SAGE 2011 Geophysics Highlights

Introduction: SAGE 2011 was the 29th year of the SAGE program. Twenty-eight students (19 NSF/REU undergraduate students, 7 graduate students, one international undergraduate student and one professional) participated in SAGE 2011 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 eastern edge of the Santo Domingo basin and the Caja del Rio area of the Espanola 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 Caja del Rio area was a new geothermal initiative at SAGE partially supported by a DOE 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 2011 also included three days of geology field trips, one day of seismic basin analysis (a short course presented by Orla McLaughlin and Ben Sanderson 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 2011 data. Six Native American college undergraduate and high school students from the Cochiti and Santo Domingo Pueblos also participated in 7 days of the SAGE program to provide them with an introduction to Earth science, geophysics and 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 2011 data and interpretations are shown below.

CMP Seismic Reflection Profile: Common Midpoint (CMP) seismic reflection data were collected along two approximately east-west profiles (Figure 1) in the San Francisco fault area associated with the eastern boundary of the Santo Domingo basin in the Rio Grande rift of New Mexico. The data were collected using a vibroseis source (vibroseis truck provided by INOVA) with an 8-80 Hz sweep at Vibrator Points (VPs) spaced at 20 m along the profile. The recording equipment consisted of eighty 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. The profile began just east of the San Francisco fault (Figure 1) and refraction and near-vertical and wide-angle reflection data were recorded by vibrating into the active array in both directions.

Ten SAGE 2011 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 bandpass 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, 2012. The reprocessed record sections are shown in Figure 2.

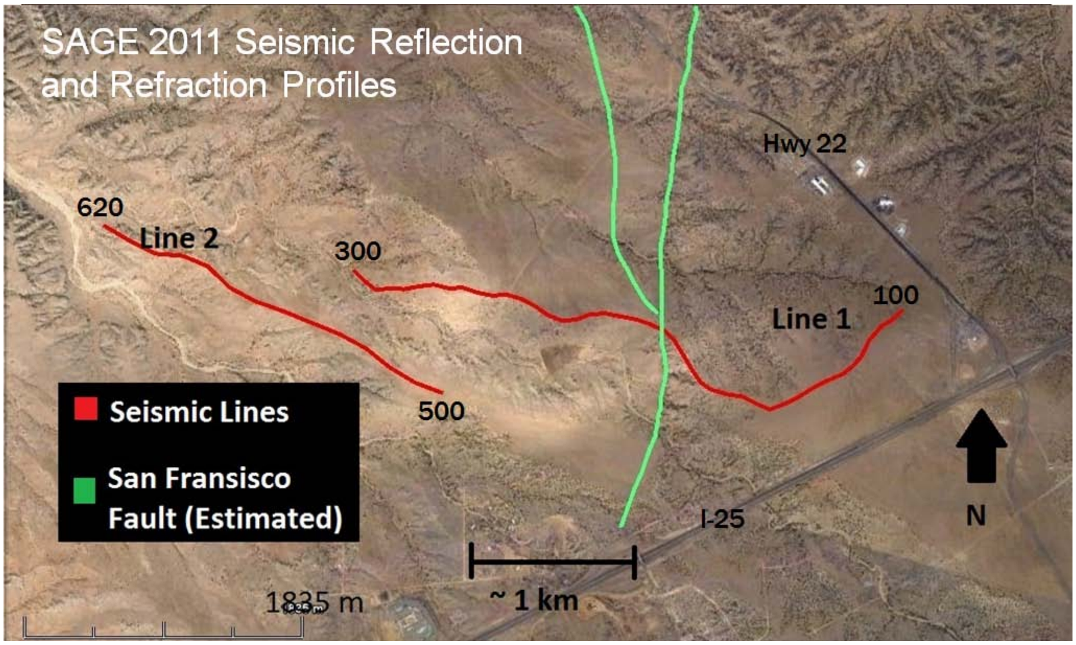

Figure 1. Map of SAGE 2011 field area showing the location of the seismic reflection and refraction profile. Flag numbers (VP and geophone locations, spaced at 20 m) for Line 1 were from 100 to 300 and from Line 2 were 500 to 620. Detailed gravity measurements were also made along the two profiles.

Reflections from a thick section of east-dipping sedimentary layers are well-imaged on the Line 2 seismic section on the west side of the profiles, and the dipping reflections continue into the western portion of the Line 1 record section. Wide-angle data collection and recording with VPs both east and west of the active 80-channel array allowed the imaging of reflections from the San Francisco fault plane indicated by the steep, west-dipping reflector on the eastern part of the Line 2 record section.

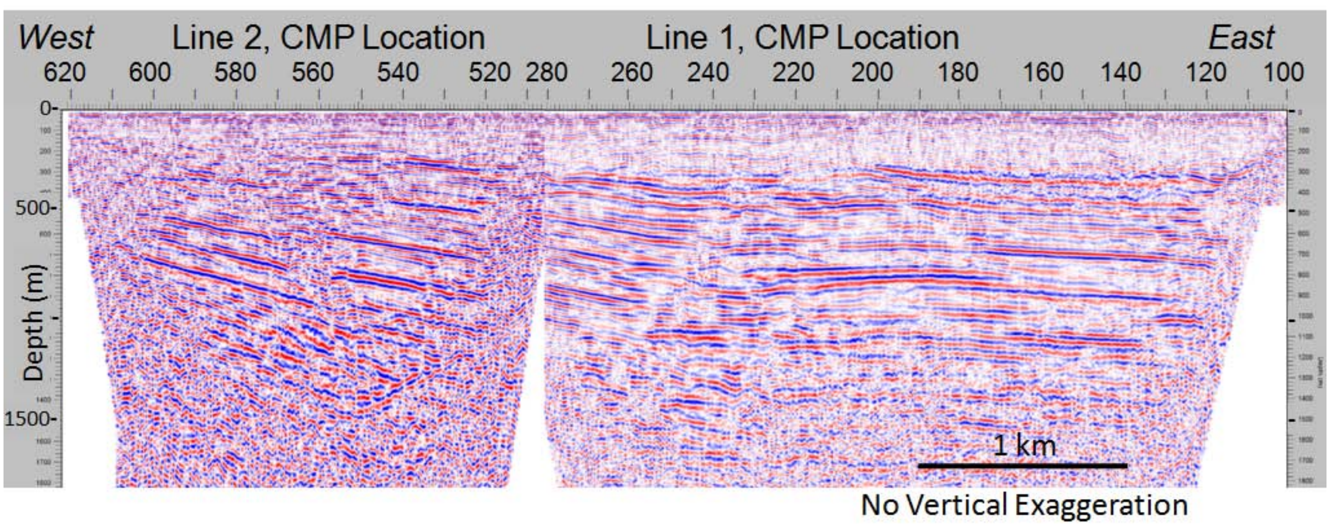

Figure 2. SAGE 2011 west-to-east CMP processed and stacked seismic reflection record section. Seismic data for lines 1 and 2 are plotted together, projecting the line 1 data to the south (see base map in Figure 1). Seismic data were recorded at a 20 m group interval from a vibroseis source with a sweep of 8-80 Hz. Seismograms plotted as a function of depth (conversion from two-way-time using derived velocity model).

An interpreted CMP stacked seismic section is shown in Figure 3. The CMP stacked data are not migrated. However, our analysis of migration of this fault plane reflection indicates that the true dip of the fault is close to 60 degrees. Another observation from the reflection record section is that the shallow sedimentary layers dip into the fault and thicken toward the fault, indicating that the fault was active during the time of deposition of these units. The seismic reflection signature of the fault on Line 1 does not show obvious offsets of reflectors. The lack of clear offsets is likely due to the oblique angle of the recording profile near the surface location of the fault (Figure 1). However, the CMP stacked seismic sections (Figures 2 and 3) show a marked change of dip of the reflectors at the location of the interpreted fault. The wide-angle reflection from the fault plane seen on Line 2 is also consistent with the inferred location of the San Francisco fault and the ~ 60 degree dip of the fault as illustrated in Figure 3.

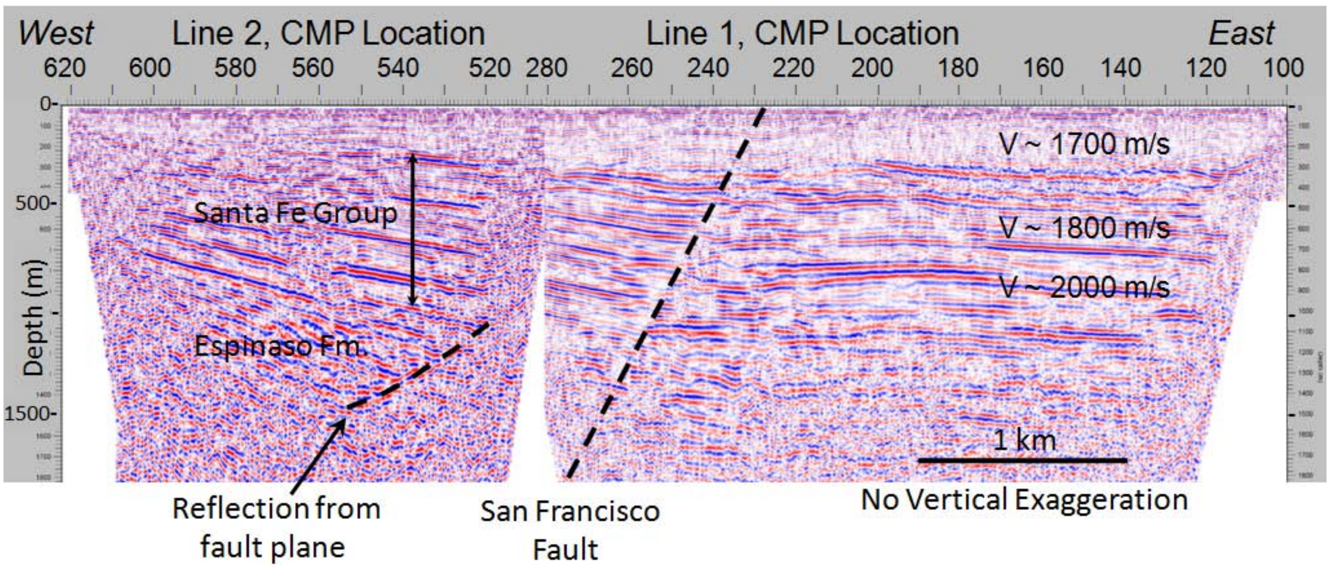

Figure 3. Interpreted SAGE 2011 west-to-east CMP processed and stacked seismic reflection record section. Approximate stacking velocities are shown on the Line 1 section.

Gravity Data Collection and Interpretation – Santo Domingo Basin Area: Over 200 gravity readings were collected during SAGE 2010 and 2011. Locations of gravity stations were determined from differential GPS measurements. The 2010 data were combined with previous SAGE gravity data and stations from the U.S. Geological Survey, the Department of Defense and the New Mexico Bureau of Mines to produce the complete Bouguer anomaly contour map shown in Figure 4. Gravity modeling, with control from surface geology, sedimentary unit structure and fault offsets from seismic profiles has been very useful in determining depth to basement (at least 3 km) in the Santo Domingo basin and other areas of the Rio Grande rift in the study area.

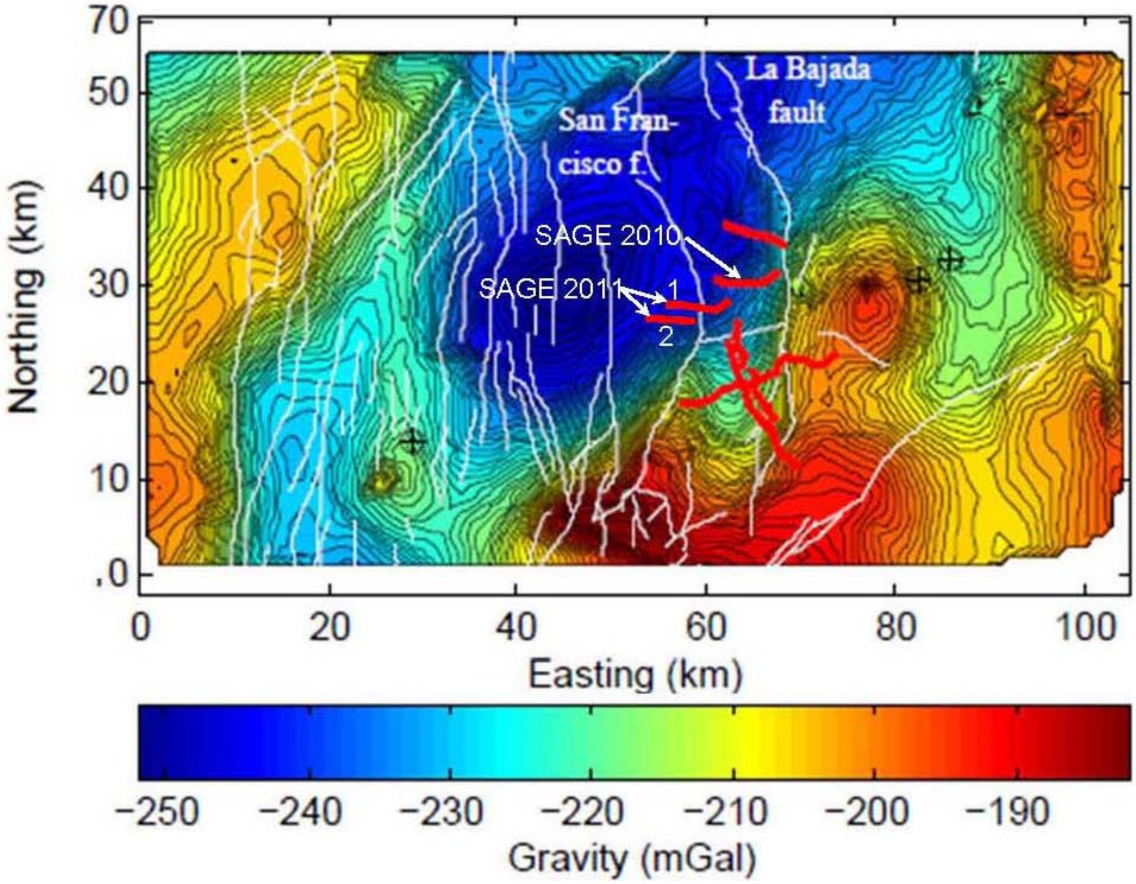

Figure 4. Complete Bouguer gravity map of the Santo Domingo basin area. Contour interval is 1 mGal. Thin white lines are faults. Bold red lines are seismic profiles. The SAGE 2010 and 2011 seismic reflection profiles which also include detailed gravity observations are also shown.

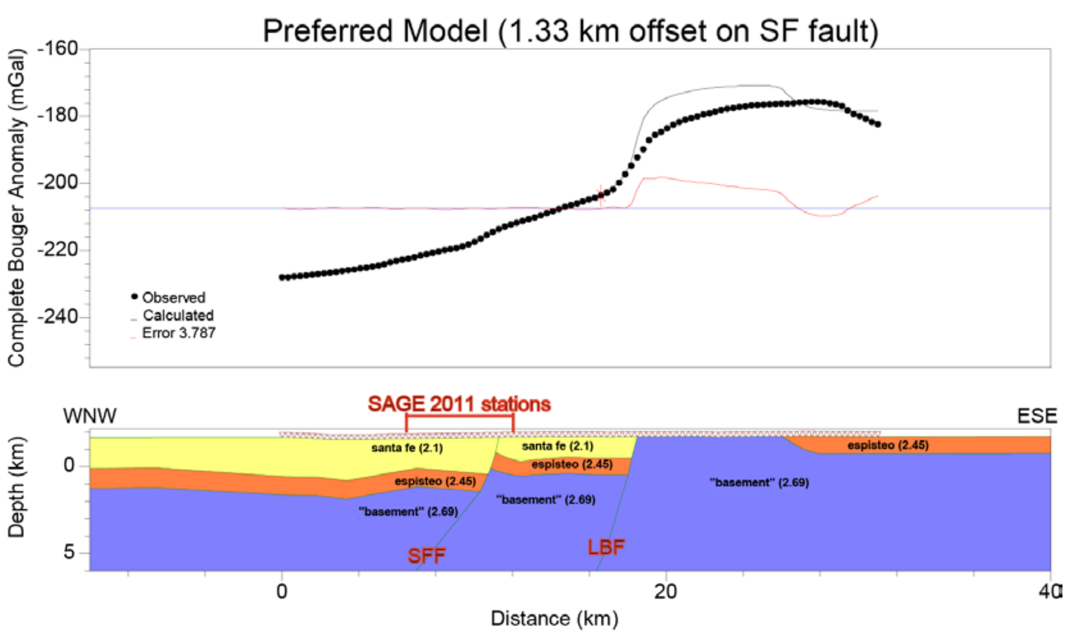

Figure 5. Gravity model by SAGE 2011 student James Worthington is based on the seismic reflection sections from SAGE 2010 and Sage 2011. It shows an offset of about 1.3 km across the San Francisco fault (SFF) in addition to the down-drop across the La Bajada fault (LBF) to the east, creating the Santo Domingo basin.

Geophysical Surveys in the Caja del Rio Geothermal Area: The SAGE program was expanded in 2011 to include geothermal assessment by taking advantage of its location in Rio Grande rift and additional short-term funding from the National Renewable Energy Lab (NREL/DOE). This expansion addressed the national call for more renewable energy and new career opportunities for students. A field site near Santa Fe, New Mexico was selected after SAGE students reviewed 28 years of SAGE geophysical results and other available geological, geohydrologic, geophysical, and geochemical data. The site is ~25 km northwest of Santa Fe, New Mexico in the Caja del Rio volcanic field. Here, 1.14-2.8 Ma volcanism has been mapped from 50 exposed vents and high temperatures recently have been reported (Manning, 2009) in deep water wells. These findings along with high $^3He/^4He$ ratios in groundwater (Manning, 2009) and numerous, rift-related faults may expose a high-temperature magmatic/mantle component in the groundwater.

SAGE 2011 gravity and magnetotelluric (MT) measurements in the Caja del Rio were focused on a large (>50 sq. km) area (Figure 6) that lacked gravity and MT results. Nearby, past SAGE results, including seismic refraction and reflection, modeled a thick (≥2 km) water-bearing sedimentary subsurface section with low-porosity, impermeable basement rocks below. All SAGE students participated in the data collection of gravity and electromagnetic data (MT and TEM) in the potential geothermal area and eleven students worked on these data for their individual and integration team research projects. SAGE student modeling of new, although sparse, SAGE 2011 gravity and MT measurements confirm depths of ~2 km to high density/resistivity basement rocks (Figure 7, left). The gravity model has a basement rise under the western part of the volcanic field that is shown in red in the figure. This is consistent with uniform basement depths of B = 2.1-2.3 km (Figure 7, right) modeled below the four MT soundings on the eastern side of the volcanic field. An added geothermal finding from the MT modeling is the relatively shallow midcrustal conductor (MC<15 km-deep). SAGE results place this conductor at depths ranging from 27 km outside of the rift to 7 km deep under the Valles caldera, a world-class geothermal feature 15 km northwest of the Caja del Rio volcanic area. The depth to the ubiquitous midcrustal conductor in the western U.S. is considered to be a proxy for the depth of the 500^{o}C isotherm (Wannamaker et al., 2008), therefore, may be a very valuable regional assessment tool.

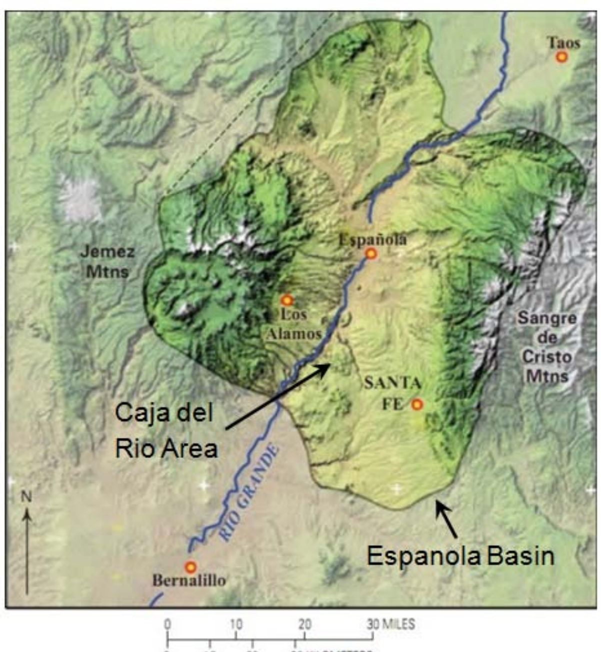

Figure 6. Base map showing the location of the Caja del Rio area for SAGE 2011 Geothermal and geophysical surveys.

SAGE 2011 results support the possibility that viable geothermal potential exists in the Caja del Rio area via upflow through deep conduits. Extrapolation of measured temperature gradients of 58°C/km (Manning, 2009) provide estimates of well over 100°C within the >2km-deep sedimentary basin. Temperatures in the impermeable basement below would easily exceed >200°C at<4 km depth which is the criterion used to define high-grade enhanced geothermal systems (EGS) (MIT, 2006). Thus, the Caja del Rio area appears to be the most attractive commercial geothermal prospect in the central Rio Grande rift outside of the Jemez Mountains-Valles caldera area for direct geothermal use or EGS.

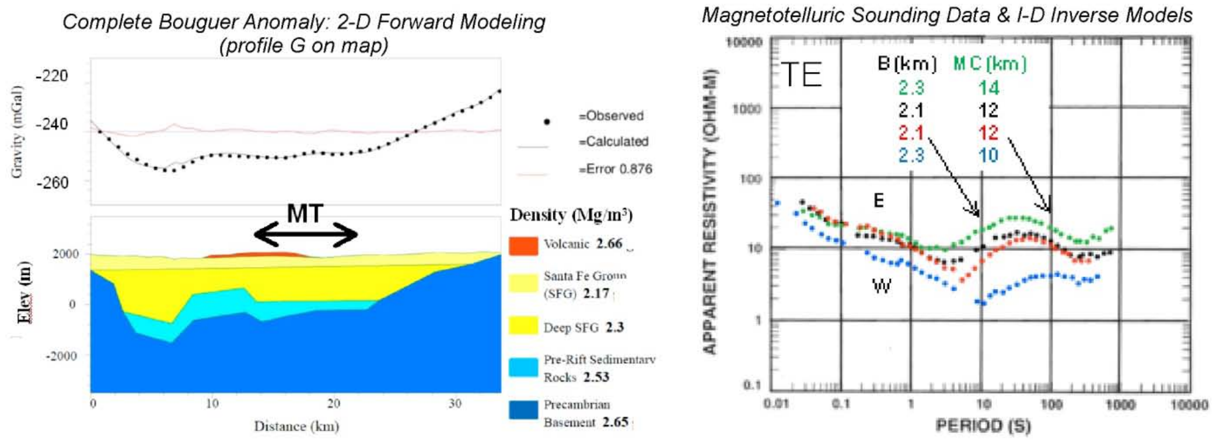

Figure 7. Left: SAGE 2011 west to east complete Bouguer gravity anomaly and density model across the Caja del Rio volcanic field (shown in red); location of four-station MT profile indicated by double-ended arrow. Basement depths are near 2 km beneath the eastern Caja de Rio and a basement high of ~0.5 km is modeled under the western end of the volcanic field. Right: Four east to west SAGE 2011 transverse electric (TE) MT sounding curves and inversion calculations of depths to resistive basement (B) and to mid-crustal conductor (MC). Basement depths are uniform at 2.1-2.3 km and the midcrustal conductor depth shallows from east (14 km) to west (10 km).

References:

Manning, A. H., 2009, Ground-water temperature, noble gas, and carbon isotope data from the Española Basin, New Mexico, U.S. Geological Survey Scientific Investigations Report 2008–5200, 69 p.

Massachusetts Institute of Technology (MIT), 2006. The future of geothermal energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century.

Wannamaker, P. E., Hasterok, D. P., Johnston, J. M., Stodt, J. A., Hall, D. B., Sodergren, T. L., Pellerin, L., Maris, V., Doerner, W. M., and Unsworth, M. J., 2008, Lithospheric Dismemberment and Magmatic Processes of the Great Basin-Colorado Plateau Transition, Utah, Implied from Magnetotellurics, Geochemistry, Geophysics, Geosystems, 9, 38 p.

San Marcos Pueblo Archaeological Site Geophysical Surveys: The SAGE program continued its studies of the San Marcos Pueblo archaeological site with collection of new Ground Penetrating Radar (GPR), electromagnetic (EM), magnetic and seismic refraction data during SAGE 2011. All SAGE students participated in the data collection of GPR, EM, magnetic and seismic refraction data at San Marcos and four students worked on these data for their individual and integration team research projects. SAGE geophysical studies related to hydrology at San Marcos were the subject of a poster presentation at the 2011 SEG meeting in San Antonio (see reference information and link to a pdf of the poster below). This presentation was recently recognized by the SEG (letter from SEG President Bob Hardage) as one of the top 31 papers presented at the San Antonio SEG meeting.

From the 2011 and previous SAGE seismic refraction data, seismic lines 9, 15, 17 and 18 (Figure 8) were chosen to map the geologic structure of the site to better understand the hydrology of San Marcos. The site "basement" is the Eocene Galisteo formation. The Pliocence Ancha formation overlies the Galisteo. The Ancha is an excellent aquifer that is recharged by snow melt at the mountain front many kilometers away. Overlying Pleistocene terraces seal the aquifer, but are locally eroded away on the West side of the site. The springs produced by this exposure would have been a very significant motivation for the settlement of the San Marcos Pueblo. The presence of the Ancha aquifer and springs is unique in the surrounding area. The velocity models obtained by detailed modeling of the refraction profiles show the importance of the topography and layering at San Marcos as controls on groundwater flow and the locations of springs (Figure 9).

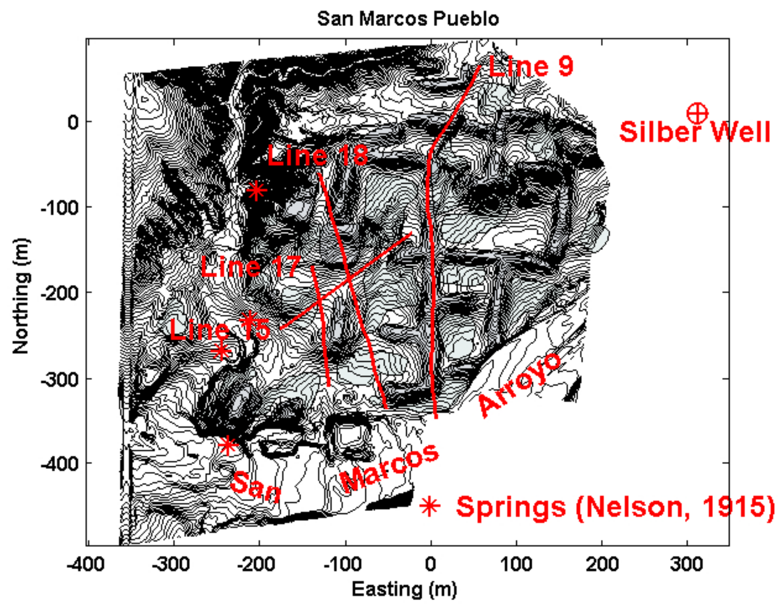

*Figure 8. The topographic base map for the San Marcos Pueblo archaeological site is shown with 0.25 m contour interval. The collapsed room blocks are clearly visible as linear mounds several meters high. The locations of historically persistent springs are indicated by the red * symbols and a currently active water well is displayed in the NE corner.*

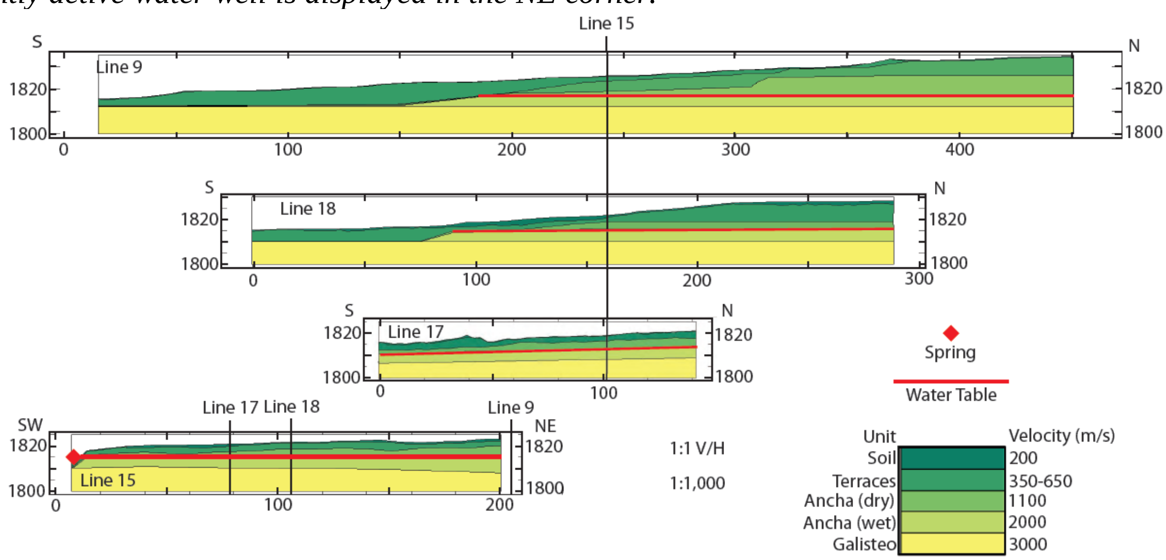

Figure 9. The 2-D velocity models corresponding to lines 9, 15, 17 and 18 are shown.

SAGE 2011 Poster Presentation at the 2011 GRC Meeting:

Geophysical Evaluation by the SAGE Group of a Newly Discovered Geothermal Prospect near Santa Fe, New Mexico

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The GRC Poster is available at: http://web.ics.purdue.edu/~braile/sage/GRCPosterOct19.pdf

SAGE 2011 Abstract of Poster Presentation at the 2011 SEG Meeting:

Hydrogeophysics and the Settlement of San Marcos Pueblo, NM: Investigations by the SAGE Geophysical Field Course

John Ferguson, University of Texas, Dallas, Daniella Rempe, University of California, Berkeley, Anna Nowicki, Michigan State University, Kate Talaksen, W. Virginia University, Nathaniel Lindsey, University of Rochester, Jason Chang, University of California, and Louise Pellerin, Green Engineering*

Summary: San Marcos Pueblo, archaeological site LA 98, was occupied in the 13th century and abandoned after 1680. This was a large community that conducted extensive trade based on local mineral resources. The Summer of Applied Geophysical Experience (SAGE) Field Course has conducted investigations pointing to unique groundwater access as a motivating factor in the pueblo settlement. The Quaternary stratigraphy of the site has been revealed by near-surface seismic refraction profiling. The specific hydrogeologic conditions leading to the reliability of San Marcos Spring are the presence of the Ancha formation, its basal juxtaposition on the Galisteo formation and the erosion of overlying Holocene terrace deposits.

The SEG expanded abstract is available at:
http://web.ics.purdue.edu/~braile/sage/FergusonSEGAbstract2011.pdf

The SEG Poster is available at: http://web.ics.purdue.edu/~braile/sage/FergusonSEGPoster2011.pdf

SAGE 2011 Abstracts of Poster Presentations at the Fall 2011 AGU Meeting:

Seismic and Gravity Investigation of the Eastern Boundary of the Santo Domingo Basin, Rio Grande Rift, New Mexico

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New seismic refraction/wide-angle reflection and CMP seismic reflection profiles were recorded by the SAGE (Summer of Applied Geophysical Experience) program across the eastern boundary of the Santo Domingo basin, Rio Grande rift, New Mexico in 2010 and 2011. In addition, new gravity data were acquired along the seismic lines, in the area of the eastern boundary and in the Santo Domingo basin. A complete Bouguer gravity anomaly map was produced from the new gravity measurements and previously existing gravity data. Two and one half dimensional modeling of approximately east-west Bouguer anomaly profiles was used to estimate basin depth and fault offsets at the eastern boundary of the Santo Domingo basin and to compare with the seismic reflection interpretations. The refraction and wide-angle reflection data were modeled using slope-intercept, 2-D ray trace and wide-angle dipping layer reflection travel times. Typical velocities for the Tertiary layers are approximately 750 m/s, 2000 m/s and 2400 m/s. Deconvolution, bandpass filtering, velocity analysis and CMP stacking were utilized to produce seismic reflection sections for the east-west reflection profiles from 2010 and 2011. The reflection data imaged the La Bajada and San Francisco faults along the eastern boundary of the Santo Domingo basin. These data and available industry reflection data to the east of our field area indicate offsets of greater than 2 km for the La Bajada fault (down to the west) and about 1 km of offset for the San Francisco fault (down to the west). Using constraints from the seismic data on depth to Tertiary and Mesozoic sedimentary units, the gravity modeling suggests a depth to crystalline basement of over 5 km in the Santo Domingo basin.

The AGU Poster is available at: http://web.ics.purdue.edu/~braile/sage/BraileAGUPoster2011.pdf

Geophysical Characterization by the SAGE Program of a Newly Proposed, Low Temperature-EGS Prospect in the Central Rio Grande Rift, New Mexico

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In 2011 the SAGE (Summer of Applied Geophysical Experience) program began initial field evaluation of a recently proposed geothermal prospect located approximately 20 km northwest of Santa Fe, New Mexico. New magnetotelluric (MT) and gravity measurements in the Caja del Rio volcanic field have been combined with previous industry seismic results and SAGE MT, gravity, and seismic data to define parameters important for potential low temperature and EGS development. A thick, 2.0-2.5 km-deep, water-saturated, electrically conductive section overlies resistive basement, presumably Paleozoic limestone on top of Precambrian granite. Therefore, by projecting a measured 58^{o}C/km near-surface temperature gradient, the area would easily meet the criterion for high grade EGS of impermeable basement rock at >200^{o}C at less than 4 km depth. MT-derived depth estimates of a ubiquitous, highly conductive

midcrustal conductor along with thermal conductivity values, and estimates of radiogenic heat flow allowed thermal modeling of the entire upper crust. This relies on recent evidence that the midcrustal conductor depth is a good proxy for the depth to the 500^{o}C isotherm in active tectonic areas. The resulting thermal calculations yield a surface heat flow of 80 mW/m^2 for a 2 km-deep sedimentary column and a 14 km-deep conductor. Forced, westward flowing groundwater convection over a basement high has been proposed for the thermal anomaly. Our initial geophysical results do not provide strong evidence for this. Rather, we favor the possibility that deeply penetrating, permeable fault conduits provide pathways for ascending warm water beneath the volcanic field. This is supported by high ^{3}He/ ^{4}He ratios measured in groundwater samples. The Caja del Rio area appears to be the most attractive geothermal prospect in the central Rio Grande rift outside of the near-by, world-class Valles caldera geothermal area.

The AGU Poster is available at:
http://web.ics.purdue.edu/~braile/sage/JiracekAGUPoster2011.pdf

Field Geophysics at SAGE: Strategies for Effective Education

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SAGE (Summer of Applied Geophysical Experience) is a unique program of education and research in geophysical field methods for undergraduate and graduate students from any university and for selected professionals. The core program is held for four weeks each summer in New Mexico and for an additional week in the following academic year at San Diego State University for U.S. undergraduates supported by the NSF Research Experience for Undergraduates (REU) program. Selected from a wide range of large and small colleges and universities, 25-30 students participate in SAGE each year. Since SAGE was initiated in 1983, 730 students have participated in the program. NSF REU funding for SAGE began in 1990 and 319 REU students have completed SAGE through 2011. The primary objectives of SAGE are to teach the major geophysical exploration methods (seismic, gravity, magnetics, electromagnetics); apply these methods to the solution of specific problems (environmental, archaeological, hydrologic, geologic structure and stratigraphy); gain experience in processing, modeling and interpretation of geophysical data; and integrate the geophysical models and interpretations with geology. Additional objectives of SAGE include conducting research on the structure and tectonics of the Rio Grande rift of northern New Mexico, and providing information on geophysics careers and professional development experiences to SAGE participants.

Successful education, field and research strategies that we have implemented over the years include: 1. learn by doing – an immersion approach to the program; 2. mix lecture/discussion, field work, data processing and analysis, modeling and interpretation, and presentation of results; 3. a two-tier team approach – method/technique oriented teams and interpretation/integration teams (where each team includes persons representing different methods), provides focus, in-depth study, opportunity for innovation (technique oriented teams), and promotes teamwork and a multi-disciplinary approach (interpretation/integration teams); 4. emphasis on presentations/reports – each team (and all team members) make presentation, each student completes a written report; 5. experiment design discussion – students help design field program and consider issues – safety, constraints, data quality/quantity, research objective, educational experience, survey parameters, why multidisciplinary?, etc.; 6. knowledge of multiple geophysical field methods (each student works with all methods); 7. information on geophysics careers and networking provided by industry visitors; 8. experience and interaction (many of the students become friends and colleagues for life); 9. measures of success of the program include high rate of continuation to graduate school (about 75% of SAGE undergraduates) and careers in geophysics, support and feedback from industry participants and visitors, student evaluations at end of program, presentations at professional meetings, publications, and faculty evaluation of student work.

The AGU Presentation is available at: http://web.ics.purdue.edu/~braile/sage/FieldGeophysics.ppt