600 ft) on Sept. 14th. Furthermore, when the drilling depth was at 198 m (650 ft) on Sept. 21st, the pressure in WF-1#2 dropped quite markedly, as can be seen in the figure. The pressure in WF-1#2 has not recovered since, but has tracked the rest of the zones in response to rainfall events.
4. The pumping in WF-4#3 and other pressure-disturbing activities, including packer installations and plug failures, affect the pressure in the WF-1 zones, with the response magnitudes in decreasing order from #5 to #2.
5. As can be seen in Figure 5-10, the pressure response in WF-1#3 to the WF-4#3 pumping is much greater than that in WF-2#5, although both zones are at a similar linear distance from the Fd feature identified by Kiho, et al. (2011), which is suspected to be the main inflow point in #3. Table 5-2 compares the linear distances from Fc and Fd features in WF-4.

5.4.2 SSL Boreholes

A pump that was installed in SSL-1 to mitigate landslides has been pumping for a few decades. The latest known pumping rate was 10 GPM. We installed flow and pressure sensors in these boreholes for our project, as described in Karasaki et al. (2010). Figure 5-18 shows the pressure transients in SSL-1 and SSL-2 since the installation of sensors and the daily precipitation measured at LBNL. Installation of a sensor in SSL-2 (10/21/2009) predates that of SSL-1 (2/1/2010). The location of SSL holes can be found in Figure 5-1. Spikes on the SSL-1 pressure curve result from an accidental shutdown of the pump due to unknown causes. As can be seen from the figure, the pressure has been declining ever since the monitoring started. The effects of the precipitation can be seen from the slowdown of the pressure decline since the

beginning of this year. The pumping rate and the water-level data are used to constrain the hydrologic model described in the next section.

While it was not meant to be a pump test, and the initial conditions and other borehole parameters (such as the screen length and locations) are not known, the pumping in SSL-1 was effectively a pump test. The pressure drawdown is plotted against a time log in Figure 5-19, using the time of the restart of pumping as time zero. As can be seen from the figure, two straight lines can be fit to the drawdown curve. Using the Jacob's method, we obtain a transmissivity of $3.0 \times 10^{-5} \text{ m}^2/\text{s}$ from the first slope and $8.3 \times 10^{-6} \text{ m}^2/\text{s}$ from the second slope. Because the screen length is not known, it is difficult to calculate permeability. The maximum zone length would be 100 m, which is the approximate length of the borehole, and the minimum would be the current water level above the pump, ~30 m. We use this number to arrive at the high and low permeability listed in Table 5-1. That there are two straight-line portions in the drawdown curve, and that the latter slope is ~1/4 of the former, indicate that the aquifer is limited in extent, perhaps by a fault or faults.

The head transient curve of SSL-2 in Figure 5-18 shows two humps (increase and decrease in pressure), first in mid-February 2010 and the second in late April 2010. The first hump was initially thought to be the response to the pump shut-off in SS-1 for the sensor installation reaching the peak 20 days after the restart of the pump in SSL-1. However, the second hump was observed in late April without any activities in SSL-1 to cause such an increase. This is most likely caused by the infiltration of the rain, as can be seen from the precipitation rate during those months. At this time we are not sure if the first hump was an actual interference signal from SSL-1. Lennert (1979) reported that there is a "University fault" between the two boreholes and that they are hydraulically separated by it. (Converse (1984) refutes the existence of such a fault (Figure 5-21)). We plan to shut off the pump in SSL-1 during dry months to see if interference can be observed in SSL-2.

5.4.3 All Boreholes

Figure 5-20 shows the head transients of selected intervals in WF and SSL boreholes in the last 1.5-year period. As can be seen from the figure, the overall trend is for a decrease in heads in all the intervals. SSL-1 and 2 decreased the most, which makes sense considering the pumping in SSL-1. Among the WF boreholes, WF-1 appears to be most responsive to the rainfall (and to the

lack thereof). During the dry months, the head decreased more rapidly than the other WF holes, and increased more than those other holes after the rainy season started in November 2010. Putting it all together, all WF holes appear to be behaving independently. Now there is even doubt whether SSL-2's head decline is caused by the pumping in SSL-1. However, the monitoring period is still too short to make definitive conclusions.

5.4.4 Hydraugers

As part of landslide mitigation efforts, there have been many hydraugers drilled into the hills of the LBNL site, in order to drain water off the hills. Many of them were drilled some 30 years ago, and not much of a record has been kept on them. Some were destroyed by new road and building construction, and some collapsed naturally. Some locatable outfalls of hydraugers have no flow, but we have identified three hydraugers that have significant flow (Figure 5-22). Lennert-1 is the longest, over 1200 ft in length, which produced >2000 GPM initially. It was drilled in the direction of Well 789-1, which we now call SSL-2. The flow meter we installed at the outfall now (as of March, 2011) measures only 7–8 liters/min throughout the year (Figure 5-23). It may very well be broken somewhere in the middle—the flow rate does not seem to correlate to the rainfall. Another hydrauger that produces an even more significant amount of water is Quarry-1, with 23~61 liters/min. This hydrauger was installed to drain the artesian well dug by the farmer who used to have a ranch nearby before LBNL was built. A flow meter was installed only quite recently, so that the seasonal fluctuation is unknown at this time. However, as can be seen in the figure, the outflow responds to rainfall events rather quickly and sustains increased flow for quite some time after the events.

5.5 References

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- Cooper, H.H., J.D. Bredehoeft, and I.S. Papadopoulos, 1967, Response of a finite-diameter well to an instantaneous charge of water, *Water Resources Research*, 3, pp. 263-269.
- Karasaki, K., C.T. Onishi, W. Black and S. Biraud, 2009, Development of Hydrologic Characterization Technology of Fault Zones: Phase I, 2nd Report, LBNL-1635E-2009.
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- Karasaki, K., J.C.S. Long, P.A. Witherspoon, 1988, Analytical Model of Slug Tests, *Water Resources Research*, 24(1), 115-126.
- Lennert and Associates, 1979, Hill Area Dewatering Program, Letter Report from Lennert to CP Russo, Job 789, November 26, 1979 includes map and plates.

Table 5-1 Calculated transmissivity and averaged permeability in WF boreholes. The low in WF-3 indicates those at some distance, whereas the high are for the immediate vicinity.

	Geology	Zone Length(m)		Transmissivity (m ² /s)		K (m/s)	
				Low	High	Low	High
WF-1 bottom	Tc	117		2.9E-05	9.5E-05	2.5E-07	8.1E-07
WF-2 bottom	Tc	76		1.2E-06	2.9E-06	1.6E-08	3.8E-08
WF-3 bottom	Tsp/Tc	112		2.3E-07	6.5E-06	2.1E-09	5.8E-08
WF-4 bottom	Tc	46		1.50E-05		3.26E-07	
SSL-1	Moraga Volcanic	100	30	3.00E-05		3.00E-07	1.0E-06

Table 5-2 Comparison of linear distances from the features in WF-4 to the intervals in WF-1 and WF-3

	x	y	z	Distance from WF-4 Feature	
				Fc	Fd
WF-1#2	566936.7	4192575	242.7	81.7	144.8
WF-1#3	566936.7	4192575	175.4	73.0	83.5
WF-1#4	566936.7	4192575	157.7	80.5	69.3
WF-1#5	566936.7	4192575	134.7	94.3	53.9
WF-2#2	566886.2	4192537	232.3	49.8	147.6
WF-2#3	566886.2	4192537	201.8	37.1	122.3
WF-2#4	566886.2	4192537	171.3	46.2	99.9
WF-2#5	566886.2	4192537	140.8	69.0	82.9
WF-4#2	566911.9	4192511	199	250	
WF-4#3	566961	4192537	105	606	



Figure 5-1. Aerial map of the boreholes in the study area. Also shown are hydraugers, Lennert-1 and BG-1.

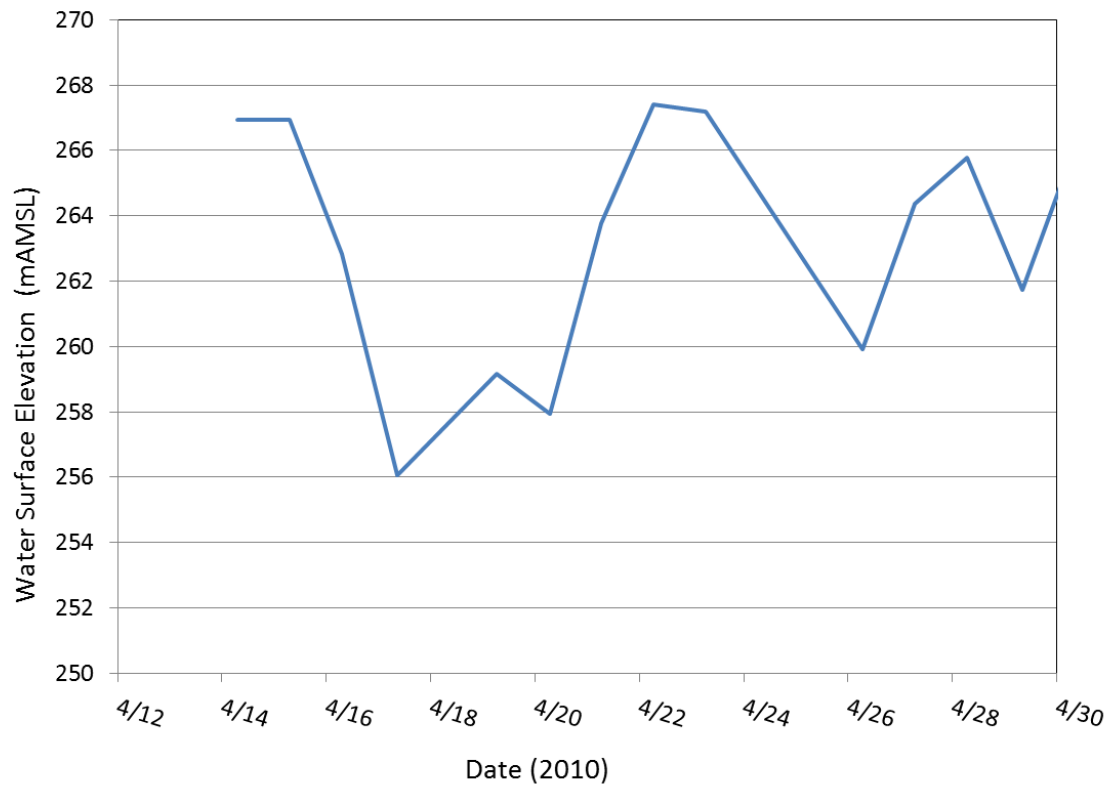


Figure 5-2. Water elevation fluctuation during the drilling period measured at ~6AM every morning before the day's drilling started.

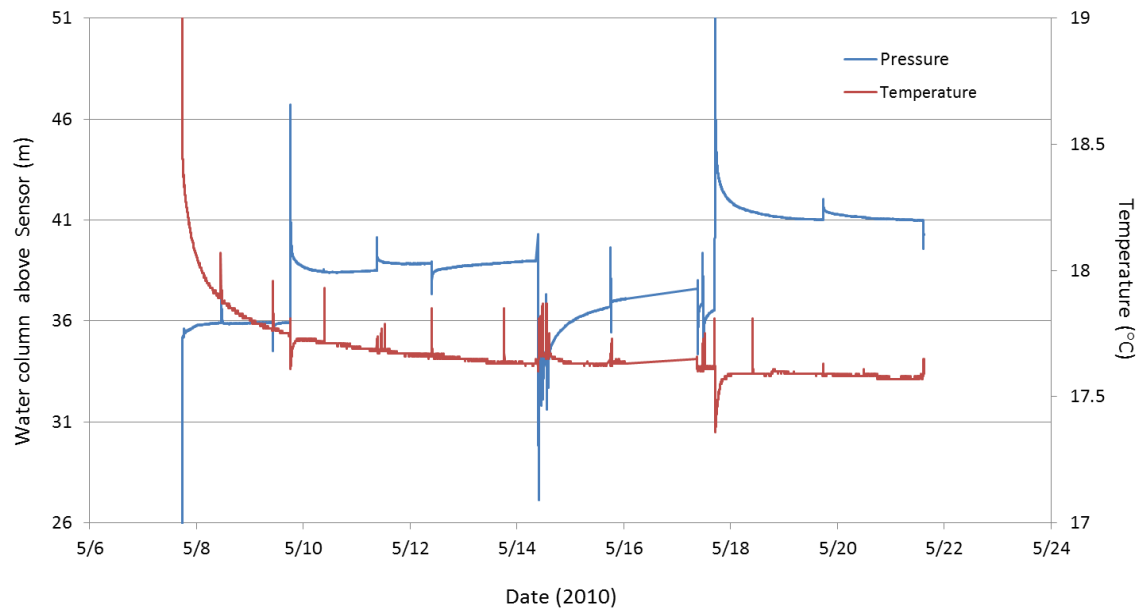


Figure 5-3. Series of slug injection/withdrawal tests and pump tests conducted in WF-3.

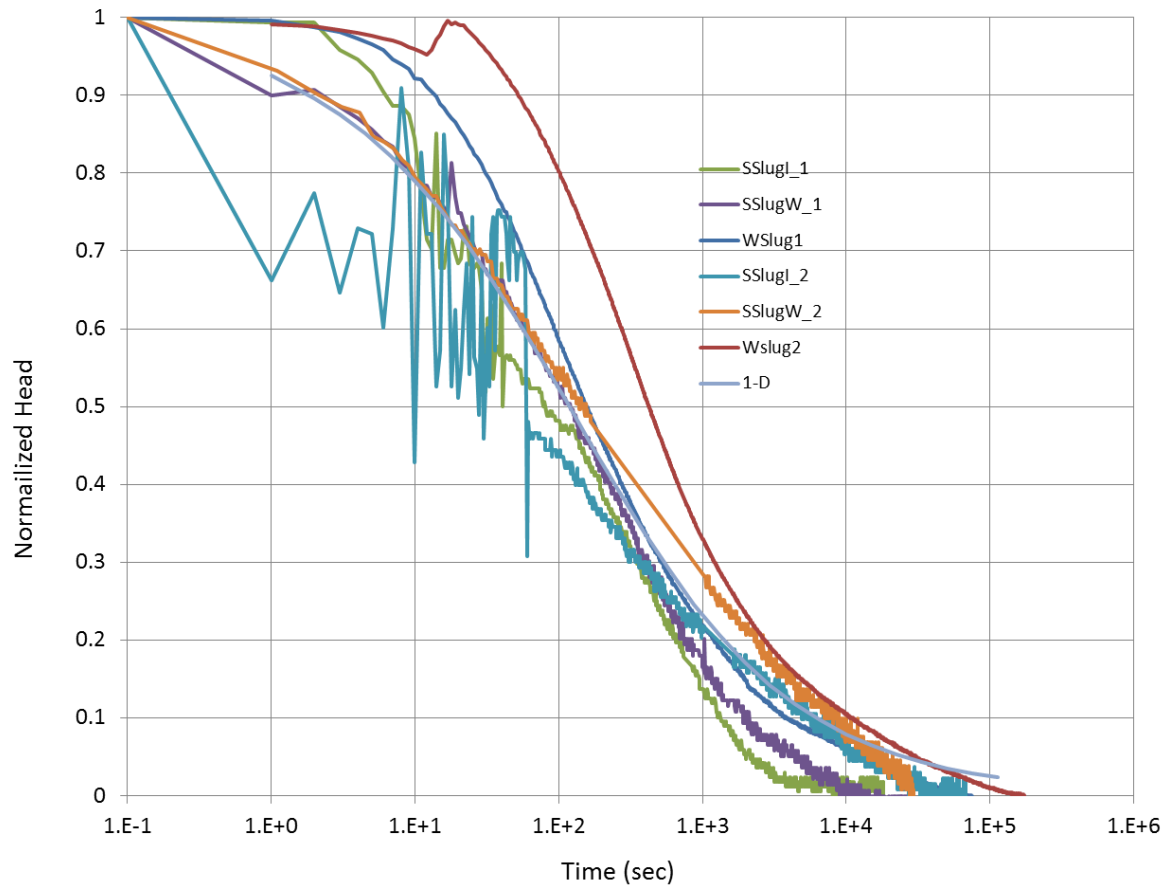


Figure 5-4. Sumperimposed plot of selected slug test data from WF-3.

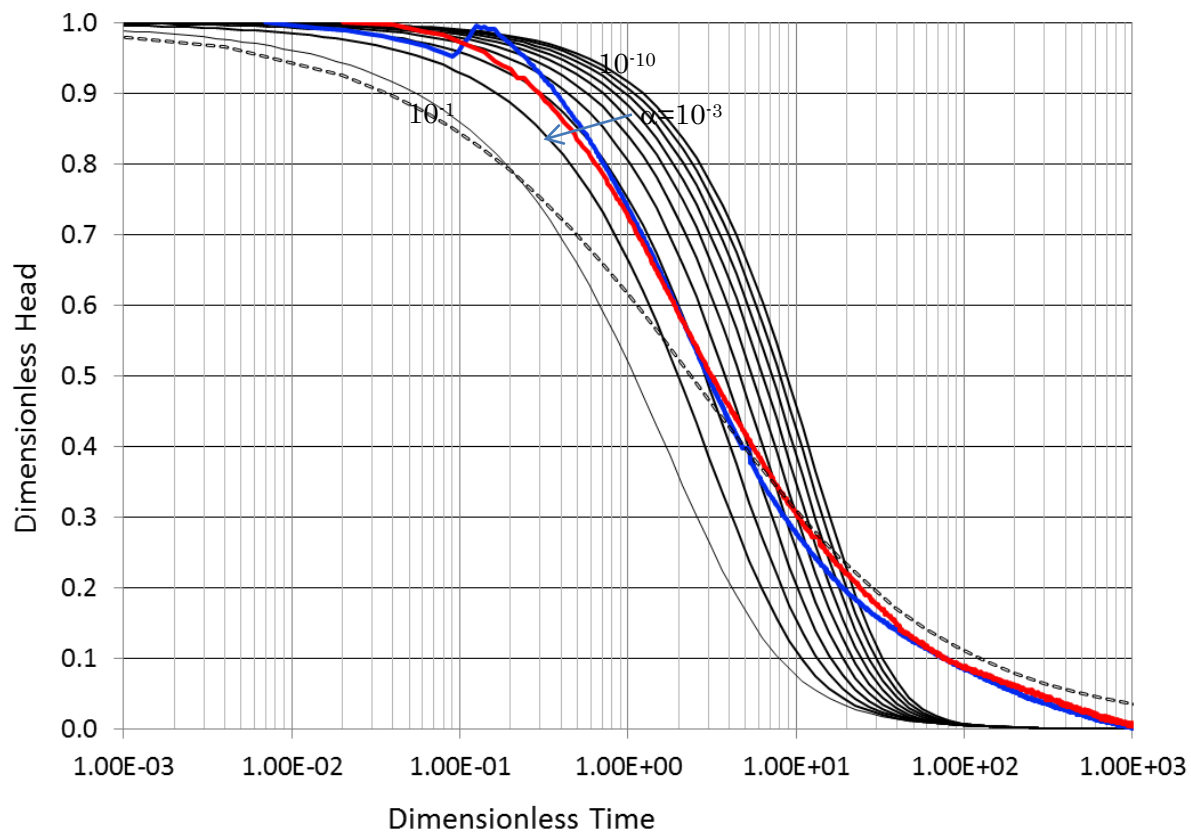


Figure 5-5. Type curve match of the slug test data in WF-3. The data are the water slug tests conducted on May 9th (red) and May 17th (blue), respectively. Broken line is the 1-D flow solution.



(a)



(b)

Figure 5-6. (a) The packer string used in WF-1~3 holes. (b) The double packer system used in WF-4 being surface tested. Soapy water is used to detect any potential leaks from the fittings and the glands.

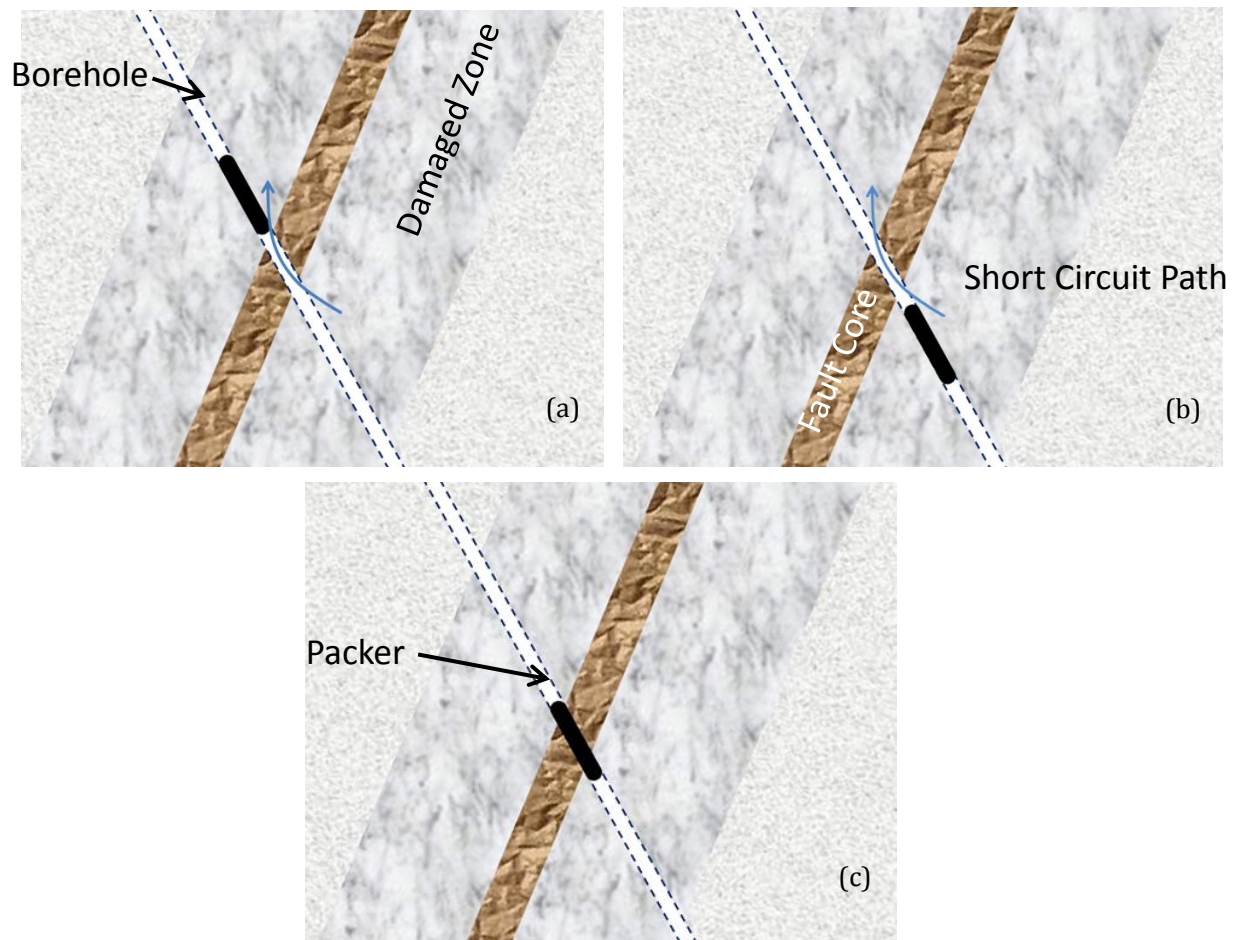


Figure 5-7. Packer seating in relation to fault core. (a) Packer above the fault, (b) below the fault, and (c) on the fault. Note that neither (a) or (b) isolates the zone on either side of the fault.

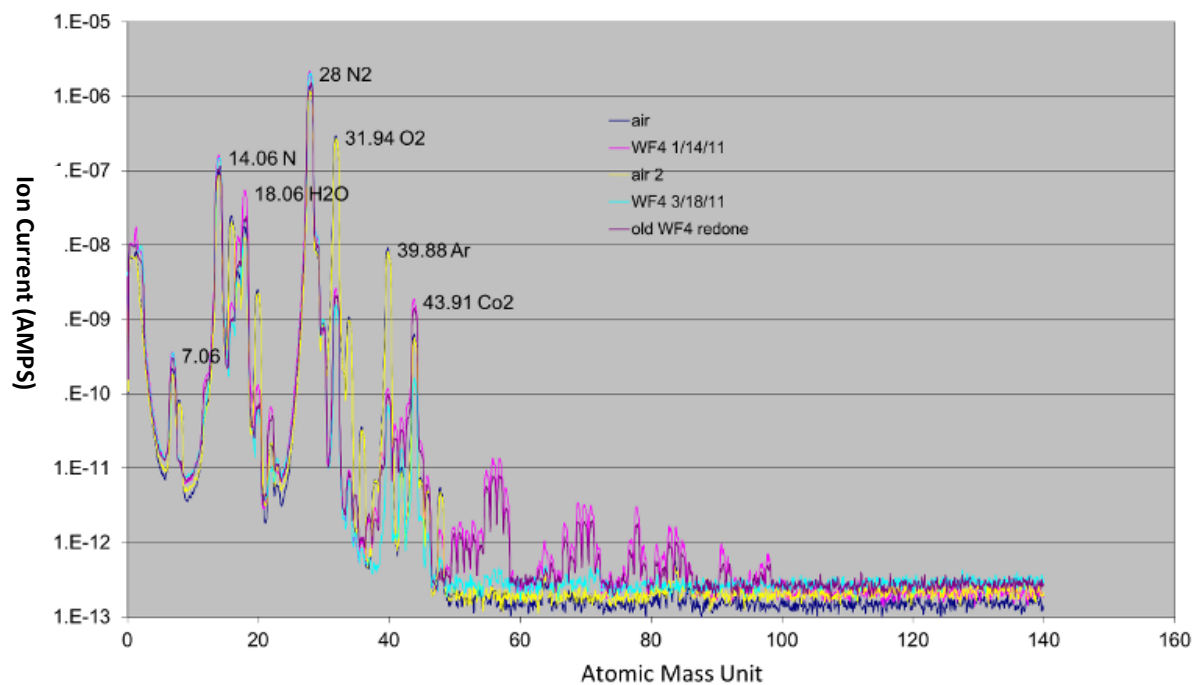


Figure 5-8. Mass spectroscopy results from the gas collected in WF-4.

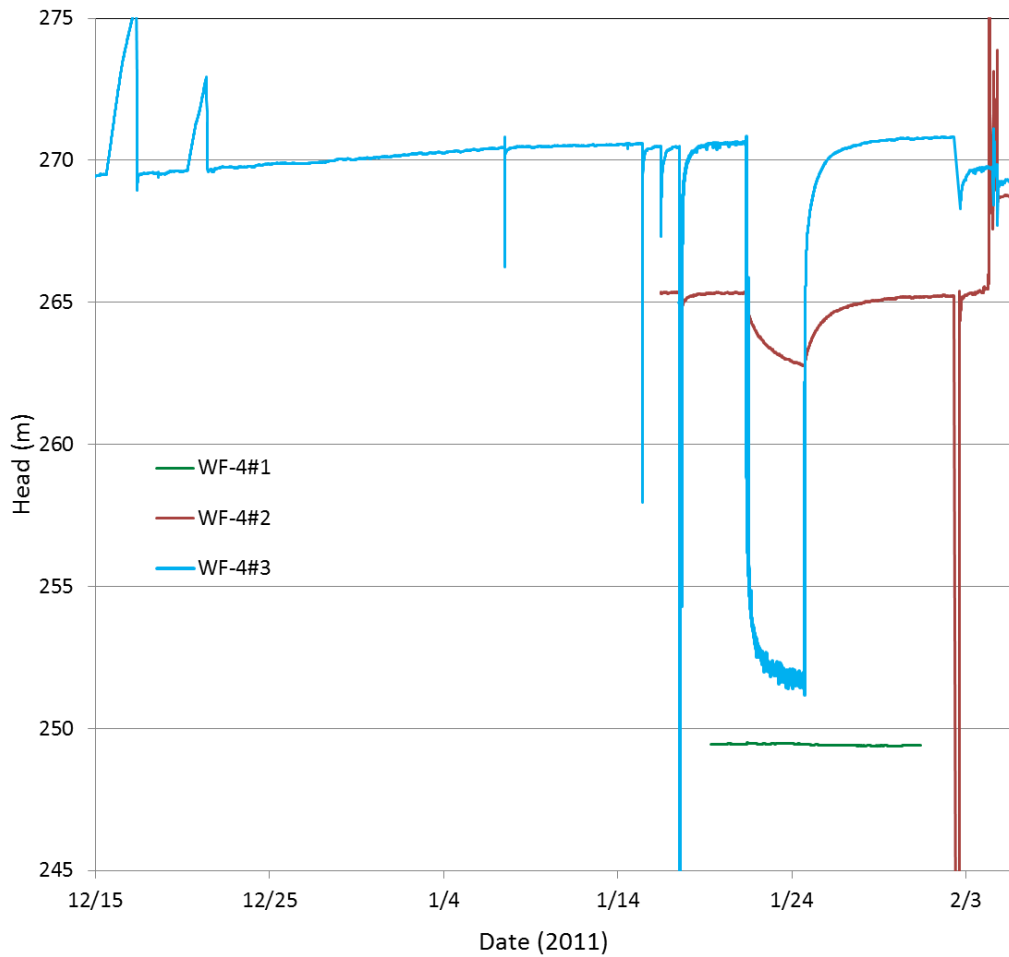


Figure 5-9. The head transients in three packed-off zones of WF-4 between 12/16/2010 and 2/14/2011, during which a free flow test (on January 17) and a three-day pump test in (January 22–24) were conducted.

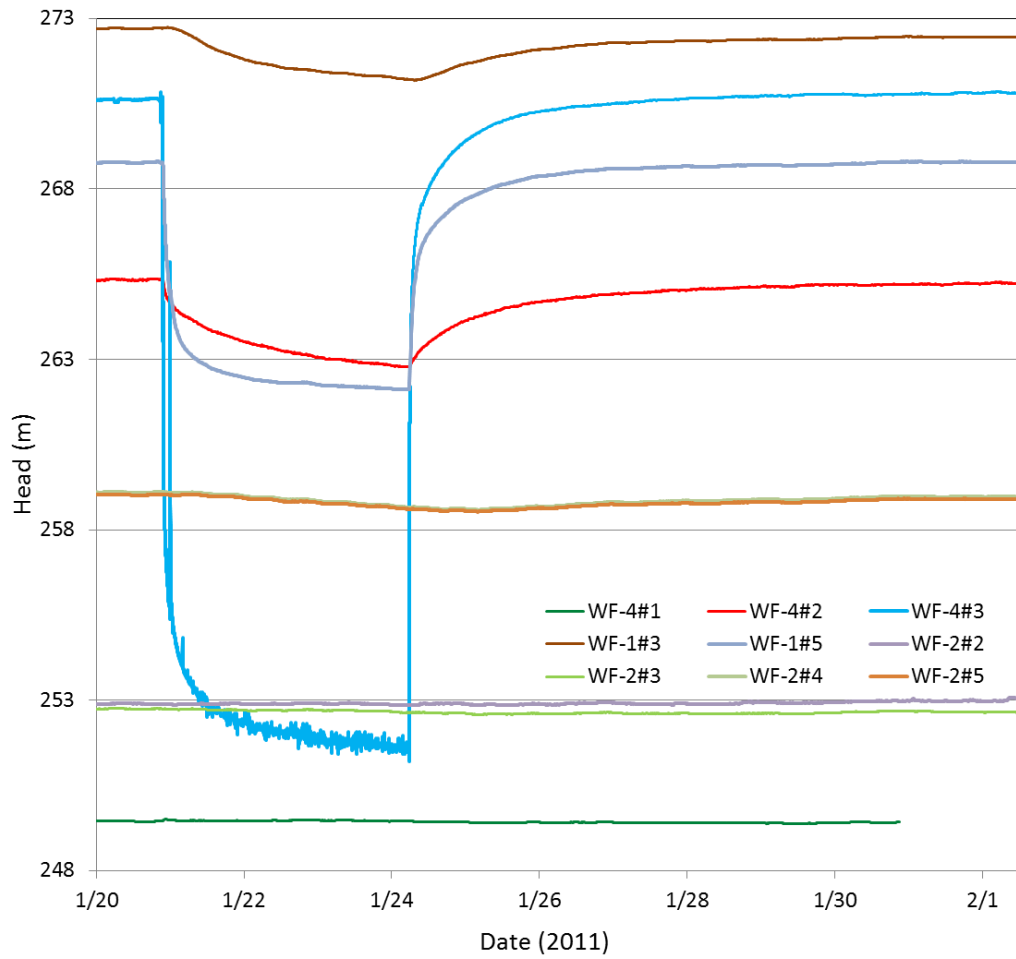


Figure 5-10. Head transients in WF-4#1~#3, WF-1#5, WF-2#5 during the pumping in WF-4#3.

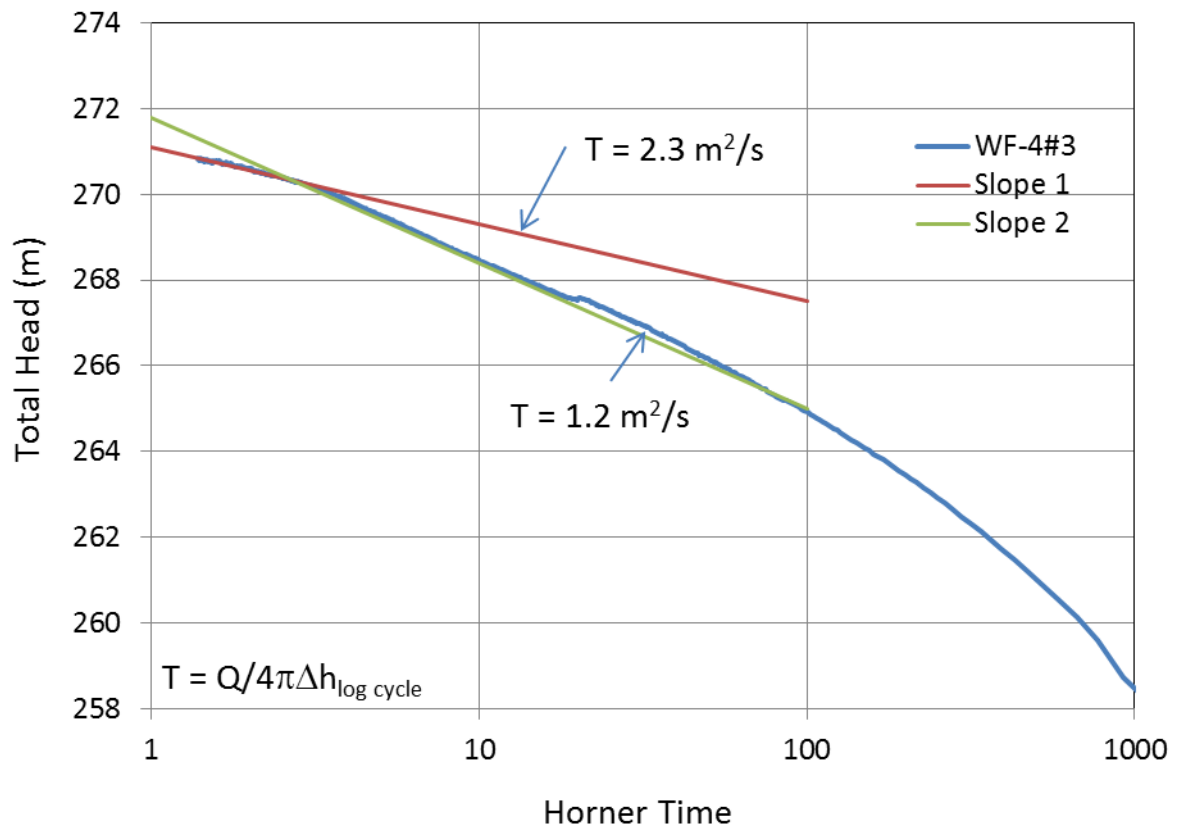


Figure 5-11. Horner plot of the recovery data of the pump test in WF-4#3.

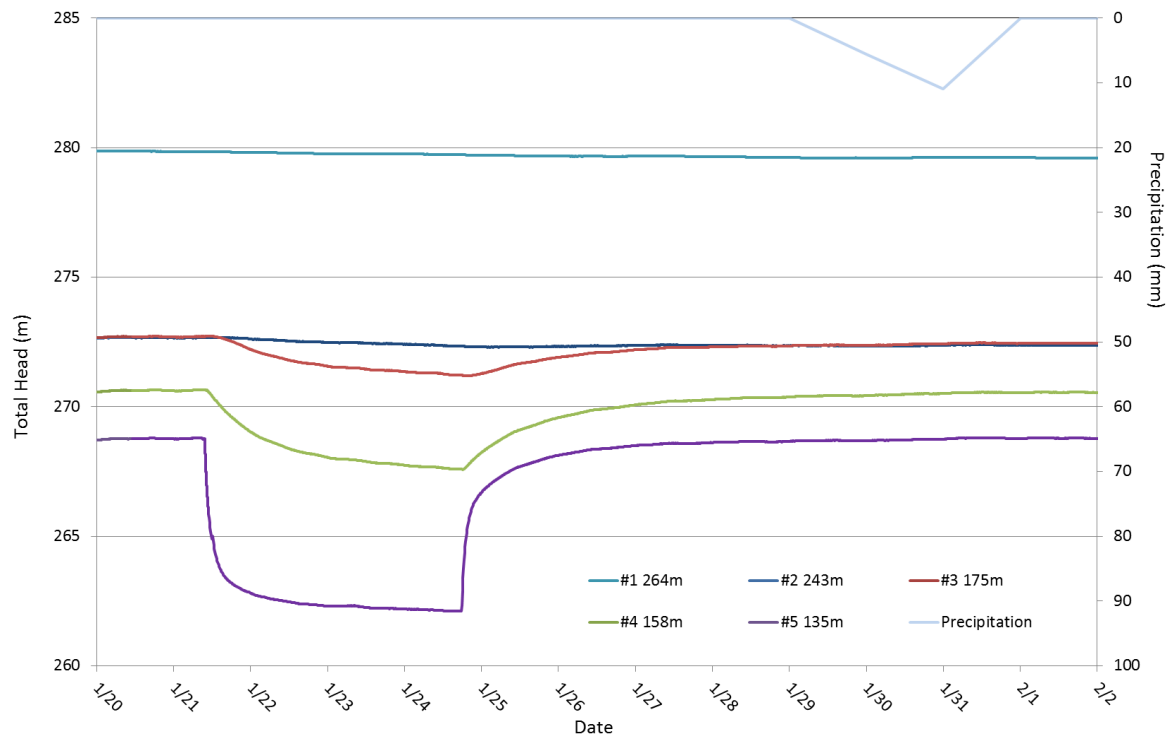


Figure 5-12. Responses in WF-1 intervals to WF-4 pumping in Jan21-24 followed by the recovery period of one week.

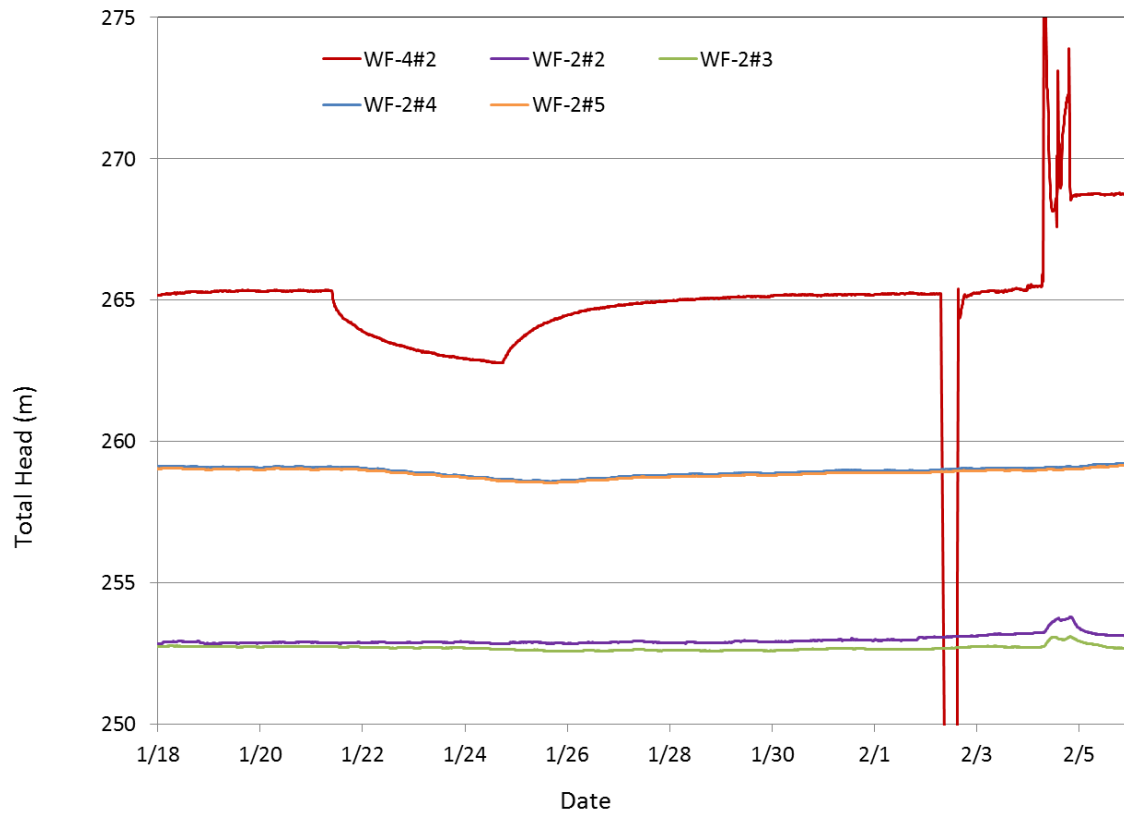


Figure 5-13. Pressure response in WF-2 intervals to the pumping test on Jan. 21st and the massive packer leak on Feb 4th in WF-4#2.

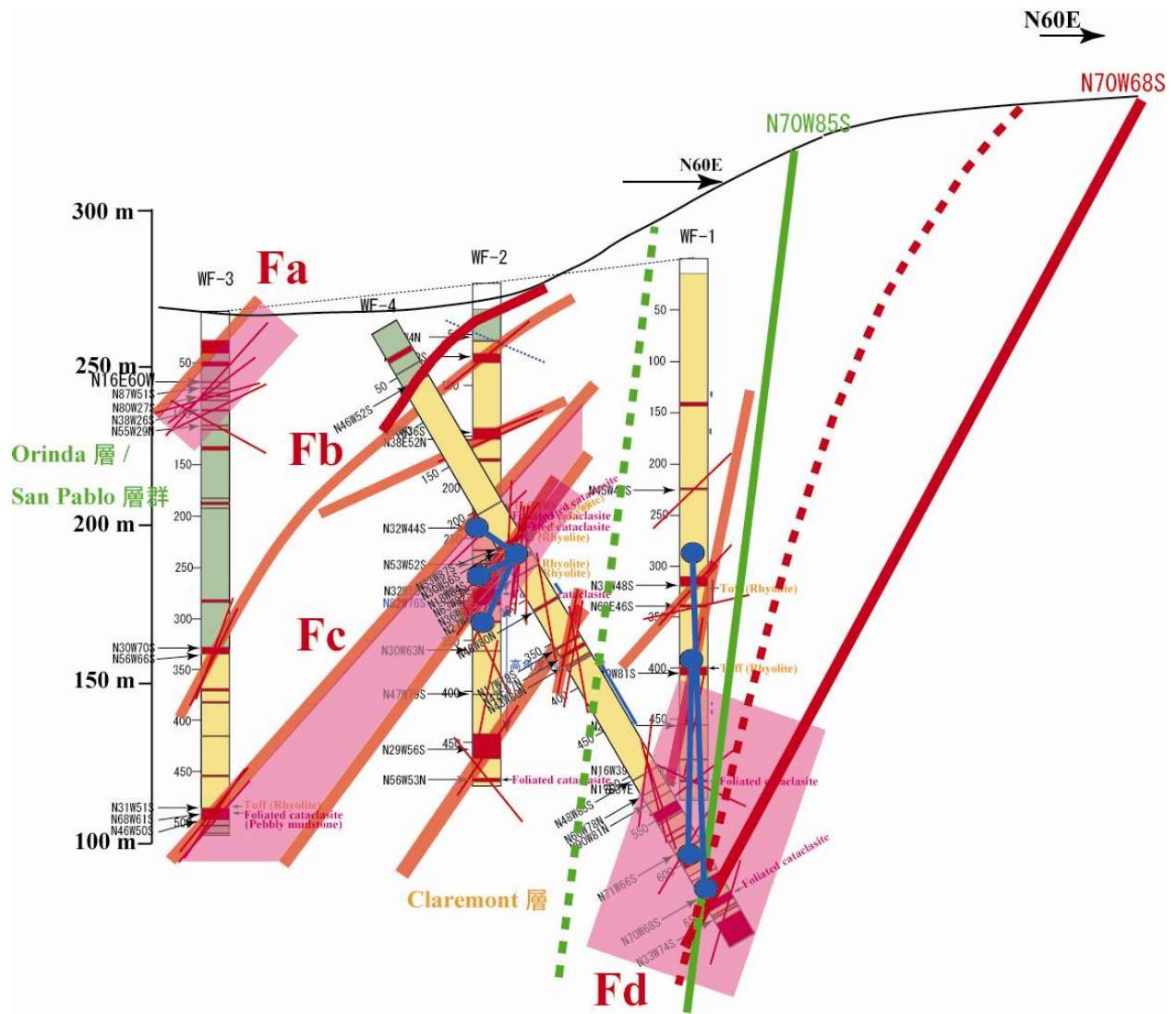


Figure 5-14. The Wildcat Fault zone structure intersecting WF holes (Kiho et al., 2011).

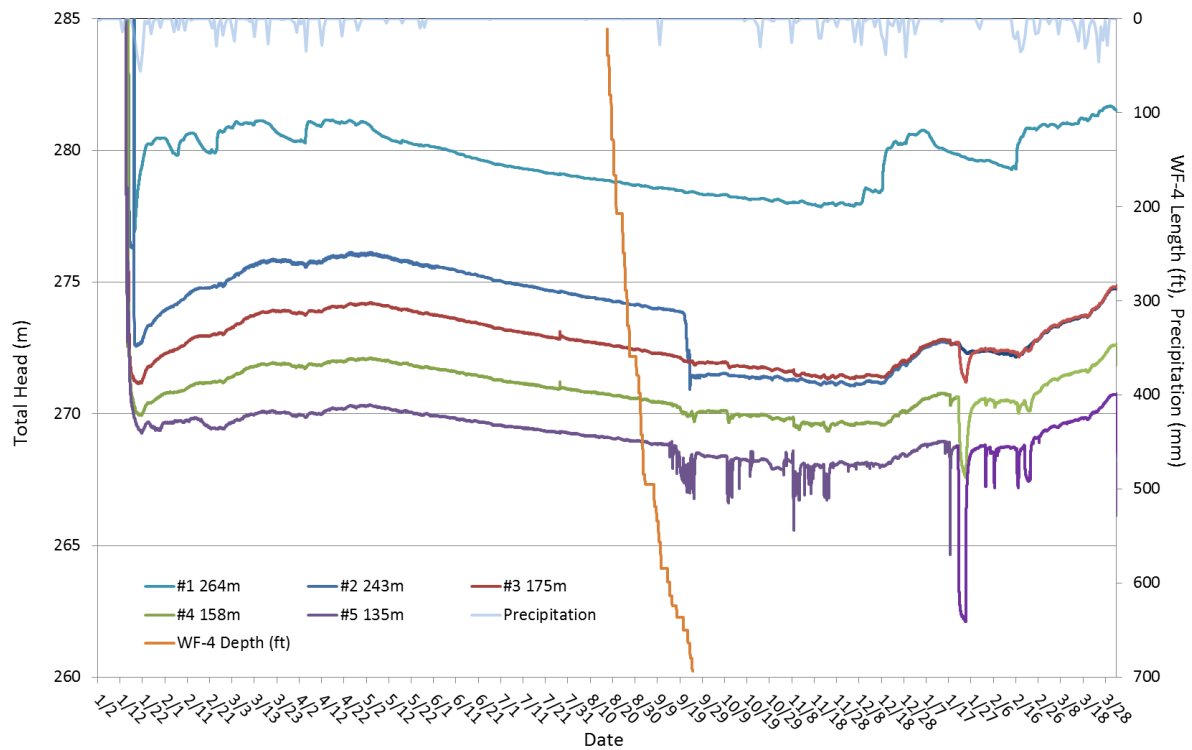


Figure 5-15. Head transient in WF-1 since installation.

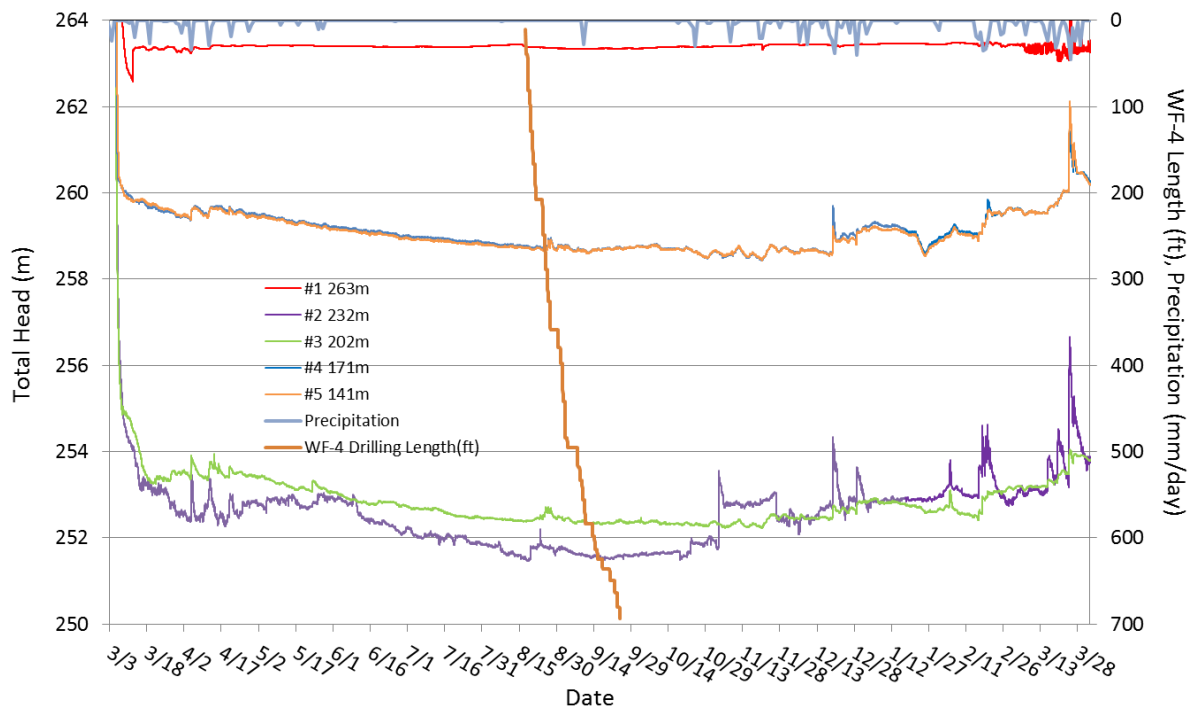


Figure 5-16. Head transients in WF-2 since installation.

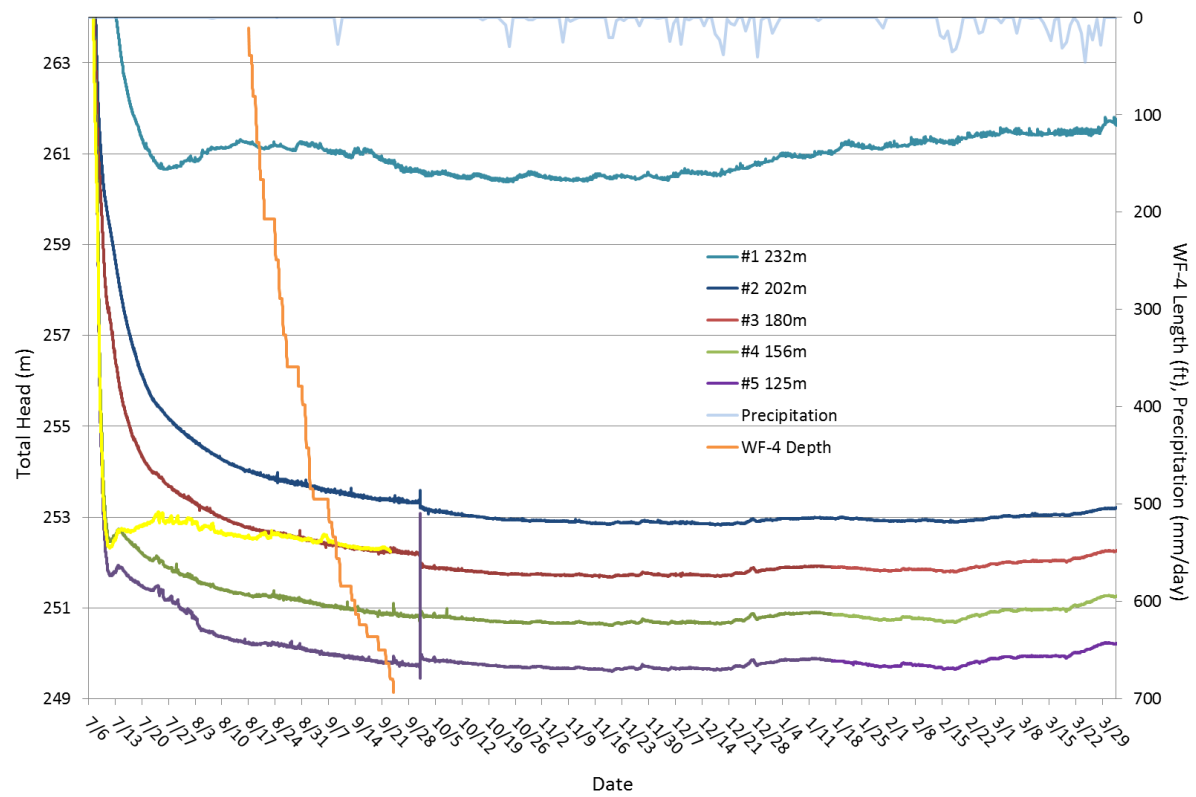


Figure 5-17. Head transients in WF-3 since installation.

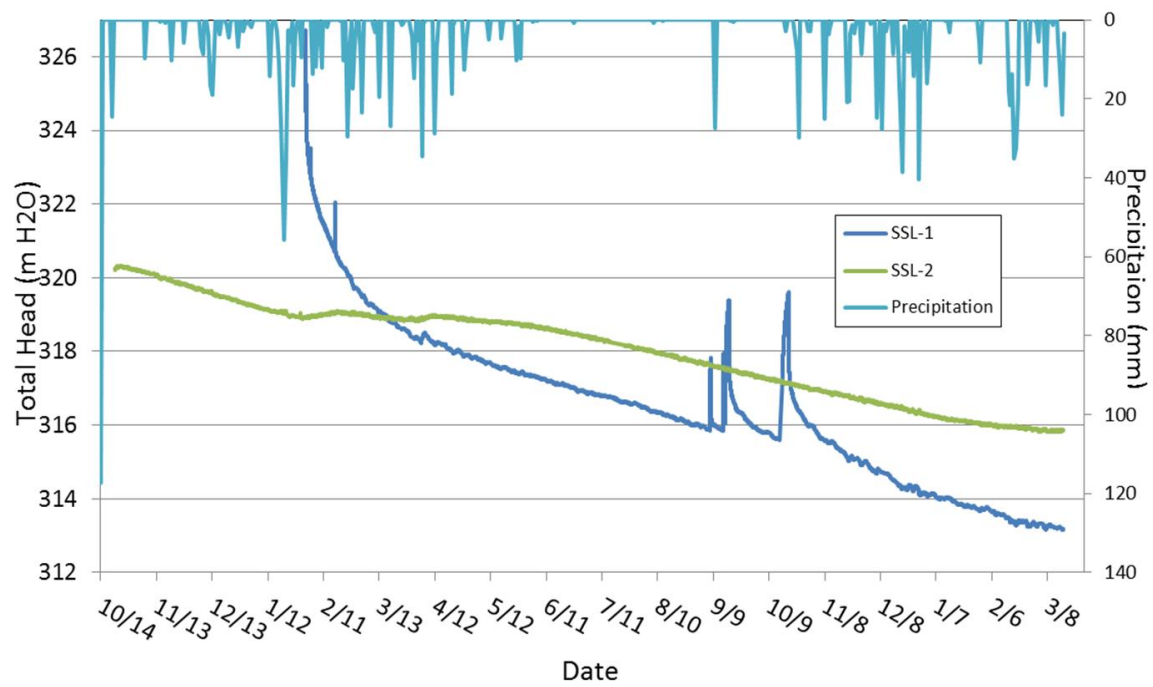


Figure 5-18. Head transients in SSL-1 and SSL-2

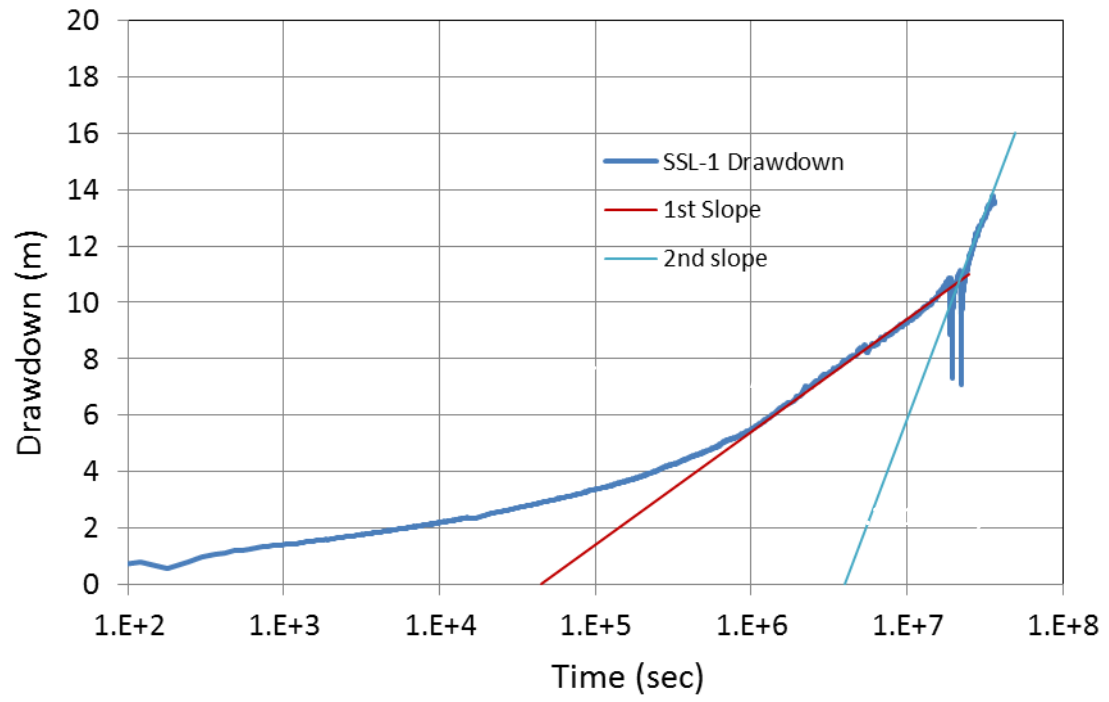


Figure 5-19. Semi-log plot of the drawdown at SSL-1.

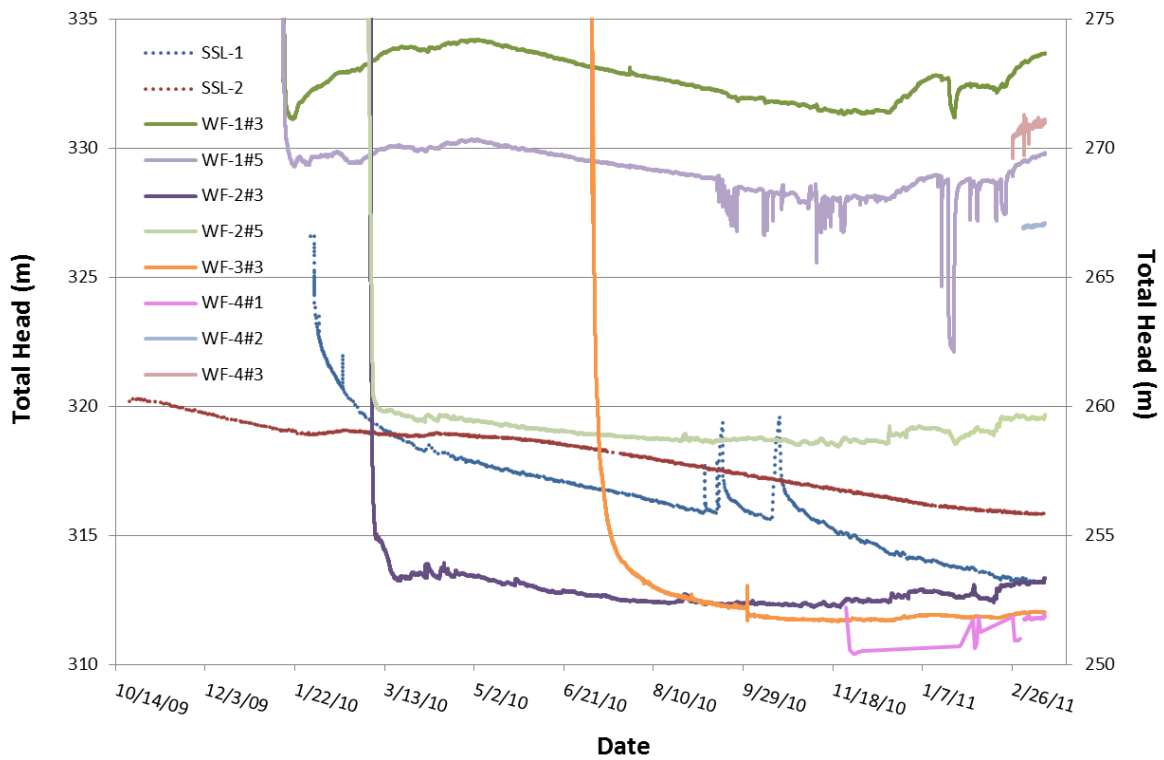


Figure 5-20. Comparison of head transients in selected intervals from WF and SSL boreholes. The left vertical axis is for SSLs and the right is for WF holes. Note that both axes are in the same scale.

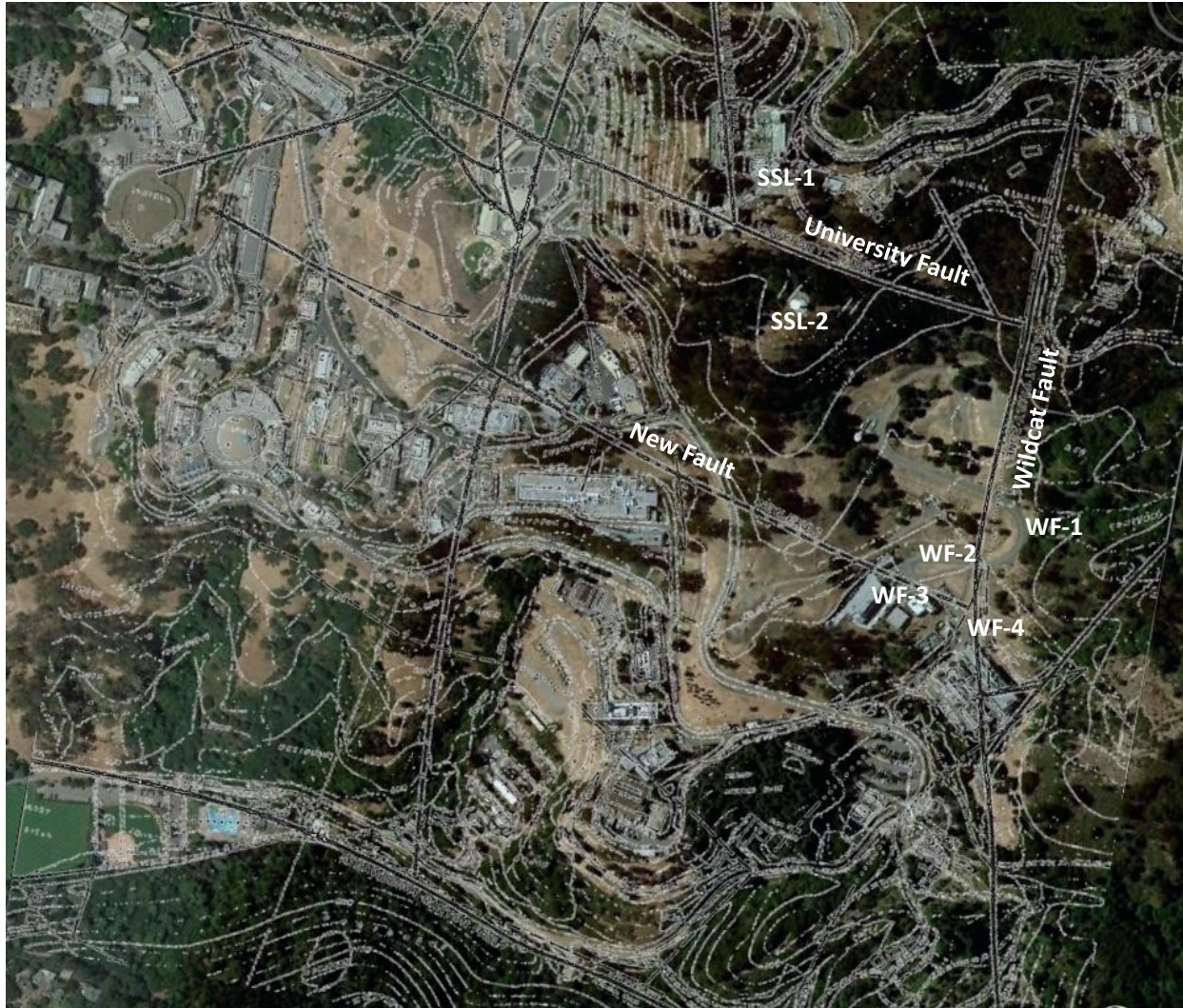


Figure 5-21. Fault maps by Lennert (1979) superimposed on a Google Map.

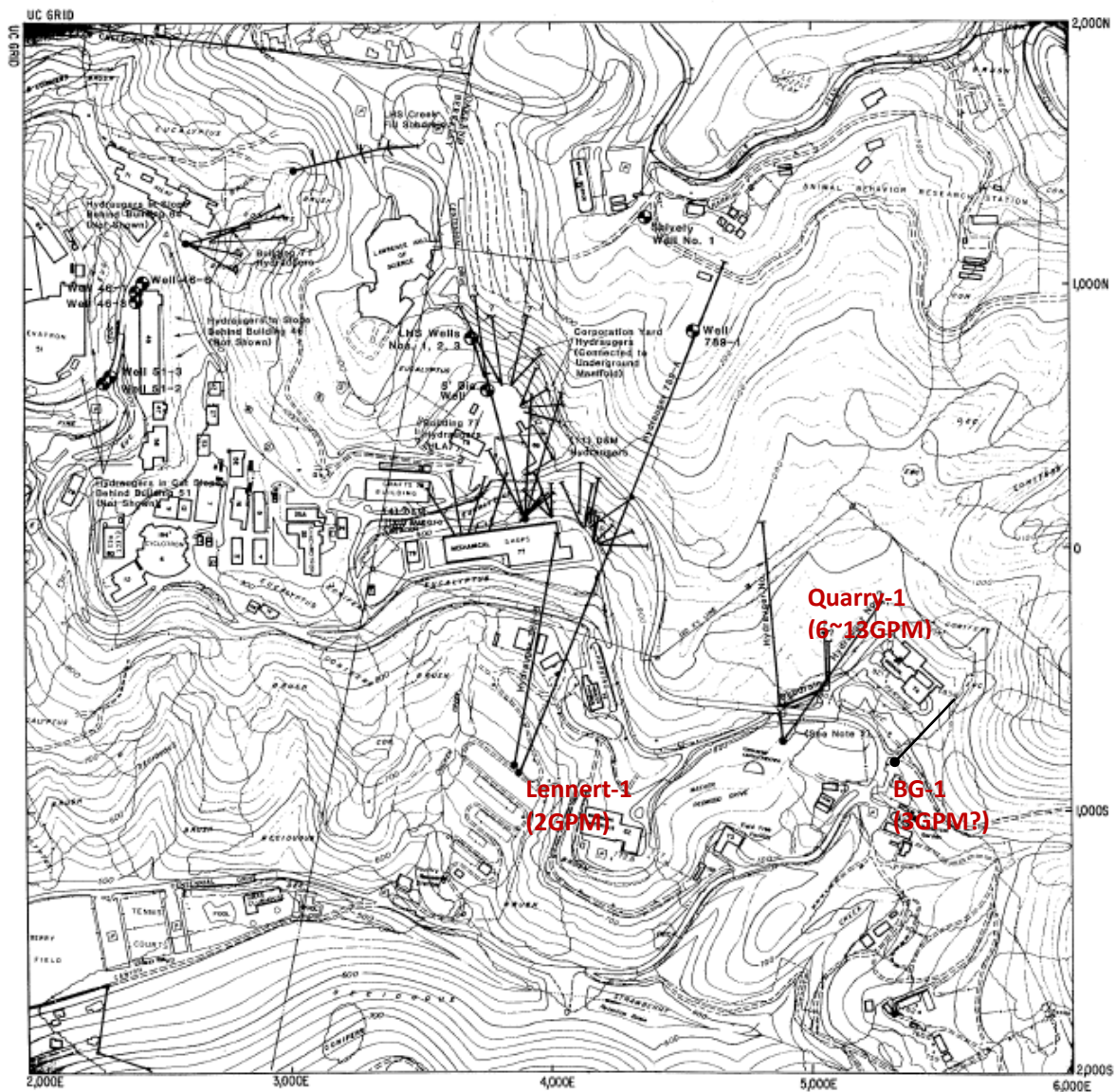


Figure 5-22. Locations of hydraugers and the average flow rate in the East Canyon area of LBNL.

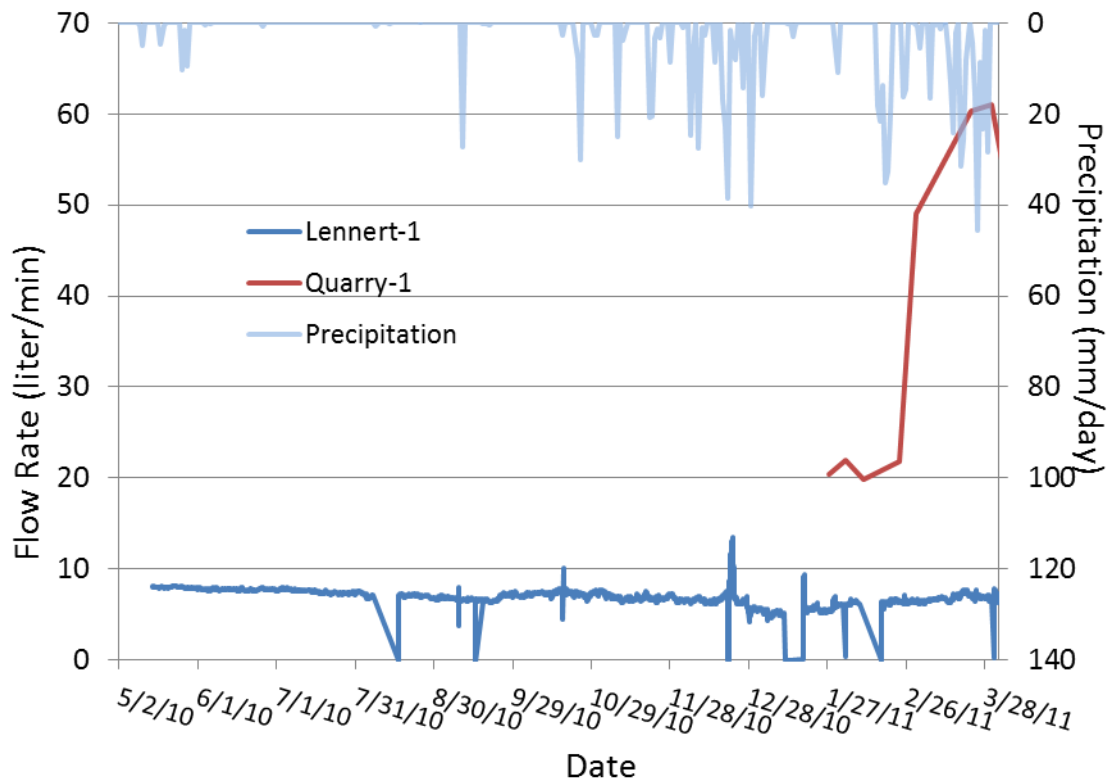


Figure 5-23. Flow-rate fluctuations at the outfalls of the Lennert-1 and Quarry-1 hydraugers.

6 Geochemical Investigation

6.1 Introduction

Our main goal in this project to develop an effective characterization methodology of fault-zone hydrology. As is often the case with any characterization effort, available hydrological data were limited both spatially and temporally. We thus needed to utilize all available and relevant data and integrate them to develop a reliable predictive model, based on the correct conceptual model of the fault-zone hydrology. We examined the geomorphology of the area and conducted geologic mapping and geophysical surveys. We drilled four boreholes (WF-1~4) and carefully examined the cores. In these boreholes, we conducted hydraulic tests to estimate transmissivity. We also gathered pressure and flow data from SSL-1 and pressure data only from SSL-2. We also measured the outflow rate from the outfall of historic hydraugers. These [sources of information are not yet enough to characterize the hydrology of the Wildcat Fault definitively. At this juncture, we are not yet certain if or where the main fault plane of the Wildcat is.

In this section we describe the geochemical analysis of water and rock, which may help in estimating the hydrologic properties of the Wildcat.

6.2 Water Chemistry

We have analyzed the chemistry of the water samples taken from WF-1, WF-2, and SSL-1. Table 6-1 shows the dissolved metal concentrations analyzed by ICP-MS, and Table 6-2 shows other chemical analysis results, including the pH and the concentration of carbonates and sulfates. (In these tables, differences of over or near one order of magnitude are highlighted in yellow.) As can be seen from the tables, the waters from the three boreholes appear to have distinct chemistries.

As can be seen in Table 6-1, the water from WF-1 has a much higher concentration of such metals as magnesium, aluminum, calcium, and strontium as compared to those of WF-2, while the concentration of titanium, chromium, and iron are much lower. Table 6-2 shows that some chemical properties, such as pH and electrical conductivities, are similar among the three waters, while differences in the concentration of carbonates and sulfates stand out between WF-1 and WF-2. In fact, the water in WF-1 is much closer in chemical properties to SSL-1 than to WF-2. The causes for these differences are still unknown, but they may be related to the differences in the lithology that the these waters flow through, which may point to the possibility that there is

indeed a Wildcat Fault between WF-1 and WF-2, and that the fault separates the groundwater-flow pathway.

6.3 Isotopic Analysis of Carbonates

As was discussed in Chapter 4, the frequency of calcite veins and deformation zones are closely correlated. Some fifty samples of calcite veins were collected from the cores of WF-1~4. Most samples (31) were collected from WF-4, partly because it had the most occurrences of calcite veins and partly because the borehole diagonally penetrates the major fault zone, because it is an inclined borehole. Thin-section analysis of some of the samples can be found in the respective sections in Chapter 4. We have conducted isotopic analysis, specifically of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios, on these samples.

Figure 6-1 shows the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios along the depth (linear length) of WF-4. Lower $\delta^{18}\text{O}$ values (left y-axis) represent approximate equilibrium with present-day groundwater at approximately -6.6‰. This is a possible indication that the zones at 82 m (~268 ft), 137m (451 ft), 161 m (~535 ft), 181 m (595 ft) and 201 m (660 ft) depths represent active fluid-flow zones. The lower $\delta^{13}\text{C}$ values (right y-axis) of carbonates approach isotopic equilibrium with measured $\delta^{13}\text{C}$ values of groundwater dissolved inorganic carbon (~ -7‰), which is consistent with recent deposition. The source of the high $\delta^{13}\text{C}$ values (>5‰) is not clear at this time.

These samples were taken from the cores where cores were recovered. Recall that there were many sections in WF-4, particularly at depths deeper than 150 m (500 ft). Thus, the estimated locations of the active fluid-flow zones may not be exact. Nonetheless, the fact that there were considerable differences in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios across the Wildcat Fault means that the fault may have moved at different times, and that the major deformation zone below 180 m, identified through the core analysis, may be relatively young.

6.4 Hexadiagram

Kiho et al. (2011) analyzed water samples from the boreholes and hydraugers, specifically from WF-1, WF-2, SSL-1, MW74-92-12, MW74-94-7, Lennert, and BGS-2, whose locations are shown in Figure 6-2. The latter three are hydraugers. Analysis results are shown in Table 6-3. The hexadiagrams of these waters superimposed on the area topography map is shown in Figure

6-3. Based on the diagrams, Kiho et al. concluded that SSL-1 is in the recharge zone, WF1~3 is in the transitional zone, and MW wells are in the discharge zone.

6.5 Groundwater Ages

Kiho et al. (2011) analyzed waters from the abovementioned boreholes and hydraugers for concentrations of tritium, ^{14}C , and CFCs, to estimate the ages of the groundwater. Figure 6-4 shows the ages of the water from each location. Based on the ^3H and ^{14}C concentrations in WF-1 and WF-2 that were similar, they concluded the waters from these boreholes are relatively old (65 yrs) compared to those from SSL-1 and BGS-2, which suggested 1~5 yrs. The water age from MW74 holes and Lennert were considered to be in between (18–26 yrs), with these ages mainly based on the tritium concentrations, because CFSs and ^{14}C showed mixed and/or inconclusive results.

6.6 Groundwater Flow Direction

Based on the hexadiagram analysis and age dating discussed above, Kiho et al. (2011) arrived at a conceptual model of the groundwater flow in the study area (shown in Figure 6-5). They postulated that the water starts from the SSL-1 area, where the age appears to be very young, and travels to the elevation of WF boreholes, whose ages are ~65 yrs. The groundwater level decreases with the elevation. Although the waters in WF-1 and WF-2 appear to have similar ages, the hexadiagram suggests that the water evolves from a Ca-HCO_3 type in SSL-1 to a Na-HCO_3 type starting from SSL-1 through WF-1 and to WF-2, as shown in the figure.

Although the model corroborates with multiple threads of evidence, Kiho et al. also suggested the possibility that the water pathways that flow through WF-1 and WF-2 may be separate, because the chemical composition between the two boreholes are different.

6.7 References

Kiho, K., Ueta, K., Miyakawa, T., Hasegawa, T., Tanaka, S., Ito, H., Hamada, M., Tsukuda, K, 2011, CRIEPI Technical Report, Survey and Analysis related to Development of Hydrologic Characterization Technology of Fault Zones.

Table 6-1. ICP-MS results of dissolved metals in WF-1, WF-2 and SSL-1 water ($\mu\text{g/L}$)

	Na	Mg	Al	Si	K	Ca	Ti	V	Cr	Fe	Cu	Zn	Sr	Zr	La	Tl	Pb	Th
WF1	135,133	31,470	67.0	9,213	5,273	36,179	3.09	1.33	0.420	9.11	59.5	10.6	1,631	0.36	0.007	<0.01	<0.1	0.034
WF2	324,025	913	1,697	12,947	1,906	3,625	97.8	10.6	6.930	623	229	47.2	85.1	2.05	0.208	0.023	0.659	0.103
SSL1	31,622	25,581	55.5	13,834	862	38,220	1.85	15.3	1.016	10.2	15.7	20.8	490	0.08	0.007	<0.01	<0.1	0.027

Table 6-2. Other notable chemistry in WF-1, WF-2, and SSL-1 waters

	Bicarbonate (mg/l)	Carbonate (mg/l)	Chloride (mg/l)	Nitrate/Nitrite as NO ₃ (mg/l)	Sulfate (mg/l)	pH	Electrical Conductivity @25°C (μS/cm)	Total Dissolved Solids @180°C (mg/l)
WF-1	480	<2.5	17	8.3	94	7.8	955	560
WF-2	680	24	19	8.1	15	8.7	1180	790
SSL-1	200	<2.5	29	<0.4	51	8	500	300

Table 6-3. Major dissolved iron and ^2H and ^{18}O isotope ratios by Kiho et al. (2011)

サンプル名	採取日	pH	EC mS/cm	温度 °C	Na mg/L	K mg/L	Mg mg/L	Ca mg/L
WF-1	2009/12/16	8.27	N. M	N. M	127	4.06	32.0	40.1
WF-2	2010/02/19	8.43	N. M	N. M	314	1.07	0.65	2.2
SSL-1	2010/09/08	8.08	0.43	18.2	29	0.53	26.9	39.3
Lennert	2010/09/08	8.30	0.74	17.7	162	0.62	13.8	20.2
BGS	2010/09/09	7.80	0.15	19.9	11	0.55	3.36	14.2
BGS-2	2010/09/09	7.75	N. M.	N. M.	140	0.95	97.4	75
MW74-94-7	2010/09/10	7.97	1.9	24.7	395	2.41	26.5	44.1
MW74-92-13	2010/09/10	8.26	2.2	20.5	565	3.21	3.01	13.4

サンプル名	Cl mg/L	SO4 mg/L	HCO3 mg/L	F mg/L	Br mg/L	NO3 mg/L	δD ‰	$\delta^{18}\text{O}$ ‰
WF-1	18.2	92.5	475.80	0.10	0.04	0.45	-42.3	-6.5
WF-2	19.7	16.4	757.01	0.33	0.05	0.11	-42.0	-6.2
SSL-1	30.0	51.5	201.79	0.09	0.13	<0.01	-46.4	-6.7
Lennert	28.7	78.1	404.55	0.19	0.12	0.19	-39.1	-6.2
BGS	6.46	19.6	52.21	0.78	0.15	0.65	-86.1	-11.7
BGS-2	68.9	220	644.16	0.10	0.38	<0.01	-40.4	-6.2
MW74-94-7	77.2	331	797.27	0.16	0.26	1.17	-39.8	-6.0
MW74-92-13	70.8	369	966.85	0.08	0.17	0.02	-38.4	-6.0

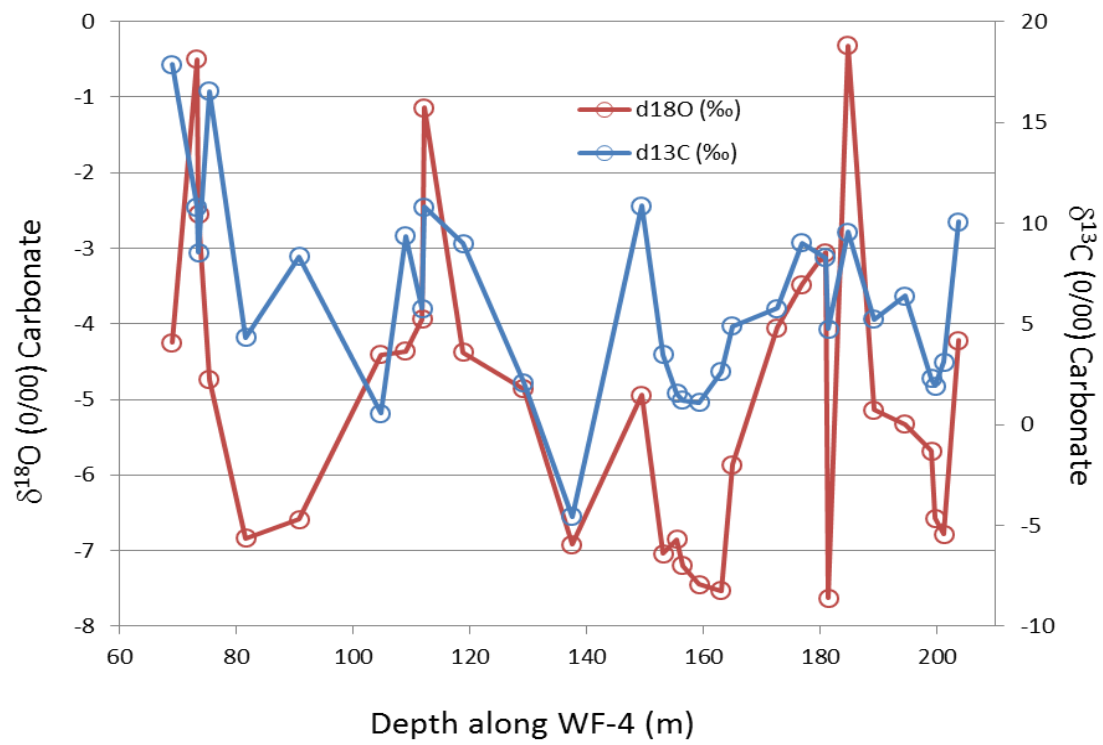


Figure 6-1. Carbonate isotopic distribution along WF-4.

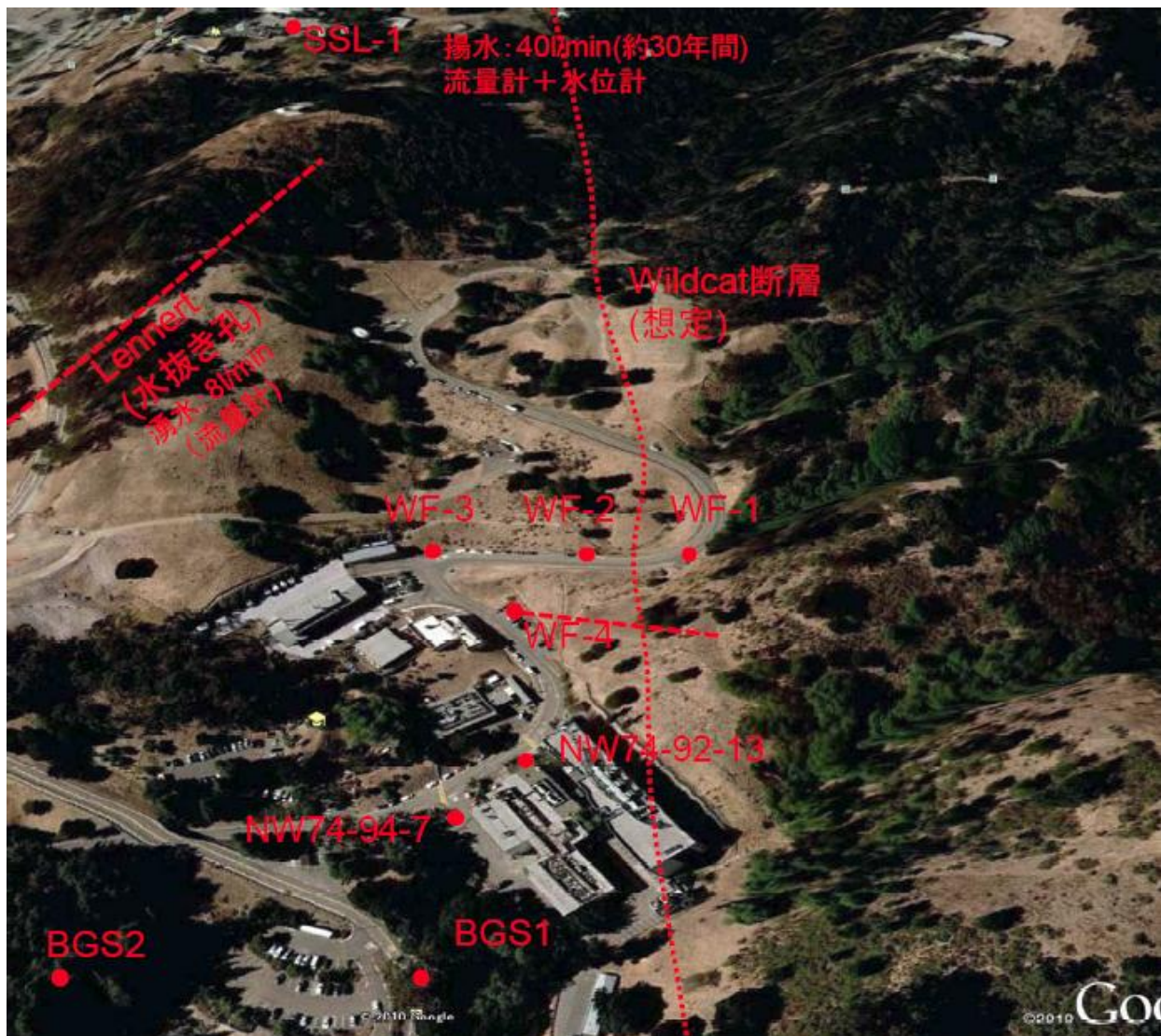


Figure 6-2. Bird's eye view of the study area showing the boreholes where water samples were collected (Kiho, et al., 2011).

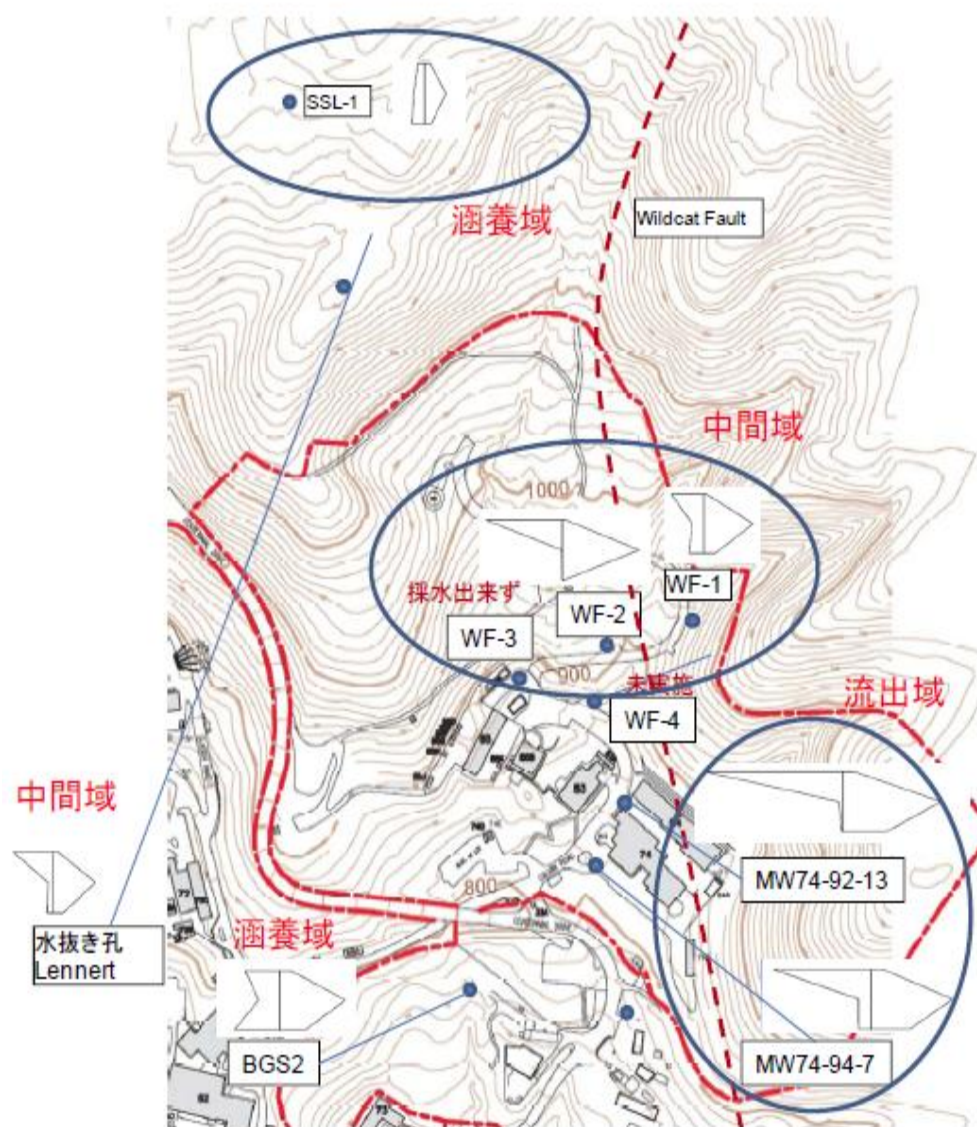


Figure 6-3. Hexadiagram of the waters form the boreholes near the study area (after Kiho et al., 2011).

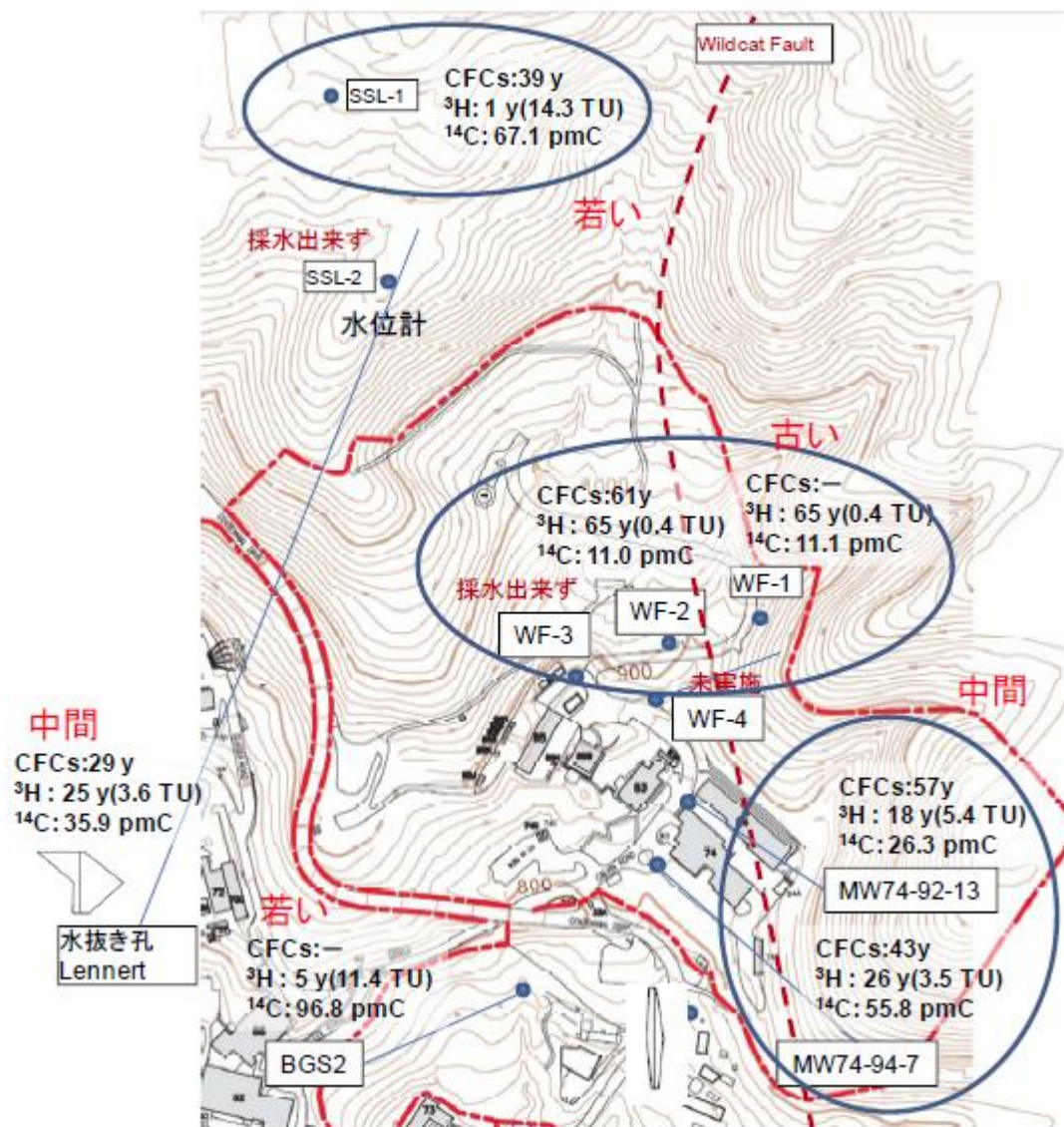


Figure 6-4. Estimated ages of the groundwater sampled from the boreholes in the study area analyzing CFCs, ^3H and ^{14}C concentration (after Kiho et al., 2011).

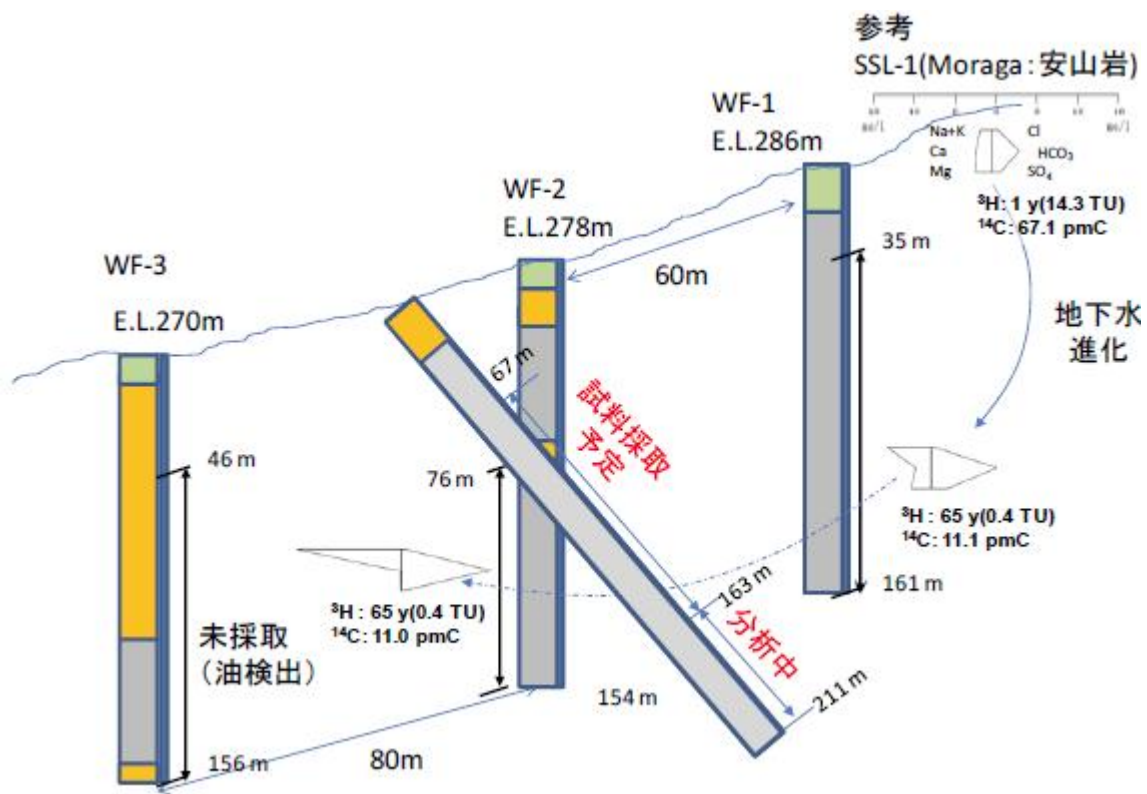


Figure 6-5. Conceptualization of groundwater flow direction in the WF borehole area (Kiho et al., 2011).

7 Hydrologic Modeling

7.1 Introduction

The primary objective of the Fault-Zone Hydrology Project is to develop an effective and reliable methodology for fault-zone characterization. To this end, we have been conducting field investigations of the Wildcat Fault, starting with a literature survey, aero-photo-based geomorphological studies, geologic mapping, geophysical surveys, trenching, borehole drilling, and hydraulic testing in the LBNL area. According to the systematized investigation steps proposed in Karasaki et al. (2009) and Kiho et al. (2011), a geologic model would be constructed as information and data gathered by field investigations started to come in. Then the geologic model would become the basis of a hydrologic model that would honor hydraulic data obtained by passive and active hydrologic tests. The hydrologic model would then be used to make predictions of the outcome of the next stage of investigations and to identify data holes, if any. Thus, the field investigation, geologic model, and hydrologic model would form a circular feedback loop.

In this section, we outline the preliminary effort of constructing the geohydrologic model of Strawberry Canyon, which is a basin within our current study area. Our goal is to understand the role of Wildcat Fault in controlling natural-state groundwater flow. One way to assist in developing this understanding is to develop a numerical model of groundwater flow in the basin containing the fault. Our strategy for flow modeling is to calculate the natural-state flow field and also to investigate the transient interwell response to drilling, well-tests, long-term pumping, and precipitation.

7.2 Data available

A great deal of site characterization data is available for construction of the Strawberry Canyon model, including

- Geologic map (Graymer, 2000; Karasaki et al., 2009 and 2010, Kiho, et al., 2011)
- Digital elevation model (up to 3 m resolution)
- Surface fault location in trenches (TR-1~5)
- Three vertical wells with geophysical log information and permanent pressure and temperature sensors at 5 depths (WF-1~3)
- One diagonal well crossing the fault (WF-4)
- Two deep wells with water-level and pumping rate data (SSL-1 and 2)

- Flow rates for three existing wells/hydraugers (Lennert, BG-1, Quarry)
- Many shallow wells with water-level data and permeability estimates (often from slug tests) from the LBNL Site Environmental Remediation Project
- Precipitation record
- Air-temperature record

7.3 Numerical Simulator

The TOUGH2 code is used for the numerical simulations. TOUGH2 is a general purpose numerical simulator for fluid flow and heat transport in geological media (Pruess et al., 1999). Preliminary simulations use the equation-of-state module EOS9, which considers single-phase liquid water or a two-phase water/air system in which air is a passive spectator (a common soil-physics approximation) and temperature does not change. Results from TOUGH2/EOS9 simulations include steady-state and transient hydraulic head distributions, infiltration rates, and flow rates from various outlets in the model (creeks, springs, hydraugers). In the future, we plan to use equation-of-state module EOS3, which considers fully coupled multiphase flow of water, air, and heat. Temperature profiles in wells can provide signatures of upflow or downflow of groundwater.

7.4 Model Domain

Figure 7-1 shows a 3 m resolution digital elevation map (DEM) of the Berkeley Hills area. The map is shaded to show the topographic reliefs, so that basins are easily identified. Note that our study area is in a well-defined basin, Strawberry Canyon. We chose the model area to coincide with the basin (Figure 7-2), which covers the Strawberry Creek watershed east of the Hayward Fault. The model is roughly diamond-shaped, with diagonal lengths 3 km in the E-W direction and 2.4 km in the N-S direction. Boundaries to the northwest, northeast, and southeast were determined by following ridgelines on the DEM. The surface trace of the Hayward Fault forms the southwest boundary of the model. It follows a strong break in slope between the hilly terrain of the model and the much gentler slope that extends to San Francisco Bay. The elevation along this boundary is gently undulating, with several creeks running NE-SW crossing the fault. The rectangular area with no streets shown is the University of California, Berkeley Campus. Note that there are a couple of creeks running EW, which are the continuation of Strawberry Creek displaced by the Hayward Fault.

In the vertical direction, the model extends from the ground surface, which ranges from about 120 masl to 540 masl, to an elevation of -1100 masl. No wells extend any deeper than 0 masl, and the model is quite coarse below this depth, but the large vertical extent is provided so that the model horizontal-to-vertical aspect ratio is near one, in order to avoid artificially constraining the natural groundwater flow lines.

7.5 Boundary Conditions

The boundary conditions for the preliminary version of the model are as follows.

- Ridgelines: closed (symmetry lines between watersheds)
- Hayward Fault: closed, except at surface, which provides outflow from model
- Bottom: closed
- Top: constant pressure at $P=P_{\text{atm}}$ (allows infiltration)

Conditions at the bottom boundary are unknown, but the boundary is purposefully placed far below the depths of the boreholes, so as not to unduly influence groundwater flow. Our initial conceptualization for major faults such as the Hayward Fault is that at depth, they provide barriers to flow across the fault. This hypothesis will be tested by trying different flow conditions at this boundary. When the water level is within one gridblock thickness of the ground surface (currently 30 m), then the constant-pressure top-boundary condition is appropriate, and essentially eliminates the vadose zone from the model. For thicker vadose zones such as may be encountered at higher elevations, a saturation boundary condition, which enables modeling of the vadose zone, will be investigated as well.

7.6 Grid

The preliminary numerical grid is constructed of 23 horizontal layers, each with the same lateral grid spacing. Lateral grid spacing is variable, with 15 m lateral resolution near the wells, and a gradually coarsening grid beyond that (Figure 7-3). The fine portion of the grid (Figure 7-4) has a rectangular geometry, with one axis aligned with the presumed Wildcat Fault, to enable more accurate representation of the fault. Voronoi tessellation is used to create the grid using the program WinGridder (Pan, 2008). The layers are then truncated where they intersect the DEM. Each full layer has 6201 gridblocks, and the total number of gridblocks for the model is 93,735. In the upper portion of the model (above the bottom of the deepest well), layer

thickness is 30 m. In the lower portion of the model, layer thickness gradually increases. Figure 7-5 shows a perspective view of the entire grid, as a scatter plot with a square representing each grid block.

7.7 Natural-state Head Distribution

Results of a preliminary natural state simulation assuming all gridblocks have the same properties are shown in Figure 7-6–Figure 7-10. These simulations illustrate the effect that topography has on the hydraulic head distribution. This is not a complete description, because the actual hydraulic head distribution is strongly influenced by rock properties and the presence of faults. Additionally, the existence of a vadose zone as well as past man-made pumping and injection events, may be important.

Figure 7-6–Figure 7-8 show several views of the simulated hydraulic head distribution by showing scatter plots of the gridblocks. Seeing the entire head distribution helps us understand the features that control the groundwater flow system, but head profiles in only a few wells are all that can be directly compared to field observations. Figure 7-9a shows the simulated head profiles in wells WF-1, WF-2, WF-3, SSL-1, and SSL-2. The head profiles observed in the three WF wells are shown in Figure 7-9b. Neither the shape nor the magnitude of the simulated head profiles matches the observed profiles, indicating that the features not included in the model are important in controlling groundwater flow.

Figure 7-10 shows the surface flow rate into the model (infiltration, positive) and out of the model (surface discharge into springs and creeks, negative). The magnitude of the values shown are not expected to be realistic, because rates are very sensitive to the permeability of near-surface soils and rocks, which may be much lower than the value assumed for the simulation (100 md). But the distribution of inflow and outflow is reasonable, with the largest inflow at high elevations and the largest outflow at the topographic low along the Hayward Fault boundary.

7.8 Features to include

The model presented so far represents just the first stage of model development. Key features to incorporate include:

- Representative permeabilities of geologic formations, as shown in Figure 7-11
- Wildcat and other faults
- Vadose zone where thicker than 30 m (primarily at high elevations)
- Pumping at well SSL-1, out flow at the Quarry well and other hydraugers
- Artificial water release at Botanical Garden
- Precipitation record, adjusted to determine infiltration rate

In addition to comparing model results for natural-state hydraulic head and flow rates, the transient responses of different wells to drilling and pump tests will be analyzed. Additionally, nonisothermal simulations will be done to predict temperature profiles in the Wildcat Fault wells.

7.9 Alternative Model

In the above discussion, we outlined our main modeling pathway using WinGridder (Pan, 2008) as the mesh generator and TOUGH2 code for simulation. In this section, we discuss our parallel effort of model development using PetraSim software, which allows for relatively quick model development. PetraSim also uses TOUGH2 as its simulation engine. PetraSim actually functions as a model development environment with an integrated mesh generator and an output visualization tool. Using this parallel approach to gain understanding of the effects and roles of the processes we listed in Section 7.8 above, we incorporate surface recharge rate based on the precipitation measurements, pumping at SSL-1, and discharge from the outfalls of hydraugers.

7.9.1 Model Area and Boundary Conditions

The area modeled is essentially the same as that discussed in Section 7.4, except for the model's southwest corner, where the boundary takes the northernmost ridge in the alternative model as opposed to that shown in Figure 7-2. The vertical extent is -500 m ASL, as opposed to -1000 m in the main model. The boundary conditions are the same as discussed in 7.5, except for the surface boundary condition. Figure 7-12 illustrates the model domain with surface topography. The locations of the boreholes are also shown.

7.9.2 Geologic Model

Because the available geologic maps are two dimensional, some assumptions have to be made regarding the subsurface geologic structure. Kiho et al. (2011) refined the geologic map proposed by Graymer (2000) through conducting additional field geologic mapping along the Wildcat and building upon Karasaki et al. (2009), in addition to using the new information obtained from the cores from WF-3 and WF-4. Kiho et al. proposed the geologic cross sections

shown in Figure 7-15. At the scale of the WF borehole cluster, we again refer to the structural model proposed by Kiho et al. (2011), as shown in Figure 7-16. In fact, the Kiho et al. fault structure model and the “Model B” discussed in Chapter 4 have much in common. The current geologic model used in the hydrologic simulation can be seen in Figure 7-17. It essentially incorporates the Fb, Fc, and Fd structures proposed by Kiho et al.

Currently, Fb is modeled as the geologic boundary between Orinda Fm./San Pablo Gr. And the Claremont Fm. without any thickness or independent permeability. Fc is modeled as a permeable structure, while Fd is modeled as a dual structure, with a low permeability core on the west side of the plane and a high permeability zone on the east side. All the features are treated as a plane.

7.9.3 Grid and Permeabilities

Based on the geologic model shown in Figure 7-17, we constructed numerical grids with two different grid spacings: a coarse grid with 15,380 elements and a fine grid with 61,040 elements. The former is used to generate a quick simulation turnaround, so that the manual trial-and-error approach can be employed. The fine grid is constructed after developing some understanding about the effects of such parameters as the amount of recharge and fault zone properties on the overall outcome of the simulation. We used iTOUGH2 (Finsterle, 1999) to search for the optimum permeability values for different materials.

We assumed that there are two types of rocks in the Orinda Fm. and Claremont Fm. The Orinda Fm., observed in WF-2, WF-3, and WF-4, appears to be subhorizontal, whereas the same formation east of the Wildcat Fault is reported to be subvertical, as is the Claremont Fm. on the same side of the Wildcat (Geomatrix, 2008). In general, a sedimentary layer is anisotropic, with a lower vertical permeability than horizontal permeability, when it is in the original depositional state. Therefore, we expect a lower permeability in the vertical direction of the Orinda Fm. in the west and vice versa in the east. As for the Claremont Fm., we assumed that the Claremont to the west of the fault is made of a different material than that on the east of the fault.

7.9.4 Simulation Results

We initially simulated groundwater flow assuming a uniform permeability. We iterated just on the surface recharge rate, to see if the pumping rate of ~40 liters/min at SSL-1 could be sustained for a long duration (without pumping it dry) while matching the heads at WF boreholes.

Figure 7-13 shows one successful case in which the pumping was sustained indefinitely. Figure 7-14 shows the flow vectors in the uniform model. Note that they run primarily in the EW direction.

Using the coarse grid, we manually adjusted the permeabilities and recharge rate on the surface, depending on the rock type, until we got a reasonable match to the head profiles observed in WF-1, WF-2, and WF-3. We initially assumed that the Fd structure was only a high permeability feature. Without assuming a low permeability structure, we could not reproduce the observed head separation between WF-1 and WF-2, although we were able to duplicate the general pattern of decreasing head at depth (Figure 7-18). We then added another planar feature with low permeability juxtaposed to the high permeability feature, so that the Fd fault has a binary structure. Figure 7-19 shows the pressure contours with the low permeability feature between WF-1 and WF-2. Table 7-1 shows the final result of the optimized parameters, and Figure 7-20 shows the comparison between the data and the model prediction.

We then refined the mesh and quadrupled the number of elements. Finer mesh would allow a better rendition of fault planes, thus enhancing the continuity of the planar structure. It would probably take an even finer-resolution mesh to ensure that the faults are actually continuous in the model. In this regard, the localized mesh refinement discussed above would be better suited.

Table 7-2 shows the initial and final optimized values of permeability after the inversion analysis using iTOUGH2. Figure 7-21 shows the comparison between the observed data and the inversion results. The automated inversion algorithm in iTOUGH2 minimizes the objective function defined by the square difference between the data and the model prediction, obtained by using TOUGH2 as the forward simulator.

7.10 Conclusions

We developed a preliminary model of the Strawberry Canyon basin that incorporates most of the geologic features and faults identified thus far. We performed both manual and automated inversion analysis and produced reasonable matches between the observed head data and model predictions. It was found that a good match could be obtained by varying the recharge rate depending on the surface rock type from 0–3% of the average annual precipitation of ~1,000 mm for Orinda Fm. to >18% for the Moraga Fm.

7.11 References

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Table 7-1. Optimized permeability values for the coarse grid case

	Orinda		Claremont		Moraga	Great Valley	Fault Core	Fault Damage
	To _H	To _V	Tc _H	Tc _V				
K _x	8.0×10^{-16}	4.0×10^{-16}	1.0×10^{-14}	1.0×10^{-15}	7.0×10^{-15}	7.0×10^{-15}	1.0×10^{-17}	1.3×10^{-13}
K _y	8.0×10^{-16}	4.0×10^{-16}						
K _z	1.0×10^{-16}	8.0×10^{-16}						

Table 7-2. iTOUGH2 inversion of the permeability values for the fine grid case, with starting initial values and the optimized value

	Orinda		Claremont		Moraga	Great Valley	Fault Core	Fault Damage
	To _H	To _V	Tc _H	Tc _V				
Initial	1.0×10^{-16}	4.0×10^{-16}	2.0×10^{-14}	1.0×10^{-15}	7.0×10^{-15}	7.0×10^{-15}	1.0×10^{-17}	1.3×10^{-13}
Final Optimized	6.0×10^{-15}	4.9×10^{-18}	1.7×10^{-15}	1.0×10^{-11}	9.1×10^{-13}	2.5×10^{-14}	3.7×10^{-18}	3.0×10^{-14}

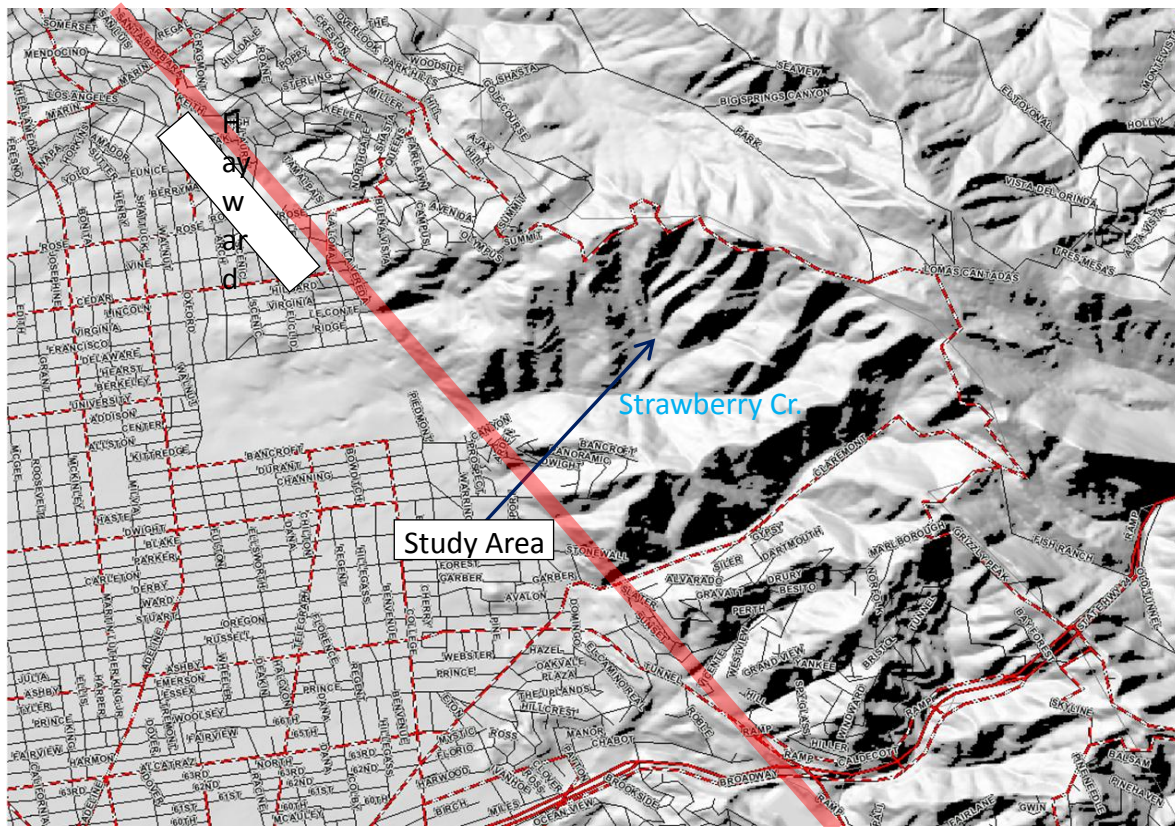


Figure 7-1. Shaded DEM map of the Berkeley Hills.

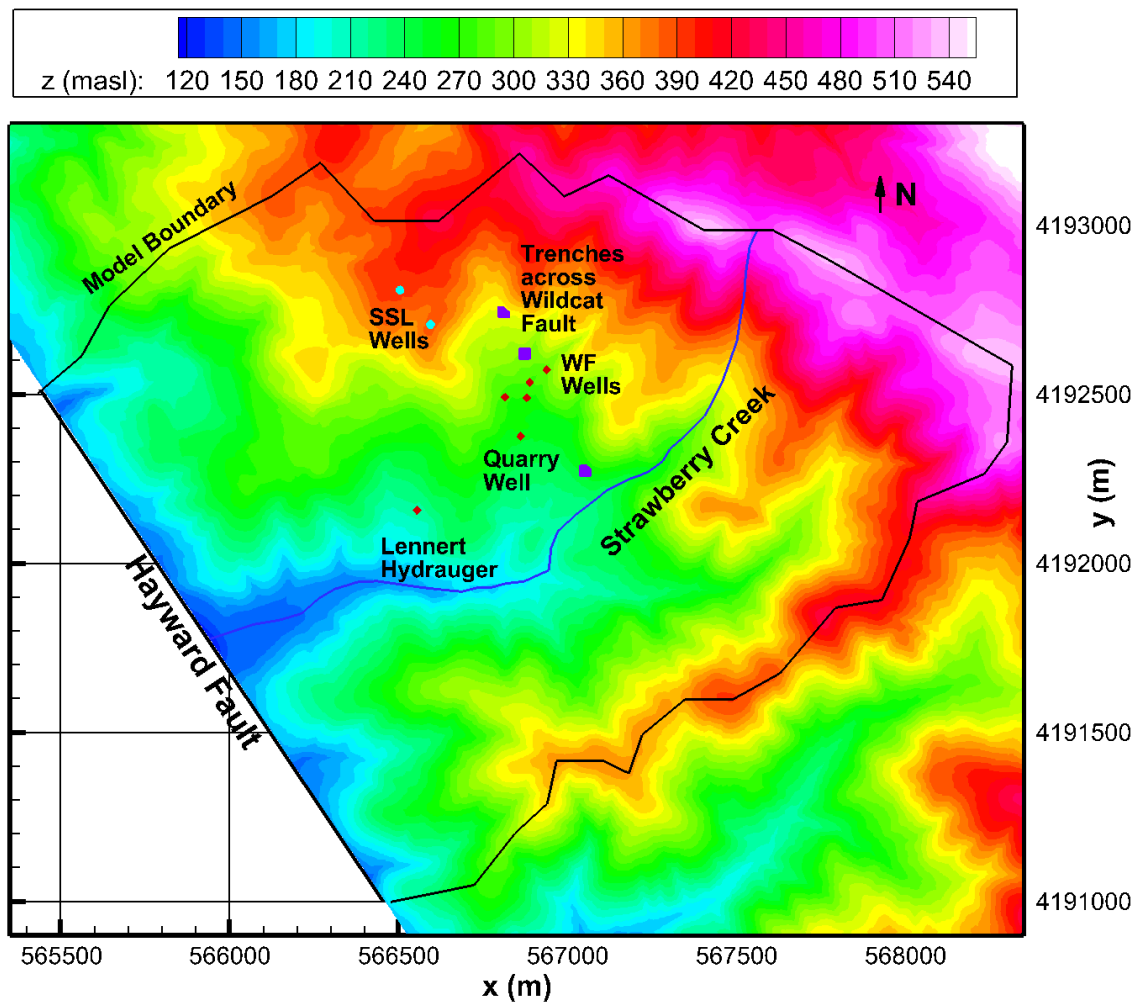


Figure 7-2. DEM with model boundary and various features shown: purple squares—trenches across the Wildcat Fault; red or cyan circles—wells.

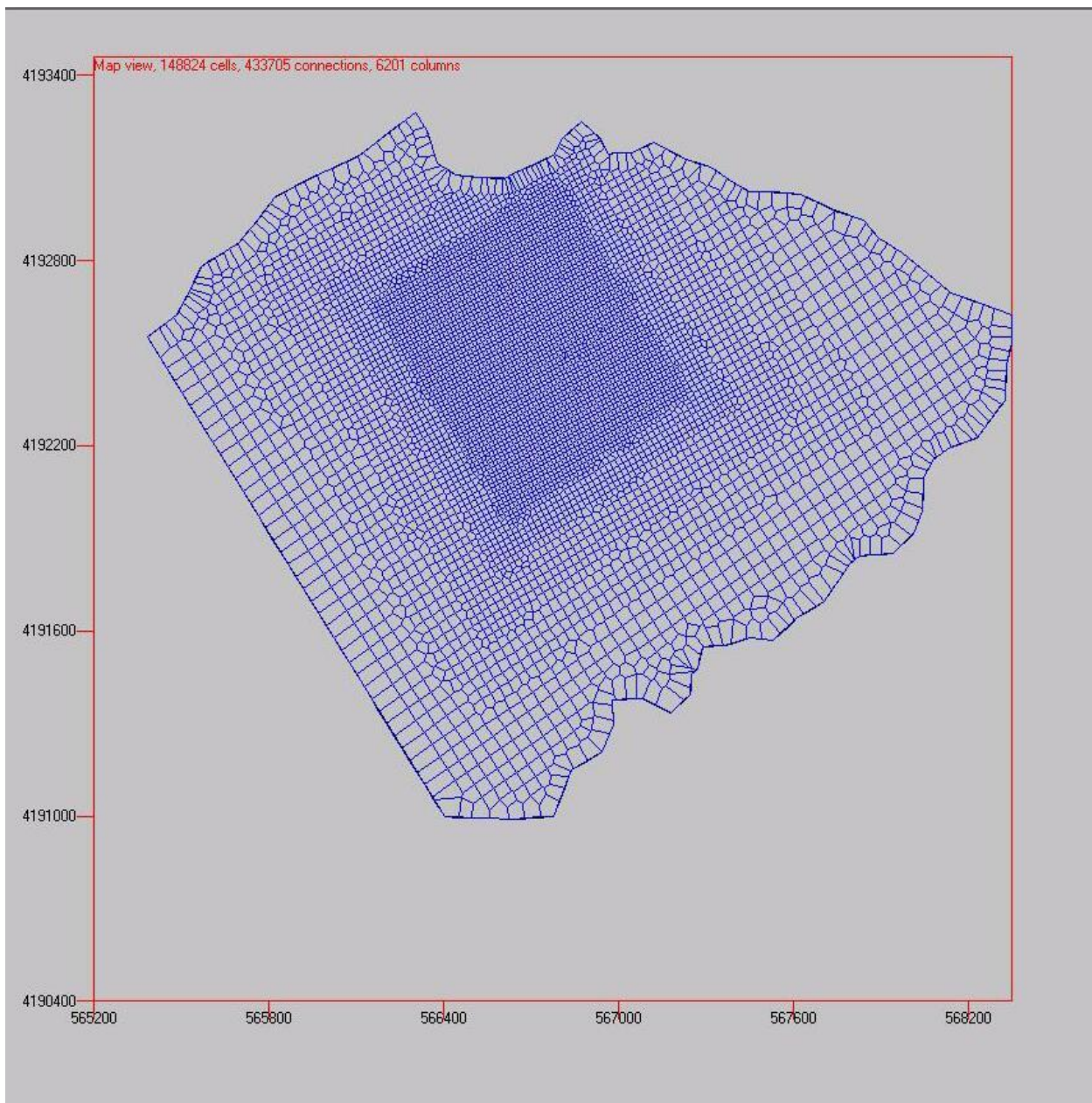


Figure 7-3. Plan view of computational grid, full domain.

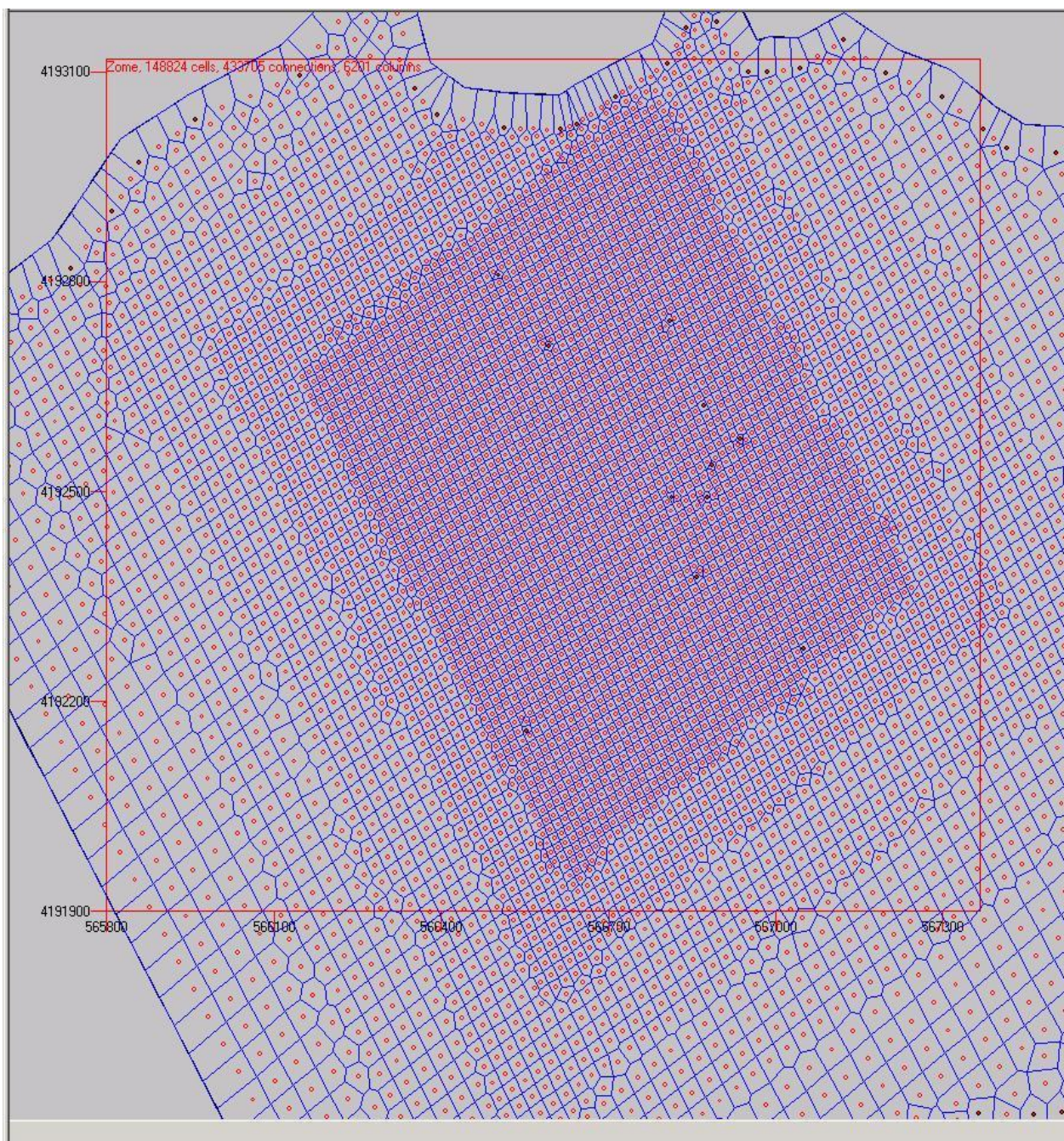


Figure 7-4. Plan view of computational grid, region around wells.

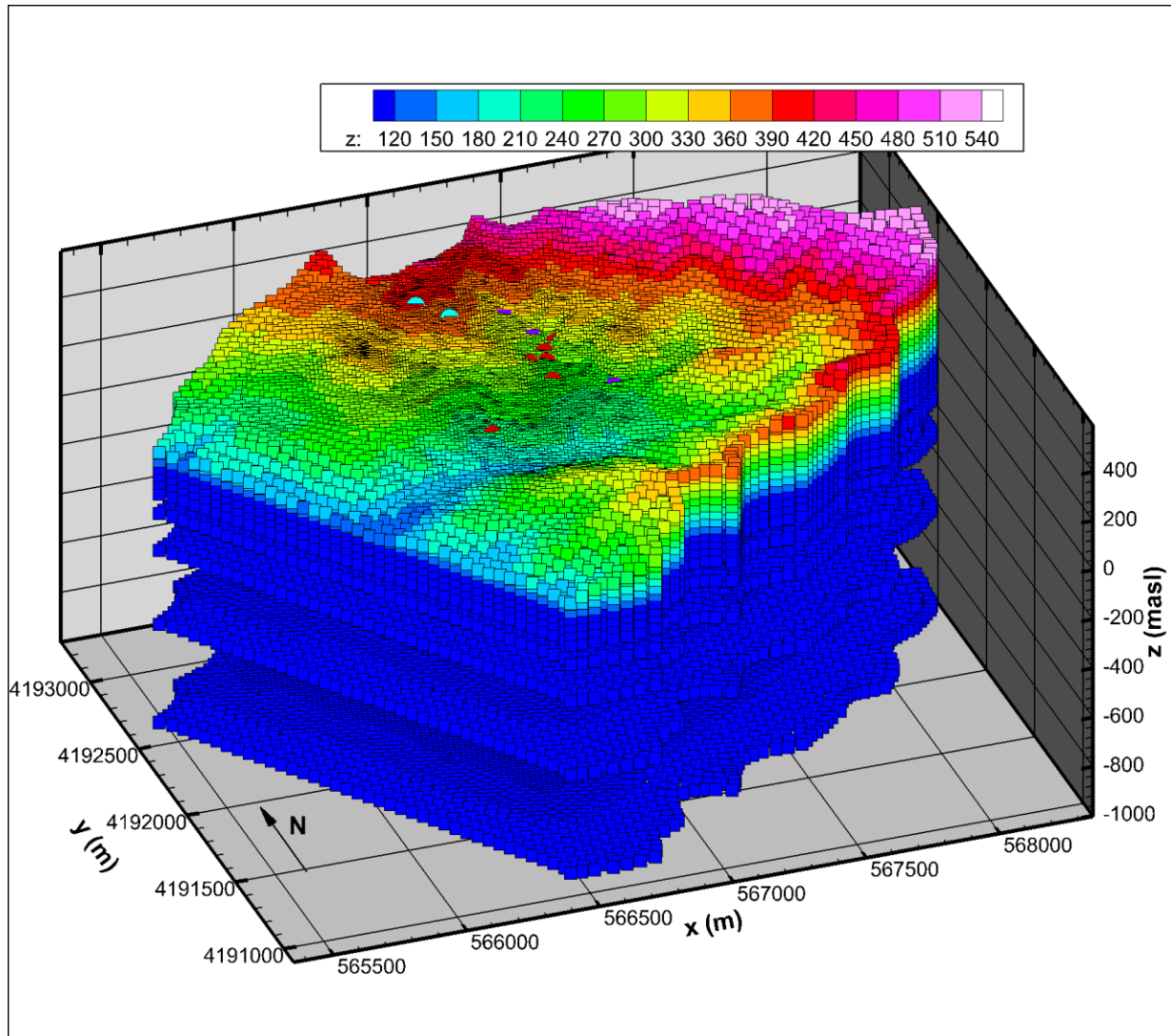


Figure 7-5. Perspective view of grid. The depth scale ends at 120 masl to enable details of the surface topography to be shown; the deepest model layer is centered at -930 masl.

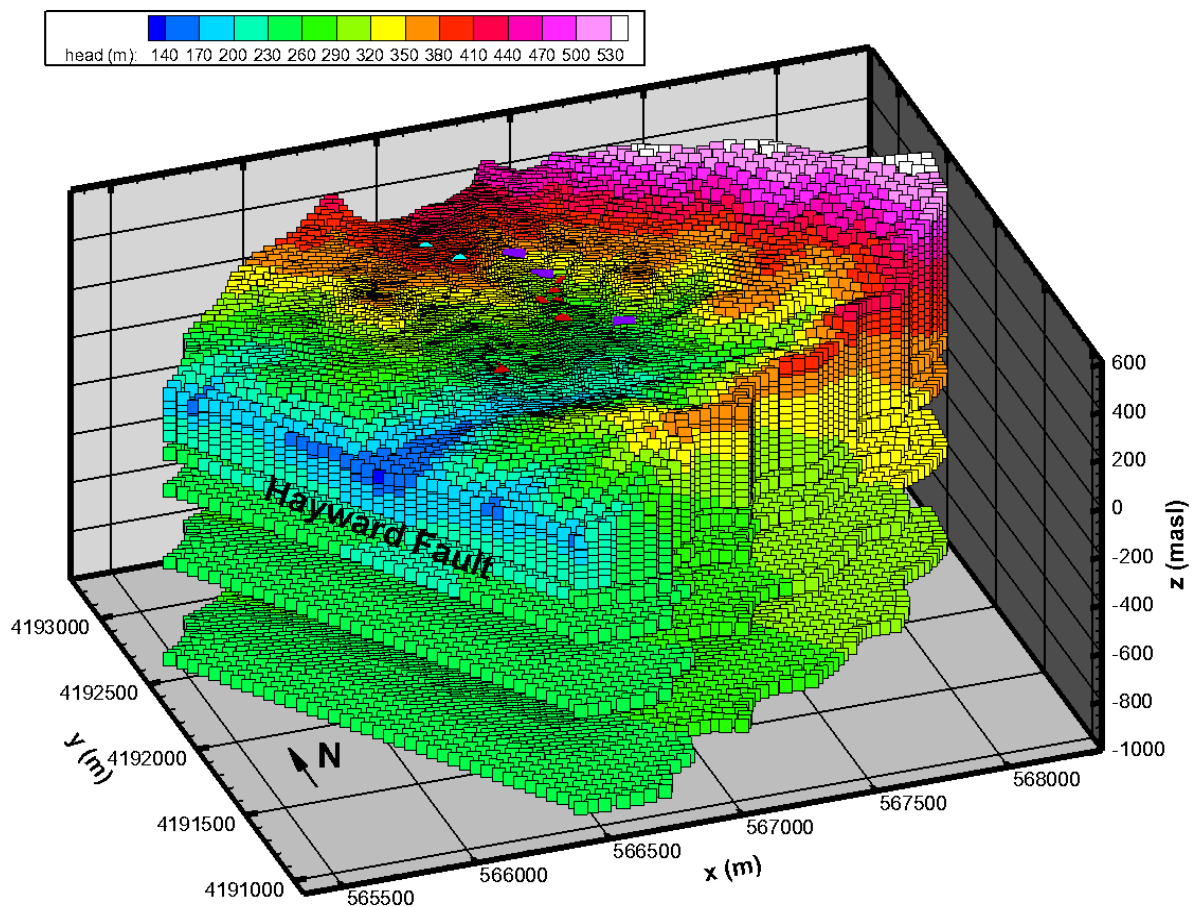


Figure 7-6. Perspective views of the natural-state head distribution for Case CJ, with a uniform permeability distribution. Full model.

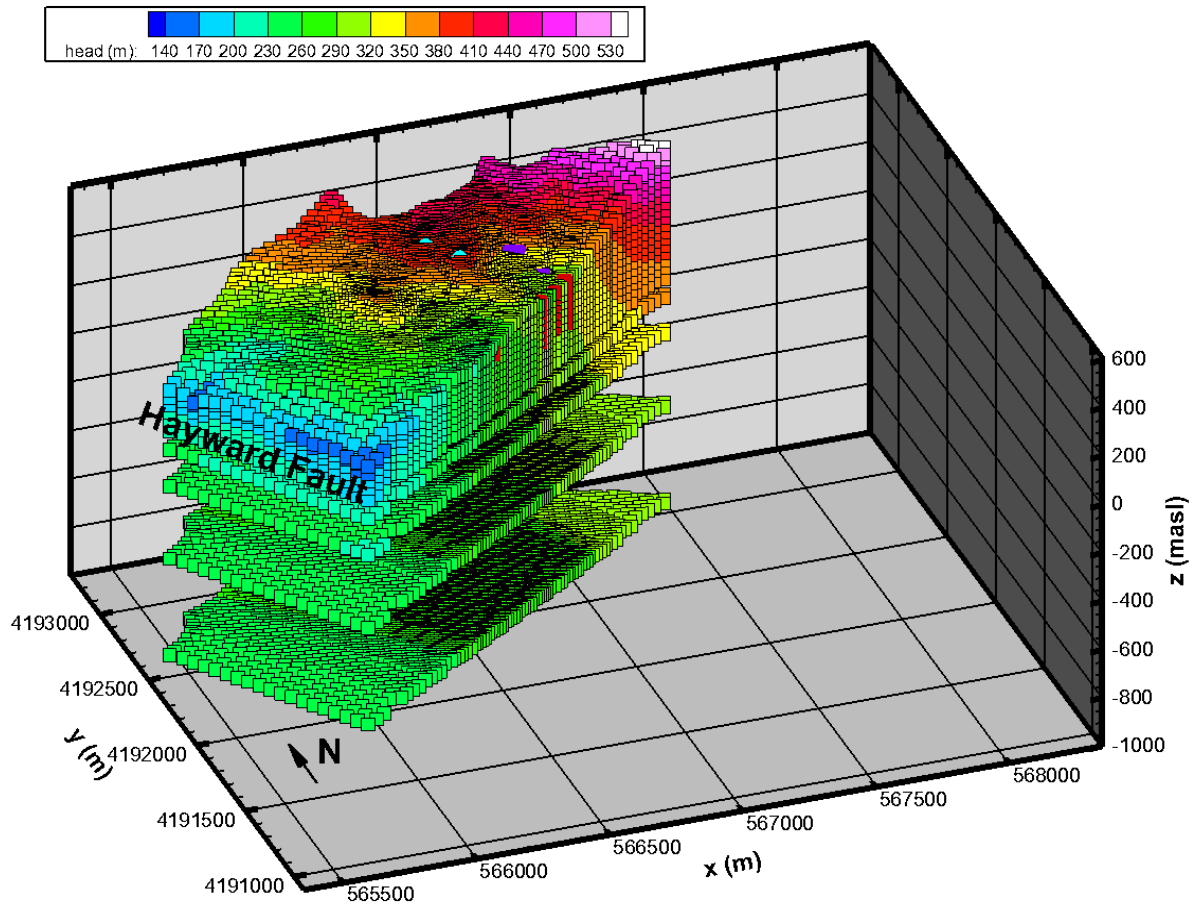


Figure 7-7. Perspective views of the natural-state head distribution for Case CJ, with a uniform permeability distribution. Cut-away view along line made by Wells WF-1, WF-2, and WF-3.

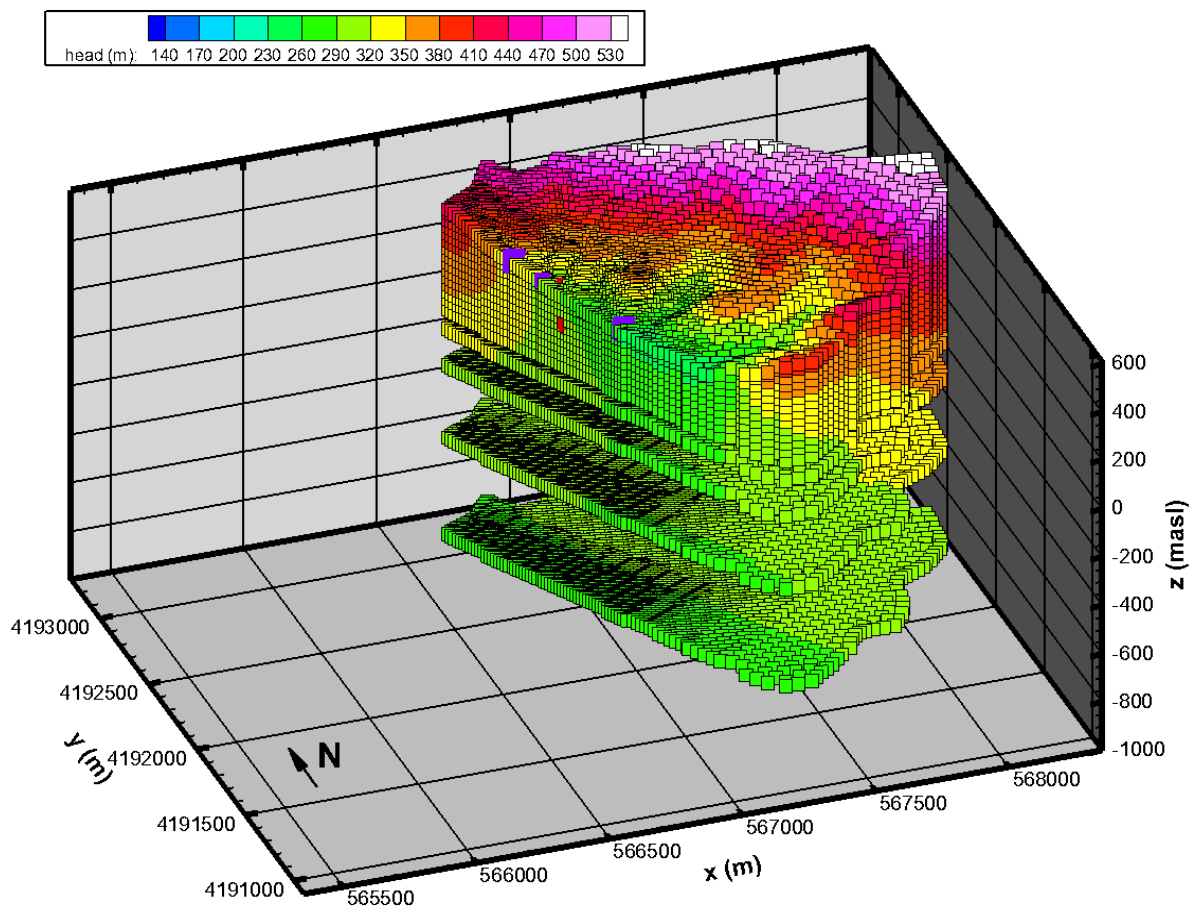


Figure 7-8. Perspective views of the natural-state head distribution for Case CJ, with a uniform permeability distribution. Cut-away view along Wildcat Fault.

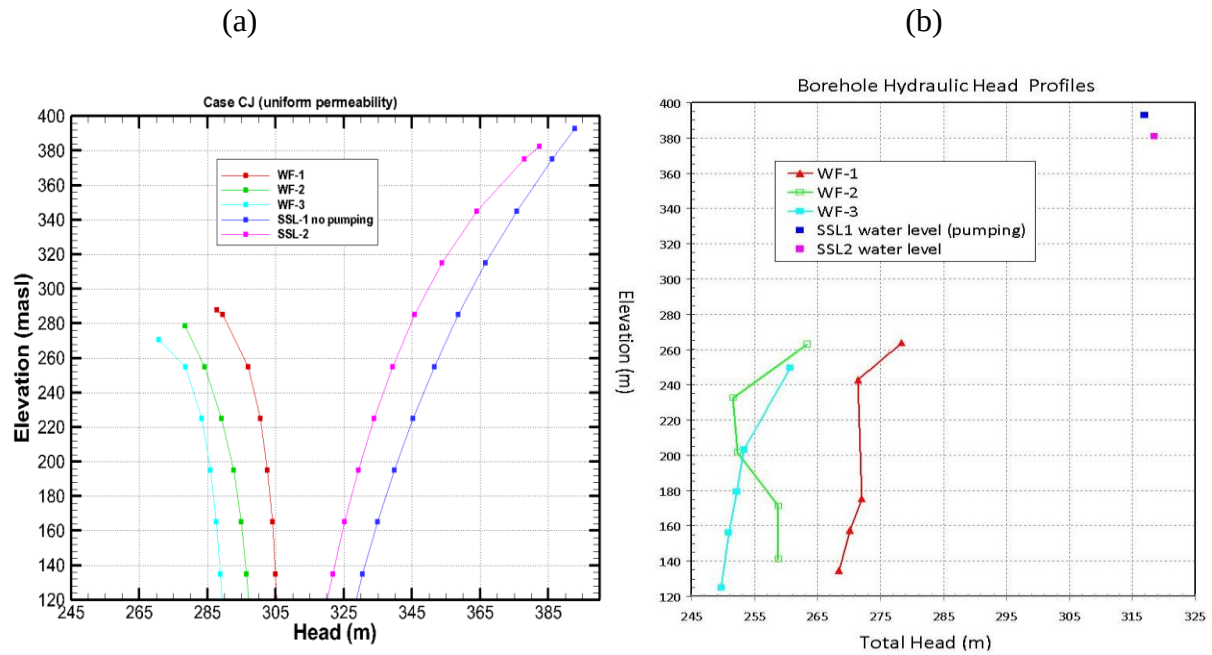


Figure 7-9. Hydraulic head profiles and water levels in WF and SSL wells (a) simulated results for case CJ, with a uniform permeability distribution; (b) field data. Note that Well SSL-1 is pumping continuously, but is not included in this preliminary version of the model.

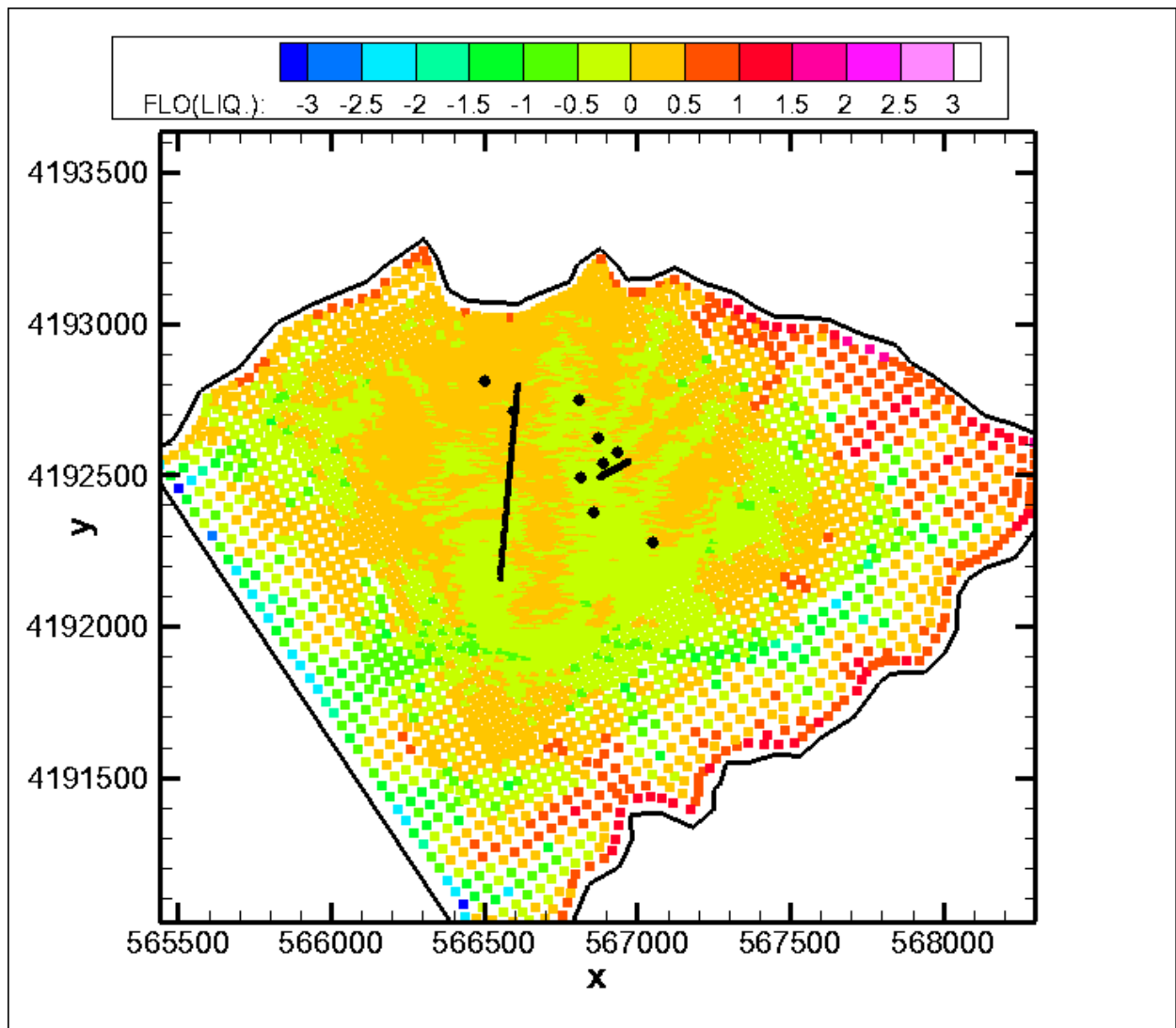


Figure 7-10. Surface flow rate for Case CJ with a uniform permeability distribution. Positive numbers represent infiltration and negative numbers represent surface discharge to springs and creeks. The locations of two directional wells projected onto the ground surface are shown as line segments, while vertical wells and trenches are shown as dots.

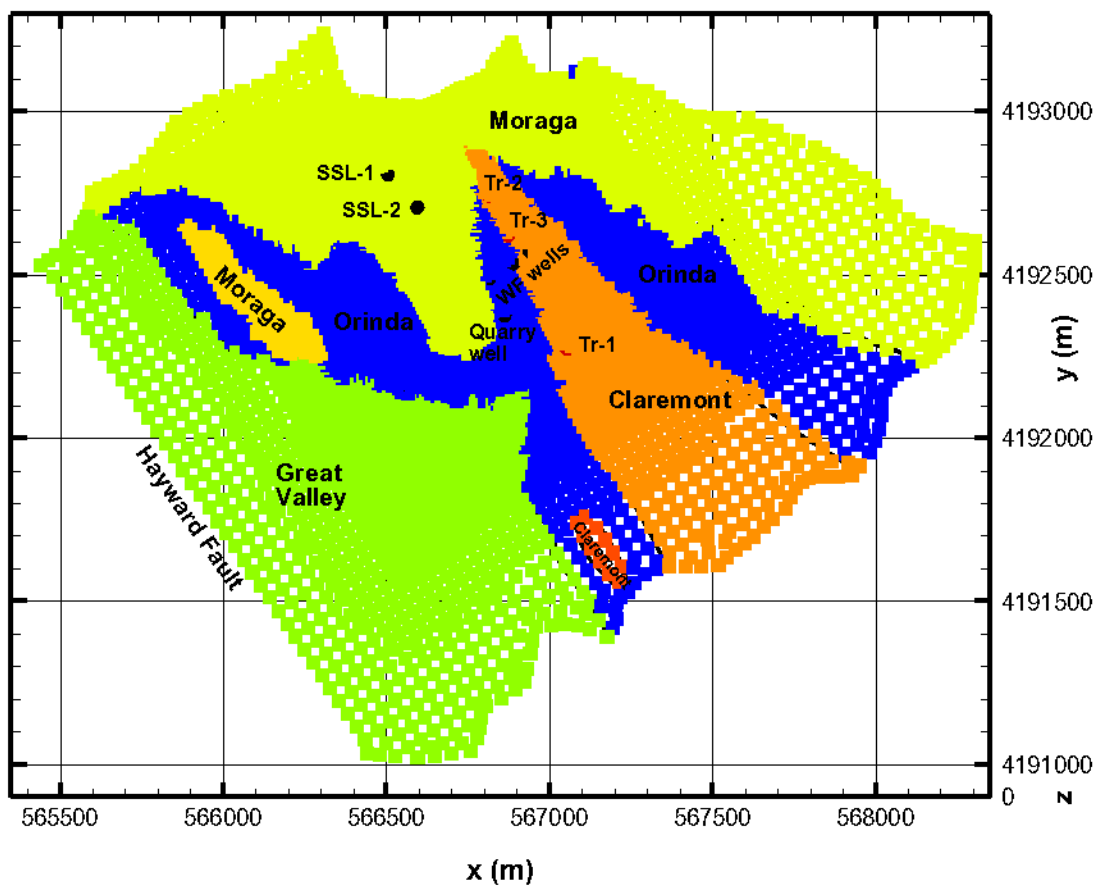


Figure 7-11. Geologic units to be assigned to the grid.

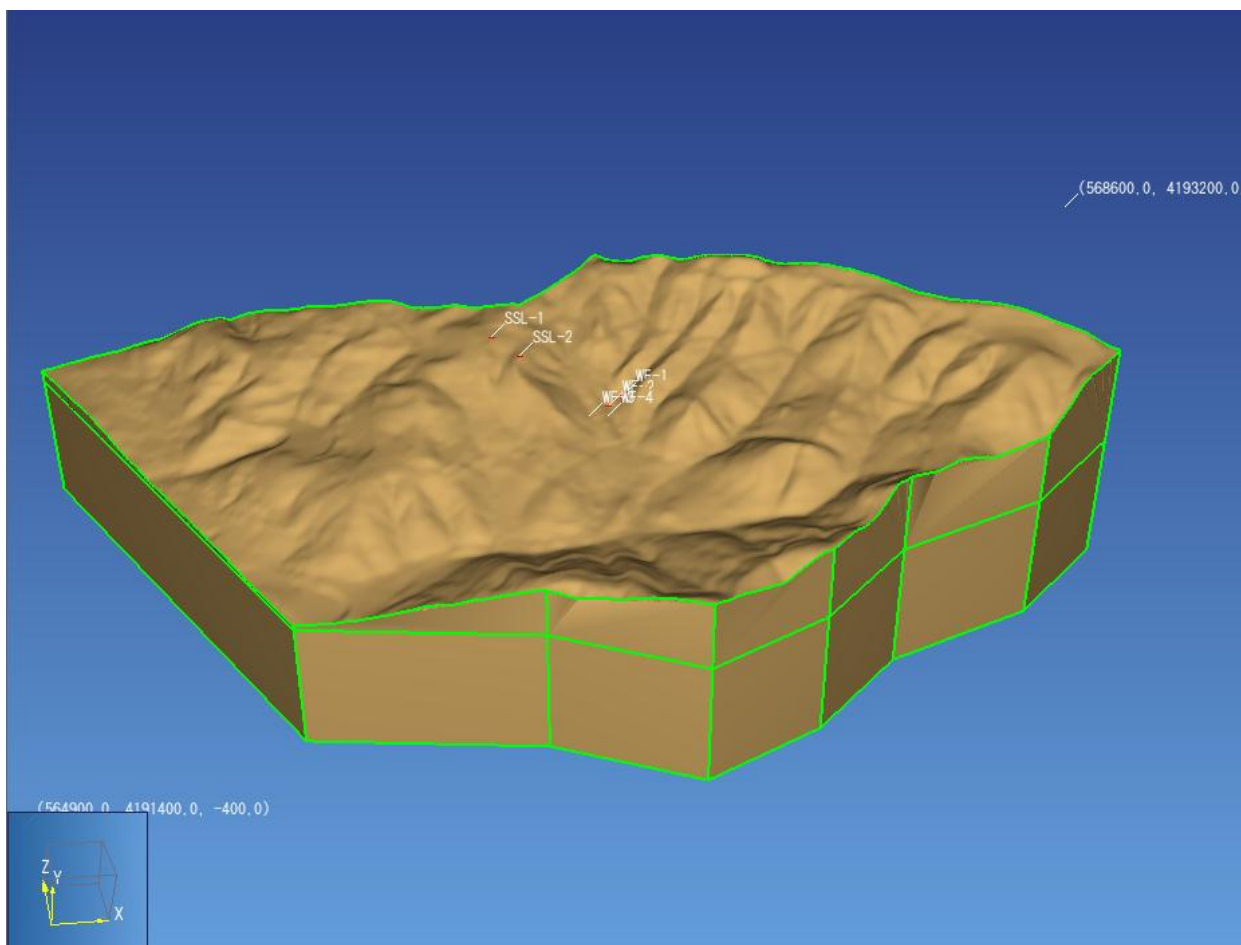


Figure 7-12. The domain of the alternative model showing the surface relief and boreholes.

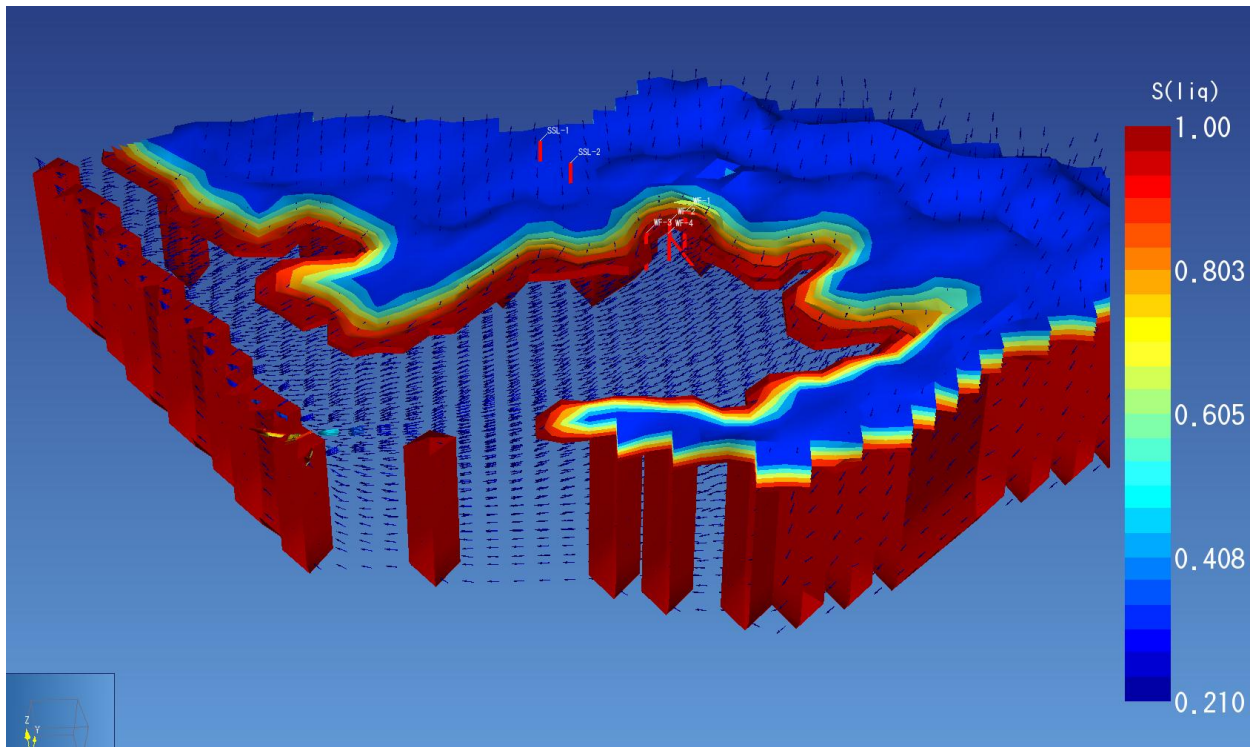


Figure 7-13. A cutout of a predicted saturation profile and flow vectors of the model with uniform permeability and constant flux at 30% recharge of 1000 mm/yr/m² with the assumed Strawberry Canyon Fault.

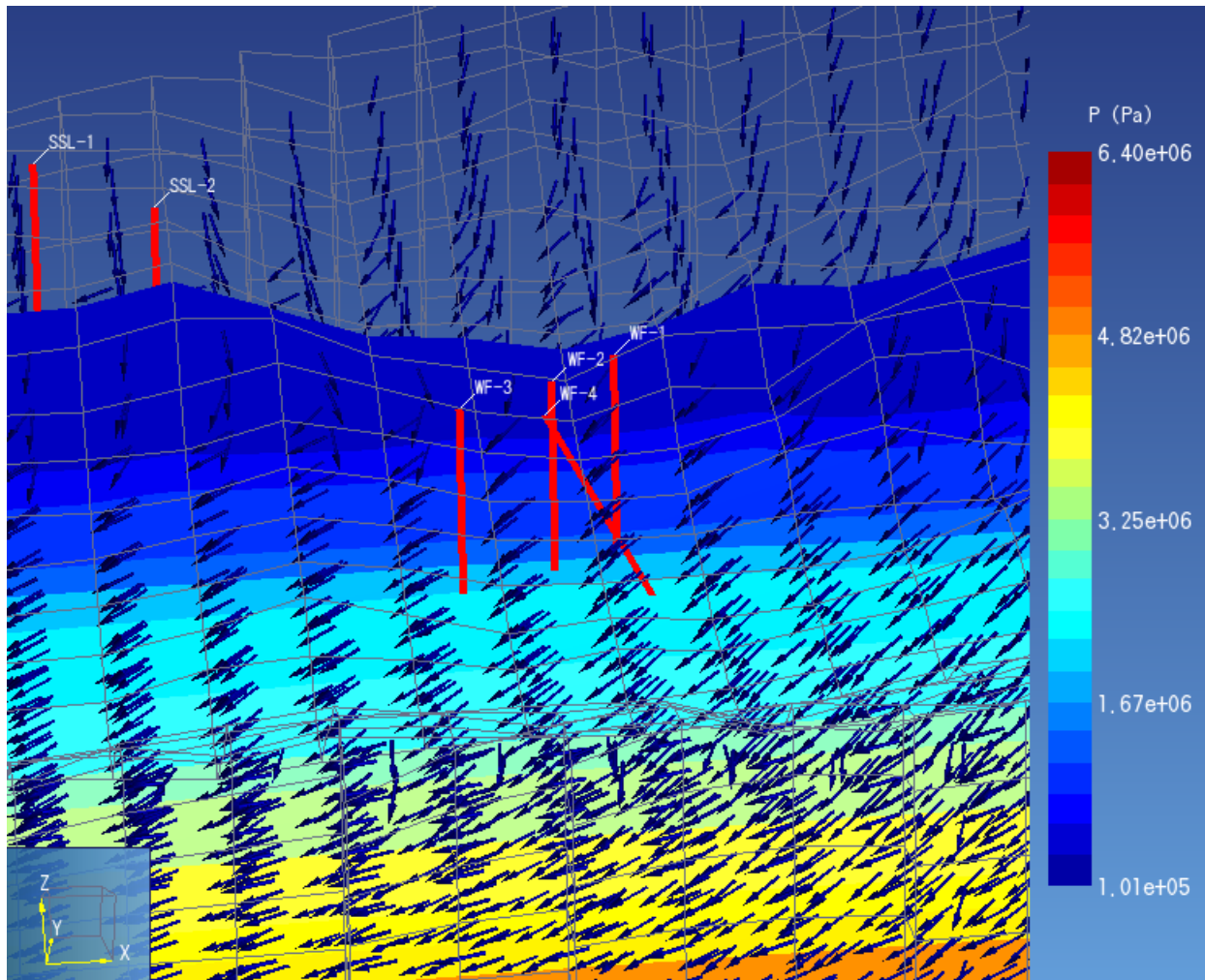


Figure 7-14. An enlarged view of Figure 7-14 showing the flow vectors around the SSL and WF boreholes.

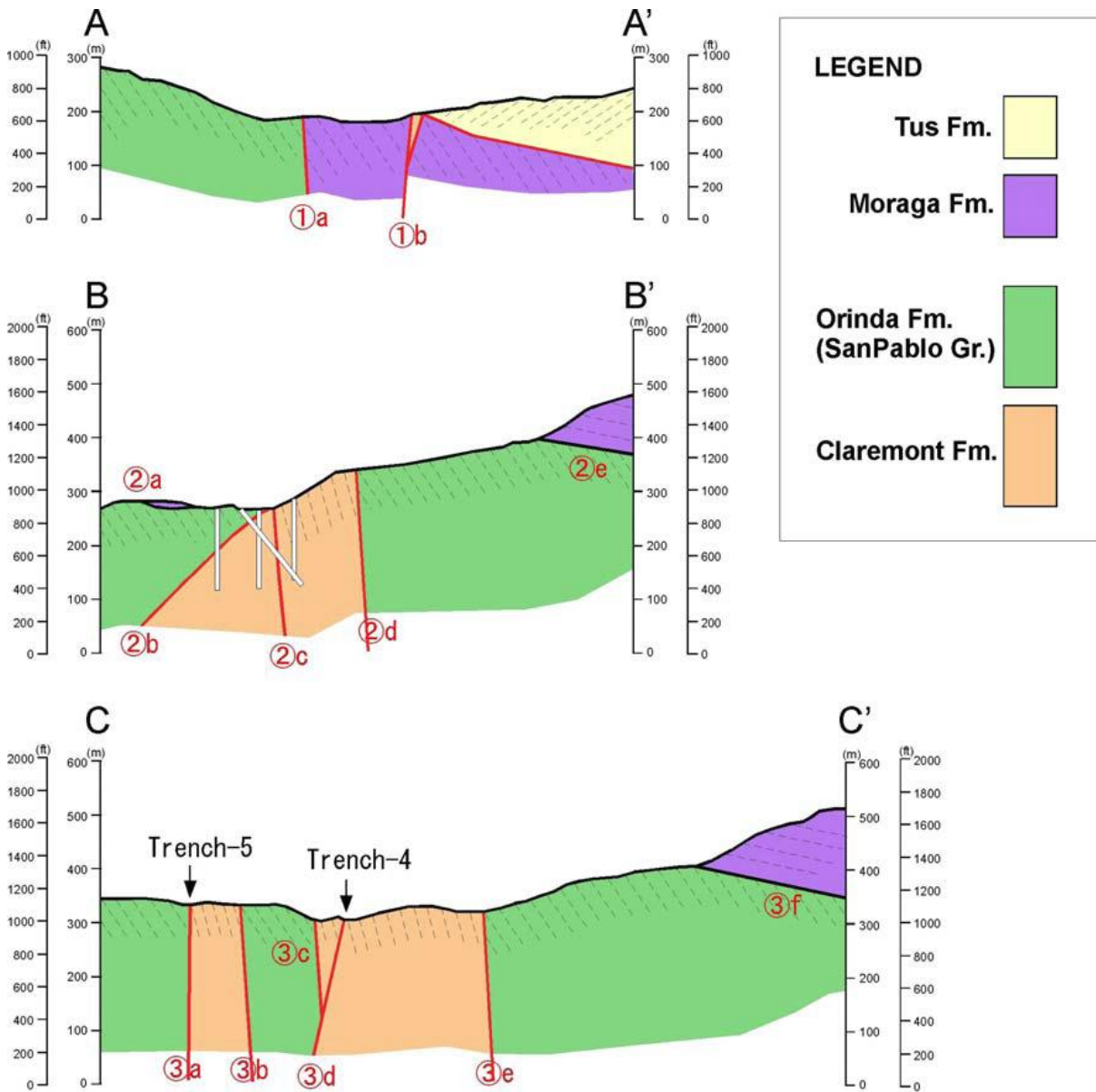


Figure 7-15. The cross sections of the geology along the Wildcat Fault (Kiho et al., 2011).

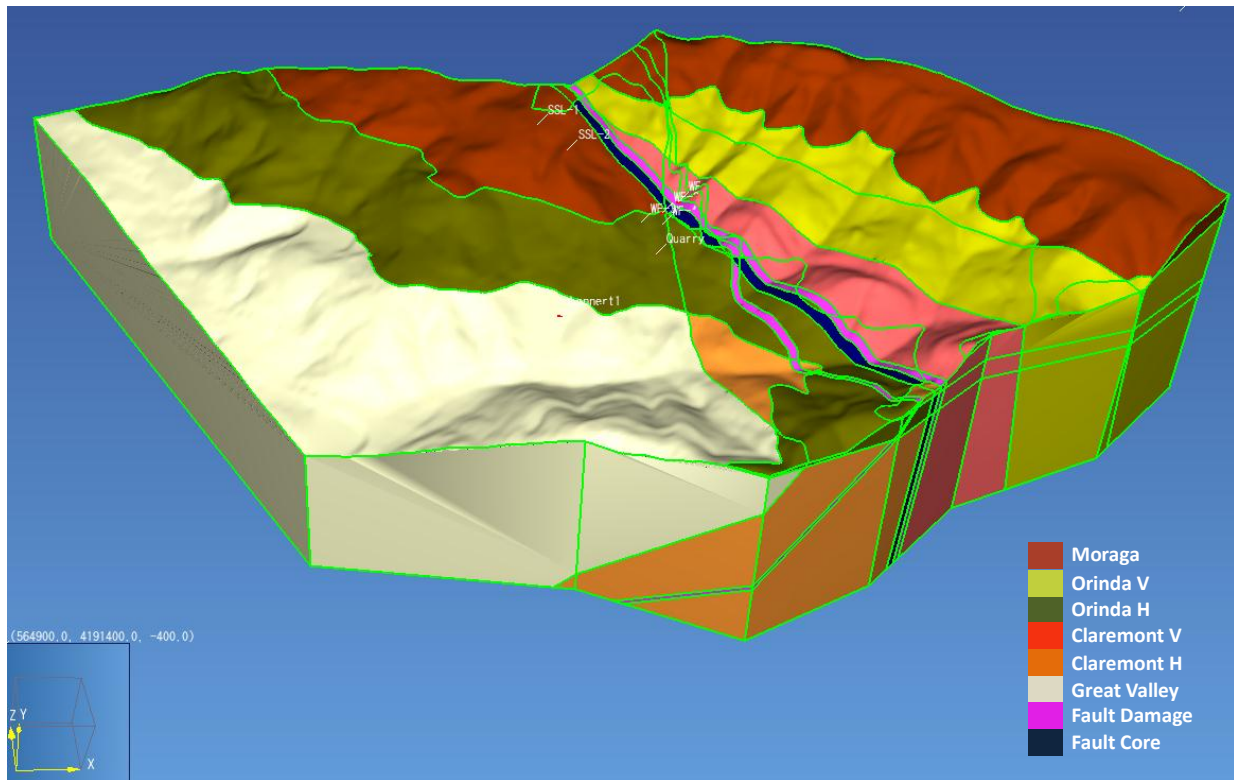


Figure 7-17. Preliminary geologic model of the Strawberry Creek basin with presumed faults.

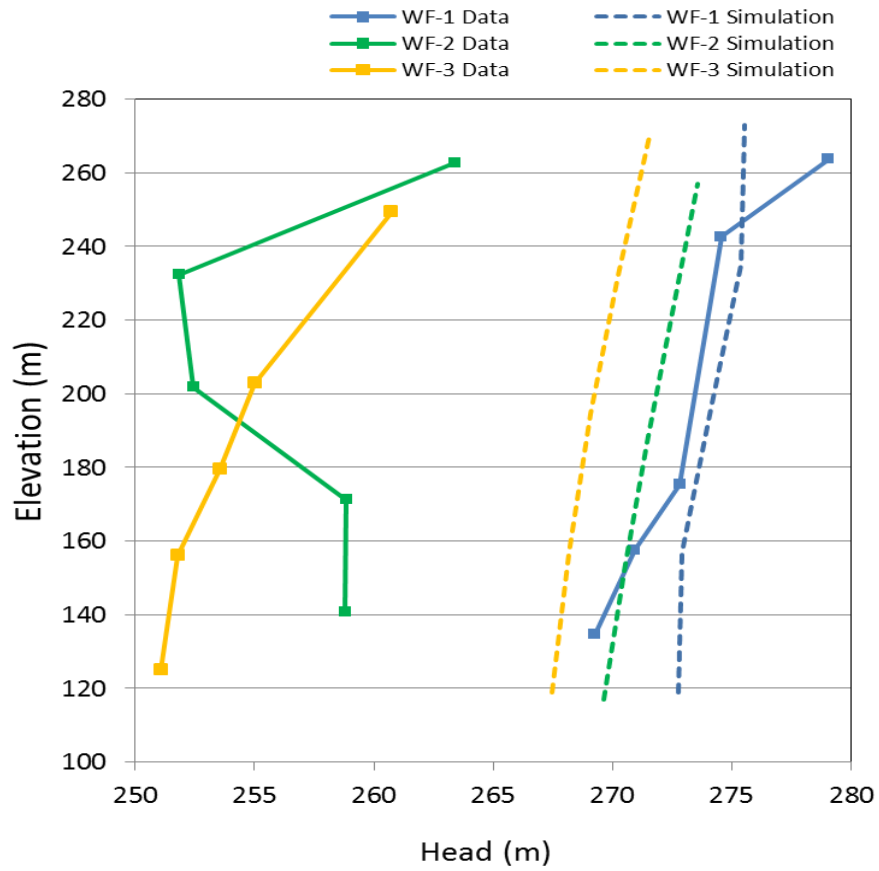


Figure 7-18. Comparison of measured head data and model prediction with no low permeability feature between WF-1 and WF-2.

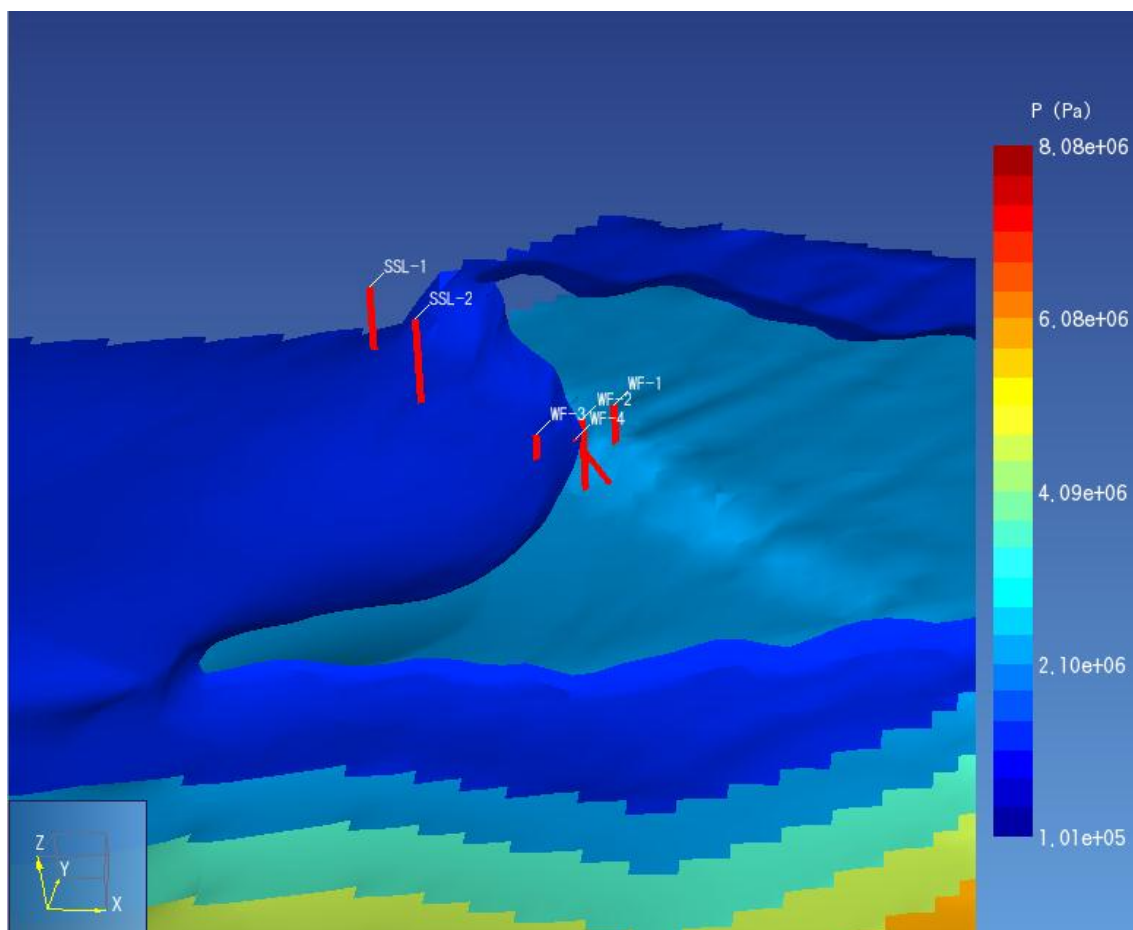


Figure 7-19. Pressure contour plot showing the effects of a low permeability plane feature between WF-1 and WF-2.

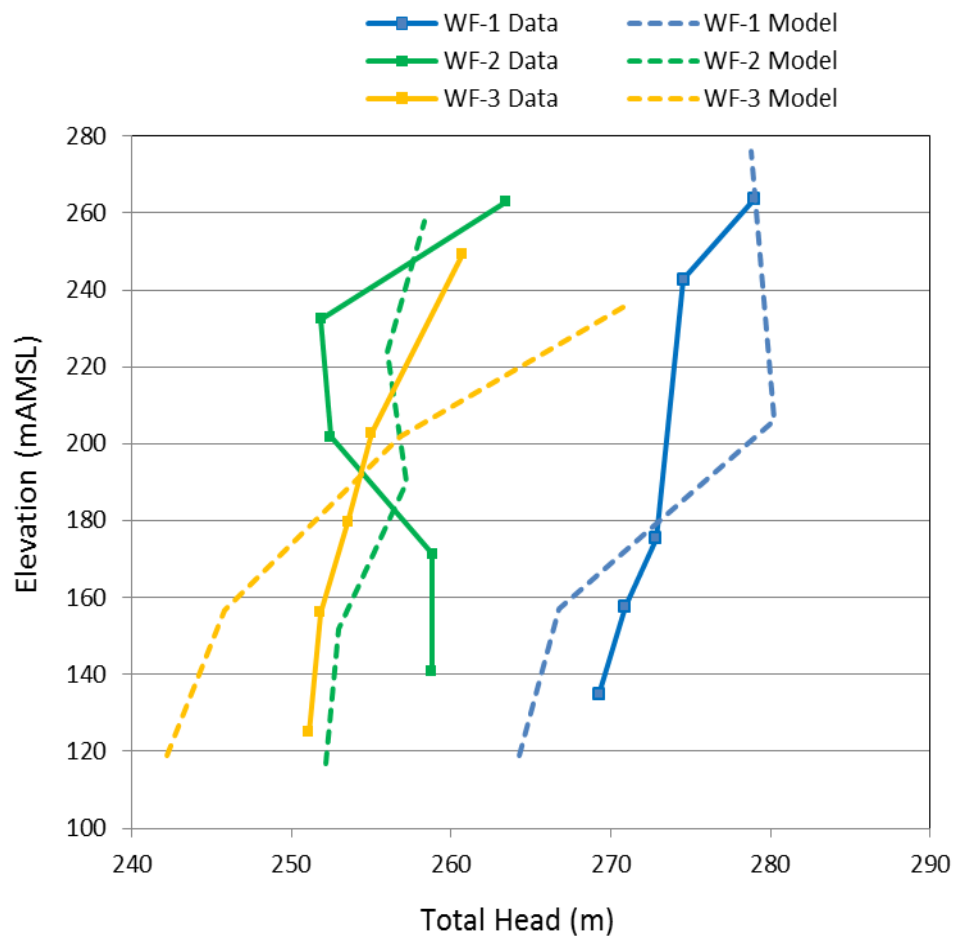


Figure 7-20. Comparison of measured data and model prediction of the heads in WF holes using the parameters shown in Table 7-1.

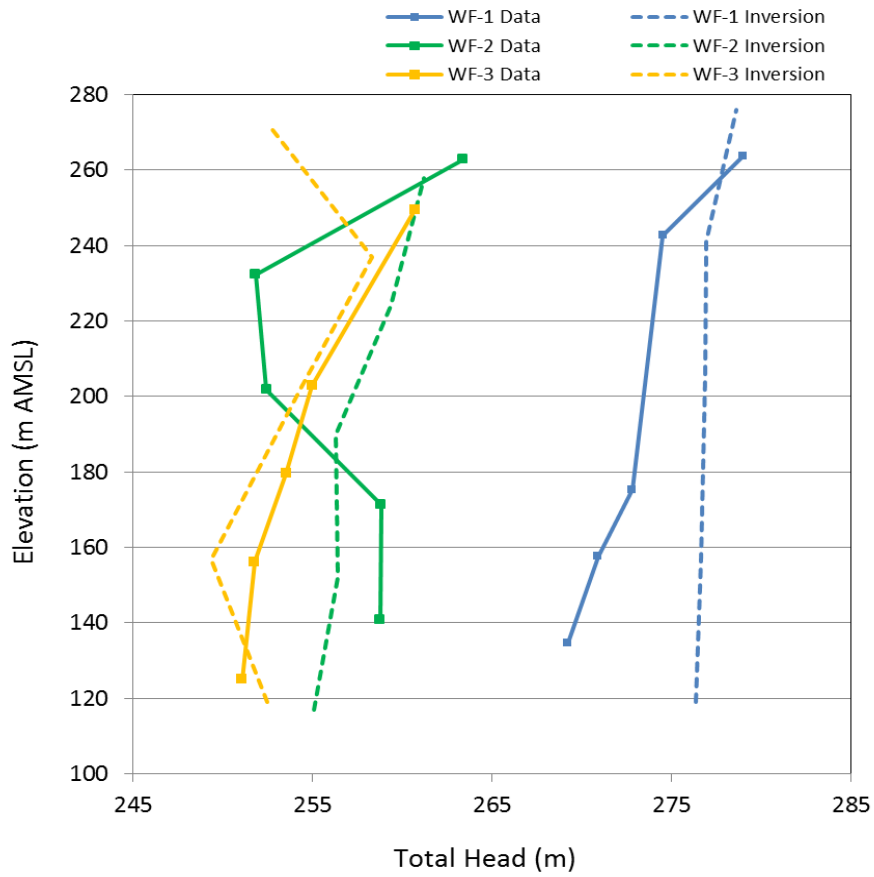


Figure 7-21. Comparison of measured head data in WF boreholes and iTOUGH2 inversion results.

8 Conclusions and Lessons Learned

8.1 Summary Conclusions

Here we give the major conclusions drawn from our investigation activities and analyses discussed in the preceding chapters.

- Electrical resistivity tomography may be more effective than seismic tools in a complex geologic setting.
- The Wildcat Fault probably consists of multiple fault planes, and the main plane most likely lies between WF-1 and WF-2.
- The fault plane with the most recent movement may be too young to develop fault gauges, evidenced by core losses and flowing zones with very fine particles.
- The permeability along the presumed direction of Wildcat Fault appears to be much higher than the perpendicular direction
- Analysis of long-term monitoring data related to groundwater pressure in response to precipitation events may be used to evaluate the hydrologic communication between boreholes
- Geochemical composition analysis of the groundwater suggests that the direction of groundwater evolution is from SSL-1, to WF-1, to WF-2.
- Markedly different concentrations of certain dissolved metals suggest that WF-1 and WF-2 are in separate groundwater pathways.
- Carbonate isotopic analysis of core samples indicate multiple water flow zones, which corroborates our structural analysis of cores.
- Preliminary hydrologic modeling successfully incorporated the major features identified by the structural analysis
- The modeling shows that the head difference between WF-1 and WF-2 may be explained by a low permeability zone separating the two
- Model results suggest that the recharge rate may vary from <3% through Orinda Fm. to >18% through Moraga Fm.
- Inversion results show a reasonable fit to the head profiles in WF boreholes.

8.2 Lessons Learned

8.2.1 Murphy's Law

Below are the valuable lessons learned though carrying out the field investigations described in this report. There have been numerous incidents that were not planned or anticipated before the start of the project. Overall, the project has been a great success; however, investigators should never assume that field work will go smoothly.

8.2.2 Murphy's Law

We have been using sensors from various name brands—namely, Schlumberger, DGSI, and In-Situ. Approximately half of the Schlumberger sensors failed, as well as half of the optical interface cables. At least one DGSI's vibrating wire sensor failed outright, and the other's performance was questionable. We are now on the second Grundfos pump; the first one stopped working. When we were drilling, a drill pipe was caught in a gouge zone and had to be over-cored. The drill string was accidentally dropped several times, and the boreholes caved in many times. After all, we should be respectful of Murphy's Law: If anything *can* go wrong, it *will*. In conducting field investigations, one must expect unexpected things to happen and plan schedules and budgets accordingly.

8.2.3 Quality Assurance

To conduct hydraulic tests in deeper and more fractured zones, new sets of double packer systems were purchased. However, these packers leaked and caused major problems. Although these packers were new and were assumed to be of good quality, rigorous surface tests should have been conducted ahead of time. Such tests translate to time and money, and when resources are limited, doing such tests is very difficult. However, conducting the preliminary tests would have been much better than pulling up packers after they were installed. This may mean less time to conduct tests, but (and needless to say!) it is far better to conduct one good test than many marginal tests.

8.2.4 Fault Gouge

In WF-3, we encountered a ~30 cm thick gouge zone that caught the drill bit, thereby prolonged drilling for one month (to release the bit by over-coring). In drilling WF-4, we expected to see a thick gouge zone, yet no gouges thicker than 5 cm were encountered. There were many sections from which no core was recovered. It is very unlikely that a thick gouge zone would get washed away by drilling. A more plausible scenario is that the Wildcat Fault is either too young to develop a gouge zone, or that some geochemical/hydrothermal conditions are missing, and thus the core material may be pulverized, incoherent (non-solid), extremely fine-grained rock. It may be incorrect to assume that every fault has a gouge zone.

8.2.5 Main Fault Plane

We assumed that the Wildcat Fault is one planar feature. As it turned out, there are many fault planes between WF-1 and WF-2, penetrated by WF-4. None of them appear to be the main fault plane.

8.2.6 Redundancy

This relates to the first two sections. When conducting tests, or monitoring, redundant equipment is necessary. Some of the data may be irretrievable, so that it is better to have redundancy to prevent repeating tests or permanently losing data. While conducting pressure monitoring, in addition to the sensor failures, we experienced a logger failure. Spare equipment should be always stocked and on hand.

8.2.7 Gas Buildup

Even when dealing with a fresh groundwater system, dissolved gas may be present. When gas builds up in an isolated interval, it not only gives erroneous head data, it could ruin the test, or cause spills. In WF-4, the presence of gas in the bottom section, which is open to the surface through 2" pipes, caused various problems. We finally devised a float valve and effectively solved the problem. It should be kept in mind that gas can be present where it is not expected, as in a fresh water system—particularly in a deep system.

8.2.8 Packer Location

Packers need to be seated within a relatively smooth walled section of the hole. This placement has to be balanced with the need of testing at a particular depth or for a particular lithology. It is very difficult to ensure/verify isolation of zones by packers; consequently, a new approach to isolating the entire length of a borehole is in order.

8.2.9 Take Time

It is important to collect the background baseline (trend) data before conducting hydraulic tests, equally important to analyze that data correctly. Rainfall had a big impact on the hydraulic heads observed in boreholes, as seen particularly in the WF and SSL boreholes. One entire year's worth of data may not be enough to develop an understanding of the natural state.

In addition, as was discussed in the previous sections, one must allow for breakdowns and other unexpected occurrences. Field work should not be conducted in a hurry. In particular, a good hydraulic test typically can take weeks if not months.

8.2.10 Geophysics

Do not rely too heavily on geophysics when trying to obtain hydrologic information. Geophysical techniques yield at best indirect information regarding the hydrologic properties of rocks (e.g., density, formation electrical resistivity, porosity) depending on the technique used. These properties oftentimes do not directly correlate with hydrologic properties. In a complex geologic setting like our study area, one may get very noisy data or inaccurate results.

ACKNOWLEDGEMENT

The authors are grateful to Wayne McKinney and Peter Takacs for very useful discussions. The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Science Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 at Lawrence Berkeley National Laboratory.

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