SAGE 2013 Geophysics Highlights

Introduction: SAGE 2013 was the 31st year of the SAGE program. Thirty students (18 NSF/REU undergraduate students, seven graduate students, one international undergraduate student, and four geosciences professionals) participated in SAGE 2013 in the Rio Grande rift area of New Mexico. Geophysical field work (2 days of near-surface geophysics at an archeological site and 5 days of basin-scale geophysics near the western edge of the Española Basin and the Buckman area of the Española Basin northwest of Santa Fe) provided significant new seismic refraction and reflection, electromagnetic, ground penetrating radar, magnetic and gravity data. The geophysical work in the Buckman area was a new geothermal initiative at SAGE partially supported by a DOE/NSF REU grant. All students gained experience with the theory and principles of applied geophysical techniques and with all of the geophysics field equipment and methods as well as surveying for accurate gravity station locations using differential GPS. SAGE 2013 also included three days of geology field trips, one day of seismic basin analysis (a short course presented by Orla McLaughlin and Robert Bielinski of ExxonMobil) and five days of data processing, modeling, interpretation, and written and oral report preparation. There were also several evening talks presented by visiting industry professionals. The last two days of the program were devoted to student presentations of their research results. Each student selected at least one geophysical technique and data set for a research project. The students were also organized into teams (each of the five teams included the various geophysical methods) and presented their individual and integrated interpretations of the SAGE 2013 data. Three Native American college undergraduate and high school students from the Santo Domingo Pueblo also participated in 7 days of the SAGE program to provide them with an introduction to Earth science, geophysics and geophysical field work. The interaction of the SAGE students and faculty with the Native American students and their advisors also provides a very positive cultural experience.

Highlights of some of the SAGE 2013 data and interpretations are shown below.

CMP Seismic Reflection Profile: Common Midpoint (CMP) seismic reflection data were collected along a W-E profile (Figures 1 and 2) south of Buckman (and just east of the Caja del Rio plateau where we worked in SAGE 2012) in the Española Basin in the Rio Grande rift of New Mexico. The data were collected using a vibroseis source (vibroseis truck provided by Dawson Geophysical and INOVA) with an 8-80 Hz sweep at Vibrator Points (VPs) spaced at 20 m along the profile. The recording equipment consisted of one-hundred-twenty 10 Hz, 3-component geophones connected by cables and digital telemetry along a communications cable to a recording truck. Data were recorded on an ARAM (division of INOVA) digital recording system.

Nine SAGE 2013 students focused on seismic data for processing and interpretation. CMP reflection processing was performed using the SPW (Seismic Processing Workshop, Parallel Geosciences) processing software. The processing included assigning geometry, merging shot gathers, trace kills, notch and band-pass filtering, deconvolution, velocity analysis, CMP sorting, muting, NMO correction and CMP stacking. Reprocessing with improved velocity models was also accomplished by REU students attending the SAGE one-week follow-up workshop held in San Diego (San Diego State University) in January, 2014. The most prominent feature of this area of the Espanola Basin is the deepening of the basin to the west. The thickness of basin fill is about 3 km in the western part of our study area. These results are also consistent with modeling of gravity data discussed in sections below. A thick section of Tertiary sedimentary and volcaniclastic rocks exists above the Precambrian crystalline basement. The thickness of the Tertiary section is consistent with a nearby deep well

(Yates #2 La Mesa, Myer and Smith, 2006). There is no evidence of a Mesozoic or Paleozoic section at the location of our seismic line. A small-offset, down-to-the-west fault is also visible in the seismic section.

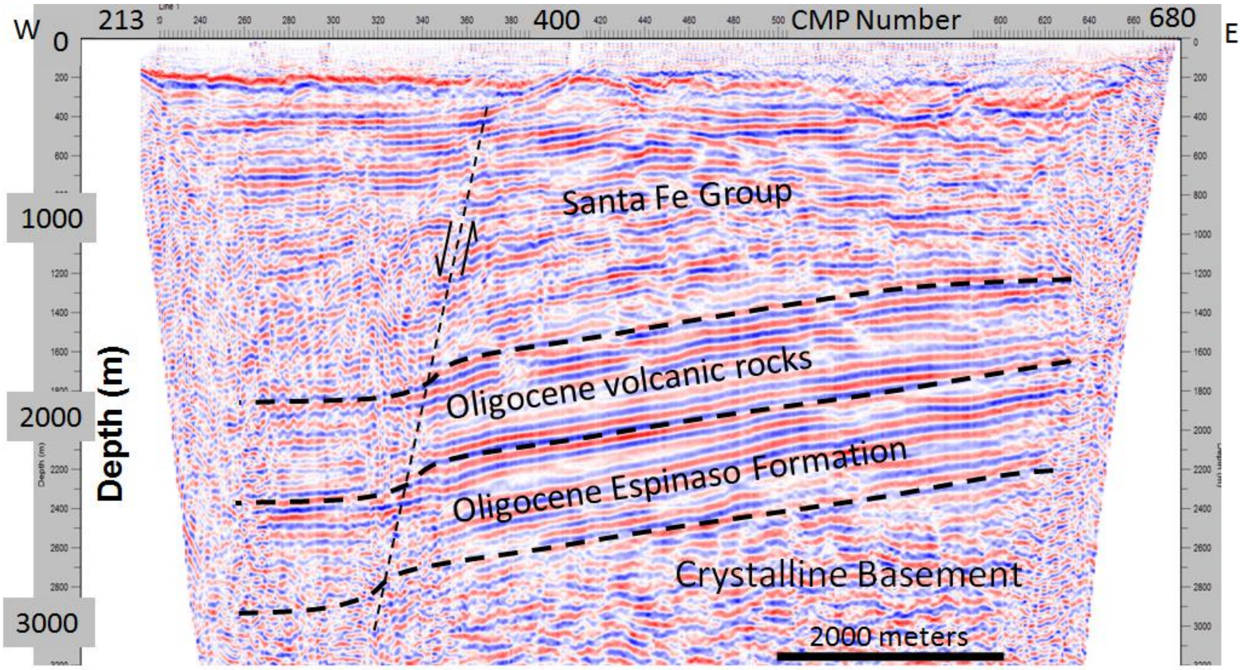


Figure 1. Interpreted CMP stacked seismic reflection record section from the Buckman area west of Santa Fe, NM (from Braile et al., 2013). Location shown on Figure 2.

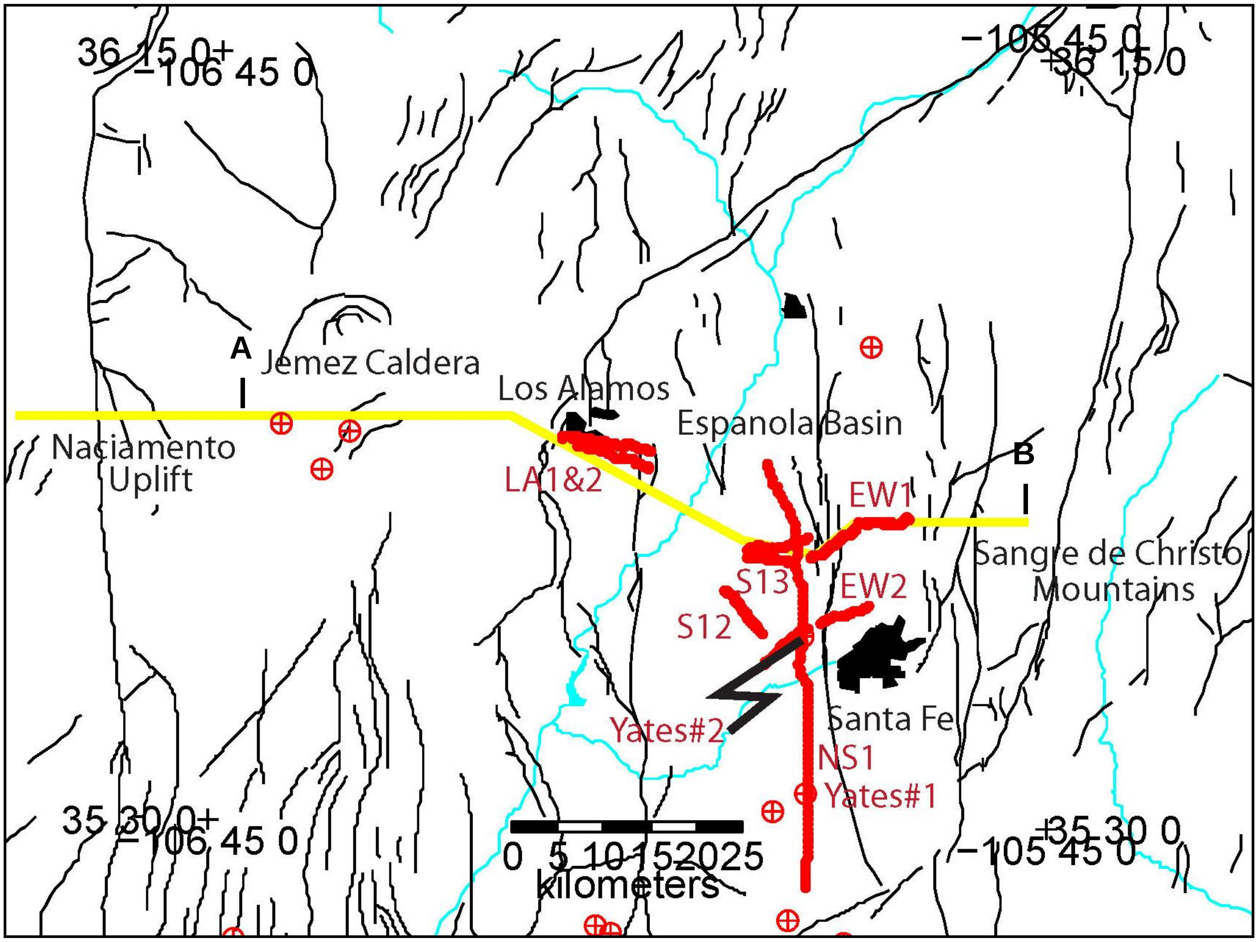


Figure 2. Fault map of the Española Basin area. Red lines are seismic reflection profiles. S13, NW of Santa Fe, is the SAGE 2013 seismic reflection and refraction profile. Yellow line shows gravity model profile (A to B, Figures 3, 4 and 5). Crossed circles are deep drill holes.

Gravity Data Collection and Interpretation – 2013 Update: SAGE has been producing new geophysical data in the Española Basin of northern New Mexico for 31 years. We also have access to seismic reflection and borehole data from petroleum exploration in the 1970s. A wave of new geological and geophysical mapping by the NM Bureau of Geology and Mineral Resources and the U.S. Geological Survey has also become available over the past 10 years. SAGE investigators are now seeking to integrate all of this information into a coherent tectonic model of the Española Basin and its transitions with the adjacent Santo Domingo and San Luis Basins. The SAGE 2013 work shown on the maps and profiles (Figures 2-5) is a good example of this integration. The majority of the gravity data incorporated into these models (Figure 5) was collected by SAGE. The models are constrained by seismic reflection data (Figure 2). These data include exploration data and data collected by SAGE. The models are primarily constrained by gravity data and geologic mapping west of 80 km. A compilation of borehole data in the Jemez Volcanic Field was recently made at the SAGE 2013 REU Winter Workshop and a revised map (Figure 4) and revised models using these data are shown in Figures 3 and 5.

The SAGE gravity study for 2013 has focused on improved modeling of the structure of the Espanola Basin. A transect across the basin was refined with improved geologic control in the Jemez Mountains and Valles caldera. The Cochiti cone fault is now seen to be the eastern bounding fault of the Los Alamos graben. This fault runs north-south just to the west of the town of White Rock. It appears that a rift related extensional basin may have existed to the west of the Pajarito fault and is now under the subsequent volcanic features of the Jemez complex. A series of profiles was constructed from the

Santo Domingo Basin north into the Los Alamos graben. The central section of the basin-wide profile just discussed, forms the northern-most of these profiles (upper profile on Figures 3 and 5). These profiles illustrate the transition from the Santo Domingo (or Albuquerque) basin into the Espanola Basin as extension is handed off from the west dipping La Bajada fault to the east dipping Pajarito fault. The symmetry of the profile (third profile from top in Figures 3 and 5) that passes through the termination points of these faults is remarkable.

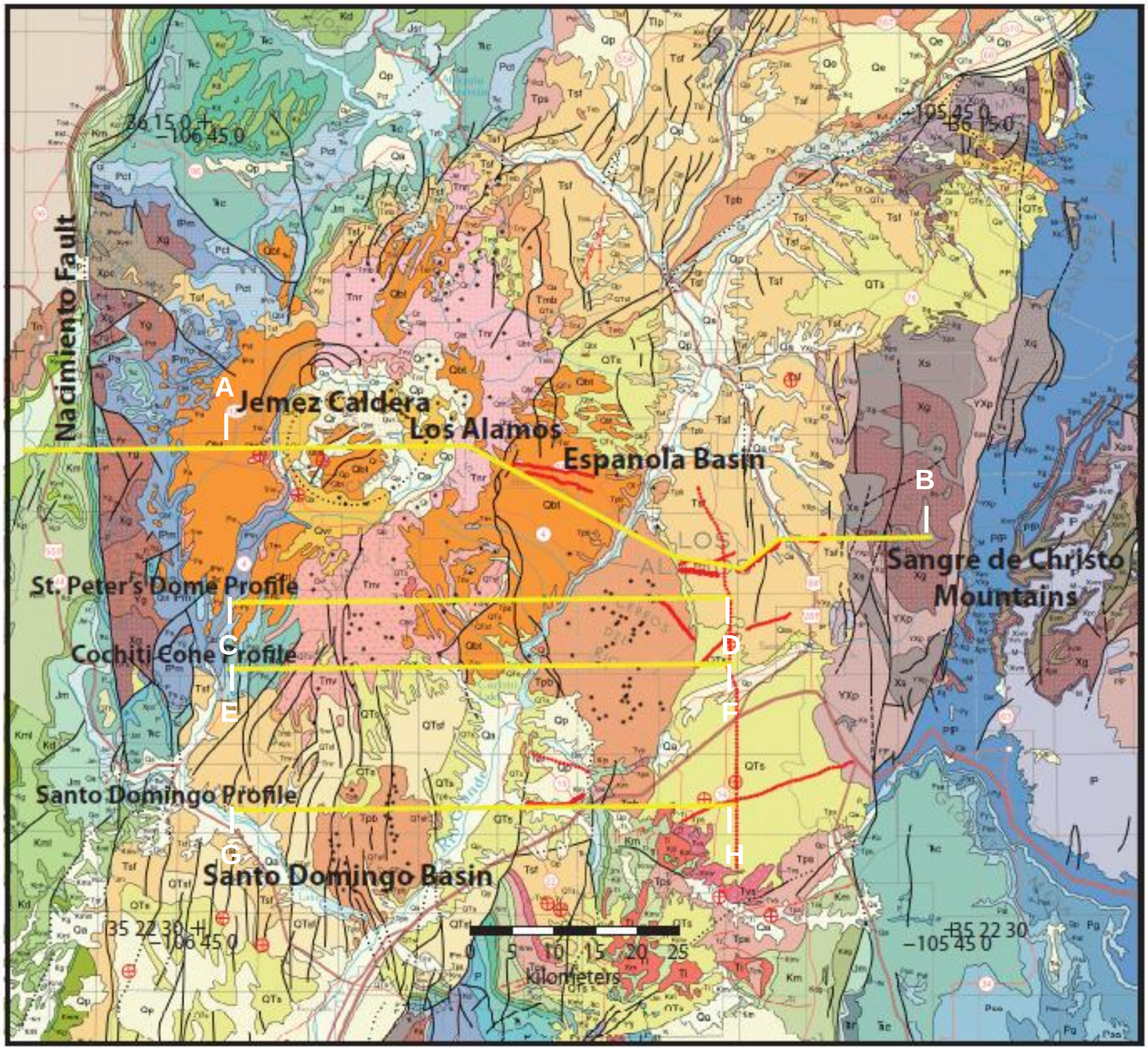


Figure 3. Geological map. Red lines are seismic profiles. Yellow lines are gravity model profiles A-B, C-D, E-F and G-H (Figure 5). Crossed circles are deep drill holes.

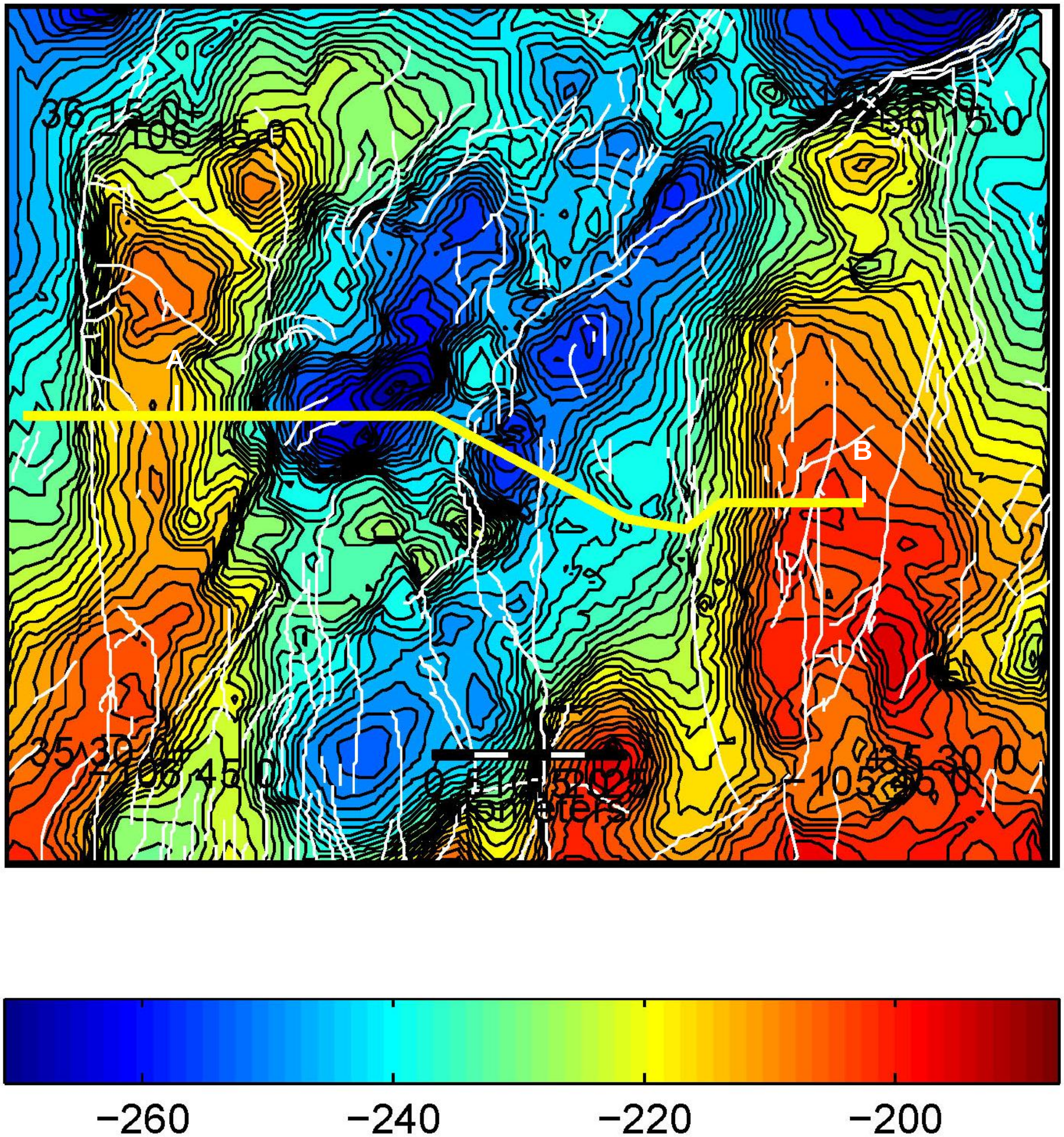


Figure 4. Complete Bouguer anomaly map of the Española Basin area; contour interval is 2 mGal. Yellow line is the Tesuque 2013 gravity model profile.

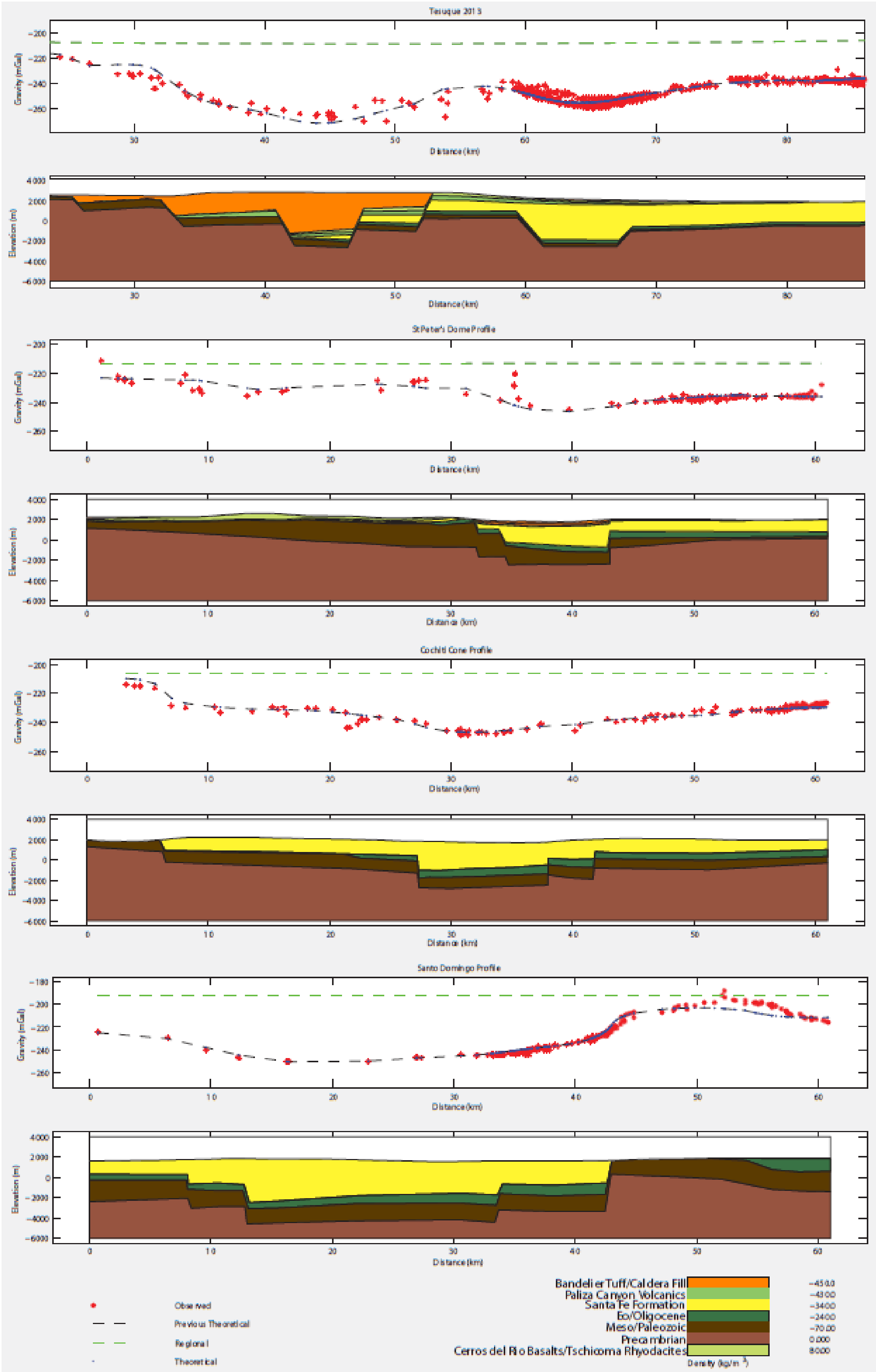


Figure 5. Gravity models along profiles shown in Figure 3, A-B, C-D, E-F, G-H, top to bottom.

Electromagnetic Methods: Electromagnetic methods, including magnetotellurics (MT), audiomagnetotelluric (AMT) and transient electromagnetic (TEM), have been employed by SAGE students for the past three years to furthered our understanding of the geothermal anomaly discovered by high borehole temperature gradients measured over short spatial scales in the Buckman Well Field located within the Espanola Basin (Manning, 2009). The localized nature of the anomaly suggests a local, rather than regional controlling structure. Data acquired in 2013 extended the profiles from previous years to the east. The length of main profile is ~18km as shown in Figure EM1.

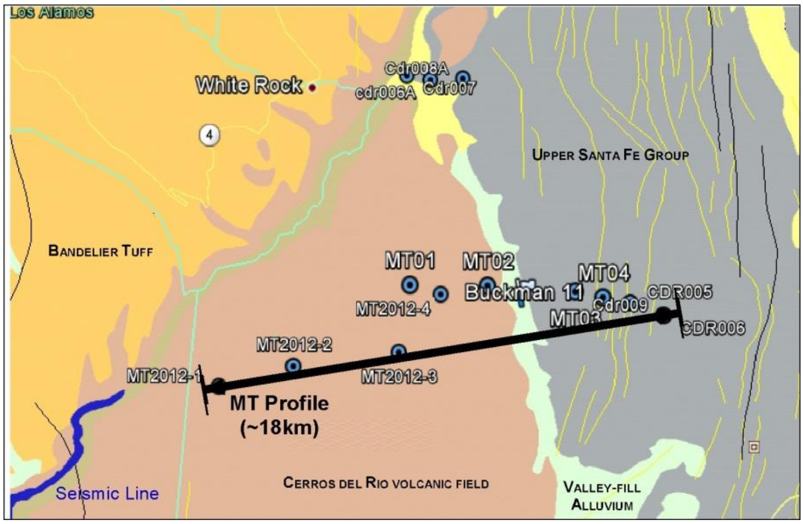


Figure 6. General geology of the studied area. The black line shows the approximate location of the MT survey line in the southern Espanola Basin, the Cerros del Rio Volcanic field, and stations to the north of the Buckman Field.

After investigating inverse strategies and algorithms, TEM data were modeled with respect to the hydrogeologic structure of the top hundred meters of the Buckman Field. Using conventional and state-of-the-art methods, in addition to developing a new technique, the dimensionality of the MT profile data were analyzed and the validity of a two-dimensional (2-D) approach used in inverse modeling and interpretation was verified. The final 2-D resistivity model (Figure 7) was constructed using AMT and MT data acquired during 2011-13 seasons.

The MT model estimates basin depth at 3-4 km in accordance with geologic mapping (Koning and Read, 2010), gravity models and seismic imaging. The thin, black dashed line outlines a conductive layer at a depth of 1-3 km, and the solid line a zone of enhanced conductivity that is likely due to clay minerals resulting from weathering and erosion of volcaniclastic materials in the Tesuque and Abiquiu Formations. The thick, dashed line shows the interpreted top of the resistive crystalline basement. The depression near the center of the profile may reflect offset along an east-dipping normal fault. Imaged basement topography may reflect a fault-related offset at the edge of a proposed horst block, however evidence of a horst block in the MT models is debatable and may be due to artifacts in the inversion.

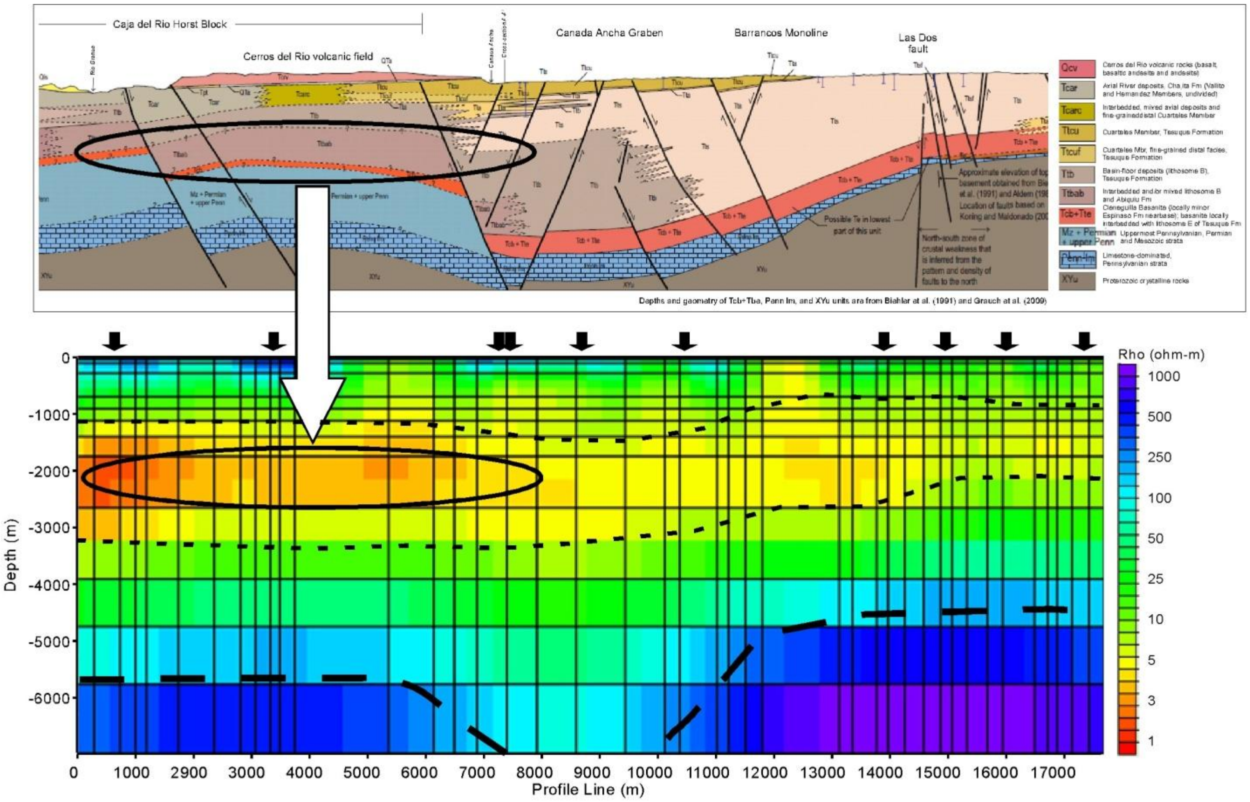


Figure 7. Geologic cross-section (Koning and Read, 2010) and the corresponding 2-D resistivity model derived from MT data.

San Marcos Pueblo Archaeological Site Geophysical Surveys: Over the past five years the SAGE efforts at the San Marcos Pueblo archaeological site have focused on creating detailed (0.5 m sample interval) maps of a 2.25 hectare area (about 10% of the site, Figure 8) using a total field magnetometer, EM-31 electromagnetic sensor, and 250 MHz ground penetration radar. The San Marcos geophysical map area covers four room blocks and an extensive plaza area. The area is underlain by Pleistocene terrace and Pliocene Ancha formation sediments. Spanish Colonial age metal smelting operations have been excavated at the points plotted near the center of the Magnetic Map. The maps are being used to identify other potential archaeological features and to constrain the geologic model of the site. There are trains of magnetic material in shallow channels eroded into the hill-slope below the room blocks. These debris plumes may be related to the smelting operations and this hypothesis is under investigation. There are also ten high resolution seismic refraction and reflection lines in the map area. Current and future efforts are being directed at integration of these data, which were collected over a 9 year period, and the siting of additional seismic lines in areas of particular interest.

Investigations in SAGE 2013 at the San Marcos Pueblo archaeological site were primarily concerned with completing the mapping of the large, high-resolution San Marcos geophysical map. This is now about 95% complete. A major effort was put into the reprocessing and merging of the ground penetrating radar (GPR) data for the San Marcos geophysical map. A photographic image, topographic, magnetic vertical derivative maps are shown along with GPR depth slices at 0.4-0.5, 0.6-0.7 and 0.8-0.9 m depth. The magnetic vertical derivative map can be very profitably compared to the GPR scattering response. A number of features of likely anthropogenic origin can be correlated among the images.

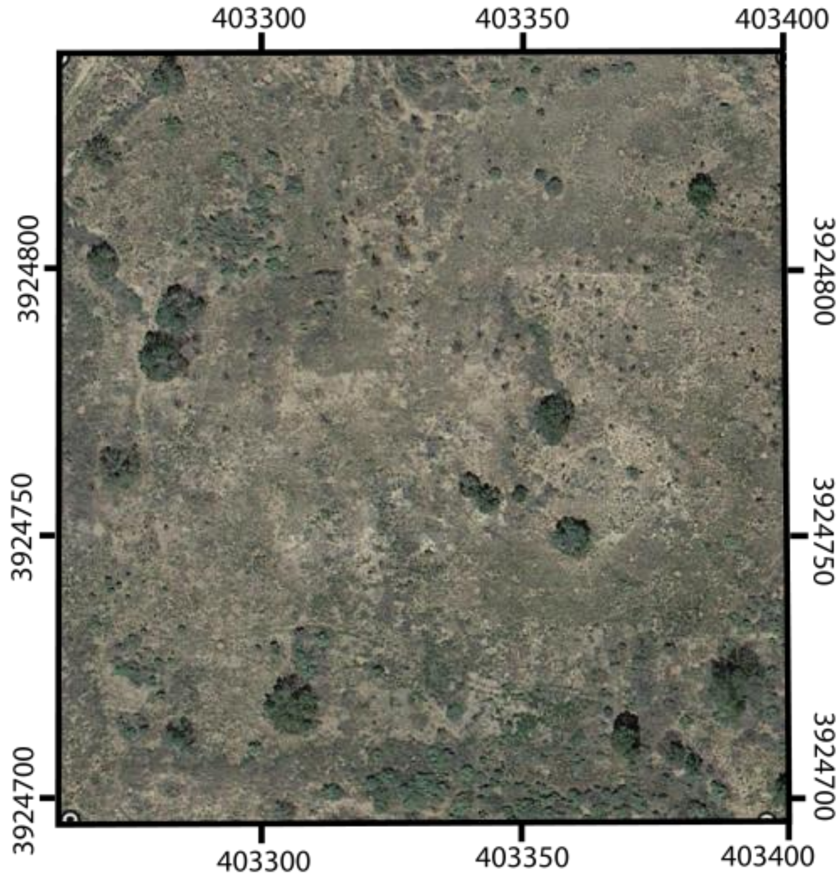


Figure 8. Areal photograph of the SAGE San Marcos geophysical map investigations at the San Marcos Archaeological site. Coordinates are UTM in meters. North is up.

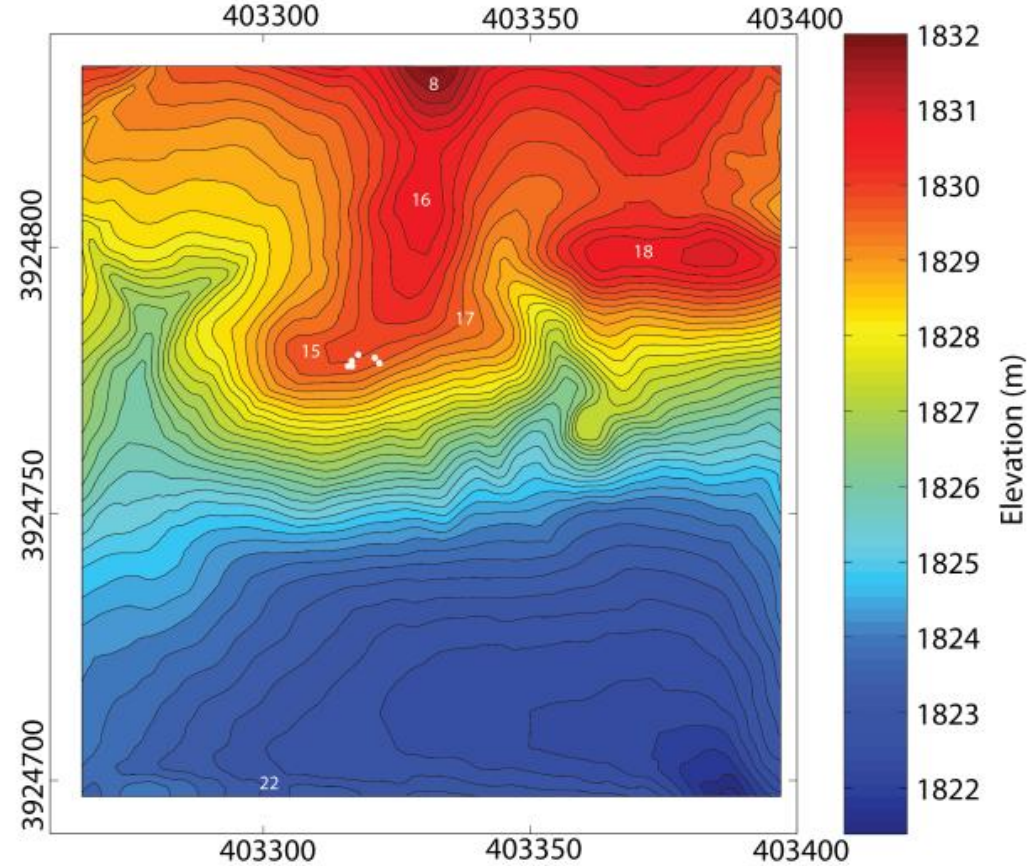


Figure 9. Elevation map of the San Marcos geophysical map area.

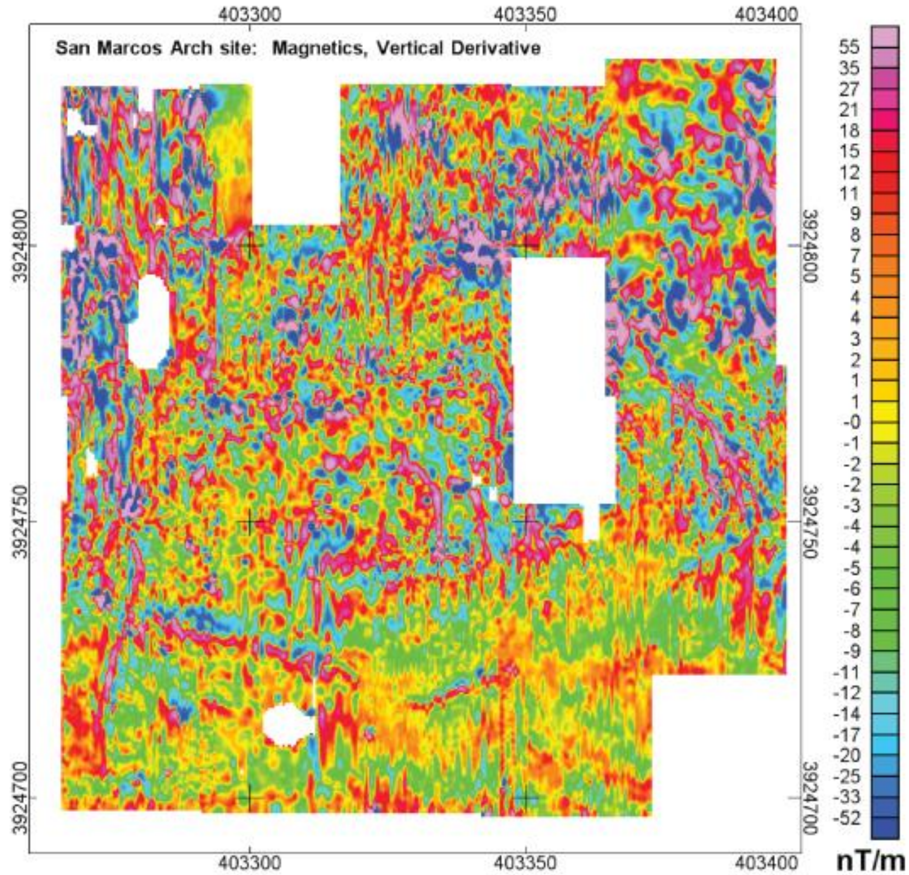
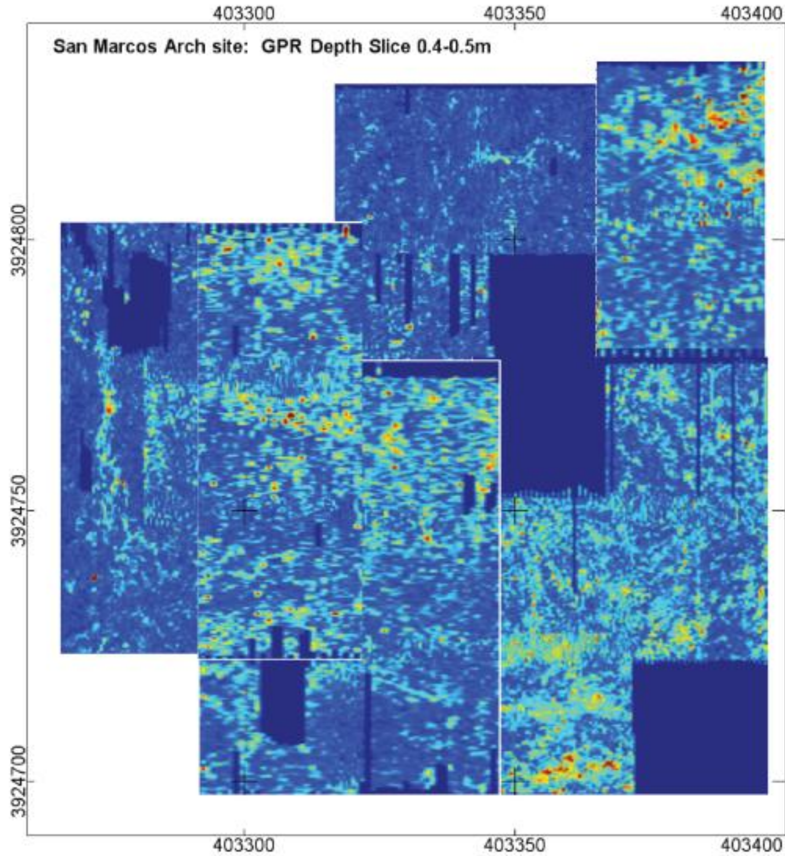


Figure 10. Vertical derivative magnetic field anomaly map of the San Marcos geophysical map area.


San Marcos Arch site: GPR Depth Slice 0.4-0.5m
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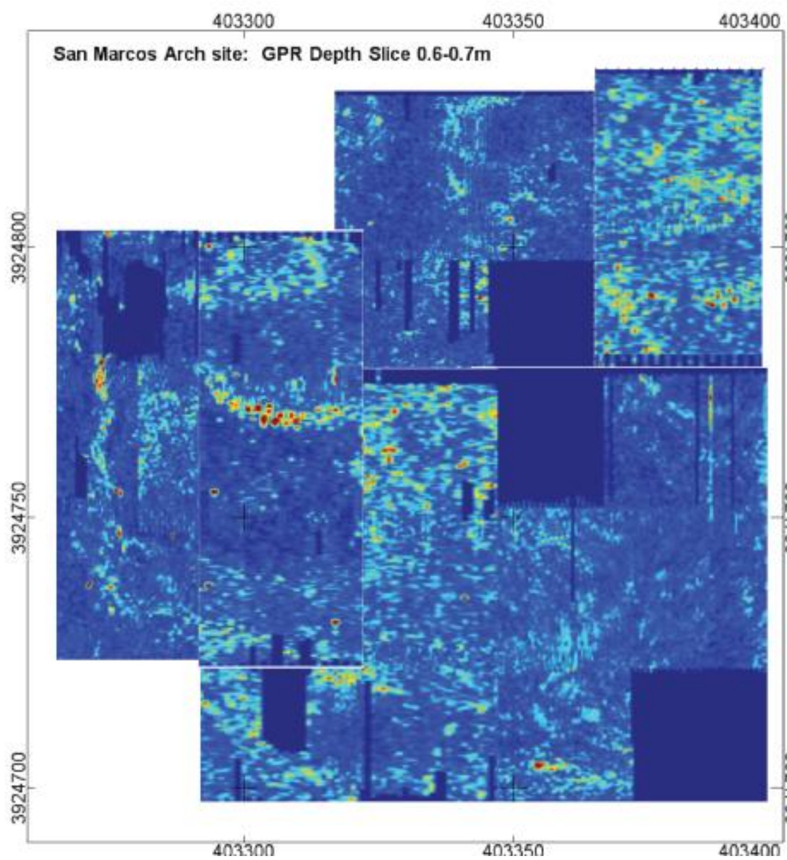
San Marcos Arch site: GPR Depth Slice 0.6-0.7m
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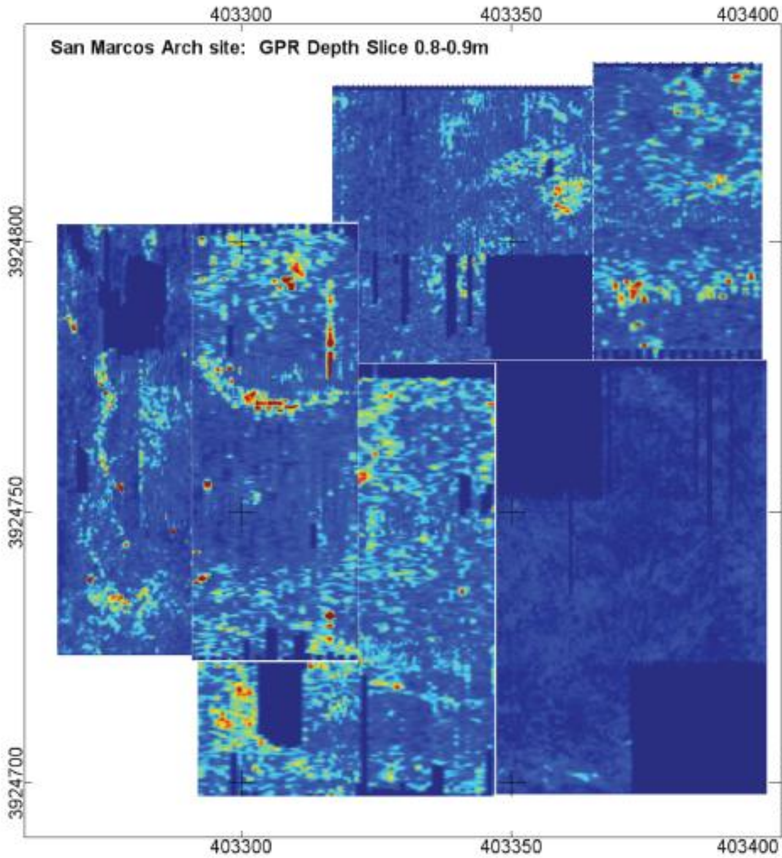

Figure 11. Depth slices through the 3-D GPR image: upper image 0.4-0.5 m, middle image 0.6-0.7 m, lower image 0.8-0.9 m.

SAGE Geothermal Program: The recent SAGE geothermal program is an example of the how SAGE leveraged the SEG Field Camp Program (http://www.seg.org/web/foundation/programs/fieldcamps) support to initiate new, real world research and education for students in the renewable energy sector. Three initiatives were instituted to enhance professional development and the skills needed for geothermal geophysics:

1. A potential commercial geothermal occurrence near Santa Fe, New Mexico that exhibited high geothermal gradients, >50^{o}C/km in water wells was selected for SAGE field geophysical studies. Geophysical measurements, analysis, and reporting have included electromagnetic, gravity, magnetics, vibroseis, and most recently (2013), borehole temperature measurements. Since 2010 there have been over 20 related SAGE student final reports, 8 co-authored posters presented at AGU annual meetings, and a 10-SAGE-student-authored poster at the 2012 Geothermal Resources Council meeting.

2. A $10 k grant was received from the National Renewable Energy Laboratory to assess the geothermal energy potential of the Rio Grande rift. SAGE was one of 11, mostly university, teams that participated in this student program. A presentation and report entitled "Geothermal Evaluation of the Central Rio Grande Rift in New Mexico" was completed in 2011.

3. A $150 k grant was awarded by the National Science Foundation'sInternational Research Experience for Students (IRES) for selected SAGE students to do "Applied Geothermal Exploration and Assessment in New Zealand." The goal of the IRES program is to prepare a globally-engaged science and technology workforce for the future through active collaboration

with foreign researchers at an international site. Eleven SAGE undergraduate and graduate students took part in the program in 2010- 2012.

The initial SAGE geothermal efforts have been enhanced by partnerships with private sector, state, and local organizations such as the New Mexico Office of the Engineer and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), and City of Santa Fe Water Division. Individuals have interacted with SAGE students by presenting talks, one-on-one advising, participating in field activities, and discussing job and career opportunities.

Enthusiastic response from SAGE students to the geothermal initiative have been immediate and impressive. A SAGE 2013 questionnaire on student career interests placed geothermal second between #1 Research and #3 Oil and Gas. A SAGE 2011 student finished his M.S. degree and now heads up his home state's geothermal, geophysics program. Another student worked for a field geophysics contractor before currently being enrolled in a geophysics Ph.D. geothermal program. A recent SAGE B.S. degree student reported that his co-presentation of a geothermal poster at anAGU meeting was pivotal in his current employment with Schlumberger. He met a Schlumberger recruiter at the AGU meeting who gave him his contact information and strongly encouraged him to apply online.

SAGE 2013 Geothermal:

SAGE geophysical measurements in 2013 continued to cast doubt on the economic potential of a geothermal occurrence near Santa Fe. For the first time at SAGE, borehole temperature gradients were measured in 10 available wells thanks to cooperation with Shari Kelley, a geophysicist with the NMBGMR. Six wells were USGS monitoring wells in the Santa Fe Buckman municipal well field (Figure 12). Geothermal gradients increased from 20°C/km, 17 km east of Buckman, to 76°C/km at Buckman (Figures 12 and 13). Within the Buckman well field, the two eastern wells revealed temperature gradients of 32°C/km (SF2B) and 42°C/km (SF2C) (Figures 12 and 13). The latter well was improperly reported in the past to have a gradient of 58°C/km. Only 300 m west, the geothermal gradients increase to anomalously high values of 76°C/km (well number SF4A), 62°C/km (SF4B), and 68°C/km (SF3A) in three shallow (<100 m) wells (Figures 12 and 13).

All Buckman wells are located inside a 25 km^2 area of ground subsidence (documented by InSAR measurements) caused by excessive pumping from 1993 to 2000 (Figures 12, 13 and 14). The short wavelength, areal locations of the high (>60°C/km) geothermal gradients demand a shallow (~100 m-depth) source. Subsidence/compaction, thermal conductivity changes, energy conservation, and geologic structures were considered as explanations for this anomaly. But, only a shallow subsidence-induced fissure explanation is considered viable (Figure 15). A fissure may cause a localized isothermal plume in the ~100-200 m depth range, and anomalously high geothermal gradients at depths shallower than ~100 m. Such a shallow isothermal prediction does not encourage commercial geothermal interest compared to what deep 70°C/km gradients would have. The fissure possibility was completely discussed in a SAGE poster co-authored and presented by three SAGE students (Pollack et al., 2013) at the 2013 Fall AGU meeting.

Figure 12. Drill holes in the Buckman well field area that were logged for temperature in SAGE 2013.

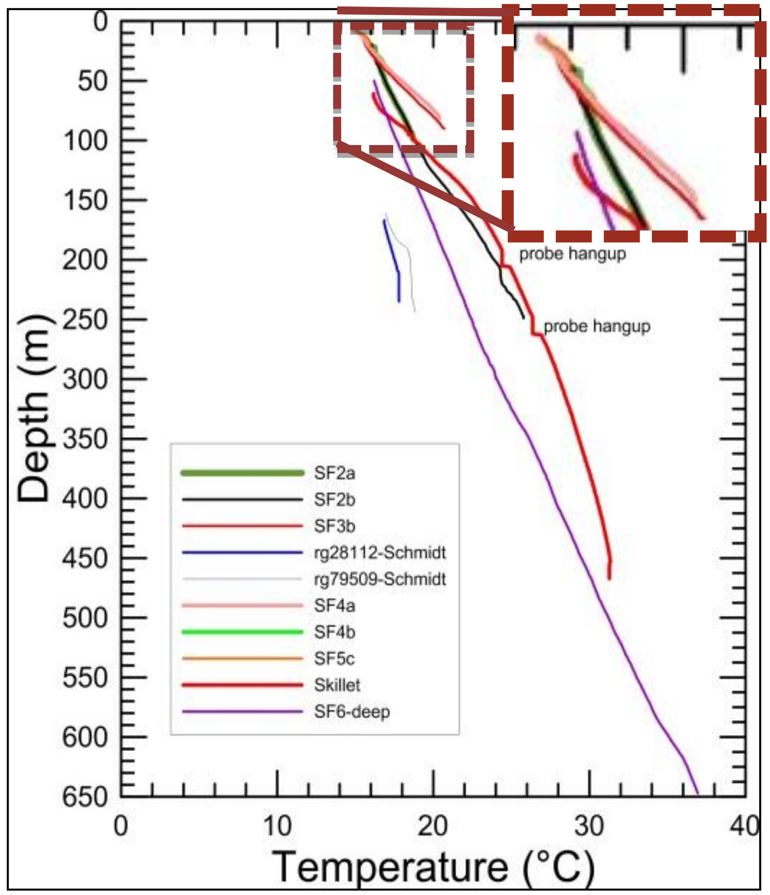

Figure 13. Temperature as a function of depth of the ten sampled wells in the Santa Fe region with expanded insert of the upper 100 m showing anonalous gradients.

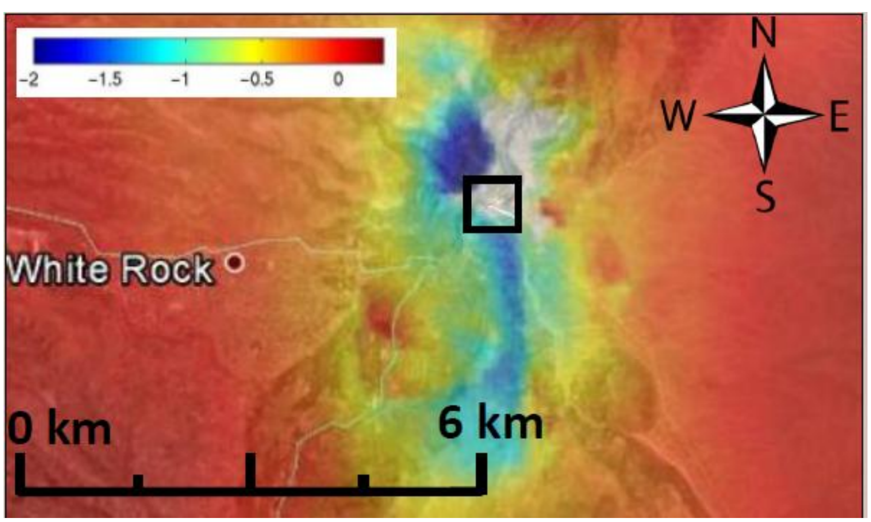

Figure 14. Line-of-sight displacement rate (cm/yr). Negative numbers indicate downward displacement. Buckman area is marked by black rectangle (Thomsen and Fialko, 2003).

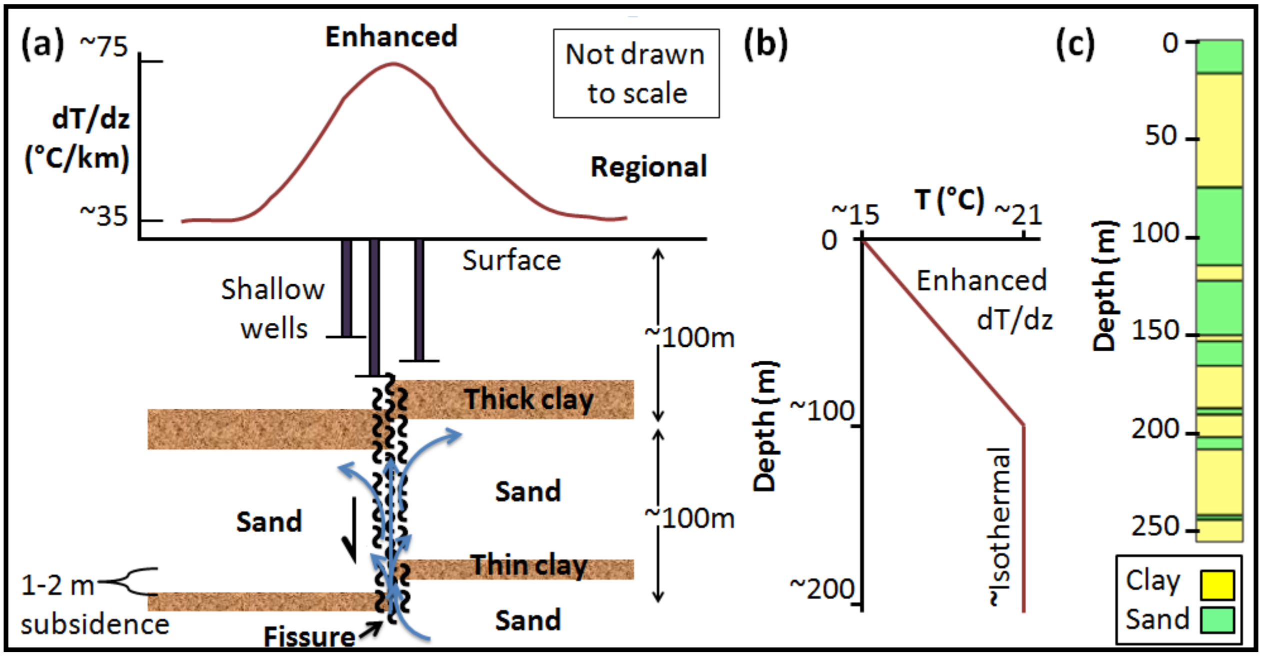

Figure 15. (a). A ~1-2 m subsidence-induced offset causes a shallow (~100-200 m depth) warm water, isothermal plume. (b). Temperature gradient associated with Figure 15a. Enhanced dT/dz in upper ~100 m is similar to those measured in wells SF3A and SF4A (insert of Figure 13). (c). Lithology of well SF2B, showing alternating thin and thick layers of clay and sand. This stratigraphy is similar to that hypothesized in Figure 15a. It is typical of the top layers of the Española Basin, which consists of Santa Fe Group fan and river deposits.

Recent SAGE Publication: Baldridge, W.S., L.W. Braile, S. Biehler, G.R. Jiracek, J. Ferguson, D. Hasterok, L. Pellerin, P. Bedrosian, D.K. McPhee, and C. Snelson, SAGE at 30, *The Leading Edge*, June, 2012, p. 702-708.

SAGE Publications – 2013

Poster presented at Fall 2013 AGU meeting: Braile, Lawrence W.; Brenna Coldren; Austin Baca; Joseph Fontana; Michael Olheiser; Matteo Ziff; Amber Keske; Andrea Rhode; Robert Martin-Short; Wai Allen; Kevin M. Denton; Christopher Harper; W. Scott Baldridge; Shawn Biehler; John F. Ferguson; Darcy McPhee; Catherine M. Snelson, *Seismic and Gravity Investigations of the Western Espanola Basin, Rio Grande Rift, New Mexico*, (http://web.ics.purdue.edu/~braile/sage/AGU.Poster.2013.Braile.pdf).

Poster presented at Fall 2013 AGU meeting: Grimes, Kimberly; Caleb J. Joiner; Dea Musa; Isaac Allred; Robert P. Delhaye; Nikita Zorin; Danny W. Feucht; Greg Johnston; Louise Pellerin; Darcy McPhee; John F. Ferguson, *Archaeological Geophysics at the San Marcos Pueblo, New Mexico, USA*, (http://web.ics.purdue.edu/~braile/sage/AGU.Poster.2013.Grimes.pdf).

Poster presented at Fall 2013 AGU meeting: Jones, Drew; Shanna Chu; Kevin McCormack; Lubna K. Barghouty; Akram Mostafanejad; Ben Lasscock; Paul Bedrosian; Louise Pellerin, *Magnetotelluric*

Investigation of Structures Related to a Geothermal Anomaly in the Buckman Well field in the Rio Grande Rift, New Mexico, (http://web.ics.purdue.edu/~braile/sage/AGU.Poster.2013.Jones.pdf).

Poster presented at Fall 2013 AGU meeting: Pollack, Ahinoam; Rachel Munda; Thomas F. Farrell; Shari A. Kelley; Jack Frost; George R. Jiracek, *Anomalously High Geothermal Gradients in the Buckman Well Field, Santa Fe County, New Mexico*, (http://web.ics.purdue.edu/~braile/sage/AGU.Poster.2013.Pollack.pdf).

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