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Geobotanical Remote Sensing for Geothermal Exploration

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ABSTRACT

This paper presents a plan for increasing the mapped resource base for geothermal exploration in the Western US. We plan to image large areas in the western US with recently developed high resolution hyperspectral geobotanical remote sensing tools. The proposed imaging systems have the ability to map visible faults, surface effluents, historical signatures, and discover subtle hidden faults and hidden thermal systems. Large regions can be imaged at reasonable costs. The technique of geobotanical remote sensing for geothermal signatures is based on recent successes in mapping faults and effluents the Long Valley Caldera and Mammoth Mountain in California.

INTRODUCTION

The United States Department of Energy is developing "GeoPowering the West", a program whose goal is to dramatically increase the use of geothermal energy in the western United States. One element required to accomplish that goal is to increase the resource base for hydrothermal systems that can potentially be used to produce electric power. One strategy for making incremental changes in the resource base is to expand the use of the borders of currently exploited hydrothermal systems. However, to significantly increase the resource base, we need to identify and locate new classes of hydrothermal systems.

Most geothermal fields have been discovered by their surface effluents. Typically, springs and fumaroles are sampled and geochemical analyses are used to infer the maximum temperatures that the fluids are exposed to in the subsurface. Those areas with highest geochemical temperatures are further explored in detail, drilled and, with good results, utilized. The fields with surface manifestations comprise the bulk of the undeveloped resource base at this time, and we believe that in the western US they have been well cataloged.

To increase the resource base significantly, we must assess whether there are a large number of currently undetected hidden thermal systems, and develop means to locate them. Hidden thermal systems are those that have little outflow to the surface. A small number of fields have been found despite having no obvious surface manifestations, generally, by exploration drilling for some other resource or by drilling heat-flow holes on a regular grid. Historically, other agencies, such as the USGS, would have had responsibility for a broad assessment of these systems. Today, DOE needs to lead the effort to evaluate the potential of Hidden Systems. Recently work that was started by the LLNL Geothermal Program three years ago to develop visible and near IR hyperspectral imaging for mapping subtle geobotanical surface expressions of geothermal systems has shown great promise. The results of this research has given us encouragement that we can explore for hidden surface expressions to extend known geothermal areas and to discover new ones. An overview of the newly emerging field of hyperspectral geobotanical remote sensing and the collaborative team at LLNL and University of California Santa Cruz developing these techniques can be viewed at http://emerald.ucsc.edu/~hyperwww/ and http://emerald.ucsc.edu/~hyperwww/proj.html

The promising new results that include the discovery of hidden faults at Mammoth Mountain can be viewed at http://emerald.ucsc.edu/~hyperwww/mammoth.html
and are summarized below.

On September 7, 1999, seven LLNL-funded lines of hyperspectral data were flown of the caldera with the HyMap instrument (Integrated Spectronics, Ltd.), satisfying our initial objective to acquire higher spatial resolution imagery than previously available (Figure 1).

Figure 1.

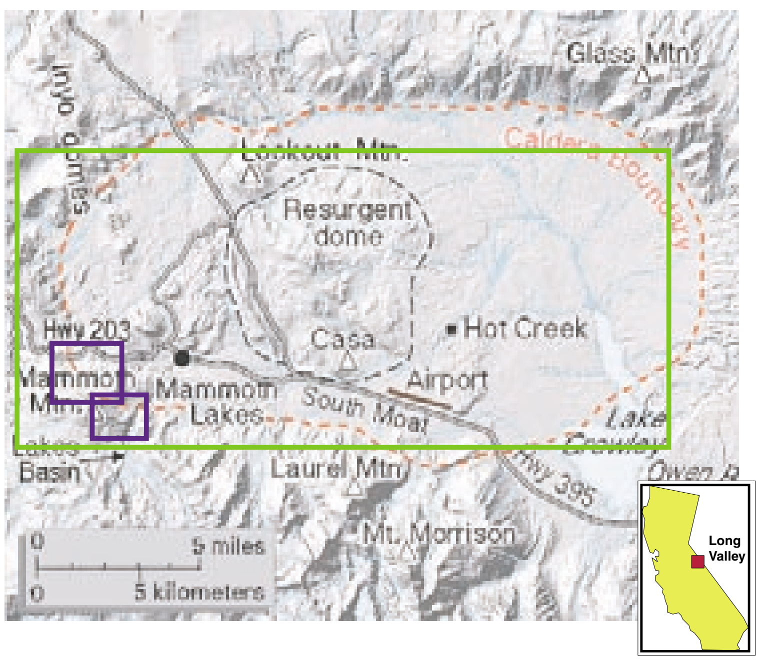

Figure 1. Location map of the Long Valley caldera. Light rectangle shows approximate boundary of September 7, 1999 acquistion. Darker rectangles are the subsets discussed in this study. Modified from http://quake.wr.usgs.gov/VOLCANOES/LongValley/

The Long Valley dataset samples reflectance's from 400 to 2500 nm, in 126 separate but contiguous bands. Each pixel is from 3-5 m in dimension and the signal-to-noise is reportedly greater than 1000:1. The atmospherically corrected images were processed spectrally using an algorithm called the Minimum Noise Fraction (MNF), and spatially using the Purest Pixel Index (PPI) algorithm contained within the software program ENVI. The goal in this processing is to isolate spectrally pure endmembers of earth materials for use in an array of supervised classifications and unmixing algorithms.

Figure 2 shows spectral-based mapping on a small subset of the HyMap imagery from the southwestern flank of Mammoth Mt., a small stratovolcano located on the southwestern rim of the caldera (location in Fig. 1). By comparing previously constructed geologic maps with spectroscopic-based maps, it is possible to ascertain both that spectroscopy can produce comparable fault maps to those created by traditional field methods, and that spectroscopic maps can reveal faulting previously unrecognized. Linear distributions of hydrothermal alteration minerals are used as proxies for fault and fracture locations.

Figure 2.

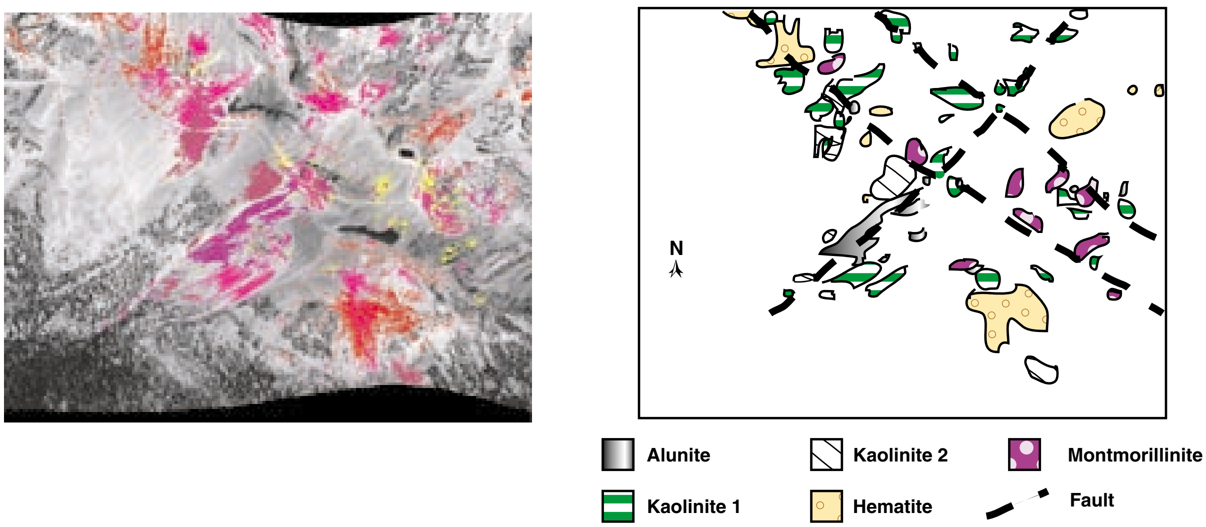

Figure 2. Classification results from the southwestern flank of Mammoth Mt. The image on the left is a grey-scale (2.2um) subset with overlayed alteration distributions. The image on the right shows these distributions with more clarity. Also plotted on the right-hand image are faults that coincide with these linearly distributed alteration minerals.

Figure 2 highlights a northeast-trending lineament mapped out by kaolinite and alunite distributions, as well as several northwest-trending lineaments. The pattern seen in the processed image of higher temperature minerals (alunite) surrounded by lower temperature clays (kaolinite) is very common in hydrothermal environments. Though not currently discharging gasses or hydrothermal fluids, the northeast-trending zone seems to be a paleo-fumarolic zone. The presence of alunite in particular, indicates a high acid-sulfate temperature and low pH, in agreement with the hypothesis that a high temperature hydrothermal reservoir exists beneath Mammoth Mt. (Ref 2)

The northeast-trending fault that we see spectroscopically on the southwestern flank, is consistent with faults mapped just to the northeast of Mammoth Mt. in the Discovery Fault Zone

(Ref 3). In addition, regional northeast-trending structures can be found to the south in the Deep Springs Fault Zone, to the northeast in the Excelsior Mountains, and to the north in the Bodie Hills. Local minimum compressive stress in the western caldera is orientated NW-SE (Ref 4) and the 1989 dike intrusion beneath Mammoth was orientated approximately N20E and lay beneath the southwestern flank (Ref 5). We interpret these NE-trending faults as part of a rotational fault system slipping left-laterally in a larger NW-trending system of right shear. This kinematic pattern results in local extension along the NE-trending faults and easier egress of both magma and geothermal fluids in the Long Valley caldera and in other geothermal systems associated with the Eastern California Shear zone (Ref 6).

The effect of volcanic phenomena on caldera ecosystems is also studied. Biological-geological interactions can be identified and mapped such as the spectral-based tree-kill map shown in Figure 3. Massive magmatic CO_2-induced tree kills were initiated in 1989 after the dike intrusion event mentioned previously (Ref 5). Since 1989, over 50 hectares of trees have died surrounding the volcano.

Figure 3.

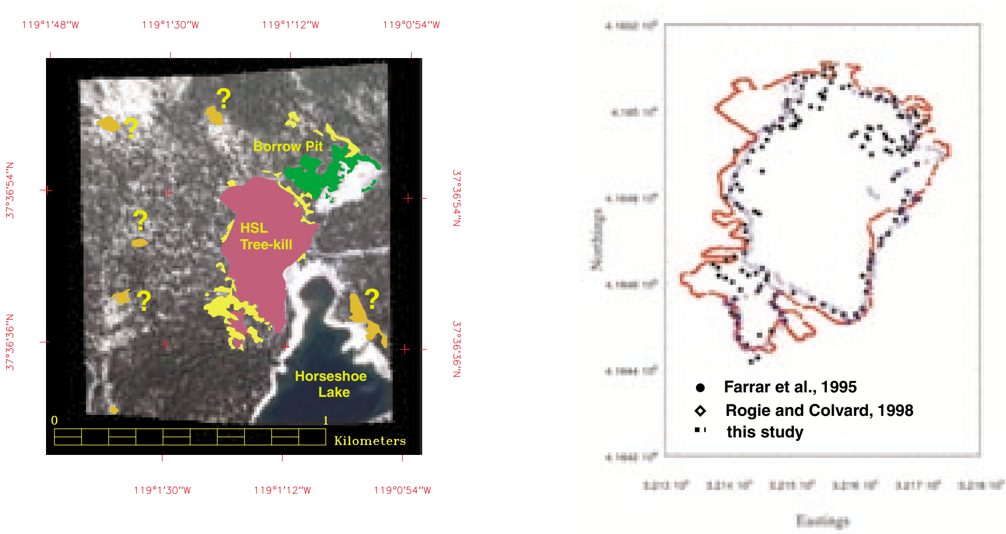

Figure 3. The image on the left shows Horseshoe Lake tree-kill mapping results. The lightest shades represent transitional zones (sub-lethal tree populations), while the darker shades show the present boundaries of dead populations. On the right is a comparison of hyperspectral based size estimates of the kills with previous estimates via more traditional means.

The Horseshoe Lake Tree-kill shown in Figure 3 is the site of highest flux on the mountain with approximately 100 tons/day fluxing diffusively out of the ground (Ref 7 and . http://quake.wr.usgs.gov/VOLCANOES/LongValley/CO2.html) Spectral signatures of healthy robust trees, dead trees, and physiologically stressed trees were extracted from the imagery and used in several mapping schemes. The kill itself is mapped in Figure 3, including transitional zones of sub-morbid populations. Figure 3 also shows the comparison of the kill boundaries as mapped by traditional field methods and via hyperspectral data analysis. Such maps are available for other kill regions on the volcano.

The examples above suggest that hyperspectral data can provide geological and biological information about a system quickly, synoptically and without a host of other ground-based monitoring programs. This makes it an attractive tool for studying other calderas around the world which often lack basic maps as well as dense seismic, GPS, and geochemical monitoring programs. The expense of hyperspectral data will likely decrease once such instruments are spaceborne and the computational size and time required for analysis is increasingly attainable.

These new techniques developed by Brigette A. Martini as part of her Ph. D. thesis have shown that the need for intensive fieldwork on the ground is eliminated. The airborne imaging techniques can survey large areas quickly and at a reasonable cost. Based on these results, we suggest a research framework, that would enable DOE to access how useful these techniques will be in finding hidden systems or hidden parts of known systems in the "Basin and Range". The research strategies must be based on conceptual models that are broadly accepted by a number of exploration disciplines. For the Basin and Range, Kenneth Wisian, of Southern Methodist University has described the general characteristics of extensional, non-magmatic geothermal systems.

The conceptual models must identify a number of attributes that can be explored for. In the Basin and Range extensional systems, these attributes would include, among others to be determined, appropriate orientation of range-bounding fracture systems to local and regional stress field, adequate water supply, appropriate host-rock permeability, evidence of weak outflow, active deformation, and possibly appropriate topographic relief.

The exploration strategy must match those attributes. For example, in the Basin and Range, one would explore along the major fault traces looking for evidence of favorable stress and permeability. The hyperspectral overhead imagery techniques being developed by the LLNL/UCSC collaboration would be particularly useful in this task. The slight changes in water permeability and sometimes temperature along hidden faults often produce a distinctive geobotanical hyperspectral signature in the overhead imagery as Brigette Martini has recently shown in her results at Mammoth Mountain presented earlier in this paper (Ref 8) and (Ref 9). The airborne hyperspectral imagery remote sensing technology is capable of covering large areas with 3 meter resolution. This will allow us to identify favorable targets for further investigation. In the moderately high heat-flow areas (90-99 mW/m^2) of the Basin and Range, Wisian and colleagues have shown that there is about one discovered high-temperature field per 14,000 square kilometers. A cursory examination of the Nevada State fault map suggests that there is 500-1100 km of significant faults in the same area. Finding hidden systems twice as often would significantly increase the resource base, but will still require the exploration of 250 to 550 km of fault for each new field found. This size is well with in the airborne hyperspectral imaging capability that we currently contract with HyVista Corp. http://www.hyvista.com/ We have acquired 850 linear km of hyperspectral images with 1.2 km wide flight lines, with 3 m spatial resolution, in two hours at solar noon in recent missions at Elkhorn Slough CA. Hyperspectral visible and near infrared images of 850 Square kilometers at 3 meter spatial resolution costs 25k$ and takes 1 day. The data comes georectified by the onboard differential GPS for that price. The lay days are 12 K$ each and to come over is a one time 50 K$ shared out so about 10 K$. I find these amounts extremely encouraging for imaging most of the geothermal hidden resources in the US at a very reasonable cost for the hyperspectral imagery acquisition.

This new wide area geobotanical hyperspectral airborne remote sensing is easily combined with existing understanding of the areas imaged. Additional measurements by the methods traditionally applied to geothermal exploration, geochemistry, heat flow, seismic, electrical, gravity, magnetic, SP, can then be used in highly targeted areas by the results of the airborne imagery. This is important because the traditional techniques are expensive, slow, and focus on small areas. For those regions already surveyed by the traditional methods the airborne hyperspectral imagery provides an overview that can integrate the point measurements producing a more complete understand of the extended region. The new technology of airborne high resolution hyperspectral imagery, which is aircraft-based and soon will be satellite based will definitely improve our understanding of the Basin and Range geothermal resource base.

In addition to finding hidden faults, the hyperspectral imagery reveals many signatures of geothermal surface expressions. As described earlier in this paper, Brigette Martini has been using hyperspectral overhead imagery to map the CO_2 leakage from the Mammoth Mountain. Exhalation of CO_2 from the flanks of Mammoth Mt., Ca., that has been occurring since 1989-1990. The releases have resulted in massive tree kills in several locations around the mountain. The largest is located near Horseshoe Lake on the southern flank. Several researchers using portable CO2 sensors on the ground have carefully studied the CO2 emission in this area. Please see
http://www.geosc.psu.edu/~jrogie/ and
http://quake.wr.usgs.gov/VOLCANOES/LongValley/CO2.html

The lower levels of CO_2 emissions measured by the "on the ground CO_2 sensors" is approximately 1 gram/square meter/day. These levels occur near the edges of the CO_2 emission zone shown in the map produced by John Rogie, et al. The Map is shown in Figure 4. This figure is from John Rogie's web site found at http://www.geosc.psu.edu/~jrogie/hslmap.jpg . Rogie is publishing a newer map. (Ref 7)

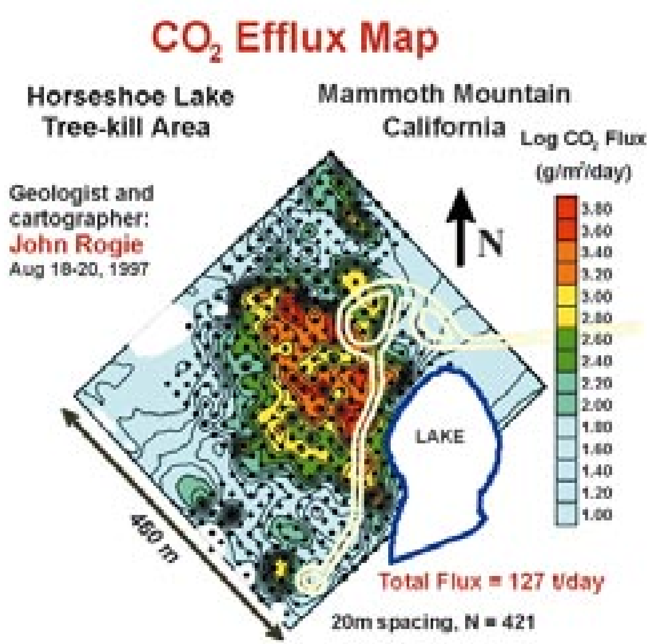

Figure 4. from http://www.geosc.psu.edu/~jrogie/hslmap.jpg

It is instructive to compare this map generated by very many on the ground samplings of CO2 by Rogie to Martini's map of integrated bio-response to the CO2 emissions shown in Figure 2 in this paper. Brigette Martini has shown that varying amounts of physiological stress in the forest communities, due to the elevated CO_2 gas emission levels, can be seen. She has found that the 3 meter hyperspectral imagery does have sufficient spatial and spectral resolutions to map general plant species categories and to map relative plant health within these categories. Martini's mapping of the stressed vegetation using the hyperspectral imagery agrees very well with mapping done on the ground by Rogie. Her mapping does extend the affected area beyond that studied by Rogie. The geobotanical technique takes advantage of the fact that the biosphere has an integrated response to released soil CO_2. In the case of geothermal formations, CO_2 effluents are highly variable in spatial location and change rapidly on short time scales like hours, presumably due to barometric pressures at the various parts of the site and hidden faults. Recently Rogie has published an excellent paper (Ref 7) that provides very detailed spatial and time dependent distributions of CO2 fluxes he ahs measured at Horseshoe Lake. His paper is "Dynamics of Carbon Dioxide Emission at Mammoth Mountain, California, John D. Rogie, et al accepted for publication and in press by Earth and Planetary Science letters. We will be using his detailed CO2 emission map at Horseshoe lake to provide a calibration of Martini's average biological impact mapping using the overhead imagery. This should provide semi quantitative interpretation of the plant effects that will be seen in airborne hyperspectral imaging of large regions that have CO2 emissions. This is very important because the terrestrial plants, grasses, trees, bushes, and the aquatic species of algae and plant life sample the CO_2 effluents and generally respond with observable surface distributions that are indicative of the average CO_2 effluent very locally over wide areas. Our overhead imaging techniques can be then be calibrated locally with relative few of the expensive, on-the-ground in place measurements for CO_2 effluents.

Another example of detectable signatures of geothermal surface expressions is the sensitive detection of altered minerals and specific types of temperature and chemical dependent microorganisms found in geothermal springs.

HYPERSPECTRAL IMAGING METHODS

The hyperspectral geobotanical remote sensing techniques that we are developing use advanced commercial airborne imaging spectrometer systems available in the USA and worldwide. The system that we normally contract for in overhead imaging missions produces visible and near IR reflected light images with spatial resolution of 1 to 5 meters in 128 wavelength bands. Please see http://www.hyvista.com/ The average spatial resolution of about 3 meters allows us to detect and discriminate individual species of plants as well as the complexities of the geological and man made objects in the images. We then can interpret the observed plant species distributions and their relative health along with a detailed understanding of the local geology, and the local human activities. We are able to distinguish terrestrial and aquatic plant species, all types of geological formations and soil types, and many different types of human activities. We can then look for biological impacts of seepages in large complicated areas. These techniques do not require before and after imagery because they use the spatial patterns of plant species and health variations present in the one image to detect and discriminate geothermal surface signatures.

Additionally we expect that commercial hyperspectral satellites will be operational in the next year or so. Please refer to the imaging sensor table at

http://emerald.ucsc.edu/~hyperwww/instruments.html which is on the geobotanical remote sensing web site http://emerald.ucsc.edu/~hyperwww/chevron.html that we maintain in collaboration with Chevron Corp. In particular, the hyperspectral satellite Warfighter http://www.orbital.com/Template.php3?Section=News&NavMenuID=32&template=PressReleaseDisplay.php3&PressReleaseID=93
on the Orbital Sciences platform http://www.orbimage.com/
will be available for real time imaging. We also expect to see more and improved airborne hyperspectral imaging services available for hire. This should allow for continued hyperspectral imaging over many areas in the western US.

The visible and near infrared (VISNIR) hyperspectral techniques are relatively well established by our work. We would like to extend our technique to include radar and the two thermal wavelength regions of hyperspectral imagery (MWIR 3 to 5 micron, and LWIR 8 to 12 micron). This could be easily accomplished by including acquisitions with SAR radar and the SEBASS hyperspectral thermal infrared instrument. Please see
http://www.lpi.usra.edu/science/kirkland/Mesa/text.html and
http://www.aero.org/technology/index.html for information about SEBASS. The costs for this type of acquisition would be approximately the same as for the Visible and near IR (VISNIR) hyperspectral. The Hyperspectral Applications division at Aerospace Corp. in El Segundo would do the SEBASS acquisitions.

We would like to try to use images from the DOE 12 band VISNIR, MWIR, and LWIR satellite called MTI, to see how it compares to the hyperspectral imagery for all the purposes discussed in this paper.

CONCLUSION

We have developed a research plan to test the hyperspectral geobotanical concept for expanded mapping of the geothermal resource base in the western US. The areas under consideration have known, but not well exploited systems with some areas of minimal surface expression. This will determine if we are able to detect and discriminate low signature geothermal systems. Candidate areas include, but are not restricted to, extensional systems in the Basin and Range, Sierra Front Bounding magmatic systems, and California Coast range systems.

Our plan combines the established hyperspectral imagery tools with other classical geothermal exploration and development tools.

References and Bibliography

1. Goetz A.F.H., G. Vane, J.E. Solomon, B.N. Rock, "Imaging Spectrometry for Earth Remote Sensing," *Science* **228**, 1147-1153 (1985).

2. Sorey, M.L., G.A. Suemnicht, N.C. Sturchio, G.A. Nordquist, "New evidence on thehydrothermal system in Long Valley caldera, California, from wells, fluid sampling, electrical geophysics, and age determinations of hot-spring deposits," *Journal of Volcanology and Geothermal Research* **48** 229-263 (1991).

3. Suemnicht, G.A. and R.J. Varga, "Basement structure and implications for hydrothermal circulation patterns in the western moat of Long Valley Caldera, California," *Journal of Geophysical Research* **93** 13,191-13,207 (1988).

4. Moos, D. and M.D Zoback, "State of stress in the Long Valley caldera, California," *Geology* **21** 837-840 (1993).

5. Hill, D.P., et al., "The 1989 earthquake swarm beneath Mammoth Mountain, California: An intial look at the 4 May through 30 September activity," *Bulletin of the Seismological Society of America* **80** 325-339 (1990).

6. Reheis, M.C., T.H. Dixon, "Kinematics of the Eastern California shear zone: Evidence for slip transfer from Owens and Saline Valley fault zones to Fish Lake Valley fault zone" *Geology* **24** (339-342).

7. Rogie, J.D., "Dynamics of carbon dioxide emission at Mammoth Mountain, California," Accepted and in Press at Earth and Planetary Sciences Letters, May, 2001

8. B. A. Martini, E. A. Silver, W. L. Pickles, "Hyperspectral Remote Sensing for Research and Monitoring in Active Volcanic Regions", American Geophysical Union (AGU), San Francisco, paper V22F-05, December, 2000

9. Martini, B.A., Silver, E.A., Potts, D.C., Pickles, and W.L. (2000). Insights into the Hydrothermal, Magmatic, and Structural Systems of a Restless Caldera, Long Valley Caldera, CA, USA, Proceedings of the Fourteenth International Conference on Applied Geologic Remote Sensing. p. 28-35

10. Potts, D.C., Siciliano, D., Martini, B.A., Pickles, W.L. Silver, E.A., "Use of hyperspectral sensing to obtain micro-scale ecological data on meso- to macro-scales", 9th Intl. Coral Reef Symp., 2000

11. Siciliano, D., Potts, D.C., Martini, B.A., Pickles, W.L., Silver, E.A., "Hyperspectral applications across land-sea gradients from open ocean to watershed uplands", IEEE 2000 Intl. Geosci. Remote Sens. Symp., 2000

12. Siciliano, D., Potts, D., Martini, B., Silver, E., Pickles, W. L., "High resolution hyperspectral sensing as an environmental monitoring tool for coastal and shallow marine habitats", 6th Intl. Conf. Remote Sens. Mar. Coast. Envir. [Best Paper Award], 2000

13. B. A. Martini, S. A. Cochran, E. A. Silver, W. L. Pickles, D.C. Potts, "Geological and Geobotanical Characterization of a Hydrothermal System Using Hyperspectral Imagery Analysis", ERIM, Summer Meeting, Vancouver BC, July 1999

14. Martini, B.A., Cochran, S. A., Potts, D.C., Silver, E.A., Pickles, W.L., Carter, M. R., Priest, R. E., Wayne, B. M., White, W. T., Anderson, T., "New hyperspectral remote sensing techniques using geobotany, geology, and gas emission observations, for applied geothermal exploration and exploitation", 13th Intl. Conf. Appl. Geol. Remote Sens., 1999

15. "Geological and Geobotanical Studies of Long Valley Caldera and Mammoth Mountain CA Utilizing New High Resolution Hyperspectral Imagery", EOS, Fall AGU Meeting, San Francisco, CA, B. A. Martini, Eli. A. Silver, W. L. Pickles, D. C. Potts, 1999

16. "Mapping environmental stress in Elkhorn Slough, central California using hyperspectral data: a management tool for an at-risk coastal ecosystem", Cochran, S. A., Martini, B.A., Jacobs, J. R., Potts, D.C., Silver, E.A., Pickles, W.L., 5th Intl. Conf. Remote Sens. Mar. Coast. Envir., 1998

17. "Geological and Geobotanical Characterization of Hydrothermal System Utilizing Hyperspectral Imagery Analysis", EOS, Fall AGU Meeting, San Francisco, CA, B. A. Martini, S. A. Cochran, Eli. A. Silver, W. L. Pickles, D. C. Potts, 1998

18. "Detecting Plant Metabolic Responses Induced by Ground Shock Using Hyperspectral Remote Sensing and Physiological Contact Measurements", W. L. Pickles, G. A. Carter, UCRL-ID-127061, December 3, 1996

19. "Observations of Temporary Plant Stress Induced by the Surface Shock of a 1-Kt Underground Explosion", William L. Pickles, UCRL-ID-122557, December 4, 1995, available through National Technical Information Service, U.S. Dept of Commerce, Springfield, VA 22161

20. "Low Altitude Overhead Imagery Acquisition Pre-and Post-NPE", William L. Pickles, LLNL, Janet E. Shines, David L. Hawley, Michael D. Pelan, and Stanley B. Brewster, Jr., EGG RSL, Proceedings of the Symposium on the Non-Proliferation Experiment: Results and Implications for Test Ban Treaties, pages 8-63 through 8-70, CONF 9404100, April 19-21, 1994