Paleomagnetic record determined in cores from deep research wells in the Quaternary Santa Clara basin, California

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ABSTRACT

Paleomagnetic study of cores from six deep wells provides an independent temporal framework for much of the alluvial stratigraphy of the Quaternary basin beneath the Santa Clara Valley. This stratigraphy consists of 8 upward-fining cycles in the upper 300 m of section and an underlying 150 m or more of largely fine-grained sediment. The eight cycles have been correlated with the marine oxygen isotope record, thus providing one means of dating the section. The section has also proved to contain a rich paleomagnetic record despite the intermittent sedimentation characteristic of alluvial environments.

Each well was designed to reach a depth of ~300 m, although 2 were terminated at shallower depth where bedrock was encountered and one (GUAD) was deepened to bedrock at 407.2 m. Cores were taken at intermittent intervals in most of the wells, composing ~20%–25% of their depths. In GUAD an attempt was made to core the entire upper 300 m, with core recovery of 201.8 m (67%).

The paleomagnetic framework ranges from the 32 ka Mono Lake excursion near the top of the second sedimentary cycle to below the 780 ka Brunhes-Matuyama geomagnetic reversal beneath the eighth cycle. These ages nicely fit those assigned to the section based on correlation with the marine oxygen isotope record. Several episodes of anomalous magnetic inclinations were also found within the cyclic section in some of the wells. Some of the episodes of anomalous magnetic inclinations are only separated by short normal intervals in a pattern similar to that described for some well-documented excursions. We consider that a geomagnetic excursion was likely only if the anomalous inclinations were found at approximately the same stratigraphic position in more than one drill hole. A deeper time constraint is provided by the upper boundary (990 ka) of the Jaramillo Normal Polarity Subchron recognized at a depth of 302 m in one deeply penetrating well (GUAD). Approximately 100 m of normal Jaramillo section is evident below that in wells GUAD and EVGR.

The reversal that we identify as the 780 ka Brunhes-Matuyama boundary, found at depths of 291–303 m in three wells, indicates an average rate of deposition in this upper section of ~37 cm/k.y. In GUAD, the top of the underlying normally polarized section, which we assign to the upper part of the Jaramillo Normal Polarity Subchron, was found between 301.8 and 304.5 m. The resultant 10 m of reversed polarity section above the Jaramillo seems anomalously short for this 210 k.y. part of the Matuyama Chron, during which several times that thickness of section probably should have accumulated. This observation indicates that a significant unconformity should be present in that short section between the Jaramillo Subchron and the Brunhes-Matuyama boundary. Deeper cores in two wells (GUAD and EVGR) all have normal polarity and seem to represent much of the Jaramillo Subchron, although no base for that subchron was found. The resultant minimum rate of sedimentation for this lower section beneath the unconformity is 170 cm/k.y.

The Mono Lake (ca. 32 ka), Pringle Falls (ca. 210 ka), and Big Lost (ca. 565 ka) geomagnetic excursions all seem to be represented in the Santa Clara Valley wells. Possible correlations to the Laschamp (ca. 40 ka) and Blake (ca. 110 ka) excursions are also noted. Three additional excursions that have apparently not been previously reported from western North America occur within cycle 6 (between 536 and 433 ka), near the base of cycle 5 (after 433 ka), and near the middle of cycle 2 (before ca. 75 ka).

INTRODUCTION

Stratigraphic and paleomagnetic study of the Quaternary alluvial fill beneath Santa Clara Valley (California, USA; Figs. 1 and 2) has been made possible by the drilling and partial coring of six deep wells in a collaborative effort between the U.S. Geological Survey and the Santa Clara Valley Water District. The immediate purpose of the drilling was for long-term monitoring by the water district of groundwater levels and chemistry, but geologic study of the wells and cores was also possible. The total depth of each of the wells was projected to be ~300 m, although drilling was terminated in 2 wells where bedrock was encountered. One well along Guadalupe Creek (GUAD, Fig. 2) was extended deeper in an effort to reach the bedrock reflection evident in a nearby seismic reflection profile (not shown; Williams et al., 2002), and bedrock was reached at a depth of 407.2 m. Sediment cores were taken at intermittent intervals throughout 5 of the wells, composing ~20%–25% of the total depth of each, whereas in GUAD most of the upper 300 m was cored with recovery of 201.8 m of core (67% recovery). All the section sampled for this study is alluvial, and thus involved intermittent rather than continuous sedimentation, as indicated by soils scattered through the cores. Despite the intermittent deposition and intermittent coring, which guaranteed incomplete sampling through the
time represented by the section, a very rich paleomagnetic record has been obtained for the Santa Clara basin.

The first well drilled under the program (CCOC), begun in September 2000 and located along Coyote Creek, was described in Hanson et al. (2002), Mankinen and Wentworth (2003, 2004), and Newhouse et al. (2004). Stratigraphic studies of the basin were reported by Wentworth et al. (2005, 2010, 2015), the third being a detailed presentation of the physical stratigraphy and subdivision of the upper 300 m of section into 8 repetitive sedimentary cycles separated by unconformities. Here we review the geomagnetic framework and the geologic context of the drill holes and then describe the paleomagnetic results, which provide chronological information and a separate means of correlation among the several wells.

### GEOMAGNETIC FRAMEWORK

#### Geomagnetic Polarity Time Scale

The pattern of reversals of the Earth’s magnetic field during the past 5 m.y. is well established (e.g., see Baksi, 1995; Gradstein et al., 2004); consequently, ages of the reversal boundaries are often used to provide accurate time lines for geologic correlation. We are concerned here with only the youngest reversals (Fig. 3), because the sedimentary section penetrated by the new wells postdates earliest Quaternary time (Wentworth et al., 2015). The ages of the youngest reversal boundaries are very well constrained because lava flows erupted during the various transitions have been found and radiometrically dated. By determining the relative positions of the lower and upper boundaries of these cycles, it is possible to estimate the ages of the reversals and to produce a time-scale for correlation of the well sections.
The Brunhes-Matuyama boundary has been found in Chile (Brown et al., 1994), Tahiti (Chauvin et al., 1990), Maui, Hawaii (Baksi et al., 1992; Coe et al., 2004), La Palma, Canary Islands (Quidelleur and Valet, 1996; Valet et al., 1999), and La Guadeloupe, French West Indies (Carlut et al., 2000). Several of these transitional flows have been dated using the \(^{40}\text{Ar}/^{39}\text{Ar}\) method (Baksi et al., 1992; Singer and Pringle, 1996; Singer et al., 2002, 2005; Coe et al., 2004). The unspiked K-Ar method (Cassignol and Gillot, 1982) was used to date the La Guadeloupe lava flows (Carlut et al., 2000). Although some of the ages group near 795 ka, Singer et al. (2002, 2005) argued that these represent initial instability of the geodynamo and that the actual polarity reversal occurred ~18 k.y. later at 780 ka, generally considered the best age for this boundary. The Matuyama Reversed Polarity Chron lasted from 2581 to 780 ka.

The Jaramillo Normal Polarity Subchron. It was the discovery of this subchron that confirmed the concept of seafloor spreading and helped lead to the modern theory of plate tectonics (Glen, 1982). Although the approximate duration of the Jaramillo has been well known for many years, various attempts have been made to accurately date its boundaries. The \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of transitional lava flows from Tahiti (Singer et al., 1999) indicates that the lower and upper boundaries of this subchron are 1050 and 990 ka, respectively. The other reversal within the latter half of the Matuyama is the Cobb Mountain Normal Polarity Subchron. Although it was of very brief duration (~10–25 k.y.; Mankinen et al., 1978; Clement, 1992), this subchron represents a full reversal of the geomagnetic field that has been recorded worldwide both on land and...
in deep-sea sediments. Re-dating of a rhyolite flow from the type locality by the $^{40}$Ar/$^{39}$Ar method (Turrin et al., 1994) yielded an age of 1186 ± 6 ka for the Cobb Mountain Subchron.

**Geomagnetic Excursions**

In contrast to geomagnetic reversal boundaries, the use of geomagnetic excursions for stratigraphic correlation and dating is much more problematic. Excursions are wide departures from the normal geomagnetic field, typically defined as having occurred when a virtual geomagnetic pole (VGP) departs more than 45° from its time-averaged direction at any given locality. They are generally brief, ranging from ~500 yr to perhaps 3–5 k.y. (Gubbins, 1999), and may record a complete polarity reversal, but more often do not. Excursions may represent extreme variation of normal paleosecular variation, or possibly represent aborted or failed reversals (e.g., Valet et al., 2008). Although unusual magnetization directions have been found in paleomagnetic records from many areas, some have proven to be due to physical disturbances within sedimentary sequences, chemical alteration, remagnetization effects, or other non-geomagnetic processes. Even many probable excursions occur in sedimentary sequences where their age cannot be determined directly by any of the absolute dating methods and thus must be estimated indirectly. A single geomagnetic excursion can appear to occur at different stratigraphic levels in separate geologic sequences because of the presence of hiatuses, variable sedimentation rates, or structural complications. It is easy to understand how the number of suspected excursions can proliferate; ~20–30 have been proposed within the Brunhes Epoch, despite the fact that many sedimentary sequences were deposited too slowly to record any excursions (Roberts and Winklhofer, 2004). For a thorough review of the difficulties in using geomagnetic excursions for geological correlation, see Bol’shakov (2007).

Most of the excursions reported worldwide probably will prove to have occurred during periods of very low dipole intensity, which typically lasted some tens of thousands of years (e.g., see Guyodo and Valet, 1999). When the strength of the dipole field is weak, non-dipole fields will predominate and unusual field directions can be expected, albeit generally on a regional rather than global scale, depending on proximity of the site to a strong non-dipole source. Thus, one should not expect anomalous field directions of relatively brief duration (hundreds of years) in different regions to be entirely synchronous or to have the same morphology. As a result, any similarities in geomagnetic behavior over large distances are likely to be coincidental, and attempts at long-range correlation of such excursions should be avoided. Merrill and McFadden (2005) cautioned, based on their analysis of spherical harmonics of the geomagnetic field, that correlation of excursions be limited to angular distances of <30°. Unusual field directions may also occur repeatedly during these weak dipole intervals, as non-dipole features wax and wane or drift geographically (Bullard et al., 1950; Yukutake and Tachinaka, 1968; Merrill and McElhinny, 1983). Lund et al. (1988), for example, reported four recurrences of

Figure 3. Part of the late Cenozoic geomagnetic polarity time scale modified to include those geomagnetic excursions considered most likely to be found in the San Francisco Bay region. Ages are from various sources (see text). Column to the left of the polarity scale is a plot of relative magnetic paleointensity adapted from Valet et al. (2005). Dashed vertical lines on the relative paleointensity curve are the mean values for the Brunhes and the preceding 500 k.y. (Valet et al., 2005). VADM—virtual axial dipole moment.
an excursional waveform, each with diminishing amplitudes, apparently initiated by the Mono Lake excursion ca. 32 ka (calendar years before present). Negrini et al. (1994) similarly described a repeating waveform near an earlier excursion.

**Possible Excursions in the San Francisco Bay Region**

Because of the regional aspect of geomagnetic excursions, the total number of excursions recorded in any given area is probably limited. Accordingly, in Mankinen and Wentworth (2003) discussion was restricted to those excursions that have been reported from the western North America–eastern Pacific region under the assumption that they are the most likely to have been recorded by sediment of the Santa Clara basin. Thus the Mono Lake, Laschamp, Blake, Pringle Falls, and Big Lost were considered to be the most likely excursions to have been recorded near San Francisco Bay during the Brunhes Chron.

**Laschamp Excursion**

The Laschamp excursion was one of the earliest found and best documented, in part because it was recorded in volcanic rocks. Two reversed polarity lava flows were discovered near Laschamp and Olby in the Chaîne des Puys volcanic province (France) by Bonhomme and Babkine (1967). Revised ages obtained using thermoluminescence and 14C methods on sediment baked by the Laschamp lava flows (Huxttable et al., 1978; Gillot et al., 1979), and K-Ar, 40Ar/39Ar, and 230Th/238U methods on the flows (Condomines, 1978; Hall and York, 1978; Gillot et al., 1979) indicated that the age of this excursion was probably in the range 45–40 ka. Excursions occurring at about this time have since been reported from many localities worldwide, in on-land sequences and deep-sea sediments. Extensive new paleomagnetic sampling and age determinations from the Chaîne des Puys provide a revised age of 41.3 ± 0.6 ka for the Laschamp excursion (Laj et al., 2014).

**Mono Lake Excursion**

Following the discovery of the Laschamp excursion, which was initially estimated to have occurred between 20 and 8 k.y. ago (Bonhomme and Zähringer, 1969), Denham and Cox (1971) undertook a paleomagnetic study of the Wilson Creek Formation of Lajoie (1968) near Mono Lake, California (estimated age 30,400–13,300 yr) to search for additional evidence of this excursion. Their study showed that a large, rapid, and counterclockwise excursion of paleomagnetic directions occurred at an estimated 24,600 yr ago (Denham and Cox, 1971; Denham, 1974). Although this anomalous field behavior occurred in the same general time frame as that reported for the Laschamp excursion, the fact that a full reversal in direction was not recorded apparently led the authors (Denham and Cox, 1971; Denham, 1974) to conclude that the Laschamp had not been recorded at Mono Lake. Extensive sampling of the Wilson Creek Formation of Lajoie (1968) at four additional sites along Wilson Creek, northwest of Mono Lake, by Liddicoat and Cox (1979) provided more details about the Mono Lake excursion and the period of time immediately preceding it. Liddicoat and Cox (1979) found that the counterclockwise rotation of the excursion reported by Denham and Cox (1971) was preceded by a larger, clockwise rotation of direction. Other records of what is considered to be the Mono Lake excursion have been reported from southern Oregon (Negrini et al., 2000, 2014), Nevada (Liddicoat, 1992), Ocean Drilling Program (ODP) Site 919 from the Irminger Basin (Channell, 2006), and perhaps the island of Hawaii (Holt et al., 1996).

Dating of tephra in the Summer Lake basin, Oregon (Negrini et al., 2000) yielded an age of ca. 29,500–27,300 yr (radiocarbon years) for the Mono Lake excursion. The age of Ash #15 (midpoint of the Mono Lake excursion) in the Pyramid Lake basin, Nevada (Benson et al., 2003), was determined to be 28,620 ± 300 14C yr B.P. Organic material between 2 intermediate polarity paleomagnetic samples in core 17 from the CCOC drill hole, Santa Clara Valley, California (Mankinen and Wentworth, 2004) yielded an age of 28,090 ± 330 14C yr B.P. (32.8 ± 0.3 ka; calibrated according to Bard, 1998).

There have been suggestions that only a single excursion occurred ca. 40 ka in the Mono Lake basin (e.g., Kent et al., 2002; Guillou et al., 2004; Zimmermann et al., 2004; Cox et al., 2012; Vazquez and Lidzbarski, 2012). These suggestions are based on new radiocarbon dates, ages determined by the 40Ar/39Ar and 230Th/238U methods, and interpretation of a paleointensity correlation to a global reference curve. Several problems with attributing this excursion to the Laschamp have been pointed out (see the discussion by Negrini et al., 2014).

Despite the ongoing controversy concerning the identification of the excursion recorded at Wilson Creek, the preponderence of evidence is that the Mono Lake and Laschamp are separate excursions within this general time interval, with Mono Lake being ~10 k.y. younger. Two excursions in this time frame were recorded from the Southern Hemisphere in the Auckland volcanic field of New Zealand (Cassata et al., 2008). Eight basaltic lava flows with anomalous directions have yielded 40Ar/39Ar ages of 39.1 ± 4.1 and 31.6 ± 1.8 ka. It is important that these excursions all seem to have occurred during the same general interval during which dipole intensities were ~40% below average (Mankinen and Champion, 1993; Laj and Kissel, 1999; Teanby et al., 2002; Laj et al., 2002).

Although the entire interval containing these two excursions was characterized by below normal geomagnetic intensities, two very pronounced drops in paleointensity were recorded by lava flows in the Chaîne des Puys (Cassata et al., 2008). Eight basaltic lava flows with anomalous directions have yielded 40Ar/39Ar ages of 39.1 ± 4.1 and 31.6 ± 1.8 ka. It is important that these excursions all seem to have occurred during the same general interval during which dipole intensities were ~40% below average (Mankinen and Champion, 1993; Laj and Kissel, 1999; Teanby et al., 2002; Laj et al., 2002).

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**Blake Excursion**

Paleomagnetic results from deep-sea cores from the Greater Antilles Outer Ridge indicated a reversed polarity interval within abyssal brown clay deposited during part of the last interglacial period (Smith and Foster, 1968; Denham, 1976; Denham et al., 1977). This excursion has been reported as occurring in numerous deep-sea sediment cores from different oceans, in loess deposits in China and Germany, and has been tentatively identified in a few volcanic rocks. Sedimentary sequences recording this excursion typically show two reversed polarity intervals separated by a short normal interval. Its existence has been generally accepted by many, even though its precise age remained elusive. Estimates of its age have been made using biostratigraphy, correlation with oxygen isotope curves, and with thermoluminescence, fission-track, and K-Ar dating methods. These estimates generally range from 100 ka to as old as 160 ka for some of the volcanic rocks. It is far from certain, however, that all of the supposed correlations to the Blake episode are correct. If sediment at the original locality is representative of marine oxygen isotope stage 5, as seems likely, the excursion probably can be no older than ca. 130 ka (see summary original locality is representative of marine oxygen isotope stage 5, as seems likely, the excursion probably can be no older than ca. 130 ka (see summary).

Intermediate polarity directions found in tuffs and lava flows of the Reykjanes Peninsula, Iceland, by Kristjansson and Gudmundsson (1980), referred to as the Skalamaelfell excursion, were initially correlated with the Laschamp excursion (Levi et al., 1990). However, new $^{40}$Ar/$^{39}$Ar incremental heating experiments on an additional 4 transitional polarity samples from the area yield an age of 91 ± 13 ka (Jicha et al., 2011). Combining these ages with $^{238}$U/$^{230}$Th ages from 2 of the lava flows (Jicha et al., 2011), yields a weighted mean age of 94.1 ± 78 ka for this excursion. Jicha et al. (2011) considered this excursion to be the younger of 2 excursions in the 125–90 ka interval of low geomagnetic field intensity. Results were obtained from $^{40}$Ar/$^{39}$Ar incremental heating and unsiked K-Ar experiments (Singer et al., 2014) on intermediate polarity lava flows from Lipari and Amsterdam Islands, and from New Mexico, USA (the Laguna flow of Champion et al., 1988). The Amsterdam Island lava flow yields an age of 120 ± 12 ka, whereas the Lipari Island and New Mexico flows are 105 ± 1 and 104 ± 12 ka, respectively. Thus the two Blake excursions seem reasonably well determined at 120 and 100 ka. We refer to these two excursions in Figure 2 as Blake 1 and 2, respectively, whereas Jicha et al. (2011) and Singer et al. (2014) referred to the younger as the post-Blake. Although the Blake excursions seem well represented globally, they have not been conclusively documented in the western United States other than at the one locality in New Mexico.

**Pringle Falls Excursion**

Paleomagnetic records from a sedimentary sequence near Pringle Falls, Oregon, revealed a magnetic excursion that Herrero-Bervera et al. (1989) initially correlated with the Blake excursion. This correlation was based on the presence of two reversed intervals separated by a short normal interval similar to the pattern described for the Greater Antilles Outer Ridge cores. Herrero-Bervera et al. (1994) later estimated that the excursion must have occurred between ca. 218 and 171 ka based on $^{40}$Ar/$^{39}$Ar ages on a tephra layer exposed at a second locality near Pringle Falls and tephra from a correlated sequence. Using K-Ar, Ar-Ar, and thermoluminescence ages, along with correlation of tephra layers from various sites within Pleistocene pluviial Lake Chewaucan, Negrini et al. (1994) considered the age of this excursion to most likely be in the interval from ca. 190 to 180 ka. Several lines of evidence point toward deposition of sediment containing both the Pringle Falls and the correlative Summer Lake II excursion (Negrini et al., 1994) as having occurred during oxygen isotope stage 6, compatible with the age ranges reported by Herrero-Bervera et al. (1994) and Negrini et al. (1994). An excursion found only in marine and lake sediment cores, the Iceland Basin excursion (Channell et al., 1997), has been found near the marine isotope stage 6-7 boundary and is a likely correlative. Eight North Atlantic sites with age control from oxygen isotope data yield an age of 190.2 ± 1.8 ka (Channell, 2014) for this excursion.

Cinder cones in the Albuquerque-Belen Basin that record a short excursion (Geissman et al., 1990) have yielded whole-rock K-Ar ages of 155 ± 47 ka, and a $^{206}$Pb/$^{238}$U age of 156 ± 29 ka (Peate et al., 1996). Uncertainties in these ages made it possible that these rocks could be recording either the Blake or Pringle Falls excursions. Basalt from the Albuquerque volcanoes and Ash D from Pringle Falls were redated using the $^{40}$Ar/$^{39}$Ar method (Singer et al., 2008). Results now indicate that excursions at both localities are the same, yielding a weighted mean age of 211 ± 13 ka. Thus there seems to be strong evidence for two excursions occurring in the same general time interval. As with the Blake excursions, we refer to these two excursions as Pringle Falls 1 and 2 in Figure 3.

**Big Lost Excursion**

Shallow negative (reversed) inclinations were recorded by 2 of 13 lava flows sampled in a drill hole from the Snake River Plain, Idaho, by Champion et al. (1981); they determined a whole-rock K-Ar age of 465 ± 50 ka for this episode. This reversed episode was found in a second drill hole (Champion et al., 1988), and additional K-Ar determinations revised its age to 565 ± 14 ka. Intermediate polarity magnetization directions also were found at two sites within the informally designated basaltic andesite of Hootman Ranch (Lanphere et al., 1999) near Mount Lassen, northern California. Based on a $^{40}$Ar/$^{39}$Ar plateau age of 565 ± 12 ka and an isochron age of 576 ± 12 ka for this flow, along with the age of the underlying Rockland tephra (weighted mean plateau age 609 ± 7 ka), Lanphere et al. (2004) considered the andesite of Hootman Ranch to be another record of the Big Lost excursion.

**Late Matuyama Excursion**

Within the late Matuyama Chron, intermediate polarity directions from a rhyolite dome (Cerro Santa Rosa I) in the Valles caldera, New Mexico, along with a K-Ar age of ca. 900 ka led Doell and Dalrymple (1966) to propose that the rhyolite represented the termination of the Jaramillo Normal Polarity
Subchron. With the revised ages (1050–990 ka) for this subchron provided by Singer et al. (1999), it is apparent that Cerro Santa Rosa I episode is distinctly younger than the Jaramillo and represents an excursion during the latter part of the Matuyama Reversed Polarity Chron (Singer and Brown, 2002). The currently accepted age for this excursion, determined by the 40Ar/39Ar method (Singer and Brown, 2002), is 936 ± 8 ka. Singer et al. (1999) also concluded that the Santa Rosa excursion is separate from and ~37 k.y. older than an excursion reported from Haleakala caldera on Maui, Hawaii. Because Cerro Santa Rosa I is an intrusion, however, there is no stratigraphic evidence from this locality to show that two separate excursions occurred in the same general time interval.

A thorough sampling of the Haleakala sequence (Maui; Coe et al., 2004) revealed 16 intermediate polarity lava flows that were bracketed by reversed polarity units, confirming an excursion in the late Matuyama Chron prior to the Brunhes-Matuyama boundary. A mean 40Ar/39Ar age of 900.4 ± 4.7 ka was determined for this excursion, which Coe et al. (2004) referred to as the Kamiatsura event. Only one excursion was recorded in this sequence even though the sequence clearly overlaps the time interval when Cerro Santa Rosa I was emplaced, as evidenced by ages ranging from 961 to 915 ka (Coe et al., 2004) for the reversed polarity lava flows preceding the excursion. Although there is convincing evidence for anomalous geomagnetic field behavior, currently available data are not able to distinguish whether a single excursion ca. 900 ka is represented, or if 2 occurred very close in time, in a fashion similar to the Mono Lake and Laschamp excursions. Preliminary data from the Cascade Range (Lanphere et al., 1997), if confirmed, may indicate that this excursion was recorded by lava flows at Mounts Baker and Hood.

It is unfortunate that the best documented excursion in this interval (Coe et al., 2004) was called the Kamiatsura, because that name is based on a tentative correlation to a single normal polarity lava flow that underlies an undated reversed polarity flow in southwest Japan (Hirooka and Kawai, 1967). The re-calculated K-Ar age (Mankinen and Dalrymple, 1979) for that normal polarity lava is 0.85 ± 0.03 Ma. This age was later correlated with anomalous directions recorded by sediments of the Osaka Group, which are associated with the Kamiatsura Tuff and occur between the Jaramillo and the Brunhes-Matuyama boundary (Maenaka, 1983). Further study of the Osaka Group (Takatsugi and Hyodo, 1995) shows a second, younger excursion overlying the Azuki Tuff, referred to as the Takatsuki excursion. Neither the Takatsuki nor the Kamiatsura excursions have been directly dated; instead, their ages are estimated by extrapolation of sedimentation rates for Holocene marine clay as determined by radiocarbon dating. Takatsugi and Hyodo (1995) estimated that the Takatsuki excursion occurred ca. 0.85 Ma and that the Kamiatsura must be a few tens of thousands of years older, perhaps ca. 0.87 Ma; they also suggested that multiple excursions or regional reversals may have occurred during the period 0.87–0.84 Ma. Only a single excursion at about that time was recorded in marine sediment collected from the Philippine Sea (Horng et al., 2002) that was dated by astronomically tuning the oxygen isotope record from that piston core, with a resulting age of 925–920 ka. It is clear that there were 2, and perhaps 3, excursions ca. 900 ka recorded in the southwest Pacific. There is no certainty as to which of these excursions, if any, the Maui and New Mexico excursions can be correlated. To avoid perpetuating a dubious correlation, we propose that the name Kamiatsura be restricted to the southwest Pacific region. Because the excursion on Maui was recorded by lava flows of the Kula Formation (MacDonald, 1978), we informally refer to the excursions seen on Maui and in New Mexico as the Kula–Santa Rosa excursion, in order to keep the designation regional in scope and to allow a distinction between the two in the event that multiple excursions occurred at nearly the same time.

**Tentative Excursions**

We emphasize the possibility that additional, as yet undetected anomalous magnetic field behavior may have been recorded by rocks of the western United States, although we cannot predict with any degree of certainty where new anomalous directions are likely to be found. One possibility for an additional excursion is a reversed polarity lava flow from the Snake River Plain (site sr40; Tauxe et al., 2004) that yielded a 40Ar/39Ar age of 0.39 ± 0.04 Ma. Because of the low to very low paleointensities occurring at about this same time (e.g., see the VADM curve shown in Fig. 3), Tauxe et al. (2004) suggested the possibility that site sr40 may have recorded a previously unreported excursion. Evidence for three excursions in the age range of our interest (Fig. 3) was reported by Michalk et al. (2013) from the trans-Mexican volcanic belt. These may correspond to the Big Lost, the Kula–Santa Rosa, and a previously unreported excursion from western North America ca. 670 ka. However, errors for all ages (reported at 1σ) are large, and those excursions are considered tentative.

**GEOLOGIC SUMMARY**

The Quaternary section beneath the Santa Clara Valley accumulated in a subsiding basin (the Santa Clara basin) as alluvial deposits supplied primarily from the Santa Cruz Mountains to the west (Fig. 1). This section was described in detail in Wentworth et al. (2015). The basin is between the San Andreas and Hayward-Calaveras faults, and its western and eastern margins are marked by reverse and thrust faults. All sediment sampled by the 6 new drill holes is alluvial (Wentworth et al., 2015), as is the section sampled by a 305 m well (SUNY) drilled in the 1960s (Meade, 1967). Estuarine deposits are present farther north around and beneath San Francisco Bay. The alluvial section (Fig. 4) consists of an upper cyclic sequence ~300 m thick and a lower, finer grained sequence as thick as 150 m or more, all overlying an unconformity on bedrock having more than 365 m of relief. That unconformity is cut across bedrock of the Mesozoic Franciscan Complex and Coast Range Ophiolite beneath the center of the basin and Miocene fill of the buried Cupertino basin to the west; east of the Silver Creek fault it is underlain by late Cenozoic fill of the buried Evergreen basin. No age-diagnostic fossils have been found in the section that might help in its subdivision, and no radiometric ages are available beyond several 14C dates in the shallow section.
The upper, cyclic section contains eight upward-fining cycles of interlayered gravel, sand, silt, and clay that, because of the upward fining, can each be subdivided into a fine top and a coarse bottom (Fig. 5; Wentworth et al., 2015). The cycles and their fine and coarse subdivisions are laterally continuous and extend throughout the basin, and thus can be used in correlating between wells. In Wentworth and Tinsley (2005), a climate-driven process to account for the cyclicity was proposed. An anomalous departure from this generally fining-upward pattern within the cycles occurs in the top of cycle 2, where an upper coarse interval (C2a) within the cycle can be mapped around the basin (Wentworth et al., 2015).

The bases of the eight sedimentary cycles are unconformities that have been correlated with sea-level lowstands indicated by the marine oxygen isotope record (Wentworth and Tinsley, 2005; Wentworth et al., 2015), which yields estimates of the ages of the unconformities that range back to 718 ka in stage 18 at the base of cycle 8 (see Figs. 4 and 5). The early discovery of the Brunhes-Matuyama boundary just beneath the base of cycle 8 in well EVGR, the lower part of the cyclic section is thinned, apparently due to gradual uplift above a presumed underlying thrust (see description of the Evergreen seismic reflection line [EG of Fig. 2] in Williams et al., 2006). As an accumulation of alluvial sediment, the Santa Clara section contains numerous breaks in sedimentation, both at the unconformable base of each of the sedimentary cycles and scattered throughout the section, as indicated by numerous relict soils evident in the well cores (Wentworth et al., 2015). The formation of each of those soils required exposure of the ground surface for periods of tens to thousands of years. Thus the sedimentary section is rife with hiatuses of varying duration, and was sampled by cores scattered through the section that amounted to ~20% of the depth of 5 of the new wells and 66% of the upper 305 m of GUAD.

The time significance of the different parts of the sedimentary cycles varies. The cycle boundaries have been assigned specific ages. The duration of the cycle boundary unconformities is probably relatively short, based on carbon ages near the base of cycle 1 (Fig. 5) and the lack of well-developed soils beneath those boundaries (Wentworth et al., 2015).

Wentworth et al. (2015) subdivided the cycles into laterally continuous coarse bottoms and fine tops, with the bottoms consisting of one to several coarse layers that persist across the basin, above which other less continuous coarse layers come and go. The resistivity curves of Figure 5 indicate this coarse-fine variation in the section, with the peaks representing coarse layers and the troughs representing fine layers (the coarse-fine textural boundary is placed at fine sand). For each cycle, the top and bottom boundaries are of essentially uniform age and limited duration, and according to the model of Wentworth and Tinsley (2005), the laterally persistent basal coarse layers represent relatively brief periods of time, also of essentially uniform age. The interiors of the cycles are probably less regular, marked by various pulses of
Figure 5. Stratigraphic details of wells with cores in the Santa Clara Valley. Bases of sedimentary cycles are marked by green lines, with cycle numbers (black) and boundary ages in thousands of years (green) in central column; coarse basal intervals are in orange and coarse top of cycle 2 (C2a) is in green; resistivity logs are in black (16 inch normal, scale 0–75 ohm-m), and coarseness curves are in red (scale 0%–100%). Carbon ages are recalculated according to Bard (1998). Modified from Figures 11, 14, and 15 of Wentworth et al. (2015).
rapid supply scattered both in time and space, separated by hiatuses of differ-
ning duration, and all superimposed on a generally declining rate of accumu-
lation, which would deny simple linear interpolation of ages between cycle
boundaries. We can thus make fairly confident inter-well correlations between
similar positions near the cycle boundaries and within the basal coarse layers,
but must be more cautious for the cycle interiors. Correlation within a cycle
between positions high in one well and low in another should be avoided;
however, because the age of the boundary within a cycle between its coarse
bottom and fine top may differ from well to well and coarse layers in one well
may grade laterally to fine layers in an adjacent well, the situation near the
interior coarse-fine boundary is less clear. That boundary is a guide, but cannot
be taken as a strict time boundary, and thus correlations that cross it or are
otherwise not quite parallel to it could be reasonable.

■ METHODS

Cores from the wells were obtained with a Christensen 94 mm wireline
core barrel attached behind a donut-shaped drill bit within a clockwise-rotating
drill stem (looking down the hole). As the drill bit advanced downward, the
6.2-cm-diameter core was pushed up into a rigid plastic tube (liner) within the
core barrel. Upon wireline recovery, this liner was cut to fit the actual length of
the core and capped at each end. Recovered lengths ranged from quite short
to rarely the full 152 cm of a typical coring advance (push). Core axes were
vertical and the shallow end of each core was marked at the time of recovery.
Compass orientation could not be determined. The core and cylindrical plastic
liner were kept undisturbed until they were split longitudinally in the labora-
tory with a mechanical knife and then a stiff wire. One half of the core was
described and sampled, and the other half reserved as an archive. Cores were
numbered sequentially downward and their position in the hole recorded as
depth to the top of the core (in feet), with the position of a sample within the
core recorded as depth within the core (in centimeters).

The cores were typically intact and internally undisturbed, but downward
drag associated with insertion of the core into the liner during the push oc-
curred along the perimeter in some cores. Other, more extreme disturbances
involving injection of drilling mud and other processes were clearly evident in
places. Some fine-grained intervals in the cores contain thin horizontal lam-
inae dragged downward at the margins that separate and define apparently
intact blocks of sediment typically 1–2 cm thick. Some of these laminae can
be shown to truncate primary features, and thus were imposed after deposi-
tion. Structures like this were routinely recognized and called “biscuits” in
the Deep Sea Drilling Program (e.g., see Shipboard Scientific Party, 1995), and
are observed there only in cores taken during rotary drilling. Although the
core barrel rides on bearings to isolate it from the rotating drill stem, some
torque apparently can still be applied. Care was taken during paleomagnetic
sampling to avoid all recognizable core deformation, including the interfaces
between biscuits.

A total of 515 cylindrical samples, ~18 cm³ in volume, and 90 additional
7 cm³ samples were taken for paleomagnetic study from the split cores. Paleo-
magnetic sampling was generally confined to the finest grained portions of the
core, ranging to fine-grained sand and silty sand. The cores were oriented only
with respect to stratigraphic top, thus permitting magnetic inclination to be
determined, but not declination (azimuth). Samples were taken near the center
of the split core to avoid any deformation along the core margins that could
deflect the magnetic inclination. Noting where biscuits occurred also was im-
portant because it determined in which cores relative differences in direction
between samples could not be used to interpret geomagnetic behavior. In the
absence of biscuits, relative directional variations can be determined because
all samples were taken from the same face of the split core. Deformation at bis-
cuit boundaries or similar zones could also destroy part of the magnetic signal
or otherwise significantly affect the paleomagnetic inclinations.

Natural remanent magnetization (NRM) of each sample was measured
using a superconducting magnetometer housed in a magnetically shielded
room. Progressive alternating-field (AF) demagnetization experiments on the
large 18 cm³ specimens were performed using a modified three-axis tumbling
demagnetizer (Doell and Cox, 1967). Doell and Cox recognized that this type of
demagnetizer could impart a spurious component of magnetization along its
innermost rotation axis. This rotational remanent magnetization (RRM; Wil-
son and Lomax, 1972) is particularly prevalent in sediments with low magnetic
stability. To eliminate the effects of RRM, samples were demagnetized twice
at each increment of AF above the point where unsystematic behavior was
first suspected (generally 20 mT or higher). For the second of these demagne-
tization pairs, the long axis of the cylindrical sample was reversed 180° with
respect to the innermost tumbler axis and the data were averaged using the
method of Hillhouse (1977a). The smaller, 7 cm³ specimens were AF demagne-
tized sequentially (i.e., not inverted after each demagnetization step) using an
in-line nested Helmholtz coil set mounted above the superconducting magne-
tometer (Kirschvink et al., 2008).

■ DATA AND ANALYSIS

The geometric mean NRM intensity for 375 large 18 cm³ samples from
wells CCOC, GUAD, MGCY, STPK, and WLLO (Fig. 2) is 18.4 nAm (5.8–58.3
nAm = range of 1 standard deviation). Samples taken below ~225 m in the
WLLO well were not used in the calculation of this mean because of the pres-
ence of abundant coarse (and strongly magnetic) serpentinite clasts (Oze et al.,
2003). Similarly, a sedimentary source area for the EVGR well that differs from
that for most of the drill holes in the center of the valley results in a somewhat
higher (28.7 nAm) mean NRM intensity. The Great Valley sequence on the
east side of the Santa Clara Valley is the principal source for the Evergreen
section, whereas the southeastern Santa Cruz Mountains on the west side of
the valley are the primary source for most of the basin (Wentworth et al.,
2015). Progressive AF demagnetization of representative samples from cores
throughout the basin revealed similar response to the experimental treatment for all sampled grain sizes (Fig. 6). Anomalous components of magnetization were rare and, where present, were generally removed by AF of 10 mT or lower. Based on behavior during stepwise demagnetization, all remaining specimens were demagnetized at a minimum of three AF values (5, 10, 15 mT) to confirm their stability and direction. The median destructive field, the strength of the AF required to reduce the remanent intensity to half of its initial value, is typically between 10 and 30 mT in these samples. These values are consistent with titanomagnetite being the magnetic carrier in these sediments. Representative magnetic inclinations for each sample were determined by fitting least squares lines (Kirschvink, 1980) to three or more vector endpoints of the magnetic component isolated during demagnetization, and these are shown in Figure 7 and listed in Supplemental Tables 1–6 in the Supplemental File.

### Table 1. Paleomagnetic data from the Coyote Creek Outdoor Classroom drill hole

<table>
<thead>
<tr>
<th>Core</th>
<th>Sample</th>
<th>Depth (m)</th>
<th>Dip (degrees)</th>
<th>Inclination (degrees)</th>
<th>Polarity</th>
<th>A.I. (degree)</th>
<th>M.A. (degree)</th>
<th>Iensity (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20.02</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>3</td>
<td>20.03</td>
<td>0.05</td>
<td>32.7</td>
<td>13.7</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>20.04</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>5</td>
<td>20.05</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>6</td>
<td>20.06</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>7</td>
<td>20.07</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>8</td>
<td>20.08</td>
<td>0.05</td>
<td>32.7</td>
<td>14.8</td>
<td>12.7</td>
<td>11.9</td>
<td>11.6</td>
<td>6.9</td>
</tr>
</tbody>
</table>

### Interpretation

A summary of the results from the six drill holes is given in Figure 9; normal magnetic polarities are shown in blue, reversed polarities in red, and excursions in yellow. Numbers to the right of each excursion are the numbers for the cores in which the excursions occur. The purple shading in the individual drill-hole logs are indicative of intervals composed of gravel or other material too coarse for paleomagnetic sampling. The upper part of the Quaternary section has been subdivided into eight upward-finling alluvial sequences that can be correlated with the major climate-driven oscillations evident in the marine oxygen isotope record (Wentworth and Tinsley, 2005; Wentworth et al., 2010, 2015). If each of the eight cycles represents sediment accumulated during a particular glacial cycle, then each cycle represents a distinct interval of time. No age-diagnostic fossils have been recovered from these drill holes, but their correlation with the dated marine isotope record provides a means of estimating the age of each of the cycles (Fig. 5). Green lines in the figure denote boundaries of the climate cycles and the cycles are numbered to the left of MGCY. Correlations based on the magnetostratigraphy from each drill hole are discussed below.

#### Brunhes-Matuyama Boundary

More than 10 m of reversed polarity sediment occurs below 291 m in the GUAD drill hole. This interval is much thicker than those considered to be possible excursions (described below) indicating that the upper part of the Matuyama Chron is represented. The first fully reversed polarity sample at 291.1 m in the GUAD well is taken to be the Brunhes-Matuyama boundary. Eight normal, reversed, and intermediate polarity samples occur over a 1.6 m span near the base of the CCOC well (beginning at 305.1 m). This can be best characterized as a mixed interval. A similar mixed interval occurs near the base of the STPK well, beginning at 303.0 m. Even though there is not a direct transition from reversed to normal polarity in the CCOC and STPK drill holes, mixed polarities are commonly found near polarity transitions in sedimentary sequences because of variations in the magnetization lock-in process (e.g., Okada and Niiyama, 1983; van Hoof et al., 1993), overprinting of weak magnetizations acquired during a polarity transition (Coe and Liddicoat, 1994), and complexities in the reversal process (Mankinen et al., 1985; Bogus and Merrill, 1992).
Figure 6. Orthogonal projection of remanence vector endpoints during alternating field demagnetization showing behavior of representative lithologies from various drill holes. Open circles are projections into the vertical plane. Solid circles are projections into a horizontal plane whose axes are arbitrary because the cores were not azimuthally oriented.
Reversed polarity samples occurring at about the same depth in the CCOC, GUAD, and STPK drill holes indicate that the same reversal boundary (the Brunhes-Matuyama) has been recorded. In Figure 9, the relative positions of the base of cycle 8 (ca. 718 ka) and the proposed Brunhes-Matuyama boundary are mutually consistent. If our interpretation that the Brunhes-Matuyama has been recorded in these 3 drill holes is correct, a long-term post–780 ka deposition-subsidence rate of ~37 cm/k.y. is indicated and may be expected almost basin wide. The southeastern Evergreen basin (including at well EVGR) is an exception; structural compression seems to be offsetting some of the basin subsidence, leading to a thinner cyclic section (see Figs. 4 and 9).

The Brunhes-Matuyama boundary was detected only in those three drill holes. In MGCY and WLO, bedrock was encountered before that stratigraphic
level was reached. Reversed polarities occur near the bottom of the MGCY drill hole (~253–240.8 m), but the material there is Miocene bedrock (containing ca. 8 Ma diatoms; L. White, San Francisco State University, 2004, written commun.). In well WLLO, serpentinite bedrock was encountered at a depth of 245 m. In well EVGR, the Brunhes-Matuyama was not detected, although the well extends far below the base of cycle 8. No core was taken in the interval just below the base of cycle 8, where that boundary would be expected.

### Jaramillo Subchron

In the GUAD well, 3 m of normal polarity sediment occur below the reversed polarity interval representing the upper part of the Matuyama. This interval is thicker than any of the suspected excursions, and we interpret it to represent the upper part of the Jaramillo Subchron. The mixed interval near the top (cores 199–200) is similar to the mixed polarities at the Brunhes-Matuyama boundary. The top of the Jaramillo Subchron occurs in the top of the lower fine-grained unit (Fig. 4), which is deeply penetrated by two of the cored wells, GUAD and EVGR (Fig. 5). Only one core located just above the underlying bedrock was taken in that deeper interval in GUAD, but several were taken in EVGR that span the lower 72 m of that well (Fig. 9). All of these samples have normal polarity, and thus should represent more of the Jaramillo Subchron. It is not clear where its bottom is; no underlying reversed polarities were found, and it could predate the bottom of the lower fine-grained unit. These relations are consistent with the conclusion (see geologic summary discussion) that the lower fine-grained unit postdates the Pliocene and early Pleistocene gravels that are exposed around the edges of the basin.

The upper Matuyama reversed interval is not recognized in EVGR, probably because the relevant section just below the base of cycle 8 was not cored. The greatest thickness of normal polarity section in these two wells is controlled by the deep sample from GUAD, which indicates a minimum of 102 m of section that we would assign to the Jaramillo Subchron, which was 60 k.y. long. Those dimensions yield a sedimentation rate for most of the lower fine-grained section of 170 cm/k.y. That is a minimum for the Jaramillo here, because this assumes that the base of the subchron occurs at the deep normal sample in GUAD and not earlier. This rate is much higher than that obtained for the upper cyclic section (37 cm/k.y.).

### Mid-Quaternary Unconformity

The 10-m-thick reversed interval representing the upper Matuyama Chron seems much too thin for its 210 k.y. duration (990–780 ka), given the long-term average rates of accumulation determined for the sections above and below.

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**Table 1. Inclination-Only Statistics for Individual Drill Holes from the Santa Clara Valley, California**

<table>
<thead>
<tr>
<th>Drill hole</th>
<th>Mean inclination (°)</th>
<th>Number of samples</th>
<th>Angular S.D. (°)</th>
<th>α95 (°)</th>
<th>Concentration factor (κ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCOC</td>
<td>55.4</td>
<td>97</td>
<td>17.4</td>
<td>2.9</td>
<td>21.7</td>
</tr>
<tr>
<td>EVGR</td>
<td>59.2</td>
<td>73</td>
<td>14.7</td>
<td>2.7</td>
<td>30.4</td>
</tr>
<tr>
<td>GUAD</td>
<td>58.4</td>
<td>252</td>
<td>17.4</td>
<td>2.3</td>
<td>21.8</td>
</tr>
<tr>
<td>MGCY</td>
<td>59.1</td>
<td>55</td>
<td>15.2</td>
<td>3.2</td>
<td>28.5</td>
</tr>
<tr>
<td>STPK</td>
<td>56.0</td>
<td>78</td>
<td>16.3</td>
<td>2.9</td>
<td>24.7</td>
</tr>
<tr>
<td>WLLO</td>
<td>57.2</td>
<td>49</td>
<td>10.0</td>
<td>2.1</td>
<td>65.9</td>
</tr>
</tbody>
</table>

*Note: Inclinations calculated using McFadden and Reid (1982); S.D.—standard deviation; α95—95% confidence cone about average direction; κ—concentration factor of Fisher (1953).*
that interval (37 and 170 cm/k.y.); those rates would produce thicknesses for that interval of 77.7 and 357 m, respectively. The long-term rate for the cyclic section may not apply locally; a local rate estimated for the interval between the base of cycle 8 (718 ka) and the Brunhes-Matuyama boundary (780 ka) is quite different. The thickness of that interval (see Fig. 9) in the three wells in which we can define it (GUAD, CCOC, and STPK) averages 5.2 m. The local rate (5.2 m in 62 k.y.) is thus a relatively low 8.4 cm/k.y. The model of Wentworth and Tinsley (2005) calls for just such lower accumulation rates in the fine tops of the sedimentary cycles, and this interval below the base of cycle 8 is, in effect, the fine top of a cycle 9. Applying this rate to the upper Matuyama reversed interval would yield a thickness of 17.6 m. Although this is closer to the actual 10 m thickness of the interval, that interval still seems too thin for its duration,
evenly considering that some part of it probably accumulated at the much higher rate determined for the underlying normally polarized section. An unconformity below the Brunhes-Matuyama boundary seems indicated. The mixed polarities at both the Brunhes-Matuyama boundary and the top of the Jaramillo indicate that these are true polarity transitions, which requires that the unconformity be entirely within the upper Matuyama interval. That unconformity thus forms the base of the overlying cyclic section, accounts for the absence of the lower part of a cycle 9, and should separate the high accumulation rate of the underlying section from the lower rate above. Some considerable, but unspecified, thickness of missing section, including the lower part of cycle 9, implies a considerable hiatus that could occupy much of the 210 k.y. upper Matuyama interval.

The fact that the Kula–Santa Rosa excursion (Fig. 3) was not found within the reversed section is further, albeit just permissive, evidence for this conclusion. In Wentworth et al. (2010, 2015) other evidence for an unconformity just below the base of cycle 8 was described, and the unconformity was placed within the upper Matuyama reversed interval. The broad extent of the evidence, ranging from well MOFT through GUAD to the Evergreen seismic reflection line (Fig. 2), together with the considerable hiatus involved, indicates that this unconformity is a basin-wide event.

Excursions

Some of the difficulties in attempting to use geomagnetic excursions for geological correlation were mentioned here. Assigning ages within the Santa Clara section is not straightforward, because the only direct dating available is from several radiocarbon samples that are limited to the upper 25 m of the section. However, the stratigraphic subdivision of the upper 300 m of the section into 8 upward-fining cycles provides lateral correlations across the basin, and correlation of those cycles with the marine oxygen isotope record provides estimates of age. Being able to confine any given excursion to within the age range of one of those cycles greatly improves the chances of a correct identification. Subdivision of each cycle into a fine top and coarse bottom (Wentworth et al., 2015) offers further constraint, as those subdivisions are also approximately equivalent between wells. The coarse bottoms probably accumulated relatively quickly relative to the fine tops, as indicated by the sedimentary model proposed in Wentworth and Tinsley (2005), although more detailed rates are uncertain and considerable variation within short sections is likely.

Mono Lake–Laschamp Excursions (Cycle 2)

The youngest anomalous magnetic inclinations were initially encountered in core 17, taken from the CCOC drill hole along Coyote Creek in central San Jose (Figs. 2 and 9). A large counterclockwise swing of the total magnetic vector over a depth range of 0.88 m (Mankinen and Wentworth, 2003, 2004) strongly indicates that a true geomagnetic excursion has been recorded. This anomalous interval occurs ~2.5 m below the base of postglacial alluvial cycle 1 (within cycle C2a) in this drill hole and contains organic fragments (bark and/or woody twiglets or roots) within black clayey silt between the intermediate polarity paleomagnetic samples taken. These fragments yielded an age of 28,090 ± 330 14C yr B.P. (uncalibrated years), which, when using the Bard (1998) approximation to correct for atmospheric 14C concentrations through time, converts to a calendar age of 32,840 yr ago (Mankinen and Wentworth, 2004). The uncorrected age compares well with the 28,620 ± 300 °C yr B.P. determined by Benson et al. (2003) for a volcanic tephra layer (Ash #15) near the midpoint of the Mono Lake excursion at the type locality. The close agreement in ages between both studies clearly indicates that the anomalous inclinations in core 17 are a record of the Mono Lake excursion. Excursional directions were encountered in GUAD core 14, STPK core 4, and EVGR core 9. Large within-core directional swings were found in WLOD core 3 and WLO2 core 5 (Fig. 10). All occur within cycle 2a and are thus most likely correlated with the Mono Lake excursion in CCOC (Fig. 9).

At a depth of 9–11 m below the Mono Lake excursion in GUAD, large clockwise swings in the magnetic vector, without corresponding anomalous inclinations, occur in GUAD cores 20–22 (Fig. 10). The total angular distance covered by the magnetic vector in cores 22 and 21 is ~103° over a thickness of ~1 m, and ~71° in core 20. This behavior seems reminiscent of the recurring waveforms reported by Lund et al. (1988). We suggest correlation of this behavior with the Laschamp excursion. If this is correct, then the expression of that excursion in our region is subtle and could easily be missed. The feature that Holt et al. (1998) correlated with the Laschamp excursion in a drill hole on Hawaii also is near the limit of normal geomagnetic secular variation at that locality.

A second interval with an anomalous inclination in CCOC was found in core 21 (depth range 30.78–32.27 m). Although the inclinations here only reach 30° shallower than expected, and are thus exactly at the limit that we use for defining an intermediate polarity, a large clockwise swing of the total magnetic vector (Mankinen and Wentworth, 2003, 2004) strongly suggests that an excursion was recorded. Because this anomalous interval is only slightly below the Mono Lake excursion, in Mankinen and Wentworth (2003, 2004) the possibility that it could represent either the Laschamp or another excursion within the geomagnetic intensity low between ca. 50 and 15 ka was considered (see Mankinen and Champion 1993; Lej et al., 2004). Such a correlation would, however, cross the base of the upper coarse interval (C2a) in sedimentary cycle 2 (defined by Wentworth et al., 2015), and that boundary should probably be considered an approximate time surface, like the cycle boundaries.

A more likely correlative of CCOC core 21 would be GUAD core 30, which also occurs within the upper fine-grained interval of cycle 2. Hillhouse (1977b) conducted a paleomagnetic study of a sediment core taken at south end of the Dumbarton Bridge (well DUMB in Wentworth et al., 2015). He found a sample (77C-1070) with an anomalous inclination of ~27° at a depth of 42.87 m, also within the upper fine-grained interval of cycle 2. Although simple linear interpolation of ages between cycle boundaries is probably not valid, the ca. 75 ka
Figure 10. Directional changes of the magnetic vector in samples from WLLO1 and WLLO2 cores probably representing the Mono Lake excursion, and GUAD cores 22–20, possibly correlative to the Laschamp excursion (see text). Solid dots are directions on lower hemisphere of an equal area projection. Because cores from the drill holes are not azimuthally oriented, each plot was rotated an arbitrary amount about a vertical axis so that the beginning of the excursion is near the expected normal polarity direction (star) for the area.
midpoint age of cycle 2 provides a guide. Given the high early and low later sedimentation rates within a cycle (Wentworth and Tinsley, 2005), the ages of these events should be somewhat older than that midpoint age. That would be too old for Laschamp and probably somewhat too young for Blake 2, and would thus leave the GUAD 20–21–CCOC 21 event without known correlative.

**Big Lost Excursion (Cycle C7)**

A reversed polarity interval was found in the MGCY drill hole in the upper part of cycle 7 that extends over at least 0.6 m from the top of core 72 to the bottom of core 71 (depth range 218.7–219.3 m). This interval is overlain by more than 1.6 m of normal polarity (top of core 71 to core 70), and is followed by another reversed polarity sample at 215.6 m in core 69 (Fig. 7). Intermediate polarity samples were similarly found high in cycle 7 in core 152 (depth of 230.2 m) in the GUAD drill hole. The anomalous behavior seen in all these drill holes and samples is probably also represented in core 65 (~223.5 m) of the CCOC well and core 39 (~177.6 m) in EVGR. None of the samples from these last two cores have inclinations that are in the intermediate polarity range that we have tentatively defined, but 2 samples in CCOC core 65 are at the upper and lower limits (30.6° and 79.0°) of the presumed normal range, and one is near the upper limit (77.9°) in EVGR. Large directional swings are also seen in these two cores (Fig. 11). The same level was not cored in the STPK well. Anomalous directions in three other wells at approximately the same level as the MGCY reversed polarity interval leave little doubt that an excursion was recorded. Anomalous behavior in the GUAD, CCOC, MGCY, and EVGR drill holes at 230, 223, 219–219, and 178 m, respectively, occur in the fine-grained interval near the upper boundary of cycle 7 (536 ka) and are thus consistent with the 565 ± 22 ka age (Lanphere et al., 2004) of the Big Lost excursion. The occurrence of two anomalous directions near the top of cycle 7 in the MGCY (~219 and 216 m) drill hole may indicate that more than one excursion may have also occurred in a short time interval around the Big Lost excursion, such as noted for other excursions described here.

**Pringle Falls Excursion (Cycle 3)**

An intermediate polarity inclination was found in GUAD core 56 (870–879 m) within the fine-grained interval of cycle 3. Stratigraphically lower, in the coarse-grained interval, is an ~115° counterclockwise swing of direction (Fig. 11) in GUAD core 64 (99.0–100.1 m). The estimated difference in age between the anomalous directions in cores 64 and 56 is 32 k.y. using our Pleistocene average sedimentation rate, or 42 k.y. using a linear interpolation between the boundaries of cycle 3. Although these two estimates show a somewhat larger time gap between the two Pringle Falls episodes than we show in Figure 3, we suggest that this behavior represents their occurrence in the San Francisco Bay region. Clockwise swings in relative direction (Fig. 11) recorded in STPK core 17 (total ~148°) and EVGR core 21 (total ~88°), both in the coarse-grained interval, are most likely correlative with GUAD core 64. The occurrence of similar behavior in three drill holes at depths of ~99 m (GUAD), ~73.5 m (STPK), and ~78.0 m (EVGR) at the same approximate level in cycle 3 (Fig. 9) is consistent with this episode being representative of one of the Pringle Falls excursions, likely Pringle Falls 1. GUAD core 56 may represent Pringle Falls 2.

**Other Possible Excursions**

Reversed polarity in GUAD core 43 (66.8 m) defines an excursion occurring in the coarse-grained lower interval near the base of cycle 2 (Fig. 9). This could represent the Blake 1 excursion; however, cores from this stratigraphic level were not obtained from any of the other drill holes, making it impossible to test for the presence of similar events elsewhere in the basin.

Fully reversed and intermediate polarity samples were recovered in the coarse bottom of cycle 5 over 1.4 m (at ~150.5 m depth) in cores 49B to 51 in the MGCY drill hole (Fig. 7). The mixed polarities here are suggestive of an excursion with anomalous directions separated by normal polarity. A possible correlative in this same part of cycle 5 is the ~75° declination swing (Fig. 11) in EVGR core 34 (~142 m). Another intermediate polarity interval was recovered from GUAD core 97 (~150 m). Core 97 occurs in the upper fine-grained interval high in cycle 5 and thus probably does not represent the same behavior seen in the MGCY and EVGR wells. The location of these excursion or excursions within cycle 5 do not correspond to any excursion thus far reported from the western U.S. Inasmuch as MGCY cores 49B to 51 occur above the 414 ka cycle6-cycle5 boundary, they might be correlative with the 390 ± 4 ka reversed polarity flow from the Snake River Plain (Tauxe et al., 2004). GUAD core 121 (185.6 m) and MGCY core 52 (153 m) are from the fine-grained interval near the top of cycle 6 and are possibly correlative. From this same interval in well DUMB, 3 samples with anomalously shallow inclinations (9.4°, 8.2°, and ~2.7°) occur between 169.37 and 173.93m (Hillhouse 1977b). One sample with a normal inclination (57.2°) occurs between the first two anomalous samples at 173.24 m. In the lower coarse-grained interval of cycle 6, intermediate to reversed polarity found in MGCY cores 65 and 66 (depth range 189.3–191.1 m), intermediate polarity in STPK core 41 (depth of 186 m) and in GUAD core 138 probably record the same behavior. The indications here are that two separate excursions occurred during cycle 6, between 531 and 414 ka (Fig. 4). Neither corresponds to any excursion thus far reported from the western North American region. Reports of excursions between 500 and 400 ka are rare worldwide, with the possible exceptions of the West Eifel (Schnepp and Hradetzky, 1994) and Calabrian Ridge 2 (Langereis et al., 1997) excursions, and excursions 11A and 13A in ODP Leg 172 cores from the western North Atlantic Ocean (ODP Leg 17 Scientific Party et al., 1998). These excursions have yielded ages between 515 and 510 using either the 40Ar/39Ar method or an astronomically tuned oxygen isotope record. We are not proposing a correlation to those excursions, but suggest that they may be indicative of a low
Figure 11. Directional changes of the magnetic vector in samples from CCOC core 65 and EVGR core 39 are interpreted as representing the Big Lost excursion (see text). Directional changes in GUAD core 64, STPK core 17, and EVGR core 21 are considered to represent the Pringle Falls 1 excursion. EVGR core 34 is probably correlative with reversed and intermediate samples from MGCY cores 49B to 51, and perhaps a reversed polarity lava flow from the Snake River Plain (see text). See Figure 10 for additional explanation.
Geomagnetic intensity at about that time, and one that may have been long lasting. Note the two pronounced dips in the strength of the geomagnetic field between ca. 500 and 450 ka (Fig. 3). Our results from these three cores could fall within such an interval and represent excursions occurring ca. 490 ka that have not been previously documented from the western U.S.

**DISCUSSION AND CONCLUSIONS**

We obtained 608 paleomagnetic samples from cores taken in 6 research drill holes in the Santa Clara Valley. Stability of magnetization, inclinations that agree with the expected direction for the region, and statistical parameters (angular standard deviation, concentration parameter) of the paleomagnetic data all indicate that the sediment obtained from the Santa Clara Valley drill holes provides an accurate recording of the geomagnetic field. Paleomagnetic results show a reversal boundary below the base of cycle 8 in the GUAD, CCOC, and STPK wells (depths ranging from 291 to 303 m), which we interpret as representing the 780 ka Brunhes-Matuyama boundary. A long-term deposition-subidence rate of ~37 cm/k.y. for the cyclic section in the central basin is indicated using this boundary as reference.

The paleomagnetic record between 301.7 and 304.5 m in the GUAD drill hole is indicative of a significant unconformity between the Jaramillo Subchron and the Brunhes-Matuyama boundary. This unconformity must underlie the entire Santa Clara Valley and thus merge with the bedrock unconformity underlying the entire basin where it rises toward the basin margins and cuts out the lower sedimentary cycles, including in the cored holes WLLO and MGCY.

Intervals recording large swings of within-core direction, some including anomalous magnetic inclinations, were found in all the wells. Both clockwise and counterclockwise swings were observed, providing evidence that this behavior is not an artifact of the coring process. Anomalous inclination intervals that occur within the same part of a sedimentary cycle in more than one research well strongly indicate that true geomagnetic excursions were recorded. Some of the anomalous intervals are separated by short normal intervals similar to the pattern described for some well-documented excursions elsewhere. ODP Leg 17 Scientific Party et al. (1998) also noted the occurrence of bundles of closely spaced excursions. The Mono Lake (ca. 32 ka), Pringle Falls (ca. 210 ka), Big Lost (ca. 565 ka), and possibly the Laschamp (ca. 40 ka) and Blake (ca. 110 ka) geomagnetic excursions all seem to be represented in the Santa Clara Valley wells, along with three others (ca. 75, 400, and 490 ka) that have apparently not been previously reported from western North America.

A composite paleomagnetic stratigraphy developed in a drill core from the pluvial Lake Manix in the Mojave Desert (Reheis et al., 2012) indicates that 8 geomagnetic excursions occurred there during the past ~480–500 k.y. Age information on the core was based on comparison with outcrop stratigraphy constrained by 40Ar/39Ar, tephras, and U-series ages. Excursions were identified by tentative correlation to other excursions and relative paleointensity from marine records (e.g., Lund et al., 2006), most of which are far removed from the western North America–eastern Pacific region. Some comparisons can be made between the Manix and Santa Clara Valley core records. Reheis et al. (2012) considered their youngest excursion (excursion 3b) to represent the Laschamp excursion. Because our analysis indicates the Mono Lake excursion to be better expressed than the Laschamp in our region, excursion 3b may instead be the Mono Lake excursion. The Reheis et al. (2012) age model correlates their excursion 5b to one of the Blake excursions, and thus is a possible correlative to GUAD cores 30 or 43. Reheis et al. (2012) did not make a correlation for excursion 7a, but estimated its age to be ca. 190 ka. This estimate fits well with the age of the Pringle Falls 2 excursion (Fig. 9). The Reheis et al. (2012) excursion 7b could then be Pringle Falls 1; the oldest excursion they identify (excursion 11a) is estimated to have occurred ca. 400 ka. This assignment fits well with our data from MGCY cores 49B to 51 and the possible correlation with the 390 ± 4 ka reversed polarity flow from the Snake River Plain. We find no counterparts to the Reheis et al. (2012) excursions 8a and 9a or 9b in the Santa Clara Valley wells.

A mid-Quaternary unconformity occurs beneath the base of cycle 8 throughout the basin that separates the cyclic upper section from the lower fine-grained unit. That lower unit appears to include much of the Jaramillo Subchron; all samples from that section below the upper Matuyama reversed section in the two cored wells that penetrate it have normal polarity. The base of the Jaramillo was not reached, and may be older than the base of the fine-grained unit, which is on a bedrock unconformity, as observed in GUAD. A minimum sedimentation rate of 170 cm/k.y. for the known lower interval is required, a rate much higher than the ~37 cm/k.y. average for the upper section. The two sections are independent, however, as they are separated by that mid-Quaternary unconformity.

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