Arkosic rocks from the San Andreas Fault Observatory at Depth (SAFOD) borehole, central California: Implications for the structure and tectonics of the San Andreas fault zone

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ABSTRACT

The San Andreas Fault Observatory at Depth (SAFOD) drill hole encountered indurated, high-seismic-velocity arkosic sedimentary rocks west of the active trace of the San Andreas fault in central California. The arkosic rocks are juxtaposed against granitic rocks of the Salinian block to the southwest and against fine-grained Great Valley Group and Jurassic Franciscan rocks to the northeast. We identify three distinct lithologic units using cuttings, core petrography, electrical resistivity image logs, zircon fission-track analyses, and borehole-based geophysical logs. The upper arkose occurs from 1920 to 2530 m measured depth (mmd) in the borehole and is composed of five structural blocks defined by bedding orientations, wireline log character, physical properties, and lithologic characteristics. A clay-rich zone between 2530 and 2680 mmd is characterized by low V_p and an enlarged borehole. The lower arkose lies between 2680 and 3150 mmd. Fission-track detrital zircon cooling ages are between 64 and 70 Ma, appear to belong to a single population, and indicate a latest Cretaceous to Paleogene maximum depositional age. We interpret these Paleocene–Eocene strata to have been deposited in a proximal submarine fan setting shed from a Salinian source block, and they correlate with units to the southeast, along the western and southern edge of the San Joaquin Basin, and with arkosic conglomerates to the northeast and the Buzzard Canyon fault to the southwest. Significant amounts of slip appear to have been accommodated on both strands of the fault at this latitude.

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INTRODUCTION

The primary component of the San Andreas Fault Observatory at Depth (SAFOD) is a 3-km-deep deviated borehole that crosses the San Andreas fault zone in central California (Hickman et al., 2004, 2005) (Fig. 1). Numerous questions about fault behavior, structure, composition, physical properties, and fluid-rock interactions in fault zones are being addressed in this project (i.e., Boness and Zoback, 2006; Solum et al., 2006; Erzinger et al., 2006; Hole et al., 2006; Schleicher et al., 2006; Bradbury et al., 2007).

A comprehensive suite of geophysical data and geological studies (see *Geophysical Research Letters* special volume 31, numbers 12 and 15, 2004; Dibblee, 1971; Sims, 1990; Page et al., 1998; Thayer and Arrowsmith, 2005; M. Rymer, 2005, personal commun.) was used to develop a subsurface model that pre-

dicted the borehole would encounter Salinian granitic rocks on the southwestern side juxtaposed against a Franciscan complex northeast of a nearly vertical San Andreas fault (Hickman et al., 2004; McPhee et al., 2004). A vertical pilot hole drilled in 2002 went through a 1 km thick Cenozoic sedimentary section overlying Salinian granite, consistent with the geologic model. In 2004 and 2005, phases 1 and 2 of the main SAFOD hole were drilled, and at 1920 m measured depth (mmd-the distance measured along the borehole), the borehole encountered an abrupt change from Salinian granodiorite into arkosic sedimentary rocks where the borehole is deviated northeast (Bradbury et al., 2007). This section of arkose is present from 1920 mmd to 3157 mmd along the track of the borehole. At 3157 mmd the borehole encountered fine-grained sandstones and mudstones, and at 3360 mmd it encountered rocks that are now identified as Cretaceous Great Vallev Group (Evans et al., 2005) based on their texture, composition, and the presence of Late Cretaceous Great Valley fossils (K. McDougall, 2006, written commun.). The rocks between

3157 and 3410 mmd appear to be a complex zone of low-seismic-velocity rocks that are the subject of other studies (Hickman et al., 2008).

The presence of arkosic sedimentary rocks on the southwestern side of the fault and the presence of Great Valley sedimentary rocks northeast of the fault, and the apparent juxtaposition of Salinian granitic rocks against the arkosic rocks, pose several geological and tectonic questions regarding fault zone structure and the tectonic evolution of the San Andreas fault in this area. These questions include the following: What is the origin of the arkosic sedimentary rocks-are they a part of the Salinian block? Have these rocks been transported a long distance along older strands of the San Andreas fault? The offset of the Salinian block is distributed over several different parallel strike-slip fault systems (Graham, 1978; Dickinson and Butler, 1998; Whidden et al., 1998; Dickinson et al., 2005), which accounts for the ~500 km offset from the Sierra Nevada plutonic complex. In the vicinity of the SAFOD site the Buzzard Canyon fault is subparallel to the San Andreas fault, having an unknown amount of slip

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(Rymer et al., 2003; Thayer and Arrowsmith, 2005). The Buzzard Canyon fault exposed at the surface has been correlated to the fault that separates the granodiorite from the arkosic rocks in the SAFOD borehole (Bradbury et al., 2007). Arrowsmith (2007) suggests that several faults lie southwest of the San Andreas fault, and these faults may have accommodated a significant amount of the total slip across the San Andreas fault plate boundary in central California.

This paper provides the first detailed lithologic characterization of the arkosic rocks as a first step toward understanding their geologic history and answering the questions posed above. The composition of the arkosic rocks is evaluated to interpret provenance, depositional environment, and diagenetic history. The observations of composition are then used to identify surface units that may be equivalent to the SAFOD arkose section. These possible correlations constrain the geometry and evolution of the San Andreas fault in the area of the SAFOD site.

Methods

We use five data sets to characterize and interpret the arkosic sedimentary rocks: drill cuttings, spot and sidewall core, borehole geophysical logs, electrical image logs, and zircon fission-track analyses. Drill cuttings are silt- and sand-sized rock fragments created by rotary drill bit action on the rock at the bottom of the hole that circulate to the surface in the drilling mud, where they emerge as a mix of engineered drilling mud and rock fragments. Cuttings composition was examined as a function of depth along the borehole to identify major changes in wall rock composition. The spot cores range from centimeters to meters long, are 10-15 cm in diameter, and were collected using a rotary coring tool bit at the end of the drilling string. Sidewall samples are 5-8 cm long, 2 cm diameter cores that were collected with a percussive sidewall core tool that shoots a hollow bullet-style core tube laterally into the borehole wall. Borehole geophysical logs measure physical properties including velocity, density, and porosity. Resistivity-based image logs reveal the nature of lithology, bedding, faults, and fractures by measuring the resistivity of the borehole wall. Highquality data enable us to determine the bedding orientation and character, formation thickness, sedimentary structures, and fault, fracture, or vein orientations and character, and general lithologic characteristics such as grain size, shape, and sorting (Thompson, 2000). Dynamically normalized electrical image logs were collected in the arkosic section from 1920 mmd to 3050 mmd with the Schlumberger Formation Microresistivity Sonde (FMS) tool (Ekstrom



et al., 1986). The Geomechanics International (GMI) ImagerTM software was used to examine the electrical image logs and to plot bedding and fracture orientations.

Drill cuttings provide a nearly continuous sampling of the rocks encountered in drilling. Care must be taken when using cuttings to infer lithology or structure in the borehole. Contamination can occur as drilling fluids pick up and transport cuttings. This can be especially problematic in the deviated portion of the hole, where a bed of cuttings may accumulate in the out-of-gauge sections of the hole. The stability of the SAFOD main hole varied through the deviated portion of the hole; breakouts and caving were common, as seen in the caliper log (Fig. 2). These problems with borehole integrity may cause cuttings from higher in the hole to fall and mix with the cuttings lower in the hole. At the drill site, cuttings were gently washed with water through small-mesh sieves to eliminate coatings of drilling mud. Some of the clay-sized grains from the cuttings may have been washed away, possibly skewing the compositional analysis by an unquantifiable amount.

Within these limitations, compositional analysis of cuttings is effective in characterizing subsurface lithologic types (Winter et al., 2002), especially when used in conjunction with other methods (Solum et al., 2006; Bradbury et al., 2007). We examined cuttings and data collected in 2004 and 2005. We used optical microscopic methods to systematically quantify the mineralogy, deformation textures, and the degree and nature of alteration in the rocks. We used a riffle splitter to split an ~1 cm³ subsample of cuttings from every 15.3 mmd of the archived cuttings samples. Magnetic separation of the dry subsample removed shards of drill bit material. The magnetic material was examined in a binocular microscope, and magnetic rock fragments were integrated back into the sample to maintain the representative nature of the subsample. After magnetic separation, samples were lightly washed and decanted in distilled water to remove drilling mud additives such as walnut shells. These grains were used to make thin sections of grain mounts. A total of 83 thin sections were analyzed for this study. We used a modified Gazzi-Dickinson petrographic point-count method (Dickinson, 1970) to quantify the composition of the cuttings and core. The grain classification was modified to account for the limitations of the sampling procedures and the nature of cuttings. A grain may be classified both for its composition and for its texture, resulting in point counts that may sum to greater than 100%. Previous work on these rocks used the Gazzi-Dickinson method to count the bulk composition of the entire borehole, quantifying the ratio of quartz to feldspar to lithics, and dividing the lithic grains into several categories (Bradbury et al., 2007). We tailored this method and applied it to the arkosic section in order to deduce the diagenetic and deformational history as well as provenance of these rocks. For more detail regarding the standard compositional analyses of these rocks, see Bradbury et al. (2007). The raw data are presented in the GSA Data Repository (Appendix A).¹

We counted grains of quartz, unaltered feldspar, opaque minerals, and accessory detrital minerals such as muscovite, fuchsite (a chromiumbearing muscovite), amphiboles, and pyroxenes to quantify the composition of the cuttings. We observed and recorded diagenetic features that include cements or matrix (these are grouped as it is difficult to differentiate between cement and matrix in cuttings), secondary quartz overgrowth, vein fragments, calcite, clay minerals, zeolites, and iron oxides that can also be considered an alteration feature derived from the alteration of mafic minerals. Alteration and deformational features such as cataclasite, altered feldspar, and biotite replaced by chlorite were recorded. The only clay minerals we counted as diagenetic features are those that show textural evidence of being either matrix or cement. This division of clay minerals is different from that of Solum et al. (2006), who used X-ray diffraction methods to quantify clay minerals in the subsidiary fault zones and the country rock of the SAFOD main hole. Iron oxides include free hematite grains and fine-grained material that is red in reflected light and in plane-polarized and cross-polarized transmitted light. Altered feldspar grains fall into three categories. The most common is the sericitized and vacuolated phase of alteration. Within the scope of the cuttings petrography, we define the alteration product of the first category to be illitic material, a phrase Moore and Reynolds (1989) use to encompass illite, mixed-layer phases, and other minerals such as sericite. The second altered feldspar category includes feldspars that show evidence of being altered directly to muscovite. In some cases the alteration products are coarse-grained clays or mica. The third category of alteration consists of feldspars that have been replaced almost completely by calcite; the grains still display feldspar twinning but with characteristic calcite birefringence. Damage characteristics are confined to cataclasites in the arkosic rocks and are discussed in a previous paper (Bradbury et al., 2007).

Twelve meters of nonoriented 10.16 cm diameter core was recovered from 3055 mmd to 3067 mmd (~2.8 km vertical depth) in the arkosic section (Fig. 3). Two 1.9 cm diameter, 3 cm long percussive sidewall cores were collected at 3084.6 mmd and 3121.2 mmd in the arkosic section. Fourteen petrographic thin sections were prepared from representative intervals in the spot core, and two thin sections were taken from the sidewall cores. Using thin sections we also evaluated evidence for crosscutting relationships and diagenetic features such as cementation, compaction structures, and mineral authigenesis.

A comprehensive suite of borehole-based, industry-standard geophysical logs was collected at the SAFOD site during all phases of drilling (see http://www.icdp-online.org/ contenido/icdp/front_content.php?idcat=712). The primary logs we used for this study are P-wave velocities (V_p) derived from the sonic monopole velocity log, dipole S-wave velocity (V), resistivity, neutron porosity, density, caliper, gamma ray, and spectral gamma ray (Fig. 2). These logs were used to constrain the composition of the rocks, to determine bedding orientations and the orientation of fractures, and to evaluate regions where alteration products may be present. Raw data for the image log for unit thicknesses, bedding orientations, and fracture orientations and density are in the GSA Data Repository (Appendices B-D). A Hostile Environment Gamma Ray Neutron Sonde (HNGS) tool resolves the gamma ray signature into potassium, uranium, and thorium concentrations. These data are used to determine which elements have the dominant influence in the overall gamma ray signature.

Zircon fission-track analyses were performed on six samples from depths of 3121-3375 mmd using the method outlined in Bernet and Garver (2005). Zircons were separated from the arkosic sediment cuttings and analyzed for their fission-track dates. These dates provide some constraints on the age of sediment deposition. Four samples are from the coarsegrained sandstones and pebble conglomerates west of the San Andreas fault zone, and two are from fine-grained rocks in the region termed the "low-velocity zone" (Hickman et al., 2008) within the fault zone. Fifteen zircon grains per sample were dated. The annealing temperature of zircon is ~240 °C (Hurford and Carter, 1991), and in the case of sedimentary rocks, we do not date the time at which the sedimentary rocks cooled past 240 °C but rather when the source rock cooled through the annealing temperature, and as such these data are related to the provenance of the strata and not the thermal history of this part of the SAFOD hole.

¹GSA Data Repository item 2009160, Appendices A–D, is available at www.geosociety.org/pubs/ ft2009.htm, or on request from editing@geosociety. org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.





RESULTS

Three main lithologic units have been identified in our analysis of the arkosic section. These units are subdivided into 11 structural domains (Fig. 2) based on bedding orientations determined from the analysis of the electrical image log data. The three main lithologic zones are referred to as (1) the "upper arkose," which extends from 1920 to 2530 mmd, (2) the "clayrich zone" from 2530 to 2680 mmd, and (3) the "lower arkose" from 2680 to 3157 mmd. The lithology and structure of each of these zones is provided below.

Upper Arkose

MHP1-B11, as in "main hole phase 1 box 11". Here the stars

form

the

is of t

for labeling samples

sections in order to capture interesting features of the sample). The nomenclature used

are labeled with a condensed form of the sample number, i.e., B11

iron oxide-stained sandstone. Red stars indicate where a sample was made into a thin section for our study (the samples in boxes 12, 14, 17, 20, and 22 were made into multiple thin

The upper arkose was encountered between 1920 and 2530 mmd in the borehole. Its porosity ranges from 0.01 to 0.44, with an average of 0.10, or 10%. The density is 2.13-2.72 g/cm³ (average of 2.56 g/cm³), and values of V_p range from 3.2 to 5.76 km/s, with an average of 4.57 km/s (Table 1). Sonic velocities generally increase with depth, although several low-velocity zones were encountered through the middle portions of the upper arkose.

Point-count analysis reveals that the rocks of the upper arkose are quartz and feldspar rich and contain 1%-10% clay-sized minerals as cement or matrix (Fig. 4). The layer silicate is typically chlorite or kaolinite. The seemingly anomalous gamma ray signatures averaging 129.08 API are typically associated with fine-grained rocks; however, the arkosic nature of the rocks makes the base level of the gamma ray log signature inherently higher. The gamma ray signature in the upper arkose is reasonably consistent through the section, with shallow peaks and troughs. This gamma ray pattern is interpreted to reflect relative homogeneity of the upper arkose. Quartz grains are generally undeformed aside from brittle fracturing, some of which is interpreted to have occurred as a result of drilling (Fig. 5A). Undulatory extinction and other plastic deformation of the quartz crystals are rarely observed in cuttings. Discrete quartz grains are the largest component of the unit, ranging from 45% to 60% (Fig. 4). Feldspar concentrations are higher in the upper arkose than in the other zones, constituting 4%–10%of the sample, showing approximately equal proportions of plagioclase to K-feldspar. The K-feldspar component is primarily microcline that contains classic tartan twinning. Orthoclase is present in small amounts.

The amount of iron oxide cements and staining ranges from 5% to 30% (Figs. 4 and 5). Some iron oxides occur as fracture fill or

TABLE 1. RANGE AND MEAN VALUES FOR THE WIRELINE LOG DATA FROM THE ARKOSIC ROCKS

AT SAFOD										
Porosity	Density	Velocity	Gamma ray							
(ratio)	(g/cm³)	(km/s)	(API)							
0.01-0.44	2.13-2.72	3.20-5.76	77.73-258.45							
0.10	2.56	4.57	129.08							
0.02-0.46	2.05-2.70	2.69-6.08	73.45-266.56							
0.19	2.52	4.25	152.54							
0.01-0.44	1.95-2.79	3.66-6.40	72.49-259.63							
0.08	2.53	5.04	112.48							
	Porosity (ratio) 0.01–0.44 0.10 0.02–0.46 0.19 0.01–0.44 0.08	Porosity Density (ratio) (g/cm ³) 0.01-0.44 2.13-2.72 0.10 2.56 0.02-0.46 2.05-2.70 0.19 2.52 0.01-0.44 1.95-2.79 0.08 2.53	Porosity Density Velocity (ratio) (g/cm ³) (km/s) 0.01-0.44 2.13-2.72 3.20-5.76 0.10 2.56 4.57 0.02-0.46 2.05-2.70 2.69-6.08 0.19 2.52 4.25 0.01-0.44 1.95-2.79 3.66-6.40 0.08 2.53 5.04							

Note: Values for the four wireline log data sets discussed in the text. The ranges of values for the data are given, and the mean value is in bold. Velocity is the P-wave velocity. SAFOD—San Andreas Fault Observatory at Depth; API—Standard unit of radioactivity defined by the American Petroleum Institute.



Figure 4. Composition of arkosic section derived from petrographic point counts, expressed in modal percentages. Graph is divided into the three different lithologic units: upper arkose, clay-rich zone, and lower arkose.

grain coatings, but the majority of iron oxide present forms cements and matrix of the grains (Fig. 6). Detrital micas such as muscovite, fuchsite, and biotite and Fe-Mg-bearing minerals are never present in an amount more than 1% of the sample (Fig. 7). Rock fragments other than granitic clasts are rarely observed. Altered feldspars make up 12%–20% of the sample (Fig. 8). Feldspar alteration ranges from slight with small amounts of illite to high where the feldspar is almost indistinguishable. The majority of altered feldspars contain sericite and clay minerals.

Throughout the upper arkose, the wireline logs and cuttings data suggest that there is little variation in composition. One exception to the homogeneity is in the region of 2022–2045 mmd where the V_p drops to a range of 3.20–4.6 km/s and porosity increases to 18%. This zone provides an excellent example of how cuttings microscopy can be combined with wireline logs to more fully characterize

the rocks. The two cuttings thin sections evaluated here (2026.92 and 2041.4 mmd) show a marked increase in iron oxide-rich grains (17%-24% of the sample) from the samples above and below. Only 4.00%-8.00% of the grains in the samples from this depth range contain cataclasite, less than most of the other upper arkose samples. We interpret this zone to be a high-porosity, high-permeability zone that acted as a conduit for oxidizing fluids and that exhibits little evidence for faulting.

We divide the upper arkosic section into five structural blocks. Each block has distinct sedimentary and structural characteristics as revealed in their wireline log responses (Table 2). We calculate the sedimentary thickness of each package using simple trigonometry:

$$x = y (\cos \phi), \tag{1}$$

where x is the true thickness, y is the apparent thickness, and ϕ is the angle between the trend

and plunge of the borehole and the pole to bedding of the block. While there were minor variations in the bearing of the borehole, these were too small to significantly alter the true thickness result. We used an average bearing of 35° toward 045° for the borehole orientation in our calculations. An average pole to bedding was determined using the statistical methods of a stereonet program. A complete catalogue of stereograms and calculations for each block can be found in Table 3.

Block 1 is composed of fine- to coarsegrained, poorly bedded sandstone. Conductive and resistive spots likely represent different clast lithologies in the coarse sandstone, leading to a speckled or mottled appearance. The rocks are highly fractured in some portions. We define a fracture density of >15 fractures per 10 m drill distance to be highly fractured, 5-15 fractures per 10 m to be moderately fractured, and 0-5 fractures per 10 m to be slightly fractured. Three different bedding orientations with dip magnitudes that range from shallow to steep occur over a 10 m distance. If these trends were observed over a larger area, it could be interpreted to be a zone of postlithification tectonic folding. However, we interpret it as a soft-sediment slump fold.

In block 2, the rocks are well-bedded conglomeratic sandstone that dips 0° and 30° to the northwest, striking south to southwest. Assuming the beds are upright and nearly flatlying, we calculate a true thickness for block 2 of 44.9 m (Table 3). With little bedding observed in block 1, the boundary between the two blocks is based on a change in rock character from massive pebble conglomerate in block 1 to distinctly bedded sandstone at 2145 mmd.

The interface between blocks 2 and 3 is marked by an abrupt dip change from shallow northwest-dipping beds to variably southwestdipping beds (Fig. 9). Block 3 has a stratigraphic thickness of 20.1 m and consists of fine-grained sandstone and siltstone beds that dip 30°-90° southwest. Block 4 extends from 2250 to 2290 mmd, with a thickness of 18.8 m, and lithologically is nearly identical to block 2. Like block 2, the bedding in block 4 is nearly horizontal to shallowly dipping to the northwest. Bedding in block 3 is coherent and exhibits clear bedding trends throughout. The transitions from block 2 to block 3 and from block 3 to block 4 are abrupt. No diagnostic features of discrete fault planes were observed in the image logs. Block 5 has a true thickness of 72.6 m and consists of coarse-grained, speckled, sandstonebearing zones of laminated bedding dipping 60° to 90° to the northeast. Without considering the thickness of block 1, the total measured thickness of the upper arkose is 156.4 m. If



Figure 5. Examples of features commonly observed in cuttings. Photomicrographs are all taken with cross-polarized light except photo D, which is taken with plane-polarized light. Photos B, D, and E taken with a blue filter. A: Conchoidally fractured quartz grains. Fractured texture is drillinginduced. B: Clay-rich grain from the lower arkose, with several compositions of clay mineral present in the grain. Greenish color is due to the presence of fine-grained chlorite. C: Fuchsite in cross-polarized light. Interference colors are higher-order than in chlorite. D: The same fuchsite grain in planepolarized light. Notice distinct green color. E: Plastically deformed quartz grain. F: Devitrified volcanic grain from the lower arkose. Photo light levels have been altered digitally in order to see features in the grain. Petrographically, volcanic grains are typically very dark.

block 1 is similarly oriented to block 2, the unit would be a fining-downward sequence, and the thickness of block 1 would be 134.78 m. Adding the total maximum stratigraphic thickness, the upper arkose is 291 m thick.

The Clay-Rich Zone

A clay-rich zone containing as much as 60% clay minerals and clay-sized particles and registering high gamma ray signature, high porosity log values, and low seismic velocities is observed from 2530 to 2680 mmd (with the exception of a small block from 2565 to 2595 mmd). Clays cannot be fully characterized optically due to the small grain size. The clay-rich zone was initially identified at the SAFOD site by the dramatic increase in gamma ray and porosity log signatures and a decrease in V_p and V_s (Fig. 2) (Boness and Zoback, 2006). The lowest velocity in the clay-rich zone is 2.69 km/s with an average velocity of 4.00-4.27 km/s (Table 1), considerably lower than in the upper and lower arkose units. The average neutron porosity is 0.18-0.27, higher than the average porosities of 0.10 and 0.08 in the upper and lower arkose units, respectively. The clay minerals vary in composition from illite to smectite to mixed-layer illite-smectite (Fig. 5B), and from chlorite to muscovite (see Solum et al., 2006, for details). Calcite grains and grains stained by Fe oxides are more abundant in the clay-rich zone (8.26%) than in the lower arkose but less than in the upper arkose (Fig. 8). The chromium-bearing muscovite mineral fuchsite is present in the clay-rich zone and the lower arkose (Figs. 5 and 7).

Between 2565 and 2595 mmd the borehole encountered 27.33% clay, 37.66% quartz, and 10% feldspar in the clay-rich zone, similar to the composition of the lower arkose (Fig. 8). The increase in quartz and feldspar grains in this zone indicates an increase in grain size from the rest of the clay-rich zone, and wireline logs also indicate coarser-grained sediment in this interval (Table 2). Sonic velocities increase to 4.48 km/s, porosity decreases to 0.12, and there is a corresponding increase in density from 2.48 to 2.88 g/cm³. This thin interval represents a different lithology than the rest of the clay-rich interval and is not considered in the physical property calculations of the rest of the clay-rich lithological unit.

The borehole in the clay-rich zone was often elliptical, making the caliper in this unit rarely in gauge. The short axis of the caliper stayed approximately uniform at 25-30 cm diameter, but the long axis often exceeded the 50.8 cm maximum reach of the caliper tool (Fig. 2). The loss of borehole integrity results in compromised image logs throughout much of the entire clay-rich zone. Thus few fractures and no bedding orientations were recorded in the clay-rich portions of this zone. Bedding observed in block 7 strikes southeast and dips shallowly to the southwest from 2565 mmd to 2595 mmd, with a true thickness of 28.7 m (Table 3). Gamma ray and porosity values decreased while density and velocity increased compared to the rest of the clay-rich zone (Fig. 2). Point counts show a marked decrease in the amount of clay-rich grains. These data indicate that block 7, which is significantly different from the rest of the clay-rich zone, is coarser grained than blocks 6 and 8.



Figure 6. Photomicrographs showing characteristic features from cuttings samples. Depths of the samples (meters) are noted at the lower right-hand corner of the photographs. All photographs were taken in cross-polarized light. Differences in color are due to different light levels. Scale bar applies to all photomicrographs. A: High-birefringence clay minerals fill space between quartz crystals. B: Altered plagioclase in center of photo shows alteration typical in the upper arkose. The grain is still easily recognizable as plagioclase with small areas of sericite formation. C: Grains displaying iron oxide-rich matrix/cement. The grain in the upper right of the photo shows deposition-related iron oxides (matrix), while the iron oxides in the grain in the lower left look postdepositional, either staining or an iron oxide-rich cement. D: Altered grain of feldspar to muscovite, with Fe oxide. E: Calcite within feldspar. F: Example of a cataclasite grain.



Figure 7. Minor compositional components that make up less than 10% of any given sample. If plotted against the other components of the system, these would look insignificant in scale; thus they are plotted separately as modal percentages. Graphs have been split into the three lithologic units: upper arkose, clay-rich zone, and lower arkose.



Figure 8. Abundance of altered and unaltered feldspars, cataclastically deformed feldspar, and cement abundances in the drilled section, expressed in modal percentages.

	Porosity (ratio)	Density	Velocity	Gamma ray			
Block 1	0.01_0.37	2 17_2 68	3 20-5 65	77 73_172 01			
DIOCK	0.01=0.37	2.17-2.00	4 53	121 80			
Block 2	0.02-0.34	2 26-2 67	3 45-5 68	82 61-154 38			
DIOCICE	0.02 0.04	2.20 2.07	1 /1 /18	125.05			
Block 3	0.02_0.29	2.0	3 53_5 66	84 02-163 40			
DIOCK 0	0.02-0.23	2.40-2.00	1 31	133.06			
Block 4	0.01-0.33	2 13-2 70	3 48-5 66	86 40-257 27			
DIOCK 4	0.01 0.00	2.10 2.70	4 61	135 51			
Block 5	0.01_0.44	2 25_2 72	3 73-5 76	79 54-258 45			
DIOCK 0	0.01 0.44	2.20 2.72	4 96	135 70			
Block 6	0.02_0.46	2.57	2 60_7 08	77 15_255 33			
DIOCK O	0.02-0.40	2.05-2.05	2.03-7.00 / 00	183 /3			
Block 7	0.02.0 32	2.40 2 /1_2 70	2 80_5 03	73 /5_213 00			
DIOCK /	0.02-0.02	2.41-2.70	2.03-0.00 1 /18	197 /1			
Block 8	0.02_0.42	2.00	2 80_5 50	80 51_266 56			
DIUCK O	0.02-0.42	2.19-2.00	2.09-0.09	1/9 73			
Block 0	0.10	2.33	267 6 02	72 05 250 62			
DIUCK 9	0.01-0.44	2.03-2.77	5.07-0.03	11/69			
Plack 10	0.09	2.33	2.03	70.40.004.50			
DIUCK IU	0.02-0.35	1.90-2.79	5.00-0.40	12.49-224.50			
	0.08	2.52	5.07	109.55			

Note: Wireline log ranges and average values for each individual structural block (see Fig. 9 for index of blocks). Upper values in each box are the range of values measured in that block; the lower bold value is the arithmetic mean value for the block. Wireline log measurements are collected every 15 cm.

Lower Arkose

The lower arkose, from 2680 to 3157 mmd, is characterized by a variable wireline log signature that exhibits a wider range of values for gamma ray, velocity, and density than the upper arkose (Table 1; Fig. 2). Porosity exhibits a similar range in values in the lower arkose as in the upper arkose. However, the lower arkose exhibits a larger number of excursions, likely caused by the presence of differing lithologies (Fig. 2; see also Boness and Zoback, 2006). The porosity averages 0.08, which is generally less than the porosity calculated for the upper arkose. The average density of the lower arkose is 2.53 g/cm³. The average gamma ray value is 112.48 API, which is less than the upper arkose, and the gamma ray curve is more irregular than the homogeneous curve of the upper arkose.

The lower arkose is generally finer grained than the upper arkose. Clay-sized particles and minerals compose on average 15.5% of the samples. Clay minerals include illite and smectite and almost no kaolinite. There are similar amounts of chlorite present in the lower arkose as in the upper arkose, although altered biotite is much less common in the lower arkose.

Distinct compositional differences exist between the upper and lower arkoses. Quartz is less common in the lower arkose than the upper arkosic section, ranging from 33% to 60% of the total grains, averaging 48.12% (Fig. 4). The majority of quartz in the lower arkose is plastically deformed (Fig. 5E), and in places full subgrains have developed in the crystal structure.

There are fewer feldspar grains overall (both altered and unaltered) in the lower arkose than the upper arkose, although the ratio of plagioclase to K-feldspar remains the same (Fig. 8). The upper arkose contains more altered feldspar grains, but the degree of alteration in the lower arkose is generally greater. Feldspar grains have been altered to muscovite in the lower arkose. There are some instances of nearly complete replacement by muscovite (Fig. 6D).

Iron oxide–rich grains have concentrations that range from 2% to 15%, averaging 5% of the sample (Figs. 4 and 6). The characteristics of the iron oxides are similar to those in the upper arkose and clay-rich zone, in some cases appearing dark red in plane- and crosspolarized light, and in other sites opaque under both forms of light but red in reflected light. Iron oxide is present as fracture fill, grain coatings, and fine-grained matrix. Porphyritic volcanic clasts that contain very fine-grained, often devitrified groundmass (Fig. 5F) are present in every thin section examined in the lower arkose, constituting an average of 1.8% of the sample. Fuchsite concentrations range from 0.1% to 2.0% of the sample in the lower arkose (Fig. 7). Fuchsite occurs as small grains within a larger fine-grained, clay-rich grain and rarely as discrete grains, in contrast to the upper arkose.

The lower arkose contains a larger amount of laumontite than the upper arkose. Solum et al. (2006) also detected relatively large amounts of laumontite through X-ray diffraction (XRD) analysis in the lower arkose with little to no laumontite in the upper arkose. This evidence led them to define two distinct arkosic units similar to our designations. The geophysical signature of the rocks (Boness and Zoback, 2006; Bradbury et al., 2007) likewise indicates that the two arkosic units are lithologically distinct.

Image log data, where quality is good, provide further constraints on lithofacies and bedding orientation (Figs. 10 and 11). We divide the lower arkose into three blocks (Fig. 9) on the basis of the image log data. Block 9 has a true thickness of 158.9 m (Table 3), dips shallowly to the south and southwest, and consists of homogeneous fine-grained sandstones cut by fractures parallel or perpendicular to bedding. Block 10 is lithologically similar to block 9, consisting of well-bedded, laminated, and locally fine-grained sandstone and siltstones. An abrupt change in dip magnitude and direction is observed at 2880 mmd. Bedding dips steeply and uniformly to the northeast to a depth of 3010 mmd. (The borehole extended to 3050 mmd, but due to the tool configuration, image logs were not collected to the bottom of the borehole.) The apparent thickness of block 10 is 170 m if we assume that the block continues to the shear zone encountered in the phase 1 spot core. The calculated thickness is 65.1 m (Table 3). Representative image logs from block 10, along with the corresponding composition (Fig. 12), show the bedding to be 5-10 cm thick. Block 11 is the last block in the sequence drilled during phase 2 drilling, and image logs are not available.

Block 11 has an apparent thickness of 107 mmd. The extent of block 11 ends at the abrupt lithology change seen at 3157 mmd, where the cuttings character changes from arkosic to very fine-grained mudstones and siltstones (Evans et al., 2005; Hickman et al., 2005; Bradbury et al., 2007). No bedding or fracture data were available for this section of the hole. The thicknesses of blocks 9 and 10 give a minimum thickness of block 11 to be the maximum possible thickness of that block. The total maximum thickness of the lower arkose is 331 m.

Fractures were identified on the basis of their resistivity character and disruption of bedding (Figs. 10 and 11). We observe four zones



Note: Thickness calculations for blocks 2–10 from bedding orientation data derived from electrical image logs. Blocks 1, 6, and 8 were excluded due to a lack of clear bedding data. The value α is the angle between bedding and borehole bearing; *y* is the apparent thickness. Circles indicate a95 values for means.

of relatively high fracture density (>10 fractures per 10 m) in the upper arkosic rocks. These are found at 1920–1980, 2020–2085, 2190–2215, and 2275–2530 mmd. Below the clay-rich zone, a fracture zone occurs from 2515 to 2725 mmd, and much of the lower arkosic section is highly

fractured (Fig. 2). Several of these zones of increased fracture density are associated with boundaries between structural blocks, and the uppermost region is associated with the fault that juxtaposes the Salinian rocks against the arkosic rocks. The increase in fracture density



Figure 9. Southwest to northeast cross section of the entire arkosic section in the SAFOD borehole, with individual structural blocks labeled. Blocks 1–5 are the upper arkose, blocks 6–8 are the clay-rich zone, and blocks 9–11 are the lower arkose. Depths are in measured dimension, along the deviation of the borehole, in meters. Faults are noted but are not necessarily oriented correctly. Bold faults are projected to predicted surface fault equivalents. Stereonets for each block are equal-area nets with bedding plotted as great circles, black point is the trend/plunge of the borehole. Interpretation of the lowermost section is modified on the basis of core retrieved in 2007. SAF—San Andreas fault.

around the clay-rich zone may suggest that this region is a fault zone, as suggested by Boness and Zoback (2006).

Core Analysis

The spot core (Fig. 3) collected during phase 1 drilling intersected a section of the coarse-grained sandstone and conglomerate and a small clay-rich shear zone at 3067 mmd. Other studies have examined the composition and frictional properties of this shear zone (Tembe et al., 2005; Schleicher et al., 2006; Solum et al., 2006). The sedimentary rocks in the spot core are thoroughly damaged and deformed (Almeida et al., 2005) (Figs. 3 and 12), perhaps as a result of the faulting that has occurred in the cored shear zone. The core samples a sequence of quartzo-feldspathic, indurated, and coarse-grained arkose and conglomerate. Over the 12 m length of core, grain

sizes grade abruptly from a coarse pebble/ cobble conglomerate to coarse sandstone, and from fine sandstone to siltstone (Fig. 3). The pebbles and cobbles of the conglomerate are granitic and volcanic, consisting of significantly more granite than volcanic clasts.

Porphyritic volcanic clasts are similar to those observed in the lower arkose cuttings. They contain large plagioclase crystals in a finegrained devitrified groundmass (Fig. 12C). In some cases, phenocrysts are oriented in a primary flow texture. Granitic clasts commonly are altered (Fig. 12D) and composed of quartz, feldspar, amphiboles, and chloritized biotite. The majority of laumontite observed in the core occurs in granitic clasts as veins or cement between grains (Fig. 12E).

Macroscopically and microscopically the core is stained by iron oxides (Fig. 12F). The arkose is highly damaged, riddled with micro-fractures, and shows little evidence of healed

fractures (Fig. 12G). Grains are locally broken, and evidence for grain size reduction is common (Fig. 12B). Evidence for cementation is not commonly observed. Rare veins are filled with laumontite, calcite (Fig. 12G), secondary quartz, or muscovite (Fig. 12H). Feldspar grains are generally unaltered through the core. The lack of significant amounts of laumontite, calcite, and secondary quartz corresponds to what has been observed in the cuttings. Authigenic muscovite was observed as vein material in several locations in the core samples (Fig. 12H). These veins, no more than 0.10 mm wide, cut across several grains, which is evidence that they are postdepositional features.

The fine-grained portions of the spot core are similar to grains counted as clay-rich in the cuttings (Fig. 12I). The fine-grained rocks are composed of texturally immature quartz and feldspar in a matrix of high-birefringence clay minerals. In most areas of the core, clay



Figure 10. Examples of different lithologies or image log "facies" for the upper arkose. Each example is displayed in a 1:1 aspect ratio but at different scales to highlight features. The color scale represents the electrical resistivity of the rock. The lighter shading represents higher resistivities. The four strips are the images resulting from the four pads that are arranged on the tool 90° apart. The sinusoidal lines in the images are examples of lithologic boundaries or fractures picked from the image. A: Conglomeratic interval in the upper arkose. Notice the abundance of resistive clasts, likely granitic in composition. B: Chaotic interval in the upper arkose with good image clarity but no discernable bedding or fractures. This interval is interpreted to be a slump fold or similar soft-sediment deformation due to the lack of brittle-deformation features that would be present in postlithification deformation. C: An example of poor image quality in the clay-rich zone. Image may represent a brecciated or cataclastic zone, but the clast/matrix features are more likely a result of blurring from poor data. The majority of the clay-rich zone image quality is good; granite is highly fractured.

minerals are a depositional feature rather than a secondary cementation. Small angular mica grains consisting of muscovite and fuchsite are similar to those seen in the finer-grained cuttings and those observed in the spot core samples. The clay minerals do not exhibit any preferred orientation in the core samples. No microfossils were observed in either cuttings or core, even in the finest-grained intervals.

Diagenetic Textures

The thin-section petrography of the core and cuttings samples indicates several types of cement and alteration products that may have been caused by diagenesis of the sedimentary sequence. Calcite, laumontite, secondary quartz, iron oxide, and clay cements were all observed to some degree in the cuttings as well as the core samples. Iron oxide cement is most commonly observed as grain coatings and as interstitial cement (Figs. 6C and 12F). The iron oxide cements were most likely produced from the oxidation of biotite and amphibole coming from a granitic source (Dapples, 1979). This reaction is common in arkosic sandstones because biotite is rarely stable enough for the reaction products to remain long after deposition (i.e., Scholle, 1979; Carozzi, 1993).

Calcite and silica cements are rare. The majority of calcite grains are either discrete calcite crystals or feldspar altering to calcite. Very few calcite veins or grains cemented with calcite were encountered. The spot core also showed very little evidence of these cementing mechanisms as a pervasive trend. Most calcite veins observed in the spot core thin sections occur near cataclasite zones. Quartz overgrowths are rare with quartz veins ranging from 0.21% to 0.44% of the sample counted in the cuttings (Fig. 8). The compaction features observed in the quartz and feldspar grains are not as well developed

as stylolites, but there are instances of convexconcave contacts and quartz indentor grains, similar to those features seen in deeply buried clastic sedimentary rocks (i.e., Liu, 2002).

The ubiquitous alteration products in these rocks are illite, muscovite, and laumontite. Illite appears to replace K-feldspar in the upper arkose, whereas muscovite is the more common alteration phase in the lower arkose. Other workers have examined the morphology of SAFOD clay minerals using SEM and TEM methods and have found that mixed-layer illite-smectite forms as films and fibers along shear surfaces along with fibrous to columnar laumontite forming in the pores of rock chips collected during coring (Solum et al., 2006; Schleicher et al., 2006).

If the illite in the SAFOD arkoses formed at 70–150 °C (Huang, 1992; Worden and Morad, 2003), then these rocks may have been buried at depths slightly greater than those at which they were encountered. The measured borehole



Figure 11. A composite image from a 2 m interval in the lower arkose. Here the rocks are laminated fine-grained sandstone/siltstones. Solid purple lines on image log are interpreted fractures, while dashed purple lines are interpreted bedding planes. Image quality in this interval is some of the best in the entire arkosic interval.

temperatures yield a modern geothermal gradient of 38 °C/km (C. Williams, 2006, written commun.), within the range of or slightly higher than the temperature gradient for this area (Sass et al., 1997; Page et al., 1998; Blythe et al., 2004). Using the measured geothermal gradient, 70 °C to 150 °C corresponds to depths of 1.3 km to 3.4 km. This overlaps with the current depth of the arkose units but may be as much as 0.8 km deeper than the deepest present extent of the arkose.

Zircon Fission-Track Analysis

There are no direct measures of the age of these rocks available from either micropaleontology or radiometric analyses. Zircon fission-

track analysis was used on detrital zircons to constrain the thermal history of the arkosic rocks (Wagner and Van der Haute, 1992; Bernet and Garver, 2005), and we combine the fission-track analyses with other tectonic studies of the area to determine the cooling history of the source rocks to the SAFOD arkoses and to constrain the age of deposition (Figs. 9 and 13). Uranium concentrations in the samples range from 50 to 450 ppm U, with a mean between 200 and 250 ppm (Table 4), which is typical for detrital suites (see Garver and Kamp, 2002). Four of the samples come from depths of 3122-3160 mmd, at the base of the arkosic section in block 11 and possibly slightly below or within a fault (Bradbury et al., 2007) (Figs. 9 and 13). Two samples come from depths of 3338 and 3375 mmd, within the region interpreted to be the fault zone (Hickman et al., 2008).

Most of the zircon grains have statistically similar Late Cretaceous to earliest Paleocene annealing ages of 70–62 Ma, passing the chisquare test evaluating the likelihood that the zircon ages cluster (Table 4). Several samples show some age dispersion, but overall the data are consistent with a common thermal history for all sampled grains. This homogeneity implies that the dated zircons from the arkoses are likely derived from a single source terrain or from source regions with a homogeneous thermal history. The grains are mainly clear and euhedral: The suites of zircons from these units lack rounded, abraded grains or grains



1 mm

Figure 12. Photomicrographs of phase 1 spot core and phase 2 sidewall cores. All photos except photo B are taken in cross-polarized light; photo B is taken in plane-polarized light. Scale bar applies to all photomicrographs except E and H. Depths are based on the distance from the lower end of the core to the sample collected. A: Fractured or brittlely damaged quartz grain. B: Quartz grain broken apart with individual slivers remaining in place, the beginning of grain size reduction. C: Fine-grained, devitrified volcanic clast takes up left half of photo. Opaque minerals at center of photo and edge of volcanic clast are not identifiable in reflected light. D: Altered granitic clast with amphibole beginning to oxidize. From sidewall core 69. E: Veins filled with laumontite. F: Iron oxide cementation in sidewall core 71. G: Localized calcite cementation in lower left-hand corner of photo. Grains are extremely fractured in this portion of the core. H: Postdepositional muscovite vein formation in quartz grain. I: Siltstone portion of spot core; grains are texturally immature with little to no mineral alignment. Closely resembles fine-grained cuttings.



Figure 13. Location of the six zircon fissiontrack samples in relation to the inferred subsurface geology and location of earthquakes below the hole. Four of the samples come from the lower arkose, and two come from within the low-velocity zone. This is an enlarged view of the lower part of the borehole, and some of this interpretation is a result of coring in 2007. This view encompasses the lower portion of block 11. The V_p data are plotted along the borehole, and the cross indicates the ±50 m uncertainty associated with the earthquake locations (C. Thurber, 2009, personal commun.). Two of the fault zones interpreted to be at the edge of or within the low-velocity zone are shown. with significant radiation damage. We observe no significant variation in zircon fission-track age as a function of depth, and this, along with the narrow range of colors and grain shapes, suggests that the zircons were derived from the same thermally homogeneous source, and it was likely that the source of the zircons was first-cycle detritus, otherwise rounding and pitting of grains would have been common.

The source rock of the arkose units cooled through the effective closure temperature of zircon (~240 °C) during the Late Cretaceous, between 64 and 70 Ma. The zircons do not show evidence of being reset after deposition, or buried to temperatures exceeding 200-240 °C (see Garver et al., 2005). This inference is supported by low thermal maturation of organic detritus from this interval that has %R values of 0.74-1.01. In the SAFOD hole, we predict that temperatures would equal or exceed the zircon annealing temperature of 240 °C at ~5.7 km depth. Assuming a constant geothermal gradient over time, the lack of evidence for thermal resetting of the grains implies that the arkosic rocks have not been buried to a depth greater than the present depth of 5.7 km, or 3.1 km more than zircon fission-track samples 37-61 and 37-62 (Table 4) since deposition.

The four fission-track ages from the lower arkose samples and the two ages from the lower fine-grained rocks show that the two groups have similar thermal histories. We are confident that the higher set of samples was derived from a relatively restricted part of the arkosic section, as the hole was cased to a depth of 3065 mmd at the end of phase 1 drilling in 2004. The lower two samples have consistent cooling ages and $%R_{o}$ values, pointing to a common thermal history for the samples. This indicates that the fault zone may consist of slivers of rocks from a range of sources, including the arkosic and clayrich rocks we ascribe to the Salinian terrain.

The Maastrichtian-Paleocene cooling ages of the zircons recovered from the four samples derived from the arkosic section serve as a maximum depositional age for the SAFOD arkoses. Based on the petrography, composition, and zircon fission-track analyses, it seems unlikely that the SAFOD arkosic rocks are part of the Great Valley Group. Vermeesch et al. (2006) report zircon fission-track ages of 93.3-106.5 Ma for Upper Cretaceous Great Valley samples from ~15 km east of the SAFOD site, indicating a very different thermal history for rocks northeast of the San Andreas fault. Degraaff-Surpless et al. (2002) report similar ages, and cite the work of Linn (1991) to indicate that Great Valley Group rocks northeast of SAFOD have depositional ages 10-15 million years older than the fission-track cooling ages that we report. A Late

TABLE 4. SUMMARY OF ZIRCON FISSION-TRACK DATA FOR SAFOD MAIN HOLE

Sample	Measured	Measured	Mineral	ρ _s	N _s	ρ _i	N	ρ _d	N _d	n	χ2	Age	-2σ	+2σ	U ± 2 se
	depth	depth		(cm²)		(cm²)		(cm²)				(Ma)	(Ma)	(Ma)	
	(ft)	(m)													
37-59	10,240	3121.2	Zircon	7.37×10^{6}	658	5.24×10^{6}	468	2.553 × 10⁵	1911	15	90.4	64.3	-4.2	4.5	252.7 ± 25.3
37-61	10,280	3133.3	Zircon	7.56×10^{6}	690	4.89×10^{6}	446	2.532 × 10⁵	1904	15	78.7	70.1	-4.6	4.9	237.7 ± 24.4
37-62	10,310	3142.5	Zircon	6.02×10^{6}	521	4.11 × 10 ⁶	356	2.522 × 10⁵	1901	15	91.3	66.1	-4.8	5.1	200.5 ± 22.8
37-63	10,370	3160.8	Zircon	7.18×10^{6}	564	5.01 × 10 ⁶	394	2.512 × 10⁵	1898	15	32.4	64.4	-4.5	4.8	245.5 ± 26.7
37-64	10,954	3338.8	Zircon	7.15 × 10 ^⁰	695	4.61 × 10 ⁶	448	2.501 × 10⁵	1894	15	17.8	69.5	-4.5	4.9	226.6 ± 23.4
37-65	11,074	3375.4	Zircon	6.30×10^{6}	512	4.42×10^{6}	359	2.491 × 10⁵	1891	15	27.2	63.6	-4.6	5.0	218.2 ± 24.9

Note: Depths of samples are given in feet and meters; ρ_a is the density (cm²) of spontaneous tracks; N_a is the number of spontaneous tracks counted; ρ_i is the density (cm²) of induced tracks; N_a is the number of spontaneous tracks counted; ρ_a is the density (cm²) of tracks on the fluence monitor (CN5); N_a is the number of tracks on the fluence monitor; n is the number of grains counted; χ_a is the chi-square probability (%); U is the uranium concentration in ppm, ±2 standard errors. Fission-track ages (±1 σ were determined using the Zeta method, and ages were calculated using the computer program and equations in Brandon (1996). All ages with $\chi_a > 5\%$ are reported as pooled ages. For zircon, a Zeta factor of 360.20 ± 8.04 (in a cm²/track ±1 standard error-main mode) is based on determinations from both the Fish Canyon Tuff and the Buluk Tuff zircon. Glass monitors (CN5 for zircon), placed at the top and bottom of the irradiation package, were used to determine the flux gradient. All samples were counted at 1250x using a dry 100x objective (10x oculars and 1.25x tube factor) on an Olympus BMAX 60 microscope fitted with an automated stage and a digitizing tablet.

Cretaceous exhumation rate of >2–3 mm/a has been calculated for the Salinian block (Kidder et al., 2003), the likely source terrain for the detrital zircon. Using this rate of exhumation, we estimate that the granitic body that supplied zircons in the SAFOD arkoses could have reached the surface 1.9–7 million years after passing through the zircon annealing temperature. Following this reasoning, the maximum depositional age for these rocks is latest Cretaceous (younger than 70 Ma) to Paleocene.

INTERPRETATION

We synthesize our data with other data from the SAFOD rocks, as well as other studies in the area, to interpret the depositional setting of the arkosic rocks, and to constrain the structure of the fault zone and offset history of the San Andreas fault at this site. We begin with a discussion of the origin of the sedimentary rocks. Next we discuss how these rocks fit into the structure of the fault zone, and in particular the tectonic setting of the arkosic sections relative to the San Andreas fault.

Structural Interpretation

We have identified three rock units in the section—the upper arkose, clay-rich zone, and lower arkose—which differ in framework composition, alteration, and deformational features. Interpretation of stratigraphic and age relationships between the three units is complicated by the likely presence of faults or folds in the arkosic section. With a total of ten possible faults identified, the entire arkosic section has been offset and deformed to such a degree that it may be impossible to precisely determine original depositional or stratigraphic relationships.

The data presented here, along with Boness and Zoback (2006), Solum et al. (2006), and Bradbury et al. (2007), indicate that the arkosic

section is bounded and cut by faults. The three main faults lie at 1920, 2560, and 3067 mmd. The highest fault juxtaposes the Salinian granitic rocks and the arkosic rocks; the middle fault juxtaposes the two arkosic units. The lower fault juxtaposes the arkosic section against a fine-grained sedimentary unit. In addition, we interpret the presence of as many as nine other faults or narrow fold hinge zones within the arkosic section. Several studies provide a variety of data that support a model that the clayrich region is a fault zone (Boness and Zoback, 2006; Solum et al., 2006; Bradbury et al., 2007). The clay-rich zone is a boundary between lithologically distinct units that are from different sources. The difference in composition between the upper and lower arkoses could be the result of juxtaposition of two units from different basins and different ages.

The uppermost fault contact between the Salinian granitic rocks and the arkosic section is interpreted to be the downdip continuation of the Buzzard Canyon fault and its associated damage zone. The lower fault encountered at the end of phase 2 drilling juxtaposes the arkosic section against sheared mudstone. These data indicate that the fault zone structure at depth is complex, and that the seismicity associated with the current San Andreas fault lies below and eastward of the lowest fault observed here (Hickman et al., 2008). Geophysical investigations of the site suggest that the active fault zone is narrow, and the region between what we infer to be the Buzzard Canyon fault and the San Andreas fault is a zone of high-V rocks (Thurber et al., 2004) overlain by low-velocity sedimentary rocks. Other workers suggest that the fault zone at this depth is relatively wide and marked by low-velocity or seismically imageable rocks associated with damage zones (Hole et al., 2001; Bleibenhaus et al., 2007; Catchings et al., 2007; Li and Malin, 2008), and that some of these faults extend to the near-surface

region (Catchings and Rymer, 2002). Based on the work presented here and in related papers (Bradbury et al., 2007; T.N. Jeppson, 2009, personal commun.), we infer that the faults within the section have relatively modest offsets and do not affect the overall velocity character of the section. Wireline- and image-log characteristics along with the lithologic analyses indicate that rocks on either side of these inferred faults are similar, and the boundaries therefore displace or fold a relatively uniform package of rocks within each main rock body.

Depositional Environments

We use the petrographic and compositional data to infer depositional environments. The presence of subangular to subrounded feldspar grains and the textural immaturity of the arkosic rocks indicate that they were deposited in a proximal or high-energy setting. We cannot determine whether the arkosic rocks were deposited in a marine or terrestrial setting. If they are marine sediments, they likely represent the most proximal portion of a marine fan sequence. Clasts in the arkoses are almost entirely granitic, including no more than 2% volcanic clasts in the lower arkose, which implies that the arkosic units were shed from a granitic highland that contained a minor source for volcanic clasts.

Based on the range of grain sizes, the somewhat regular bed spacing, the angularity of clasts observed in image logs and core, and the textural immaturity associated with unaltered feldspars, we interpret the arkoses to have been deposited in a subaerial or subaqueous fan setting weathered from a granitic source terrain. Overall, there are more sandstone and siltstone intervals than conglomerate in the arkosic section, indicating periods of low energy alternating with intervals of high-energy deposition. The alternation of the fine-grained sequences and the coarse-grained arkosic sandstones and



Figure 14. Three slip distributions for the San Andreas fault system in the vicinity of the SAFOD site. A sedimentary rock unit correlative to the SAFOD arkoses would be found in a different location depending on which hypothesis is correct. Gray unit represents the SAFOD arkoses and the equivalent sedimentary rocks. A: Slip on the San Andreas fault, with very small amounts of slip on Buzzard Canyon fault, results in roughly 300 km of slip, displacing the arkosic section such that arkosic rocks would lie northwest of SAFOD. B: Partitioning of slip on the Buzzard Canyon fault and San Andreas fault satisfies the total slip (see Fig. 14D) and results in arkosic rocks spread >30 km northwest of SAFOD. C: If most of the slip were on the Buzzard Canyon fault, arkosic rocks would be observed in the subsurface at the western edge of the Great Valley. Note that the star that shows the location of SAFOD shifts to show the relative location of the sediments, and is not shifted in an absolute sense. D: For reference, offset units along the San Andreas fault zone. Location of SAFOD drilling site marked by star. Eagle Rest Peak–Logan offset based on Ross (1970); Pinnacles–Neenach from Matthews (1976). Location of La Honda and San Joaquin Basins from Clarke and Nilsen (1973) and Graham et al. (1989). Map modified after Ingersoll (1988) and Irwin (1990). Dark ellipse near bottom of map represents the area that is ~315 km southeast of the SAFOD site on the opposite side of the San Andreas fault.

conglomerates may represent the alternating high- and low-energy portions of submarine flows (e.g., Falk and Dorsey, 1998; Clifton, 2007) in which coarse-grained sequences are deposited in relatively deep water. Chaotic intervals in the image logs may represent slump or slope failure deposits, both of which could be present in a number of environments, including a fluvial or marine fan setting.

Stratigraphic Correlations

How might these rocks correlate with rocks observed in the field or in drill holes in western California? The Late Cretaceous to early Eocene age estimate of these rocks combined with their petrography and physical properties suggests several likely correlative units. Late Cretaceous to Eocene siltstone to conglomerate units occur in small but widely distributed exposures throughout western California (Grove, 1993; Seiders and Cox, 1992; Burnham, 2009) (Fig. 14). Given the petrography and general age constraints, we suggest the rocks are latest Cretaceous to Paleocene–Eocene deposits on or associated with the Salinian block. This correlation may help constrain the evolution of the San Andreas fault in central California, because other correlation studies have successfully established amounts of offset on different strands of the San Andreas fault (Nilsen and Clarke, 1975; Nilsen, 1984; Graham, 1978; Graham et al., 1989).

The age and history of the Salinian block matches the interpreted thermal history of the source terrain for the SAFOD arkoses. The fission-track cooling ages of detrital zircons in the arkoses are younger than U/Pb geochronology that dates Salinian magmatism at between 130 and 70 Ma (Kistler and Champion, 2001; Barth et al., 2003; Kidder et al., 2003; Barbeau et al., 2005). The ⁴⁰Ar/³⁹Ar cooling ages of biotite of 76–75 Ma in the Salinas Valley, northwest of SAFOD, are consistent with the U/Pb ages of the Salinian block (Barth et al., 2003).

From ca. 80 to 65 Ma the Salinian block was rapidly exhumed from 25 km depth (Barbeau et al., 2005). The zircon fission-track ages represent when the zircons passed through the effective closing temperature. Our data and the data of others indicate that the Paleogene exposed a Salinian granitic source with 70–64 Ma cooling ages at the surface. The homogeneous zircon fission-track cooling ages of the SAFOD arkoses likely reflect their derivation from a granitic source with a homogeneous history, and rule out a more complex and lithologically heterogeneous source terrain.

Clay alteration reactions in the arkosic rocks limit the depth of burial. Illitization of K-feldspar occurs between 70 °C and 150 °C, which corresponds to depths of 1.30-3.4 km. Authigenic muscovite forms at >100 °C, corresponding to a depth of 2.1 km given the modern geothermal gradient. Authigenic muscovite is only observed in the lower arkose at 2.3 km vertical depth; the upper arkose has limited feldspar alteration with almost no evidence of authigenic muscovite. The upper arkose extends from 1.9 to 2.2 km vertical depth; the lack of authigenic muscovite may indicate a different fluid chemistry at that level than in the lower arkose. In that case, authigenic clay mineral development is more dependent on fluid chemistry than temperature or pressure (Montoya and Hemley, 1975). In light of these observations, we suggest these rocks were not buried much more deeply than their present depth.

There are few direct constraints on the youngest possible age for the SAFOD arkosic rocks. They are interpreted to be unconformably overlain by the Etchegoin and Santa Margarita Formations (Thayer and Arrowsmith, 2005), which are 10-4 Ma old (see Sims, 1993). Stratigraphic studies of strata on the Salinian block suggest that most deposition ceased in the late Eocene to early Oligocene, although Oligocene deposition is recorded in some places of the western Coast Ranges (see discussion in Barbeau et al., 2005). Rocks younger than the Neenach/Pinnacles volcanic rocks (early Miocene, ca. 23 Ma) exhibit a markedly different character from the SAFOD section due to the marine sedimentation and initiation of the transform plate margin. Thus, we propose that the SAFOD arkoses were deposited sometime in the very latest Cretaceous to the Paleocene or Eocene, during exhumation of the nearby Salinian granite.

If this age assignment is correct for the arkosic rocks, then it is worth briefly considering possible correlatives. In evaluating possible correlative strata, we are interested in finding similar lithologies allied with the Salinian basement. This regional assessment will allow us to form a testable hypothesis for future strati-

graphic work. Paleocene and Eocene sedimentary rocks are common in central California (i.e., Dibblee, 1971, 1973, 1980; Nilsen and Clarke, 1975; Graham, 1978; Clifton, 1984; Bent, 1988; Graham et al., 1989; Seiders and Cox, 1992; Sims, 1990, 1993; Cronin and Kidd, 1998; Dibblee et al., 1999; Dickinson et al., 2005; Burnham, 2009) and are mostly marine fan deposits deposited in basins that formed on or next to the Salinian/Sierran block (Nilsen and Clarke, 1975; Nilsen, 1984; Ingersoll, 1988; Graham et al., 1989; Wood and Saleeby, 1997) (Fig. 14). Paleocene conglomerates that lie on the Salinian block (Bachman and Abbott, 1988; Clifton, 1984; Seiders and Cox, 1992; Cronin and Kidd, 1998) may also correlate with the SAFOD arkoses. The San Francisquito Formation (Upper Cretaceous to Paleocene) and Carmelo Formation (Paleocene to lower Eocene) are composed of granite-rich conglomerates interbedded with arkosic sandstones and mudstones. The Paleocene-Eocene San Francisquito Formation crops out in the Ridge Basin, the Liebre Mountain block, and the Pinyon Ridge block (Seiders and Cox, 1992) (Fig. 14), and the Late Cretaceous Carmelo Formation lies on granodiorite at Point Lobos (Clifton, 1981, 2007). Rocks older than Miocene are not mapped at the surface in the immediate vicinity of the SAFOD site (Dibblee, 1971; Sims, 1990; Thayer and Arrowsmith, 2005). The closest Paleocene-Eocene sedimentary rocks similar to the SAFOD arkoses on the southwestern side of the San Andreas fault are thick sequences of unnamed marine sedimentary rocks in the La Panza and Sierra Madre Ranges ~50 km southwest of the SAFOD site (Fig. 14) (Jennings and Strand, 1976; Bachman and Abbott, 1988). The rocks in this area to the southwest consist of interbedded arkosic sandstones, siltstones, clay shale, and granitic conglomerates ranging in age from Upper Cretaceous to middle Eocene (Chipping, 1972; Vedder and Brown, 1968; Dibblee, 1973: Bachman and Abbott, 1988: Nilsen, 1986). The unnamed unit has been estimated to be between 600 and 910 m thick, but this encompasses the entire age range. The unit is not subdivided into different age units due to the paucity of fossils encountered (Dibblee, 1973). A complex series of folds and faults could result in similar rocks in the subsurface adjacent to the San Andreas fault.

The Butano Sandstone (Eocene) of the Santa Cruz Mountains and the Point of Rocks Formation (middle to upper Eocene) of the southwestern San Joaquin Basin are similar in provenance, sedimentary characteristics, and depositional environment (Clarke, 1973; Clarke and Nilsen, 1973). The Butano Sandstone is part of the La Honda Basin, ~200 km

to the northwest of the SAFOD site (Fig. 14), and the Point of Rocks Formation is part of the southern San Joaquin Basin, ~100 km to the southeast of the SAFOD site (Clarke and Nilsen, 1973; Graham et al., 1989). The Butano-Point of Rocks Formation is composed of moderately well-indurated arkosic conglomerate, sandstone, and siltstone sequences hundreds to thousands of meters thick (Critelli and Nilsen, 1996), and in some ways is similar to the SAFOD arkoses. The Butano Sandstone in the Santa Cruz Mountains has been divided into three members: a 9-80 m thick bedded upper sandstone, a 75-230 m thick siltstone member, and a >460 m thick sandstone interbedded with pebble conglomerate (Clark, 1981). The three members of the Butano Sandstone are similar in lithology and thickness to the SAFOD arkoses, although at the surface the Butano Sandstone is significantly less well indurated than the SAFOD arkosic rocks, and we find few of the fine-grained sandstones common in the Butano-Point of Rocks sections in the SAFOD arkoses.

A third candidate for rocks equivalent to the SAFOD arkosic section are the sandstones and conglomerates of the Eocene Tejon Formation, which are exposed at the southern end of the Great Valley (Fig. 14) (Critelli and Nilsen, 2000). These rocks consist of cobble- to pebble-rich conglomerates of granitic and metamorphic rock source, fine-grained sandstones, and siltstones and mudstones. The Tejon Formation rocks are petrologically different from the Butano-Point of Rocks sequence, having been deposited in a proximal fan setting (Critelli and Nilsen, 2000). However, the Tejon Formation contains a small amount of gabbro clasts derived from mafic basement upon which the Tejon Formation lies (Critelli and Nilsen, 2000), and we found no gabbro grains in the SAFOD arkoses. It is possible that mafic grains did not survive the drilling and washing for this study and might be present at depth.

There are a number of possible correlative units that are worth considering in our stratigraphic comparison. One problem we encounter is that although many of these units are lithologically and compositionally similar, there are few comparable diagnostic criteria that we can use to separate or distinguish between them. For example, our zircon fission-track results might allow for a distinction between the specific exhumation evolution of the source rocks through time and in different areas, but comparable data from other units are not available. So, one very fruitful avenue of future research would be provenance studies of these units using varietal studies, such as the zircon fission-track work on the SAFOD arkoses presented here.

Tectonic Implications

The structural and tectonic issues posed by the presence of these rocks include deciphering the fault zone structure at depth, how these rocks correlate with other latest Cretaceous to early Tertiary arkosic rocks in the region, and the implications for how slip is distributed along the San Andreas fault.

The tectonic history of the San Andreas fault is commonly thought to be reasonably simple in central California, by having the majority of offset occurring along a single strand of the modern trace of the fault (Irwin, 1990; Wright, 2000). However, other studies have documented the presence of several parallel strands along this portion of the fault in this area, and slip along the strands has switched over time (Dickinson, 1966; Rymer, 1981; Ross, 1984; Sims, 1993), as documented along the southern San Andreas fault (Powell, 1993). One such strand appears to be the Buzzard Canyon fault (Arrowsmith, 2007; M. Rymer, 2005, personal commun.; Thayer and Arrowsmith, 2005). The presence of the SAFOD arkosic section and a set of unnamed sedimentary rocks in the fault zone from 10 to 80 km northwest of the SAFOD site (Gribi, 1963; Walrond and Gribi, 1963; Forrest and Payne, 1964a, 1964b; Walrond et al., 1967; Rogers and Church, 1967; Dibblee, 1971) adds a measure of complexity to the offset history of the San Andreas system near the SAFOD site. The 315 km of total Neogene offset on the San Andreas fault zone is well established (Ross, 1970; Clarke, 1973; Clarke and Nilsen, 1973; Matthews, 1976; Graham et al., 1989; Sims, 1993; Dickinson et al., 2005; Burnham, 2009), with key offset markers including the San Joaquin-La Honda Basin sequences, the Pinnacles-Neenach andesite-dacite-rhyolite complexes, and the gabbros and gabbroic conglomerates of the Eagle Rest Peak-Logan-Gold Hill-Gualala system. The presence of multiple fault strands and fault-bounded zones of rock from SAFOD northwest to the central Gabilan Range on the southwest side of the fault (~95 km strike distance along the fault) and the presence of exotic lithologies, including Cretaceous (?) sedimentary rocks, metamorphosed limestones, granitic rocks, and small blocks of Franciscan rocks indicate that the fault consists of multiple strands along this section (Jennings and Strand, 1958; Dibblee, 1971; Rymer, 1981; Ross, 1984).

The presence of both the Buzzard Canyon fault and the seismically active San Andreas fault bounding the SAFOD arkosic section suggests three models for slip on the San Andreas fault system in the vicinity of SAFOD (Fig. 14): (1) The majority of dextral offset occurred on the current trace of the San Andreas fault, and only a small component of offset on the Buzzard Canyon fault (Fig. 14A); (2) the 315 km offset could have been distributed more evenly across both the Buzzard Canyon and related faults and the modern San Andreas fault (Fig. 14B); or (3) the Buzzard Canyon fault could have been the major strand of the system until recently, and the majority of offset has occurred along the Buzzard Canyon fault rather than the modern San Andreas fault (Fig. 14C). Because of the lack of a piercing point in the SAFOD arkosic rocks, we can only consider ranges of offset. It is important to explore the implications of these three models because each model results in a specific prediction that can be tested by future stratigraphic studies.

In model 1, rocks equivalent to the SAFOD arkosic section would lie ~300 km to the south, on the northeast side of the fault. This model predicts a small amount of offset across the Buzzard Canyon fault (Fig. 14A). If most of the slip occurred along the San Andreas fault, the correlative sequence should be found ~300 km southeast of the SAFOD site, southeast of the Neenach volcanic complex (Fig. 14A), and the SAFOD arkoses would have correlatives nearby and west of the SAFOD site.

Model 1 is not supported by the available data. Correlative rocks to the arkosic section are the Paleocene and Eocene marine fan deposits of the La Honda Basin (Nilsen and Clarke, 1975; Nilsen, 1984; Graham et al., 1989) (Fig. 14D). Restoring 315 km of right-lateral slip in the San Andreas system does not place these rocks at the SAFOD locality. No Paleocene and Eocene sedimentary rocks are found northeast of the San Andreas fault, and one possible correlative, the San Francisquito Formation, lies within a faultbounded block southwest of the San Andreas fault zone and provides no offset constraints. Overlap relationships interpreted near SAFOD rule out a Miocene age for the arkosic section in the SAFOD drill hole (Thayer and Arrowsmith, 2005). Eocene rocks in the Orocopia Mountains (Crowell and Susuki, 1959) are the only other known arkosic rocks on the northeast side of the fault, but they are either much coarser or much finer than the arkosic section of the SAFOD rocks, and lack significant thicknesses of sand-bearing rock. Because they lie too far to the southeast, ~450 km southeast of SAFOD, a correlation is very unlikely. At the surface, there are no rocks similar to the SAFOD section nearby and northwest of SAFOD on the southwest side of the San Andreas fault. Subsurface data are scant; Upper Cretaceous or Paleogene rocks are reported to lie on Salinian rocks in wells 35-60 km to the northwest (Gribi, 1963; Forrest and Payne, 1964a; Rymer et al., 2006) (Fig. 14).

Model 2, which requires significant amounts of slip on both the San Andreas fault and the Buzzard Canyon fault, predicts that there are equivalent units to the southeast of the San Andreas fault midway between maximum and minimum possible offset distances (i.e., between 0 and 315 km), and as such could accommodate a broad area. There are a number of Paleocene-Eocene units distributed across the region from the San Andreas fault to the coast that are likely the remnants of a set of widespread deposits that are cut by the San Andreas, Sur-Nacimiento, and other strike-slip faults (Nilsen, 1987; Graham et al., 1989; Dickinson et al., 2005; Burnham, 2009). Rocks within these deposits might correlate with the SAFOD arkosic section, and depending on the correlation, up to 100 km of slip would be recorded on the Buzzard Canyon fault. The remainder of slip on the San Andreas fault modern strand would result in a correlation with early Tertiary arkosic rocks of the southern San Joaquin Valley-San Emigdio Mountain area, a slip of up to 200 km on the modern trace of the San Andreas fault (Fig. 14B). Model 2 appears to best explain the available data (Fig. 14D).

Finally, model 3 predicts that there has been only a small amount of offset on the modern San Andreas fault, and therefore rocks similar to the SAFOD arkoses lie somewhere nearby northeast of the San Andreas fault. Correlative arkosic rocks would lie ~300 km to the northwest on the southwest side of the San Andreas fault (Fig. 14C). To the northwest at this offset distance, no early Tertiary sedimentary rocks that resemble the SAFOD arkoses are present at the surface. The Tertiary sedimentary rocks east of the fault zone are the Miocene Monterey Formation (Dibblee, 1971, 1980; Sims, 1990; Dibblee et al., 1999), a sequence of argillaceous Miocene shale and mudstone (i.e., Dibblee, 1973; Sims, 1990), which do not resemble the SAFOD arkoses. Exposures of the Miocene Temblor Formation ~20 km southeast of the SAFOD site on the northeast side of the San Andreas fault (Sims, 1990) are only tens of meters thick and are volcanic-rich in composition. Likewise there are no reports of rocks similar to the SAFOD arkoses in well logs or imaged in seismic reflection profiles (Forrest and Payne, 1964b; Wentworth and Zoback, 1990) east or south of SAFOD. On the western side of the fault, the large displacement on the Buzzard Canyon fault would result in the equivalent rocks being faulted well to the north. Because Paleogene sedimentary rocks are relatively common northwest of SAFOD, and absent nearby to the southeast, we reject this model for the faulting of the arkosic rocks and the offset along the San Andreas fault system.

Our data, combined with the work of others in the region (Nilsen, 1984, 1986; Graham et al.,

1989; Dickinson et al., 2005; Burnham, 2009) suggest that a model for partitioning of slip on the modern San Andreas fault and the Buzzard Canyon fault (model 2) provides a viable testable hypothesis for further work. The San Andreas fault consists of several strands from Parkfield northwestward to near Hollister, with small blocks of exotic rocks within the zone. Further work on the nature of these rocks, and provenance and petrographic analyses of sedimentary rocks in the SAFOD hole and northwest of SAFOD, would provide insight into the partitioning of displacement of the San Andreas fault zone in central California.

Summary

We infer that the faulted sedimentary arkosic section encountered in the SAFOD borehole, between the trace of the modern San Andreas fault and the Buzzard Canyon fault to the southwest, are latest Cretaceous to early Eocene rocks deposited in broad fan complexes proposed by Clarke and Nilsen (1973) and Nilsen and Clarke (1975). Both the continental borderland and granitic-cored Salinian terrains shed arkosic sediment westward and northward in a series of fan complexes (Nilsen and McKee, 1979; Graham et al., 1989) (see Fig. 14). Subsequent slip along faults of the San Andreas fault system have dissected and transported slivers within the fault zone northwestward 100-200 km. Similar complex structure and fault slivering has been mapped previously at a variety of scales from the Parkfield area northwestward up to 120 km from SAFOD (see Jennings and Strand, 1958; Dibblee, 1971; Rymer, 1981; Sims, 1993; Thayer and Arrowsmith, 2005).

CONCLUSIONS

We use wireline logs, cuttings microscopy, core samples, and electrical image logs to fully characterize the SAFOD arkosic rocks. As a whole, the 1230 m of arkosic rock between the modern-day San Andreas fault to the northeast and the Buzzard Canyon fault to the southwest is heavily faulted with at least 12 faults and 11 fault-bounded structural blocks. The arkosic section consists of three distinct lithologic units: the upper arkose, the clay-rich zone, and the lower arkose. The upper arkose is 156.4-381.4 m thick, interrupted by intraformational faults that separate five distinct structural blocks with different bedding orientations and fracture densities. The five blocks are coarsegrained quartzo-feldspathic conglomerates and sandstones that contain rare clav-rich grains. Feldspar altered to illitic material and iron oxide alteration products are abundant. The clay-rich zone is a 28.7-121.3 m thick, low-velocity zone that exhibits anomalously high gamma ray signatures. It is characterized by abundant clayrich grains composed of high-birefringence clay minerals such as illite and smectite. A 27 m thick block of well-bedded, coarser-grained rock is incorporated into the clay-rich zone, from 2565 to 2595 mmd. The lower arkose has more variable log signatures than the upper arkose, with generally higher velocities and lower porosities. It is 224–331 m thick and is finer-grained with a higher abundance of clay-rich grains than the upper arkose. The lower arkose contains more volcanic clasts than the upper arkose.

We interpret the arkosic section to have been deposited in either a subaerial or subaqueous fan setting, perhaps as part of a transtensional subbasin system common to the Salinian block. Fission-track cooling ages of 64–70 Ma constrain the maximum age of the SAFOD arkoses to be latest Cretaceous to earliest Paleocene. Diagenetic mineral assemblages of authigenic muscovite and laumontite indicate that at the modern-day geothermal gradient of 38.5 °C/km the arkosic rocks have not likely been buried more than 0.8 km deeper than the depth they are today. Lithologic comparisons show that the rocks are no older than Eocene to latest Cretaceous.

The arkosic rocks are divided into blocks that are defined on the basis of common lithologies, bedding characteristics, and orientations that are cut by numerous faults and/or folded. We document the presence of the seismically inactive Buzzard Canyon fault, a western strand of the San Andreas fault, and an intermediate fault within the section, along with as many as eight other faults that define the boundaries of structural blocks. The three largest faults are associated with clay-rich mineralogy and locally high degree of imaged fractures and cataclastically deformed grains. We test several models for the partitioning of displacement across strands of the San Andreas fault system in the vicinity of the SAFOD site that predict where sedimentary rock units equivalent to the SAFOD arkoses would have lain before faulting. Based on our data and the tentative correlations to Paleocene-Eocene rocks of the region, we suggest that the SAFOD arkosic rocks are a stranded, faultbounded sliver with correlative units 30-150 km to the northwest and >100 km to the southeast, on the northeast side of the fault.

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