CONFERENCE PROCEEDINGS

Implications of results from CO_2 flux surveys over known CO_2 systems for long-term monitoring

Rick Allis[1], Deborah Bergfeld[2], Joe Moore[3], Kevin McClure[1], Craig Morgan[1], Tom Chidsey[1], Jason Heath[4] and Brian McPherson[4]

[1] Utah Geological Survey, PO Box 146100, Salt Lake City, UT84114-6100; ph 801-537-3300; fax 801-537-3400; rickallis@utah.gov
[2] U.S. Geological Survey, Menlo Park, 345 Middlefield Rd., MS434, CA94025; ph. 650-329-4657; dbergfel@usgs.gov
[3] Energy and Geoscience Institute, 423 Wakara Way, Suite 300, Salt Lake City, UT84108; ph 801-585-6931; fax 801 585 3540; jmoore@egi.utah.edu
[4] New Mexico Tech., 801 Leroy Place, Socorro, NM87801, ph. 505-835-5259 brian@nmt.edu

FOURTH ANNUAL CONFERENCE ON CARBON CAPTURE AND SEQUESTRATION DOE/NETL
May 2-5, 2005

Abstract

Soil CO_2 flux surveys have been carried out over three regions with natural occurrences of CO_2 on the Colorado Plateau. At Farnham Dome, Utah, and Springerville-St. Johns, Arizona, proven CO_2 reservoirs occur at 600 - 800 m depth, but no anomalous CO_2 flux was detected. Background fluxes of up to about 5 g m^{-2} day^{-1} were common in poorly vegetated, arid areas, and up to about 20 g m^{-2} day^{-1} were found at Springerville-St. Johns in heavily vegetated, wet ground adjacent to springs. The higher fluxes are attributed to shallow root zone activity rather than to a deep upflow of CO_2. At the Crystal Geyser-Ten Mile Graben in Utah, localized areas of anomalously high CO_2 flux (~ 100 g m^{-2} day^{-1}) occur along a fault zone near visibly degassing features. Isotopic measurements on CO_2 collected from nearby springs indicate that it originated at depth. Evidence of widespread vein calcite at the surface (Farnham Dome) and travertine deposits at the other two areas suggests that discharge of CO_2-rich fluids has occurred in the past. Despite the lack of evidence for significant present day leakage of CO_2 to the atmosphere at Springerville-St. Johns and Crystal Geyser-Ten Mile Graben, there are significant outflows of high-bicarbonate water in both areas suggesting continuous migration of CO_2 in the aqueous phase from depth. The very localized nature of the CO_2 flux anomalies, and the outflow of ground water containing dissolved CO_2 present challenges for effective, long-term monitoring of CO_2 leakage.

Introduction

The most critical issue confronting acceptance of geologic sequestration of anthropogenic CO_2 is the assurance that most of the CO_2 will stay in the subsurface. Natural CO_2 systems on the Colorado Plateau provide insights to the characteristics of CO_2 reservoirs and their overlying sealing rocks (Allis et al., 2001; White et al., 2004; Moore et al., 2005). The existence of these reservoirs appears to confirm that favorable structures can trap CO_2 on a geologic time scale. However, there has been little work to evaluate the effectiveness of reservoir seals, and the nature, if any, of CO_2 leakage to the surface. In this paper we present the results of soil CO_2 flux surveys over three regions of known CO_2 accumulation on the Colorado Plateau. The implications for quantitative characterization of the surface CO_2 flux and long-term monitoring are then discussed.

Although considerable work has been published on leakage of hydrocarbons from reservoirs (e.g., Schumacher and Abrams, 1996), most of the scientific literature referring to anomalous fluxes of diffuse CO_2 has been in volcanic and geothermal settings (Cardellini et al., 2003, and references therein). There does not appear to be any published literature on the anomalous soil gas emissions from natural CO_2 systems within sedimentary settings. Klusman (2003a, b) carried out CH_4 and CO_2 soil gas flux measurements over Rangely oil field, Colorado where there has been CO_2 injection for enhanced oil recovery since 1986. There a low level of CH_4 and CO_2 "microseepage" was detected, and most of the CO_2 was attributed to methanotropic oxidation of CH_4 in the unsaturated zone. Soil CO_2 fluxes locally ranged up to 1 – 3 g m^{-2} day^{-1}. At another oil field, Teapot Dome in Wyoming, average fluxes during winter at a time of low bacterial activity were an order of magnitude lower (Klusman, 2004).

The three natural CO_2 systems that are the subject of this paper are Farnham Dome (Utah), Springerville-St. Johns (Arizona-New Mexico), and Crystal Geyser-Ten Mile Graben (Utah) (Figure 1). In all three regions, CO_2 has accumulated in the Mesozoic – Paleozoic sedimentary section that is common on the Colorado Plateau. Nearly 5 BCF of CO_2 was produced from Farnham Dome between 1931 and 1979, when the wells were shut-in because of the lack of a market. The main reservoir is in the Jurassic Navajo Sandstone at about 600 m depth. CO_2 has also been tested in deeper formations, and has been found in several wells over 4 km apart on the east flank of the anticlinal structure (Morgan and Chidsey, 1991; White et al., 2004). The CO_2 reserves have been estimated at 1.5 TCF (D. Davis, pers. comm., cited in White et al., 2004).

At the Springerville-St Johns system, the proven CO_2 field covers > 1000 km^2 and contains approximately 14 TCF of CO_2 (S. Melzer, pers. comm., in White et al., 2004). The CO_2 mostly occurs at about 500 m depth in clastic and carbonate units of the Permian Supai Group in an anticlinal structure, with overlying anhydrite and mudstone acting as sealing units (Rauzi, 1999). Some CO_2 has also been tested in gravels immediately above the Precambrian granite beneath the Supai Group sediments. There are large volumes of travertine at the surface, natural bicarbonate-rich springs and groundwater, and nearby Quaternary and Neogene volcanics (0.3 – 3 Ma) suggestive of a possible recent, deep CO_2 source (Moore et al., 2005).

At Crystal Geyser-Ten Mile Graben, east-west trending faults cut two north-dipping anticlines (Doelling, 2001). Several natural CO_2 features (four bubbling pools) and CO_2-charged fluids that erupt intermittently (e.g., Crystal Geyser) from two abandoned petroleum exploratory wells occur along the fault zones near the axis of the structural highs (Doelling, 1994; Heath, 2004). Actively precipitating travertine, and significant amounts of fossil travertine deposits, occur near these features, and cap adjacent terraces and buttes. Recent work has characterized the geology and geochemistry of the area (Dockrill et al., 2004; Heath 2004; Williams, 2004).

Soil CO_2 Flux Measurements

Method

The purpose of the CO_2 flux measurements was to provide reconnaissance-scale surveys over the three areas of subsurface CO_2 accumulation to identify areas of anomalous flux. The areas of CO_2 accumulation are large (100 – 1000 km^2), so a systematic grid survey across each area was not feasible. Instead, locations for each investigation were chosen based on geologic and hydrologic factors with sites preferentially located over areas of possible leakage. Our surveys included fault zones and structural highs, areas located near calcite veins, thick travertine accumulations, and around bubbling springs and pools. We recognized that results from such surveys could not be used to assess total CO_2 emissions, but hoped the results would confirm or deny CO_2 leakage from the reservoirs and provide qualitative estimates of the scale of the soil CO_2 fluxes.

Measurements were made using a Westsystems flux meter containing a LI-COR 820 infrared gas analyzer (IRGA) connected to a palm computer. The IRGA was calibrated at the start of each field survey using CO_2–free air and 1000 ppm CO_2 standards. CO_2 measurements are made by placing an accumulation chamber (AC) on the soil surface and pressing it into the soil to obtain a seal. AC gases are pumped through a desiccant to the IRGA and are returned to the AC in a closed loop. During the measurement CO_2 concentration data and elapsed time are displayed on the computer. Data were collected for a minimum of 2 minutes at each site. Atmospheric pressure (P) and the soil temperature (T) at 10 cm depth were recorded at each site. The CO_2

flux (F_{CO2}) in units of grams of CO_2 per m^2 per day ($g\ m^{-2}\ d^{-1}$) is calculated from the rate of change of CO_2 concentration (*dc/dt*) using Equation 1, where R is the gas constant, V is the system volume, A is the area of the AC footprint, and k is a constant for unit conversion:

$$F = k\left[\frac{P}{RT} \times \frac{V}{A} \times \frac{dc}{dt}\right] \qquad 1$$

An example of the raw data from a site with a flux of 120 $g\ m^{-2}\ d^{-1}$ is shown in Figure 2.

Because our goal was to measure anomalous fluxes, if the CO_2 concentration in the AC did not increase sufficiently to produce a good correlation coefficient for *dc/dt* in two minutes, the flux was defined as "zero." Given the chosen sampling time constraint the minimum flux value we recorded was 1.3 $g\ m^{-2}\ d^{-1}$. Low flux values in this range are similar to what has been described from basin-fill sediments at Dixie Valley, Nevada, and are likely related to biogenic CO_2 emissions (Bergfeld et al., 2001).

Expected variability

The variation in replicate flux measurements at an individual site is a function of the amount of soil disturbance, meteorological conditions, operator skill, instrument stability and natural variations in CO_2 emissions (Lewicki et al., 2005). Expected measurement errors are reported from laboratory experiments as under representing actual values by 12% (Evans et al., 2001), or varying by ± 10% (Chiodini et al., 1998). A recent field-based comparative study of diffuse CO_2 emissions on the flanks of Comalito Volcano, Nicaragua showed that consecutive flux measurements by five teams of researchers at thirty-six grid points over very high-flux thermal ground (F_{CO2} from 218 to 14,719 $g\ m^{-2}\ d^{-1}$) varied between 5 and 167% (Lewicki et. al., 2005).

Results from replicate flux measurements from thirty-four moderate to high-flux thermal sites (F_{CO2} from 6 to 1,368 $g\ m^{-2}\ d^{-1}$) over geothermal systems in Long Valley caldera, California and Dixie Valley, Nevada, suggest that measurement variations over the low to moderate flux sites typical of this study will be lower than what is reported for diffuse volcanic emissions (Fig. 3). The geothermal data exhibit a positive exponential relation between increasing flux and the standard deviation of replicate measurements. The coefficient of variation for replicate measurement at these sites was between 0.2 and 29%. Since most fluxes at the Green River sites are ≤ 50 g m^{-2} d^{-1}, and assuming the field sites will be properly sited and sufficiently prepared, we expect replicate measurements will vary at or below what was found in the geothermal locations.

Field Survey Techniques

The sampling design varied for each of the three investigations. At Farnham Dome, the first of the areas to be surveyed, we initially set up 40 flux measurement nodes on a 25 m grid. This sampling scheme took several hours to complete, and once it was realized that the gas flux was uniformly low, the number of measurement nodes per grid was decreased. After the first grid, the average number of measurement nodes per grid at Farnham Dome was 18, and in most cases, these were still on a grid spacing of 25 m. This enabled us to complete about five to eight grids a day, depending on ease of access and distance between sites. At Springerville-St. Johns, the number of measurements per grid was further reduced to about 10 after the first day of measurements also showed uniformly low values. It was decided that the priority should be to make measurements in a survey mode in order to investigate as many prospective sites as possible rather than concentrate on acquiring the systematic coverage needed for the determination of average emissions rates. At Crystal Geyser-Ten Mile Graben, the obvious fault control on visible CO_2 outflow areas, and (in places) the limited access through washes at right angles to the faults, required we make long linear traverses with measurements at a 25 m spacing. In the areas where gas anomalies were detected, additional measurements were usually made to improve delineation of the anomaly.

Results

Farnham Dome

CO_2 flux results were first presented in White at al. (2004), and are reproduced here in Table 1, and displayed against the surface geology in Figure 4. Measurements were made at 14 sites during April 2004. The average soil CO_2 fluxes and the 95% confidence intervals for the grid means were between 0.5 (0.2-0.9) and 3.7 (2.6-4.7) g m^{-2} d^{-1}. Lower fluxes were measured at grids sited on soils derived from shale as compared with grids that were sited on sandstone-derived soils.

These CO_2 fluxes are very low and are consistent with a low level of shallow biogenic CO_2 production in arid terrain, indicating negligible input of CO_2 from reservoir depths. Klusman (2004a) reports similar values at Rangely oil field, Colorado. In comparable arid sagebrush terrain, background fluxes of 1 to 5 g m^{-2} d^{-1} have been observed adjacent to the Dixie Valley geothermal field, Nevada (Bergfeld et al., 2001), and at Long Valley, California (Bergfeld, in review). In comparison, soil CO_2 respiration rates of 10 to 20 g m^{-2} d^{-1} are characteristic of temperate grasslands, croplands, and tropical savannas (Raich and Schlesinger, 1992).

Although it is possible that seepage, and therefore leakage, of CO_2 derived from the Farnham Dome reservoir may be occurring at other locations away from areas we investigated, we suggest that because we surveyed the most likely sites and all fluxes were uniformly low, it is unlikely that CO_2 seepage is occurring. The lack of a flux anomaly at all 14 sites suggests that Farnham Dome is likely to be sealed, and that the CO_2 deposits could have been present for a geologically long time ($\sim10^7$ years, perhaps coinciding with the time of maximum burial).

During reconnaissance mapping of the faults and structural trends at Farnham Dome, widespread calcite veins were noted in joints in sandstone units of the Cedar Mountain Formation, and linear calcite debris mounds were found in some of the shales. The locations of the calcite veins are shown on Figure 4; however, because the mapping was not comprehensive, other areas are likely to exist. We believe that these calcite veins reflect past leakage of CO_2 from the Farnham Dome reservoir. The flux measurements indicate these zones are now tightly sealed and are not leaking.

Springerville-St. Johns

CO_2 flux measurements were made at 27 areas around the known extent of the CO_2 field during May 2004. The areas were widely spaced and were located in places where geologic or hydrologic factors enhance the possibility of leakage. The locations included sites adjacent to travertine domes, the interior craters which mark vent locations of the domes, basalt cinder cones, the ground adjacent to bicarbonate-rich springs, and next to ground water wells and deep wells that encounter CO_2 gas or bicarbonate-rich water at depth. We also made measurements over deeply eroded structural highs where some of the low-permeability seal rocks were likely to be thin or absent.

The results are tabulated in Table 2, and are superimposed on a map showing selected geologic units in Figure 5. For 22 areas, the average flux is 4 ± 4 g m^{-2} d^{-1}, and is similar in magnitude to the values at Farnham Dome. At five areas, the flux ranged between 10 and 25 g m^{-2} d^{-1}. In all these cases the sites were located on wet, vegetated ground adjacent to springs, the Little Colorado River, or a reservoir. Disturbance of the wet soil often released visible bubbles of CO_2-rich gas, occasionally with an H_2S smell. The higher soil fluxes in these areas are interpreted as resulting from shallow root zone activity in the permanently saturated soil, and not to an upflow of CO_2 from greater depth.

Crystal Geyser-Ten Mile Graben

Flux measurements were concentrated along the Little Grand Wash fault zone (LGWFZ, on which Crystal Geyser is located), and along Ten Mile Graben about 8 km to the south of the LGWFZ. Figure 6 shows the 10 profiles along the LGWFZ in relation to the fault zone traces as mapped by Doelling (2001). The variability of the results can be seen in Figure 7, where the profiles are stacked according to their north coordinate (the LGWFZ strikes approximately east-west). Note that each data point represents one flux measurement, in contrast to the data shown for Farnham Dome and Springerville-St. Johns, which were averages of several flux measurements. On five of the profiles (1, 2, 5, 6, and 8), the anomalous fluxes appear to coincide with the southern trace of the LGWFZ. Two of the profiles closest to Crystal Geyser (1, 2) show a second spike of anomalous flux that occurs approximately 100 m north of the main spike. This appears to coincide with the dual fault trace comprising this part of the LGWFZ.

The highest fluxes occurred close to Crystal Geyser (profile 1), with the highest flux site (> 700 g m^{-2} day^{-1}) located on an outcrop of pre-geyser travertine close to the Green River (Figures 6 and 7). This outcrop appears to have been deposited by springs that existed prior to the drilling of the now-abandoned, Glen Ruby #1-X oil exploration well (now known as Crystal Geyser) in 1935. Zones of gas bubbles were seen along a 50 m stretch of the Green River adjacent to the travertine apron below the geyser, and adjacent to the opposite shore where more travertine

outcrops. During the flux measurements, a H_2S odor was noticed on Profile 3 between the two fault strands, and near the north end of Profile 8 (Figure 6). Shipton et al. (2004) also note a gas seep in about the same position of our Profile 3. An oil seep occurs on the southern fault strand, between Profile 3 and Profile 10.

In Ten Mile Graben, one profile straddled the entire graben (#13), whereas all other profiles were close to the northern fault strand. We chose this configuration because all the bubbling pools and springs occur close to or immediately north of this fault strand (Figure 8). On Profile 13, the measurements indicated there was no anomalous flux on the mapped fault zones defining either side of the graben. However, at the north end of this profile, approximately 400 m from the northern fault trace, the CO_2 flux at one site was 23 g m^{-2} d^{-1}. Three other measurements within about 10 m of this site were not anomalous. The one anomalous site was on top of a subtle ridge (< 0.5 m elevation) of travertine debris suggesting a fracture at depth. On Profile 14 a similar pattern was observed. At the northern end of the profile, close to a bubbling spring surrounded with a travertine apron and about 400 m north of the fault trace, three fluxes of 3 – 5 g m^{-2} d^{-1} were measured. Elsewhere the flux was less than 1 g m^{-2} d^{-1}. Some significant flux anomalies were also detected in Profile 12 (Figure 9), where in one location, the flux ranged to over 100 g m^{-2} d^{-1}. At this location, several sites within about a 50 m radius gave anomalous fluxes. Most of the sites in Profile 12 were in a broad wash that was covered with broken sheets of recent but inactive travertine. The two active features, overflowing pools with gas bubbles, were precipitating travertine, which was cementing the sands in the wash. The scattered travertine deposits suggest this type of spring activity may have occurred elsewhere in the wash in recent geologic time.

In contrast to the flux measurements at the LGWFZ, with one exception the sites having anomalous fluxes at Ten Mile Graben were not directly associated with mapped fault zone traces. The exception was a site near the western end of Profile 12 (Figure 9) where we recorded a flux of 21 g m^{-2} d^{-1}. The flux anomalies typically appeared to be localized leakage points within the Entrada Sandstone that outcrops on the north side of the graben. In places, it appeared that the sites of CO_2 leakage were controlled by jointing in the sandstone, but there were also many sites on joint trends that showed no anomalous flux.

Discussion and Implications

We were surprised that no anomalous CO_2 fluxes were found over the Farnham Dome and Springerville-St. Johns natural CO_2 reservoirs. In the case of Farnham Dome, we are confident that flux measurements were made at the most likely sites for potential CO_2 leakage. At Springerville-St. Johns, the extent of the CO_2 field is much larger than at Farnham Dome, and it is possible that we missed leaking areas. For example, the travertine trend in the north-central part of the field (Figure 5), which appears to define a structural lineament, was poorly sampled and could conceivably contain sites where the reservoir is leaking. Even so, we are confident that significant, widespread, diffuse CO_2 leakage is not occurring at Springerville-St. Johns. At both Farnham Dome and Springerville-St. Johns the reservoirs are at a relatively shallow depth (~ 600 m). This implies that low-permeability layers are acting as effective seals on the reservoirs. The existence of natural CO_2 reservoirs that appear to be geologically long-lived demonstrates that the overlying rock column is preventing significant leakage of CO_2 to the surface. Our flux measurements confirm that CO_2 seepage, if occurring at all, is below our measurement threshold of 1 g m^2 d^{-1}.

In contrast, the LGWFZ - Ten Mile Graben region has sites with a visible gas flux. The main anomalies on the LGWFZ occur over a distance of about 1 km along the fault zone east of the Green River (Figure 6). The map shows three discrete anomalies along the washes that cross the fault zone. It is not known whether the CO_2 flux is, in fact, more uniform along this part of the fault zone, because the profiles were only located in the washes, and not on the steep topography between the washes. In Ten Mile Graben, some of the anomalies were very localized, and were located on fortuitously chosen sites. There could be more widespread seepage of CO_2 through the Entrada Sandstone outcropping on the north side of the graben. Based on the pattern of the anomalies discovered so far, they appear to be point sources (some < 10 m in diameter) of anomalous flux. This has implications for future monitoring programs. Localized leakage would require that a monitoring program comprise both a combination of less frequent but spatially dense surveys across the region, and more frequent monitoring focusing on known CO_2 outflow features.

We believe the CO_2 flux at the LGWFZ and Ten Mile Graben areas is originating from at least several kilometers depth. Previous work (Heath, 2004) has supported the following conceptual model for generation, accumulation, and migration of CO_2 in the Crystal Geyser-Ten Mile Graben area: the formation of separate phase CO_2 occurred at depths greater than ~ 2 km due to lower temperature (100-200°C) clay-carbonate reactions or higher temperature metamorphic reactions. This CO_2 then migrated upward along the faults to charge shallower aquifers. Some deeper water may have migrated upward with the separate CO_2 phase. If clay-carbonate reactions are the source, then these reactions may have occurred during deep burial of the Paradox Basin. Elevated temperatures during deep burial (starting about 95 Ma and continuing to 37 ma [Nuccioi and Condon, 1996]) of clay and carbonate bearing formations could have facilitated the release of CO_2 though clay-carbonate diagenetic reactions. Subsequent exhumation and uplift of the Colorado Plateau then caused these clay and carbonate-bearing formations to be moved to shallower depths, where exsolution of a separate phase CO_2 could occur.

Higher temperature reactions could have also produced the CO_2, but the Tertiary laccoliths in east-central and central Utah are located more than 45 km away from the field area. At any rate, the carbon isotopic signatures of the gases emanating at the surface (- 6.62 ± 0.11‰ VPDB) evince a predominantly inorganic source. Thermal maturation of hydrocarbons contributing a large portion of the CO_2 is unlikely, since the isotopic signature of oil in a surface oil seep close to Crystal Geyser (within ~ 1 km) is much lighter than the isotopic signature of the CO_2 (saturated and aromatic hydrocarbon carbon isotopic signatures of the oil are -28.47‰ and -29.26‰, respectively; Lillis et al., 2003).

The LGWFZ-Ten Mile Graben and Springerville-St. Johns areas have high bicarbonate springs and other waters (Heath, 2004; Moore et al., 2005). Geochemical models (Moore et al., 2005) of the deposition of travertine, and discharge of CO_2 from springs suggest that the fluids are, in places, close to saturation with respect to calcite and dissolved gas. At Springerville-St. Johns, analyses of well samples demonstrate that bicarbonate-rich ground water overlie much of the CO_2 reservoir. Studies of core samples record little evidence of mineral sequestration. Thus a significant proportion of the CO_2 migrating towards the surface may be carried away from the reservoir as bicarbonate-rich fluids, although we can not rule out some precipitation of carbonate minerals along the flow path (e.g., upflow regions). These observations imply that monitoring of the total CO_2 flux requires monitoring surface- and ground-water flows including changes in the

chemical composition of the waters. This would involve ground-water wells and techniques to estimate the rate of ground-water movement. At Farnham Dome, a weak seepage of high-bicarbonate water was found at one location. This seepage appeared to be ephemeral, and given the very arid climate (8 inches of precipitation per year), it is suspected that there is no significant lateral flow of CO_2-saturated ground water in the vicinity of this field.

The lack of a measurable CO_2 flux over two natural CO_2 reservoirs (Farnham Dome and Springerville-St. Johns) is evidence that Colorado Plateau reservoir sequences are capable of trapping CO_2 over geological time periods. However, the very localized nature of soil CO_2 seepage on the LGWFZ-Ten Mile Graben, and evidence that ground water plays a role in dispersing CO_2, present challenges for effectively monitoring the fate of injected CO_2 in artificial CO_2 sequestration reservoirs.

Acknowledgements

This work was supported by a grant from the U.S. Department of Energy (DE-FC26-00NT4096, Program Manager David Hyman) and cost share support from the Utah Geological Survey, the USGS, and the Energy and Geoscience Institute at the University of Utah. We thank Ridgeway Arizona Oil Company, Steve Melzer, and Tucson Electric Power Company for access to, and information about, the Springerville-St. Johns CO_2 field. Tom Dempster and Dave Langton assisted with some of the field measurements.

References

Allis, R.G., Chidsey, T., Gwynn, W., Morgan, C., White, S.P., Adams, M., and Moore, J. 2001. Natural CO_2 reservoirs on the Colorado Plateau and Southern Rocky Mountains: candidates for CO_2 sequestration. Proc. 1st National Conference on Carbon Sequestration, May 14-17, 2001, Washington DC, DOE-NETL CD DOE/NETL-2001/1144.

Bergfeld, D., Goff, F. and Janik, C.J., 2001. Elevated carbon dioxide flux at the Dixie Valley geothermal field, Nevada; relations between surface phenomena and the geothermal reservoir. Chem. Geol., 177 (1-2), 43-66.

Bergfeld, D., Evans, W.C., Howle, J.F., and Farrar, C.D., (in review) Carbon dioxide emissions from vegetation-kill zones around the resurgent dome of Long Valley caldera, eastern California, USA. J. Volcanol. Geotherm. Res.

Cardellini, C., Chiodini, G., Frondini, F. 2003. Application of stochastic simulation to CO_2 flux from soil: Mapping and quantification of gas release. J. Geophys. Res., 108(B9) (doi:10.1029/2002JB002165).

Chiodini, G., Cioni, R., Guidi, M., Raco, B. and Marini, L., 1998. Soil CO_2 flux measurements in volcanic and geothermal areas. Appl. Geochem., 13 (5), 543-552.

Dockrill, B., Shipton, Z.K., Kirschner, D.L., Evans, J.P. 2004. Understanding leakage from a fault-sealed CO_2 reservoir in east-central Utah: a natural analogue applicable to CO_2 sequestration. Abstract No. 234-11, Annual Meeting of Geological Society of America, Denver, November, 2004.

Doelling, H. 1994. Tufa deposits in west Grand County. Utah Geological Survey “Survey Notes”, 26, 2-3, 3 p.

Doelling, H. 2001. Geologic map of the Moab and eastern part of the San Rafael Desert 30' x 60' quadrangles, Grand and Emery Counties, Utah, and Mesa County, Colorado. Map 180, Utah Geological Survey.

Evans, W.C., Sorey, M.L., Kennedy, B.M., Stonestrom, D.A., Rogie, J.D. & Shuster, D.L. 2001. High CO_2 emissions through porous media: transport mechanisms and implications for flux measurement and fractionation. Chem. Geol., 177 (1-2), 15-29.

Heath, J.E., 2004, Hydrogeochemical characterization of leaking carbon dioxide-charged fault zones in east-central Utah. MS thesis, Utah State University.

Klusman, R.W. 2003a. A geochemical perspective and assessment of leakage potential for a mature carbon dioxide-enhanced oil recovery project and as a prototype for carbon dioxide sequestration; Rangely field, Colorado. Amer. Assoc. Pet. Geol., 87, 1485-1508.

Klusman, R.W. 2003b. Rate measurements and detection of gas microseepage to the atmosphere from an enhanced oil recovery/sequestration project, Rangely, Colorado, USA. App. Geochem., 18, 1825-1838.

Klusman, R.W. 2004. Comparison of gas flux and soil gas composition at two oil fields: Rangely, Colorado with CO_2-EOR, and Teapot Dome, Wyoming at baseline condition. Abstract GC54A-01, American Geophysical Union Fall Meeting, San Francisco, December 17, 2004.

Lewicki, J.L., Bergfeld, D., Cardellini, C., Chiodini, G., Granieri, D., Varley, N., and Werner, C., 2005. Comparative soil CO_2 flux measurements and geostatistical estimation methods on Masaya volcano, Nicaragua. In press, Bull. Volcanol.

Lillis, P.G., Warden, A., King, J.D., 2003, Petroleum systems of the Uinta and Piceance Basins– Geochemical characteristics of oil types. In: Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado, chap. 3, Digital Data Series DDS-69-B, U.S. Geological Survey, Denver. 25 pp.

Moore, J., Adams, M., Allis, R., Lutz, S., Rauzi, S., 2005. Mineralogical and geochemical consequences of the long term presence of CO_2 in natural reservoirs: An example from the Springerville-St. Johns field, Arizona and New Mexico, U.S.A. Chemical Geology, in press

Morgan, C.D., and Chidsey, T.C., Jr., 1991. Gordon Creek, Farnham Dome, and Woodside fields, Carbon and Emery Counties, Utah, *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, 301-309.Morgan and Chidsey, 1991.

Raich , J.W., and Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus, Ser. B, 44, 81-99.

Rauzi, S.L. 1999. Carbon dioxide in the St Johns-Springerville area, Apache County, Arizona. Arizona Geological Survey Open-File Report 99-2.

Schumacher, D. and Abrams, M.. 1996. Editors, Hydrocarbon migration and its near surface effects: American Association Petroleum Geology Memoir 66, pp. xxx.

Shipton, Z.K., Evans, J.P., Kirschner, D., Kolesar, P.T., Williams, A.P. and Heath, J. 2004. Analysis of CO_2 leakage through 'low-permeability' faults from natural reservoirs in the Colorado Plateau, east-central Utah. In: Baines, S.J., and Worden, R.H. (eds.) Geological Storage of Carbon Dioxide. Geological Society, London, Special Publications, 233, 43-58.

White S. P., Allis R. G., Bergfeld D., Moore J. N., Chidsey T. C., Morgan C., McClure K., Adams M., Rauzi S. 2004 Evaluating the seal integrity of natural CO_2 reservoirs of the Colorado Plateau. *Proceedings of the 3rd National Conference on Carbon Sequestration*, Washington DC, May 2004, pp. 32.

Williams, A.P., 2004. Structural analysis of carbon dioxide leakage through the Salt Wash and the Little Grand Wash faults from natural reservoirs in the Colorado Plateau, southeastern Utah. MS thesis, Utah State University.

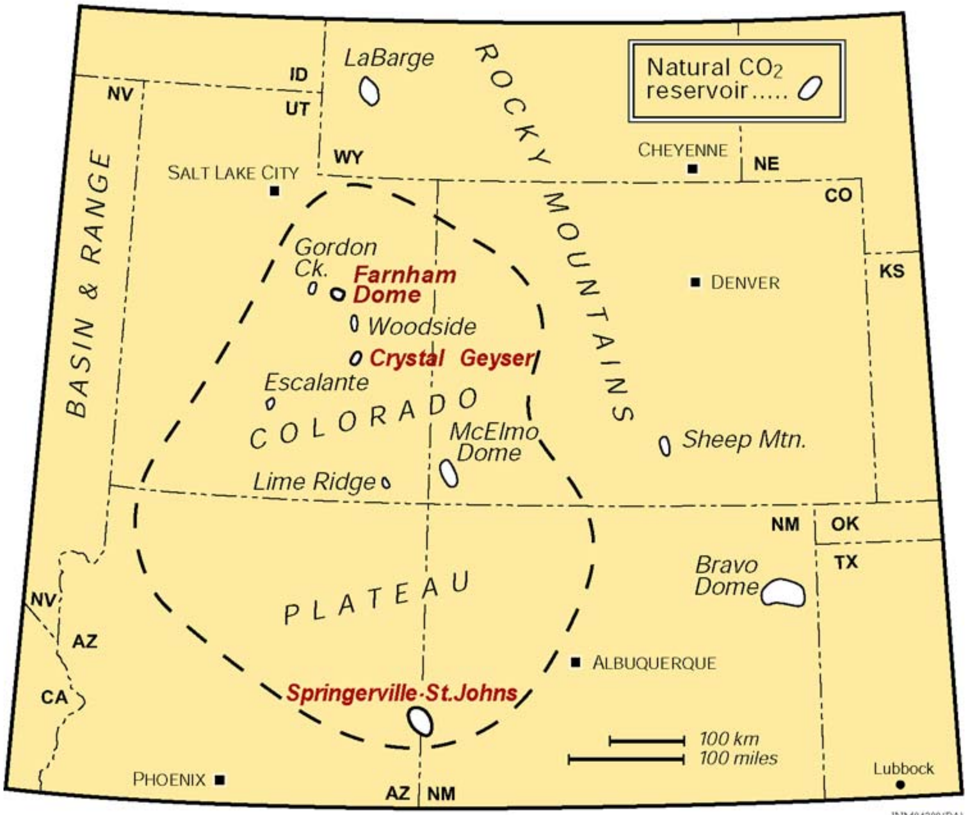

Figure 1. Natural CO_2 occurrences on the Colorado Plateau, with the three occurrences discussed in this paper highlighted in red. Crystal Geyser is the site of CO_2 seepages along the Little Grand Wash fault zone, and in the Ten Mile Graben.

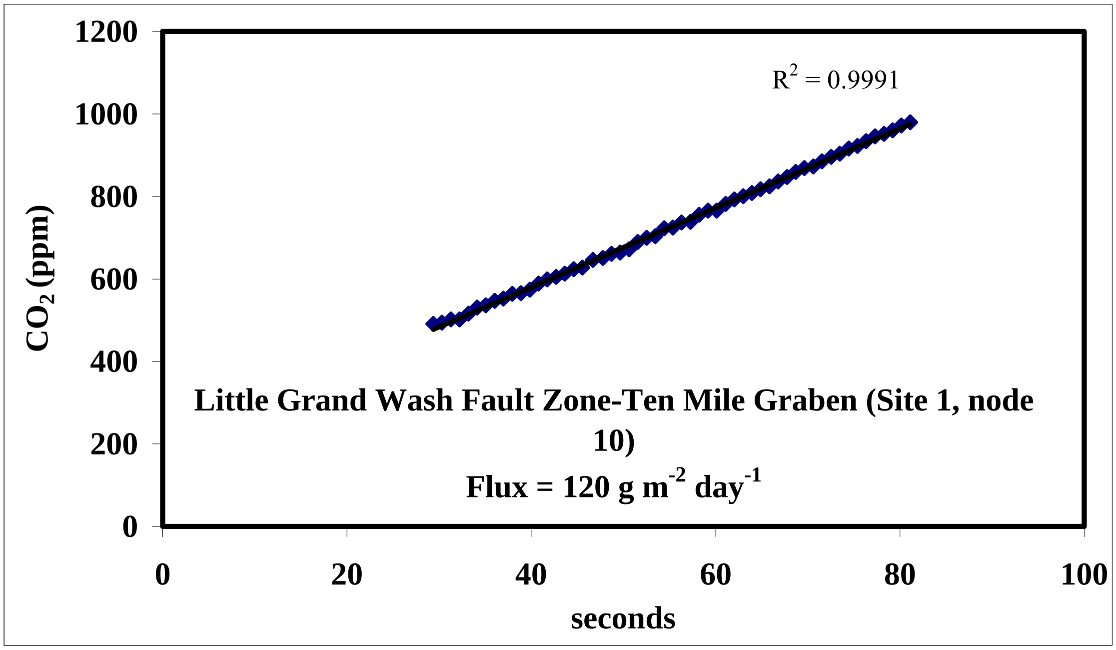

Figure 2. Example of the CO_2 concentration change with time in the accumulation chamber. The flux is calculated from the slope of the line and the other factors defined in Equation 1 (see text).

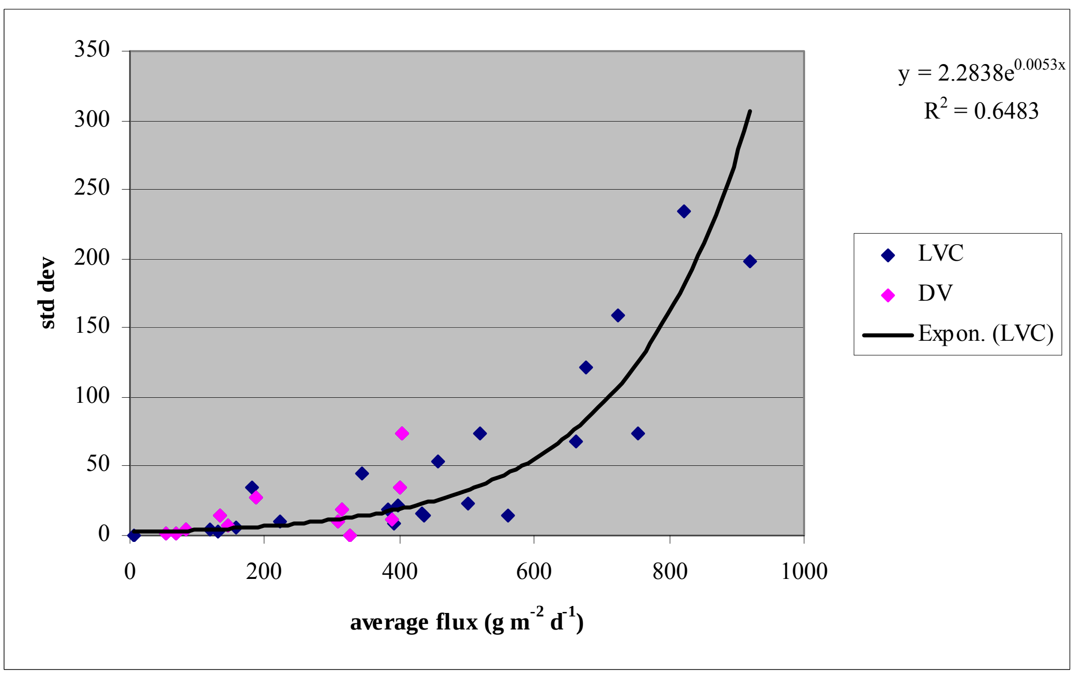

Figure 3. Plot of the average flux vs. standard deviation for 34 geothermal sites at Long Valley caldera, California and Dixie Valley, Nevada. A minimum of three replicate measurements was taken at each site. Similar behavior of increasing standard deviation with increasing flux is expected for measurements over sedimentary-hosted CO_2 reservoirs.

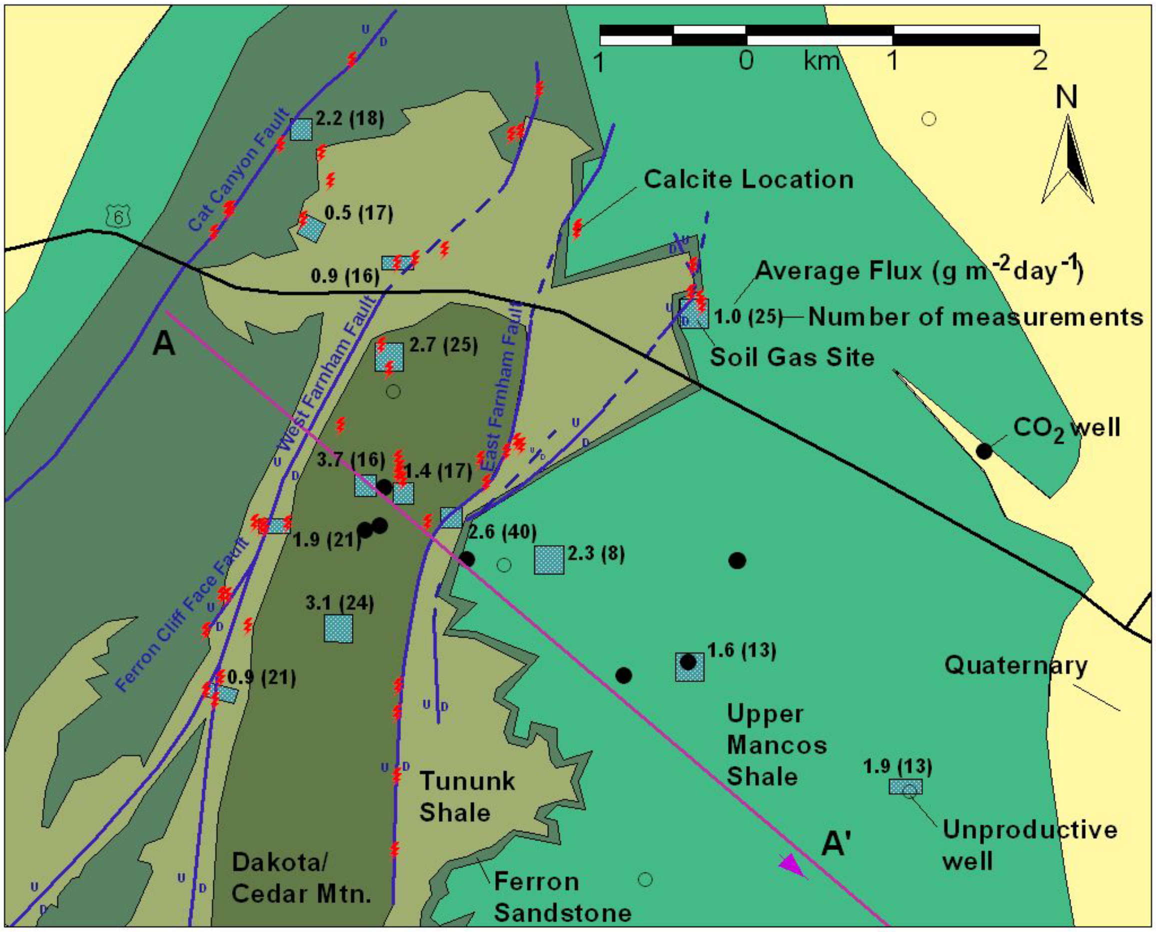

Figure 4. Average CO_2 flux values and geology at the Farnham Dome field site. Average fluxes (g m^{-2} d^{-1}) are shown in bold. The number of measurements for each area are shown in parentheses. Red zigzag symbols are locations with significant calcite debris or veins at the surface.

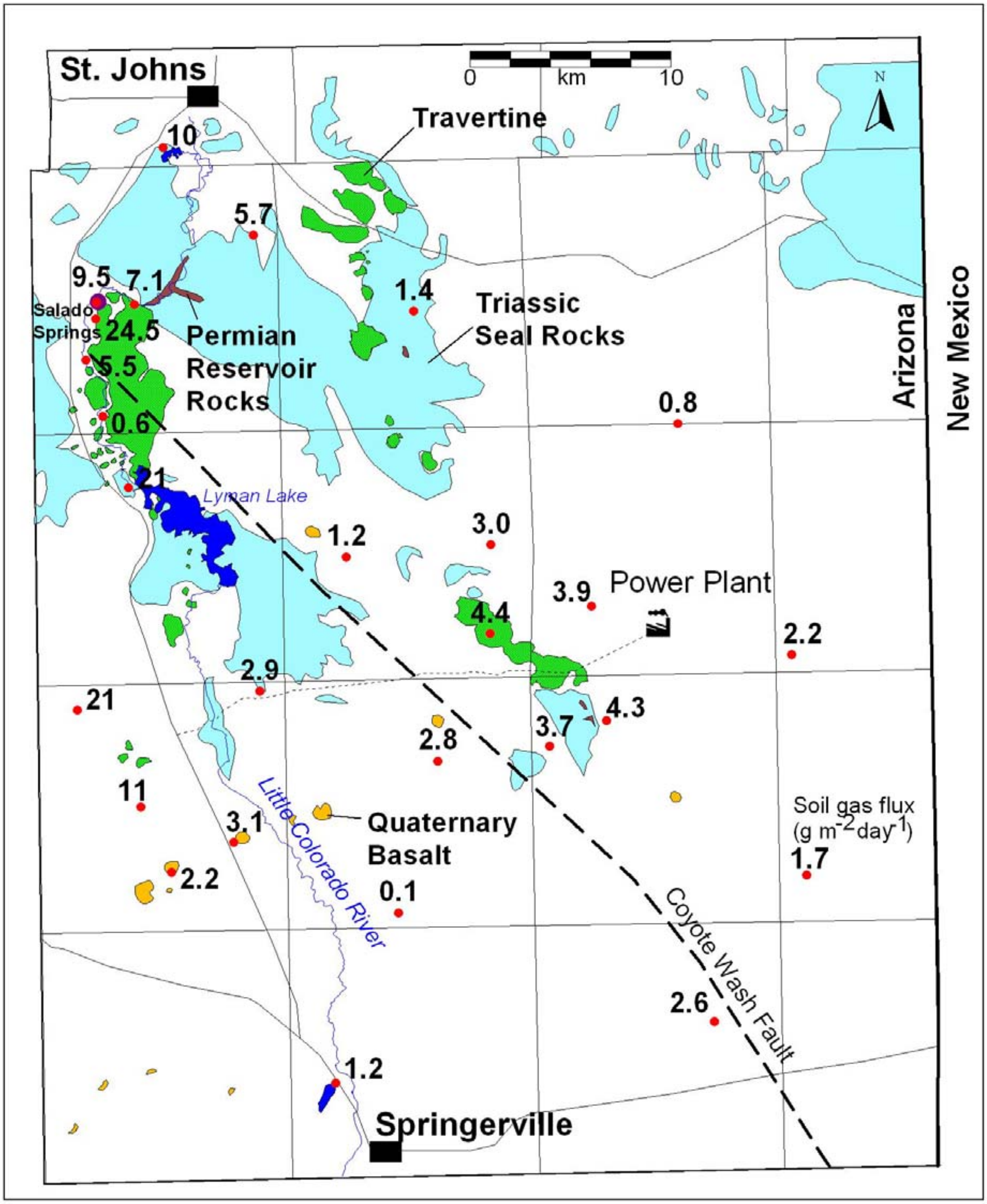

Figure 5. Average CO_2 flux values (g m^{-2} d^{-1}) and distribution of selected rock units at the Springerville-St. Johns field site, Arizona and New Mexico (from Sirrine, 1953). Green areas are travertine deposits.

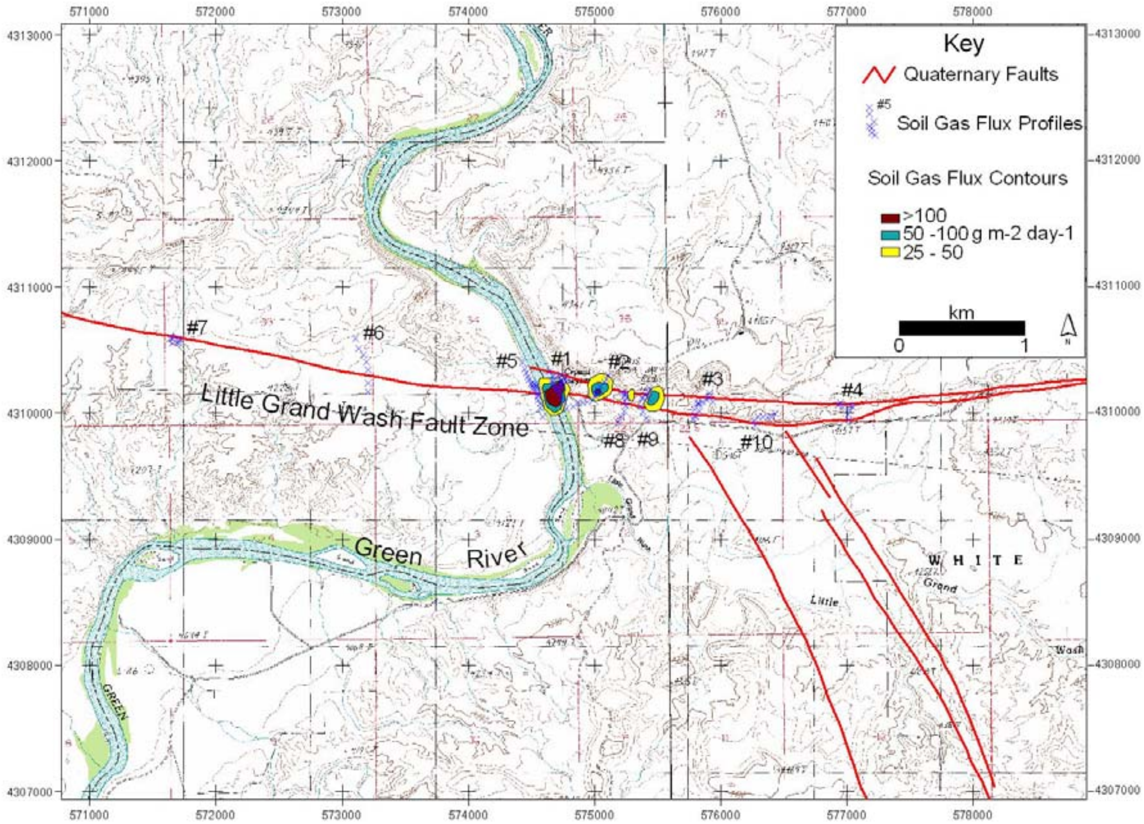

Figure 6. Location of 10 soil CO_2 flux profiles along the LGWFZ, and fault strands (Doelling, 2001; faults are suspected as Quaternary). Each cross represents a single flux measurement. Green areas show vegetation.

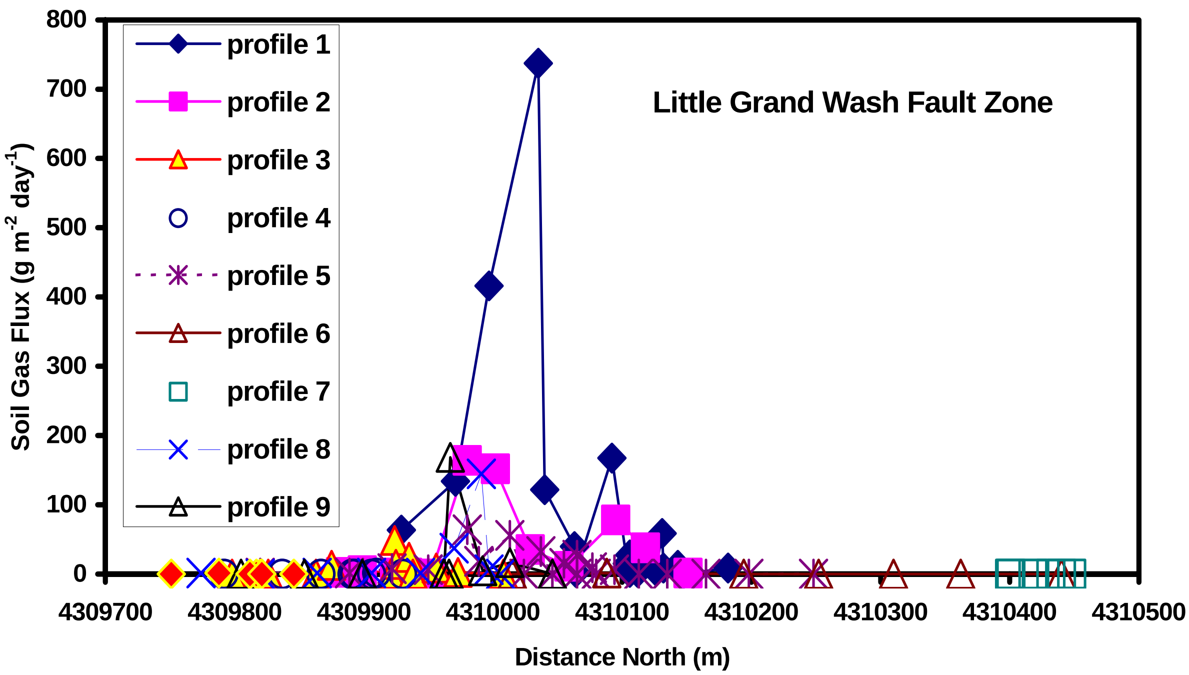

Figure 7. Pattern of CO_2 flux results obtained by superimposing data based on the northing coordinate of the measurement site.

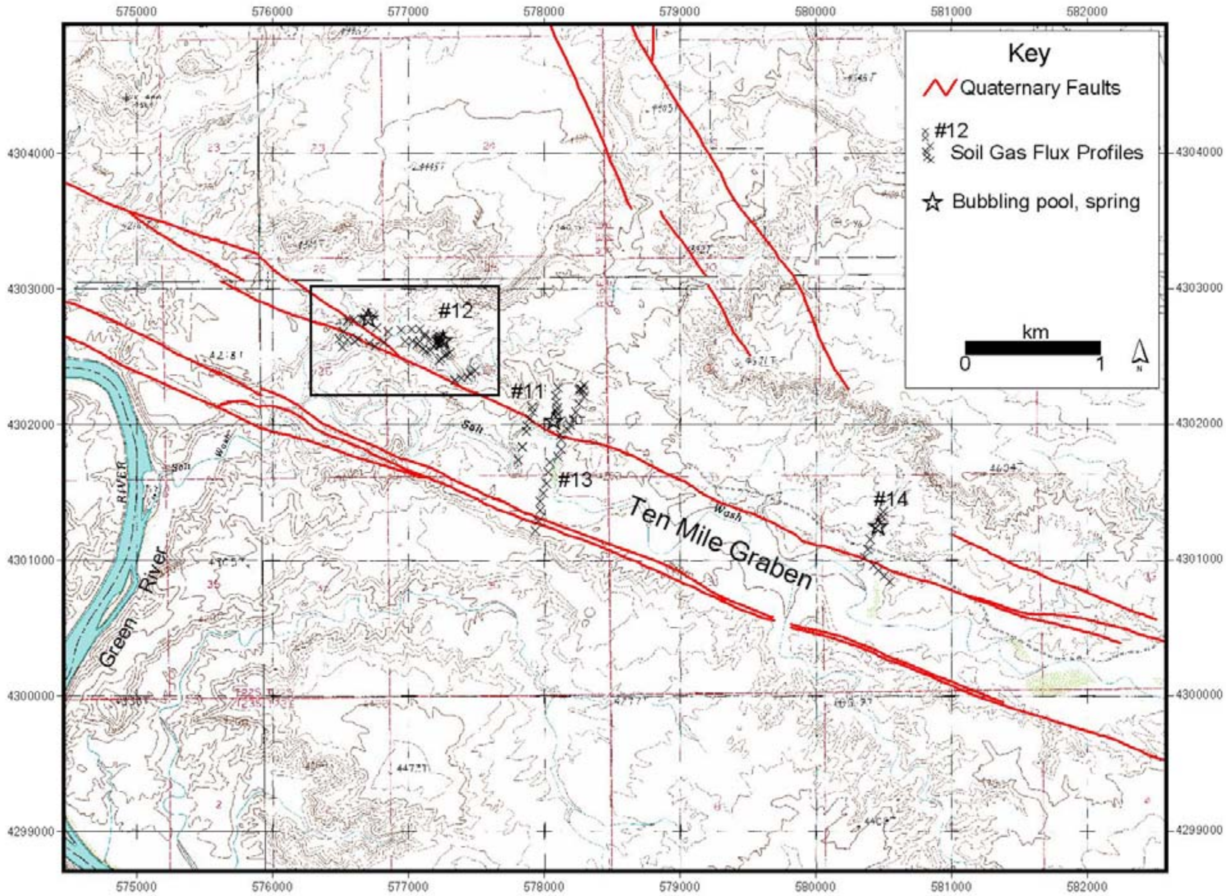

Figure 8. CO_2 flux locations in the Ten Mile Graben area. Fault strands, suspected as being Quaternary, are from Doelling (2001). All measurements but one on Profiles 11, 13, and 14 were less than or equal to 5 g m^2 d^{-1}. That one measurement was at the north end of Profile 13, with a value of 23 g m^2 d^{-1}. Profile 12 measurements are shown in Figure 9.

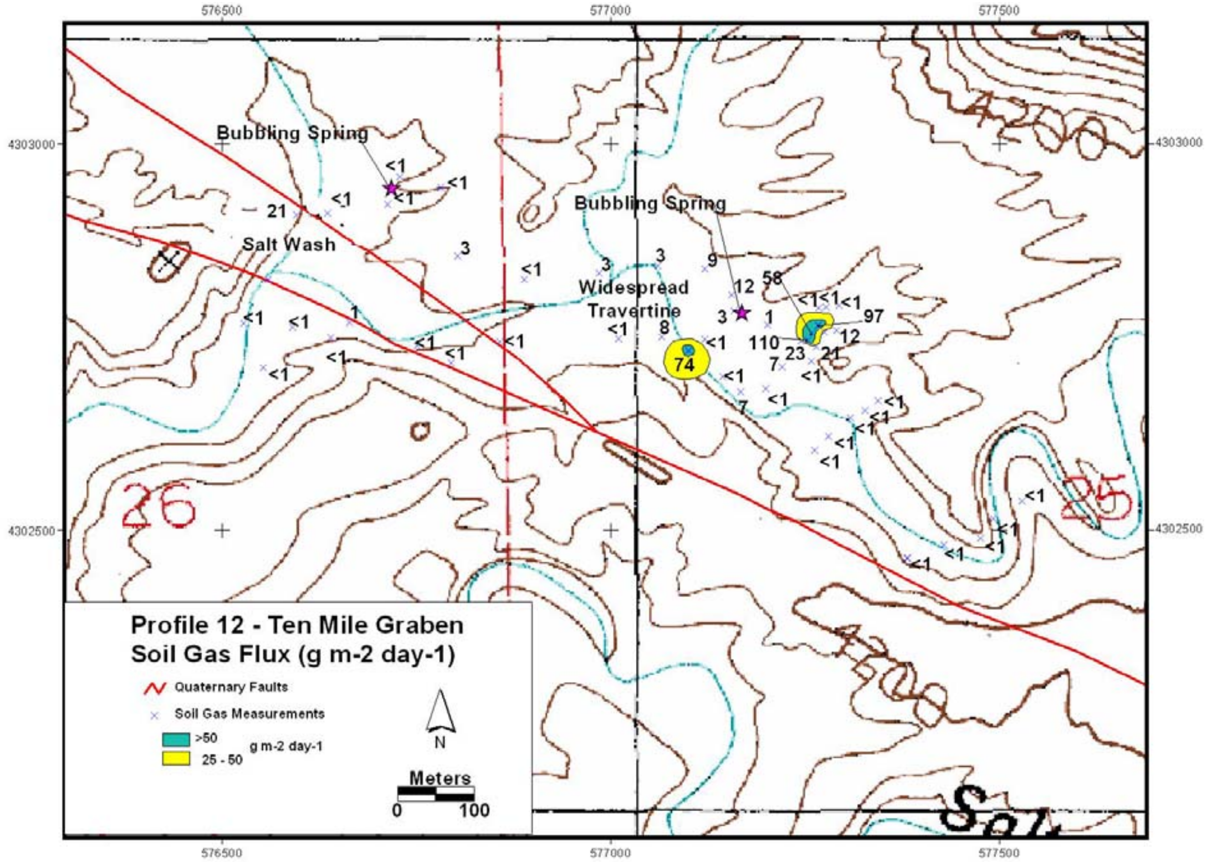

Figure 9. Details of CO_2 flux results at the west end of Ten Mile Graben (Profile 12). Faults are from Doelling (2001).

Table 1. CO_2 flux results and associated data from the Farnham Dome study.

AREA	Easting	Northing	Number of sites	Avg. Flux (g m^{-2} d^{-1})	Std. Dev.
1	530950	4377803	17	0.5	0.8
2	531542	4377558	16	0.9	0.6
4	535132	4373800	13	1.9	2.6
5	531314	4375959	16	3.7	1.9
6	531583	4375905	17	1.4	1.4
7	530292	4374487	21	0.9	0.7
8	530671	4375695	21	1.9	0.9
9	530862	4378481	18	2.2	1.0
10	534923	4367764	40	2.6	1.6
12	531485	4376868	25	2.7	1.7
13	531127	4374944	24	3.1	3.3
14	532612	4375428	8	2.3	1.2
15	533611	4374673	13	1.6	2.1
16	533637	4377175	25	1.0	0.8

Table 2. CO_2 flux results and associated data from the Springerville-St. Johns study.

AREA	Easting	Northing	Number of sites	Avg. Flux (g m^{-2} d^{-1})	Std. Dev.
2	3811268	647174	16	9.5	8.8
3	3809035	646750	20	5.5	4.8
4	3804020	648410	20	20.8	14.3
5	3801320	656960	20	1.2	1.2
6	3787380	659010	20	0.1	0.5
7	3793330	660540	10	2.8	1.8
8	3793905	664910	10	3.7	2.1
9	3798305	662585	9	4.4	2.4
10	3799395	666570	9	3.9	1.6
11	3801795	662620	9	3.0	1.1
12	3796055	653560	10	2.9	1.7
13	3780715	656545	9	1.2	1.5
14	3788950	650110	13	2.2	1.8
15	3790145	652535	9	3.1	1.8
16	3795310	646425	12	**21.2**	**13.9**
17	3810630	647140	10	**24.5**	**18.0**
18	3811205	648660	10	**7.1**	**5.3**
19	3806825	647430	9	0.6	1.0
20	3617355	649790	12	**10.2**	**4.7**
21	3813910	653325	10	5.7	1.9
22	3810935	659595	9	1.4	1.9
23	3806535	669945	9	0.8	1.3
24	3797490	674395	9	2.2	1.5
25	3794905	667140	9	4.3	2.0
26	3788860	674990	9	1.7	1.6
27	3783130	671385	9	2.6	1.6
28	3791530	648900	9	**10.5**	**7.5**

Bold data are from areas with heavy vegetation where some soil disturbance occurred.
A correction factor has been applied. Coordinates use NAD27 datum.