



# Volatile fluxes through the Big Bend section of the San Andreas Fault, California: Helium and carbon-dioxide systematics



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## ABSTRACT

To investigate the source of volatiles and their relationship to the San Andreas Fault System (SAFS), 18 groundwater samples were collected from wells near the Big Bend section of the SAFS in southern California and analyzed for helium and carbon abundance and isotopes. Concentrations of <sup>4</sup>He, corrected for air-bubble entrainment, vary from 4.15 to 62.7 ( $\times 10^{-8}$ ) cm<sup>3</sup> STP g<sup>-1</sup> H<sub>2</sub>O. <sup>3</sup>He/<sup>4</sup>He ratios vary from 0.09 to 3.52  $R_A$  (where  $R_A$  = air <sup>3</sup>He/<sup>4</sup>He), consistent with up to 44% mantle helium in samples. A subset of 10 samples was analyzed for the major volatile phase (CO<sub>2</sub>) – the hypothesized carrier phase of the helium in the mantle–crust system: CO<sub>2</sub>/<sup>3</sup>He ratios vary from 0.614 to 142 ( $\times 10^{11}$ ), and  $\delta^{13}\text{C}$  (CO<sub>2</sub>) values vary from –21.5 to –11.9‰ (vs. PDB).

<sup>3</sup>He/<sup>4</sup>He ratios and CO<sub>2</sub> concentrations are highest in the wells located in the Mil Potrero and Cuddy valleys adjacent to the SAFS. The elevated <sup>3</sup>He/<sup>4</sup>He ratios are interpreted to be a consequence of a mantle volatile flux though the SAFS diluted by radiogenic He produced in the crust. Samples with the highest <sup>3</sup>He/<sup>4</sup>He ratios also had the lowest CO<sub>2</sub>/<sup>3</sup>He ratios. The combined helium isotope, He–CO<sub>2</sub> elemental relationships, and  $\delta^{13}\text{C}$  (CO<sub>2</sub>) values of the groundwater volatiles reveal a mixture of mantle and deep crustal (metamorphic) fluid origins. The flux of fluids into the seismogenic zone at high hydrostatic pressure may cause fault rupture, and transfer volatiles into the shallow crust.

We calculate an upward fluid flow rate of 147 mm a<sup>-1</sup> along the SAFS, up to 37 times higher than previous estimates (Kennedy et al., 1997). However, using newly identified characteristics of the SAFS, we calculate a total flux of <sup>3</sup>He along the SAFS of  $7.4 \times 10^3$  cm<sup>3</sup> STP a<sup>-1</sup> (0.33 mol <sup>3</sup>He a<sup>-1</sup>), and a CO<sub>2</sub> flux of  $1.5 \times 10^{13}$  cm<sup>3</sup> STP a<sup>-1</sup> ( $6.6 \times 10^8$  mol a<sup>-1</sup>), ~1% of previous estimates. Lower fluxes along the Big Bend section of the SAFS suggest that the flux of mantle volatiles alone is insufficient to cause the super hydrostatic pressure in the seismogenic zone; however, results identify crustal (metamorphic) fluids as a major component of the CO<sub>2</sub> volatile budget, which may represent the additional flux necessary for fault weakening pressure in the SAFS.

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## 1. Introduction

The San Andreas Fault System (SAFS) in California is the most active fault system in the continental USA. In the historical record, numerous high-magnitude earthquakes have resulted in displacement along the SAFS. In the central and southern sections, these include, in chronological order, the Fort Tejon ( $M=7.9$ ; 1857), Imperial Valley ( $M=7.8$ ; 1892;  $M=7.1$ ; 1940), San Francisco ( $M=7.8$ ; 1906), Loma Prieta ( $M=6.9$ ; 1989), Landers (Mojave) ( $M=7.3$ ; 1992), Northridge ( $M=6.7$ ; 1993), Hector Mine (Mojave) ( $M=7.1$ ; 1999), and Mexicali ( $M=7.2$ ; 2010) (U.S. Geological Survey, 2011) earthquakes. Nearly 30 million people live in close proximity to the SAFS and are at risk from earthquake-related damage. Understanding the timing and

mechanisms that lead to fault failure is essential for civil planning, and for a deeper understanding of tectonic processes.

One explanation for weakness along the SAFS is the reduction of the effective stress by fluid overpressure. Models that invoke elevated fluid pressure for fault-weakening propose several different fluid sources, including crustal metamorphic-derived and mantle-derived fluids. Some crustal-fluid models suggest the infiltration of fluids from the surrounding host rock, and subsequent compaction and thermal expansion of sealed fault-zone materials (Sleep and Blanpied, 1992; Byerlee, 1993) requiring that the base of the seismic zone, the brittle–ductile transition, to be an impermeable boundary. Others identify metamorphic alteration of the underlying Franciscan formation and local limestone compaction as the fluid sources (Pili et al., 2002, 2011) or combine mantle and crustal dehydration fluxes (Faulkner and Rutter, 2001). In these cases, the recurrent overpressure would require fluid recharge. The continuous mantle–fluid flux

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model explains the increased pore pressure as a result of a vertical flux of deep crust or mantle fluids into the seismogenic zone (Barnes et al., 1984; Bredehoeft and Ingebritsen, 1990; Rice, 1992; Kennedy et al., 1997; Kharaka et al., 1999; Chiodini et al., 2011). The investigation of exhumed faulted rocks, vein fillings, and fluid inclusions (Pili et al., 2011) or fault-zone drill fluids (Wiersberg and Erzinger, 2011) offer promising approaches for investigating the origin, evolution, and flowpaths of the fluids.

The study of helium in earthquake-prone regions is of particular interest because helium isotope systematics in fluids is sensitive to mixing between crustal and mantle end members. Indeed, helium, when coupled with CO<sub>2</sub>, also can be used to quantify mixing between crustal and mantle-derived volatiles in fluids, and to estimate mantle He and CO<sub>2</sub> fluxes, as shown by Kennedy et al. (1997) for the SAFS. In this vein, we report helium and CO<sub>2</sub> abundances and isotopic characteristics of groundwater collected at wells adjacent or close to the Big Bend section of the SAFS. Our aims are four-fold: (1) determine the origin of fluids, and calculate the mixing proportions between crustal and mantle volatile inputs, (2) estimate the absolute flux of CO<sub>2</sub> released to the surface via this section of the SAFS, (3) evaluate whether observed fluxes are sufficient to sustain pore-fluid pressure in the seismogenic zone at a level sufficient to cause fault weakening, and (4) explain the heterogeneity in helium isotope values in wells which are in close proximity to one another, as observed elsewhere along the SAFS (e.g. Kennedy et al., 1997).

## 2. Cuddy Mil Potrero, and Cuyama valleys, California

### 2.1. Tectonic environment

The ~1300-km-long San Andreas Fault System (SAFS) delineates the boundary between the North American and Pacific plates (Wallace, 1990). It began forming ~30 Ma – following a shift from subduction to transform motion, and the development of the northward-migrating Mendocino Triple Junction (Wallace, 1990). The relative motion between the North American and Pacific plates along the transform boundary over the past 3 to 4 million years has been estimated at ~50 mm a<sup>-1</sup>, based on marine magnetic anomalies (DeMets et al., 1987), with a N 35° W direction of dextral slip between the plates. Geologic offset and geodetic data for the SAFS, on the other hand, suggest a slip rate between 7 and 43 mm a<sup>-1</sup> (Stirling et al., 1996), with a mean value of ~35 mm a<sup>-1</sup> (Hill et al., 1990), with the main fault trace striking N 65–70° W. This discrepancy in direction and slip rates can be accounted for by extensional deformation of the western margin of the North American Plate at 10 mm a<sup>-1</sup> in a N 56° W direction (Hill et al., 1990).

The last major earthquake along the central section of the SAFS, the 1857 Fort Tejon earthquake, resulted in a 300 km-long rupture from the Cholame Valley to Wrightwood (Sieh, 1978). The maximum fault displacement of ~9 m occurred in the Carrizo Plain section, with less slip occurring to the north and south. Crustal deformation measurements along the Carrizo Plain section of the SAFS indicate 30 mm a<sup>-1</sup> of right-lateral slip (Sieh, 1978).

The Cuyama, Mil Potrero, and Cuddy valleys lie within the seismically-active SAFS which, in this region, is dominated by northwest-trending, right lateral strike-slip faults. The Cuyama Valley is bounded to the north by the Morales Fault and to the west and south by the South Cuyama, Ozena, and Big Pine faults, all of which are associated with the SAFS.

### 2.2. Hydrogeology of the study area

The study area includes the Cuyama Valley, and to the east along the SAFS, the Mil Potrero and Cuddy valleys (Fig. 1). The primary water-bearing formations are mainly unconfined and are composed of younger (Holocene) and older (Pleistocene) alluvium (consisting

of alternating layers of sands, gravels, silts, and clays) (Mathany et al., 2009). The study area is bounded on the west and south by the Sierra Madre Mountains, on the south by Mount Pinos, Cerro Noroeste, and Sawmill Mountain, on the north by the Caliente Range and Tecuya Ridge, and to the east by the Tehachapi Mountains. Altitudes of land surface range from about 600 m in the Cuyama Valley to the west, to about 2688 m at Sawmill Mountain to the southeast. The groundwater basins are mostly Quaternary alluvial fill, while the surrounding mountains are Mesozoic granites, volcanics and sedimentary units (Mathany et al., 2009).

## 3. Field and laboratory methods

Groundwater samples were collected from 18 wells in the Cuyama, Cuddy, and Mil Potrero valleys of southern California (Fig. 1), from August to December 2008, as part of the Priority Basins Project of the Groundwater Ambient Monitoring and Assessment Program (<http://ca.water.usgs.gov/gama/>). The wells included 10 public supply wells, 5 domestic wells, and 3 irrigation wells with a median well depth of ~100 m (Mathany et al., 2009). Dissolved gas (helium and CO<sub>2</sub>) samples were collected in 3/8 inch-diameter copper tubes (~35 cm long) using braided nylon tubing connected to a hose bib at the wellhead. Groundwater was flushed through the tubing to dislodge bubbles before the flow was restricted with a back-pressure valve. Refrigeration clamps on either end of the copper tube were then tightened, trapping a sample of groundwater for analyses of dissolved noble gases and CO<sub>2</sub> (e.g. Weiss, 1968; Kulongoski and Hilton, 2011).

At the Scripps Institution of Oceanography, samples were released into an ultra-high vacuum extraction line (Kulongoski and Hilton, 2002) where dissolved gases were exsolved from the water phase, aided by acidification to ensure complete release of dissolved CO<sub>2</sub>. The CO<sub>2</sub> and He–Ne fractions were isolated from other gases, by a combination of active-gas gettering and/or cryogenic separation, and captured in glass breakseals for transfer to dedicated lines for further purification and manometric measurement. Isotopic analyses proceeded adopting analytical protocols described previously (Shaw et al., 2003; Kulongoski and Hilton, 2011). A fraction of the CO<sub>2</sub> gas was collected in a Pyrex glass tube, on which the δ<sup>13</sup>C values were measured using a Delta V isotope ratio mass spectrometer (Ray et al., 2009; Hilton et al., 2010). The international standard Pee Dee Belemnite (V-PDB) was used for calibration, and an overall precision of less than 0.1‰ was achieved. The accuracy of the δ<sup>13</sup>C determination (±0.5‰) was estimated by repeat analyses of a working laboratory standard, itself calibrated relative to V-PDB.

Noble gas samples were analyzed at the Lawrence Livermore National Laboratory (LLNL) using an isotope dilution protocol and VG-5400 mass spectrometer (Cey et al., 2008). Uncertainties were calculated as the highest of the following: (1) best typical precision for the parameter (2% for <sup>3</sup>He/<sup>4</sup>He, He, and Ne contents); (2) reproducibility of concurrently run air standards; (3) propagated uncertainty of the unknown sample ratio (for <sup>3</sup>He/<sup>4</sup>He analyses only, to account for instrumental variation in background <sup>3</sup>He count rates).

## 4. Results

Results of the He analyses (isotope compositions and concentrations) are reported in Table 1. In addition, Ne concentrations are given, in order to correct for the presence of excess air-derived atmospheric helium, together with tritium (<sup>3</sup>H) contents of the water phase to assess possible contributions to the <sup>3</sup>He inventory from the decay of atmospheric tritium generated in the 1960s by nuclear-weapons testing. Results of the CO<sub>2</sub> analyses (isotope compositions and concentrations) along with CO<sub>2</sub>/<sup>3</sup>He molar ratios are reported in Table 2.

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