Geologic Setting, Stratigraphy, and Detailed Velocity Structure of the Coyote Creek Borehole, Santa Clara Valley, California

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ABSTRACT

The Coyote Creek borehole and adjacent William Street Park in the Santa Clara Valley, California, provides a reasonably well-defined and simple geologic setting for the study of seismic velocity structure in Quaternary alluvium. The borehole transects 308 m of the approximately 400 m of flat-lying Quaternary alluvium that overlie basement in the center of the valley. It is located about 720 m southwest of the Silver Creek fault, which separates this shallow basement from the deep Evergreen basin to the northeast.

The Quaternary alluvial section in the borehole consists of interbedded fine- and coarse-grained layers one to tens of meters thick that we define from wire-line geophysical logs. In the upper 90 m of the section, the layers are organized as three fining-upward cycles, the first of which is the Holocene cycle of alluviation. Below these prominent cycles, the section is more regularly interlayered.

Both P-wave and S-wave velocity, measured at 1-m resolution in a down-hole suspension velocity log, increase generally with depth. In the shallow section, Vs is relatively stable with depth, whereas Vp increases rapidly through the first 12 m and then more gradually. The fine-grained part of the third cycle forms a distinct low-velocity zone with a top at 51 m. Throughout the borehole section Vp and Vs correlate closely with the detailed lithologic layering, being higher in the coarser layers, which average 8.6 m in thickness. The Vp/Vs ratio also correlates with the layering, but is higher in the fine-grained layers. Two-way travel time calculated from the suspension velocity log steepens downward in typical fashion, and reaches values of 0.325 and 1.33 seconds at a depth of 293 m for Vp and Vs, respectively. The effects of the alternating fast and slow layers are clearly evident, particularly in Vs. Vp determined from the sonic log closely tracks that from the suspension log, but shows anomalously low values in many coarse layers for which the caliper log shows borehole washouts.

The Vp/Vs ratio for the five wells for which suspension velocity logs were obtained shows two distinct patterns that correlate with sedimentary environment. In the two wells representing fluvial deposition, the ratio rolls over to higher values in the upper part of the section, whereas in wells representing alluvial fan deposition, the ratio remains steep throughout the section.

INTRODUCTION

Selection of the Coyote Creek borehole and adjacent William Street Park as a site for coordinated studies of shallow seismic velocity places those studies in the midst of a multidisciplinary investigation of the Santa Clara Valley being carried out by the U.S. Geological Survey. That investigation seeks to determine the stratigraphy and structure of the Santa Clara Valley, with deliberate attention to the unconsolidated Quaternary alluvial fill of the valley, and to portray the result as a full three-dimensional representation of a 45-km square by 14-km deep block (Jachens and others, 2001). As a result, we are in a position to define the geologic context of the velocity studies in some detail as well as to examine the details of the stratigraphy and velocity structure at the borehole.

Eight deep boreholes have been drilled to a nominal depth of 1000 feet (305 m[1]) in the Santa Clara Valley for the Santa Clara Valley Water District. One of these, the borehole named Coyote Creek Outdoor Classroom (here called Coyote Creek, or CCOC), is the focus of this collection of papers. Various wire-line geophysical logs were collected in the boreholes, including suspension velocity in five, and cores were taken from most. The broad study has also involved areal geology, potential-field geophysics, seismic reflection and refraction profiling, paleomagnetic study, stratigraphic analysis, and groundwater modeling by a team of more than a dozen investigators. The Coyote Creek borehole has been described by Hanson and others (2002), and data collected from all eight boreholes are reported in Newhouse and others (2004).

1 Depths in water wells are originally recorded in feet, here henceforth rendered in meters.

We describe the geologic setting of the Coyote Creek borehole and adjacent William Street Park, and then examine the details of borehole stratigraphy and velocity structure from cores, a shallow cone penetrometer test, and caliper, natural gamma, resistivity, suspension velocity, and sonic logs of the borehole.

The Borehole

The Coyote Creek borehole (State well number 007S001E09L001M) is located in San Jose at -121.86835, 37.33702 (NAD27), which is just west of the William Street crossing of Coyote Creek and seven blocks east of the campus of San Jose State University. The elevation of the ground surface at the borehole is 25.7 m (from 10-m DEM based on 1:24,000-scale contours).

The borehole was drilled using conventional mud-rotary techniques to a depth of 308.2 m (1011 feet) by the U.S. Geological Survey in August-September, 2000, for the Santa Clara Valley Water District. The nominal diameter of the pilot hole was 5.9 inches. Wire-line logs were collected in the uncased pilot hole, after which the hole was reamed to larger diameter and four wells were installed and separately screened at different depths for long-term groundwater monitoring. The deepest well, with an inside diameter of 3 inches, extends beyond the screened interval to the bottom of the borehole. Seventy five cores were taken at scattered intervals down the hole during drilling of the pilot hole.

It is uncertain where the top of saturated sediment is in the borehole, but it is probably very shallow. No observation of depth to the unconfined water table in the shallow section was made during drilling. Water levels measured in the shallowest of the monitoring wells installed at the Coyote Creek site show levels that vary several feet through time around a depth of 10 ft (3 m) and levels in the deeper aquifers that vary between depths of about 20 and 110 ft (6 and 34 m) (Newhouse and others, 2004, figures

3 and 16A). There is no evidence of perched water in the borehole section, and the whole section below creek level (depth in CCOC of about 6 m) can be presumed to be saturated (R.T Hanson, written commun., 2004).

GEOLOGIC SETTING

The Santa Clara Valley is a subsiding Quaternary alluvial basin flanked by mountains that have been rising across inward-directed reverse faults (figures 1 and 2). Surface geology suggests that the Quaternary basin fill has been deposited principally as alluvial fans emanating from the flanking uplands, with axial drainage flowing northwestward between the alluvial fans to the south end of San Francisco Bay. This pattern is evident in the present topography, which defines large fans on the southwest, much smaller fans on the northeast, and an axial trough draining northwestward between them. Sediment cored in the deep boreholes is almost entirely alluvial as well, indicating that the alluvial sedimentation indicated by surface geology has persisted through time.

The valley is floored by Holocene alluvium that is inset into and overlaps most of the older late Pleistocene fans as a relatively thin sheet of sediment that is typically 10-20 m thick in the center of the Valley (Helley, 1990). The base of the Holocene unit, which was the topographic surface in latest Pleistocene time prior to Holocene alluviation, mimics the shape of the present ground surface, with a similar axial trough down which axial drainage must have flowed.

This asymmetric position for an axial trough must have persisted through time, because gravel in cores and cuttings from CCOC was derived from the Santa Cruz Mountains on the southwest. The gravel contains abundant Franciscan greenstone (Andersen and Metzger, 2004), which requires supply from the Santa Cruz Mountains to the southwest where the Franciscan rocks contain much greenstone, rather than from the Diablo Range to the northeast where there is almost no greenstone. The position of CCOC has thus probably occupied an axial drainage trough throughout accumulation of the alluvial section, and therefore has probably experienced predominantly northwesterly directed stream flow. One implication of this setting is that stratigraphy in the CCOC borehole is probably closely similar to that a few hundred meters to the southeast in William Street Park where some of the seismic velocity studies were performed (see borehole and park locations on figure 1).

The base of the Quaternary section (figure 2) is a regionally flat unconformity that truncates basement beneath the center of the valley and Miocene sedimentary rock of the Cupertino basin to the west. East of CCOC and the Silver Creek fault the Quaternary section overlies Tertiary fill of the Evergreen basin. The Quaternary section is 200-400 m thick, and specifically is 240 m thick at MGCY (bottoms in Miocene), 244 m thick at WLLO (bottoms in serpentinite), 407 m at GUAD (bottoms in Franciscan or Great Valley sequence), and is estimated (R.C. Jachens, oral commun. 2004) to be about 410 m at CCOC (below the 308-m-deep bottom of the borehole).

The alluvial section is younger than the Cupertino basin (late Miocene), and probably younger than most of the Santa Clara and other Plio-Quaternary gravels, which are not recognized in any of the boreholes. No gravel compositions characteristic of those units have been found in cores or cuttings. Radiocarbon dates and paleomagnetic events in CCOC provide some control on age, and indicate that the top of the section is Holocene and the bottom of the borehole is probably 780 thousand years. An age of 780 thousand years at a depth of 305 m in CCOC (Mankinen and Wentworth, 2003) makes the entire 410-m alluvial section at CCOC about 1 million years old. The subsidence rate relative to present sea level required to make room for this section is about 0.4 mm per year.

Layering in the alluvial section must be essentially horizontal, at least in the central part of the Quaternary basin, given the low regional relief apparent on its base and the orientation of bedding in the cores perpendicular to their lengths. A seismic reflection profile extending northeastward from the central basement high across the Silver Creek fault (figure 3) confirms this expectation.

The CCOC borehole overlies the eastern margin of the central basement high, but about 720 m to the northeast this basement surface is truncated by the Silver Creek fault, as indicated by termination of the basement reflection in the seismic profile (figure 3). InSAR comparison of ground elevations in the Santa Clara Valley shows an abrupt contrast across the fault in the slight subsidence and recovery of the ground surface produced during the annual ground-water pumping cycle (Galloway and others, 1999). This sharp gradient is used to position the central part of the trace of the Silver Creek fault in figure 1. Despite this sharp break in the subsidence pattern, no simple offset of the alluvial section is evident in the reflection profile. Instead, there is a 1-km-wide sag in the shallow reflections that straddles the basement termination (figure 3, bounds of sag shown on figure 1). The offset history of the Silver Creek fault has principally involved strike slip, but with great reduction in its rate in the past 2 Ma or so (Graymer, 2003). If the sag is of tectonic origin associated with the Silver Creek fault, it is reasonable to project its southwestern extent southeastward along the Silver Creek fault, where it falls slightly northeast of the CCOC borehole (see relative locations in figure 3). There is thus no evidence that the CCOC section is faulted.

The schematic cross section (figure 2) summarizes the geologic relations. The CCOC borehole transects about three quarters of the flat-lying Quaternary alluvial fill near the center of the Santa Clara Valley and just west of the Silver creek fault, where the central basement high is about 400 m deep. Farther west, that alluvial section unconformably overlies a late Miocene basin, whereas east of the Silver Creek fault it overlies the fill of the Evergreen basin, which is much thicker and ranges from Holocene at the surface to probably Miocene in the deep basin.

STRATIGRAPHY

The Quaternary section is layered, as indicated by its reflectivity (figure 3), with beds consisting variously of clay, silt, sand, and gravel, as sampled in the cores. We have defined the layering at CCOC more specifically using geophysical logs calibrated by cores from that well (figure 5). The layers are in turn organized into several cycles, the uppermost three of which are of specific interest here. The cone penetrometer sampled the upper cycle and a half (38.5 m), and provides the most detailed and specific continuous information on layering (figure 4).

Cores

The cores provide the only direct evidence of the nature of the sediment, and therefore have been used to help calibrate our use of the geophysical logs. The seventy-five cores taken in CCOC ranged from 13 to 155 cm in recovered length, in aggregate representing 20 percent of the depth of the hole (figure 5). Each core was carefully described at centimeter resolution in the laboratory, with grain size estimated under the hand lens in comparison to sieved standards (grain-size card) and silt distinguished from clay by testing the cohesiveness of a rolled “worm” of moist sediment. The result is descriptions ranging from clay and silty clay, through fine-grained silty sand and medium-grained sand, to coarse- to medium-grained gravelly sand and well sorted pebble to cobble gravel.

All the cores are unconsolidated, except very locally where carbonate cement is present. The unconfined compressive strength of cohesive sediment was estimated using a Soiltest-brand TM pocket penetrometer, with direct measurement at 1 cm of penetration up to 4.5 tons/square foot. The cohesive sediment is soft at shallow depths, generally firm below 46 m, and exceeds the 4.5-t/sqft limit of the instrument below about 150 m.

Cone Penetrometer Test

A cone penetrometer test (CPT, figure 4) was conducted at the Coyote Creek site prior to drilling. In this test, an instrumented rod 3.6 cm in diameter was hydraulically pushed into the ground at 2 cm/s and continuous measurement was made of load against the conical tip (tip resistance) and frictional resistance along the trailing sleeve (local friction, here reported through its ratio to tip resistance). Soil behavior type is inferred from relations between these measures and known physical properties of various materials (Noce and Holzer, 2003).

Low friction ratios (<1%) typically indicate non-clayey granular materials with little or no cohesive strength (sand, gravelly sand), whereas higher friction ratios typically indicate progressively more cohesive material (clayey silt, silty clay, clay). The density of the material is indicated by the tip resistance, with low values indicating relatively loose sandy or soft silty or clayey materials and high values indicating dense sandy or hard clayey materials. Bedding is indicated by changes in these parameters.

The CPT penetration depth at CCOC is 38.5 m, which is relatively deep for alluvial fan and floodplain materials in the San Francisco Bay area, and this fact alone indicates that these CCOC materials are mainly fine-grained. The friction ratio typically ranging from 2 to 5 percent throughout the sounding confirms this. The main exception is the interval from about 18.5 to 23 m, where the low friction ratio (<1%) implies nearly clay-free material. The associated high values of tip resistance are consistent with the material being sand and gravelly sand. Several other thin layers having low friction ratios and higher tip resistance are also probably relatively dense and clay-free layers.

The clayey material between 10 and 18.5 m is normally consolidated, as indicated by the fact that a line fit to the tip-resistance curve there projects up through the origin (figure 4). Beneath the sand and gravel at 18.5 to 23 m, however, a similar line fitted to the finer grained parts of the section is not coincident with the first, and its projection intersects zero depth above the origin. Such a relationship is typical of clayey material that is over-consolidated relative to its depth. This contrast in consolidation of the two intervals of clay indicates the presence of an intervening unconformable contact. Because the overconsolidated sediment has never been deeply buried in this subsiding alluvial basin, its higher density is probably due to dessication during weathering and exposure at the ground surface prior to deposition of the overlying sediment. The coring program, designed to test this circumstance, confirmed it and identified the unconformity as the base of the Holocene cycle (see below).

No observation of the depth to shallow water was possible in this CPT sounding because of the necessity to grout while the probe was withdrawn from the hole.

Lithologic Interpretation

We defined the lithologic layering in CCOC at meter scale (figure 5) in order to characterize the sedimentary section and compare it with velocity structure. The cores and CPT log provide important local detail, but it is the wire-line geophysical logs that provide continuous information down the length of the borehole. Interpretation of the full lithologic section must thus be based on interpretation of these logs. A broad suite of detailed logs -- including natural gamma, 16-inch normal resistivity, caliper (borehole diameter), sonic, and P- and S-wave velocity (suspension velocity) -- was collected in the borehole. We reserve the velocity logs for independent comparison with the lithologic interpretation, and focus first on the caliper, gamma, and resistivity logs. In this saturated fresh-water environment, the gamma and resistivity logs respond principally to clay content. Gamma radiation is typically high from clay and low from sand, whereas electrical resistivity is low in clay and high in sand. Thus, in figure 5, the two curves define a complex spindle with the cores plotted down its axis, in which the narrow parts are finer grained and wider parts are coarser grained. For convenience here we refer to large departures of the curves from the spindle axis as highs and small ones as lows, despite the fact that such gamma highs actually have low gamma values. The caliper log is shown in figure 9.

We compared the lithology of the cores with the gamma and resistivity logs to develop empirical rules for interpretation. This indicated that only the most prominent gamma highs represent medium- and coarser grained sand and gravel, and these correspond with high resistivity peaks, whereas slightly lower but still prominent gamma highs, such as at a depth of about 80 m, lack equivalent resistivity highs and represent much finer grained core material. Intervals with strong gamma highs and equivalent resistivity highs were therefore distinguished as coarse sediment. The resistivity highs for some of the strong gamma highs are much less prominent, such as at a depth of about 77 m, and the cores indicate that these relations involve mixed coarse and fine sediment. The very deep gamma lows that have equivalent low resistivity were distinguished as clay. Because the gamma curve tends to have high gradients where the unit boundaries are picked, the locations of these boundaries are relatively insensitive to the exact location of the picks.

A further subdivision of the coarse intervals was made using the caliper log (figure 9). We expect that washouts of the borehole wall within coarse-grained intervals indicate that the material is relatively loose and permeable sediment, and therefore distinguish coarse intervals where the borehole diameter is unusually large (here, greater than about 6.8 inches).

The result is a subdivision of the section into five kinds of material, as shown in figure 5, with the lithologic composition of each kind determined from the cores:

1. coarse intervals (high gamma, high resistivity) with deep washouts: principally medium to coarse sand and gravel, relatively loose and permeable;
2. coarse intervals without deep washouts: principally medium to coarse sand and gravel;
3. high gamma intervals with moderate resistivity peaks: sand and gravel with abundant finer sediment;
4. intervals marked by particularly low gamma and low resistivity: principally silty clay and clayey silt;
5. the remainder, characterized by intermediate to low gamma values and relatively low resistivity: clayey silt to silt and fine-grained sand.

It is important to note that the section is layered at scales ranging from millimeter-thick laminations to beds many meters thick, and then as packets of different sets of lithologies at scales ranging from centimeters to tens of meters and more. At the relatively fine scale of the geophysical logs many of the measurements are still of sets of beds rather than of individual lithologies, whereas layering at coarser scales is directly revealed by the logs.

This lithologic interpretation for CCOC is much more detailed than that of Hanson and others (2002, figure 2), and differs considerably in the relative abundance of coarse sediment. That representation is based largely on field and office descriptions of cuttings, which seem to emphasize the coarser materials relative to the abundant fine-grained sediment inferred here from the geophysical logs and confirmed by comparison with the cores.

Organization of Lithologic Layers

Inspection of figure 5 reveals that there is considerable organization to the many lithologic layers. The upper 90 meters of section involve a prominent alternation of fine and coarse intervals that represents three upward-fining sequences with abrupt, unconformable bases (cycles 1-3). The remainder of the section is more uniformly interlayered, although in detail several more complex fining-upward cycles can be resolved (not further discussed herein). A further distinction can be made between the coarse layers above 164 m, most of which involve washouts (high caliper readings) and therefore are inferred to be relatively loose and permeable, and the deeper coarse layers, which generally lack washouts.

Age

The uppermost cycle (1) can be identified as the Holocene pulse of alluviation. This pulse occurred during the climatic warming and associated rise in sea level that followed the last glacial maximum. Coring guided by the contrast in consolidation indicated by the CPT log succeeded in capturing the base of this sequence (core 15), where loose and unweathered sand and gravel overlies a partially eroded soil developed in silty clay. This Holocene alluvial pulse in the Santa Clara Valley actually began somewhat earlier than the formal beginning of the Holocene epoch (10-11.5 ka). Radiocarbon dates on rootlets 4.9 m above and 2.5 m below the basal contact at 22.6 m yield calibrated calendar ages[4] of 12,388 and 32,843 years, respectively. The unconformity at the base of the cycle represents a hiatus of almost 20,000 years and associated erosion that occurred during the last low stand of sea level, which reached its maximum some 18,000 years ago.

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4. Radiocarbon ages of about 10,600 and 28,000 years were calibrated using the second-order polynomial model of Bard (1998).

Beyond these radiocarbon dates, direct age control in the CCOC section is limited to three paleomagnetic events. One paleomagnetic excursion occurs in the same core as the deeper radiocarbon date (core 17), and that date helps constrain the age of the Mono Lake excursion with which this event is correlated (Mankinen and Wentworth, 2004). Just 6 m deeper a second excursion occurs that Mankinen and Wentworth correlate with the Laschamp excursion at about 45 ka. Finally, an excursion at a depth of 305 m in CCOC (Mankinen and Wentworth, 2003), together with excursions encountered at similar depths in the GUAD and STPK boreholes, are now considered to represent the top of the Matuyama Reversed Polarity Chron, with an age of 780 ka (Mankinen, oral commun., 2004). The Big Lost excursion, viewed as an alternative identification of the CCOC excursion by Mankinen and Wentworth (2003), is now considered to be represented by a much shallower excursion encountered in cores from GUAD and MGCY.

SEISMIC VELOCITY

Detailed Vp and Vs measurements that resolve the detailed velocity structure of the CCOC section are provided by a suspension velocity log that was collected for the U.S. Geological Survey under contract by R.A. Steller of GeoVision using an Oyo suspension logging system. The most striking aspect of this structure is its close relation to the detailed lithologic layering of the section. The measurements were made at depth spacings of 0.5 m from 3 to 50 m and then at 1.0 m to a depth of 293.1 m near the bottom of the borehole. Each measurement averages velocity over a column of sediment around the borehole 1 m in height.

The Vp and Vs measurements from the suspension log are overlaid in figures 6and 7 on a version of the layered section of figure 5 in which the coarser and finer lithologic units are grouped into one coarse and one fine unit. The velocity curves show structure at several scales, the most general of which is a gradual increase of Vp and Vs with depth. Values range from about 1340 and 195 m/s (Vp and Vs respectively) at 13 m to about 2275 and 745 m/s near the bottom of the borehole.

Superimposed on this general downward increase in velocity is a short-wavelength variation that correlates strongly with the coarse- and fine-grained lithologic layers of the section. Both Vp and Vs are higher in the coarse layers than in the fine, with a local amplitude that is variable but generally increases downward from about 150 (Vs) and 325 m/s (Vp) at a depth of 50 m to about 350 and 500 m/s respectively near the bottom of the borehole. The coarse layers with which the high velocity peaks correlate range in thickness from 1.7 to 30 m, with an average of 8.6 m.

In the shallow section (figure 7), Vp and Vs behave quite differently. Vp increases rapidly downward through the 17 m of fine-grained Holocene section in cycle 1 from the first measured value of 388 m/s at 3-m depth to an average[2] of 1435 m/s in the lower 6 m. Values in the 13-m-thick fine-grained section below the basal Holocene sand and gravel in cycle 2 are higher but relatively constant with an average of 1680 m/s. Vs, in contrast, shows relatively constant values in the Holocene fine-grained section with an average of 195 m/s, and steps up slightly to values averaging 260 m/s in the fine-grained upper half of cycle 2. This step in otherwise well-behaved Vs values across the base of the Holocene mimics the step in tip resistance of the CPT log (figure 4). Note that, in contrast to Vs in coarse layers deeper in the section, Vs in the basal coarse layer of cycle 1 is similar to that in the adjacent fine layers, reflecting its complete lack of consolidation.

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2 All averages of velocities are simple arithmetic averages; time-thickness relations are not considered.

The 22-m-thick fine-grained section of cycle 3 forms a prominent low velocity zone with its top at 51 m beneath the 6 m of sand and gravel at the base of cycle 2. Here Vp steps back about 300 m/s and Vs about 100 m/s relative to the base of cycle 2.

Beneath cycle 3 both Vp and Vs increase fairly regularly and without prominent breaks to the bottom of the borehole.

The Vp/Vs ratio provides a sensitive indicator of contrasts between Vp and Vs throughout the section (figures 6 and 10). The general trend of values, following an initial downward increase across the first 12 m of section in cycle 1 (tracking increasing Vp), is a gradual decrease, more rapid in the upper 150 m, from an average of 7.1 between 13 and 22 m in cycle 1 to 3.3 below 259 m Expressed as Poisson's ratio[3], 0.49 and 0.45 respectively, these values fall well within the range compiled by Brown and others (2002) for 100-m, water-saturated alluvial sections in ten 100-m-deep wells in southern California.

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3 Poisson's ratio = $\frac{1}{2} * (r^2-2)/(r^2 - 1)$, where r = Vp/Vs.

Like Vp and Vs, the Vp/Vs ratio differs between the coarse and fine layers, but with distinctly higher values in the fine-grained layers. Thus, although both Vp and Vs are higher in the coarse than in the fine layers, there is a systematic difference in the Vp/Vs ratio between the two lithologies. This local range in Vp/Vs values decreases downward in the borehole.

TRAVEL TIME

Two-way travel time for Vp and Vs calculated from the suspension velocity log is shown in figure 8. The curves steepen downward in the typical manner, and reach values of 0.325 and 1.33 seconds at a depth of 293 m for Vp and Vs, respectively. Superimposed on the general arch of the Vs curve are local steps reflecting the influence of the alternating higher and lower velocities of the coarse and fine intervals in the section. This influence is also evident, but less clearly so, in Vp when its curve is stretched to a shape similar to that of Vs. The detailed shape of the curves is thus a combination of the general downward increase in velocity in the section and the particular organization of the coarse and fine layers. No break is evident at the base of the Holocene cycle, nor is one evident at 164 m between the upper section containing coarse layers with high caliper values and the lower section without such layers. There is a slope break of about 5 degrees at 190 m between two fairly straight segments of the Vs curve, but it not clear that this has any stratigraphic significance.

Vp FROM SONIC LOG

The basic suite of geophysical logs collected in the CCOC borehole includes a sonic log, which provides an alternate source of Vp. That can be calculated from transit time per foot (BHC-DELT), as corrected for borehole diameter with the caliper log and reported every 0.1 ft. in microseconds. This form of Vp, smoothed in a running 1.5-ft window

(0.45 m), is superimposed in figure 9 over Vp from the suspension log. The original sonic Vp values are quite noisy, and even with the smoothing shown here the curve is much busier than the suspension Vp. For the most part, however, the two Vp curves are quite similar.

In one important respect, however, they are quite different. Careful inspection reveals that the sonic Vp values in many of the coarse layers are anomalously low relative to suspension Vp (highlighted in figure 9 by white ovals). Although the source of this discrepancy is not certain, we point out the close correlation between the intervals of discrepancy and relatively high caliper readings, implying that the compensation for borehole diameter was incomplete. But the inverse is not true, as some coarse layers with high caliper values exhibit sonic Vp that tracks suspension Vp quite well. Regardless of the cause, it is clear that Vp calculated from sonic log data may be seriously in error in coarse unconsolidated layers.

ENVIRONMENTAL CONTROL ON Vp/Vs RATIO

Comparison of Vp/Vs ratio for the five wells for which suspension velocity logs were collected (figure 1) reveals that two consistent patterns exist (figure 10). The curves for both CCOC and GUAD roll over toward higher values in the upper 150-200 m, whereas those for STGA, STPK, and MGCY do not. CCOC and GUAD both lie in the axial drainage area of the valley, and therefore probably represent largely fluvial sediment, whereas the others lie to the west in an alluvial fan environment. The implication is that there is a consistent difference in velocity structure between the two sedimentary environments in the valley that is effectively revealed by Vp/Vs ratio.

Inspection of the velocity curves for CCOC and STGA (figure 10), representing the two environments, shows that Vs tends to be lower in CCOC than in STGA in the upper part of the hole, but that Vp tends to be somewhat lower as well.

CONCLUSIONS

The Coyote Creek site and borehole are relatively simple geologically, consisting of about 400 meters of flat-lying alluvial sediments overlying a subhorizontal basement unconformity. The nearby Silver Creek fault and probable associated deformation do not seem to affect the site, and the inferred depositional flow direction implies that CCOC stratigraphy probably extends upstream through the nearby William Street Park where some of the velocity experiments were performed.

The stratigraphic section, which is layered at several scales and contains three prominent fining-upward sedimentary cycles in its upper part, can be defined in considerable detail. Lithologic layering determined from the geophysical logs and confirmed by comparison with cores occurs on a scale of 1-30 m and correlates closely with detailed variations in P- and S-wave velocity. The uppermost fining-upward cycle is the Holocene cycle of alluviation, as indicated both by lack of consolidation and control from radiocarbon dates. The balance of the 300-m section is almost entirely above the Bruhnes/Matuyama paleomagnetic boundary, and is therefore largely less than 780,000 years old. Extrapolation to the base of the section makes that about 1 Ma, and the whole 400-m thick section thus entirely Quaternary.

The suspension velocity logs define detailed velocity structure that includes shallow adjustments to burial and geologic contacts, a low velocity zone at 51 m, and a general increase of velocity and decrease in Vp/Vs ratio with depth. Velocity differs markedly between coarser and finer grained layers. These differences increase downward in the borehole for Vp and Vs, but decrease downward for Vp/Vs ratio. Vp determined from the sonic log generally tracks suspension Vp, but shows anomalously low values in many coarse layers marked by high caliper values (borehole washouts). Vp/Vs ratio for the five wells with suspension velocity logs differs between two sedimentary environments, rolling over to high values in the upper 150 m or so in the fluvial sections but not in the alluvial fan sections.

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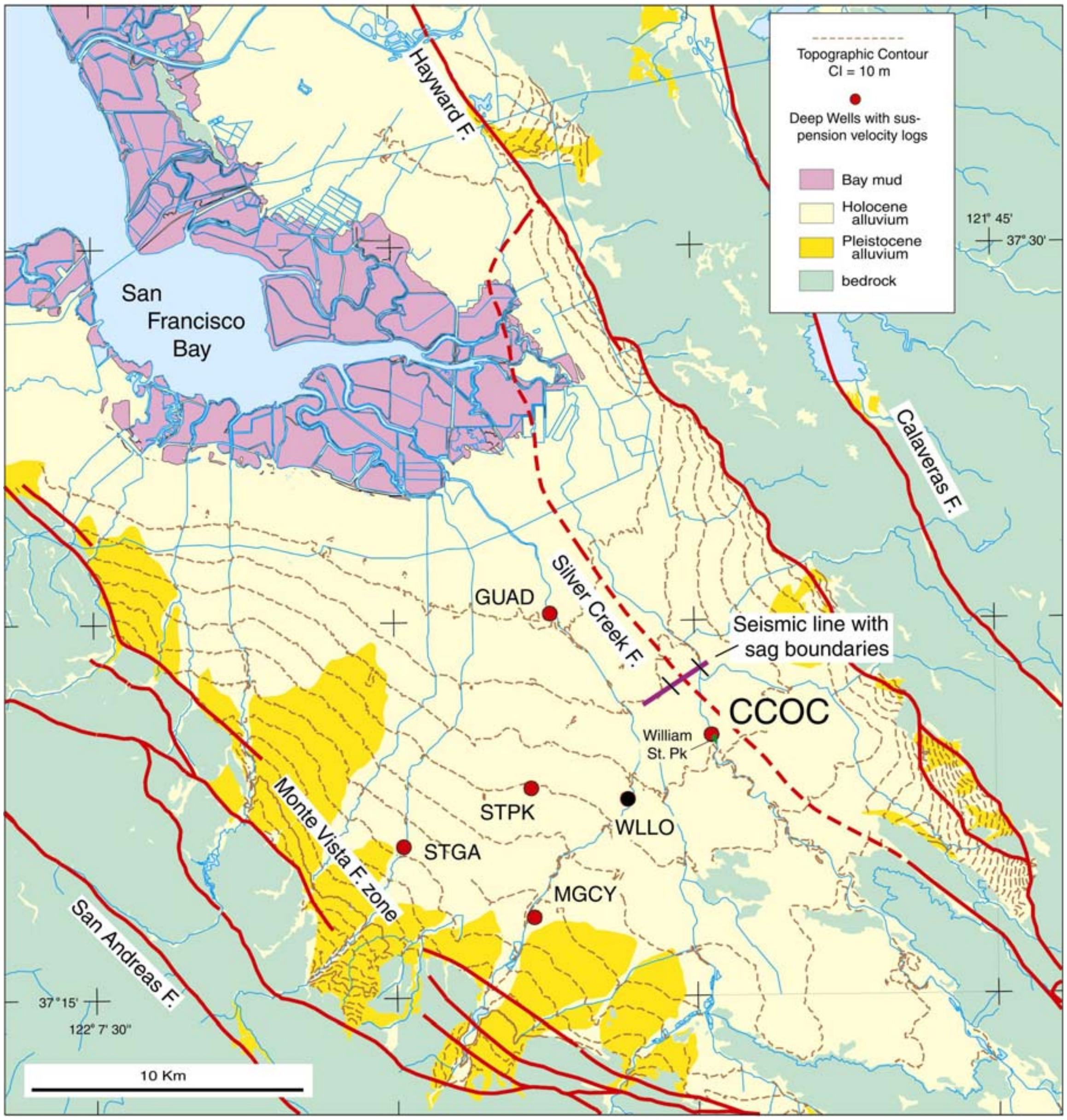

Figure 1. Geologic map of the Santa Clara Valley showing the location of CCOC and adjacent Williarm Street Park, which is largely enclosed by the well symbol. Other wells shown are those with suspension velocity logs plus WLLO, which together with GUAD and MGCY reaches bedrock beneath the Quaternary alluvial section. Note also the topographic surface, the Silver Creek fault, and the location of the seismic reflection profile and associated sag in reflections across that fault (figure 3). Geology compiled from Brabb and others (1998a and b), Graymer and others (1996), Knudsen and others (2000), and Wentworth and others (1998).

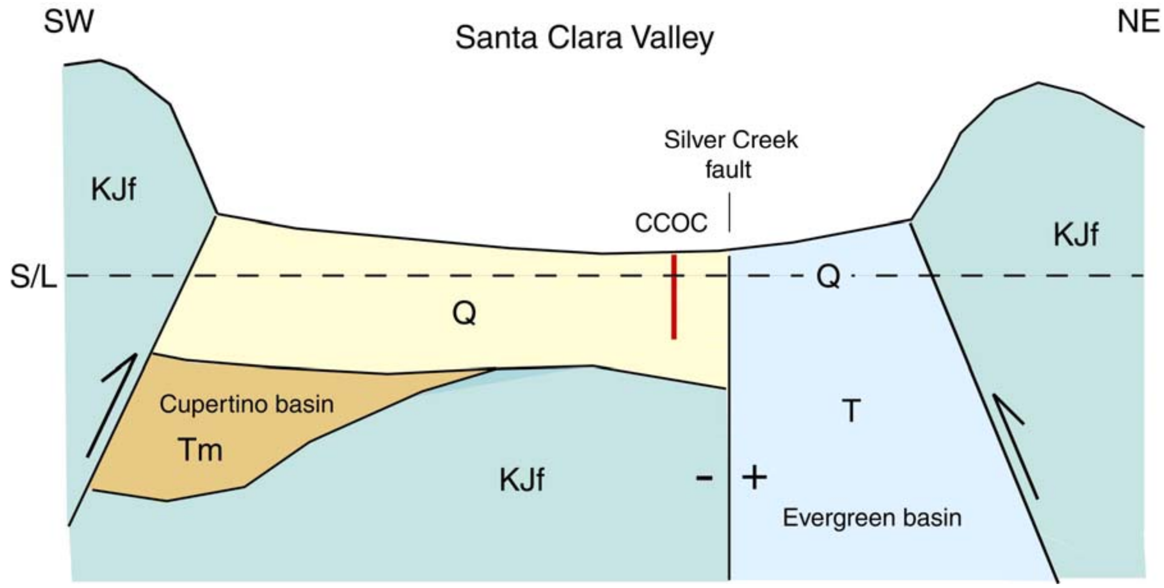

Figure 2. Schematic cross section across the Santa Clara Valley, showing location of the CCOC borehole relative to the Quaternary alluvial section (Q), the basement surface, and the Silver Creek fault. KJf – Franciscan assemblage, Tm – Miocene sedimentary rock, T – Tertiary sedimentary rock. The drawing is not to scale, and involves large vertical exaggeration.

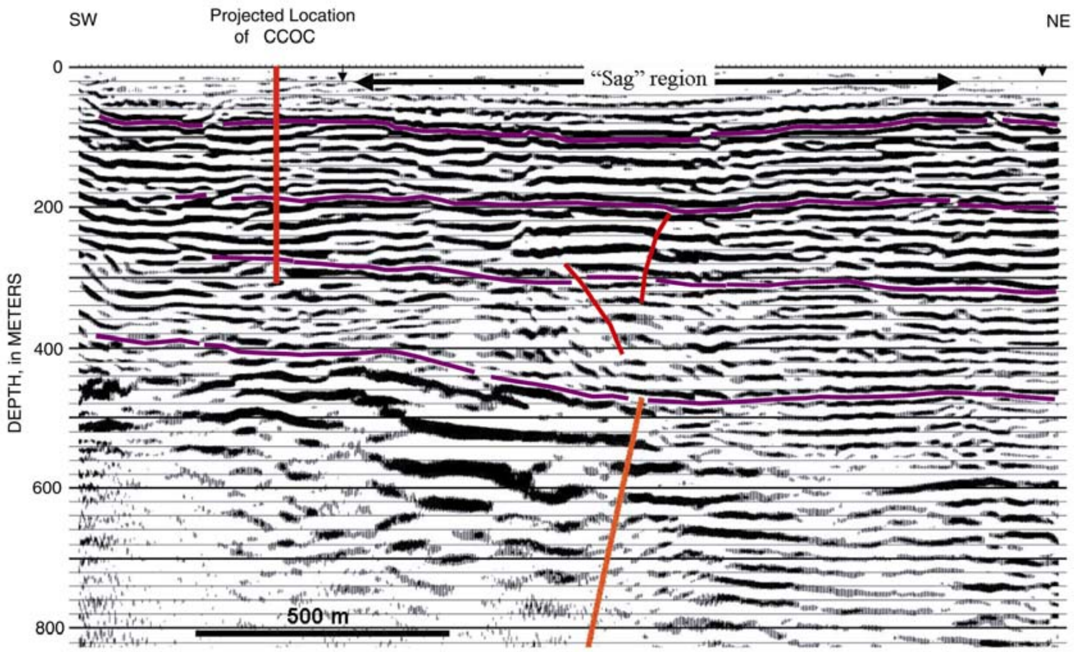

Figure 3. Seismic reflection profile extending northeast from the central basement high across the Silver Creek fault into the Evergreen basin (location shown on figure 1). The Silver Creek fault, selected reflection horizons, and two of the many faults in the sag region are highlighted. Approximate position of the CCOC borehole has been projected northwestward along the strike of the Silver Creek fault from its real location 2.3 km away. Reflection profile provided by R.A. Williams (2004).

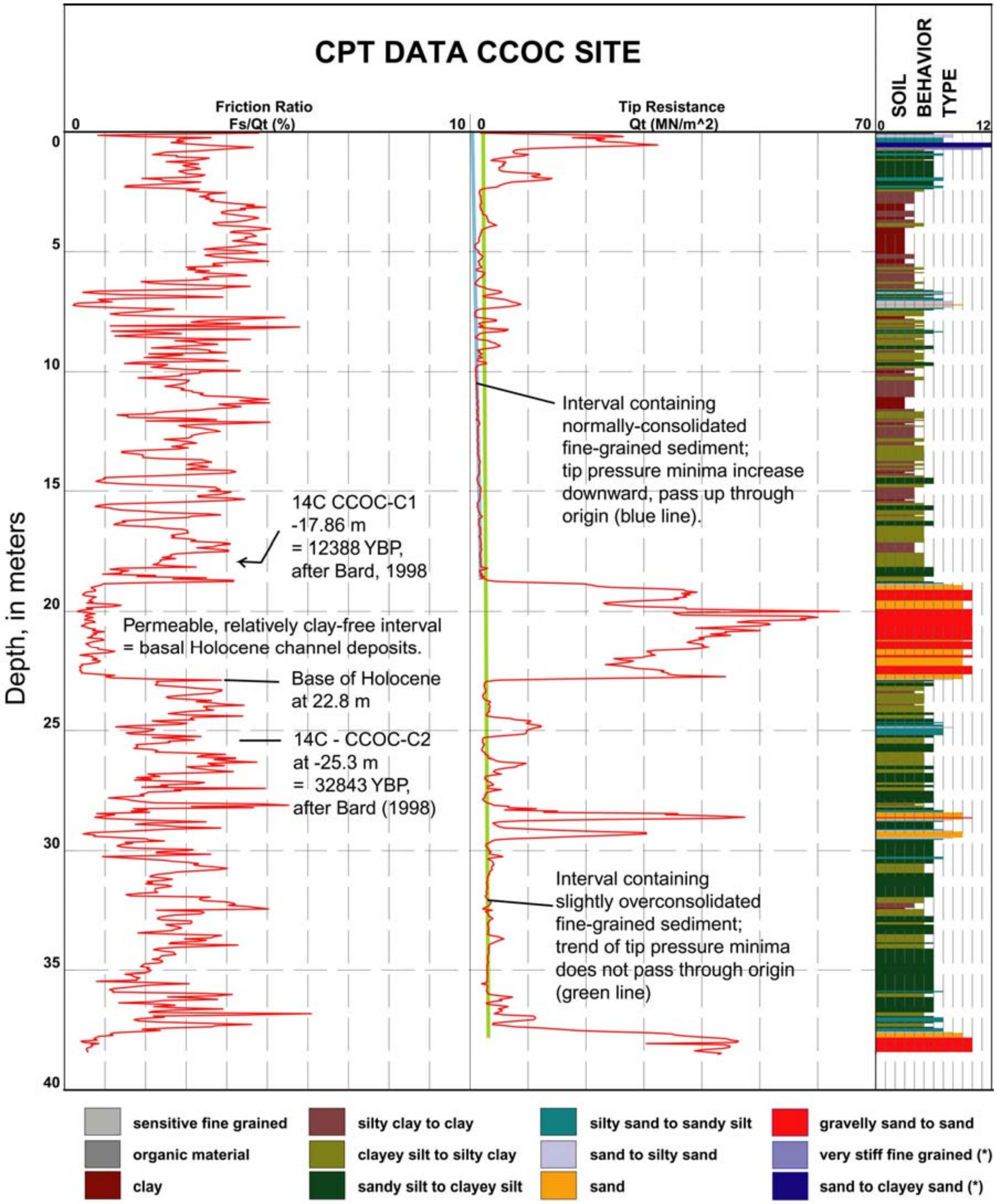

Figure 4. Log of cone penetrometer test at the Coyote Creek drill site (USGS number SCC131). Test performed by T.E. Noce August 24, 2000 prior to the drilling of the borehole. Soil behavior type inferred from friction ratio (Noce and Holzer, 2003).

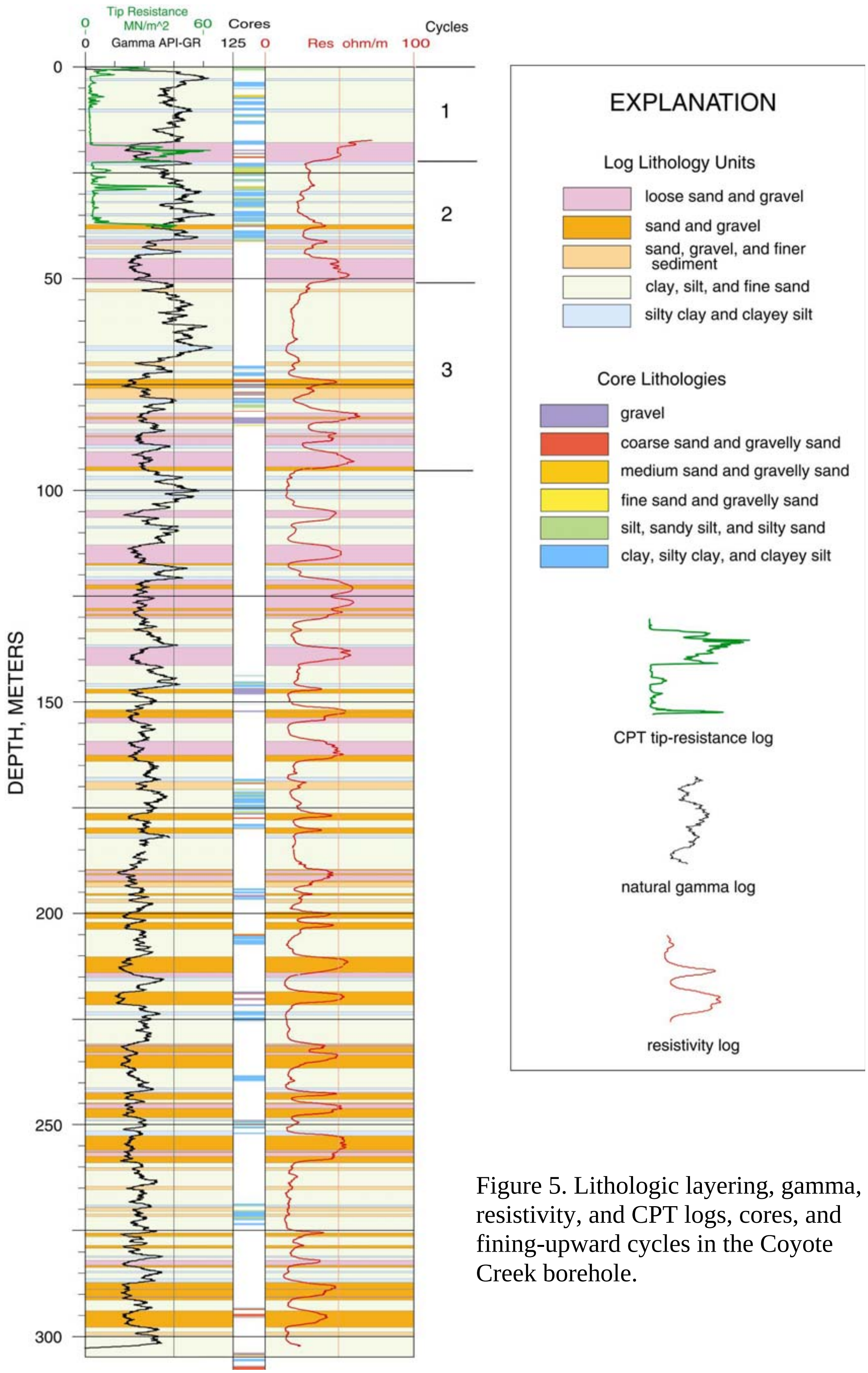

Figure 5. Lithologic layering, gamma, resistivity, and CPT logs, cores, and fining-upward cycles in the Coyote Creek borehole.

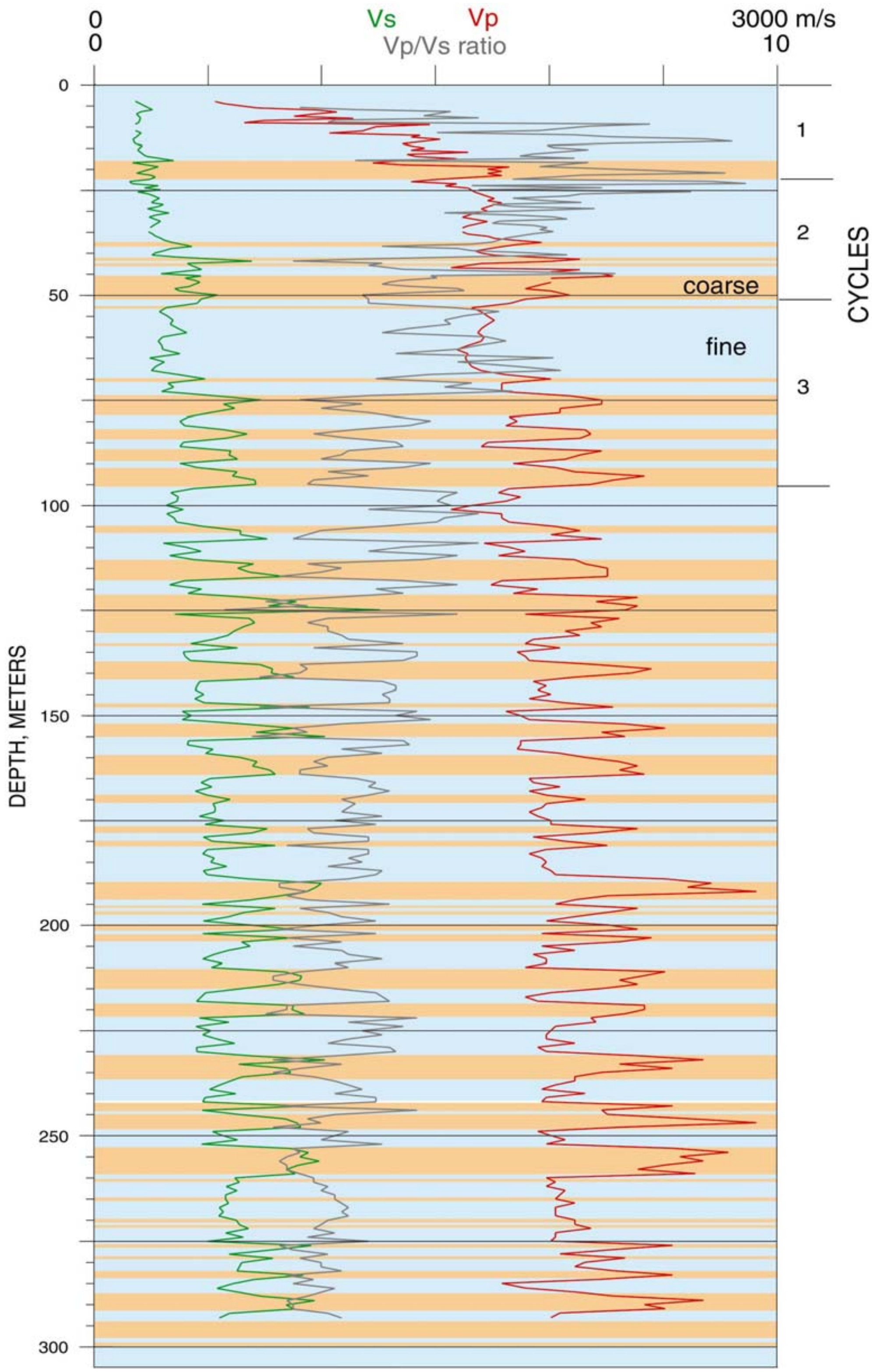

Figure 6. Velocity structure in the Coyote Creek borehole, showing coarse and fine layering, Vp and Vs logs, and Vp/Vs ratio.

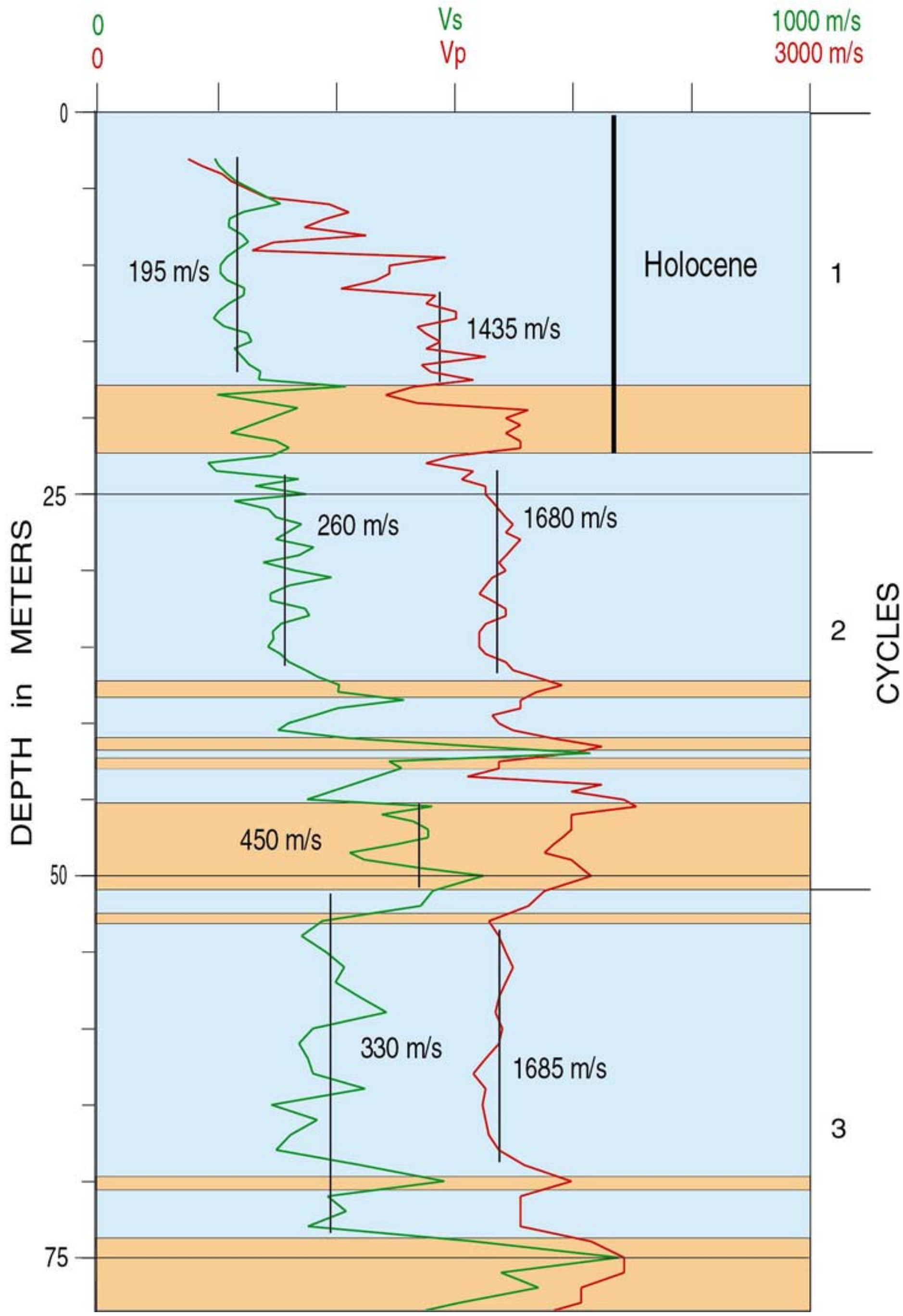

Figure 7. Detail of velocity structure in the uppermost three sedimentary cycles. Coarse and fine layers and Vp and Vs logs as in figure 6. Average velocities over specified depth intervals shown by annotated black bars. Base of cycle 3 is below the depth range of the figure. Note that the Vs and Vp velocity scales are different.

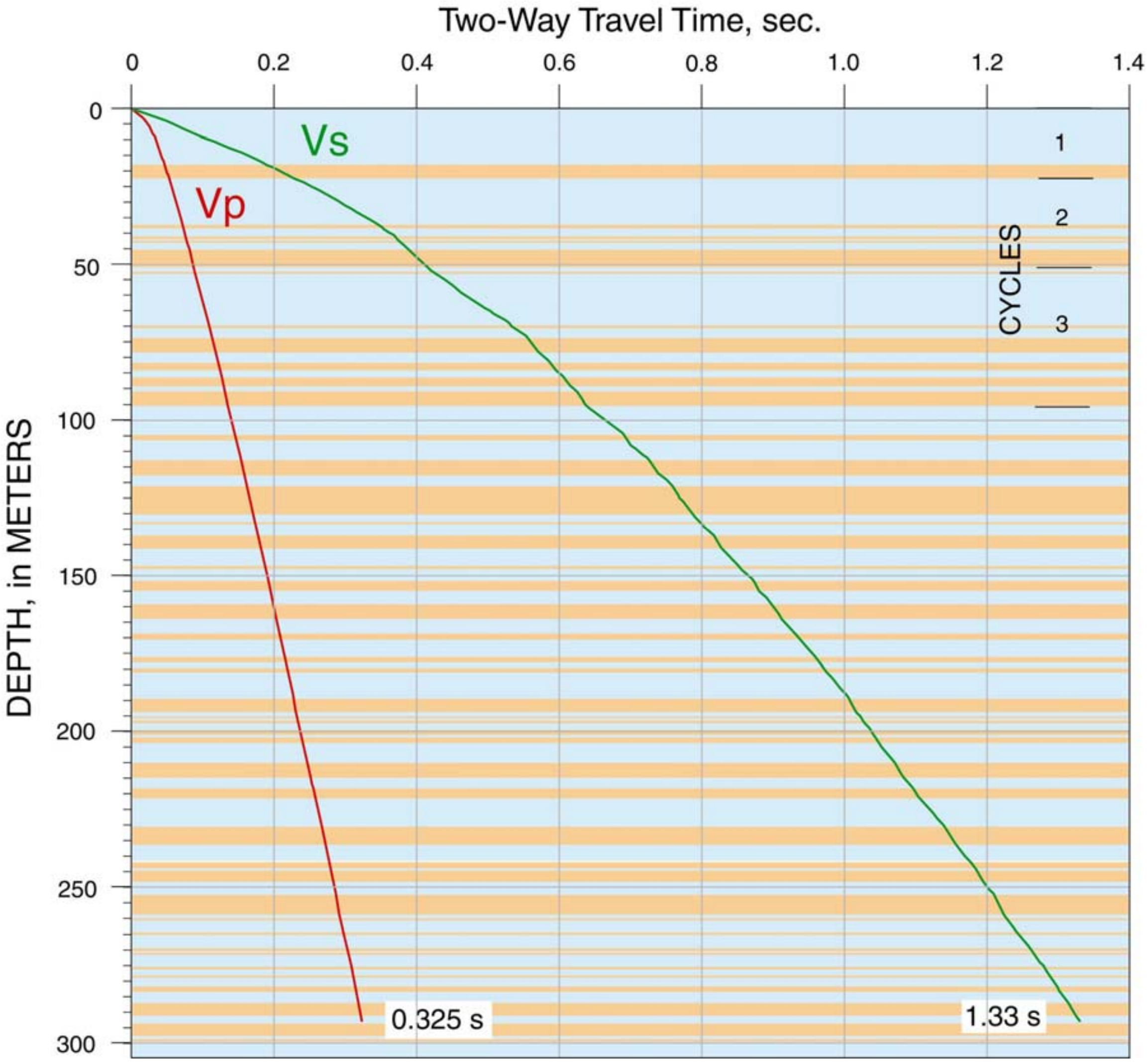

Figure 8. Two-way travel time in CCOC calculated from suspension Vp and Vs.

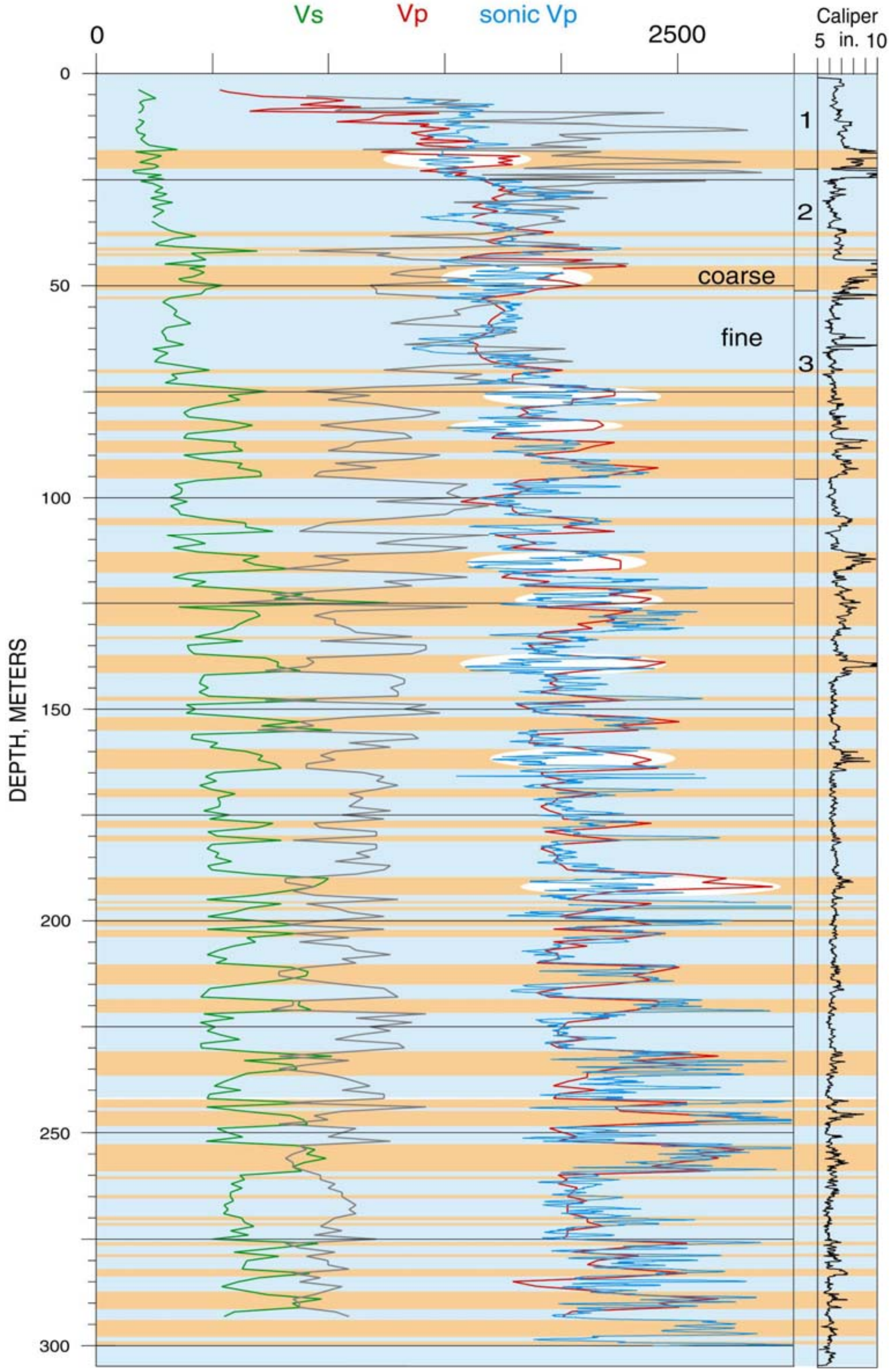

Figure 9. Velocity structure in the Coyote Creek borehole, as in figure 6, showing sonic Vp (blue curve) in comparison with suspension Vp (red), with large disparities between the two in coarse layers highlighted by white ovals. Caliper log (black) at right.

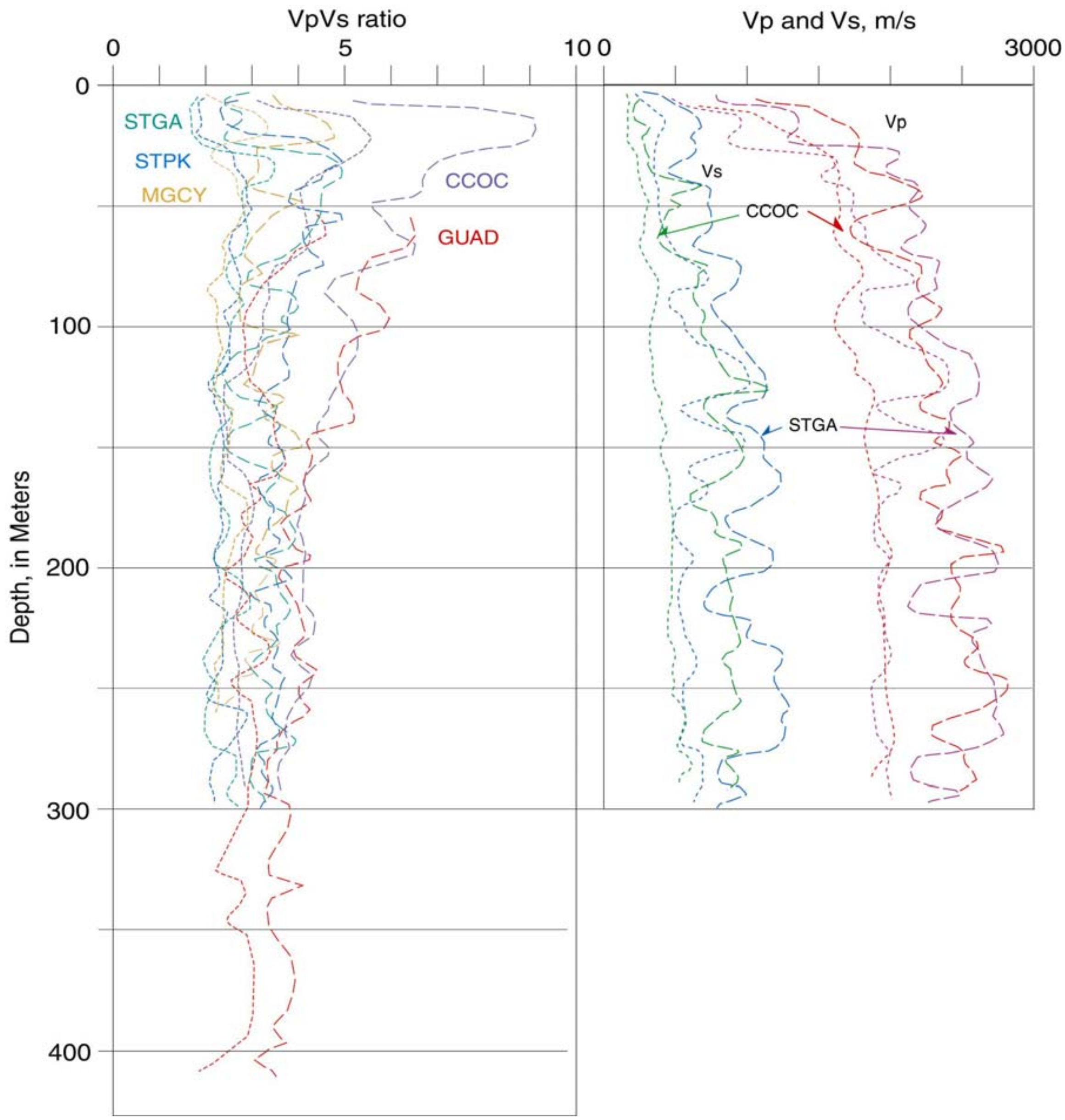

Figure 10. Envelopes on Vp/Vs ratio for the five wells with suspension velocity logs (left) and envelopes on Vp and Vs for CCOC and STGA, representing axial and fan environments, respectively (right). Envelopes on high values dashed, those on low values dotted.