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The Wister Mud Pot Lineament: Southeastward Extension or Abandoned Strand of the San Andreas Fault?

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Abstract We present the results of a survey of mud pots in the Wister Unit of the Imperial Wildlife Area. Thirty-three mud pots, pot clusters, or related geothermal vents (hundreds of pots in all) were identified, and most were found to cluster along a northwest-trending line that is more or less coincident with the postulated Sand Hills fault. An extrapolation of the trace of the San Andreas fault southeastward from its accepted terminus north of Bombay Beach very nearly coincides with the mud pot lineament and may represent a surface manifestation of the San Andreas fault southeast of the Salton Sea. Additionally, a recent survey of vents near Mullet Island in the Salton Sea revealed eight areas along a northwest-striking line where gas was bubbling up through the water and in two cases hot mud and water were being violently ejected.

Introduction

Mud pots and mud volcanoes are geothermal features produced when water and/or gas is forced upward through soil and sediments (e.g., Planke *et al.*, 2003). They are usually associated with volcanic and seismic activity and thus reveal activity at plate boundaries and hot spots (Martinelli and Panahi, 2005). The most common gases are H_2O and CO_2, although significant amounts of H_2S, CH_4, C_2H_{10}, and NH_3 may also be present, as well as other noble gases such as He, Ar, Rn, Ne, and Kr.

Mud pots can assume a variety of morphologies, typically being depressions or enclosed basins containing gas seeps, bubbling water, or viscous mud (Fig. 1). They can also be water laden and appear as bubbling muddy water. Mud volcanoes are elevated conical structures composed of accumulations of viscous mud extruded from a central vent. According to Milkov (2003), "mud volcanoes often occur at the surface and the seafloor as a result of migration of fluidized sediment along active faults due to overpressure, and may also form on top of seafloor-piercing shale diapirs." Mud volcanoes can range from finger sized to several kilometers across, and the eruption of some may be associated with earthquake activity (Mellors *et al.*, 2007). Small mud volcanoes on land (1–3 m tall) are usually called mud cones or gryphons.

Mud pots are of interest because of their unusual gaseous emissions and their potential role in influencing the atmosphere and climate. They also indicate subsurface activity and effects of changing land use, such as anthropogenic introduction and variation in levels of surficial or groundwater in an area with high heat flow.

In the Salton Trough, a relatively shallow magma body results in high heat flow in the area, hydrothermal alteration of near-surface sediments (Sturz, 1989), as well as a number of active geothermal features including mud pots, mud volcanoes, and gas vents (Sturz *et al.*, 1997; Svensen *et al.*, 2007). Wells in the area were formerly a commercial source of CO_2 used to manufacture dry ice. For a good historical review of mud volcanoes in the Salton Trough and Colorado River delta region, see Strand (1981).

The region of study (Fig. 2) is a quadrilateral defined by geographic coordinates 33°13.188′–115°31.152′ and 33°18.440′–115°37.323′, and it is situated immediately east of the southeastern-most portion of the Salton Sea in Imperial County, California. This encompasses the northern end of the Brawley seismic zone (BSZ), a region of enhanced earthquake activity (e.g., Meltzner *et al.*, 2006) and frequent earthquake swarms, sometimes accompanied by surface faulting (e.g., Johnson and Hadley, 1976; Sharp, 1976). The BSZ encloses a right-hand step in the plate boundary (releasing bend for right-lateral motion) that serves to transfer plate motion between the Imperial fault and the San Andreas fault (SAF) to the north (Lomnitz *et al.*, 1970; Elders *et al.*, 1972; Hill *et al.*, 1975; Dokka *et al.*, 1990). The BSZ also contains the Salton Buttes (Salton Domes), five young (16,000 yr before present [B.P.]) rhyolitic volcanoes (Wood and Kienle, 1990) within the Salton Sea geothermal field (Elders *et al.*, 1972; Rex, 1972; Robinson *et al.*, 1976). This area overlies what is generally considered to be the northern-most spreading center of the East Pacific Rise (Menard, 1960; Robinson *et al.*, 1976). Most of the seismicity and active faulting within the BSZ, however, appears to be on strike-slip structures. Northwest- and north-northwest-oriented faulting is predominantly right lateral within the BSZ. The northeast-oriented faulting in the BSZ, while ex-

Figure 1. Typical mud pot (W12—see Table 1). Most of the major mud pots in the Wister Unit are circular, steep-sided holes 0.5–3 m deep and 0.5–10 m in diameter with varying amounts of bubbling water, spattering mud, and hissing gas. Some are completely inactive. Their activity and morphology varies seasonally with the amount of rain and the level of the water table. It is likely that the surface structure of many pots has been influenced by the earthen rings constructed around some of them. Unlike the hot steaming mud pots and mud volcanoes (*M* 9 in Table 1) a few kilometers south in the Salton Sea geothermal field (Svensen *et al.* 2007), the temperature of water and mud in the Wister mud pots is not noticeably elevated.

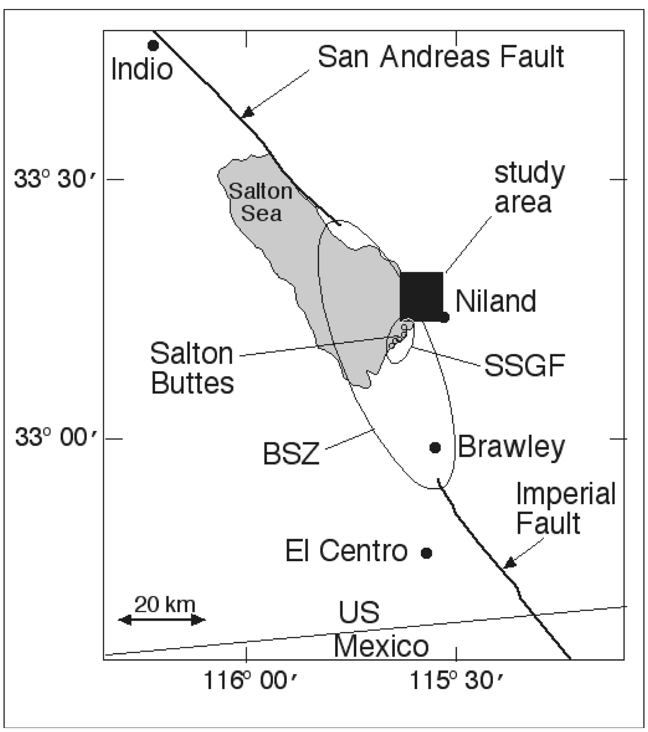

Figure 2. Index map of the study region. The study area is shown as a solid black quadrilateral defined by the coordinates 33°13.188′–115°31.152′ and 33°18.440′–115°37.323′. The BSZ is a region of enhanced seismicity that links the San Andreas fault and the Imperial fault. It contains the young rhyolitic Salton Buttes (volcanic necks) and the SSGF.

pected from a classic pull-apart model to be normal faulting, is instead left lateral, as first recognized on their fault *A* by Johnson and Hadley (1976) and dramatically demonstrated by the 1987 Elmore Ranch event (e.g., Hudnut, Seeber, and Rockwell, 1989; Hudnut, Seeber, Rockwell, Goodmacher, *et al.*, 1989; Magistrale *et al.*, 1989). Recently, Lohman and McGuire (2007) deduced the existence of a northeast-trending left-lateral fault associated with the 2005 earthquake swarm. This fault appears to terminate to the northeast in the Wister Unit, part of our study area.

The Wister Unit of the Imperial Wildlife Area is presently a large field of levee-partitioned seasonal wetlands managed by the California Department of Fish and Game. Ponds are created by man-made levees whose water levels are maintained through a network of fresh water delivery channels. The source of the water is the Colorado River, along with natural and agricultural runoff. Ponds are filled in the fall and winter to provide nesting sites for migratory birds and to provide sport for duck hunters and bird watchers. A. Hernandez (personal comm., 2007) reported that some of the ponds are filled with fresh water in late summer to accommodate migrating birds, and some mud pot fields are covered. As the ponds evaporate or are emptied after duck hunting season ends (in January), some mud pots and volcanoes are exposed. Hernandez noted that new mud pots can appear anytime. Just such an event happened some years ago (exact date unknown) when a new pot appeared outside of a fenced area designed to keep people away from the W11 mud pots (see Table 1). In 2006, new gas vents (W2, W23 in Table 1) developed in water delivery channels.

In this article, we report the result of a comprehensive survey of mud pots and related geothermal structures in the Wister Unit. We also relate the mud pot locations to the known faults in the area—especially the Sand Hills and San Andreas faults—and to nearby geothermal features in the BSZ.

Methods and Results

We first searched satellite imagery and identified possible mud pots in the rectangle defined previously. The survey was unbiased in the sense that we searched the entire area without regard for possible fault locations. Visibility of many pots was enhanced because of the earthen dams around them that were constructed by the California Department of Fish and Game (CDF&G). With these sites in hand, we asked personnel of the CDF&G (Imperial Wildlife Area, Wister Unit) if they knew of any mud pots or related geothermal features in the area that we might visit. They kindly led us to about a dozen, some of which we had identified from the satellite imagery. Further *in situ* reconnoitering revealed a number of other mud pot regions in the Wister Unit, totaling 32 in all (Table 1). We also surveyed vents in the Salton Sea between Mullet Island and the mainland. Several entries in Table 1 refer to clusters of pots, some with too many pots

Table 1

Known Mud Pots, Mud Volcanoes, and Related Geothermal Features in the Survey Area (Black Rectangle in Fig. 2)

Geothermal Vents in the Wister and Mullet Island Areas			
Designation	Latitude	Longitude	Notes
W1	33°16.548′	−115°35.633′	Four large pots with parking area (local attraction)
W1A	33°16.487′	−115°35.661′	Two large active pots, two small inactive pots, trending N30°W
W1B	33°16.598′	−115°35.621′	Gully of ~10 pots trending N6°W, younger to south and one large active pot
W1C	33°16.567′	−115°35.604′	Two small inactive mud volcanoes
W2	33°15.913′	−115°34.789′	Bubbles in water delivery ditch (new 2006)
W3	33°14.733′	−115°33.379′	Three large pots
W4	33°14.706′	−115°33.228′	Small pot (private)
W5	33°14.911′	−115°33.448′	Very large pot Spoony Road
W6	33°15.713′	−115°34.424′	Two large pots straddling road
W7	33°16.270′	−115°35.238′	Small pot, little activity
W8	33°14.216′	−115°33.366′	Large active pot
W9	33°17.117′	−115°34.620′	Large active shieldlike pot (private)
W10	33°17.295′	−115°34.630′	Large area of active shieldlike pots (private)
W11	33°17.580′	−115°35.144′	Five small pots, one of them outside fence
W12	33°17.355′	−115°36.263′	Large active pot
W12E	33°17.356′	−115°36.218′	Two medium active pots
W13	33°17.030′	−115°35.846′	Two dry pots
W14	33°16.833′	−115°35.827′	One dry pot
W15	33°16.851′	−115°35.761′	Small gas vent and bubbles
W16	33°17.085′	−115°36.050′	Small volcano
W16A	33°17.085′	−115°35.864′	Small volcano
W17	33°17.013′	−115°36.063′	Large pot (6’ across), little activity
W18	33°17.218′	−115°36.260′	Four medium active pots, many small ones
W19	33°16.281′	−115°35.386′	Wet spot with perimeter of vegetation
W20	33°13.804′	−115°30.059′	Large shield pot in alfalfa field (private) Niland
W21	33°17.169′	−115°36.245′	New (1 yr?) bubbles in pond near W18 (inaccessible)
W22	33 17.118′	−115°35.496′	Several bubbling vents in water delivery channel
W23	33°17.165′	−115°36.233′	Loud gurgling in brush (new) near W18
W24	33°14.684′	−115°34.743′	Bulldozed ring in pond (inaccessible)
W25	33°16.623′	−115°35.806′	Two large dry pots
W26	33°16.608′	−115°35.858′	Three pots, main and southwest attached pots wet
W27	33°16.574′	−115°35.881′	Very large field of wet and dry pots and volcanoes
W28	33°16.376′	−115°35.271′	One large pot, wet but not active
W29	33°16.516′	115°35.568′	One large dry pot
W30	33°16.278′	115°35.315′	Wet semicircle of vegetation
W31	33°16.960′	−115°36.062′	One 6’ pot, one 1’ pot , two small vents, all dry
M1	33°13.466′	−115°36.376′	Three bubble vents, east end of Mullet Island
M2	33°13.260′	−115°36.204′	5–10 bubble vents
M3	33°13.180′	−115°36.114′	Several bubble vents
M4	33°13.121′	−115°36.077′	Main vent, hot, steam, black mud, 1 acre
M5	33°13.134′	−115°36.126′	Smaller vent, hot, steam, black mud
M6	33°12.732′	−115°35.723′	Hundreds of bubble vents, 1/2 acre
M7	33°12.810′	−115°35.596′	Several dozen bubble vents, H_2S odor
M8	33°12.895′	−115°35.616′	Another cluster
M9	33°12.048′	−115°34.687′	Large field of volcanoes and pots (well known)
R1	33°11.434′	−115°35.120′	~dozen bubbles in water with mud pot sign
R2	33°11.354′	−115°35.104′	~dozen bubbles in water with mud pot sign
R3	33°11.305′	−115°35.188′	Bubbles (approximate location)
R4	33°11.294′	−115°35.134′	100-m-long line of bubbles striking ~N12° E

Prefix W refers to the Wister area. Prefix M refers to vents southeast of Mullet Island in the Salton Sea, except for M9, the well-known field of mud pots and volcanoes at the corner of Davis and Schrimpf Roads. Prefix R refers to mud pots southeast of Red Island. Underlined entries represent a field of pots, usually dozens. For completeness, mud pots and vents associated with the former CO_2 wells are listed in Appendix I.

to count, for example, W10, W27, and M9. Most features were ordinary mud pots and a few were small mud volcanoes or gas venting through shallow water. We visited each site and measured the pot's geographic position, photographed it, and characterized its structure.

Most of the mud pots in the Wister area had similar morphologies (Fig. 1): they are composed of a circular depression that is usually shallower than the diameter of the pot, typically 1:2, probably representing the angle of repose for the poorly consolidated sediments of the Salton

Trough. The walls of the pot often show collapsed material and incised rings indicating a changing water level. Such rings may be found as high as the lip of the pot, a probable sign of overflow by ground water. Many pots are circumscribed by partial or complete ring scarps that form as the pot grows and its walls begin to collapse inward. Some pots are wet and show recent activity; others appeared to be completely dry with significant collapse and aeolian debris suggesting little or no recent activity. It seems likely that dry pots continue to emit gas, their absence of moisture probably being due to a lack of ground water. Indeed, some dry pots are heard to hiss.

We have broadly referred to many features as mud pots because of the bubbling mud—or evidence of it—but many of them have morphologies that are more similar to sinkholes (dolines) or collapse pits (Delle Rose *et al.*, 2004). Sinkholes are basinlike, funnel-shaped, or vertical-sided depressions in the ground's surface that have formed with essentially no horizontal material transport. They are the result of subsidence (Abbass Fayad *et al.*, 2003) and can occur by any of several mechanisms such as dissolution of rock or withdrawal of ground water. Like sinkholes, virtually all of the mud pots in the study area are circular and most lack crater rims or obvious ejecta blankets. Even in the loosely consolidated sediments, many have steep sides and circumscribed ring scarps. This suggests recent formation or perhaps frequent renewal. Even if occasionally filled with sediments by flooding, the continuous emission of CO_2 from below would probably reform the structures. The subsidence mechanism is probably local compaction as upwelling CO_2 is displaced by collapsing soil. This is similar to the bathtub model of sinkhole formation (Kochanov, 1999).

The distinction between pots and volcanoes is not always clear, with some mud pots being slightly elevated shieldlike structures overflowing with water or having a central pool in the caldera that sits below grade. There seems to be a continuum of features between pots and volcanoes and one may evolve into the other with time as water levels and gas supply change. Rains and flooding can also dramatically alter or destroy the surface morphology of pots and volcanoes without affecting the subsurface forces that produce them. In their early stages, both may begin their lives as small wet spots on otherwise dry, unremarkable ground. As subsurface conditions change, the pots and volcanoes may grow inactive and eventually be erased by erosion.

Mud pots in the Wister Unit fall along a lineament about 16 km long that strikes about N45°W (Fig. 3), a feature previously suggested by Meidav and Furgerson (1972[*], attributed by Schroeder [1976]) that they called the Wister fault (WF). The mud pot lineament was also noted by Muffler and White (1969) based on 16 mud pots. The indicated WF (dotted line) would seem to be a good linear fit to the pot locations. Except for three mud pots—two of whose structure is quite different from the others (W9, W10, and W11)—the mud pots define a lineament that we suppose to be a fault, possibly the previously named WF, and arguably coincident with the Sand Hills/Algodones fault. Citing Muffler and White (1969): "These lines of hot springs probably mark upward leakage of hot water from faults at depth."

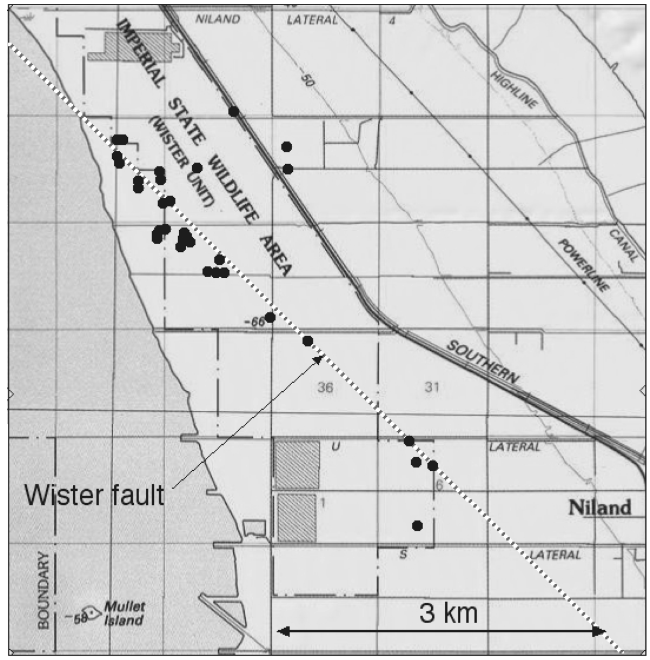

Figure 3. Study area from Figure 1 that shows the Wister mud pot field distribution. Each feature is shown as a black filled circles. The postulated Wister fault (dotted line) is defined by the coordinates 33°10.0′–115°27.6′ and 33°18.64′–115°27.92′ based on measurements of Figure 5. The mud pots tend to cluster along a northwest-trending line that is reasonably well defined by the Wister fault.

To our knowledge, the existence of the WF or Sand Hills fault has never been confirmed to exist at depth or by surface faulting, but their apparent correlation with the Wister field mud pots may provide some evidence for such a structure. Because of the relative lack of seismicity, and hence the uncertainty about whether this is a deep structure, we shall refer to this alignment of geothermal features as the Wister mud pot lineament (WMPL).

Is the Wister Mud Pot Lineament an Extension of the San Andreas Fault?

We were unable to find any *in situ* evidence of the Wister fault such as scarps, pressure ridges, etc. Most of the landforms in the Wister Unit of the Imperial Wildlife Area have been completely erased by bulldozing. Many of those outside

[*]Note: our Fig. 5 did not appear in this article as Schroeder (1976) claimed. We have been unable to locate the original source of the figure. Whatever the heritage of the figure, it seems to have been prescient so we included it. It was useful to us and represents a potentially unifying concept regarding faults in the region. In view of the fact that other people have used the same nomenclature (e.g., Calipatria, Red Hill, and Brawley faults), its inclusion seems warranted.

the Wister Unit are on private land, and some have been altered by agricultural activity intended to level the fields for irrigation. A search of modern-day satellite imagery revealed nothing to indicate the fault's presence outside of the developed areas or disturbed ground. Thus, any surficial evidence of slippage along the possible fault, or direct evidence of the supposed causal fault itself, is understandably unavailable. A search for historical air photos that predate development has begun, and it is hoped that evidence may be found of the original morphology and distribution of mud pots along the WMPL.

The BSZ and SSGF contain other mud pots and volcanoes (Fig. 4). These features are about 8 km south of the Wister Unit and are separated from the mud pots reported here by regions with no known apparent geothermal features except former CO_2 wells (see the appendix). Mud pots and volcanoes do not appear to be uniformly or randomly distributed throughout the BSZ and SSGF, but rather, they cluster along faults, mainly the Calpatria and supposed Sand Hills faults. We believe that the Wister pots reported here represent a separate and distinct body of mud pots dispersed along the Sand Hills fault.

Kelley and Soske (1936) noted that mud volcanoes near the corner of Davis and Schrimpf roads (about 8 km south of the WMPL) and those that were a popular tourist attraction in the 1920s (Laflin, 1995)—before being submerged as a result of a rise in the Salton Sea—fell along a line striking more or less N45°W that passed through Mullet Island. In 1972, Meidav and Furgerson suggested that this line might indicate the location of a fault that they called the Calipatria fault (CF). Elders *et al.* (1972) also named a feature farther to the northeast the Sand Hills fault based on Meidav and Furgerson's data. The prior basis for identification of the WF and Sand Hills fault was subsurface geophysical data, not necessarily indicative of an active structure. According to Schroeder (1976), Meidav and Furgerson posited several other northwest-trending faults in the area that they called (from north to south) the Wister, Calipatria, Red Hill, Brawley, Fondo, and Westmorland faults (Fig. 5). This map suggests that the fault locations are only conceptual because all six indicated faults are exactly parallel to each other and strike N45°W. The current status of these faults has been succinctly described by Younker *et al.* (1981, 1982): "The Brawley fault zone was identified by a portable seismic survey (Gilpin and Lee, 1978) and a resistivity survey (Meidav and Furgerson, 1972). The Calipatria fault was identified

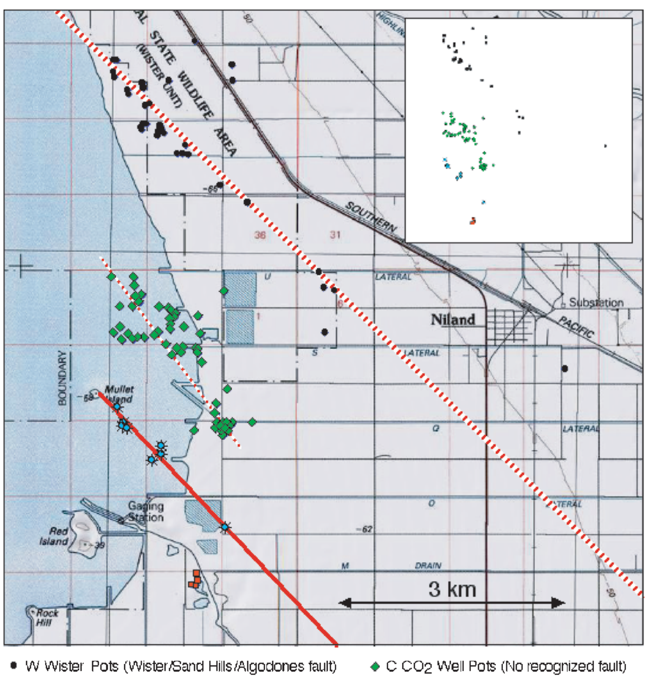

Figure 4. All known geothermal features in the area. The upper dotted red line indicates mud pots and vents in the Wister Unit. Those along the lower red solid line are associated with the Calipatria fault that is presumed to pass through Mullet Island. In the middle are old CO_2 wells indicated on the USGS topographic map based on WGS84. For reference, the inset (upper right) shows all of the features in map projection without lines or base map. See Table 1 and Appendix I for the mud pot locations.

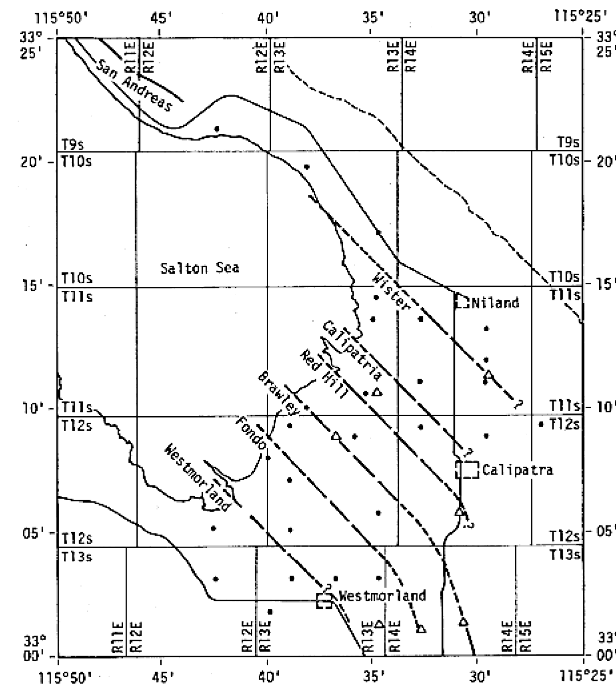

Figure 5. Conceptual fault map attributed to Meidav and Furgerson (1972) by Schroeder (1976). Based on the alignment of the Davis–Schrimpf mud volcanoes, some historically reported mud pots and fumaroles, and Mullet Island, Meidav and Furgerson suggested that their might be a series of en echelon faults trending northwest that reach from Westmorland to Niland. Since that time, the Brawley, Calipatria, and Red Hill faults have been verified. The heretofore unrecognized Wister fault seems to be coincident with another hypothesized fault, the Sand Hills fault, also called the Algodones fault.

using infrared detection (Babcock, 1971) and the alignment of thermal hot springs (Muffler and White, 1968). The Red Hill fault, located between the Brawley and the Calipatria faults, was traced with correlations derived from electric logs (Towse, 1975), interpreted from the ground magnetic survey (Meidav and Furgerson, 1972), and subsequently located with a seismic refraction survey (Frith, 1978)."

Towse (1976) further elaborated on faults in the area. The Wister fault shown in Figure 5 is essentially coincident with the Sand Hills fault of Elders *et al.* (1972) and passes nicely through the WMPL. To our knowledge, the indicated Westmorland and Fondo faults have not been identified. Commercial CO_2 wells (C series in Table 1) were operated during the early part of the twentieth century along a loosely defined northwest-trending line about 2 km north of what was to become recognized as the Calipatria fault. If this line represents a fault, it has not yet been identified.

In view of the evidence for three of the six faults, these faults appear to form an en echelon structure with slippage striking about N45°W. Some of these structures have subsequently been illuminated by seismicity, which often occurs in swarms (e.g., Johnson and Hadley, 1976), whereas others have remained seismically quiescent during the past 30 yr of intensive seismic monitoring. The Wister fault, also known as the Sand Hills fault, is one that has remained essentially silent, although a few small earthquakes appear to lie along this trend.

Along nearly the same trend as the WF of Schroeder (1976), yet extending much farther to the southeast, is the Sand Hills fault, based on the map of Elders *et al.* (1972) and shown in subsequent papers (e.g., Hill *et al.*, 1975; Johnson and Hadley, 1976). Furthermore, Fuis *et al.* (1982) identify the East Highline seismicity lineament, and Sharp (1982) shows a queried feature along this same trend. Yet the Wister and Sand Hills faults and East Highline seismicity lineament are all shown as dashed (inferred) in these original published maps, and these features are not described definitively in the literature. As cited in a footnote by Elders *et al.* (1972), the Sand Hills fault was identified by "electrical soundings [and] … unpublished aeromagnetic data." Sharp (1982) summarized this lack of clear evidence for a southeastward extension of the San Andreas fault as follows: "From the south terminus of the San Andreas fault trace near Bombay Beach, no surface evidence for recent faulting on strike with the fault zone to the southeast is known. Although a linear concealed extension of the San Andreas fault may exist under the Salton Sea or in the northern Imperial Valley, no convincing geological or geophysical evidence yet supports such a projection. Babcock (1971) argued that photolineaments in cultivated fields and offset concrete canal liners southeast of Niland, Calif., represent possible active fault traces, but comparison of these photolineaments with earlier aerial photographs show them to be recessional shoreline features of former Lake Cahuilla. The offsets of canal liners are not convincing evidence of fault movement because of structional irregularities and because buckled and misaligned liners are widespread throughout the Imperial Valley."

Figure 6 shows the southeastern side of the Salton Sea and the surface relation between the WMPL and San Andreas fault (SAF). Also shown are the locations of the mud pots from Table 1. Because fault traces can be nonlinear, a southeastern extension of the SAF through the Salton Sea coincides closely enough with the trajectory of the Wister field mud pots to lead us to believe that the WMPL may be a through-going tectonic feature.

Based on Clark (1984), the southern 8 km of the SAF strikes N48°W $\pm 1.6°$ with the southern-most two kilometers striking N51°W before the main trace vanishes about 4 km northwest of Bombay Beach. A 20-km southeastward extrapolation of the SAF striking N51°W to the Wister area (Fig. 6) falls on the northwestern end of the WMPL. The WF was shown to strike $\approx$N45°W (Meidav and Furgerson, 1972) but being uncertain, the strike could be a few degrees more or less than N45°W. Several degrees of strike variation over 30 km is entirely reasonable. More recent compilations such as the Qfaults database (see http://earthquake.usgs.gov/regional/qfaults/ and ftp://hazards.cr.usgs.gov/maps/qfault/, last accessed July 2008) from the U.S. Geological Survey (USGS), the California Geological Survey, and other partners, show a north-northwesterly strand that nearly passes through Bombay Beach and appears to be aligned with the seismicity lineaments in Figure 7. Clearly the spreading center associated with the BSZ is more complex than just two strike-slip faults bounding an extensional fault.

The possible southeastward extension of the SAF as a discrete fault through and beyond the Salton Sea is frequently mentioned in the literature but has never been resolved. Many maps show no extension beyond the accepted

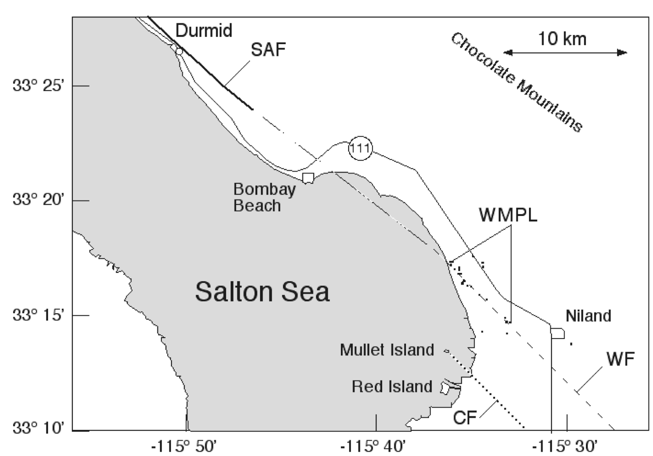

Figure 6. Map showing the spatial relation between the SAF, WF, and WMPL. SAF—thick solid line, WF)—thin dashed line (also coincident with the Sand Hills fault), SAF extrapolation—thin dot-dashed line through the Salton Sea. Mullet Island is the most northerly volcanic neck of the Salton Buttes and is part of a mud pot lineament (Kelley and Soske, 1936) associated with the CF. Red Island consists of two merged volcanic necks.

Figure 7. Known and inferred faults in the southern Salton Trough region. Most were taken from the Qfaults database (http://earthquake.usgs.gov/regional/qfaults/, last accessed July 2008). SA denotes San Andreas, HS denotes Hot Springs, CC denotes Coyote Creek, ER denotes Elmore Ranch, C denotes Calipatria, RH denotes Red Hill, W/SH/A denotes Wister/Sand Hills/Algodones, SM denotes Superstition Mountain, SH denotes Superstition Hills, B denotes Brawley, I denotes Imperial, CP denotes Cerro Prieto. LM is the fault inferred by Lohman and McGuire (2007) from the 2005 earthquake swarm. The Calipatria and Red Hill faults locations were taken from Figure 5.

southern terminus north of Bombay Beach. Crowell (1975) shows a minor fault transecting the sea slightly north of the WMPL. Crowell and Sylvester (1979) show the SAF extending through the Salton Sea east of the WMPL and joining the possible Sand Hills fault while Korsch (1979) suggests that the SAF passes just north of the Salton Sea before joining the Sand Hills fault. Sharp's map (1982), on the other hand, suggests that a SAF extension might pass through the sea south of the WMPL and in the same reference shows a map with the SAF bending well south and probably joining the Brawley fault as suggested by others. Because of the absence of direct evidence for an extension, the lack of consensus is understandable.

The tectonic complexity of the region is evident from the number of unparallel transform faults that strike predominantly N35°W and N35°E, corresponding to an intersection angle of 70°, not 90°. Based on recent earthquake relocation studies (Shearer *et al.*, 2005; Lin, Shearer, and Hauksson, 2007; Lin *et al.*, 2007), there are also northwest- and northeast-striking seismicity lineaments that are roughly parallel to the faults (Fig. 8). Cutting through the northwest-trending WMPL, and Wister, Calipatria, and Red Hills faults is a northeast-trending fault left-lateral fault (Lohman and McGuire, 2007) revealed by the 2005 earthquake swarm. The fault strikes N35°E and appears to terminate on or very near the WMPL.

In view of the nearly perfect alignment of the SAF, the Wister mud pots, and the seismicity lineament, we suggest that the SAF extends at least as far east as Niland and perhaps farther. It may be an abandoned trace of the fault or one that has simply been seismically inactive in historic times. The presence of a linear field of geothermal features is

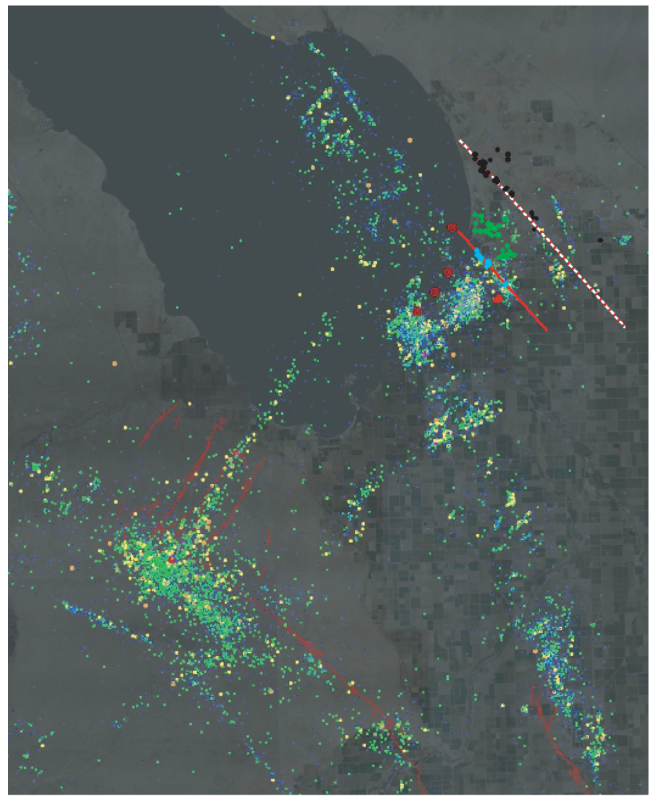

Figure 8. Precisely relocated earthquake epicenters shown as small colored dots are from the period 1981—2005 (Shearer *et al.*, 2005). Earthquake magnitudes from Lin *et al.* (2007) are shown by the color of symbols: orange are $M > 4$, yellow are $M > 3$, green are $M > 2$, and blue are $M > 1$ (approximately). Mud pots are indicated by black dots (Wister pots), blue stars (Mullet Island pots), green diamonds (CO_2 well locations), and red squares (unassigned pots). The Salton Buttes volcanoes are indicated by four orange dots and active fault traces by red lines. The two red–white dotted lines show the known CF (lower) and the putative Sand Hills/Wister fault (upper). At center right is a grouping of epicenters that trends northeast and represents the 2005 swarm. Also evident are a number of narrow seismicity lineaments that trend N36°E that seem to terminate along another lineament (top center) that trends N38°W. These lineaments do not meet at right angles. The broad northwest-trending seismicity lineament at the lower right suggests the existence of a fault but none has been identified. See Hudnut, Seeber, and Rockwell (1989) for the geologic background of the area.

evidence of a planar rift extending to considerable depth in the crust, that is, a fault. The absence of surface evidence for slippage is probably the result of intense agricultural reshaping of the landscape and the fact that there have been no surface-rupturing earthquakes along the SAF-WMPL in recent times.

Summary and Conclusions

We have surveyed and mapped the mud pots in the Wister field and shown that they show a strong clustering along the putative Wister fault (also known as the Sand Hills fault). Within the uncertainties of the trace of the San Andreas fault, a southeastward extrapolation of its trace coincides with the alignment of Wister mud pots. At present, no concrete evidence exists that we know of to definitively connect the San Andreas fault through the Salton Sea all the way to the WMPL. The alignment, however, is strongly suggestive of a deep-seated connection such as a through-going extension of the San Andreas fault towards the southeast. Although such a structure has been previously suggested and called the Wister or Sand Hills fault, neither of these were based on surficially active features. We strongly suspect but cannot prove that the WMPL is of a tectonic origin. We cannot detect a sense of finite slip across the WMPL, but we believe that the high rate of carbon dioxide flux along the WMPL may indicate a component of extension normal to the WMPL. The WMPL appears to be a southeastern extension of the San Andreas fault or at least associated with the SAF.

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Appendix

Listed in Table A1 are mud pots and vents associated with former CO_2 commercial production and identified on

Table A1

Most of the Mud Pots Listed Here Were Used in the Production of CO_2; Some Are Now Covered by the Salton Sea and All Are Now Abandoned

Designation	Latitude	Longitude	Comment
C1	33°13.018′	−115°34.752′	
C2	33°13.053′	−115°34.753′	
C3	33°13.055′	−115°34.682′	S
C4	33°13.077′	−115°35.151′	
C5	33°13.085′	−115°34.807′	S
C6	33°13.099′	−115°34.861′	S
C7	33°13.110′	−115°34.752′	S
C8	33°13.115′	−115°34.795′	S
C9	33°13.132′	−115°34.812′	S
C10	33°13.132′	−115°34.644′	S
C11	33°13.147′	−115°34.696′	S
C12	33°13.160′	−115°34.753′	S
C13	33°13.160′	−115°34.828′	S
C14	33°13.166′	−115°34.629′	S
C15	33°13.174′	−115°34.349′	
C16	33°13.177′	−115°34.807′	S
C17	33°13.269′	−115°34.854′	S
C18	33°13.383′	−115°34.840′	S
C19	33°13.559′	−115°34.693′	S
C20	33°13.857′	−115°35.042′	
C21	33°13.947′	−115°35.457′	
C22	33°13.967′	−115°35.097′	
C23	33°13.980′	−115°35.324′	
C24	33°14.017′	−115°35.098′	
C25	33°14.019′	−115°35.125′	
C26	33°14.022′	−115°35.381′	
C27	33°14.046′	−115°35.292′	
C28	33°14.070′	−115°35.529′	

(*continued*)

Table A1 (*Continued*)

Designation	Latitude	Longitude	Comment
C29	33°14.121′	−115°36.134′	S
C30	33°14.128′	−115°35.993′	S
C31	33°14.149′	−115°35.832′	S
C32	33°14.158′	−115°35.933′	S
C33	33°14.179′	−115°35.696′	S
C34	33°14.194′	−115°36.052′	S
C35	33°14.198′	−115°35.058′	
C36	33°14.209′	−115°36.250′	S
C37	33°14.214′	−115°35.635′	S
C38	33°14.241′	−115°35.472′	
C39	33°14.272′	−115°35.283′	
C40	33°14.275′	−115°36.159′	S
C41	33°14.310′	−115°35.478′	
C42	33°14.372′	−115°35.482′	
C43	33°14.385′	−115°35.416′	
C44	33°14.400′	−115°35.094′	
C45	33°14.427′	−115°35.399′	
C46	33°14.460′	−115°35.458′	
C47	33°14.489′	−115°35.504′	
C48	33°14.503′	−115°35.621′	S
C49	33°14.503′	−115°36.004′	S
C50	33°14.510′	−115°36.168′	S
C51	33°14.557′	−115°35.898′	S
C52	33°14.621′	−115°35.956′	S
C53	33°14.641′	−115°35.866′	S
C54	33°14.657′	−115°35.867′	S
C55	33°14.750′	−115°35.970′	S
C56	33°14.848′	−115°35.981′	S
C57	33°14.856′	−115°36.288′	S
A1	33°13.013′	−115°34.757′	
A2	33°13.054′	−115°34.688′	
A3	33°13.080′	−115°34.810′	
A4	33°13.110′	−115°34.810′	
A5	33°13.124′	−115°34.649′	
A6	33°13.129′	−115°34.811′	
A7	33°13.133′	−115°34.759′	
A8	33°13.171′	−115°34.698′	
A9	33°13.145′	−115°34.827′	
A10	33°13.157′	−115°34.632′	
A11	33°13.174′	−115°34.884′	
A12	33°13.179′	−115°34.649′	
A13	33°13.277′	−115°34.860′	
A14	33°13.555′	−115°34.702′	

Prefix C indicates that the pot locations were taken from identifiers on topographic maps. Prefix A indicates that the pot is clearly visible in modern aerial imagery. S indicates that the vent is in the Salton Sea or in the marshes immediately adjacent to the sea.

the World Geodetic System 1984 (WGS84) topographic survey as CO_2 well. Though not geothermal structures themselves, the wells are indicative of significant CO_2 emissions and therefore are suggestive of geologic features. Most of the accessible pots are within a few hundred meters of the intersection of Davis Road and Pound Road (33°13.214′–115° 34′.788′) where remains of the old CO_2 plant are found. There are many smaller pots and vents in the area that are not listed here.

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