Composition of sediment records late Quaternary paleogeographic evolution of Santa Clara Valley, California

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ABSTRACT

Gravel and sand samples from alluvium in five wells in the Santa Clara Valley, California, have particle compositions that help constrain patterns of Quaternary basin evolution and sediment dispersal within the valley. Samples were collected from depths as great as 307 m, and paleomagnetic results obtained by other workers suggest that the sediment sampled ranges in age to ca. 800 ka. The gravel contains common to abundant Mesozoic graywacke and metavolcanic rocks; less common clast types indicate derivation from other Mesozoic rocks. Clasts having lithologies that match Cenozoic source rocks are minor in amount. The abundance of metavolcanic rocks, as well as serpentine, blueschist, and eclogite, among the less common gravel clasts, generally increases with depth in each well. Sand samples contain a variety of mostly metamorphic heavy minerals, including some distinctive blueschist facies minerals. Blue amphibole and chrome spinel are rare to common in the sand, and their abundance also increases with depth.

The most useful clasts for determining the location of the sediment source are the metavolcanic rocks and some of the less common clasts. Metavolcanic rocks, common in modern outcrops only in the Santa Cruz Mountains south and west of the Santa Clara Valley, also are common in the gravel. In contrast, with only a few exceptions at shallow levels in the northeasternmost wells, distinctive gravel clasts with sources east of the valley are nearly absent. These observations suggest that most of the sediment was derived from the south and west. Thus, the topographic asymmetry of the valley, with its modern axial drainage east of the valley center, evidently has persisted for at least the past 800 k.y. The increased abundance of pebbles of serpentinite, blueschist, and eclogite and of sand-sized particles of blue amphibole and chrome spinel with depth suggests a change in source through time. The source for these clasts in the deeper levels, and perhaps also some of the metavolcanic clasts, evidently was a basement high within the valley that was gradually buried as the basin filled with sediment.

The gravel in the wells has a composition different from that of any previously described outcrops of Pliocene and Pleistocene nonmarine gravels, including the Santa Clara Formation, exposed around the margins of the Santa Clara Valley. This difference suggests that the Santa Clara Formation and similar units are not present in the parts of the valley penetrated by the wells.

INTRODUCTION

The Santa Clara Valley (California, USA; Fig. 1) is a tectonically active, subsiding sedimentary basin southeast of San Francisco Bay that is between strike-slip faults of the San Andreas transform system. Quaternary sediment within the valley provides a record of its history. Earlier work (e.g., Wentworth et al., 2005, 2015) provided important information about this history, and the composition of medium sand from the valley was described (Locke, 2011), but many questions remain unanswered, and other components of the sediment have not been previously described in detail. Additional knowledge of the depositional history of sediment within the basin will contribute to an understanding of the tectonic development of the basin, modern geologic hazards in the valley, and geometries of the aquifers that provide groundwater within the basin. In addition, this knowledge can be used to help constrain the age of the sediment in the valley by comparison of sediment within the basin to outcrops of known age around the valley. This age constraint will lead to a better understanding of basin evolution.

One approach to understanding the sedimentary history of a basin is to compare the sediment within it with possible sources of that sediment around the basin. This paper describes for the first time the composition of gravel and of heavy minerals in sand samples from five monitoring wells drilled within the basin by the U.S. Geological Survey and the Santa Clara Valley Water District (Newhouse et al., 2004). Our purpose is to use the composition of these samples to constrain sources of the sediment and to shed light on spatial and temporal patterns of sediment dispersal within the basin.

GEOLOGIC SETTING

The Santa Clara Valley is between the Santa Cruz Mountains and the Diablo Range in the California Coast Ranges, southeast of San Francisco Bay (Fig. 1). The San Andreas fault cuts through the Santa Cruz Mountains south and west of the valley, and the Hayward and Calaveras faults are to the north and east. In addition, there is a partially buried basement high (Fig. 2) beneath the central Santa Clara Valley (Wentworth et al., 2010; Langenheim et al., 2015) that has been imaged seismically (Williams et al., 2005, 2015) and modeled based on seismic velocities (Hartell et al., 2006) and gravity and other data (Jachens et al., 2001).
Sources of the sediment in the valley include Mesozoic and Cenozoic rock units exposed in the mountains to the west, south, and east of the valley (Fig. 2). The Mesozoic units comprise moderately to strongly metamorphosed rocks of the Franciscan Complex, which is a subduction assemblage, and the structurally overlying Coast Range ophiolite and forearc-basin sedimentary rocks of the Great Valley group (Wentworth et al., 1998; Brabb et al., 2000; Elder, 2013). Generally unmetamorphosed Tertiary sedimentary and minor volcanic rocks overlie the Mesozoic rocks. Pliocene–Pleistocene nonmarine units, which may in part be correlative with the alluvium in the valley, include the Santa Clara Formation and the Irvington, Packwood, and Silver Creek gravels.

Pliocene–Pleistocene marine units exposed in the mountains to the west, south, and east of the valley conformably or unconformably, older sediment of probable late Cenozoic age in the Evergreen basin (Williams et al., 2005; Wentworth et al., 2010, 2015). The upper ~300 m of the Quaternary alluvium was divided into 8 upward-fining depositional sequences by Wentworth and Tinsley (2005) and Wentworth et al. (2015). Wentworth and Tinsley (2005) attributed these sequences to variations in climate associated with Quaternary glacial-interglacial cycles, with the sequence boundaries representing unconformities developed during global glacial maxima and the sequences recording sediment accumulation mostly soon after glacial maxima and during interglacial times. Seven of these sequences are present in all of the wells discussed herein, although the youngest is very thin in the southernmost well. The eighth sequence and part of a ninth underlying sequence are present in three of the wells. The oldest part of the alluvium sampled for this study is from this ninth sequence and was deposited ca. 800 ka, based on paleomagnetic data from one of these wells (Mankinen and Wentworth, 2003). In this paper we use the sequences defined by Wentworth and Tinsley (2005) to help clarify stratigraphic correlations of our samples.

Methods

We collected samples of gravel and sand from five wells drilled within the Santa Clara Valley. These are the Coyote Creek Outdoor Classroom (CCOC), Guadalupe (GUAD), McGlincy (MGCY), Santana Park (STPK), and Willow (WLLO) wells (Fig. 2). We collected samples at the most uniform possible spacing with depth, so the sample patterns do not necessarily reflect the abundance of gravel or sand. In addition, gravel and sand samples were collected independently and do not come from the same depths.

Gravel was collected from the shaker table at each well during drilling. Gravel samples were washed, dried, and sieved to isolate the 8–16 mm size fraction (medium pebbles). These pebbles were then identified using a binocular microscope. To enhance identification, some clasts were etched with hydrofluoric acid, and thin sections of 50 pebbles were studied using a petrographic microscope.

Sand samples were collected from cores from the same wells. Samples, generally representing an interval ~2 cm thick, were taken from the interior of the cores to avoid contamination, then disaggregated in an ultrasonic bath, washed, dried, and sieved to isolate the medium and fine sand fractions. The medium-grained sand from these samples was studied (Locke, 2011), and we describe here the heavy minerals from the fine sand. Dense grains, including heavy minerals and heavy-mineral–bearing rock fragments, were separated from the fine sand with bromoform. Grains were mounted in epoxy, and thin sections of 50 pebbles were studied using a petrographic microscope.

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Figure 2. Geologic map showing distribution of rock units around the Santa Clara Valley (after Wentworth et al., 1998; Brabb et al., 2000). Location of Arastradero lithofacies is from Vanderhurst (1981). Wells discussed in this report are Coyote Creek Outdoor Classroom (CCOC), Guadalupe (GUAD), McGlincy (MGCY), Santana Park (STPK), and Willow (WLLO). Cupertino and Evergreen basins (after Langenheim et al., 2015) are concealed beneath Quaternary alluvium and indicated by diagonal lines. Area under San José between these basins is a buried basement high.
RESULTS

Gravel

We studied 44 samples of gravel, collected from depths to 284 m. We counted at least 300 medium pebbles in each, where possible (in 30 of the samples); the average number of clasts per sample was 353, with a minimum of 149. We analyzed 10 or 12 samples of gravel from each of 4 of the wells, but only 2 of the samples from the GUAD well yielded enough medium pebbles to compare with the other samples.

The results of pebble counts are listed in Supplemental Table 1 and summarized in Figure 3. The figure shows the relative proportions of graywacke, metavolcanic rocks, and all other rock types in the well samples. Also shown for comparison are modal compositions of samples from three upper Cenozoic alluvial units, the Santa Clara Formation (Vanderhurst, 1981), and the Packwood and Silver Creek gravels (Wills, 1995).

The most abundant constituent in each of the gravel samples from the wells is slightly to strongly metamorphosed graywacke, which ranges from ~34% to 73% of all clasts; 16% of the graywacke contains quartz veins; 6% is visibly foliated. Metavolcanic rocks, mostly greenstone, are also common in nearly all of the well samples. Other constituents relatively common in some samples include argillite, radiolarian chert, and vein quartz. All of these abundant and common rock types occur in one or more of the Mesozoic rock units that crop out in the mountains on three sides of the Santa Clara Valley, including the Franciscan Complex, the Coast Range ophiolite, and the Great Valley group (Wentworth et al., 1998; Brabb et al., 2000). Tonalite, gabbro, ultramafic igneous rocks, metadiabase, serpentinite, eclogite, blueschist, and other schist are present in the gravel but are less abundant. All of these rock types also occur in Mesozoic source rocks. Granite, diorite, volcanic porphyry, and quartzite, which are present but relatively rare in the samples, also occur as clasts in conglomerate in the Mesozoic rocks. The Mesozoic rocks described here make up ~90% of the clasts in our gravel samples. The remaining 10% are clasts of sedimentary and volcanic rocks, which resemble rocks of Cenozoic age in the mountains adjacent to the Santa Clara Valley (Wentworth et al., 1998; Brabb et al., 2000).

There is some spatial variation in the percentages of different types of clasts among the well samples. Some samples from CCOC and WLLO are similar to samples from the other wells, but samples from those two wells have a wider range of compositions and include some with considerably lower proportions of graywacke and correspondingly higher percentages of other types of clasts, especially metavolcanic clasts and chert (Supplemental Table 1).
Gravel composition also varies with depth in the wells, but no conspicuous layers of distinct composition can be correlated from well to well. Figure 4 shows that graywacke percentage generally decreases slightly with increasing depth. In addition, the proportion of graywacke that has quartz veins increases from 15% in shallower samples to 22% in deeper ones, and the proportion that is visibly foliated increases from 5% in shallower samples to 10% in deeper ones.

In the 4 wells with 10 or more samples of gravel (CCOC, MGCY, STPK, and WLLO), the decrease in graywacke with depth generally is accompanied by a slight to pronounced increase in metavolcanic rocks (Fig. 5) and some of the minor constituents, including serpentinite, blueschist, and eclogite (Fig. 6). A sample from ~20 m in STPK, with 5% serpentinite, is a notable exception. The very deepest samples from CCOC, STPK, and WLLO have somewhat lower concentrations of the minor constituents than do samples above them and are also exceptions to the latter trend.

Two significant types of clasts are rare in the gravel studied here: laminated chert and porphyritic volcanic rocks. Laminated chert was identified as a very minor component in only 4 of 44 samples (8 clasts in total). Seven of these clasts are in samples from CCOC and GUAD, the two northeasternmost wells. Five of these seven clasts are in sequence 3 and two are in sequence 1 of Wentworth et al. (2015). Porphyritic volcanic clasts are more common than laminated chert; they make up ~1% of all clasts counted but are not abundant in any sample.

Abundant gravel is present in both shallow and deep samples from CCOC and WLLO. In GUAD, MGCY, and STPK, however, gravel was recovered only from relatively shallow depths, and only a few medium pebbles are present in samples from deeper levels.

The MGCY well is of particular interest for potential correlation with surface outcrops, because it is the closest well to outcrops of the upper Cenozoic Santa Clara Formation. The deepest counted sample from this well shown in Figures 3–6 is from a depth of ~125 m. Qualitative inspection of deeper samples, one from a depth of 240 m, shows that the deeper gravel is mostly graywacke with common metavolcanic clasts and a variety of other rock types, including a small amount of serpentinite. These deeper gravel samples are all different from gravel in the Santa Clara Formation (Fig. 3) and thus likely reflect a different source.

### Sand

We studied 50 samples of sand from the wells, representing depths from 14 to 307 m. The proportion of dense grains (specific gravity >2.89) in the finesand fraction of the samples ranges from <1% to >23%. The abundance of dense grains generally but irregularly increases with depth (Fig. 7).

Supplemental Table 2 summarizes grain counts of the heavy minerals in monomineralic dense grains and shows that >80% of the dense grains are polycrystalline rock fragments that contain heavy minerals. A grain was considered monomineralic if one mineral makes up >90% of the grain. Approximately 40% of the nonopaque monomineralic grains are polycrystalline aggregates of one heavy mineral, and the rest are monocrystalline heavy minerals. We counted at least 300 nonopaque monomineralic grains in each sample, where possible (in 42 of the samples). The average number of grains counted per sample was 312; the minimum was 129.
Amphiboles are the most abundant heavy minerals in both monomineralic grains and polyminerallc rock fragments. Most amphiboles are colorless or light green in thin section, and some are blue; dark amphiboles are rare. Microprobe data indicate that the amphiboles include actinolite, edenite, tschermakite, glaucophane, ferroglaucophane, winchite, and magnesiohornblende, using the terminology of Leake et al. (1997). Clinopyroxenes also are common in most samples; most are colorless in thin section. Microprobe data indicate that the clinopyroxenes include augite, diopside, and omphacite, using the criteria of Morimoto et al. (1988). Epidote and garnet were observed in all samples and are common in some. Jadeite, zircon, orthopyroxene, pumpellyite, sphene, biotite, and tourmaline are present but rare. Chrome spinel was observed as monomineralic grains in most samples, and it is common in several. It also is present in serpentinite rock fragments in most samples. Carbonate grains, mostly clear and monocrystalline, were detected in fewer than half of the samples, but make up >10% of the grains in some of them. Opaque grains include common magnetite, hematite, and pyrite. We did not observe any clear trends in the spatial distribution of types of dense grains from well to well, but we did observe variations with depth in the abundances of two minor constituents: blue amphibole and chrome spinel.

Blue amphibole abundance generally increases with depth (Fig. 8). It is not detected or is present in small amounts in most of the samples from depths <150 m, and it generally increases in abundance in samples from depths >150 m. For example, blue amphibole makes up >14% of the sample from 191 m in MGCY and nearly 17% of the sample from 304 m in STPK. All but 2 of the samples with >10% blue amphibole occur within or below sequence 5 of Wentworth et al. (2015), and samples with relatively abundant blue amphibole are present in all of the wells at these deeper levels. The 2 samples with >10% blue amphibole in younger sediment are both from sequence 3 in CCOC, from ~75 m and 80 m, each with nearly 12% blue amphibole. The sample from 80 m also contains nearly 5% jadeite (Supplemental Table 2). A sample from sequence 3 at 82 m in GUAD has 6% blue amphibole and >7% jadeite.

In addition, chrome spinel generally is more abundant in samples from the deeper parts of each well (Fig. 9). For example, 3 samples from sequence 5 of Wentworth et al. (2015) in MCGY and WOLLO each contain >20% chrome spinel, and the deepest sample from WOLLO, 6 m above the serpentinite bedrock at the bottom of the well, has >50%. Most of the samples with >10% chrome spinel occur within or below sequence 5. Samples from ~17 m in MGCY and 73 m in STPK are exceptions, with high concentrations of chrome spinel at shallow depths. In contrast, all samples from GUAD have a relatively low percentage of chrome spinel.

Microprobe data indicate that the chrome spinels in these samples display a considerable compositional range (Fig. 10). The samples with the highest Cr content, with Cr/(Cr + Al) as high as 81%, are from WOLLO, whereas the 2 with the lowest Cr, with Cr/(Cr + Al) as low as 36%, are from MGCY.

**INTERPRETATION AND DISCUSSION**

We use our observations of sediment composition described in this paper to address three main points. (1) We infer which areas in the surrounding mountains supplied most of the sediment. Although there are variations in abundance of some constituents with depth and location, the major compo-
nents, such as graywacke and metavolcanic clasts in the gravel and actinolite in the sand, are similar in all of the samples. This similarity suggests that the same sources have been important since this sediment began to accumulate. (2) Subtle changes in sediment composition suggest that different sources have supplied sediment at least locally over time as the valley evolved. (3) Comparison of sediment in the wells with that from outcrops of known age around the valley helps us to evaluate estimates by other workers of the age of the sediment in the wells.

Sources of the Sediment

We infer that most of the gravel sampled from five wells in the Santa Clara Valley was derived from Mesozoic rocks. Graywacke is present in rocks of the Franciscan Complex and the Great Valley group in mountains on the east, south, and west sides of the valley, whereas metavolcanic rocks are abundant in source rocks to the south and west but not to the east (Wentworth et al., 1998). The abundance of metavolcanic rocks in all of our gravel samples thus suggests that sediment from the south and west reached as far northeast as the CCOC and GUAD wells during the entire time represented by these samples.

Two types of distinctive and durable lithologies that are present in some of the source areas are important because of their rarity in gravel from the wells: laminated chert of the Miocene Claremont Shale, which is widespread in the Diablo Range east of the valley (Wentworth et al., 1998), and slightly to strongly metamorphosed volcanic porphyry, inferred to have been derived from clasts...
in Mesozoic conglomerate, especially from rocks of the Great Valley group east of the valley (Crittenden, 1951; Wills, 1995). The paucity of these two lithologies in our samples suggests that very little gravel from the east side of the valley is present in the wells. Alluvial fans currently are larger on the west side of the valley than on the east, so the valley currently is asymmetric, with the main axial drainages northeast of the center of the valley. This condition evidently has persisted since initial deposition of this sediment, estimated by Mankinen and Wentworth (2003) to be ca. 800 ka. Asymmetric sedimentary basins are common in many tectonically active settings (e.g., Miall, 2000) such as the Santa Clara Valley, and the alluvial fans in this valley also may be larger on the west side partly because there is more rainfall there (e.g., California Water Resources Board, 1955).

Although laminated chert is very rare in the gravel samples studied here, seven of the eight clasts observed are in sequences 1 and 3 of Wentworth et al. (2015) in CCOC and GUAD, the two wells closest to the Diablo Range. These two wells evidently received at least a minor amount of sediment from the east, and this minor sediment mixed with the more abundant sediment from the south and west. This mixing suggests that a main axial drainage of the valley was near the site of these wells at least some of the time.

Most of the heavy minerals in the sand also typically are found in Mesozoic metamorphic rocks surrounding the valley (Elder, 2013). Colorless and pale green amphiboles are common in these Mesozoic rocks. Locally common blue amphibole and rare jadeite, in particular, are distinctive blueschist facies minerals that indicate sources in the high-pressure metamorphic rocks of the Franciscan Complex (Elder, 2013). A few rare grains, such as zircon and tourmaline, are not characteristic of the Mesozoic rocks and may be reworked from Cenozoic sandstone that overlies the Mesozoic rocks.

Oze et al. (2003) described chrome spinel grains from WLLO with fairly high proportions of Cr and Fe. Our data show that chrome spinels are present with a wide range of compositions, reflecting a fairly normal range of chemistry typically found in ophiolites worldwide (Barnes and Roeder, 2001) and, more locally, in the Coast Range ophiolite in Del Puerto Canyon east of San José (Evarts et al., 1999). The few analyses presented here suggest differences in the composition of the spinels from different wells. A larger sample may show whether this variation will be useful for constraining specific sources of sediment for different parts of the valley.

The medium-grained sand fraction of the same samples we describe here was described in Locke (2011), where it was reported that most of the samples are very lithic, with 34%–76% rock fragments, and most of the identifiable lithics are grains of metamorphic rocks. Quartz, including chert, is less abundant than lithics in most samples, averaging slightly >40%, and feldspars are even less common, averaging ~3%. The deepest sample from WLLO, from 238 m, contains ~73% serpentinite. All of those results are consistent with the results and interpretations we present here.

Wong et al. (2013) studied heavy minerals in sand from the San Francisco Bay coastal system, including one sample, their CR_09, from the Guadalupe River ~400 m downstream from the site of the GUAD well described herein; their results for CR_09 are similar to the results reported here (Supplemental Table 2) in that most of the heavy minerals are reported to be amphiboles and pyroxenes, but their results differ from ours in many details. We suggest that these differences are due largely to the different methods used in the two studies. Wong et al. (2013) studied whole sand grains mounted in epoxy, whereas we studied standard thin sections; in their grain mount of CR_09, many of the sand grains appear dark. Wong et al. (2013) identified most of the amphiboles, for example, as hornblende. In our thin sections, in contrast, most of the amphiboles are colorless or light green. Our microprobe data confirm that these pale amphiboles are actinolite and not hornblende. In addition, polyminerallc rock fragments, which in our results far outnumber the monomineralic grains, are much easier to recognize in thin section than in a grain mount.

### Paleogeographic Evolution of the Valley

We infer that patterns of sediment dispersal in the valley changed subtly through time. The major constituents of gravel and sand samples change little with depth in the wells, and we do not recognize different layers of sediment from different sources. Our data are thus not very helpful in corroborating the correlations of Wentworth et al. (2015), which are based largely on sediment texture, but our analyses do not contradict those correlations. Some of the less abundant constituents of our samples change with depth, and these changes may be significant.

Small changes in composition of gravel and sand with depth suggest at least a partial change in the sediment source over time. Metavolcanic rocks are more abundant in the deeper parts of CCOC and WLLO than at shallower levels (Fig. 5), and serpentinite, blueschist, and eclogite, although present in minor amounts in most of the well gravel samples, generally are more common near the bottom of CCOC, MGCY, STPK, and WLLO wells (Fig. 6). A sample from 20 m in STPK, with 5% serpentinite, is a striking exception. Graywacke pebbles with quartz veins and/or foliation also increase with increasing depth in the wells. There is a fairly consistent increase with increasing depth in the abundance of dense sand grains (Fig. 7) and in the proportion of dense grains that are blue amphibole (Fig. 8) and chrome spinel (Fig. 9). The marked shift in all of the wells from low concentrations of blue amphiboles above sequence 5 of Wentworth et al. (2015) to higher concentrations in and below sequence 5, in particular, suggests a change in sediment source.

Our findings support the idea that the sediment in deeper well levels was derived from a nearby source of metamorphic rocks. We suggest that this source is the now-buried basement high near the center of the valley (Fig. 11A). The abundance in the deepest samples of serpentinite, blueschist, and eclogite in the gravel and of chrome spinel and blue amphibole in the sand suggests that rocks in this basement high include the Coast Range ophiolite and the Franciscan Complex. Because ophiolite at the site of the WLLO well was exposed during deposition of sequence 8 of Wentworth et al. (2015), it is unclear how metavolcanic clasts, which are common in the deepest samples
from CCOC, reached the site of that well. Clasts may have been carried eastward from the Santa Cruz Mountains and then northward into the Santa Clara Valley, in much the same way as some sediment from the southern Santa Cruz Mountains is carried into the valley today. If so, streams carrying that sediment must have crossed exposed bedrock of the basement high. Alternatively, these metavolcanic clasts (and others) might have been derived from the basement high, as suggested in Locke (2011). As the valley filled with sediment, the basement high became partially buried (Fig. 11B). Data from the gravel (Figs. 5 and 6) and the sand (Figs. 7–9) suggest that the basement high contributed much less sediment after deposition of sequence 5 of Wentworth et al. (2015) than before.

The abundance of blue amphibole and jadeite in some sand samples and the rare occurrence of laminated chert clasts in the gravel may indicate another change in sediment source in the northeastern part of the valley. The concentration of blue amphibole in sand from CCOC and GUAD is higher in the three samples from sequence 3 of Wentworth et al. (2015) than in other samples from shallow depths (Fig. 8). Two of these three samples also have the highest concentrations of jadeite in all of the samples studied here (Supplemental Table 2). We suggest that the most likely source of the jadeite was the highest concentrations of jadeite in all of the samples studied here (Supplemental Table 2). We suggest that the most likely source of the jadeite was the Santa Clara Formation, but the Stevens Creek typically has more abundant blue amphibole and jadeite and a minor amount of laminated chert from the Diablo Range to the east suggests that, during the time represented by sequence 3, the main axial drainage of the valley was in the vicinity of these two wells (Fig. 11B) and sediment from both the southwest and the northeast mixed there.

Comparison of Well Samples with Nearby Cenozoic Gravels

The composition of subsurface gravel described herein is different from that of any previously described gravel from surface exposures of the upper Cenozoic Santa Clara Formation and the Packwood and Silver Creek gravels (Fig. 3). Gravel from the wells is most similar to the Stevens Creek lithofacies of the Santa Clara Formation, but the Stevens Creek typically has more abundant graywacke and a generally less diverse suite of clast types (Vanderhurst et al., 1982). Gravel in the wells could be correlative with some of these units if the well gravel represents a mixture that developed farther downstream and from a larger drainage basin than that represented by any lithofacies in the Santa Clara Formation. Alternatively, gravel in the wells may be younger than the Santa Clara Formation and may reflect patterns of sediment dispersal that developed after that formation was deposited.

The Silver Creek and the Packwood gravels crop out southeast of the Santa Clara Valley (Fig. 2); they contain generally less graywacke than the well samples and essentially no metavolcanic rocks (Fig. 3). This observation supports the interpretation here that sources of the well samples, which contain common metavolcanics, are within or south and west of the valley, not to the east.

One very distinctive unit in the Santa Clara Formation is the Arastradero lithofacies, which crops out west of the valley (Fig. 2). It contains fossils of an age considered to be late Pliocene or earliest Pleistocene when the fossils

Figure 11. Maps showing inferred sediment dispersal paths (arrows) within the Santa Clara Valley during two time periods. Most sediment evidently was transported from the south and west; a minor amount of sediment from the east is recognized only in a few shallow samples from CCOC and GUAD. (A) Time ca. 700 ka; blue shading (paleobedrock) indicates previously exposed bedrock, mostly a basement high, which contributed some sediment to the valley. (B) Time ca. 300 ka and later; previously exposed bedrock in the center of the valley is becoming increasingly buried, and axial drainage may have been near CCOC and GUAD some of the time. See caption of Figure 2 for names of wells. Modern San Francisco (S.F.) Bay location is shown for reference.
were first described (Adam et al., 1983), but which has been reassigned to the early Pleistocene (Finney, 2010; Gibbard et al., 2010). The Arastradero contains common clasts of the laminated Claremont chert and Mesozoic porphyry. Because sources of these clasts are widespread east of the valley, and missing or rare west of the valley, their presence led Vanderhurst et al. (1982) to suggest that much of the sediment in the Arastradero was derived from the east and transported to the depositional site by streams that crossed the valley from northeast to southwest. The fact that well samples we studied contain only very rare laminated chert and minor volcanic porphyry suggests that Arastradero gravel is not present in any of the wells sampled for this study. These relations suggest three possible causes: (1) gravel of the Arastradero lithofacies once was present in the valley but was stripped away before the gravel in the wells was deposited; (2) gravel of the Arastradero lithofacies is present below depths reached by the wells that did not penetrate older bedrock; or (3) sediment was transported across exposed bedrock in the valley but not deposited there, bypassing the area sampled by the wells. In any case, it seems likely that the gravel in the wells is younger than the early Pleistocene Arastradero. This finding is consistent with the interpretation of paleomagnetic results from the CCOC well by Mankinen and Wentworth (2003) that the section penetrated by these wells and described here was deposited after ca. 800 ka.

**CONCLUSIONS**

Gravel from five wells drilled in Quaternary alluvium in the Santa Clara Valley is composed mostly of moderately to strongly metamorphosed graywacke and metavolcanic rocks inferred to have been derived from Mesozoic sources, primarily in the Santa Cruz Mountains south and west of the valley. Sand from the same wells also contains heavy minerals evidently derived from metamorphic rocks. Serpentinite, blueschist, and eclogite in the gravel and blue amphibole and chrome spinel in the sand generally have low abundances in samples from shallow depths, but they are more abundant in samples collected at depths >150 m, within and below sequence 5 of Wentworth et al. (2015). Metavolcanic rocks also are more abundant in deeper samples from CCOC and WLLO. These observations suggest that a basement high containing these materials contributed sediment to the sites of the wells during the early stages of sediment accumulation. The decrease in the abundance of these types of grains in younger sediment is inferred to record the burial of this basement high with time, so that an increasing proportion of the sediment was derived from the mountains around the valley.

We conclude that very little sediment in these wells was derived from sources in the Diablo Range to the east. An exception is the occurrence in the two northeasternmost wells in sequence 3 of Wentworth et al. (2015) of rare clasts of laminated chert and relatively high concentrations of blue amphibole and jadeite in several samples. The chert and jadeite have a source in the Diablo Range to the east, and the amphiboles may have come from the Diablo Range.

The composition of gravel in the wells is different from that of any previously described lithofacies of the Santa Clara Formation and the Packwood and Silver Creek gravels, which crop out around the margins of the valley. Either the well samples represent different mixtures of sediment, perhaps reflecting a larger drainage basin with more diverse rock assemblages, or these Pliocene and Pleistocene units were not encountered in the wells.

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