Crustal structure across the San Andreas Fault at the SAFOD site from potential field and geologic studies

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[1] We present newly compiled magnetic, gravity, and geologic datasets from the Parkfield region around the San Andreas Fault Observatory at Depth (SAFOD) pilot hole in order to help define the structure and geophysical setting of the San Andreas Fault (SAF). A 2-D cross section of the SAF zone at SAFOD, based on new, tightly spaced magnetic and gravity observations and surface geology, shows that as drilling proceeds NE toward the SAF, it is likely that at least 2 fault bounded magnetic slivers, possibly consisting of magnetic granitic rock, serpentinite, or unusually magnetic sandstone, will be encountered. The upper 2 km of the model is constrained by an order of magnitude increase in magnetic susceptibility at 1400 m depth observed in pilot hole measurements. NE of the SAF, a flat lying, tabular body of serpentinite at 2 km depth separates two masses of Franciscan rock and truncates against the SAF. *INDEX TERMS:* 1219 Geodesy and Gravity: Local gravity anomalies and crustal structure; 1517 Geomagnetism and Paleomagnetism: Magnetic anomaly modeling; 8010 Structural Geology: Fractures and faults. **Citation:** McPhee, D. K., R. C. Jachens, and C. M. Wentworth (2004), Crustal structure across the San Andreas Fault at the SAFOD site from potential field and geologic studies, *Geophys. Res. Lett.*, *31*, L12S03, doi:10.1029/2003GL019363.

1. Introduction

[2] Over the past several years, a wide variety of geophysical investigations, including controlled source and natural source seismic experiments, and magnetotelluric soundings, have been carried out for the purpose of characterizing the crust and the San Andreas Fault (SAF) near Parkfield, Calif. [*Eberhart-Phillips and Michael*, 1993; *Unsworth et al.*, 1997]. Investigations based on combined magnetic, gravity, and geologic data also have been used to define the geology and structure [*Simpson et al.*, 1988; *Griscom and Jachens*, 1990; *Wentworth et al.*, 1992]. With renewed interest in the Parkfield region spurred by the initiation of efforts to drill into the fault zone at seismogenic depths, we present newly compiled geologic and potential field datasets from the Parkfield region, particularly surrounding the SAFOD pilot hole, in order to help define the overall structure and geophysical setting of the SAF near SAFOD.

2. Data

[3] Aeromagnetic data were collected at a nominal 300 m above terrain along NE-SW flightlines normal to the SAF (Figure 1a). Data were recorded at 50 m spacing along flight lines 800 m apart [*U.S. Geological Survey*, 1987]. Ground magnetic data collected in October, 2000, and recorded every 5 m along lines spaced 300 m apart cover a 3 × 5 km area surrounding the SAFOD pilot hole (Figure 2a). Ground magnetic data were upward continued 50 m to suppress short-wavelength anomalies caused by sources in the top few tens of meters. The resulting filtered data can resolve magnetic sources a few tens of meters or greater in width, depending on their depth.

[4] The gravity data are distributed unevenly over the study area and compiled from three different data sets (Figure 1b): (1) scattered regional data from compilation of *Simpson et al.* [1988] generally spaced at about 1.6 km; (2) closely spaced (40 m) stations along SW-NE Profile E passing the SAFOD pilot hole and collocated with a high resolution seismic line [*Catchings et al.*, 2002]; and (3) a grid of stations spaced about 400 m apart within a few kilometers of the proposed drill site. Observed gravity values were referenced to the International Gravity Standardization net (IGSN71), and reduced to Free-Air anomalies, complete Bouguer anomalies (reduction density 2670 kg/m^3) and isostatic anomalies, referenced to the Geodetic Reference system 1967 using standard formulas [*Blakely*, 1995].

[5] The most detailed areal geologic mapping available for the Parkfield region is from *Dibblee et al.*'s [1999] 1:125,000-scale compilation along the Carrizo Plain reach of the SAF and a similar unpublished compilation extending to the northwest (Parkfield to Hollister) (Figure 1c has been simplified from these two sources).

3. Geophysical and Geological Setting of SAFOD

3.1. Regional

[6] The SAF in the Parkfield area juxtaposes Salinian granitic basement on the SW against Franciscan Complex on the NE, as is the case along much of the fault in northern California, and this contrasting geology is reflected in regional gravity and magnetic data [*Simpson et al.*, 1988; *Wentworth et al.*, 1992] (Figure 1). The Salinian block and overlying Tertiary and Plio-Quaternary rocks and sediments here are relatively undeformed. The local, highly magnetic elliptical feature along the SW side of the SAF (Figure 1a) is interpreted to be due to magnetic granitic rocks within the Salinian basement. The likely counterpart of this magnetic granitic body across the SAF lies about 300 km to the SE in the Mojave Desert, just SE of Palmdale, Calif. [*Roberts and Jachens*, 1999]. Regional prominent gravity highs observed SW of the SAF in the Salinian block in the Parkfield area are likely caused by the variable thickness

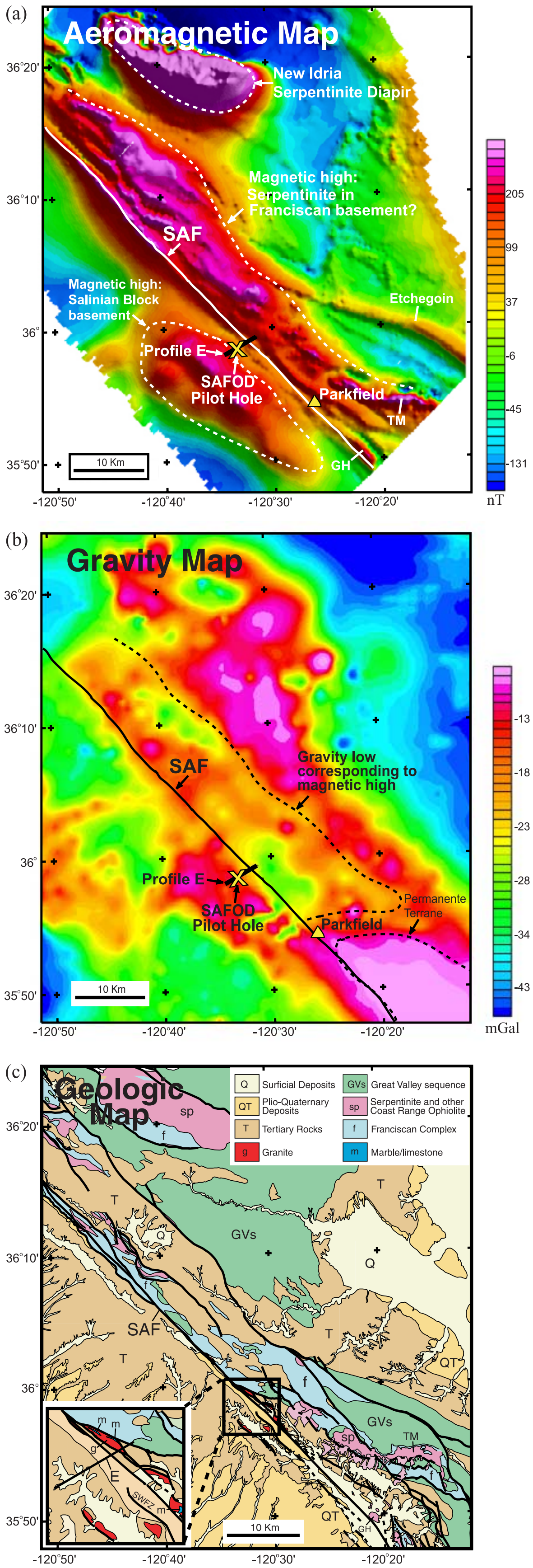

Figure 1. Regional aeromagnetic (a), isostatic gravity (b), and geologic (c) maps near Parkfield, CA. Lines: solid-fault; dashed-geophysical anomaly. Maps all the same scale, Profile E (Figure 2) shown on each map. SAF- San Andreas Fault; TM-Table Mountain; GH-Gold Hill; SWFZ-Southwest Fracture zone.

of Cenozoic deposits overlying the buried granitic basement rocks (Figure 1b).

[7] In contrast to the Salinian block, the Franciscan Complex and overlying Great Valley sequence and late Cenozoic cover to the NE of the SAF are complexly deformed. A band of intricate folding and faulting about 5 km wide here adjoins the SAF, and is marked by basement fault slivers, including the magnetic Gold Hill gabbro (GH on Figured 1a and 1c) and granitic rock and marble near Middle Mountain (g and m on inset, Figure 1c), neither of which are part of the Franciscan Complex. Similar faulting parallel to and west of the SAF is mapped from Middle Mountain southeastward, including the Southwest Fracture zone (Figure 1c). The NE side of the SAF is characterized by a large (60 km × 15 km) elliptical magnetic high and corresponding gravity low interpreted to result from a flat-lying sheet of serpentinite in Franciscan basement rocks [*Griscom and Jachens*, 1990; *Miller et al.*, 2000]. This serpentinite body is mostly concealed, but extrudes at Table Mountain (TM on Figures 1a and 1c) SE of SAFOD and is inferred to have an offset counterpart exposed at Yerba Buena ridge in the Santa Clara Valley about 175 km to the NW [*Jachens et al.*, 2002]. Superposed on this serpentinite sheet is an additional magnetic anomaly due to unusually magnetic sandstone of the Tertiary Etchegoin Formation [*Dibblee*, 1972] (Figure 1a).

[8] Serpentinite is common in the area, and the New Idria serpentinite diapir [*Coleman*, 1996] is prominent in the core of a large southeast-trending fold at the north edge of the map (Figure 1c), giving rise to a large, ellipsoidal magnetic high and a corresponding but areally smaller gravity low (Figures 1a and 1b). Blocks of Permanente terrane (composed of limestone and greenstone), are locally present and embedded in the Franciscan mélange and serpentinite shown at the south edge of the map (Figure 1c). Although the outcrop of Permanente terrane is very limited in area, we interpret the large gravity high in the SE corner of Figure 1b to be caused by a large, concealed body of dense Permanente terrane, one that has been offset from its cross-fault counterpart 175 km to the NW in the Santa Cruz Mountains [*Jachens et al.*, 1998]. The modest gravity ridge about 10 km NE of the SAF and trending diagonally NW-SE across Figure 1b reflects the background gravity level over Great Valley sequence rocks where they are not perturbed by buried serpentinite.

3.2. Local

[9] Gravity data and ground magnetic data were used to compute 2-D models along SW-NE profiles perpendicular to the SAF in the 3 × 5 km region surrounding the SAFOD pilot hole (Figure 2a). In particular, Profile E extends past the SAFOD pilot hole following the high-resolution seismic refraction/reflection survey completed in 1998 [*Catchings et al.*, 2002] along which closely spaced (40 m) gravity measurements were collected. The upper 2 km of the model

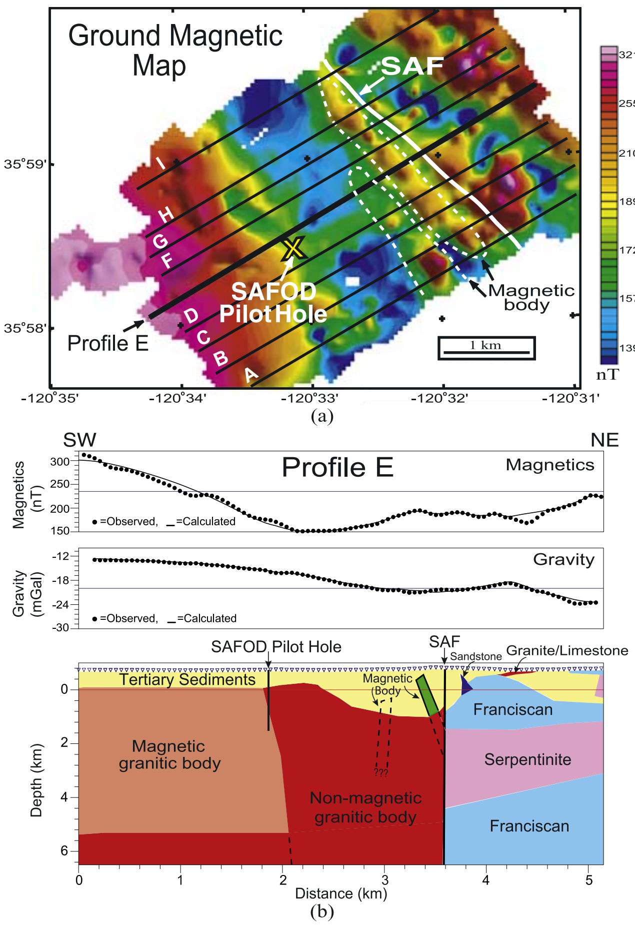

Figure 2. (a) Ground magnetic map near the SAFOD pilot hole. Lines: white-SAF; dashed white-magnetic anomalies. 2-D magnetic models prepared along Profiles A to I (solid black lines). (b) Profile E: 2-D geologic model with fit to ground magnetic and gravity data. Dashed line-magnetic body projected to Profile E from models along profiles A to D.

is constrained by pilot hole measurements (Figure 3) where a boundary between sediment and granitic rock occurs at a depth of about 770 m (M. Rymer, personal communication, 2004). An order of magnitude increase in magnetic susceptibility defines a boundary between non-magnetic and magnetic granitic bodies at a depth of about 1400 m, collocated with an observed gamma/SP offset [*Boness and Zoback*, 2004].

[10] The SW side of the SAF shows a shallow dipping Tertiary sedimentary section, which coincides with the low velocity zone observed with seismic measurements [*Catchings et al.*, 2002], overlying granitic basement rocks (Figure 2b). A dense and magnetic granitic body lies about 1600 m SW of the SAF and gives rise to the large aeromagnetic high (Figure 1a). Where it intersects the pilot hole, the northeastern edge of this steeply dipping magnetic body, to which we can attribute the increase in pilot hole magnetic susceptibility measurements, corresponds to a highly fractured and faulted zone [*Boness and Zoback*, 2004]. The depth extent of this body is only approximate and cannot be determined from gravity and magnetic data alone.

[11] A shallow steeply dipping magnetic body about 200 m SW of the SAF (shown in green in Figure 2b), possibly consisting of a sliver of granitic rock, serpentinite, or magnetic sandstone, gives rise to a significant NW trending high parallel to the SAF on the ground magnetic map (Figure 2a). A slight gravity high indicates that this body is denser than the surrounding Tertiary sediments and so is likely granitic rock, but serpentinite cannot be precluded. Although the exact nature and depth of this body is currently unknown, its shape and location with respect to the SAF implies a fault-bounded sliver. 2-D models along the other profiles (not shown) show this body to extend the length of the entire study area (Figure 2a). It is modeled as a steep, NE-dipping sliver that rises to within a few hundred meters of the surface and truncates against the SE edge of the study area. A similar, linear body further to the SW of the SAF (marked as a dashed box in Figure 2b) is modeled along profiles A through D and extends approximately 20 km to the SE parallel to the SAF, ending adjacent to and SW of Gold Hill (Figures 1a, 2a, and 2b). This body is likely fault-bounded, with its western limit corresponding to the Southwest Fracture zone and its bounding faults extending into the basement.

[12] NE of the SAF, a flat lying, tabular body of serpentinite at about 2 km depth separates two masses of Franciscan rock and truncates against the SAF (Figure 2b). This body of serpentinite begins at about 2–3 km depth on all profiles, and extends NE from the SAF beyond the map area. Although it is modeled as one unit, it is likely that the serpentinite is interleaved with Franciscan rocks at depth as is observed elsewhere NE of the SAF. The depth of the serpentinite agrees with velocity models of *Eberhart-Phillips and Michael* [1993], who model a low-velocity, low-resistivity zone NE of the SAF inferred to be overpressured Franciscan or Great Valley sequence material capped by a serpentinite body at about 2–3 km depth. The depth also agrees with the low velocity zone modeled by *Thurber et al.* [2004] and the decrease in resistivity observed by *Unsworth and Bedrosian* [2004], likely due to a possible aquifer underlying the serpentinite.

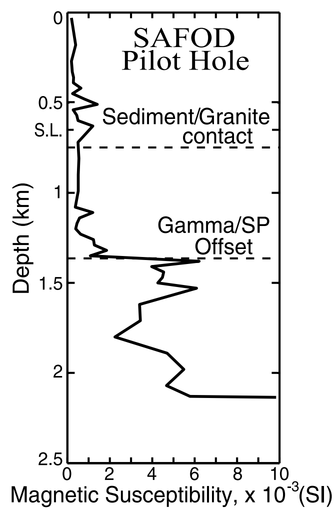

Figure 3. Magnetic susceptibility of pilot hole cuttings. Surface elevation of pilot hole: 660 m. S.L. - sea level.

[13] Marble and granite outcrop just NE of the SAF (see m and g in Figure 1c) [*Dibblee et al.*, 1999; M. Rymer, personal communication, 2003], although, geophysically, it is impossible to differentiate between these outcrops and the Franciscan rocks modeled just below them. This marble and granite has affinities to the Salinian basement rocks SW of the SAF [*Diblee*, 1972]. Franciscan rocks outcrop on the NE end of Profile E [*Dibblee*, 1972], as shown by the blue sliver at the surface in Figure 2b. However, gravity data suggest that the Franciscan rocks lie on top of low-density Cenozoic deposits. Additional gravity data along a profile to the NE of the SAF in November 2003 will help to address the extent of shallow Franciscan rocks in this area.

4. Discussion

[14] Although SAFOD should ultimately provide more definitive answers about the composition of the SAF zone at depth, magnetic, gravity, and geologic data offer several clues about the geologic structure of the fault zone at depth. In addition, these data, when combined with other geophysical data, will address questions of finer scale structure near the SAFOD site [*Roecker et al.*, 2004].

[15] Our results suggest that as drilling proceeds NE toward the fault zone, it will encounter a broad zone separating granitic basement on the SW and Franciscan basement rocks on the NE, and it is likely that the drill will eventually encounter interleaved Franciscan rocks and serpentinite, if not a mass of serpentinite itself. Of particular significance is the magnetic body located just SW of the SAF (shown in green in Figure 2b) as well as the similar body modeled along Profiles A–D (not shown), which may be too small along Profile E to model. Although the exact nature and depth of these bodies is unknown, they appear to be steeply dipping, fault-parallel, and likely fault-bounded, slivers. It is possible that slivers of serpentinite and/or Etchegoin Sandstone, typically observed NE of the SAF, exist on the SW side as well. Consequently, as drilling proceeds NE toward the fault zone it is likely that the drill may encounter at least 4 faults, those bounding the two magnetic slivers of potentially exotic composition, as well as other faults lacking a geophysical signature.

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