PLIOCENE AND PLEISTOCENE EVOLUTION OF THE MOJAVE RIVER, AND ASSOCIATED TECTONIC DEVELOPMENT OF THE TRANSVERSE RANGES AND MOJAVE DESERT, BASED ON BOREHOLE STRATIGRAPHY STUDIES NEAR VICTORVILLE, CALIFORNIA

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ABSTRACT

Pliocene and Pleistocene continental sediments near Victorville, California, record the early history of the Mojave River drainage basin. Boreholes at former George Air Force Base penetrate three conformable stratigraphic units with an aggregate thickness of about 525 ft (160 m). These include a lower alluvial unit of lithic-arkose sand and polymictic gravel deposited by a southward-flowing braided stream and associated alluvial fans, a middle lacustrine unit of clay and silt laid down in a shallow lake or wetland, and an upper fluvial unit of granitic sand, silt, and gravel deposited by the northwest-flowing ancestral Mojave River. Based on magnetostratigraphy of borehole cores, the overall sequence ranges from about 4.2 Ma to less than 0.78 Ma. The upper fluvial unit forms a northwest-thinning clastic wedge with the middle lacustrine unit rising to the northwest along its base. The clastic wedge appears to be an orogenic deposit derived from the San Bernardino Mountains, and the underlying lakebeds evidently were deposited at the tip of the wedge as it slowly expanded to the northwest against a southward-facing alluvial slope. The bases of the lacustrine unit and overlying fluvial unit are dated at about 2.55 Ma and 1.95 Ma, respectively, in a borehole near the southeast corner of the air base. Using sediment accumulation rates determined at the air base, we estimate that a much thicker southeastward extension of the upper fluvial unit beneath southernmost Victorville is about 3.3 Ma at its base. These findings imply that the ancestral Mojave River originated well before 2.55 Ma and quite possibly before 3.3 Ma. Thus, the birth of the river may predate significant uplift along the north flank of the San Bernardino Mountains, which occurred after about 2-3 Ma according to previous studies. The river may have emerged in response to initial uplift in the core of the range, which lies farther south adjacent to the San Andreas Fault.

The lakebeds pinch out directly north of George Air Force Base. From there to Iron Mountain, about 15 mi (25 km) to the north, a thin (25-80 ft, 8-25 m) tabular extension of the upper fluvial unit rests unconformably on the lower alluvial unit and associated deposits. A southward-flowing stream deposited much of the lower unit along this stretch, so the northward advancement of the ancestral Mojave River denotes a significant reversal of the regional paleoslope. The unconformable base and nearly uniform thickness of the upper fluvial unit imply that the opposing slope was not overwhelmed by fluvial aggradation; prior northward tilting evidently is required. We propose that very gentle tilting occurred on the north limb of a large east-west-trending anticlinal arch. The crest of this arch apparently lies directly north of the air base, and its broad northern limb extends northward to Harper Lake. The arch probably was produced by regional contraction in the early Pleistocene. Sometime after 780 ka, most likely between about 575-475 ka, the river overtopped the crest of the arch at a wind gap inherited from the former southward-flowing stream. The fluvial tract subsequently advanced rapidly to the north. After a possible brief confinement at Harper Lake, the river proceeded eastward to Lake Manix basin, where previous studies date its arrival at about 500 ka. The final major event in the history of the upper Mojave River is the incision of its modern canyon between Victorville and Barstow. Downcutting apparently began about 60-70 ka, based on preliminary luminescence dates from the top of the upper fluvial unit. Incision most

likely was induced by renewed regional contraction that broadly arched the southern Mojave Desert.

INTRODUCTION

The Mojave River occupies the largest drainage basin in the Mojave Desert region of southern California (fig. 1). Its headwaters debouch at the northwest front of the San Bernardino Mountains, converging in an intermittent alluvial channel that sweeps northward and eastward about 200 km to a terminal sink at Silver Lake playa (Martin, 1994; Enzel and Wells, 1997). Given the broad extent of its mountain headwaters and alluvial basin, the deposits and geomorphic surfaces of the Mojave River contain an important record of regional tectonic and climatic history.

The development of the existing system of internal drainage in the Mojave Desert culminated a series of late Cenozoic paleogeographic events. During the middle Miocene, before about 10 Ma, the Mojave Desert drained to the south near Cajon Pass (fig. 1) (Woodburne and Golz, 1972; Woodburne, 1975; Foster, 1980). In the late Miocene, about 10-5 Ma, south-vergent thrusting elevated the ancestral central Transverse Ranges, which presumably blocked streams flowing southward from the Mojave Desert (Meisling and Weldon, 1989). During the Pliocene, about 5-2 Ma, fluvio-lacustrine basins developed on both the north and south sides of the uplifted region. The Old Woman Sandstone of Shreve (1968) and the Phelan Peak Formation of Weldon and others (1993) accumulated in east-west-trending basins along the north edge of the ancestral San Bernardino Mountains (Shreve, 1968; Sadler, 1982b; May and Repenning, 1982; Meisling, 1984; Meisling and Weldon, 1989; Powell and Matti, 1998). Meanwhile, streams draining the south slope of the ancestral San Gabriel Mountains deposited a southward-prograding wedge of sand and gravel in the San Timoteo Badlands (fig. 1) (Matti and Morton, 1993; Albright, 1999). These episodes of basin development and sedimentation suggest that north-south contraction and moderate uplift of the Transverse Ranges continued or resumed in the Pliocene (Sadler and Reeder, 1983; Meisling and Weldon, 1989; Albright, 1999).

Meisling (1984) and Meisling and Weldon (1989) proposed that the ancestral Mojave River emerged at the northwest front of the San Bernardino Mountains in the latest Pliocene to early Pleistocene, about 2.0-1.5 Ma, in response to rapid uplift along the northern flank of the range. They obtained their chief evidence from the "Ord River deposits"—a deeply eroded mass of fluvial sand and gravel near the mouth of Deep Creek (figs. 1, 2). Despite its early appearance at the mountain front, the river evidently did not reach its lower drainage basin east of Barstow until the middle Pleistocene, about 0.5 Ma, when fluvial and lacustrine sediments began accumulating in the Lake Manix basin (fig. 1) (Jefferson, 1985, 1994, 1999; Nagy and Murray, 1996). In combination, these findings suggest that the modern internal drainage system of the Mojave Desert developed gradually over a span of at least 1 Ma.

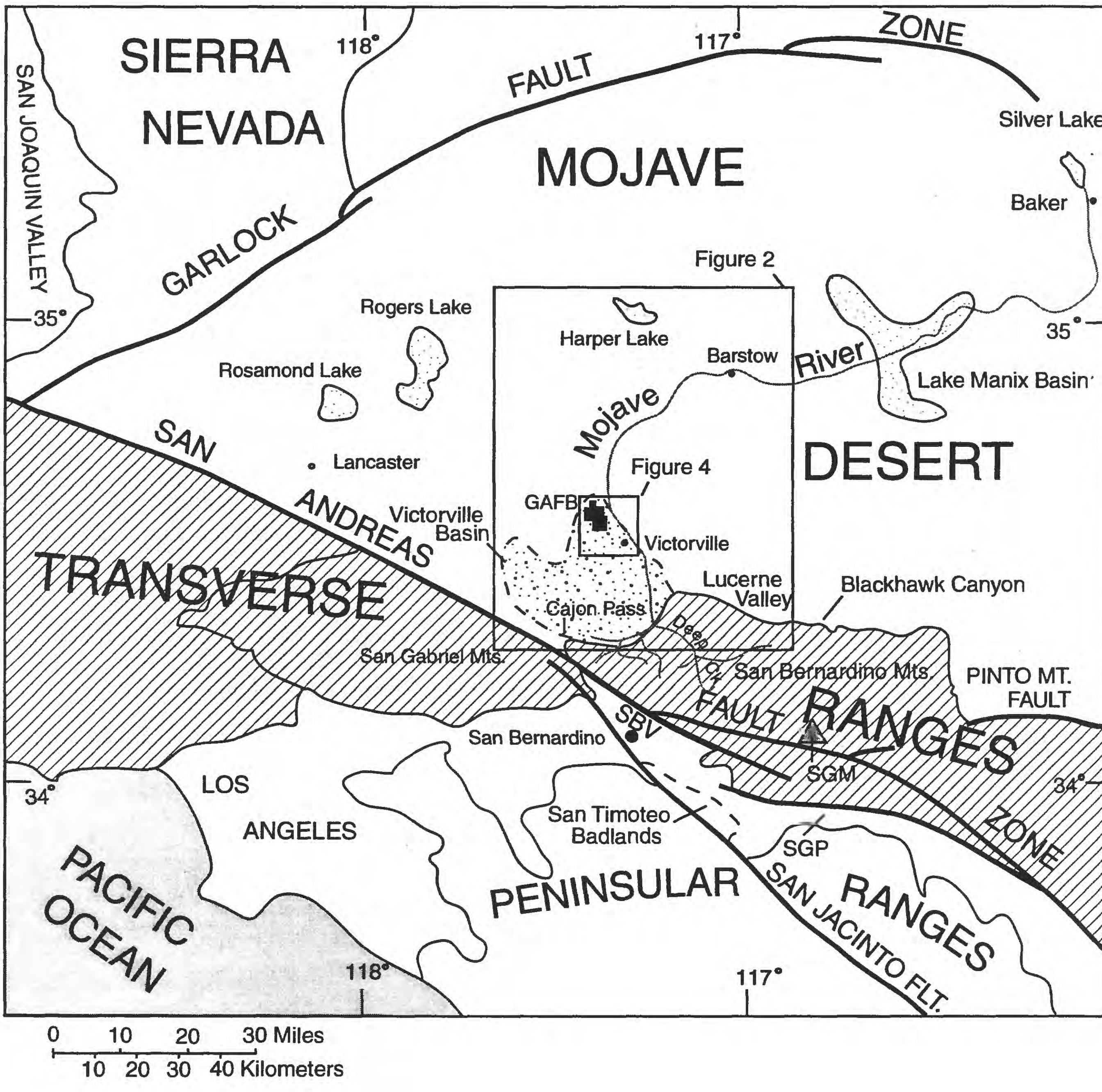


Figure 1. Index map showing location of George Air Force Base (GAFB) and Victorville basin in relation to geologic provinces and major fault systems of southern California. Inset boxes show location of figures 2 and 4. SBV, San Bernardino Valley; SGM, San Gorgonio Mountain; SGP, San Gorgonio Pass.

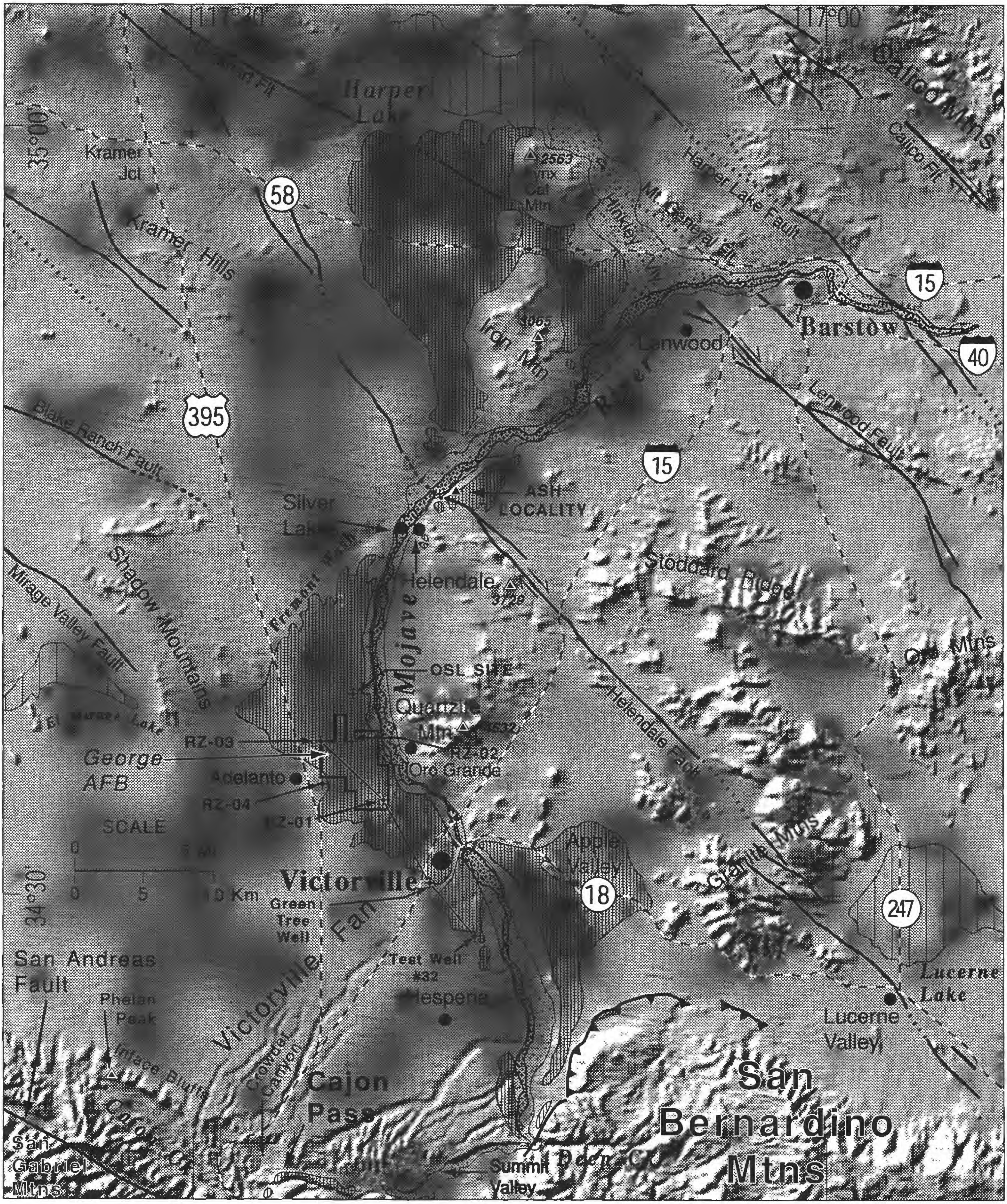


Figure 2. Shaded-relief map showing distribution of ancestral Mojave River deposits (narrowly ruled) and location of study sites between Cajon Pass and Barstow, California. Also shows active channel (densely stippled) and Holocene floodplain (sparsely stippled) of the modern Mojave River, and dry lakes (broadly ruled). Modified after Cox and Tinsley (1999). Location of stratigraphic section (figure 11) is shown by narrow line between borehole RZ-03 and Test Well #32. Elevation in feet above sea level is indicated for several major peaks between Victorville and Harper Lake (triangles).

Nagy and Murray (1996) envisioned more rapid, climatically controlled, growth of the early Mojave River. They argued that an integrated drainage system probably would have been achieved during a single Pleistocene "pluvial" cycle, thus within about 100,000 years. This hypothesis requires that the river either emerged at the mountain front much later, or arrived at Lake Manix basin much earlier, than the available evidence allows. Granting the importance of climatic factors, the effects of topography and tectonics must also be considered. The circuitous route of the modern Mojave River between the San Bernardino Mountains and the Lake Manix basin (fig. 1) implies that the ancestral river may have encountered significant obstacles as it expanded its basin to the north. Such obstructions may have included relict uplands inherited from the middle Miocene landscape, as well as younger uplifts generated by north-south crustal contraction that affected the Mojave Desert during late Miocene through Holocene time (Bartley and others, 1990). Therefore, an interval of 1 Ma or more for the river's pioneering journey across the desert may not be unreasonable.

Several previous studies reported deposits of the ancestral Mojave River in the Victorville region, particularly in the subsurface at former George Air Force Base (GAFB) (IT Corp., 1992; Sibbett, 1996, 1999; Chrisley, 1997), and in the bluffs of the Mojave River between Victorville and Helendale (Bowen, 1954). These deposits, which received little attention until recently, hold the key to reconciling the contrasting drainage histories of the upper and lower regions of the Mojave River basin. In the present study, we analyzed sediment cores from four deep boreholes at GAFB to establish the physical stratigraphy, depositional environments, and age of the ancestral Mojave River deposits and associated sedimentary units. This work included a detailed magnetostratigraphic investigation of each borehole. Supplementary paleomagnetic measurements were performed on oriented samples from several outcrops near GAFB and from a layer of volcanic ash that directly underlies the ancestral Mojave River deposits near Helendale. The magnetostratigraphic studies allowed us to date and correlate the stratigraphic section by referring to the geomagnetic polarity timescale (fig. 3). We also inspected drilling records from other boreholes in the Victorville region to test and expand the results obtained at GAFB. Finally, we incorporated new stratigraphic and structural observations from ongoing geologic mapping studies along the Mojave River between Victorville and Barstow (B. Cox, unpublished mapping).

We address the following key questions: (1) When did the Mojave River originate and what was the nature of the pre-existing regional drainage and topography? (2) How and when did the river develop its integrated drainage basin across the Mojave Desert? (3) How does the depositional and erosional history of the Mojave River correlate with the growth and abandonment of the Victorville Fan? (4) What is the age and significance of the deeply incised modern channel of the Mojave River between Cajon Pass and Barstow? (5) What does the drainage history of the Mojave River imply about the regional tectonic history of the Mojave Desert and central Transverse Ranges? Some preliminary results and interpretations were summarized by Cox and others (1998), Cox and Tinsley (1999), and Reynolds and Cox (1999).

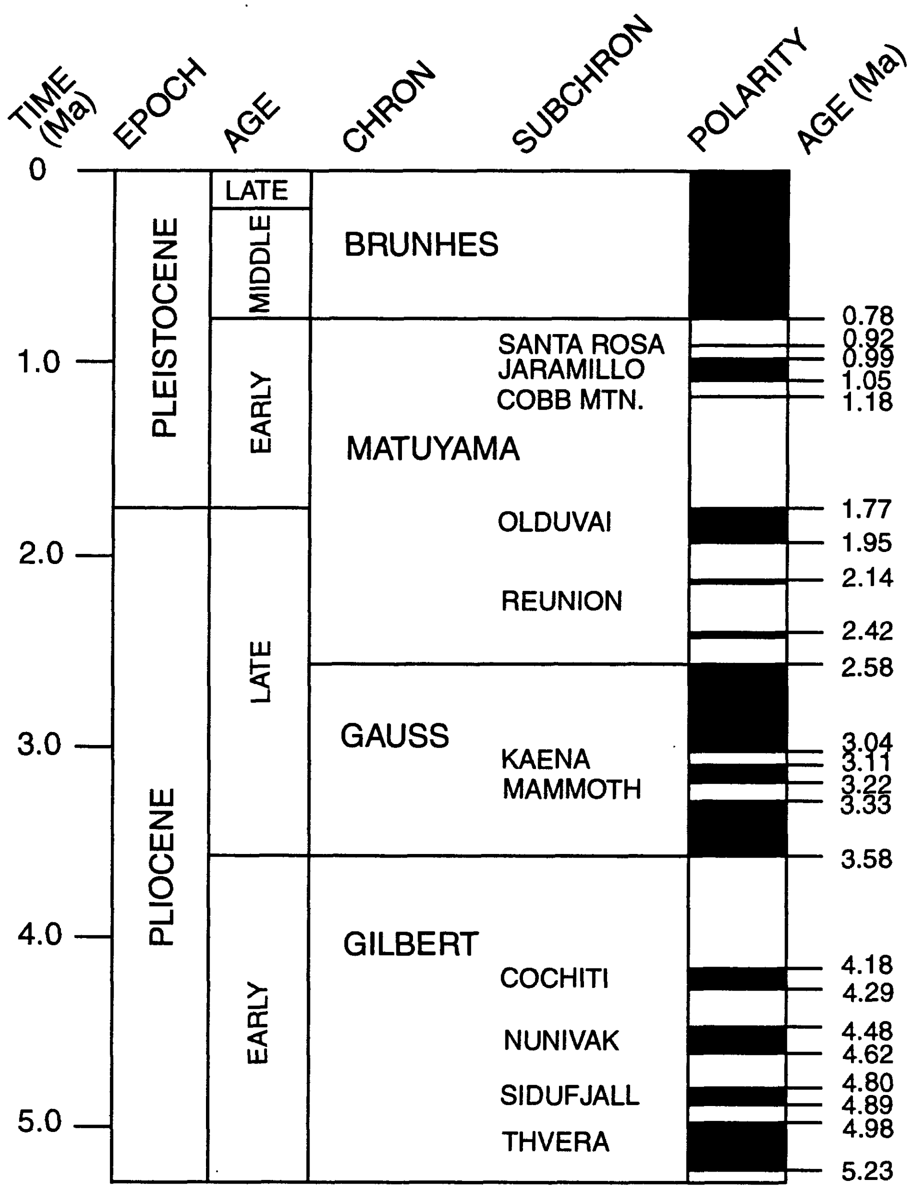


Figure 3. Correlation of geologic epochs and ages with the geomagnetic polarity timescale (Berggren and others, 1995) for Pliocene and Pleistocene time. Polarity zones (black, normal polarity; white, reversed polarity) are calibrated according to Singer and others (1999) and Cande and Kent (1995).

GEOLOGIC SETTING

This study focuses on the Victorville region and neighboring George Air Force Base (GAFB), which lie in the southern Mojave Desert about 60 mi (100 km) northeast of Los Angeles (fig. 1). The geologic framework of the study area is tied to the evolution of the nearby San Andreas Fault, which is the main structural break between the North American and Pacific tectonic plates in southern California. The San Andreas Fault slices obliquely across the central Transverse Ranges near Cajon Pass, about 20 mi (30 km) southwest of Victorville, separating the San Gabriel Mountains on the west from the San Bernardino Mountains on the east. These two mountain ranges were squeezed up between the Mojave Desert and the Peninsular Ranges by transpressional stresses generated along a major restraining bend of the fault (Dibblee, 1975a; Sadler, 1982a, 1982b; Sadler and Reeder, 1983; Meisling and Weldon, 1989; Matti and Morton, 1993; Morton and Matti, 1993; Weldon and others, 1993).

Regional gravity surveys indicate that a sedimentary basin about 25 mi (40 km) wide and up to 5,000 ft (1,500 m) deep extends between Cajon Pass and GAFB (fig. 1) (Mabey, 1960; Biehler and others, 1988; Subsurface Surveys, 1990). This structural depression has been termed the Cajon basin (Dibblee, 1967, fig. 71; 1975b), but here we will call it the Victorville basin to maintain a clear distinction with the drainage basin of Cajon Creek, which is located nearby to the south (fig. 2).

The Victorville basin is bordered to the southeast by the western San Bernardino Mountains, which consist mainly of granitic rocks and sparse pendants of metasedimentary rocks (fig. 1). It meets these mountains along a steep arcuate front produced by tectonic uplift in the Pleistocene and late Pliocene (Meisling and Weldon, 1989). Near Deep Creek, along the northeast-trending segment of the front, southeast-dipping thrust and reverse faults have displaced granitic rocks atop alluvial deposits of the basin (fig. 2) (Meisling, 1984; Meisling and Weldon, 1989). To the west near Cajon Pass, the granitic basement rocks and overlying basin sediments have been uplifted and tilted to the north by monoclinal arching that produced the northwest-trending "western wing" of the San Bernardino Mountains (Dibblee, 1975b; Meisling and Weldon, 1989; Kenney and Weldon, 1999). High peaks of the eastern San Gabriel Mountains lie nearby across the San Andreas Fault, framing the southwest side of the Victorville basin. These mountains contain extensive bodies of schistose metagraywacke and metabasalt (Pelona Schist), in addition to granitic rocks.

The basin is bordered to the north by local peaks and ridges of pre-Tertiary basement rocks (Bowen, 1954; Dibblee, 1967; Bortugno and Spittler, 1986). The Mojave River exits the north end of the basin through an alluviated gap between Quartzite Mountain and the southeastern Shadow Mountains (fig. 2). The uplands on either side of this gap contain large pendants of metasedimentary rocks that are intruded by Mesozoic plutonic rocks. Silicic metavolcanic rocks crop out extensively in neighboring ridges north and east of Quartzite Mountain. Complex faulting and warping probably produced the irregular northern, western, and eastern margins of the basin. The associated deformational structures are largely concealed by the upper levels of the basin fill, however, and are therefore poorly understood.

A deep stratigraphic cross-section of the basin sediments and underlying rock units is exposed where the headwaters of Cajon Creek breach the south edge of the Victorville basin. This section contains a thick succession of Miocene to Pleistocene nonmarine sediments. The aggregate thickness is as great as 10,350 ft (3,150 m) (Meisling and Weldon, 1989), but less than half of this (about 3,950 ft, 1,200 m) appears to be physically and genetically related to the Victorville basin.

The great bulk of the succession comprises two partly coeval Miocene units of granitic sandstone, siltstone, and conglomerate—the Cajon Formation of Meisling and Weldon (1989) (8,000 ft, 2,440 m) and the Crowder Formation (3,200 ft, 980 m). These formations accumulated about 18-13.5 Ma and 17-9.5 Ma, respectively (Woodburne and Golz, 1972; Weldon, 1985; Reynolds, 1991), and were deposited in separate basins by streams draining southward from the Mojave Desert (Woodburne and Golz, 1972; Foster, 1980). The two basins were juxtaposed by southwest-directed thrusting between about 9.5 and 4.1 Ma, during the uplift of the ancestral San Bernardino and San Gabriel Mountains (Meisling and Weldon, 1989; Weldon and others, 1993). The Cajon Formation is confined to a narrow fault-bounded block near the San Andreas Fault and evidently does not extend northward into the Victorville basin. However, the Crowder Formation, lying in the upper plate of the old thrust fault, apparently is unrestricted to the north and presumably constitutes much of the deep basin fill between Cajon Pass and Victorville.

The Cajon and Crowder Formations are overlain unconformably by the Pliocene to early Pleistocene Phelan Peak Formation of Weldon and others (1993), which consists of an upward-coarsening succession of sand, silt, and gravel. The type section near Phelan Peak (fig. 2) is about 1,650 ft (500 m) thick and was deposited between about 4.4-1.4 Ma (Weldon and others, 1993, fig. 8; ages revised according to modern geomagnetic polarity timescale—fig. 3). The lower half of the section consists of low-energy fluvial and lacustrine sediments that presumably were derived from both the north and south sides of the basin, whereas the upper half, deposited after about 2.5 Ma, consists of coarse alluvial-fan deposits derived from an elevated region nearby to the south (Foster, 1980). Weldon and others (1993) proposed that the upland source area was a remnant of the late Miocene ancestral Transverse Ranges that was transported northwestward past the Cajon Pass region by the San Andreas Fault.

The stratigraphic succession at the south edge of the Victorville basin is capped by the Victorville Fan deposits of Meisling and Weldon (1989), which conformably overlie the Phelan Peak Formation between Phelan Peak and Cajon Pass (Kenney and Weldon, 1999). The Victorville Fan deposits are an upward-coarsening sequence of weakly consolidated sand and gravel about 650 ft (200 m) thick that crops out spectacularly in the Inface Bluffs (fig. 2). In ascending order, the sequence comprises the Harold Formation, the Shoemaker Gravel, and the older alluvium of Noble (1954). Based on distinctive rock detritus, including debris of the Pelona Schist and Lowe Granodiorite, all three units were derived from basement rocks of the San Gabriel Mountains lying southwest of the San Andreas Fault (Foster, 1980; Meisling and Weldon, 1989). Deposits at the head of Crowder Canyon (fig. 2) accumulated during the early Pleistocene, between about 1.7 and 0.78 Ma (Meisling and Weldon, 1989; Weldon and others, 1993). Sedimentation evidently was induced by strike-slip movements on the San Andreas Fault that transported the high, central and eastern parts of the San Gabriel Mountains alongside relatively subdued terrain of the southern Mojave Desert (Meisling, 1984; Weldon, 1986; Meisling and Weldon, 1989; Weldon and others, 1993).

Deposits at the southeast side of the Victorville basin record a different source area and drainage system associated with the San Bernardino Mountains. The Ord River deposits of Meisling and Weldon (1989), which are exposed in the walls of the Mojave River canyon along the northwest front of the range, consist of coarse-grained, well-stratified fluvial sand and gravel composed mainly of granitic debris. Meisling (1984) described these deposits and interpreted their paleogeographic significance. The younger parts of the unit contain clasts of metasedimentary and metavolcanic rocks recycled from the Crowder Formation, but Pelona Schist and other detritus indicative of the San Gabriel Mountains are absent throughout the unit. The main source area was the drainage basin of ancestral Deep Creek, which evidently was the principal tributary of the ancestral Mojave River in the early Pleistocene. The Ord River deposits intertongue to the west with deposits of the Harold Formation and Shoemaker Gravel, which demonstrates that the ancestral Mojave River and neighboring Victorville Fan simultaneously aggraded the southern Victorville basin during the early Pleistocene (Meisling, 1984; Meisling and Weldon, 1989).

Drainage issuing from the San Bernardino Mountains also is recorded in the stratigraphy of the northern Victorville basin near Victorville and GAFB. Borehole investigations indicate the uppermost 525 ft (160 m) of the basin fill beneath GAFB consists of three main units of weakly consolidated sediments. These are an upper unit of granitic sand, silt, and gravel, a medial unit of clay and silt, and a basal unit of compositionally heterogeneous sand, silt, and gravel (IT Corp, 1992; Sibbett, 1996, 1999; Montgomery Watson, 1995; Chrisley, 1997). The middle unit evidently pinches out near the north end of GAFB and is thus confined to the Victorville basin, as delineated by gravity data (Montgomery Watson, 1995; Chrisley, 1997). However, the upper and lower units continue to the north, forming an attenuated sequence that crops out downstream along the Mojave River to Iron Mountain (Cox and others, 1998; Cox and Tinsley, 1999; Reynolds and Cox, 1999, field trip stop 9). Correlation within a dense array of boreholes at GAFB disclosed northwest-trending gravel-filled channels in the upper unit, which suggest it was deposited by the ancestral Mojave River (IT Corp., 1992; Sibbett, 1996, 1999).

Vertebrate fossils collected from the upper unit at various sites around Victorville are generally consistent with a middle Pleistocene (late Irvingtonian or earliest Rancholabrean) age (Jefferson, 1986; Reynolds, 1989; Reynolds and Reynolds, 1994a).

This age interpretation was locally bolstered by the determination of normal magnetic polarity (Meisling, 1984, locality HRF; Meisling, personal commun., 1984, cited in Reynolds, 1989; Meisling, personal commun., 1985, cited in Reynolds and Reynolds, 1994a). However, a recent study reported possible early Pleistocene vertebrates in the upper part of the unit (Scott and others, 1997). Previous studies have yielded little information regarding the age and origin of the lower two units.

The Quaternary surficial geology of the greater Victorville region is dominated by three large-scale geomorphic elements: the Victorville Fan, the George surface, and the Mojave River canyon. The former two features form the upper bounding surface of the Victorville basin, whereas the Mojave River canyon is incised into the basin fill. The Victorville Fan is a broad piedmont slope or bajada that descends northeastward from Cajon Pass to Victorville (fig. 2). Early Pleistocene-age first-cycle fan gravels (Victorville Fan deposits of Meisling and Weldon, 1989) underlie the relatively steeply sloping head of the fan. The gentler lower slopes are blanketed by late Pleistocene-age alluvial and aeolian deposits recycled from the head of the fan (Bortugno and Spittler, 1986; Reynolds and Cox, 1999, fieldtrip stop 6). Erosion and sedimentary recycling likely prevailed after about 0.78-0.5 Ma, when southwestern tributaries of the ancestral Mojave River captured the trunk drainage issuing from the San Gabriel Mountains, thus cutting off the source of fresh alluvium to the fan (Meisling, 1984; Reynolds and Cox, 1999, fieldtrip stop 3). These marauding streams incised the ancestral Summit Valley and parallel northeast-trending ravines that scar the southeast shoulder of the Victorville Fan (fig. 2). They were themselves pirated sometime after about 0.5 Ma, when Cajon Creek eroded headward along the San Andreas Fault Zone and beheaded the Victorville Fan along the Inface Bluffs (Meisling, 1984).

The George surface (Cox and Tinsley, 1999) is a deeply dissected, gently inclined alluvial platform at the northeast toe of the Victorville Fan. It is well preserved near Apple Valley, Victorville, and GAFB (fig. 2). The surface is a late Pleistocene stream terrace that represents the broad floodplain of the ancestral Mojave River (IT Corp., 1992; Sibbett, 1996, 1999; Cox and others, 1998; Cox and Tinsley, 1999). Prior to the entrenchment of the Mojave River canyon in the late Pleistocene and Holocene, the floodplain was 2-8 mi (3-13 km) wide and about 45 mi (75 km) long, extending downstream from the mouth of Deep Creek to Harper Lake (fig. 2). Late Pleistocene-age recycled alluvium deposited at the toe of the Victorville Fan protrudes northward onto the George surface between Hesperia and Adelanto (fig. 2) (Cox and Tinsley, 1999; Reynolds and Cox, 1999, fieldtrip stop 6).

The Mojave River occupies a canyon about 0.6-1.2 mi (1-2 km) wide that extends from the northwest front of the San Bernardino Mountains downstream nearly to Barstow (fig. 2). The gradient of the active river channel between Deep Creek and Victorville is nearly identical to that of the adjacent George surface, which helps to confirm that the ancestral Mojave River produced the latter feature. The alluviated floor of the river canyon typically lies about 200 ft (60 m) below the George surface between southern Apple Valley and the Helendale Fault, but its depth locally exceeds 250 ft (75 m) near

GAFB. The canyon gradually shallows downstream from the Helendale Fault, ending at Hinkley Valley.

LITHOSTRATIGRAPHY

Prior to the recent closure of George Air Force Base (GAFB), many wells and exploratory boreholes were drilled to determine the geohydrologic framework and subsurface distribution of contaminants (IT Corp., 1992; Montgomery Watson, 1995). Through the courtesy of the Montgomery Watson company, we acquired nearly continuous, 2-inch-diameter mud-rotary cores from four drilling sites located around the perimeter of the base (fig. 4, sites RZ-01, -02, -03, and -04). We focused our investigation on the borehole sediment cores because our primary target—alluvium of the ancestral Mojave River—was reported to form a thick layer beneath GAFB (IT Corp, 1992; Sibbett, 1996). Moreover, the cores encompass a cumulative thickness of about 525 ft (160 m), whereas the thickness of alluvium exposed in the walls of the Mojave River canyon near Victorville and GAFB is no greater than 250 ft (75 m). We should emphasize that our survey of the four boreholes as described herein was designed to investigate major stratigraphic and structural trends and was not intended as a comprehensive subsurface investigation of GAFB.

Stratigraphic sequences observed in the four boreholes are summarized on figure 5, which also indicates inferred lateral relations between the holes. No core was available for the lowest quarter of borehole RZ-02 or the upper half of RZ-04. The lithology of these intervals was adapted from the original drilling logs (Montgomery Watson, 1995, appendix D). We extended the stratigraphic column at site RZ-01 about 45 ft (14 m) above the top of the borehole by measuring strata exposed on nearby walls of a ravine (fig. 5). In agreement with previous work (IT Corp., 1992; Montgomery Watson, 1995; Chrisley, 1997), our investigation confirms that the deposits drilled at GAFB comprise three main lithostratigraphic units, which are described below in descending stratigraphic order. The upper and lower units consist mainly of sand whereas the middle unit consists mainly of clay and silt. The elevation, thickness, and internal details of the three units vary significantly from hole to hole.

Upper fluvial unit

The uppermost unit is a texturally heterogeneous, but compositionally homogeneous, sequence of granitic sand, silt, and gravel. These deposits directly underlie the broad alluvial platform at GAFB, and thick sections through the unit are exposed in neighboring bluffs of the Mojave River canyon. The deposits are part of a belt of dissected fluvial sediments that extends about 45 mi (75 km) along the Mojave River, from Deep Creek to Harper Lake (fig. 2; Cox and Tinsley, 1999). The unit is about 360 ft (110 m) thick near the southeast corner of GAFB (borehole RZ-01, with 100 ft of surficial erosion restored),

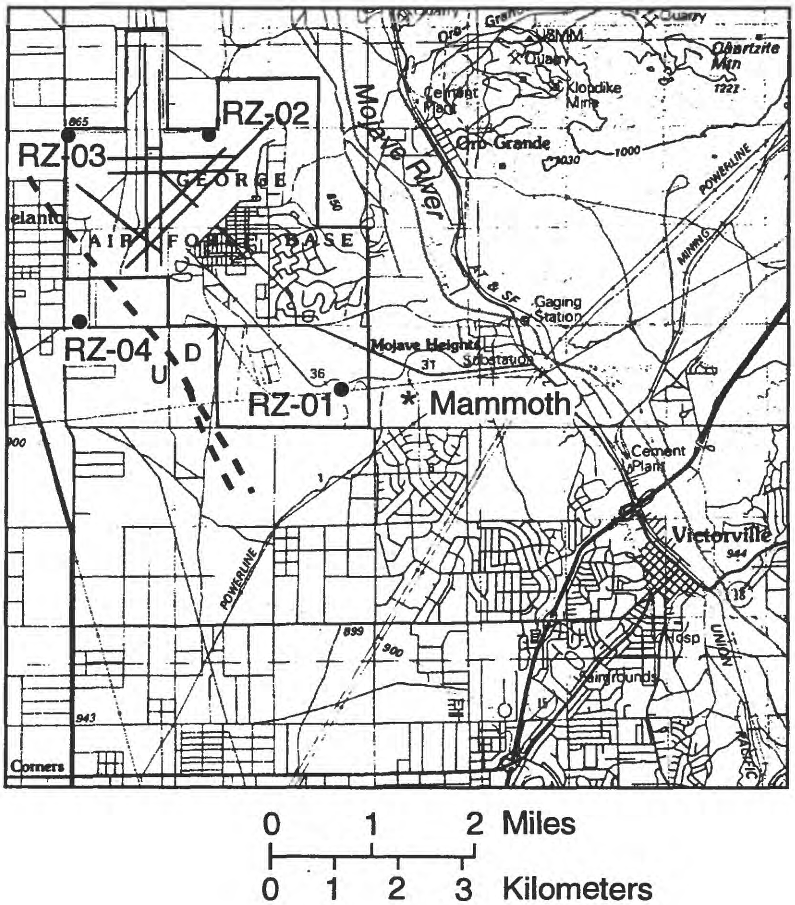
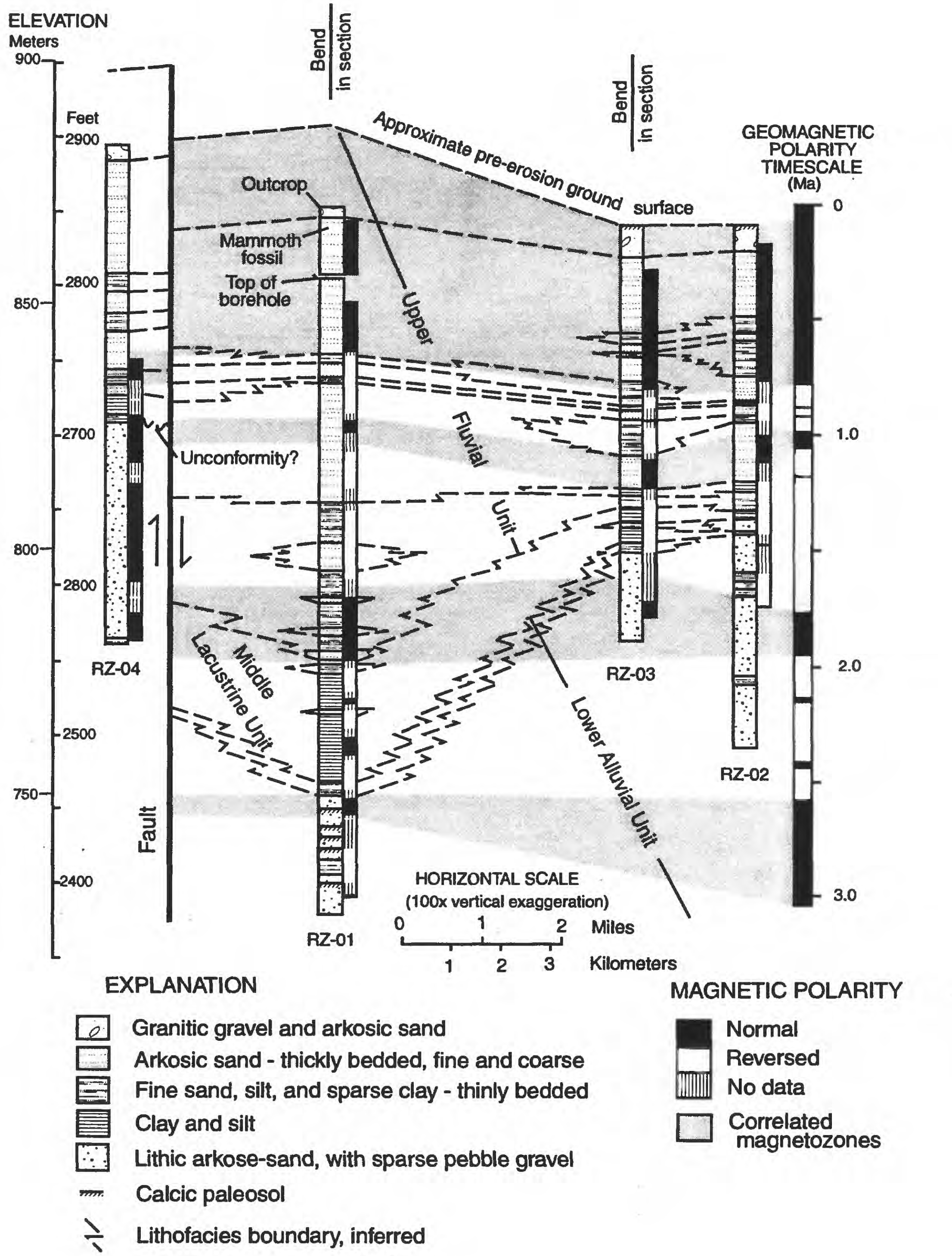


Figure 4. Map of George Air Force Base and Victorville, California, showing location of the four principal boreholes investigated for this study (RZ-01, -02, -03, -04). Star indicates location of fossil mammoth locality (Mammuthus meridionalis) reported by Scott and others (1997). Heavy dashed line is fault inferred from aerial-photographic lineament and offset stratigraphy in borehole RZ-04; D, downthrown side; U, upthrown side. Base from U.S. Geological Survey, Victorville 30x60 minute quadrangle, California, 1982.

Figure 5. Lithostratigraphy and magnetostratigraphy of boreholes at GAFB, California. Vertical scale is 100 times horizontal scale. Borehole locations are shown on figures 2 and 4. Note two sharp bends in the section, at sites of boreholes RZ-01 and RZ-03. Critical subsurface relations are most readily visualized by imagining that view is toward the northwest, with borehole RZ-01 in the foreground and the other boreholes in the background.



but thins markedly to the north and west (fig. 5). The thickness drops to about 150-175 ft (45-53 m) near the western and northern margins of the base (boreholes RZ-02, -03, and -04) and finally declines to about 80 ft (25 m) in outcrops 2 mi (3.2 km) north of borehole RZ-02. Continuing northward, the thickness remains relatively uniform for at least 14 mi (23 km) along the Mojave River to Iron Mountain. Throughout this long stretch, the thickness generally fluctuates between 25-80 ft (8-25 m) (B. Cox, unpub. mapping).

The upper fluvial unit contains four distinct lithofacies, each consisting of loose to weakly consolidated yellowish-brown and olive-brown sediments (Munsell hues 10YR and 2.5 Y). Two facies of thickly bedded sand are abundant and intimately interlayered throughout the section. One of these consists of silty fine sand and the other of pebbly coarse sand. A third facies consists of thinly bedded fine sand, silt, and sparse clay. These fine-grained sediments comprise much of the lowest third of the upper fluvial unit in borehole RZ-01, thus largely accounting for the greater depth of the unit beneath the southeastern part of GAFB (fig. 5). They are also abundant at higher stratigraphic levels in boreholes RZ-02 and RZ-03 near the north end of the air base, where they range upward to about 65 ft (20 m) below the George surface. A fourth facies includes thick beds of pebble and cobble gravel, which are interlayered with thickly bedded fine and coarse sand near the top of the unit. Overall, the unit coarsens irregularly upward, mainly due to the concentration of silt-rich and gravel-rich sediments at opposite ends of the stratigraphic column.

The thickness of beds within the gravel facies and the two thickly bedded sand facies typically ranges between 12-80 inches (30-200 cm), and multiple beds of either sand facies commonly are stacked to form compound layers as much as 12-15 ft (4-5 m) thick. The thickly bedded silty fine sand is poorly sorted, consisting mainly of fine to very fine sand, combined with abundant silt, moderate amounts of medium to very coarse sand, and sparse granules and small pebbles. This material forms nearly structureless beds that characteristically are capped gradationally with a thin layer of sandy silt.

By contrast, the pebbly coarse sand typically is moderately sorted, consisting mostly of medium to very coarse sand with only sparse interstitial silt. Associated pebbles range up to 25 mm in diameter. Textural and heavy-mineral laminations commonly are visible in the borehole cores. Outcrops in the Mojave River bluffs reveal other details such as lenticular channels, trough and low-angle cross-stratification, and "rip-up" clasts of sandy silt. The outcrops also reveal complex intertonguing and intergrading between laterally adjacent thick beds of pebbly coarse sand and silty fine sand, which indicates these two facies accumulated simultaneously in directly adjoining environments. Beds of pebble and cobble gravel near the top of the section generally resemble the deposits of pebbly coarse sand and contain a similar matrix of medium to very coarse sand. However, they differ by containing more abundant and larger clasts which, in the outcrops, range up to at least 20 cm in diameter.

In the two thickly bedded sand facies and in the gravel, sand grains are mostly subangular and are derived almost exclusively from felsic plutonic rocks. Flakes of fresh biotite are conspicuous. Pebbles are mostly subangular to subrounded and consist of granitic rocks and felsic orthogneiss, accompanied by minor amounts of quartzite and silicic metavolcanic rocks. Pebbles of schistose metagraywacke derived from the Pelona Schist of the San Gabriel Mountains were locally observed in cobble gravel near the top of the unit (e.g., Reynolds and Cox, 1999, field trip stop 8). However, fragments of the schist were not evident at deeper stratigraphic levels in any of the four borehole cores.

Deposits of thinly bedded sand, silt, and sparse clay range from about 3-25 ft (1-8 m) thick. Individual layers within these fine-grained intervals are mostly 1-8 inches (2-20 cm) thick, although beds of fine sand occasionally are as thick as 25 inches (60 cm). The layering locally is disrupted by desiccation cracks, root traces, and rare burrows. The sand consists of silty, fine to very fine-grained, micaceous (biotitic) arkose. Ostracodes are rarely observed in layers of silt and clay. In each borehole, the basal deposit of the upper fluvial unit consists of a thin (4-80 inches, 10-200 cm) interval of variegated, olive-gray to yellowish-brown, micaceous fine sand with ripple-drift cross-lamination, heavy-mineral laminations, and intercalated thin layers of silt. This interval effects a conformable transition between the highest lacustrine muds of the middle unit and the lowest coarse fluvial sands of the upper unit.

The George surface at the top of the upper fluvial unit is capped by a fossil soil profile containing well-developed argillic and calcic horizons. This feature is exposed in road cuts and other shallow excavations around GAFB, and it crops out sporadically at the crest of the Mojave River bluffs north and east of the base. In most areas, the paleosol is partly eroded and covered by a thin veneer of Holocene sheet wash and aeolian sand. We encountered several good exposures of the paleosol in a pipeline trench on the east side of Helendale Road, 2-4 mi (3.2-6.5 km) north of borehole RZ-02. There the profile is about 2.5 ft (0.75 m) thick and consists of an eroded argillic horizon about 1.5 ft (0.45 m) thick and an underlying calcic horizon about 1 ft (0.3 m) thick. The argillic horizon consists of strong-brown (damp material is 7.5YR 4/6) clayey sand with coarse prismatic peds. The calcic horizon consists of structureless, chalky, calcium carbonate that impregnates the sandy parent material, completely obscuring primary detrital texture and stratification (stage III to III+ carbonate morphology; Gile and others, 1966; Bachman and Machette, 1977).

The great bulk of the unit beneath the capping paleosol is relatively unaltered and unweathered, containing only incipient argillic soil horizons. Thus, the pedologic evidence does not reveal any major interruptions in the accumulation of the upper fluvial unit.

The deposits of pebbly coarse sand and pebble-cobble gravel closely resemble sediments in the nearby active channel of the Mojave River, and by analogy we infer they were deposited by turbulent floodwaters in shallow braided channels of the northward-flowing ancestral Mojave River. The intimately associated deposits of thickly bedded silty fine sand probably represent floodplain splays that accumulated alongside the channels when floods overtopped their banks. Thinly bedded fine sand, silt, and clay apparently are paludal sediments that accumulated in ephemeral ponds and marshes on a delta plain or river floodplain.

Middle lacustrine unit

The middle lacustrine unit consists of calcareous clay and silt, with lesser amounts of interlayered sand. The unit is about 25-83 ft (8-25 m) thick at GAFB (fig. 5). As with the overlying upper fluvial unit, the greatest thickness is found in borehole RZ-01, near the southeast corner of GAFB. The unit also crops out locally in the Mojave River bluffs at the east edge of the base. In the outcrops it is no more than about 10 ft (3 m) thick and gradually pinches out to the north, terminating about 6,700 ft (2040 m) S65°E from borehole RZ-02 (B. Cox, unpub. mapping). Based on hydrologic data, the unit evidently also pinches out toward the north in the subsurface about 7,250 ft (2,210 m) due north of borehole RZ-02 (Montgomery Watson, 1995; Chrisley, 1997).

Several lithologic features distinguish the middle lacustrine unit. It contains thick intervals of structureless to prominently laminated clay and clayey fine-grained silt. Some of these intervals are nearly devoid of sand and coarse silt (particularly in boreholes RZ-01 and RZ-03). By contrast, the upper fluvial and lower alluvial units contain only sparse thin layers of clay intercalated amongst beds of sand and coarse silt. Secondly, the lacustrine unit consists of interlayered greenish (olive-gray—Munsell hues 5Y-10Y-2.5GY) and brownish (10YR and 2.5 Y) sediments, whereas the units above and below are composed exclusively of brownish deposits. Third, the lacustrine mud contains abundant aquatic microfossils, particularly ostracodes, diatoms, and seeds and stems of water plants; fish scales and gastropods are occasionally observed (R. Forester, written commun., 1999). Furthermore, the mud typically effervesces in dilute hydrochloric acid, indicating the presence of calcium-carbonate microfossils, matrix, or cement. Muddy sediments in the upper fluvial and lower alluvial units mostly lack aquatic microfossils and generally are noncalcareous. Finally, there is virtually no evidence of soil development in the lacustrine unit, whereas the upper fluvial unit contains incipient argillic soil horizons and the lower alluvial unit contains incipient to mature argillic and calcic horizons.

The abundance and character of intercalated sand varies vertically and laterally in the middle lacustrine unit. The lowest three-quarters of the thick (83 ft, 25 m) lacustrine sequence in borehole RZ-01 consists of homogeneous clayey mud with only sparse disseminated sand grains and rare thin layers of turbiditic sand. However, in the uppermost quarter of this sequence, and throughout the entire lacustrine section in the other boreholes, the clayey mud is interlayered with coarse silt and fine sand, and locally with sparse beds of medium and coarse sand. Some of these arenaceous deposits consist of olive-gray ostracodal sand and silt, while others consist of oxidized yellowish-brown sand and silt with interspersed mudcracks and root traces. The abundant fine sand intercalated near the top of the lacustrine unit in borehole RZ-01 produces a transitional, conformable boundary with the overlying upper fluvial unit. This boundary is more abrupt, yet demonstrably conformable, in the other three boreholes. The lacustrine section in borehole RZ-02 contains thicker sandy intervals than the laterally equivalent section in borehole RZ-03 (fig. 5), which indicates the depositional environment varied significantly between these two sites.

The detrital composition of sand in the lacustrine unit varies from essentially pure, biotite-rich arkose like that in the upper fluvial unit, to sparsely micaceous, slightly lithic arkose like that in the lower alluvial unit. The lithic-arkose sand tends to be concentrated near the base of the unit and the pure arkose near the top, but the two varieties of sand are interlayered in borehole RZ-04.

The interlayered sand and fine mud, alternating green and brown colors, local root casts and mud cracks, and assorted aquatic organisms indicate the middle lacustrine unit accumulated in a shallow lake or wetland bordered by fluvio-deltaic mudflats. Lower parts of the lacustrine sequence in boreholes RZ-01 and RZ-03 contain abundant veins and nodules of calcium carbonate. The carbonate material probably precipitated from upwelling ground water, which implies the lake or wetland was recharged in part by springs.

Lower alluvial unit

In each of the four boreholes the middle lacustrine unit overlies a lower alluvial unit consisting of lithic-arkosic sand, silt, and polymictic pebble gravel (fig. 5). Although the boreholes penetrate as deeply as 165 ft (50 m) into the lower unit, none of them reaches its base, which therefore remains undefined. The lower alluvial unit crops out in the bluffs of the Mojave River directly east of GAFB, where it is conformably overlain by an attenuated lacustrine section about 10 ft (3 m) thick. The lakebeds gradually pinch out northward in the bluffs and the lower alluvial unit is capped unconformably by the upper fluvial unit, a relationship that extends for about 15 mi (25 km) downstream along the Mojave River, from GAFB to Iron Mountain (B. Cox, unpub. mapping).

As compared to the upper fluvial unit, the lower alluvial unit generally is more weathered and oxidized and contains more authigenic calcium carbonate and clay minerals. Owing to the effects of weathering and diagenesis, the deposits also tend to be more firmly consolidated and more richly colored; Munsell hues typically range from yellowish brown to strong brown (10YR-7.5 YR). Two thickly bedded sandy facies are predominant. One consists of silty sand, and the other of "clean" sand and pebble gravel. These facies locally are interlayered and jointly constitute about 90 percent of the aggregate drilled thickness of the unit in the four boreholes. The abundance of the silty sand facies generally increases upward in the boreholes at the expense of clean sand and gravel. Sparse thick beds of silt and fine sand constitute a subordinate third facies.

Deposits of the silty sand facies are poorly stratified and very poorly sorted. Silt and very fine-grained to medium-grained sand are the dominant constituents, but coarse sand, granules, and small pebbles also are abundant, particularly in the lower parts of beds. The deposits of clean sand and gravel are prominently stratified and moderately sorted, typically consisting of medium-grained to very coarse-grained pebbly sand and subordinate sandy pebble gravel. Both facies form beds 12-70 inches (30-180 cm) thick that are stacked to form compound layers as much as 10 ft (3 m) thick.

In comparison to analogous deposits of the upper fluvial unit, the sandy and gravelly facies of the lower alluvial unit are characterized by more diverse detrital textures and provenance. Sand-size grains are mainly subangular, but sparse subrounded to rounded grains record accessory aeolian transport or recycling from pre-existing sedimentary rocks. The sand consists of slightly lithic arkose with about 1-5 percent lithic fragments and conspicuous accessory epidote (also see Chrisley, 1997). Biotite typically is sparse and strongly weathered. Gravel clasts consist of aplite and other felsic plutonic rocks; silicic metavolcanic rocks, including abundant ash-flow tuff; nonmetamorphosed hornblende-biotite dacite; and various metasedimentary rocks, mainly quartzite, marble, and calc-silicate hornfels. The relative abundance of these miscellaneous clast types varies significantly from layer to layer within each borehole. Clasts as large as 15-20 cm were observed in outcrops of clean sandy gravel directly east of GAFB. Most clasts are angular to subrounded. However, many of the dacite clasts are rounded, which suggests they may have been transported a greater distance or recycled from older gravel or conglomerate.

The subordinate facies of silt and fine sand forms several beds about 3-10 ft (1-3 m) thick (fig.5). There are two variants of this facies. One comprises structureless beds of consolidated clayey silt and fine sand intercalated well below the top of the lower alluvial unit in boreholes RZ-01, -02, and -04. The other variant forms a thick layer of well-stratified friable silt and fine sand that caps the lower alluvial unit in boreholes RZ-01, -03, and -04. The latter deposit is laminated to thinly bedded and locally (in RZ-01) contains sediment-filled horizontal burrows about 0.6 inches (15 mm) in diameter. It grades upward from yellowish-brown silty sand into olive-gray sandy silt, thus effecting a gradual, seemingly conformable, transition between the lower alluvial unit and middle lacustrine unit. We suspect this boundary truly is conformable in boreholes RZ-01 and RZ-03. However, evidence discussed in a later section ("syndepositional faulting at GAFB") suggests there is a significant unconformity at the base of the transitional layer in borehole RZ-04. Interlayered alluvial and lacustrine facies establish a conformable transition between the lower alluvial unit and middle lacustrine unit in borehole RZ-02 (fig. 5).

Buried soil profiles with mature argillic and calcic horizons are common in the lower alluvial unit. The calcic horizons mainly contain filamentous and nodular calcium carbonate (stage I and II carbonate morphology; Gile and others, 1966; Bachman and Machette, 1977), but several stage-III carbonate crusts were observed in borehole RZ-01 (fig. 5). Throughout the unit, grains of plagioclase and dacite are partly altered to clay. This pervasive effect presumably is a product of intrastratal diagenesis.

The lower alluvial unit at GAFB evidently comprises an assemblage of braided-stream, alluvial-fan, and playa deposits. Deposits of clean sand and pebble gravel probably accumulated in channels of a major southward-flowing braided stream and possibly also in washes of large alluvial fans. Deposits of poorly sorted silty sand are ascribed to sheet floods in low-gradient fluvial or alluvial-fan environments, and the intercalated thick beds of clayey silt and fine sand presumably formed in small playas. Finally, the transitional layer of well-stratified silt and fine sand that caps the unit probably is a fluvio-deltaic deposit. In general, the greater degree of weathering and soil development as compared to deposits of the upper fluvial unit suggests the lower alluvial unit either accumulated more slowly or was subjected to a different climatic regime.

MAGNETOSTRATIGRAPHY

Paleomagnetic methods

We collected samples for paleomagnetic analysis from the dried cores RZ-01, -02, -03, and -04 at intervals ranging from 0.3-10 ft (0.1-3 m) apart, wherever consolidated fine-grained sediments were recovered (table 1). The larger gaps in the sampling occurred in sections of gravel and loose sand not suitable for paleomagnetic analysis. To prepare standard cylindrical specimens (10.5 cc), we sawed each sample into a 2.3-cm-thick disk, then cored the disk with a diamond drill cooled by compressed air. A few samples, too sandy to allow drilling by this dry method, were shaped with hand tools. In addition to the borehole samples, oriented blocks were collected from four outcrops of consolidated fine sand near the southeast corner of George Air Force Base (table 1, outcrops 1-4), and from a volcanic ash layer near the Helendale Fault (table 1, outcrop 5).

All measurements of remanent magnetization were made with a cryogenic magnetometer. Demagnetization treatments employed a commercial alternating-field apparatus (400 Hz, 100 mT maximum field) equipped with a specimen tumbler. Thermal demagnetization was carried out in air in a magnetically shielded furnace (< 5 nT).

Determinations of magnetic inclination required a dual demagnetization procedure consisting of first applying alternating fields of 5 mT and 10 mT followed by progressive heating from 150° C to 590° C in the low-field furnace. This procedure stripped away spurious magnetic remanence caused by the original coring, the recent geomagnetic field, and oxidation of iron-bearing minerals. The alternating-field steps were critical in determining whether a sample had been inadvertently overturned in the core box. If the magnetization removed by the low alternating field was directed downward, as would be expected from the magnetic effect imparted by the recent geomagnetic field or the drill-stem, then we were assured that the core had not been overturned during handling. We applied corrections to the few overturned specimens detected by this method. We then used principal-component analysis (Kirschvink, 1980) to calculate the best-fit magnetic direction to the thermal demagnetization data in all but a few cases. The exceptions were friable specimens that had to be encased in plastic boxes; these samples were given alternating-field treatment only.

Paleomagnetic results

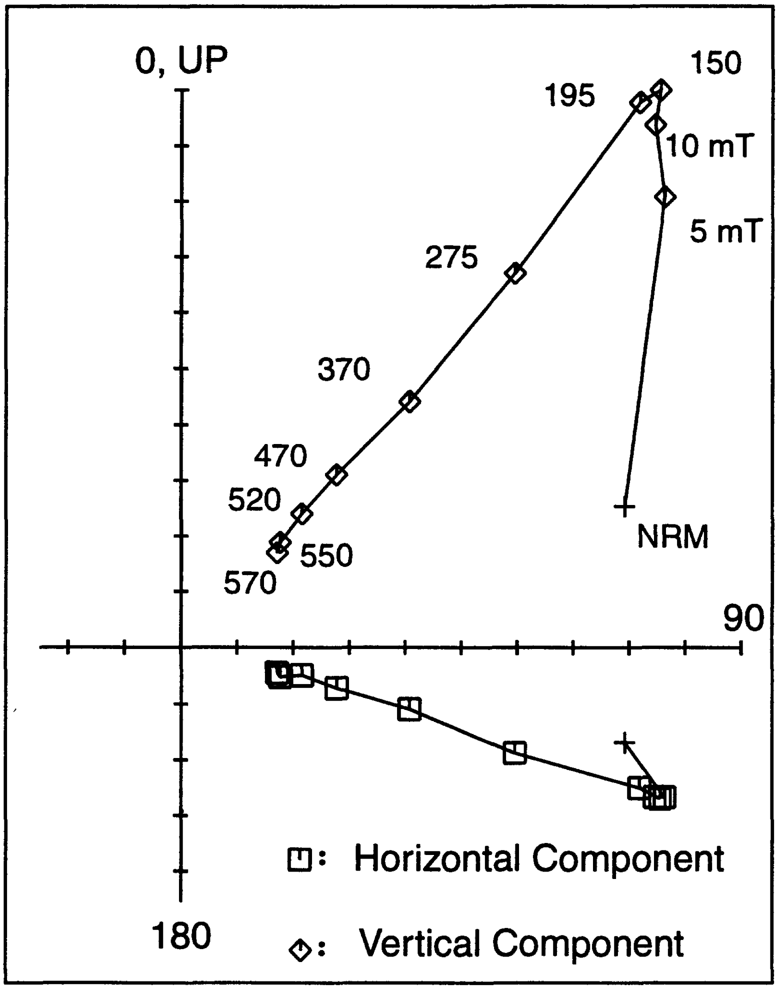
The higher-quality determinations of magnetic directions were obtained by heatings of 300-580° C (fig. 6, table 1). All but a few specimens yielded a stable magnetization direction after such treatment. A measure of quality is given by the Maximum Angular Deviation (MAD) derived from a least-squares fit to the thermal demagnetization data (Kirschvink, 1980). Seventy percent of the specimens gave MAD values of less than 5°, indicating determinations of very high quality. We have flagged the low-quality results with MAD greater than 15°, and we weigh this group, comprising 5 percent of the total collection, lightly in the polarity interpretation. For the specimens given alternating-field treatments only, we generally found that polarity was adequately determined by applying fields of 10 mT to 40 mT. Two specimens from Core RZ-03 had magnetizations that failed to stabilize after demagnetization treatment, so inclinations could not be determined. The cored strata are assumed to be flat lying and the boreholes are assumed to be vertical, so no tilt corrections were made. The declination results are not listed, because no attempt was made to reorient the cores with regard to azimuth.

We defined geomagnetic polarity from the inclination data as follows: Normal polarity, > +20°; Reversed polarity, <-20°; Intermediate, inclination 20° or shallower. These definitions take into account the natural variation of the geomagnetic field about the long-term axial dipole direction. Intermediate determinations might reflect transition of the field between polarity states, a brief excursion of the geomagnetic field, or partial removal of secondary magnetization components.

Boreholes RZ-01 and RZ-03 are well represented by samples from top to bottom. The lowest quarter of borehole RZ-02 and upper half of borehole RZ-04 were not cored, so the sampling of these holes is incomplete. From the inclination data, we defined a sequence of magnetozones for each borehole (figs. 7, 8, 9). Uncertainties in the exact stratigraphic positions of the magnetozone boundaries are caused by gaps in the sampling that are denoted on the figures.

Comparing the magnetozones of RZ-01, RZ-02, and RZ-03, we see a consistent pattern with a thick normal-polarity zone at the top, generally followed lower in the section by dominantly reversed polarity. All three cores show one or more thin zones of normal polarity within the dominantly reversed lower interval. In contrast, RZ-04 shows three reversed-polarity horizons intercalated within a broad interval of normally polarized strata.

Figure 6. Demagnetization behavior of specimen 7J078 from borehole RZ-01. Upper diagram shows projections of the magnetization components as the natural remanent magnetization (NRM) is reduced by alternating-field demagnetization (mT, milliTesla) followed by heating in a low-field furnace (in degrees C). Lower diagram shows reduction of the normalized intensity of magnetization after the alternating-field and thermal treatments.



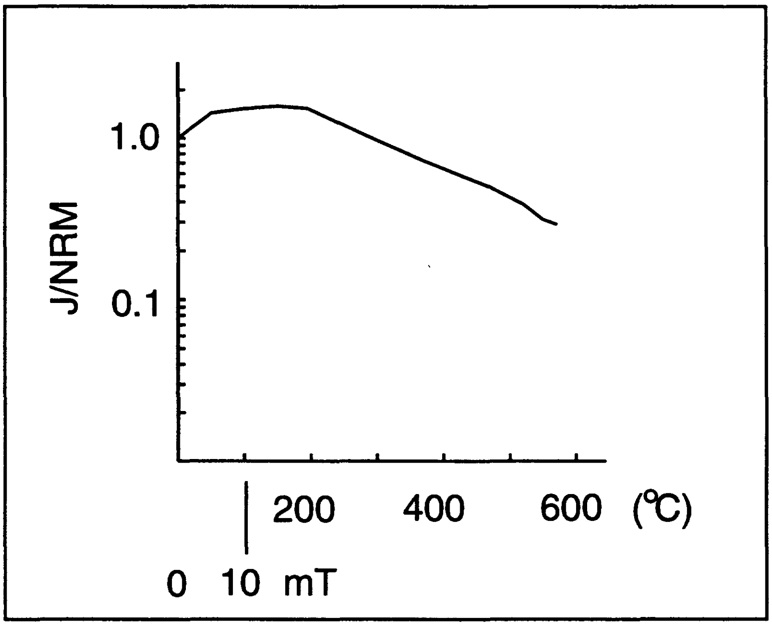
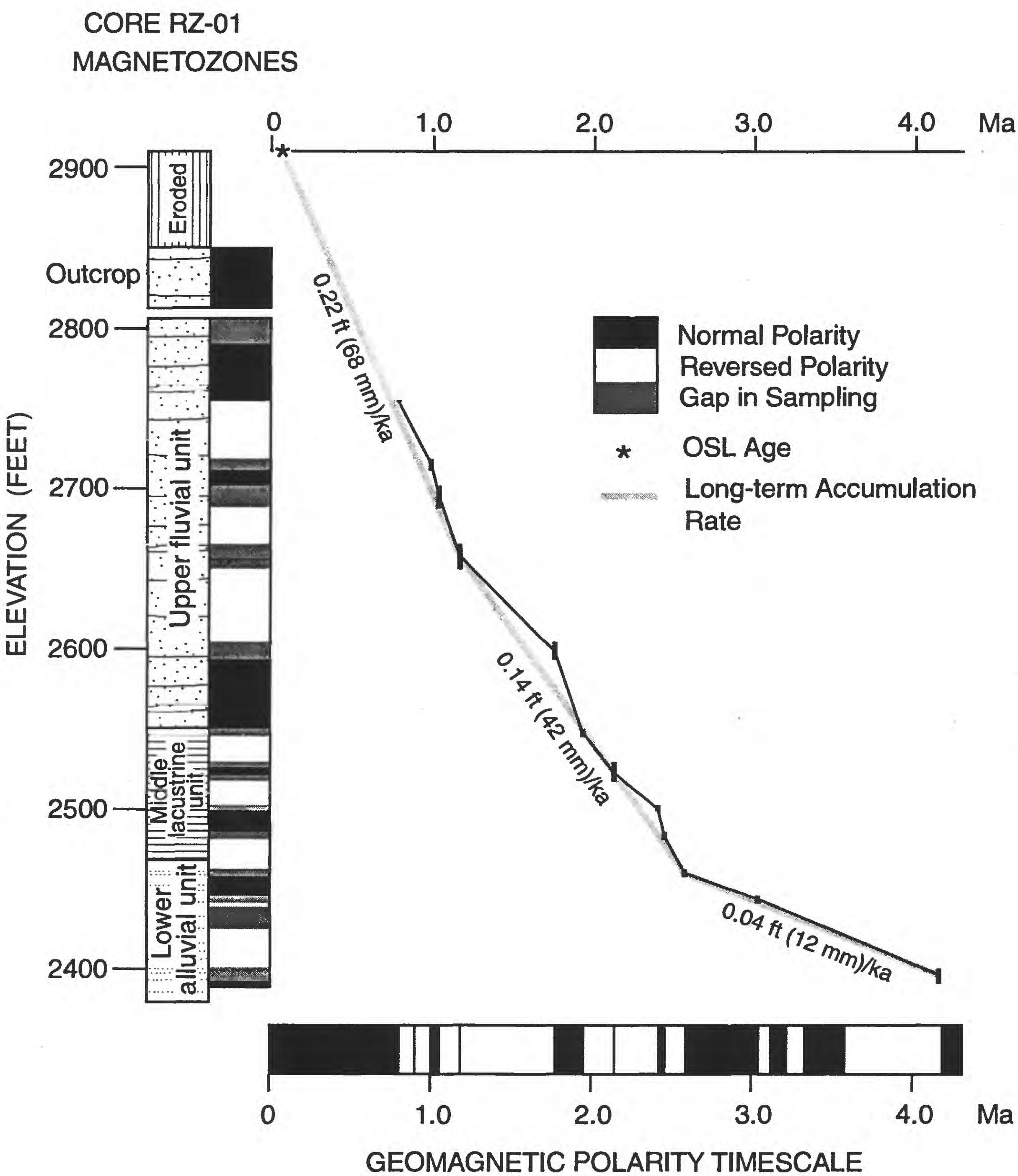


Figure 7. Time versus sedimentation at borehole RZ-01 and nearby outcrops, as correlated with the geomagnetic polarity timescale. Vertical bars indicate uncertainty in stratigraphic position of the polarity transitions. Top of section is dated by optically stimulated luminescence (OSL).



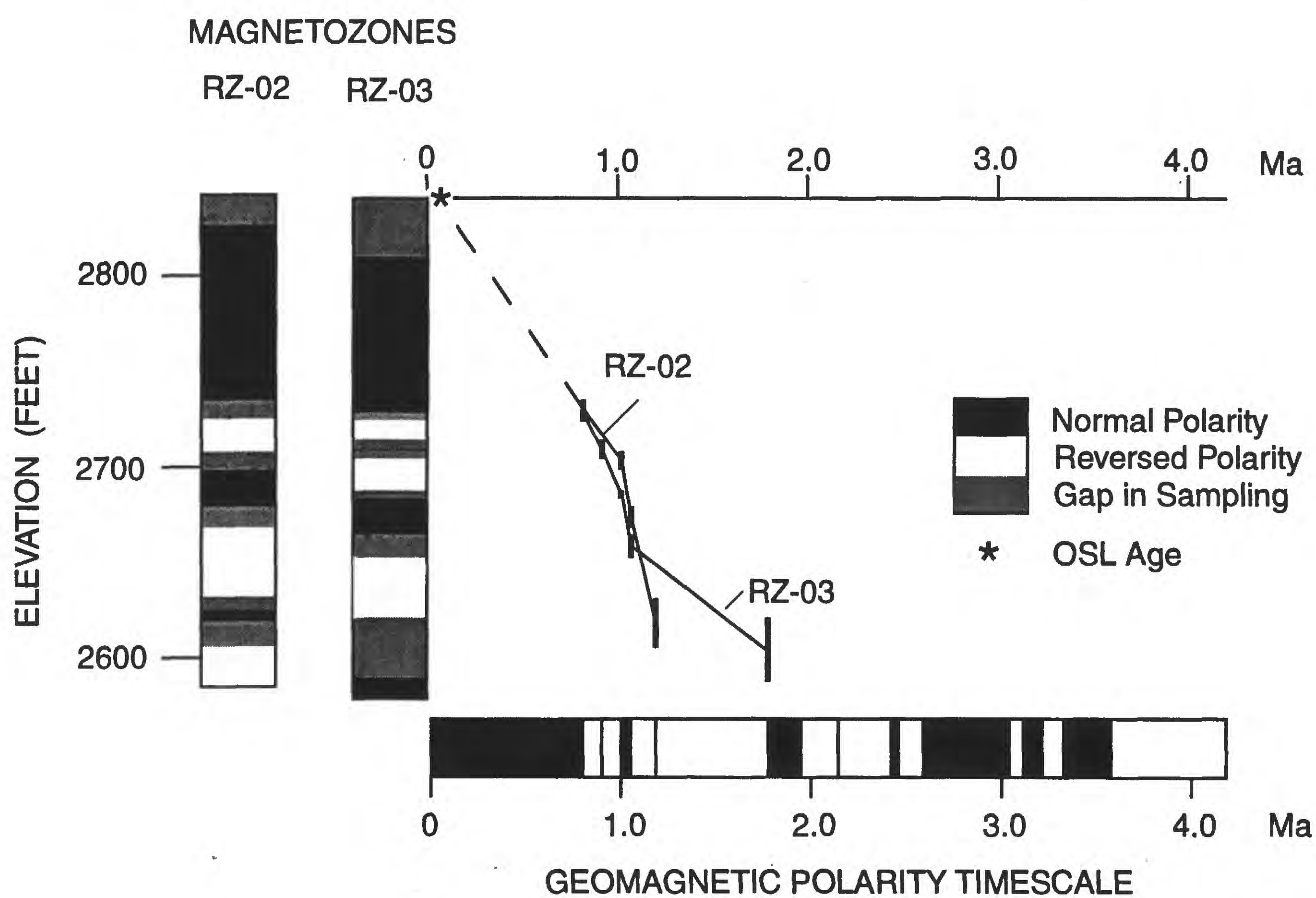


Figure 8. Time versus sedimentation at boreholes RZ-02 and RZ-03, as correlated with the geomagnetic polarity timescale. Vertical bars indicate uncertainty in stratigraphic position of the polarity transitions. Top of section is dated by optically stimulated luminescence (OSL).

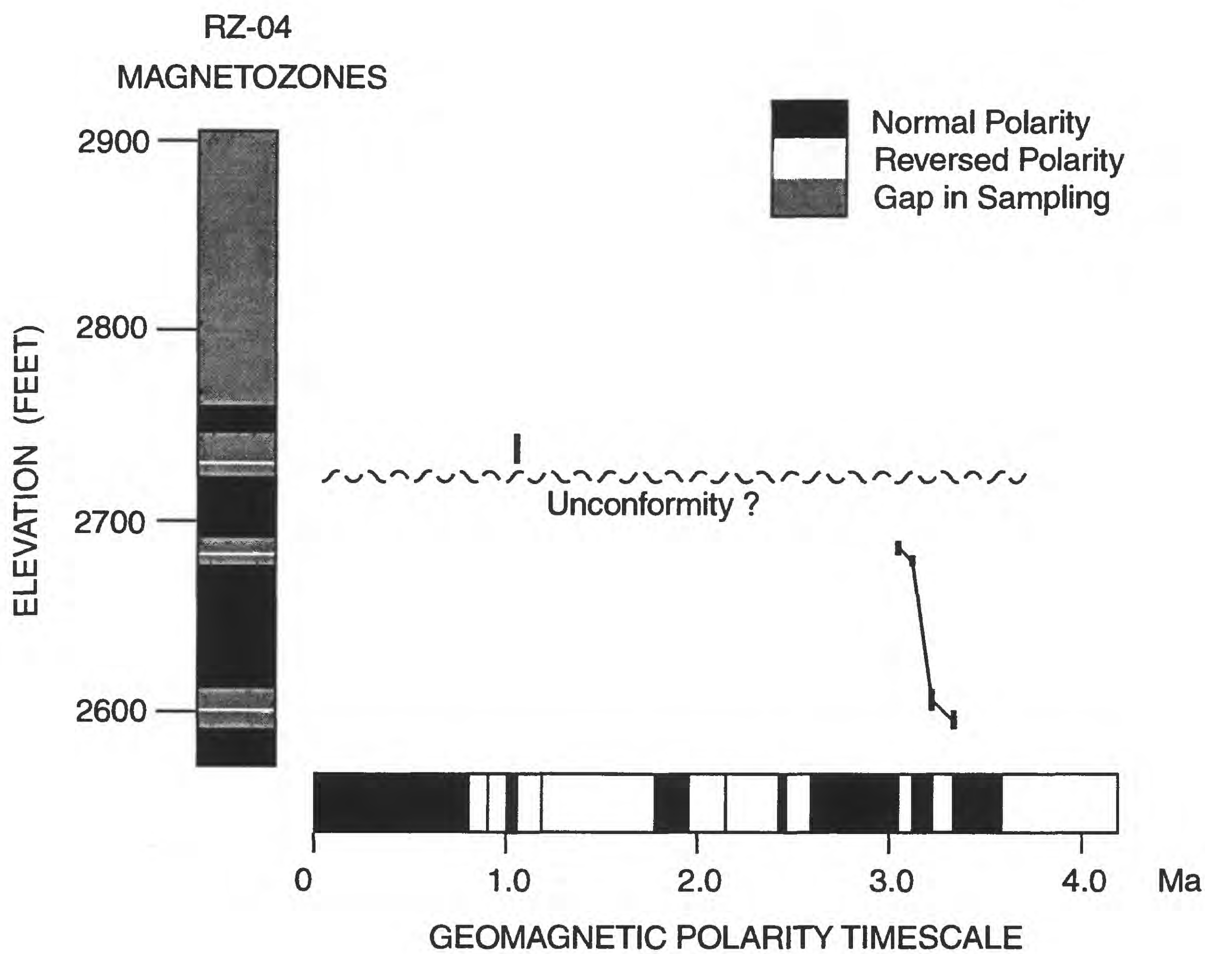


Figure 9. Time versus sedimentation at borehole RZ-04, as correlated with the geomagnetic polarity timescale. Vertical bars indicate uncertainty in stratigraphic position of the polarity transitions.

Correlation with the Geomagnetic Polarity Timescale

Figure 7 shows our preferred correlation of the RZ-01 magnetozones with the polarity timescale as calibrated by Singer et al. (1999) for the period younger than 1.2 Ma and by Cande and Kent (1995) for the interval 1.2-5.0 Ma. Our preferred correlation assumes that deposition was not broken by any lengthy hiatuses, and thereby represents the youngest possible age-determination for the stratigraphic section beneath George Air Force Base. Older age-interpretations of the magnetozones are permissible, but in our view are much less likely to be accurate because the thick normal-polarity zone, as defined at the top of RZ-01 and in the outcrop above the wellhead, is best correlated with the lengthy Brunhes Normal Polarity Chronozone. The uppermost polarity transition at about 52 ft (16 m) below the wellhead is most likely the Matuyama-Brunhes boundary dated at 0.78 Ma. The next two thin normal-polarity zones are attributed to the Jaramillo (0.986-1.053 Ma) and Cobb Mountain (1.18 Ma) subchrons. The well-defined transition near the top of the middle lacustrine unit is most likely the beginning of the Olduvai normal-polarity subchron at 1.95 Ma. The transition directly beneath the lakebeds is tentatively correlated with the beginning of the Matuyama chron at 2.58 Ma.

The sections penetrated in RZ-02 and RZ-03 overlap stratigraphically the upper two-thirds of RZ-01, with the Brunhes/Matuyama boundary, Jaramillo subchron, and the end of the Olduvai subchron correlated at similar elevations among these three boreholes (figs. 5, 8). Correlation of RZ-04 with the timescale and the other boreholes is problematical (figs. 5, 9). In contrast to the other boreholes, RZ-04 exhibits much thinner reversed-polarity zones between elevations of 2,600-2,750 ft (790-840 m). From mapping of lineaments and raised topographic features near the RZ-04 wellhead, we infer that a fault has raised the RZ-04 stratigraphic section relative to the sections in the other boreholes.

CHRONOLOGY AND STRATIGRAPHIC CORRELATION

Our studies indicate that the four exploratory boreholes at George Air Force Base (GAFB) penetrate a conformable succession of Pliocene and Pleistocene strata (fig.10). Continuity of sedimentation in the lacustrine unit and overlying upper fluvial unit is implied by the transitional contact observed between these units in each of the boreholes, and by the absence of mature paleosols or obvious erosional hiatuses. The lower alluvial unit is also transitional with the lacustrine unit in boreholes RZ-01, -02, and -03, but mature soil horizons in the lower unit in borehole RZ-01 may indicate gaps in sedimentation as great as 10-100 ka. There also appears to be an unconformity at the top of the lower alluvial unit in borehole RZ-04. The results of our magnetostratigraphic investigation and a collaborative radiometric study allow us to date and correlate most of the stratigraphic succession, especially in boreholes RZ-01, -02, and -03 (fig. 5). The correlation of tectonically dislocated strata in borehole RZ-04 is addressed in a following section ("syndepositional faulting at GAFB").

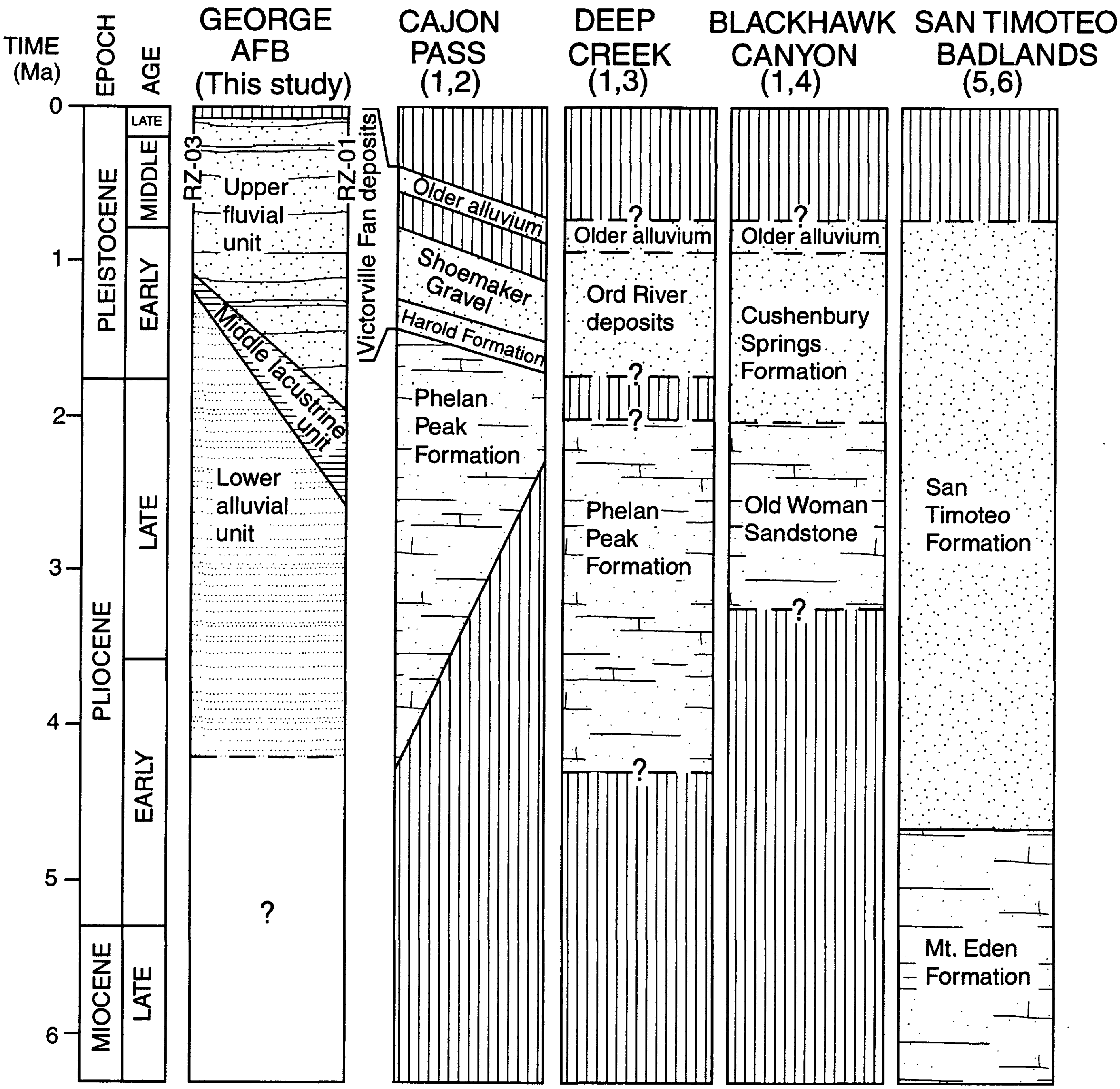


Figure 10. Correlation diagram showing age relations of upper Cenozoic strata at George Air Force Base and other sites around the margins of the San Bernardino Mountains (geographic locations are shown on figures 1 and 2). Each of the four reference sections contains two main tectonostratigraphic units defined by previous studies-an upper unit derived from uplifted rocks of the Transverse Ranges (plain stippling), and a lower unit derived at least in part from surrounding regions prior to major uplift (jointed pattern). The columns for the air base and Cajon Pass are composite and show lateral variations in age between two constituent sections. Left and right margins of Cajon Pass column correspond to Phelan Peak and Crowder Canyon sections of Weldon and others (1993), respectively. Sources of data: 1, Meisling and Weldon (1989); 2, Weldon and others (1993); 3, Meisling (1984); 4, May and Repenning (1982); 5, Matti and Morton (1993); 6, Albright (1999).

Age of George surface

The George surface or pre-erosion ground surface at the top of the upper fluvial unit is an important target for dating because it records the final filling of the Victorville basin and predates the incision of the Mojave River canyon. Our correlation with the geomagnetic polarity timescale implies that the George surface is younger than the Brunhes/Matuyama boundary, dated at 0.78 Ma. The thickness and internal character of the capping paleosol seems to further constrain the surface to the late Pleistocene. Although the paleosol has not been studied in detail, its gross field characteristics suggest an age on the order of 50 –150 ka.

To obtain a more precise age for the George surface and associated deposits, we engaged L.A. Owen at the University of California, Riverside, to conduct optically stimulated luminescence (OSL) dating near GAFB. The OSL method measures energy accumulated within the crystal lattice of detrital mineral grains due to their exposure to radiation sources in the sediment following burial. The amount of energy stored is proportional to the age of the sedimentary deposit. Four sediment cores were collected from the walls of a pipeline trench 2 mi (3.2 km) due north of borehole RZ-02. Two of the cores were collected from unweathered coarse-grained sand of the ancestral Mojave River about 0.7 ft (20 cm) below the basal calcic horizon of the surficial paleosol. The second pair of cores was extracted from a veneer of unweathered alluvial and aeolian sand that overlies the paleosol along a channeled erosional contact.

The preliminary results of the OSL measurements on quartz are 60.8 ± 5.4 ka and 71.7 ± 13.3 ka for the fluvial sediments beneath the paleosol, and 4.3 ± 1.5 ka and 6.2 ± 1.0 ka for the surficial alluvium above the paleosol (Ruppert, 1999). Thus, the George surface is provisionally dated at about 65 ka. This result allows us to extend plots of age versus elevation upward to the ground surface (figs. 7, 8). The internal consistency of the extended plots in turn suggests that 65 ka is a reasonable age for the George surface, as the resulting post-Matuyama sedimentation rate is comparable to preceding rates determined solely from magnetostratigraphic data.

Age of upper fluvial unit

In combination with the OSL data, magnetostratigraphic relations at GAFB suggest the upper fluvial unit was deposited between about 1.95-0.065 Ma, during the Pleistocene and latest Pliocene (figs. 3, 5, 10). The base of the unit evidently youngs northwestward from 1.95 Ma in borehole RZ-01, to about 1.05 Ma in boreholes RZ-02 and RZ-03 (fig. 5). The older age of the basal horizon in RZ-01 is largely accounted for by a thick interval of thinly bedded fine sand, silt, and clay deposited between 1.95 and 1.18 Ma. Although this deep sequence is largely restricted to RZ-01, an analogous fine-grained fluvial sequence accumulated between about 1.0-0.5 Ma at the sites of boreholes RZ-02 and RZ-03 (fig. 5).

Vertebrate fossils collected at numerous sites around Victorville and GAFB have elicited conflicting interpretations regarding the age of the upper fluvial unit. Most of the local fossil localities lie within the belt of ancestral Mojave River deposits located west of the Mojave River between northern Hesperia and GAFB (fig. 2). Several brief reports (Jefferson, 1986; Reynolds, 1989, Reynolds and Reynolds, 1994a) proposed that the vertebrates are chiefly middle Pleistocene (late Irvingtonian), or about 0.8-0.5 Ma. However, two taxa collected near Victorville ostensibly are older than middle Pleistocene, based on their minimum ages reported from other regions. A Pliocene(?) cotton rat, *Sigmodon* cf. *S. minor* (Reynolds and Reynolds, 1994a), and an early(?) Pleistocene mammoth, *Mammuthus meridionalis* (Scott and others, 1997), were reported from sites in southern and northern Victorville, respectively.

The results of our investigation, and sparse earlier paleomagnetic determinations (e.g., Meisling, 1984, locality HRF; Meisling, personal commun., 1984, cited in Reynolds, 1989; Meisling, personal commun., 1985, cited in Reynolds and Reynolds, 1994a), suggest that the vertebrate fossil assemblages in the Victorville region are predominantly middle Pleistocene and younger, as was originally proposed by Jefferson (1986). The combined magnetostratigraphic evidence suggests that a thick zone of normal-polarity strata extends about 110-150 ft (33-45 m) below the George surface at Victorville and GAFB. Most of the vertebrate fossils apparently were collected from this zone. If the normal-polarity zone is accurately correlated with the Brunhes Chron, then the fossils are younger than 0.78 Ma.

Mammuthus meridionalis is of particular interest to our study, because a well-preserved specimen was found near GAFB (figs. 4, 5). The specimen consists of a skull, mandible, pelvis, and several ribs discovered about 3,750 ft (1,145 m) east of borehole RZ-01 at an approximate elevation of 2,850 ft (869 m) (E. Scott, written commun., 1997). The bones were unearthed from a distinctive sequence of sand and gravel that we traced westward to the site of the borehole by mapping a laterally extensive, thick bed of cobble gravel whose base lies at about 2,815 ft (858 m) elevation. This lithostratigraphic correlation associates the mammoth with normally polarized sediments of the upper fluvial unit about 30-40 ft (9-12 m) above the top of borehole RZ-01 (fig. 5; table 1, outcrops 3 and 4). This stratigraphic level lies well above the Brunhes/Matuyama boundary, as interpreted by our study. Therefore, this specimen of *M. meridionalis* evidently is middle Pleistocene or younger, rather than early Pleistocene.

To test the foregoing interpretation, we performed paleomagnetic measurements on sediments from two outcrops near the fossil site (table 1, outcrops 1 and 2). The outcrops lie stratigraphically below and above the fossil horizon, at elevations of about 2,815 and 2,870 ft (858 and 875 m). Both samples yielded a normal polarity, which is consistent with a stratigraphic setting above the Brunhes/Matuyama boundary. Assuming, once again, that our magnetostratigraphic data are accurately correlated with the geomagnetic polarity timescale, then a more precise age for the mammoth can be estimated from its stratigraphic position about 65 ft (20 m) below the George surface and 85 ft (26 m) above the Brunhes/Matuyama boundary. By interpolation, the age of the mammoth evidently is about 375 ka, or late-middle Pleistocene.

Age and local correlation of middle lacustrine unit

The lithostratigraphic correlation of the middle lacustrine unit at GAFB was uncertain at the outset of our study because the deposits are anomalously thick and deep in borehole RZ-01 (fig. 5). This stratigraphic arrangement persuaded previous investigators that the lakebeds in RZ-01 are unrelated to those in the other boreholes (Montgomery Watson, 1995). However, a distinctive assemblage of lithologic features, and the consistent intercalation of the lakebeds between lithic-arkose sand of the lower alluvial unit and nearly pure arkosic sand of the upper fluvial unit (Chrisley, 1997), seem to confirm the original continuity of the unit. The greater depth of the lakebeds in borehole RZ-01 accordingly must reflect either a tectonic offset or time-transgressive sedimentation.

Intertonguing between the lacustrine unit and lower alluvial unit is evident in boreholes RZ-02 and RZ-03, which lie close enough together that thin intervals of strata can be traced fairly confidently from hole to hole (fig. 5). Comparison of these boreholes indicates that the lake or wetland first became established at the site of RZ-03 before expanding to the site of RZ-02. Migration of the lacustrine environment across a greater distance may have produced the large stratigraphic misalignment relative to borehole RZ-01. If so, then the lacustrine unit should be significantly older in RZ-01. This is confirmed by a distinct ostracode assemblage in borehole RZ-01 (R. Forester, written commun., 1999) and is quantified by our magnetostratigraphic correlations, which indicate the lakebeds were deposited between 2.55 and 1.95 Ma in borehole RZ-01, and between about 1.18 and 1.05 Ma in boreholes RZ-02 and RZ-03 (fig. 5). Thus, the age of the middle lacustrine unit ranges from late Pliocene to early Pleistocene at GAFB, and both its mean age and duration of accumulation decrease to the northwest (fig. 10). The lakebeds in borehole RZ-04 apparently are coeval with those in RZ-02 and RZ-03, because they contain the same ostracode assemblage found in RZ-03 (R. Forester, oral commun., 1999) and are directly overlain by a normal-polarity magnetozone that we interpret to be the Jaramillo subchron (fig. 5).

Age of lower alluvial unit

Our magnetostratigraphic interpretations suggest the lower alluvial unit in boreholes RZ-01, -02, and -03 was deposited during the Pliocene and early Pleistocene, between about 4.2 and 1.18 Ma. The maximum age of the unit is derived from the lower magnetozones of RZ-01, which we have tentatively correlated with the Gauss and upper Gilbert chronozones (figs. 3, 7). The polarity transition near the bottom of the hole is tentatively correlated with the end of the Cochiti subchron, dated at 4.18 Ma. Our proposed age-correlation requires that the Mammoth and Kaena subchrons were missed, either due to a disconformity or to a gap in sampling between elevations of 2,421.3-2,441 ft (738-744 m). Physical examination of the core from borehole RZ-01 reveals multiple disconformities in the lower alluvial unit, which are indicated by several stage-III pedogenic carbonate horizons between elevations of 2,400-2,450 ft (730-747 m) (fig. 5). Comparably developed calcic soil horizons are not found elsewhere in the stratigraphic section, except within the capping paleosol on the George surface. Depositional hiatuses corresponding to these buried paleosols could account for the missing magnetozones at the base of the section.

Sediment accumulation rates

Plots of elevation versus age (figs. 7, 8, 9) show significant changes in the rate of sediment accumulation (not corrected for post-depositional compaction) at GAFB during the Pliocene and Pleistocene. We have superimposed a generalized sedimentation-rate curve on the detailed record from borehole RZ-01 to illustrate some of the principal trends (fig. 7). Two sharp inflections at the Matuyama/Gauss boundary (2.58 Ma) and the Cobb Mountain subchron (1.18 Ma) divide the curve into three main segments. The pre-Matuyama segment indicates slow deposition of the lower alluvial unit at about 0.04 ft/ka (12 mm/ka) during the early to late Pliocene. The central segment represents deposition of the middle lacustrine unit and the thinly bedded, fine-grained basal part of the upper fluvial unit at an intermediate rate of 0.14 ft/ka (42 mm/ka) during the late Pliocene to early Pleistocene. Finally, the post-Cobb Mountain segment records relatively rapid accumulation of thickly bedded sand and gravel in the main body of the upper fluvial unit at a mean rate of 0.22 ft/ka (68 mm/ka) during the early to late Pleistocene. The basal part of this last interval, deposited between the Cobb Mountain subchron and the end of the Jaramillo subchron (1.18-0.99 Ma), evidently accumulated most rapidly, about 0.31 ft/ka (94 mm/ka). The mean accumulation rate for the entire upper fluvial unit in borehole RZ-01 is 0.19 ft/ ka (58 mm/ka).

The record for boreholes RZ-02 and RZ-03 (fig. 8) again indicates that the sedimentation rate increased dramatically following the deposition of the lower alluvial unit. Although the data from RZ-02 or RZ-03 alone do not constrain the accumulation rate of the lower unit, the combined data projected onto borehole RZ-03 restricts the rate to less than 0.07 ft/ka (22 mm/ka) between the Olduvai and Cobb Mountain subchrons (1.77-1.18 Ma). Thus, the relatively slow accumulation of the lower alluvial unit that was determined for Pliocene-age deposits near the southeast corner of GAFB also applies to early Pleistocene-age deposits of this unit at the north end of the air base. By contrast, data from borehole RZ-02 indicate that early Pleistocene-age deposits of the middle lacustrine unit accumulated nearly five times as fast, about 0.33 ft/ka (100 mm/ka), between the Cobb Mountain and Jaramillo subchrons (1.18-1.05 Ma). The overlying basal strata of the upper fluvial unit accumulated at a similar elevated pace during the Jaramillo subchron (1.05-0.99 Ma). Therefore, a pulse of unusually rapid sedimentation occurred between 1.18-0.99 Ma near the north end of GAFB. As this pulse is also recorded near the southeast corner of the air base (in borehole RZ-01), it evidently was a widespread event, possibly reflecting a transitory increase in sediment production in the

San Bernardino Mountains. The pulse had subsided by the onset of the lengthy Brunhes Chron (0.78 Ma), after which the bulk of the upper fluvial unit in boreholes RZ-02 and RZ-03 accumulated at the relatively modest rate of 0.14 ft/ka (44 mm/ka).

The data also reveal lateral variations in the rate of sediment accumulation in the upper fluvial unit and lower alluvial unit at GAFB. Deposits of the upper fluvial unit were laid down significantly more rapidly near borehole RZ-01 as compared to boreholes RZ-02 and RZ-03. Deposition after the beginning of the Jaramillo subchron (1.05 Ma), produced about 210 ft (64 m) of strata in borehole RZ-01 and about 175 ft (53 m) in each of boreholes RZ-02 and RZ-03. These thicknesses correspond to mean sedimentation rates of 0.21 ft/ka (65 mm/ka) in RZ-01 and 0.18 ft/ka (54 mm/ka) in RZ-02 and RZ-03. The deposits possibly accumulated more rapidly toward the southeast because this direction leads up-gradient toward the inferred source area in the San Bernardino Mountains. Later in this report, we exploit this lateral gradient in sedimentation rate in order to date the inception of the ancestral Mojave River.

Magnetostratigraphic and paleopedologic evidence suggests that the older, Pliocene-age, deposits of the lower alluvial unit also accumulated at a variable rate across GAFB. As we mentioned earlier, this unit evidently accumulated at about 0.04 ft/ka (12 mm/ka) near borehole RZ-01 (fig. 7). However, late Pliocene-age deposits at the site of borehole RZ-04 may have accumulated as rapidly as 0.3 ft/ka (90 mm/ka) between about 3.1-3.2 Ma (fig. 9). This interpretation is tentative, because the cited accumulation rates from both boreholes are based on provisional magnetostratigraphic correlations. However, paleopedologic evidence points to a similar conclusion. Carbonate crusts and other signs of advanced pedogenesis are common in the lower alluvial unit in borehole RZ-01 (fig. 5), whereas comparable features are rare in borehole RZ-04. Thus, the site of borehole RZ-01 evidently was a relatively stable area subject to intermittent sedimentation during the Pliocene, whereas the site of borehole RZ-04 about 2.5 mi (4 km) to the northwest seems to have been located within a zone of more active subsidence and sedimentation.

Regional correlation

The strata drilled at GAFB are broadly coeval with Pliocene and Pleistocene sediments along the north flank of the San Bernardino Mountains and eastern San Gabriel Mountains (fig. 10). In particular, the upper fluvial unit is contemporaneous with the Victorville Fan deposits and Ord River deposits of Meisling and Weldon (1989), and probably also with the poorly dated Cushenbury Springs Formation of Shreve (1968) at Blackhawk Canyon. The upper fluvial unit has the same provenance as the Ord River deposits, consisting mostly of granitic and gneissic detritus derived from the northwestern San Bernardino Mountains. However, the upper fluvial unit is predominantly sandy, rather than gravelly, and therefore appears to be the distal facies equivalent of the Ord River deposits (Cox and others, 1998). The upper fluvial unit also appears to range to a significantly younger age than the Ord River deposits (fig. 10). The upper fluvial unit and Ord River deposits are temporally, but not lithologically, correlative with the Victorville

Fan deposits, which differ by containing abundant detritus of Pelona Schist, Lowe Granodiorite, and other distinctive rock types derived from the San Gabriel Mountains (Foster, 1980; Meisling and Weldon, 1989).

The upper fluvial unit and Victorville Fan deposits each are time-transgressive, but the upper fluvial unit spans a broader interval of time (fig. 10). The oldest Victorville Fan deposits apparently are about 1.7 Ma (base of the Harold Formation at Crowder Canyon) (Weldon and others, 1993; ages adjusted to the modern geomagnetic polarity timescale—fig. 3). By contrast, our work suggests the upper fluvial unit ranges back to about 1.95 Ma at GAFB, and its southeastern extension beneath Victorville probably is considerably older, as is discussed in the following section. Aggradation of the Victorville Fan deposits apparently ceased in the middle Pleistocene. The uppermost unit in the fan sequence (older alluvium of Noble, 1954) contains the Brunhes/Matuyama boundary (0.78 Ma) and is cut by an inset stream terrace dated at roughly 0.5 Ma (Meisling, 1984; Weldon, 1986; McFadden and Weldon, 1987; Weldon and others, 1993). The antiquity of the stream terrace is gauged in part by a very thick (50 ft, 15 m) argillic soil horizon that caps the deposit (McFadden and Weldon, 1987). By contrast, the much thinner (2.5 ft, 0.75 m) paleosol on the George surface, the provisional luminescence ages of about 60-70 ka from directly underlying fluvial deposits (Ruppert, 1999), and the considerable depth of the Brunhes/Matuyama polarity boundary, all suggest sedimentation continued into the late Pleistocene near GAFB.

Pliocene to lowest Pleistocene strata at GAFB correlate temporally with the Phelan Peak Formation of Weldon and others (1993) near Cajon Pass and Deep Creek, and with the Old Woman Sandstone of Shreve (1968) at Blackhawk Canyon and neighboring areas along the north flank of the central San Bernardino Mountains (fig. 10). Owing to time-transgressive sedimentation at GAFB, the lower alluvial unit, middle lacustrine unit, and upper fluvial unit all overlap in age with the Phelan Peak Formation, but the long-ranging lower alluvial unit is the closest match. The lower alluvial unit and the Phelan Peak also are physically comparable, to the extent that they each consist largely of alluvial-fan facies and contain numerous paleosols and cemented horizons (Meisling and Weldon, 1989). However, these units differ markedly in detrital composition and thus are not lithologically equivalent. Green clay reported in the lower part of the Phelan Peak Formation (Foster, 1980; his "western facies of Crowder Formation") is reminiscent of sediments in the middle lacustrine unit at GAFB but is significantly older, about 3.8 Ma, based on magnetostratigraphy and radiometric data (Weldon and others, 1993).

SOUTHEASTERN EXTENSION OF CLASTIC WEDGE

Our stratigraphic analysis of the upper fluvial unit at George Air Force Base (GAFB) suggests it is a diachronous, wedge-shaped body deposited by the ancestral Mojave River (fig. 5). The base of the body deepens and increases in age to the southeast beneath the air base, which suggests it may be even deeper and older beneath Victorville and Hesperia. To evaluate the paleogeographic and paleotectonic significance of this clastic wedge, we attempted to determine its subsurface configuration across a broader area of the Victorville basin.

Because of its relatively fine-grained texture, the middle lacustrine unit at GAFB is readily distinguished from adjacent sandy units on borehole electrical logs. Drilling records from boreholes RZ-01, -02, -03, and -04 at GAFB (Montgomery Watson company, unpub. data) indicate that the resistivity (16-inch normal) of the middle lacustrine unit is uniformly low, mostly about 5-10 ohm-meters (excluding borehole RZ-02, where abundant intercalated sand layers yield higher values). By contrast, the resistivity of the adjacent units is typically much higher, ranging from 5-65 ohm-meters for the lower alluvial unit and 15-100 ohm-meters for the upper fluvial unit.

Using the resistivity logs as a correlation tool, we found that the stratigraphic sequence at GAFB can be traced southeastward beneath central and southern Victorville (figs. 2, 11; Green Tree well, Test Well #32). Several wells drilled at the municipal golf course in central Victorville encountered two major units: an upper unit of interlayered sand, silt, and minor clay about 510-590 ft (155-180 m) thick, and a lower unit of greenish to brownish clay and silt more than 70 ft (21 m) thick (S. Dickey, oral commun., 1997). In each of the wells, drilling was terminated before the base of the lower unit was reached. This cluster of wells is represented on figure 11 by the Green Tree well, which intersected the top of the clay-rich unit at an elevation of about 2,405 ft (733 m). Resistivity logs from the wells indicate values of 15-70 ohm-meters for the upper unit and about 2-5 ohm-meters for the lower unit (S. Dickey, written commun., 1998). Based on their lithologic and geophysical characteristics, the upper and lower units at the Victorville golf course seem to correlate with the upper fluvial unit and middle lacustrine unit at GAFB.

Test well #32 in southern Victorville penetrated a sequence of three major units. An upper unit 760 ft (232 m) thick with resistivity of 10-75 ohm-meters seems to correspond to the upper fluvial unit at GAFB. A middle unit about 120 ft (37 m) thick with resistivity of about 2-5 ohm-meters is correlated with the middle lacustrine unit. Finally, a lower unit about 190 ft (58 m) thick with resistivity of 5-15 ohm-meters is correlated with the lower alluvial unit.

The results of the foregoing analysis suggest that the upper fluvial unit thins steadily to the northwest between southernmost Victorville and the northern edge of GAFB (fig. 11). Thus, the northwestward thinning at GAFB (fig. 5) evidently is symptomatic of a broader stratigraphic pattern. The wedge-shaped configuration of the upper unit implies that the fluvial tract of the ancestral Mojave River gradually prograded to the northwest and may have reached southern Victorville long before GAFB. Therefore, in order to document the early history of the river, chronologic evidence is needed from the deeper, more southerly deposits of the wedge.

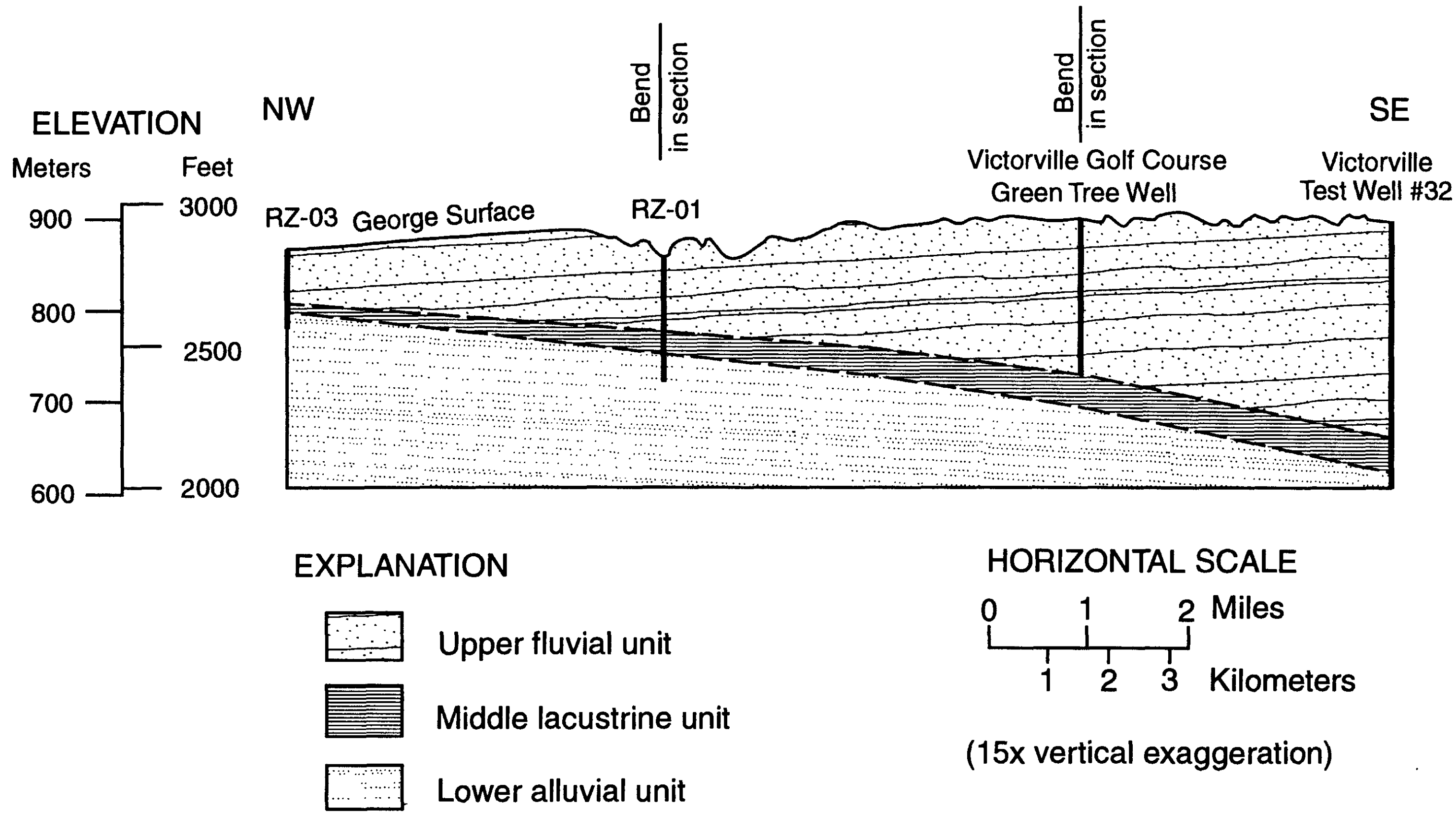


Figure 11. Stratigraphic section between George Air Force Base and Victorville, California, showing southeastward descent of the middle lacustrine unit beneath wedge-shaped mass of the upper fluvial unit. Line of section is shown on figure 2. Vertical scale is 15 times horizontal scale.

The deepest, and presumably oldest, deposits along the extended transect of the clastic wedge illustrated in figure 11 are encountered in Test Well #32. Although we have no direct means of dating these deposits, the age of the base of the wedge can be estimated by applying the sediment accumulation rates that we determined at GAFB. In a previous section, we noted that the mean accumulation rate of the upper fluvial unit increases southeastward across GAFB. Deposits laid down since the beginning of the Jaramillo subchron (1.05 Ma) accumulated at about 0.18 ft/ka (54 mm/ka) in boreholes RZ-02 and RZ-03, and about 0.21 ft/ka (65 mm/ka) in borehole RZ-01. Boreholes RZ-01 and RZ-03 are about 3.75 mi (6.0 km) apart. Thus, the rate increases southeastward at about 0.008 ft/ka/mi (2.4 mm/ka/km).

The complete thickness of the upper fluvial unit in borehole RZ-01 was deposited at a mean rate of about 0.19 ft/ ka (58 mm/ka). If this rate increased southeastward across Victorville at 0.008 ft/ka/mi (2.4 mm/ka/km), then the fluvial succession at the site of Test Well #32, about 7 mi (11 km) to the southeast, would have accrued at about 0.25 ft/ka (76 mm/ka). Before the George surface was eroded, the upper fluvial unit was about 800 ft (244 m) thick at the site of Test Well #32. If the unit accumulated at 0.25 ft/ka (76 mm/ka) until 65 ka, then the age of its base would be about 3.3 Ma.

Stratigraphic relations at the northwest front of the San Bernardino Mountains further constrain the age of the fluvial wedge. Meisling (1984), and Meisling and Weldon (1989) proposed that their Ord River deposits—more specifically a deeply dissected subunit of fluvial sand and gravel near the mouth of Deep Creek (Deep Creek facies of the Ord River gravel; Meisling, 1984)—contain the earliest deposits of the ancestral Mojave River. These sediments have reversed paleomagnetic polarity, which indicates they are early Pleistocene or older (Meisling, 1984). Judging from their antiquity and granitic provenance, they evidently are the coarse-grained proximal counterpart of the upper fluvial unit at GAFB (Cox and others, 1998). Thus, the Ord River deposits of Meisling and Weldon (1989) apparently represent the southeastern end of the clastic wedge.

Nearby in eastern Summit Valley (fig. 2), the Ord River deposits overlie fine-grained volcaniclastic sandstone, siltstone, and claystone of the Phelan Peak Formation (Meisling, 1984, his "volcanogenic eastern facies of the Crowder Formation"). A layer of volcanic ash in the latter unit yielded an apatite fission-track age of 3.8 ± 0.4 Ma (Meisling and Weldon, 1989). Together, this radiometric age and our estimated age for the base of the upper fluvial unit in Test Well #32 seem to restrict the basal deposits at the proximal end of the clastic wedge to between about 3.8-3.3 Ma. The outcrops near Deep Creek and in eastern Summit Valley are located about 8-10 mi (13-16 km) southeast of Test Well #32 (fig. 2). The expansion of the clastic wedge across this considerable distance presumably consumed much of the half million years between 3.8-3.3 Ma. Thus, it seems likely that the oldest river deposits accumulated near the beginning of this interval.

If the foregoing interpretation is correct, then the Phelan Peak Formation and Ord River deposits probably are not separated by a major depositional or erosional hiatus. Meisling and Weldon (1989, fig. 4) originally proposed that the Ord River deposits and Victorville Fan deposits are coeval and that both units unconformably overlie the Phelan

Peak Formation. However, Kenney and Weldon (1999) more recently concluded that the Victorville Fan deposits actually rest conformably on the Phelan Peak Formation near Phelan Peak and Cajon Pass. This implies that the contact relations between the Ord River deposits and Phelan Peak Formation may also warrant reevaluation. Meisling (1984, p. 48) observed that the predominantly volcaniclastic Phelan Peak Formation in eastern Summit Valley contains intercalated beds of granitic gravel derived from the San Bernardino Mountains region. These beds evidently are similar in composition to the Ord River deposits and thus might represent tongues deposited by the nascent Mojave River. Under this scenario, the embryonic clastic wedge of the ancestral Mojave River might have originated as early as 3.8 Ma, while the Phelan Peak Formation was accumulating near the future site of Summit Valley.

DEFORMATIONAL STRUCTURES AND CRUSTAL MOVEMENTS IN THE SOUTHERN MOJAVE DESERT

Our field observations and borehole studies disclosed abundant geomorphic, stratigraphic, and structural evidence of vertical crustal movements along the Mojave River between Victorville and Iron Mountain. A comprehensive structural and paleotectonic analysis awaits the completion of our ongoing geologic mapping survey. Here we summarize key evidence demonstrating that the early Mojave River evolved within a dynamic tectonic setting, and that vertical movements north of George Air Force Base (GAFB) controlled the river's advancement across the southern Mojave Desert.

Arching of the George surface at GAFB

Geomorphic evidence suggests there is a broad arch in the George surface at GAFB, which apparently developed during the late Pleistocene and Holocene. The depth of the Mojave River canyon relative to the George surface is about 240-265 ft (73-81 m) beside the air base, whereas it more characteristically is about 200 ft (60 m) in neighboring areas to the north and south. If the George surface originated with a graded fluvial profile nearly parallel to that of the modern river, then the land surface at the base has been warped upward as much as 65 ft (20 m) over the past 65 ka. The Mojave River evidently maintained its grade by incising more rapidly in the vicinity of the growing arch. Thus its flow was not blocked or diverted by this tectonic deformation.

Syndepositional faulting at GAFB

Vertical faulting near the southwest margin of GAFB evidently preceded and accompanied the broad arching of the George surface described above. Strata in borehole RZ-04 are consistently elevated relative to equivalent strata in the other three boreholes (fig. 5). The magnitude of the stratigraphic offsets increases down the hole, so some of the deformation apparently was contemporaneous with sedimentation. Strata near the middle and top of the upper fluvial unit appear to be uplifted roughly 50 ft (15 m) relative to equivalent strata in borehole RZ-01. At deeper levels, the middle lacustrine unit lies about 70-80 ft (20-25 m) higher in borehole RZ-04 than in RZ-02 and RZ-03. We infer that the lakebeds, as sampled in these three holes, were originally deposited at about the same elevation, because their thickness is fairly uniform and they apparently are about the same age, based on fossil ostracodes (R. Forester, written commun., 1999).

The lower alluvial unit in borehole RZ-04 contains a magnetostratigraphic sequence dominated by thick normal-polarity zones (figs. 5, 9). We tentatively correlate this polarity sequence with the Gauss chron, which ranges from 3.58-2.58 Ma (fig. 3). If this correlation is accurate, then the lower alluvial unit and middle lacustrine unit evidently are separated by a hiatus as great as 1.4 Ma in this borehole. At least 100 ft (30 m) of strata seem to be missing owing to erosion or nondeposition. The corresponding unconformity probably is located at the base of a thin interval of fine sand and silt that directly underlies the deposits of lacustrine clay and silt in borehole RZ-04 (fig. 5). The fine sand in this interval consists of unweathered, biotite-bearing arkose that is unlike sand of the lower alluvial unit but indistinguishable from sand of the upper fluvial unit.

In combination, the pre-lacustrine hiatus and the offset strata within the middle lacustrine and upper fluvial units suggest the site of borehole RZ-04 was cumulatively uplifted at least 170 ft (50 m) relative to the other boreholes. The corresponding structural discontinuity that separates borehole RZ-04 from the other boreholes is represented schematically by a vertical fault on figure 5. The existence of this fault is supported by a northwest-trending aerial-photographic lineament extending between boreholes RZ-01 and RZ-04 (fig. 4). The lineament is parallel to, but laterally offset from, the main strand of the Mirage Valley fault zone that crosses the Shadow Mountains about 8 miles (13 km) northwest of borehole RZ-04 (fig. 2).

Geomorphic evidence of uplift is locally evident on the southwest side of the lineament about 1.4 mi (2.2 km) south of borehole RZ-04 (NW 1/4 sec. 3, T. 5 N., R. 5 W). An elevated alluvial bench at this site is underlain by granitic gravel and arkosic sand of the upper fluvial unit (B. Cox, unpub. mapping). The bench apparently is an uplifted outlier of the George surface. The elevation of the bench as estimated from topographic contours is about 2,965 ft (904 m). By contrast, the broad alluvial platform northeast of the lineament lies at 2,905 ft (885 m), as recorded by a survey marker near the southern edge of GAFB (NW cnr. sec. 36, T. 6 N., R. 5 W.). Thus, the alluvial bench apparently was uplifted about 60 ft (18 m) relative to the main platform. This amount of displacement is consistent with the 50 ft (15 m) of uplift estimated from offset strata in the upper half of borehole RZ-04. This vertical displacement by faulting is *in addition to* the previously described arching of the George surface northeast of the lineament, which uplifted the broader area of GAFB by as much as 65 ft (20 m). Thus, the area southwest of the lineament evidently was uplifted as much as 125 ft (38 m) relative to neighboring areas southeast and north of GAFB since about 65 ka.

There may be additional faults that escaped detection by our limited survey of four boreholes at GAFB. However, we found no evidence of significant vertical displacement between boreholes RZ-01, -02, and -03. For example, our data do not support a previous interpretation that ascribed the anomalous depth and thickness of the lakebeds in borehole RZ-01 to syndepositional faulting or folding (Chrisley, 1997, fig. 40). Although such an interpretation plausibly explains the lateral variation in the depth and thickness of the middle lacustrine unit, it does not account for the contrast in the age of this unit that is indicated by magnetostratigraphy (fig. 5) and disparate ostracode assemblages (R. Forester, written commun., 1999).

Warping at northern margin of Victorville basin

The Victorville basin and its associated gravity depression (Mabey, 1960) end directly north of GAFB, where the alluvial tract constricts to pass between Quartzite Mountain and the southeastern Shadow Mountains (fig. 2). Several significant stratigraphic and structural relationships are localized in this area, where the upper levels of the alluvium lap across the northern edge of the basin. Key stratigraphic features include the pinching out of the middle lacustrine unit toward the north (Montgomery Watson, 1995; Chrisley, 1997), an abrupt end to the persistent northward thinning (fig. 11) of the upper fluvial unit, and a shift from conformable to unconformable contact relations at the base of the upper fluvial unit. Each of these changes occurs within a west-trending zone lying about 0.75-2.0 mi (1.2-3.2 km) north of borehole RZ-02. Between this area and Iron Mountain, the thickness of the upper fluvial unit generally fluctuates between 25-80 ft (8-25 m) and the unit rests unconformably on older alluvial deposits that we correlate with the lower alluvial unit at GAFB (e.g., Reynolds and Cox, 1999, fieldtrip stops 9 and 10; B. Cox, unpub. mapping).

Two noteworthy structural features approximately coincide with the stated stratigraphic changes. The first item is a local angular unconformity between the lower alluvial unit and upper fluvial unit, which is located in bluffs of the Mojave River about 1.7-2.0 mi (2.7-3.2 km) north of borehole RZ-02 (NW ¼ sec. 12, T. 6 N., R. 5 W.). Beds in the lower alluvial unit at the base of the bluffs dip southward about 8°, whereas deposits of the upper fluvial unit exposed at the top of the bluffs are nearly horizontal (±1°). The inclined bedding in the lower unit apparently does not represent an alluvial paleoslope, because the deposits include thick layers of fine sand and silt that probably accumulated on a much gentler slope. Thus, the lower alluvial unit appears to be tilted, and the angular unconformity implies that the northern margin of the basin was flexed upward and eroded prior to the deposition of the upper fluvial unit. The thickness of the latter unit is as great as 100 ft (30 m) at this locality. By comparing this thickness with the magnetostratigraphic section from borehole RZ-02 (figs. 5, 8), we derive an interpolated age of about 720 ka for the local base of the upper fluvial unit. The tilting and erosion of the underlying unit evidently occurred prior to this time.

The second notable structural feature is a pronounced northward steepening of the base of the upper fluvial unit near the basin margin. In the outcrops described above, this contact descends southward at about 80 ft/mi (15 m/km). Directly south and west of the outcrops, three boreholes drilled about 0.4-1.5 mi (0.6-2.4 km) north of borehole RZ-02 locally constrain the dip of the contact to about 33 ft/mi (6 m/km) toward the south-southwest (Montgomery Watson, 1995, fig. 5-12, boreholes NZ-07, NZ-46 and NZ-47). The northward steepening of the contact may record continued uplift of the basin margin during and following the deposition of the upper fluvial unit. Alternatively, the concave surface may be a buried geomorphic feature derived from the earlier warping and erosion of the lower alluvial unit.

Uplift by monoclinal folding along Helendale Fault

Our field survey also revealed evidence of recurrent vertical displacement along the Helendale Fault near its intersection with the Mojave River. The Helendale Fault bounds the northeast side of a large basement ridge about 10 mi (15 km) northeast of GAFB (fig. 2). This ridge terminates directly east of the Mojave River, where its northwest tip and the bordering fault zone are buried by a succession of upper Pliocene(?) and Pleistocene continental sediments. Vertical movement on the fault zone at depth has deformed the overlying sediments in this area into a gently dipping, northeast-facing monoclinal flexure. The geometry of the structure suggests the associated concealed strand of the Helendale Fault may be a southwest-dipping reverse fault. Other evidence of contraction perpendicular to the Helendale Fault is found nearby on the west side of the Mojave River, where the trace of the fault nearly coincides with the crest of a large northwest-trending anticline (Bowen, 1954; Dibblee, 1967).

The sequence of deposits exposed in the monocline and in neighboring flat-lying sections along the east side of the Mojave River comprises a lower unit of lithic-arkose sand and polymictic pebble and cobble gravel more than 100 ft (30 m) thick, a middle unit of marly fine sand, silt, and clay 0-20 ft (0-6 m) thick, and an upper unit of arkosic sand and gravel roughly 50 ft (15 m) thick. The upper and lower units are laterally extensive, cropping out for miles on either side of the Helendale Fault, whereas the middle unit is only found along and directly northeast of the fault zone. The stratigraphic sequence is similar to that at GAFB. However, in contrast to the conformable sequence at GAFB, the upper unit generally overlies the middle unit with angular unconformity. Judging from its heterogeneous detrital composition and from its southwest-flowing paleocurrents indicated by imbricated clasts, the lower unit seems to be equivalent to the lower alluvial unit at GAFB. The upper unit and a capping stream terrace at the summit of the bluffs evidently correlate with the upper fluvial unit and George surface at the air base. The middle unit is lithologically comparable to the lacustrine unit at GAFB and probably is similar in age (see below), but it evidently accumulated in a separate, relatively minor basin bounded to the southwest by the Helendale Fault.

Directly northeast of the monocline, a thin (1.5 ft, 45 cm) bed of fine-grained silicic volcanic ash locally is intercalated between the middle and upper units (fig. 2, "ash locality"). This ash layer has an unusually shallow and westerly magnetic direction (table 1, outcrop 5). It is tentatively correlated geochemically with the PICO-40A ash bed near Ventura, California, which is dated at about 1.2-0.9 Ma and has chemical affinity to ashes from the Long Valley region (A. Sarna-Wojcicki, written commun., 1998). Thus, the lacustrine deposits of the middle unit evidently are older than 0.9 Ma and may be coeval with deposits of the middle lacustrine unit in boreholes RZ-02 and RZ-03 at GAFB. Conversely, the ash bed implies that the ancestral Mojave River did not occupy this area of its drainage basin until sometime after 1.2 Ma.

Stratigraphic and structural relations within the monocline indicate the southwest side of the Helendale Fault was uplifted both before and after the arrival of the ancestral Mojave River. The cumulative uplift recorded by the deformed strata is at least 120 ft (36 m). Tilted beds of the lower and middle units in the core of the monocline dip as steeply as 10-15° to the northeast and are about 60 ft (18 m) thick. They are unconformably overlain by deposits of the upper unit that dip northeastward at about 2-3°. Thus, the southwest side of the fault zone evidently was uplifted about 60 ft between the deposition of the middle and upper units. There also appears to be a slight angular unconformity between the lower and middle units in the monocline, which implies additional uplift occurred prior to the deposition of the middle unit. This earlier movement is loosely constrained to before 0.9 Ma by the previously mentioned tephra age. Associated uplift of the land surface along the Helendale Fault during the early Pleistocene(?) probably blocked the southward-flowing streams that had previously deposited the lower unit, thereby producing a small lacustrine basin in which the middle unit accumulated.

The top of the upper fluvial unit (George surface) rises about 30 ft (9 m) as it crosses to the southwest side of the monocline, and the thickness of the unit simultaneously decreases from about 80 ft (24 m) to 50 ft (15 m). Thus, the southwest side of the Helendale Fault evidently was uplifted about 60 ft (18 m) after the ancestral Mojave River arrived in this region. Half of this displacement occurred after the Mojave River abandoned the George surface at about 65 ka.

Reversal of regional paleoslope north of GAFB

A combination of stratigraphic and structural features suggests that a large crustal block extending at least from GAFB to Iron Mountain was gently tilted to the north during the early Pleistocene, thus facilitating the advancement of the early Mojave River beyond the Victorville basin. Throughout this region, sediments of the northward-flowing ancestral Mojave River overlie a composite alluvial unit deposited by a southward-flowing trunk stream and tributary alluvial fans (Cox and others, 1998). The old Mojave River deposits correlate with the uppermost deposits of the upper fluvial unit at GAFB, and the underlying unit evidently correlates with the lower alluvial unit at the air base. Stream deposits of the ancient southward-flowing axial drainage crop out extensively east of the Mojave River between Oro Grande and Iron Mountain, and they are locally exposed west of the river near GAFB and north of Silver Lakes. Some of the best exposures are in road cuts of National Trails Highway near Helendale. The deposits consist of well-stratified, moderately sorted, coarse sand and gravel with a compositionally diverse assemblage of slightly to strongly abraded clasts. Imbricated clasts consistently indicate southward-flowing paleocurrents.

In contrast to the conformable succession beneath GAFB (excluding borehole RZ-04), the deposits of the ancestral Mojave River rest unconformably on the composite alluvial unit between GAFB and Iron Mountain. The contact generally is a disconformity or low-angle unconformity. Locally, as along the Helendale Fault, it is a pronounced angular unconformity. There apparently is a significant erosional hiatus along the contact. For example, between Oro Grande and Helendale the unconformity exposed on the west wall of the Mojave River canyon is 100-200 ft (30-60 m) lower than the highest deposits of the south-flowing stream system on the east side of the river.

Between GAFB and Iron Mountain, the thickness of the ancestral Mojave River deposits fluctuates irregularly between 25-80 ft (8-25 m). As the unit neither thins to the north nor intertongues with underlying deposits, it apparently was not deposited on a southward-facing slope. Instead, the land surface evidently was horizontal or sloped gently to the north. This implies that the former southward-inclined paleoslope was flattened or reversed by northward tilting before the ancestral Mojave River entered this region.

A very slight amount of tilting probably would have been sufficient to reverse the former paleoslope. Excluding alluvial-fan systems and mountain streams, the gradients of large fluvial channels typically are a fraction of 1°. For example, the mean gradient of the modern Mojave River between GAFB and Iron Mountain is 17.5 ft/mi (3.3 m/km), or about 0.2°. Immeasurably slight tilting would reverse such a slope.

Subtle tilting on a large scale, if present, should be reflected by lateral variation in the elevation of major stratigraphic or geomorphic reference planes. We identified two such features that gradually descend to the north in agreement with broad northward tilting. One feature is the upper boundary of sediments laid down by the ancient southward-flowing stream. On the east side of the Mojave River between Oro Grande and Helendale, deposits of sand and gravel laid down by the old fluvial system are overlain by westward-sloping Pleistocene alluvial fans. The elevation of the intervening contact, as measured about 6,500 ft (1,980 m) east of the Mojave River floodplain, drops about 240 ft (73 m) in 5.7 mi (9.1 km) between NW ¼ sec. 5, T. 6 N., R. 4 W., and SW ¼ sec. 4, T. 7 N., R. 4 W. The structural relief on the contact corresponds to a gradient of 42.4 ft/mi (8.0 m/km) or a dip of about 0.5° to the north. This evidence is consistent with northward tilting, but does not prove it. The relief on the contact could have been produced by erosion of the old fluvial deposits prior to deposition of the overlying alluvial fans, rather than by tilting.

The topography of modern basement ridges along the Mojave River is consistent with northward tilting of a large crustal block extending about 26 mi (42 km) from GAFB to Harper Lake (fig. 2). The elevation of the highest summits decreases steadily to the north between Quartzite Mountain and Lynx Cat Mountain. A line connecting these two peaks slopes northward at 76.7 ft/mi (14.5 m/km), or about 0.8°. It seems unlikely that this series of peaks would have descended consistently to the north across this considerable distance during the Pliocene or early Pleistocene, when an adjacent major stream system simultaneously drained toward the south. Therefore, we suspect that the major summits along this north-south transect were originally accordant, and that the present topographic pattern reflects differential uplift by broad northward tilting, supplemented by vertical displacement on structural discontinuities such as the Helendale Fault. The net topographic relief along the transect implies that Quartzite Mountain and neighboring areas may have been uplifted as much as 1,970 ft (600 m) relative to Lynx Cat Mountain and Harper Lake.

The time of the postulated tilting event can be inferred from stratigraphic relations near GAFB. Much of the tilting presumably postdates vigorous flow of the southward-draining stream system but predates the advancement of the ancestral Mojave beyond the Victorville basin. In borehole RZ-02, thick deposits of moderately sorted coarse sand and gravel that probably were deposited by the southward-draining trunk stream system lie at least 226 ft (69 m) below the present land surface. Shallower deposits of the lower alluvial unit generally consist of poorly sorted, silty sand that probably was deposited by local alluvial-fan drainages. The transition between the two facies lies between the Olduvai and Cobb Mountain subchrons, which suggests vigorous southward-directed flow ceased sometime between 1.77 and 1.18 Ma. In the next section, we propose that the Mojave River escaped from the Victorville basin and flowed north to Harper Lake at roughly 475-575 ka. Thus, much of the northward tilting probably occurred in the early to middle Pleistocene, between about 1.8-0.5 Ma, although the process may also have extended to earlier and later times.

PALEOGEOGRAPHIC EVOLUTION OF UPPER MOJAVE RIVER DRAINAGE BASIN

Origin and growth of ancestral Mojave River in the Victorville basin

During the Pliocene and Pleistocene, the Victorville basin was filled by separate alluvial systems originating on the southeast, southwest, and north sides of the basin. Granitic detritus eroded from the San Bernardino Mountains was delivered to the southeast side of the basin by ancestral Deep Creek, which was the principal tributary of the ancestral Mojave River. The contemporary Deep Creek drains much of the northwestern San Bernardino Mountains, but its Pliocene precursor evidently drained an even larger area of the range (Sadler and Reeder, 1983). Coarse fluvial gravel deposited near the mountain front is contained within the Ord River deposits of Meisling and Weldon (1989), whereas distal deposits of gravel, sand, silt, and clay form the middle lacustrine and upper fluvial units at George Air Force Base (GAFB).

Concentrated stream flow probably emerged at the northwest front of the San Bernardino Mountains between about 3.3-3.8 Ma. The onset of the fluvial system as early as 3.8 Ma may be recorded by lenses of granitic gravel that Meisling (1984) observed amid fine-grained volcaniclastic sediments of the Phelan Peak Formation in eastern Summit Valley. Concurrently, about 4.4-2.5 Ma, fine-grained fluvial and lacustrine deposits composed of granitic and metamorphic detritus were accumulating near Phelan Peak (Weldon and others, 1993, fig. 8; ages revised according to modern geomagnetic polarity timescale—fig. 3).

Thus, the headwaters of the ancestral Mojave River evidently initially drained into the east end of the "Phelan Peak basin," which was an early manifestation of the Victorville basin. This shallow east-west or west-northwest-trending trough was confined to the north by a broad alluvial slope draining southward from the Mojave Desert region, to the southeast by the emerging San Bernardino Mountains, and to the southwest by an area uplifted along the San Andreas fault (Meisling and Weldon, 1989). The bordering upland to the southwest apparently was very low, because coarse clastic debris did not enter from this side of the basin before about 2.5 Ma (Foster, 1980; Weldon and others, 1993).

The results of our borehole investigations suggest that the depositional tract of the ancestral Mojave River arrived at southernmost Victorville (Test Well #32) about 3.3 Ma, at the southeast corner of GAFB (borehole RZ-01) about 1.95 Ma, and at the northwest corner of the air base (borehole RZ-03) about 1.05 Ma. Thus, the fluvial tract evidently advanced relatively rapidly at first, then ever more slowly as it prograded away from the mountains. The progress of the river was impeded by the opposing southward-inclined alluvial paleoslope, which may have been steepened by north-south tectonic contraction and by isostatic subsidence of the basin. The river gradually overcame this obstacle by depositing a northwest-thinning clastic wedge (fig. 11). Several stratigraphic and sedimentologic features reflect the northward progradation of the fluvial tract during the growth this clastic wedge. These include: (1) northwest-younging contacts at the base and top of the middle lacustrine unit (fig. 5); (2) northwestward thinning of the upper fluvial unit (figs. 5, 11); (3) upward coarsening of the middle lacustrine and upper fluvial units (fig. 5; most evident in borehole RZ-01); and (4) a sharp increase in the sediment accumulation rate at the base of the middle lacustrine unit (figs. 7, 8).

The fluvial slope created by the growth of the clastic wedge was inclined to the northwest, away from the source area in the San Bernardino Mountains. The middle lacustrine unit evidently accumulated at the intersection between this slope and the opposing southward-inclined alluvial slope. The influx of debris from the San Bernardino Mountains apparently shifted the topographic axis of the basin progressively northward, such that the middle lacustrine unit lapped northwestward across the lower alluvial unit and was in turn overlapped from the southeast by the upper fluvial unit. This lateral migration of the facies belts produced the stratigraphic sequence observed in the boreholes at GAFB. A comparable northward-overlapping succession of Pliocene and

Pleistocene alluvial and lacustrine deposits was recently identified nearby to the east in Lucerne Valley (figs. 1, 2) (R.E. Powell and J.C. Matti, unpub. manuscript, 1999).

Similar basin architecture also exists in the southwestern Mojave Desert, about 45 mi (70 km) west of Victorville (fig. 1). Regional geophysical investigations (gravity studies) revealed a very deep (5,000-10,000 ft, 1,500-3,000 m) sedimentary basin near Lancaster (Mabey, 1960, fig. 30). This "east Antelope basin" (Dibblee, 1967, fig. 71) contains a diachronous body of lacustrine clay, silt, and fine sand about 50-400 ft (15-120 m) thick, which is sandwiched between much thicker bodies of alluvial sand and gravel (Dutcher and Worts, 1963, fig. 3; Londquist and others, 1993, fig. 3). The lacustrine unit lies about 800 ft (245 m) beneath the land surface near the northern front of the Transverse Ranges. It rises steadily away from the mountains, eventually intersecting the land surface about 15-20 mi (24-32 km) to the north, at the playas of Rosamond Lake and Rogers Lake. The overlying thick body of alluvial sand and gravel is wedge shaped, thinning and fining to the north away from its source area in the western San Gabriel Mountains. The deep alluvial deposits that underlie the lacustrine stratum have not been studied in detail, but they presumably were derived from sources in the western Mojave Desert.

The basins near Victorville, Lucerne Valley, and Lancaster were filled asymmetrically from the south in response to the tectonic evolution of the central Transverse Ranges. In each case, the rising mountains delivered a glut of alluvium that forced the basin axes, with their associated lakes and wetlands, to shift northward into the desert, thus overwhelming a pre-existing southward-inclined regional paleoslope. In the Victorville basin and neighboring Lucerne Valley, the northward flux of sediments was initiated by uplift of the San Bernardino Mountains in the Pliocene. The analogous clastic wedge in the east Antelope basin evidently reflects uplift and northwestward translation of the San Gabriel Mountains along the San Andreas Fault during the Pleistocene.

Alluvial-fan systems at southwest margin of Victorville basin

Coarse alluvial-fan gravels derived from elevated ground south of the San Andreas Fault form the upper half of the Phelan Peak Formation near Phelan Peak. Magnetostratigraphy dates these sediments at about 2.5-1.4 Ma (Weldon and others, 1993, fig. 8; ages revised according to modern geomagnetic polarity timescale—fig. 3). The sources of the granitic, gneissic, and marble clasts in these deposits originally lay nearby to the southwest (Foster, 1980), but they probably have subsequently been displaced 40-60 mi (65-100 km) to the northwest by the San Andreas Fault (Weldon and others, 1993). The alluvial fans grew northward into the Victorville basin contemporaneously with the clastic wedge of the ancestral Mojave River. However, the fans evidently originated later than the river and in response to a different tectonic stimulus. Whereas the fluvial wedge resulted from *in situ* uplift of the San Bernardino Mountains north of the San Andreas Fault, the fans evidently were shed from a mobile source area that was transported past the Cajon Pass region by the San Andreas Fault (Weldon and others, 1993).

The Phelan Peak Formation is overlain conformably (Kenney and Weldon, 1999) by the Victorville Fan deposits of Meisling and Weldon (1989), which comprise the Harold Formation, Shoemaker Gravel, and the older alluvium of Noble (1954)—all deposited on northeastward-sloping alluvial fans. This upward-coarsening sequence accumulated at about 1.7-0.5 Ma as the San Gabriel Mountains were translated northwestward past the Cajon Pass region by the San Andreas Fault (ages again revised slightly from Weldon and others, 1993). Clast assemblages vary upward through the succession, but each of the three constituent units contains conspicuous detritus of Pelona Schist (Foster, 1980).

Relations between ancestral Mojave River and Victorville Fan

The Ord River deposits near Deep Creek evidently overlap in age with the Victorville Fan deposits, as judged by magnetostratigraphy and intertonguing relations (Meisling and Weldon, 1989). However, the Ord River deposits apparently contain little or no detritus of Pelona Schist (Meisling, 1984). With rare exceptions, the upper fluvial unit at GAFB also lacks conspicuous detritus of Pelona Schist, at least within gravelly facies where such material would be easily spotted in the field. This contrast in detrital composition implies that the Victorville Fan and ancestral Mojave River occupied distinct depositional tracts, and that most of the coarse detritus transported northeastward across the San Andreas Fault was trapped within the alluvial fans on the southwest flank of the Victorville basin. We presume that significant amounts of fine-grained (sand-size and smaller) detritus were transported beyond the toe of the Victorville Fan. Using Pelona Schist as a tracer, petrographic studies of the upper fluvial unit might establish what proportion of the fine-grained detritus deposited by the ancestral Mojave River was contributed by drainages of the Victorville Fan.

The fan and river tracts are also distinguished by discordant geomorphic surfaces. The Victorville Fan descends northeastward relatively steeply (mean gradient of 120 ft/mi, 23 m/km) between Cajon Pass and Victorville, and the slope steepens appreciably near the head of the fan. By contrast, remnants of the George surface that cap the Ord River deposits and upper fluvial unit are inclined very gradually and uniformly to the northwest (mean gradient of 19 ft/mi, 3.6 m/km) between the mouth of Deep Creek and Victorville. The conspicuous steepening at the head of the Victorville Fan may result in part from monoclinal folding adjacent to the San Andreas Fault (Meisling and Weldon, 1989; Kenney and Weldon, 1999). Moreover, erosion and sedimentary recycling have extensively modified the surface of the Victorville Fan since it was isolated from its mountain headwaters between about 0.78-0.5 Ma. Nevertheless, the substantially greater inclination of the overall fan surface reflects a fundamental hydrologic difference between the ancestral Mojave River and the smaller, more ephemeral, or more sediment-laden streams that deposited the Victorville Fan.

Therefore, although deposits of the Victorville Fan and ancestral Mojave River form a composite alluvial wedge around the southern margin of the Victorville basin, the fan deposits and river deposits evidently were products of distinct hydrologic systems and may never have combined to form a continuous bajada. Downstream from its confluence with Deep Creek, the Mojave River probably always occupied a distinct, relatively low-gradient channel that skirted the northeast toe of the Victorville Fan (Meisling, 1984).

Geologic maps and cross-sections that show the alluvial succession of the Victorville Fan extending beneath Victorville to the Mojave River (e.g., Bowen, 1954; Dibblee, 1960, 1967; Bortugno and Spittler, 1986, section A-A') are inaccurate. Deposits of the ancestral Mojave River underlie Victorville, and the northeastern boundary of the alluvial-fan deposits lies southwest of the city (fig. 2; B. Cox, unpub. mapping). Furthermore, the depositional histories of the river and fan imply that this interface probably lies somewhat farther to the southwest in the subsurface. The river advanced across the Victorville basin to GAFB by 1.95 Ma, whereas the fan did not begin growing until about 1.7 Ma. When the Victorville Fan expanded to the northeast, it probably overran the southwest margin of the pre-existing river floodplain. After the modern Mojave River began incising its canyon at about 65 ka, distal fan lobes produced by recycling of the Victorville Fan freely encroached onto the abandoned George surface, shifting the boundary between river and fan deposits yet farther to the northeast.

Southward-draining braided-stream/alluvial-fan system

The heterogeneous detritus in the lower alluvial unit at GAFB evidently was eroded from a large area of the southern Mojave Desert north of the Victorville basin. Potential sources for the abundant granitic detritus in the lower alluvial unit are widespread west of the Mojave River (Bortugno and Spittler, 1986). Silicic metavolcanic rocks were derived from Mesozoic-age flows and welded tuffs that crop out extensively east of the Mojave River between Victorville and Barstow. Metasedimentary rocks, including quartzite, marble, and calc-silicate hornfels, probably were derived in part from the Shadow Mountains, Iron Mountain, and Quartzite Mountain, which lie northwest, northeast, and east of GAFB (fig. 2). Hornblende dacite and other nonmetamorphosed volcanic rocks evidently were derived from early Miocene-age extrusive rocks and hypabyssal intrusions that crop out farther to the northwest in the Kramer Hills, and more abundantly to the northeast around Barstow.

Local alluvial-fan streams transferred rock detritus from the various upland sources to a large southward-flowing braided stream. The location of the trunk stream channel, as deduced from outcropping fluvial deposits, approximately coincides with a chain of north-south-trending linear gravity depressions (Mabey, 1960; Biehler and others, 1988; Subsurface Surveys, 1990). The old channel evidently lies west of Iron Mountain between Harper Lake and Silver Lakes, where it is mostly buried beneath deposits of the ancestral Mojave River (fig. 2). The channel continues southward along and east of the Mojave River between Silver Lakes and GAFB. Magnetostratigraphic data from the lower alluvial unit at GAFB (figs. 5, 7) suggests that southward-directed drainage was established prior to 4.2 Ma. Vigorous southward flow probably ended sometime between 1.77-1.18 Ma, when northward tilting evidently flattened or reversed the regional paleoslope north of GAFB. With the waning of the trunk stream, local alluvial fans deposited poorly sorted silty sand near the north end of the air base until about 1.18 Ma, when the distal lake or wetland associated with the ancestral Mojave River finally inundated the area.

Escape of ancestral Mojave River from the Victorville basin

The ancestral Mojave River evidently advanced beyond the Victorville basin by overflowing onto level or gently northward-sloping ground at the north end of the basin. By establishing the depth of the buried basin margin in relation to the George surface, we can determine the time of the river's escape from the basin through reference to the magnetostratigraphic sections in boreholes RZ-02 and RZ-03 (figs. 5, 8). The depth of the margin can be estimated in two ways. First, wetland, lacustrine, and fluvio-deltaic sedimentation probably waned as the river progressed beyond the basin. Thus, the margin should be roughly parallel to the top of the uppermost thick sequence of fine-grained sediments deposited near the north end of the basin. Second, the depth of the margin probably is comparable to the thickness of fluvial sediments deposited directly downstream from the margin.

Thick fluvio-deltaic or floodplain sequences of thinly bedded fine sand, silt, and clay were encountered at depths of 65 and 72.5 ft (20 and 22 m) in boreholes RZ-02 and RZ-03, respectively (fig. 5). The northern basin margin presumably extended high enough to confine these deposits. As the tops of the fine-grained sequences lie above the level of the Brunhes/Matuyama boundary, the river evidently escaped from the Victorville basin sometime after 780 ka. By interpolating between the Brunhes/Matuyama boundary and the George surface (65 ka), the time of the river's departure is estimated to be about 475-525 ka.

The northern margin of the basin evidently intersects the west wall of the Mojave River canyon nearly due east of the OSL site, which in turn lies 2 mi (3.2 km) north of borehole RZ-02 (fig. 2). The thickness of the ancestral Mojave River deposits exposed along a 5-mi (8-km) stretch of the canyon wall directly north of the OSL site generally oscillates between 50-80 ft (15-24 m). These deposits locally are capped by remnants of a mature soil profile that is characteristic of the George surface, so they apparently have not been significantly eroded. As the river presumably overflowed at the lowest point along the basin margin, the thickest fluvial sections (80 ft, 24 m) should most accurately record the time of its escape. Deposits at this depth below the George surface in borehole RZ-02 lie above the level of the Brunhes/Matuyama boundary, once again implying the river escaped after 780 ka. Interpolation refines the estimate to about 575 ka.

Combining the results of the foregoing two approaches, we conclude that the ancestral Mojave River progressed beyond the Victorville basin after 780 ka, or more precisely between about 475-575 ka. This replaces a preliminary estimate of about 1 Ma (Cox and others, 1998; Cox and Tinsley, 1999).

Advancement of ancestral Mojave River to Harper Lake and Lake Manix

Whereas the ancestral Mojave River advanced slowly across the Victorville basin by depositing a thick clastic wedge against an opposing south-facing alluvial slope (fig. 11), it must have made rapid headway once it finally encountered a long stretch of level or northward-sloping ground. Thus, if we have correctly surmised that a large crustal block extending from Quartzite Mountain to Harper Lake was tilted to the north in the early Pleistocene, then the Mojave River probably advanced quickly to Harper Lake after escaping from the Victorville basin at about 475-575 ka.

The arrival of the ancestral Mojave River in the Lake Manix basin east of Barstow (fig. 1) evidently correlates with the deposition of the oldest fluvial and lacustrine deposits in member B of the Manix Formation of Jefferson (1985). These deposits are bracketed between about 1.1 Ma and 350 ka by radiometric and magnetostratigraphic ages, and an extrapolation suggests the base of the fluvio-lacustrine section is about 500 ka (Jefferson, 1985; 1994; 1999; Nagy and Murray, 1996). The river possibly flowed directly to the Lake Manix basin after escaping from the Victorville basin. However, topographic and geologic relations suggest that a low sill near Barstow may have temporarily confined the river to Harper Lake (Cox and Tinsley, 1999; B. Cox, unpub. data). This confinement probably was relatively brief. If the river broke out of the Victorville basin between 475-575 ka and arrived at the Lake Manix basin at about 500 ka, then its terminus was fixed at Harper Lake no longer than about 75 ka.

The ancestral Mojave River did not permanently abandon Harper Lake after entering the Lake Manix basin. Relict shorelines and fossil mollusks and ostracodes indicate that the river produced at least two deep lakes in the Harper Lake basin during the late Pleistocene, most recently about 25 ka (Meek, 1990, 1999). Vertical movements along the Lenwood and Mount General Faults (fig. 2) may have acted as a switch that diverted the flow of the Pleistocene Mojave River either to Harper Lake or to Lake Manix and other basins east of Barstow (Reynolds and Reynolds, 1994). The Mojave River presently is barred from flowing northward to Harper Lake via Hinkley Valley (fig. 2) by an artificially reinforced natural levee only about 15-20 ft (5-6 m) high. Without human intervention, a major flood or aggradation by the river could readily divert the flow back to Harper Lake (Meek, 1999).

Incision of Mojave River canyon

Luminescence ages recently determined for the George surface (Ruppert, 1999) suggest that the Mojave River began eroding its present canyon near Victorville and GAFB at about 60-70 ka. This event signals the origin of the modern Mojave River in the Victorville region. Downcutting evidently began much earlier along Summit Valley—a southern tributary of the Mojave River that borders the southeast shoulder of the Victorville Fan (fig. 2). A stream terrace near the head of Summit Valley evidently was incised as early as 0.5 Ma (Meisling, 1984; Weldon, 1986; McFadden and Weldon, 1987). Monoclinal warping along the San Andreas Fault (Meisling and Weldon, 1989; Kenney and Weldon, 1999) may have induced early incision in this area.

The large volume of sediment that was eroded during the incision of the Mojave River canyon probably was mostly redeposited in a delta and alluvial plain at the west end of the Lake Manix basin. The resulting progradation of the delta filled in much of the original broad lake basin, thereby isolating the modern basins of Coyote Lake, on the north, and Troy Lake on the south.

PALEOTECTONIC IMPLICATIONS

Uplift of the San Bernardino Mountains

We have proposed that the northward-thinning wedge of granitic sand, silt, and gravel that underlies Victorville and George Air Force Base (GAFB) is an orogenic prism that accumulated in response to uplift of the San Bernardino Mountains (fig. 11, upper fluvial unit). This clastic wedge evidently was deposited by a northwestward-prograding fluvial system that we equate with the ancestral Mojave River, and the underlying diachronous lacustrine stratum apparently was deposited at the northwest tip of the expanding fluvial wedge. This paleogeographic model implies that the inception of uplift in the San Bernardino Mountains should be at least as old as the earliest lacustrine sediments deposited at the tip of the wedge. Therefore, the initial uplift apparently predates 2.55 Ma, which is the age we assign to the deepest lacustrine deposits in borehole RZ-01 (figs. 5, 7). Our overall analysis of the clastic wedge suggests uplift may have begun at least a million years earlier, however. We have inferred that the tip of the wedge arrived at southernmost Victorville at about 3.3 Ma, and that it may have begun growing at the mountain front as early as 3.8 Ma.

Previous studies concluded that the modern San Bernardino Mountains began rising sometime after about 2-3 Ma in response to transpressional stresses along the San Andreas Fault (May and Repenning, 1982; Sadler and Reeder, 1983; Meisling and Weldon, 1989; Matti and Morton, 1993). Key biochronologic evidence was presented by May and Repenning (1982), who found late Pliocene-age (2-3 Ma) vertebrate fossils in the Old Woman Sandstone of Shreve (1968) along the northern front of the range. The fossils were recovered from beds of sand and silt that contain clasts derived from the Mojave Desert. Thus, the deposits evidently predate the development of the steep topography and vigorous northward drainage associated with the modern range front (Sadler, 1982b; Sadler and Reeder, 1983).

However, sedimentary structures and clast assemblages in the Old Woman Sandstone indicate that some of its fluvial sediments were derived from the south (Shreve, 1968; Powell and Matti, 1998). Thus, there apparently was some topographic relief in the general area of the northern San Bernardino Mountains well before the end of the Pliocene. Sadler and Reeder (1983) inferred that the sedimentary basin of the Old Woman Sandstone originated between about 7 Ma and 3 Ma as an early product of the same transpressional regime that eventually uplifted the bordering mountains. Similarly, Meisling and Weldon (1989) proposed that minor uplift on the south side of the basin might have resulted from early episodes of northward-directed thrusting that predated the main uplift of the range.

The ancestral Mojave River may have been especially responsive to the early tectonic movements that preceded major uplift of the San Bernardino Mountains, because its principal tributary, Deep Creek, originally drained a very large area of the range. Based on their analysis of the modern drainage net of the San Bernardino Mountains, Sadler and Reeder (1983) inferred that the headwaters of ancestral Deep Creek extended eastward to the core of the range, encompassing the modern watersheds of Big Bear Valley and possibly the uppermost Santa Ana River. The latter watersheds lie directly north of a strongly uplifted tectonic block that encompasses San Gorgonio Mountain (fig 1). The relative timing of uplift at San Gorgonio Mountain as compared to the adjacent northern plateau of the San Bernardino Mountains is uncertain (Spotilla and others, 1998). However, uplift may have propagated northward from a restraining bend in the San Andreas Fault near San Gorgonio Pass (fig. 1) (Matti and Morton, 1993; Sadler, 1993). If so, then the oldest deposits in the clastic wedge of the ancestral Mojave River may record the early uplift of San Gorgonio Mountain.

Deformation of the southern Mojave Desert

During the late Cenozoic, the crust of the Mojave Desert and adjacent Transverse Ranges was shortened by north-south compression (Bartley and others, 1990) and simultaneously was sheared along northwest-trending dextral faults (Dibblee, 1961; Dokka, 1983; Dokka and Travis, 1990). Prime examples of the strike-slip faults include the Helendale and Lenwood Faults between Victorville and Barstow (fig. 2). The contractional structures include thrust and reverse faults and monoclinal flexures along the north flank of the central and western San Bernardino Mountains (fig. 2) (Meisling, 1984; Miller, 1987; Meisling and Weldon, 1989; Matti and others, 1998a,b; Kenney and Weldon, 1999). Furthermore, Howard and Miller (1992) proposed that the uplands between Victorville and Barstow, which include Quartzite Mountain, Stoddard Ridge, and the Granite and Ord Mountains (fig. 2), are part of a very large west-northwest-trending basement anticline as much as 150 mi (250 km) long. They termed this hypothetical uplift the "Bullion Mountains highlands." The Shadow Mountains presumably represent an extension of this feature west of the Mojave River.

Our field and borehole investigations along the Mojave River revealed abundant new evidence of north-south regional contraction during the Pliocene and Pleistocene. Relevant structural features include broad arching of the George surface at GAFB, and a northwest-striking fault near the southwestern margin of the air base (fig. 4). The fault runs northwestward, parallel to strands of the regional strike-slip system. It is not a simple strike-slip fault, however, as its southwest side is upthrown at least 170 ft (50 m). It probably is either a southwest-dipping reverse fault, or possibly an oblique-slip fault that accommodated both contractional strain and dextral shear. North of GAFB, the Helendale Fault locally accommodated at least 120 ft (36 m) of southwest-side-up reverse displacement during the Pleistocene, possibly in conjunction with right-lateral slip.

Our studies also disclosed an east-west-trending tectonic hinge at the north end of the Victorville basin directly north of GAFB. On the south side of the hinge, alluvial deposits of presumed late Pliocene or early Pleistocene age locally are tilted gently to the south and unconformably overlain by flat-lying middle Pleistocene-age deposits of the ancestral Mojave River. Thus, the hinge evidently was uplifted relative to the Victorville basin during the early Pleistocene. North of the hinge, a broad crustal panel extending northward 28 mi (45 km) to Harper Lake apparently was tilted very slightly to the north during the early Pleistocene, which reversed a former southward-inclined regional paleoslope. Although the hypothetical tilting event seems to have rotated the land surface less than 1°, it nevertheless may have uplifted areas along the hinge about 2,000 ft (600 m) relative to the distant Harper Lake basin.

The tectonic hinge described above apparently represents the crest of a very broad, asymmetric, southward-facing anticline. Thus, the large-scale structural pattern north of GAFB seems to support the concept of the Bullion Mountains highlands advanced by Howard and Miller (1992). The anticline evidently rose at least in part during the early Pleistocene, so its growth was contemporaneous with rapid uplift along the northern front of the San Bernardino Mountains. The westernmost San Bernardino Mountains near Cajon Pass were uplifted within a *northward*-facing monocline that borders the south side of the Victorville basin (Meisling and Weldon, 1989; Kenney and Weldon, 1999). Therefore, the Victorville basin evidently evolved as a contractional feature bounded by inward-facing basement folds.

Previous models of the deep structure of the San Bernardino Mountains suggest a possible structural framework and driving mechanism for the contractile deformation in the adjacent southern Mojave Desert. From an analysis of regional seismicity, Corbett (1984) determined that the base of seismogenic upper crust dips southward beneath the San Bernardino Mountains. Based in part on this observation, Meisling and Weldon (1989) proposed that the San Bernardino Mountains are underlain by a deep northward-vergent thrust ramp that flattens northward into a decollement about 3 mi (5 km) beneath the floor of the Mojave Desert. They hypothesized that the range was uplifted partly by northward displacement of the upper plate of this thrust-decollement system. Deep seismic-reflection profiling subsequently confirmed that the base of the brittle upper crust is relatively flat-lying beneath the southern Mojave Desert and dives southward beneath the western San Bernardino Mountains (Li and others, 1992). The latter study further concluded that the brittle-ductile transition and associated decollement zone lie about 5-8 mi (8-13) km beneath the southern Mojave Desert, somewhat deeper than was initially proposed.

Besides uplifting the San Bernardino Mountains, northward displacement along the decollement may have buckled the upper crust in the southern Mojave Desert, thus producing a broad, west-trending arch north of the Victorville region (Bullion Mountains highlands). Bowen (1954) inferred that the Mojave River canyon was eroded in response to recent tectonic uplift. We endorse this hypothesis and propose that renewed arching of the crust above the deep decollement was responsible for this latest episode of broad uplift. Widespread deformation of the George surface, including faulting and broad arching at GAFB, and monoclinal folding at the Helendale Fault, confirm that the southern Mojave Desert was subjected to compressional stresses in the late Pleistocene, after about 60-70 ka.

Alternatively, it is possible that the cutting of the Mojave River canyon was induced by a nontectonic event, such as stream piracy in the headwaters of the river, or climatic change. However, we are skeptical of either option, and a climatic mechanism seems particularly unlikely. If the canyon were eroded due to climate change, then the major fluctuations in global climate that occurred repeatedly during the Pleistocene presumably would have induced comparable earlier cycles of erosion. Previous episodes of channel entrenchment should be evident from buttress unconformities and major hiatuses in the Pleistocene stratigraphic section. We found no evidence of such features, either in boreholes or in outcrops along the river.

CONCLUSIONS

Our stratigraphic investigation of borehole cores and outcrops near Victorville, California, clarifies the paleogeographic evolution and regional paleotectonic framework of the ancestral Mojave River. The river emerged at the northwest front of the San Bernardino Mountains sometime between 3.8-2.55 Ma, most likely near the beginning of this interval. It arose during the early phases of a protracted Pliocene-Pleistocene orogenic cycle, possibly during the initial uplift of the San Gorgonio Mountain block in the core of the San Bernardino Mountains.

There were two main legs in the river's journey across the southern Mojave Desert. In the relatively difficult first leg, which was completed during the late Pliocene and early Pleistocene, the river advanced only about 22 miles (35 km) in about 2-3 Ma. It progressed northwestward across the future sites of Hesperia, Victorville, and George Air

Force Base (GAFB) by gradually raising its grade against an opposing south-facing alluvial paleoslope. In the process, the river deposited a diachronous wedge of fluvial sand and gravel that graded distally into lacustrine silt and clay.

During this episode, a pulse of north-south regional contraction racked both the river's mountain headwaters to the south and the uncharted desert ahead. The San Bernardino Mountains were forced upward and northward along thrust faults and monoclinal arches, while other mountain belts were displaced northwestward past Cajon Pass by the San Andreas Fault. At the same time, broad warping of the southern Mojave Desert produced a large west-trending anticlinal arch whose crest lay directly north of GAFB. The crust subsided between this arch and the mountains to the south, producing a deep structural basin in the Victorville region. This basin was simultaneously filled from the southeast by the ancestral Mojave River, from the southwest by alluvial fans shed northeastward across the San Andreas Fault (Phelan Peak Formation and Victorville Fan deposits), and from the north by streams draining southward off the arch.

The relatively easy second leg of the journey began after 780 ka, most likely between about 575-475 Ma, when the river finally aggraded its bed to a low point at the crest of the anticline. This notch or wind gap between Quartzite Mountain and the southeastern Shadow Mountains was the abandoned canyon of a former southward-flowing stream. The route ahead had already been prepared by gentle tilting on the broad northern limb of the anticline, which reversed the former southward-inclined fluvial paleoslope between GAFB and Harper Lake. In the absence of topographic confinement, deposition of wetland and lacustrine facies largely ceased beyond this point. The river progressed rapidly across flat or northward-sloping ground to Harper Lake, where it may have been briefly confined before forging eastward to the Lake Manix basin at about 500 ka. The terminus of the river oscillated between Harper Lake and Lake Manix throughout the remainder of the Pleistocene.

In the late Pleistocene, about 60-70 ka, the ancestral Mojave River began incising its modern canyon between Victorville and Barstow. Downcutting probably was induced by a fresh pulse of regional contractile deformation that broadly arched the southern Mojave Desert between Cajon Pass and Barstow.

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Table 1. Paleomagnetic polarity, inclination, and treatments from boreholes and outcrops near George Air Force Base, California.

RZ-01 (Wellhead elevation: 2806.5 feet; Location: 34°33'48" N., 117°21'04" W.)

Depth	Sample #	Polarity	Inclination	Treatment	MAD
15.8	8J099-1	N	88.7	300-558	4.93
25	8J100-1	N	53.5	379-578	2.42
31.8	8J101-1	N	50.5	475-553	2.04
45	7J070-1	N	57.9	277-579	2.14
51	8J102-1	N	53	298-525	7.19
52.5	7J062-1	R	-32.5	380-581	23.63
68	7J063-1	I	16.5	380-529	5.55
68.5	8J103-1	R	-28.8	475-553	4.51
75	7J071-1	R	-27.8	274-559	7.59
84	7J064-1	R	-43.4	200-581	7.15
88.4	8J185-1	R	-28.8	370-507	15.6
94.2	7J065-1	N	46.8	380-581	19.18
94.5	8J104-1	R	-41.8	199-475	14.7
99.3	8J105-1	N	45.2	198-520	5.35
105	7J066-1	N	41.6	478-579	18.82
118	7J067-1	R	-69.2	277-579	10.9
131.5	7J072-1	R	-26.25	375-557	4.76
141	8J106-1	R	-37	153-473	22.1
150.2	8J107-1	N	54.8	198-520	12.94
150.5	7J073-1	N	25.3	375-557	14.75
156	7J069-1	R	-59.5	277-559	18.16
157.2	8J108-1	R	-73.9	296-567	5.48
165	7J074-1	R	-59.5	196-578	0.95
175	7J075-1	R	-45	274-572	1.17
190	7J076-1	R	-44.6	274-572	2.66
196.5	7J077-1	R	-61.7	274-572	1.1
202	7J078-1	R	-46.7	274-572	1.27
213.5	7J079-1	N	61.2	270-544	5.13
224	7J080-1	N	49.7	270-565	1.34
231.8	8J109-1	N	53	373-567	0.58
240	7J081-1	N	52	270-565	1.99
242.5	8J110-1	N	66.5	361-547	0.9
256.5	7J083-1	N	68.3	270-565	0.85
261	7J084-1	R	-38.4	265-549	0.64
264	8J111-1	I	-10.4	361-547	0.45
264.3	7J085-1	I	-15.6	265-549	1.67
277.6	7J086-1	R	-50.1	265-549	1.25
281	7J087-1	N	68.9	265-549	2.88
285.2	7J088-1	N	40.4	154-342	11.58
288.5	8J113-1	I	-16.1	146-456	14.3
293.5	7J089-1	R	-50.2	342-578	1.82
301.75	8J114-1	R	-45.8	203-302	1.24
304	8J115-1	I	12.3	361-547	2.5

307	7J090-1	N	60.2	274-578	1.01
312	7J091-1	N	83.2	154-342	4.89
320.2	7J092-1	N	43.5	268-577	7.25
322	7J093-1	R	-60	268-577	2.06
326	7J094-1	R	-49.2	268-577	0.98
328.5	7J095-1	R	-48.3	337-558	4.78
335.8	7J096-1	R	-41.2	152-336	3.73
341.5	7J097-1	R	-65.5	523-578	2.96
343.4	7J098-1	R	-52.3	336-578	4.09
348.3	7J099-1	N	74.3	H200-400	5.34
356	7J100-1	I	-9	H200-400	2.05
360.5	8J116-1	N	46.6	150-360	5.61
365.5	7J101-1	R	-53.6	520-578	13.09
385.15	7J103-1	R	-56.1	H200-400	3.28
392.7	7J104-1	R	-57	268-571	0.96
405.5	7J105-1	R	-56.4	152-335	3.61
415.5	7J106-1	N	38.7	H200-400	1.98

RZ-02 (Wellhead elevation: 2842.0 feet; Location: 34°36'02" N., 117°22'28" W.)

Depth	Sample #	Polarity	Inclination	Treatment	MAD
15.3	8J020-1	N	33.5	483-581	5.12
20.4	8J021-1	N	54.7	483-581	2.97
36.6	8J022-1	N	47.8	483-587	3.22
66.4	8J023-1	N	51.6	383-581	2.92
67.2	8J024-1	N	60.4	379-597	1.72
71.9	8J025-1	N	51.1	379-597	3.36
80.3	8J026-1	N	55.3	379-597	1.42
82.9	8J027-1	N	38.4	379-597	4.39
87.2	8J028-1	N	28.4	378-596	2.48
89.3	8J029-1	N	49	378-596	2.33
93.3	8J030-1	N	75.3	558-596	4.97
97.5	8J031-1	N	62.2	378-578	2.4
101.3	8J032-1	N	54.7	375-591	1
107	8J053-1	N	61.7	H100	-
116.3	8J054-1	I	-13.4	301-573	8.97
120.2	8J033-1	R	-43.1	573-591	6.53
122	8J034-1	R	-29.9	475-591	4.15
133.3	8J035-1	R	-27.2	475-591	8.63
142	8J036-1	N	26.7	H300-500	27.47
148.2	8J037-1	I	-9	H400-600	18.97
161.8	8J038-1	N	45.5	H200-500	3.41
173	8J039-1	R	-39.7	372-585	3.11
174.3	8J040-1	R	-31.4	372-585	3.11
185	8J136-1	R	-21.8	300-581	3.27
192.2	8J041-1	R	-86.1	372-567	7.33
193.2	8J042-1	R	-26.7	567-585	26.28
197.2	8J043-1	R	-66.5	456-566	0.78
198.3	8J044-1	R	-44	456-566	0.88

207.3	8J045-1	R	-54.7	456-566	1
209	8J046-1	R	-43.9	456-566	1.85
215.5	8J137-1	N	62.3	300-581	3.02
222	8J138-1	I	7.9	380-559	9.16
235.1	8J047-1	R	-54.4	H100	-
238.3	8J048-1	R	-40.5	377-573	7.69
246.6	8J049-1	R	-63.1	377-555	4.85
247.3	8J050-1	R	-48.5	377-573	1.37
256.5	8J051-1	R	-74.3	H100	-
260.3	8J052-1				

RZ-03 (Wellhead elevation: 2839.7 feet; Location: 34°36'03" N., 117°23'57" W.)

Depth	Sample#	Polarity	Inclination	Treatment	MAD
30.3	8J055-1	N	57.58	302-578	2.67
36	8J056-1	N	60.1	H100	-
46.9	8J057-1	N	52.9	H100	-
52.2	8J058-1	N	73.9	H100	-
61.8	8J059-1	N	45.5	H100	-
72.5	8J060-1	N	45.9	302-578	0.94
75.8	8J061-1	N	54.3	302-578	2.18
85.5	8J062-1	N	53	302-578	0.85
86.8	8J063-1	N	53.2	300-578	0.89
93.3	8J064-1	N	49	300-578	3.09
105	8J139-1	N	48.9	300-581	1.7
110.3	8J065-1	N	58.4	300-578	1.37
113.5	8J066-1	I	13.1	300-578	0.92
114.5	8J067-1	R	-35.2	300-578	1.01
122.3	8J068-1	R	-44.5	H100	-
125.5	8J069-1	I	-6.9	H100-400	10.1
130.5	8J070-1	N	35.6	H100	-
135	8J140-1	R	-50.9	300-578	2.71
141	8J071-1	R	-61.1	300-578	0.64
143.7	8J072-1	R	-56.7	300-578	1.52
144.7	8J073-1				
145.8	8J074-1	R	-54.9	300-578	0.56
147	8J075-1	R	-57.1	301-575	0.7
148.8	8J076-1	R	-33.5	301-575	0.46
151	8J077-1	R	-44	301-575	0.59
152.5	8J078-1	R	-33.4	H100	-
156	8J141-1	N	30.1	300-578	8.44
162.25	8J142-1	I	-3.1	478-557	8.74
169.2	8J143-1	N	50.24	378-557	9.8
175.8	8J079-1	N	45.8	H100	-
183	8J080-1	R	-52.3	301-575	0.59
186.7	8J081-1				
187.3	8J082-1	R	-22.5	302-570	8.55
191.3	8J083-1	R	-36.3	379-570	4.3
193	8J084-1	R	-27.2	302-570	9.64

197	8J085-1	R	-41.2	377-573	5.48
198.8	8J086-1	R	-38.9	377-573	11.12
200.8	8J087-1	R	-52.5	377-573	2.09
204.5	8J088-1	R	-46.2	377-573	2.18
205.7	8J089-1	R	-43.7	380-578	4.64
208.3	8J090-1	R	-38.5	380-578	3.91
210.5	8J091-1	R	-45.3	380-578	4.61
211.3	8J092-1	R	-47.7	380-578	4.37
215.8	8J093-1	R	-52.5	379-578	0.68
216.8	8J094-1	R	-50.8	379-578	1.55
218.3	8J095-1	R	-45.2	379-578	1.71
250.7	8J096-1	N	74.8	479-578	1.39
260.8	8J097-1	N	49.9	379-578	6.02
261.5	8J098-1	N	70.4	300-578	8.44

RZ-04 (Wellhead elevation: 2895.2 feet; Location: 34°34' 21" N., 117°23'48" W.)

Depth	Sample #	Polarity	Inclination	Treatment	MAD
142	7J111-1	N	76.2	H150-400	2.48
157.5	7J112-1	N	56.5	420-571	3.82
170.25	7J113-1	R	-49.1	420-571	4.19
179	7J114-1	N	51.9	268-566	0.63
197.15	7J115-1	N	63.8	H150-400	2.82
212	7J116-1	N	55.7	268-566	1.61
222	7J117-1	R	-23.9	515-566	6.29
225.5	7J118-1	N	46.5	201-335	1.51
240	7J119-1	N	73.4	H150-400	3.39
252.5	7J120-1	N	79.5	H150-400	11.37
264	7J121-1	N	72.4	264-553	0.51
271	7J122-1	N	73.7	264-406	4.01
286	7J123-1	N	63.1	H150-400	3.7
291.5	7J124-1	N	79.5	H150-300	9.05
302	7J125-1	R	-51.8	H150-400	0.81
311.5	7J126-1	N	26.6	198-406	11.58
331	7J127-1	N	36.5	H150-400	5.65

Outcrops

1. 8J181-1 (Elevation: 2870 feet, Location: 34°33'33" N., 117°20'16" W.)
   Inclination: 57.0; Declination: 359.5; Polarity: N; Treatment: 153-522; MAD: 0.8

2. 8J182-1 (Elevation: 2815 feet, Location: 34°33'37" N., 117°20'29" W.)
   Inclination: 33.3; Declination: 292.8; Polarity: N; Treatment: 153-522; MAD: 7.1

3. 8J183-1 (Elevation: 2810 feet, Location: 34°33'52" N., 117°20'54" W.)
   Inclination: 53.5; Declination: 5.2; Polarity: N; Treatment: 150-507; MAD: 4.7

4. 8J184-1 (Elevation: 2843 feet, Location: 34°33'52" N., 117°21'10" W.)
Inclination: 54.9; Declination: 6.1; Polarity: N; Treatment: 150-507; MAD: 2.1

5. 7J145-2 Volcanic ash near Helendale Fault
(Elevation: 2515 feet, Location: 34°45'58" N., 117°17'42" W.)
Inclination: -30.3; Declination: 272.4; Polarity: R; Treatment: 286-639; MAD: 1.8

Notes: Depth, distance in feet below wellhead; Sample #, USGS sample identifier; Polarity, N = normal magnetic polarity, R = reversed magnetic polarity, I = intermediate, polarity not determined; Inclination, magnetic inclination in degrees; Treatment, range of heating steps used in inclination determination, H indicates alternating field treatments in oersteds, other values are thermal demagnetization temperatures in degrees C; MAD, maximum angle of deviation from Kirschvink (1980). If no values are given, specimen was not recovered or was not suitable for measurement.