GL02131 orig

From: Robert_Clayton@NOTES.YMP.GOV
Date: Thu, 14 Mar 1996 11:55 -0800 (PST)
Subject: Workshop Summary
To: stuckles@qconhp.cr.usgs.gov, ken@seismo.unr.edu, cpotter@sedproc.cr.usgs.gov, ponce@mojave.wr.usgs.gov, elmajer@lbl.gov, zulanger@mojave.wr.usgs.gov, karag@ccs.lbl.gov, lrj@ccs.lbl.gov, mafeighner@lbl.gov, chornack@ympbgate1.cr.usgs.gov, wday@ympb.cr.usgs.gov, scastor@comstock.nbmg.unr.edu, brune@seismo.unr.edu, brocher@andreas.wr.usgs.gov, glenn@seismo.unr.edu, tmbandurraga@lbl.gov, "jwhitney @ ympbnwis1.cr.usgs.gov%YMPGATE"@ccmail.ymppo.ymp.gov, John_Savino@NOTES.YMP.GOV, Tim_Sullivan@NOTES.YMP.GOV, Mark_Tynan@NOTES.YMP.GOV, Daniel_Soeder@NOTES.YMP.GOV, Richard_Quittmeyer@NOTES.YMP.GOV
Cc: C.Thomas_Statton@NOTES.YMP.GOV, Jan_Rasmussen@NOTES.YMP.GOV, Stephen_Nelson@NOTES.YMP.GOV
MIME-version: 1.0

SUMMARY AND CONCLUSIONS OF THE GEOPHYSICS-GEOLOGY INTEGRATION WORKSHOP
Held March 11-13 1996 at Lawrence Berkeley National Laboratory Earth Sciences Division

This document may be placed in scientific notebooks.

Note: Attendees, please reply with any additions, subtractions, or revisions of this summary so that I can pass them on.

Session I: Data Coverage, Availability, and Limitations

* The magnetic basement map and interpretation done by Earthfield Technologies during FY1995 is controversial (E. Majer). Because the flight lines over Yucca Mountain were north-south, the data are not useful for interpreting the north-south trending structures there. Additionally, the USGS has not had time or workscope to evaluate these data and the interpretation method, and so can not make an evaluation at this time (D. Ponce).
* The Paleozoic maps done by Earthfield have resolution of about 500 to 1000 meters (E. Majer).
* For gravity data, vertical resolution is highly dependant on vertical density control. Because only one control point to the Paleozoic exists near Yucca Mountain (p#1), depth resolution is poor (E. Majer, V. Langenheim).
* Gravity and magnetic surface traverses show fault locations quite readily, but do not usually reveal information about fault dips. No unmapped faults have been found on the main part of Yucca Mountain that have offsets greater than a few tens of meters (D. Ponce).
* Estimates of fault dips in seismic profiles are only as good as the velocity control and estimates. As with density data, this information is sparse. Velocities from refraction experiments have been used to help constrain stacking and migration velocities (T. Brocher).
* Magnetic data are dominated by the highly magnetic Topopah Spring Tuff, and so most of the observed signal comes from shallow depths (D. Ponce).
* There is a one-to-one correspondence of known faults to anomalies in magnetic profiles at Yucca Mountain. Deep structures are not always expressed in the Tertiary rocks (D. Ponce).
* USGS Menlo Park has a new program that will improve their calculation of depth to Paleozoic (V. Langenheim).
* In the Earthfield Paleozoic maps, the surfaces are 1500 to 3000 feet

higher or lower than Paleozoic outcrops, with no systematic error, even though Earthfield was given extensive geologic maps (R. Spengler).
* Across Nevada, a density contrast of 0.4 g/cm3 is used at the Tertiary-Paleozoic contact, reflecting densities of 2.3 versus 2.7 (D. Ponce).
* The question was asked to the group: What does the magnetic basement map tell us? The answer from the group was: Not much.
* In a seismic refraction experiment, Walter Mooney found a body at 4 to possibly 10 km depth below Crater Flat with a (relatively high) velocity of 6.7 km/sec. This could perhaps be a stack of basaltic sills (J. Brune). This anomaly corresponds approximately to a magnetic anomaly of unidentified origin (B. Crowe).

Session II: Configuration of the Top of Paleozoic

* The favored model for the development of Crater Flat is that of a pull-apart basin in a combined strike slip--extensional regime (B. Crowe).
* The Bare Mountain fault appears to dip approximately 45 degrees east. Major Crater Flat and Yucca Mountain faults dip moderately (50-60 degrees) west, and extend from near borehole VH-1 to the west side of Jackass Flat (T. Brocher).
* The Paleozoic surface appears to have a relatively low-relief (but still faulted) section beneath eastern Yucca Mountain. Greatest fault offsets on the Pz are under western Yucca Mountain, the Windy Wash fault, and an unmapped fault just west of borehole VH-1 (T. Brocher).
* The Solitario Canyon and/or Ghost Dance faults may represent a shallower and younger expression of a fault which has greater offset at depth (T. Brocher).
* A model for fault evolution, based on the deep seismic profiles: During Miocene volcanism and extension, thermal gradients may have been higher, resulting in a shallower brittle-ductile transition in the crust. The Crater Flat pull-apart basin began to form in this high-heat environment, with the shallow Bare Mountain and steeper Crater Flat basin faults converging at the brittle-ductile transition. With time, the crust cooled and the brittle-ductile transition deepened. As a result, Crater Flat basin faulting migrated eastward as the juction of the faults deepened (T. Brocher).
* The deep seismic profiles imply that earthquake hazards on the western-central Crater Flat basin faults is reduced because these faults do not extend beyond 5-8 km depth where they intersect the Bare Mountain fault (J. Whitney).
* The shallow, conformal reflections across Crater Flat match concepts for Paintbrush Group deposition and (B. Crowe).
* Water chemistry suggests a boundary between boreholes VH-1 and VH-2 which would match the fault seen in seismic profiles (J. Stuckless).
* There is a 100's meter-wide block of west dips on the east side of Solitario Canyon, which may help explain anomalous west-dipping reflectors in the deep seismic profiles (W. Day, R. Spengler, T. Brocher).
* Some lower volcanic units (Bullfrog?) may have had initial westward dips in Crater Flat that have since been tilted east (W. Day, B. Crowe, T. Brocher).
* 3D geologic framework modelers should build a Paleozoic surface incorporating the Paleozoic elevation map of D. Ponce and the faulting concepts illustrated in the deep seismic profiles. This is the best solution (attendees).

Session III: Configuration of the Crater Flat Basin Eastern Margin

* Several structural models exist, each with different boundaries. The Miocene edge of the basin appears to have migrated with time.
* From aeromagnetic and gravity data, the CF basin structural edge would be drawn under western Jackass Flat (D. Ponce).
* The prominent aeromagnetic anomaly in Crater Flat appears to be a deep structure greater than 5 km depth (V. Langenheim), and is masking the north-south structural fabric of the basin (T. Brocher).

Session IV: Geometries of Faults At Depth

* The map geometries of faults may be reflective of their geometries in the third dimension (J. Whitney).
* The relatively short Fatigue Wash fault probably merges at depth with the longer Windy Wash fault based on the principle that a fault's depth does not greatly exceed its length (J. Whitney).
* The apparent density of faulting in Crater Flat and Yucca Mountain is similar to that north of the Timber Mountain Caldera at Pahute Mesa (J. Whitney).
* From the deep seismic profile, it would appear that the Bare Mountain fault is the major seismogenic structure, with the shallower faults responding passively on top (C. Potter).
* Quaternary displacement on the Bare Mountain fault is much less than the cumulative displacement on the Crater Flat-Yucca Mountain faults-- this is perplexing.
* The Ghost Dance fault could be a splay of the Solitario Canyon fault just as the Fatigue Wash could be a splay of the Windy Wash fault (J. Whitney).
* Below 3 km, there is not much constraint on CF-YM fault geometries (T. Brocher).
* The gravity location for the Bow Ridge fault at Exile Hill is east of the magnetic location. This results from the dip of the fault and consequent shift of the Topopah offset west of the surface trace (D. Ponce).
* Fault-related tilting of the Tertiary units dies out under Jackass Flat, where the rocks are thought to be more horizontal (W. Day, C. Potter).
* The favored mechanism for tilting of Tertiary units is a mild shallowing of fault dips with depth. This is shown in a recent cross section along the ESF South Ramp (W. Day, C. Potter).
* There are three related models of fault geometries in the Yucca Mountain region: Sub-parallel dominoes, upward horsetailing (or downward merging) of proximal faults, and partially listric curviplanar surfaces. Faulting in the region probably involves combinations of these (attendees).
* Dune Wash is a graben with Rainier Mesa Tuff fill (W. Day).
* A left-slip component on the north-south faults would permit opening of the northwest-trending grabens which are seen in a few places (W. Day).
* There is a thrust fault with dip of 35 degrees east in the South Portal area, which probably formed as fault blocks jostled (W. Day, C. Potter).
* The north-south and northwest-trending fault groups formed contemporaneously, based on mutually cross-cutting and truncating relations (W. Day, C. Potter).
* The evidence for faults merging at depth is their fault traces-- they must merge when projected to depth (W. Day, C. Potter).

* Rock properties appear to vary greatly from north to south, based on seismic reflections. Velocities vary by as much as 20% (E. Majer).
* Visual examination of core does not support widely varying properties (R. Spengler).
* There is a seismic anisotropy under Yucca Mountain, with variable slow direction (E. Majer).
* Much of the high-resolution seismic data looks like "stratigraphic vomit." (M. Tynan).
* Fault offsets of the Topopah Spring Tuff estimated from gravity and magnetic profiles agree with geologic estimates (D. Ponce).
* The Topopah Spring Tuff is not appreciably offset across Yucca Wash. Gravity and magnetic data do not allow more than a few meters offset. Any fault would have to be far under the northern side of the wash (D. Ponce, V. Langenheim).
* The Little Skull Mountain earthquake occurred on a 65 degree SE dipping plane (another seismologist calculated 56 degree dip). Main shock was at 12 km depth, aftershocks as shallow as 5 km. All aftershocks on high angle planes (greater than 45 degrees), including some strike slip. T axis (extension direction) was northwest (K. Smith).
* Very few quakes in the Crater Flat structural basin, with one at Alice Ridge and one in southern Crater Flat (K. Smith).
* The geology-geophysics group needs to develop a list of reasons and rationale why we do not interpret low angle detachment faults in the Yucca Mountain area (T. Sullivan).
* None of the faults interpreted in the deep seismic profiles are unrelated to mapped faults EXCEPT the fault just west of borehole VH-1 (T. Brocher).

Session V: Intrusions and Dikes

* Basaltic volumes in Crater Flat are quite small and feeder dikes are 1-5 meters thick, so they probably would not be seen by seismic profiling (B. Crowe).
* Aeromagnetic data detects basalts well in alluvium, but it is difficult under the bedrock at Yucca Mountain (V. Langenheim).
* Aeromagnetic and ground magnetic data are sufficient to address the intrusion and dike issue; however, the proposed aeromagnetic flights over Paiute Ridge would allow modeling of hidden intrusions and dikes at Yucca Mountain by providing a test case on known intrusions and dikes (B. Crowe).
* In teleseismic data, Crater Flat is fast compared to surrounding areas. There is nothing in the teleseismic data to indicate melts or partial melts at depth in Crater Flat (G. Biasi).
* Teleseismic data resolution is quite low-- it would not see a 400 meter cube (G. Biasi).

Session VI: Fractures

* UZ models do not have good enough information on how to characterize fractures. They use SZ information and air-K testing to help calibrate their models, but they need spatial distributions and densities, orientations, and anisotropies. Are hoping to receive some input from Larry Anna (M. Bandurraga).
* Fractures vary by lithologic unit, but the patterns are not always predictable. For example, the Topopah middle nonlithophysal zone is more fractured than the upper nonlithophysal, but the opposite is true in the Tiva middle nonlith and upper lith (C. Potter).

* VSP data from UZ#16 is being processed at the Colorado School of Mines. Subsets of that data could be evaluated in short order to assess the applicability to fractures (E. Majer).

Session VII: Natural Resources

* Metallic Resources evaluation mostly involves geochemistry, with the emphasis being on gold and silver. Samples taken across Yucca Mountain and in boreholes have ruled out shallow potential for metallic resources (S. Castor).
* The highest concentration found so far is a spike of 26 ppb gold in calcrete veins. 8 ppm would be the economic cutoff for mining (S. Castor).
* Typically, geophysical tools are not help in assessing metallic resources in this region (S. Castor).
* Calico Hills would probably be explored by a mining company because of the obvious hydrothermal alteration (S. Castor).
* Basaltic dikes are generally unimportant in economic mineralization (S. Castor).
* The interpreter of the shallow magnetic faults and intrusions map worked in relative isolation from the Project and under the model of Walker Lane-Las Vegas Valley shear zone for structure (M. Tynan).
* Magnetotellurics would show any melt present under Crater Flat (G. Biasi).
* A continuous MT profile across Yucca Mountain showed apparent conductivity at the Ghost Dance and Bow Ridge faults, with other patterns that could be interpreted in terms of geologic features (E. Majer).

Session VIII: Aluvium Thickness
* A lack of density contrast between alluvium and Rainier Mesa-Tiva Canyon Tuff makes this contact undetectable by most geophysical tools (E. Majer).
* No further information was offered.
<end of workshop>

ATTENDEES:

Name	Organization/Responsibilities	phone	e-mail
Mark Bandurraga	LBNL/UZ modeling	510-486-6452	tmbandurraga@lbl.gov
Glen Biasi	UNR/seismology	702-784-4576	glenn@seismo.unr.edu
Tom Brocher	USGS/geophysics	415-329-4737	brocher@andreas.wr.usgs.gov
Jim Brune	UNR/seismology	702-784-4975	brune@seismo.unr.edu
Steve Castor	NBMG-UNR/nat'l resources	702-784-1768	scastor@nbmg.unr.edu
Robert Clayton	M&O WCFS/3D modeling	702-794-7213	robb@romeo.ymp.gov
Warren Day	USGS/geologic mapping	303-236-5050x269	wday@ympb.cr.usgs.gov
Mark Feighner	LBNL/geophysics	510-486-6781	mafeighner@lbl.gov
Lane Johnson	LBNL/geophysics	510-486-4173	lrj@ccs.lbl.gov
Eleni Karageorgi	LBNL/geophysics	510-486-5350	karag@ccs.lbl.gov
Victoria Langenheim	USGS/geophysics	415-329-5313	zulanger@mojave.wr.usgs.gov
Ernie Majer	LBNL/geophysics	510-486-6709	elmajer@lbl.gov
David Ponce	USGS/geophysics	415-329-5314	ponce@mojave.wr.usgs.gov

Chris Potter USGS/geologic mapping 303-236-5050x253
cpotter@sedproc.cr.usgs.gov
Richard Quittmeyer M&O WCFS/geol-geop 702-794-7765
richard_quittmeyer@notes.ymp.gov
John Savino M&O SAIC/geophysics 702-794-7427
john_savino@notes.ymp.gov
Ken Smith UNR/seismology 702-784-4218 ken@seismo.unr.edu
Dan Soeder USGS M&O/geology 702-794-5101
daniel_soeder@notes.ymp.gov
Rick Spengler USGS/geology 303-236-5050x280
John Stuckless USGS/hydrology 303-236-0516x273
stuckles@qconhp.cr.usgs.gov
Tim Sullivan DOE 702-794-7915 tim_sullivan@notes.ymp.gov
Mark Tynan DOE 702-794-7940 mark_tynan@notes.ymp.gov
John Whitney USGS/geology 303-236-0516
jwhitney@ympbnwis1.cr.usgs.gov

NUMERICAL MODEL WAREHOUSE
http://romeo.ymp.gov/ympwais/nmw.html
userid: ympsco
password: warehouse

or via ftp:
romeo.ymp.gov
userid: anonymous
password: your userid

PLEASE DO NOT GIVE THE WWW OR FTP INFORMATION TO UNAUTHORIZED OR NON-YMP PERSONNEL

TECHNICAL DATA BASE
Steve Bodnar 702-295-4844 steve_bodnar@notes.ymp.gov

From: Robert_Clayton@NOTES.YMP.GOV
Date: Fri, 15 Mar 1996 11:45 -0800 (PST)
Subject: Workshop Addendum #1
To: stuckles@qconhp.cr.usgs.gov, ken@seismo.unr.edu, cpotter@sedproc.cr.usgs.gov, ponce@mojave.wr.usgs.gov, elmajer@lbl.gov, zulanger@mojave.wr.usgs.gov, karag@ccs.lbl.gov, lrj@ccs.lbl.gov, mafeighner@lbl.gov, chornack@ympbgate1.cr.usgs.gov, wday@ympb.cr.usgs.gov, scastor@comstock.nbmg.unr.edu, brune@seismo.unr.edu, brocher@andreas.wr.usgs.gov, glenn@seismo.unr.edu, tmbandurraga@lbl.gov, "jwhitney @ ympbgate1.cr.usgs.gov%YMPGATE"@ccmail.ymppo.ymp.gov, John_Savino@NOTES.YMP.GOV, Tim_Sullivan@NOTES.YMP.GOV, Mark_Tynan@NOTES.YMP.GOV, Daniel_Soeder@NOTES.YMP.GOV, Richard_Quittmeyer@NOTES.YMP.GOV
Cc: C.Thomas_Statton@NOTES.YMP.GOV, Jan_Rasmussen@NOTES.YMP.GOV, Stephen_Nelson@NOTES.YMP.GOV
MIME-version: 1.0

Please add the following to the Workshop Summary you received previously, and send any further corrections as soon as you can.
-- Robert Clayton, M&O/WCFS, 3D Modeling Coordinator

Previous Summary statement:
* The prominent aeromagnetic anomaly in Crater Flat appears to be a deep structure greater than 5 km depth (V. Langenheim), and appears to be masking the pattern produced by north-south faulting (T. Brocher).

Correction:
The source of the large positive aeromagnetic anomaly in Crater Flat is deeper than the linear anomalies produced by faulting. The maximum depth to the top of the source is about 5 km...the upper surface of the source may be shallower (but not shallower than the depth reached by VH-1 obviously; V. Langenheim).

Previous statement:
* The Topopah Spring Tuff is not appreciably offset across Yucca Wash. Gravity and magnetic data do not allow more than a few meters offset. Any fault would have to be far under the northern side of the wash (D. Ponce, V. Langenheim).

Correction:
"A few meters" should be "tens to hundreds of meters."...in other words, the potential field data rule out a significant northwest-trending fault under Yucca Wash proper. Also, it's the aeromagnetic anomaly that we believe is caused by the Topopah Spring Tuff that is not appreciably offset across the wash (V. Langenheim).

Previous statement:
* Aeromagnetic data detects basalts well in alluvium, but it is difficult under the bedrock at Yucca Mountain (V. Langenheim).

Correction:
"Bedrock" should be changed to "Tertiary volcanic rocks." (V. Langenheim).

Addition:
Seismic profiles on the repository block are early in the interpretation process. Recent migrations show good, measurable offset at the Ghost

Dance fault of 100 feet in agreement with previous geologic interpretation, and also decreased offset on the GD farther north. Other lines are expected to provide similarly useful information as the interpretation process progresses (M. Freighner).

From: Robert_Clayton@NOTES.YMP.GOV
Date: Mon, 18 Mar 1996 08:22 -0800 (PST)
Subject: Workshop Addendum #2
To: stuckles@qconhp.cr.usgs.gov, ken@seismo.unr.edu, cpotter@sedproc.cr.usgs.gov, ponce@mojave.wr.usgs.gov, elmajer@lbl.gov, zulanger@mojave.wr.usgs.gov, karag@ccs.lbl.gov, lrj@ccs.lbl.gov, mafeighner@lbl.gov, chornack@ympbgate1.cr.usgs.gov, wday@ympb.cr.usgs.gov, scastor@comstock.nbmg.unr.edu, brune@seismo.unr.edu, brocher@andreas.wr.usgs.gov, glenn@seismo.unr.edu, tmbandurraga@lbl.gov, "jwhitney @ ympbgate1.cr.usgs.gov%YMPGATE"@ccmail.ymppo.ymp.gov, John_Savino@NOTES.YMP.GOV, Tim_Sullivan@NOTES.YMP.GOV, Mark_Tynan@NOTES.YMP.GOV, Daniel_Soeder@NOTES.YMP.GOV, Richard_Quittmeyer@NOTES.YMP.GOV
Cc: Stephen_Nelson@NOTES.YMP.GOV, Jan_Rasmussen@NOTES.YMP.GOV
MIME-version: 1.0

Please add this to your Geophysics-Geology Workshop Summary:

Original Statement:
* Fault-related tilting of the Tertiary units dies out under Jackass Flat, where the rocks are thought to be more horizontal (W. Day, C. Potter).

Revision:

We have no information on tilts beneath Jackass Flat. There is no observed flattening of the east tilts on Yucca Mountain bedrock at the west edge of Jackass Flat. (Potter)

From: Robert_Clayton@NOTES.YMP.GOV
Date: Tue, 19 Mar 1996 10:33 -0800 (PST)
Subject: Geol-Geop Workshop Addendum #3
To: jwhitney@ympbgate1.cr.usgs.gov, stuckles@qconhp.cr.usgs.gov, ken@seismo.unr.edu, cpotter@sedproc.cr.usgs.gov, ponce@mojave.wr.usgs.gov, elmajer@lbl.gov, zulanger@mojave.wr.usgs.gov, karag@ccs.lbl.gov, lrj@ccs.lbl.gov, mafeighner@lbl.gov, chornack@ympbgate1.cr.usgs.gov, wday@ympb.cr.usgs.gov, scastor@comstock.nbmg.unr.edu, brune@seismo.unr.edu, brocher@andreas.wr.usgs.gov, glenn@seismo.unr.edu, tmbandurraga@lbl.gov, John_Savino@NOTES.YMP.GOV, Tim_Sullivan@NOTES.YMP.GOV, Mark_Tynan@NOTES.YMP.GOV, Daniel_Soeder@NOTES.YMP.GOV, Richard_Quittmeyer@NOTES.YMP.GOV
Cc: Stephen_Nelson@NOTES.YMP.GOV, Jan_Rasmussen@NOTES.YMP.GOV
MIME-version: 1.0

Please add this to your Workshop Summary. Thanks for all the feedback--please keep it up!

Original Statement:
* Shallow metallic resources have been ruled out.

Correction:
The metallic resource study of Yucca Mountain is incomplete. On the basis of work on the Yucca Mountain Addition, no evidence for metallic resources was found on the surface; this has been backed up by analyses of samples from hole GU-3. There are some indications of mineralization in the Paleozoic rocks encountered by hole p#1. All results from analysis of the most recent round of surface and drill hole samples are not yet available, but based on what has been seen so far there is little evidence for shallow metallic mineral deposits (S. Castor).

Original Statement:
* The highest concentration was 26 ppb Au.

Correction/Revision:
Although an analysis of 26 ppb Au was found on two samples (one surface and one drill sample), neither were verified by reanalysis of the same pulp or by analysis of resampled rock from the same locality. The highest verified analyses were at 9 ppb Au in calcrete sampled on the surface and in Paleozoic rock cuttings from hole p#1 (S. Castor).

Original Statement:
* Geophysical tools have not been important in metallic resources exploration in this region.

Correction:
While geophysical tools have generally not been very important in gold and silver exploration in the Basin and Range province, they have been found useful in the search for other types of metallic deposits such as porphyry copper deposits. Attempts to constrain subsurface geology (location of faults, etc.) using geophysical techniques could be used to find gold and silver ore in areas that are known to be mineralized, but geophysical exploration per se is generally not helpful in gold and silver exploration. (S. Castor)

REFERENCE FORMAT

oppositely dipping, concave-upward normal faults or fault systems and attendant, opposing tilt-block domains. In the Crater Flat area, the west-tilting of bedrock blocks probably results from rotation on a concave-upward, east-dipping normal fault system, particularly the Bare Mountain fault. The east-tilting in the eastern part of the map area and at Yucca Mountain stems from rotation on a system of concave-upward, west-dipping normal faults. These oppositely dipping fault systems intermesh and terminate in the Crater Flat region, producing the anticline.

Extension in the Crater Flat/Yucca Mountain region probably began during late Oligocene time (Schweickert and Caskey, 1990) and has continued, perhaps episodically, to the present. The regional extension direction has apparently rotated from west-southwest/east-northeast in early to middle Miocene time to northwest/southeast in late Miocene to Quaternary time (Zoback and others, 1981; Stock and Healy, 1988; Wernicke and others, 1988). Carr (1988) concluded that the major episode of extension occurred between 12.7 and 11.6 Ma (corrected using new ^{40}Ar/^{39}Ar dates of D. A. Sawyer and others, written commun., 1993). We concur that significant displacement took place during this time interval. For example, the 11.6-Ma Rainier Mesa Member of the Timber Mountain Tuff (Tmr and Tmrw) and underlying bedded tuffs (Tmrn) are appreciably thicker on the downthrown side of several normal faults, indicating that they were deposited in topographic lows generated by faulting. In addition, the 12.7-Ma Tiva Canyon Member of the Paintbrush Tuff is commonly more highly tilted than the Rainier Mesa Member of the Timber Mountain Tuff (Scott, 1990). Megabreccias of Paleozoic rock occur at two intervals in drill hole USW VH-2, the oldest of which is situated between the 12.7-Ma Tiva Canyon Member and 11.6-Ma Rainier Mesa Member (Carr and Parrish, 1985). The Bare Mountain block is the only probable source area for the megabreccias. Thus, unroofing of the Bare Mountain block and significant displacement along the Bare Mountain fault probably occurred prior to 11.6 Ma.

In other areas, however, the Rainier Mesa Member of the Timber Mountain Tuff and Tiva Canyon Member of the Paintbrush Tuff exhibit little discordance in the magnitude of tilting. Moreover, significant faulting and tilting disrupt the Timber Mountain Tuff throughout the Crater Flat area. Thus, a significant amount of extension in the Crater Flat-Yucca Mountain region postdated eruption of the Timber Mountain Tuff, as also surmised by Scott (1990). The major pulse of extension postdating Timber Mountain Tuff in the Crater Flat-Yucca Mountain region may have coincided with the 8- to 10-Ma pulse of extension (Maldonado, 1990) in the Bullfrog Hills area to the west. Displacements of 3.7-Ma basalts and Quaternary alluvium in Crater Flat provide younger constraints on extension in the area and likely reflect reactivation of older structures with lower rates of activity.

REFERENCES

Ackermann, H. D., Mooney, W. D., Snyder, D. B., and Sutton, V.D., 1988, Preliminary interpretation of seismic-refraction and gravity studies west of Yucca Mountain, Nevada: U.S. Geological Survey Bulletin 1790, p. 23-34.

Anderson, R. E., 1988, Hazard implications of joint-controlled basaltic volcanism in southwestern Utah: Geological Society of America Abstracts with Programs, v. 20, p. A115.

Byers, F. M., Carr, W. J., Christiansen, R. L., Lipman, P. W., Orkild, P. P., and Quinlivan, W.D., 1976a, Geologic map of the Timber Mountain caldera area, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Map, I-891, scale 1:48,000.

Byers, F. M., Carr, W. J., Orkild, P. P., Quinlivan, W. D., and Sargent, K. A., 1976b, Volcanic suites and related cauldrons of the Timber Mountain-Oasis Valley caldera complex, southern Nevada: U.S. Geological Survey Professional Paper 919, 70 p.

Carr, M. D., and Monsen, S. A., 1988, Field trip guide to the geology of Bare Mountain, *in* Weide, D. L., and Faber, M. L., eds., This extended land—Geological journeys in the southern Basin and Range: Geological Society of America, Cordilleran Section, Field Trip Guidebook, p. 50-57.

Carr, W. J., 1982, Volcano-tectonic history of Crater Flat, southwestern Nevada, as suggested by new evidence from drill hole USW-VH-1 and vicinity: U.S. Geological Survey Open-File Report 82-457, 23 p.

Carr, W. J., 1988, Volcano-tectonic setting of Yucca Mountain and Crater Flat, southwestern Nevada, *in* Carr, M. D., and Yount, J.C., eds., Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada:U.S. Geological Survey Bulletin 1790, p. 35-49.

Carr, W. J., and Parrish, L. D., 1985, Geology of drill hole USW-VH-2, and structure of Crater Flat, southwestern Nevada: U.S.Geological Survey Open-File Report 85-475, 41 p.

Carr, W. J., Byers, F. M., Jr., and Orkild, P. P., 1986, Stratigraphic and volcano-tectonic relations of Crater Flat Tuff and some older volcanic units, Nye County, Nevada: U.S. Geological Survey Professional Paper 1323, 28 p.

Christiansen, R. L., and Lipman, P. W., 1965, Geologic map of the Topopah Spring NW quadrangle, Nye County, Nevada: U.S. Geological Survey Quadrangle Map GQ-444, scale 1:24,000.

Christiansen, R. L., Lipman, P. W., Carr, W. J., Byers, F. M., Orkild, P. P., and Sargent, K. A., 1977, Timber Mountain-Oasis Valley caldera complex of southern Nevada: Geological Society of America Bulletin, v. 88, p. 943-959.

Crowe, B. M., and Carr, W. J., 1980, Preliminary assessment of the risk of volcanism at a proposed nuclear waste repository in the southern Great Basin: U.S. Geological Survey Open-File Report 80-357.

Crowe, B. M., Vaniman, D. T., and Carr, W. J., 1983, Status of volcanic hazard studies for the Nevada Nuclear Waste Storage Investigations: Los Alamos National Laboratory Report LA-9325-MS.

Crowe, B. M., Turrin, B., Wells, S. G., McFadden, L., Renault, C., Perry, F., Harrington, C., and Champion, D., 1989, Polycyclic volcanism: A common eruption mechanism of small basaltic centers in the western U.S.A.: New Mexico Bureau of Mines and Mineral Resources Bulletin 131, p. 63.

Faulds, J. E., Smith, E. I., and Feuerbach, D. L., 1991, New insights on structural controls and emplacement mechanisms of Pliocene/Quaternary basaltic dikes, southern Nevada and northwestern Arizona: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A118.

Feuerbach, D. L., Smith, E. I., and Shafiqullah, M., 1990, Structural control of Pleistocene volcanism in Crater Flat, Nevada: Geological Society of America Abstracts with Programs, v.22, no. 3, p. 23.

Fridrich, C., and Price, J., 1992, Tectonic framework of the Crater Flat basin adjacent to Yucca Mountain, Nevada: Preliminary report: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A189.

Frizzell, V. A., Jr., and Shulters, J., 1990, Geologic map of the Nevada Test Site, southern Nevada: U.S. Geological Survey Miscellaneous Investigations Series, Map I-2046, scale 1:100,000.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Lipman, P. W., and McKay, E. J., 1965, Geologic map of the Topopah Spring SW quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map, GQ-439, scale 1:24,000.

Maldonado, F., 1990, Structural geology of the upper plate of the Bullfrog Hills detachment fault system, southern Nevada: Geological Society of America Bulletin, v. 102, p. 992-1006.

McKay, E. J., and Sargent, K. A., 1970, Geologic map of the Lathrop Wells quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map, GQ-883, scale 1:24,000.

Monsen, S.A., Carr, M.D., Reheis, M.C., and Orkild, F.P., 1992, Geologic map of Bare Mountain, Nye County, Nevada: U.S. Geological Survey Map I-2201.

Orkild, P. P., and O'Connor, J. T., 1970, Geologic map of the Topopah Spring quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map, GQ-849, scale 1:24,000.

Peterson, F.F., 1981, Landforms of the Basin and Range Province defined for soil survey: Nevada Agricultural Experiment Station Technical Bulletin 28, University of Nevada, Reno, 52 p.

Peterson, F. F., 1988, Soil-geomorphology studies in the Crater Flat, Nevada area, *in* Evaluation of the geologic relations and seismotectonic stability of the Yucca Mountain area, Nevada Nuclear Waste Site Investigation (NNWSI): Center for Neotectonic Studies, University of Nevada, Reno, 26 p.

Peterson, F. F., Bell, J. W., Dorn, R. I., Ramelli, A. R., and Ku, T-L., in press, Late Quaternary geomorphology and soils in Crater Flat, Yucca Mountain area, southern Nevada: Geological Society of America Bulletin.

Ramelli, A.R., Sawyer, T.L., Bell, J.W., Peterson, F.F., Dorn, R..I., and dePolo, C.M., 1989, Preliminary analysis of fault and fracture patterns at Yucca Mountain, southern Nevada: American Nuclear Society Proceedings FOCUS '89 - Nuclear Waste Isolation in the Unsaturated Zone, Las Vegas, NV, September 18-20, 1989, p. 336-343.

Reheis, M. C., 1988, Preliminary study of Quaternary faulting on the east side of Bare Mountain, Nye County, Nevada: U.S. Geological Survey Bulletin 1790, p. 103-112.

Renault, C. E., Wells, S. G., and McFadden, L. D., 1988, Geomorphic and pedologic evidence for polygenetic volcanism in late Quaternary cinder cones: Examples from Cima volcanic field, California and Crater Flat/Lathrop Wells volcanic field, Nevada: Geological Society of America Abstracts with Programs, v. 20, p. A115.

Schweickert, R. A., and Caskey, S. J., 1990, Pre-middle Miocene extensional history of the Nevada Test Site (NTS) region, southern Nevada: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 81.

Scott, D. L., and Rosendahl, B. R., 1989, North Viking graben: An East African perspective: American Association of Petroleum Geologists, v. 73, p. 955-966.

Scott, R. B., 1990, Tectonic setting of Yucca Mountain, southwest Nevada, *in* Wernicke, B., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 251-279.

Scott, R. B., and Bonk, J., 1984, Preliminary geologic map of Yucca Mountain, Nye County, Nevada, with geologic sections: U.S.Geological Survey Open-File Report 84-494, scale 1:12,000.

Smith, E. I., Feuerbach, D. L., Naumann, T. R., and Faulds, J. E., 1990, The area of most recent volcanism near Yucca Mountain, Nevada: Implications for volcanic risk assessment, *in* Proceedings of the International Nuclear Waste Symposium: American Nuclear Society and American Society of Civil Engineers, v. 1, p. 81-90.

Snyder, D. B., and Carr, W. J., 1984, Interpretation of gravity data in a complex volcano-tectonic setting, southwestern Nevada: Journal of Geophysical Research, v. 89, p. 10,193-10,206.

Stock, J. M., and Healy, J. H., 1988, Stress field at Yucca Mountain, Nevada: U.S. Geological Survey Bulletin 1790, p. 87-94.

Swadley, W. C., and Carr, W. J., 1987, Geologic map of the Quaternary and Tertiary deposits of the Big Dune quadrangle, Nye County, Nevada, and Inyo County, California: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1767, scale 1:24,000.

Swadley, W.C., Hoover, D.L., and Rosholt, J.N., 1984, Preliminary report on late Cenozoic faulting and stratigraphy in the vicinity of Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Open-File Report 84-788, 42 p.

Swadley, W.C., and Parrish, L.D., 1988, Surficial geologic map of the Bare Mountain quadrangle, Nye County, Nevada: U.S. Geological Survey Map I-1826.

Turrin, B. D., and Renne, P. R., 1987, Multiple basaltic eruption cycles from single vents, Cima volcanic field, California; evidence for polygenetic basaltic volcanism: Geological Society of America Abstracts with Programs, v. 19, p. 458-459.

U.S. Soil Conservation Service, 1975, Soil Taxonomy: U.S. Department of Agriculture, Agriculture Handbook 436, 754 p.

Vaniman, D. T., and Crowe, B. M., 1981, Geology and petrology of the basalt of Crater Flat: Applications to volcanic risk assessment for the Nevada Nuclear Waste Storage Investigations: Los Alamos National Laboratory Report LA-8845-MS.

Vaniman, D., Crowe, B., and Gladley, E. S., 1982, Petrology and geochemistry of hawaiite lavas from Crater Flat, Nevada: Contributions to Mineralogy and Petrology, v. 80, p. 341-357.

Wells, S. G., McFadden, L. D., Renault, C. E., and Crowe, B. M.,1990, Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high-level radioactive waste repository: Geology, v. 18, p. 549-553.

Wernicke, B. P., Axen, G. J., and Snow, J. K., 1988, Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738-1757.

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: Philosophical Transactions of the Royal Society of London, v. A300, p. 407-434.

Howard,

Comments on: Wynn and Roseboom (1987)

EM Methods: Basic depths of exploration are still roughly as stated, but the bug advance in recent years is in achieving greater model confidence in 2-D and 3-D. Advances have pushed transients to shorter times or higher f to resolve shallower, smaller-scale objects. However, basic physics of diffusive EM still applies so there is a preservation of a width/depth resolution factor. 3-D inversions still have size limitations yet also require massively parallel supercomputers for calculation. Ventures in very high f EM which start to include dielectric effects are laudable, but at present people still are arguing over whether they're getting the 1-D data and computations right.

MT method: Similarly, advances in instrumentation using small controlled sources has pushed the f range up to near 100 KHz. Controlled plane-wave sources can probably handle small-scale environmental problems or others needing f not <~ 20 Hz. Contiguous bipole profiling has greatly helped the sampling problem. Multi-dimensional modeling and inversion is still relatively advanced for plane-wave vs finite sources. More than 5 layers in the upper 10 km is now resolvable due to higher f, but this yields smaller and shallower layers only. Data quality sorting and outlier removal has helped both EM and CSAMT, but especially natural field MT. Wynn's stated limit of 0.2 source-object distance as a resolution limit is still pretty fair. Again, diffusive physics is the limiting factor, but in 2-D and 3-D we can now hope to approach even that.

Phil

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B8, PAGES 7787–7796, JU

Phil –
Please comment
p. 7791
7793
any higher resolution w/
current state-of-the-Art?
Refs?

Role of Geophysics in Identifying and Characterizing
for High-Level Nuclear Waste Repositories

JEFFREY C. WYNN AND EUGENE H. ROSEBOOM

U.S. Geological Survey, Reston, Virginia

Evaluation of potential high-level nuclear waste repository sites is an area where geophysical capabilities and limitations may significantly impact a major governmental program. Since there is concern that extensive exploratory drilling might degrade most potential disposal sites, geophysical methods become crucial as the only nondestructive means to examine large volumes of rock in three dimensions. Characterization of potential sites requires geophysicists to alter their usual mode of thinking: no longer are anomalies being sought, as in mineral exploration, but rather their absence. Thus the size of features that might go undetected by a particular method take on new significance. Legal and regulatory considerations that stem from this different outlook, most notably the requirements of quality assurance (necessary for any data used in support of a repository license application), are forcing changes in the manner in which geophysicists collect and document their data.

INTRODUCTION

The search for disposal sites for high-level radioactive wastes from commercial nuclear reactors continues worldwide with increasing intensity and resources. While possible seabed disposal is being carefully studied, by far the largest efforts have gone into seeking possible repositories in deep, stable geologic formations on land. In the United States the Department of Energy (DOE) has responsibility for solving the waste disposal problem for high-level nuclear wastes produced by commercial reactors. The U.S. Geological Survey advises and assists DOE and its contractors in the earth science aspects of this task and conducts research on techniques of exploration and characterization as well as on natural processes related to disposal [*Schneider and Trask*, 1982]. The Batelle Institute, Rockwell International, Woodward-Clyde Consultants, and Law Engineering are some of the private organizations that work on major subtasks of the larger problem, along with several of the national laboratories such as Sandia, Los Alamos, and Lawrence Berkeley laboratories.

The Nuclear Waste Policy Act of 1982 (NWPA) has legislated the general sequence of activities, defined the political and regulatory process, and set a schedule for the construction of the first two mined nuclear waste repositories to be established in the United States. For each repository, at least five candidate sites are to be nominated initially. From among these, three are to be further evaluated by exploratory shafts and detailed site characterization.

The information obtained from the initial exploration phase and subsequent detailed studies and tests will be the technical basis on which a final selection is made. This information will also be required to justify a subsequent license application to the Nuclear Regulatory Commission (NRC). For any repository site selected, DOE will have to demonstrate that the limits for future possible concentrations of nuclides set by the Environmental Protection Agency (currently in draft form) will not be exceeded and that the technical criteria established by NRC for licensing a repository are satisfied.

Nine candidate sites (Figure 1) were identified by DOE for the first proposed repository; according to the NWPA schedule, three of these sites were selected by the President in December 1984 for detailed site characterization and construction of exploratory shafts by 1985. Final construction at one site should begin by 1991. Two candidate sites were identified in volcanic rocks on DOE reservations (one in basalts at the Hanford site, Washington, and one in ash flow tuffs at the Nevada Test Site), four were in bedded salt (two in the Paradox Basin, Utah, and two in the Palo Duro Basin, Texas), and three were in salt domes (two in Mississippi and one in Louisiana) [*Smedes*, 1982; *U.S. Department of Energy*, 1982, 1984*a*, *b*, *c*, *d*, *e*]. In December 1984, DOE announced that the Hanford Reservation in southeastern Washington State, Yucca Mountain at the Nevada Test Site in southern Nevada, and Deaf Smith County in the Permian Basin of Texas have been proposed for the detailed site characterization.

An additional site is being studied by the DOE for military wastes; this is the Waste Isolation Pilot Project (WIPP) located in southeastern New Mexico. This site is being independently developed to dispose of transuranic wastes from national defense programs. Both the wastes and the process of site development at this site are different from the DOE commercial nuclear waste program; WIPP is mentioned here for the sake of completeness.

The construction of the second commercial waste repository is scheduled to follow the first by about 3 years. To expand the number of possible sites available for a second repository, DOE has recently identified from a literature survey more than 200 crystalline rock bodies in the Appalachians, Adirondacks, and Lake Superior Precambrian shield that might contain suitable sites [*Office of Crystalline Repository Development*, 1983]. From these, a much smaller number will be selected for field investigation.

In addition, the U.S. Geological Survey, working in cooperation with most of the states involved, identified potential areas in the Basin and Range Province that could also be considered [*Schneider and Trask*, 1982, pp. 5–6; *Bedinger et al.*, 1985*a*, *b*; *Sargent and Bedinger*, 1985]. Like the first repository, the second one ultimately will be chosen from three that have been thoroughly characterized, including an exploratory shaft. One or two of these could be candidates previously characterized but not chosen for the first repository.

LIMITATIONS OF DRILLING

Because any repository below the water table will eventually become filled with water, all drill holes and shafts into it must be carefully sealed to minimize future groundwater circu-

Paper number 6B5981.

TABLE 1. Use of Geophysics in Potential Repository Areas

Method	Information Sought	Optimal Penetration/Sensitivity
Gravity and magnetics	Structure of the subsurface, for instance basement topography beneath sediments or ash flow tuffs, the shape of granitic bodies, or lateral continuity of major structures.	Regional scale gravity surveys can detect vertical offsets (step function) of 1 km at 5 km depth for 0.1 g/cm^3 density contrast; high-precision surveys can detect 50-m offsets at much shallower depths. Aeromagnetic surveys can detect 0.5-km offsets in a granitic basement buried 5 km deep.
Electrical methods	Presence of brine in salt, water-bearing zones, and fractures, changes in lithology, deep layers.	Dipole-dipole resistivity surveys can resolve two-dimensional features as small as 0.5 dipole spacing ("A spacings") and as deep as 1.5 A spacings, where typical A spacings are 100–500 m. VES (Schlumberger) methods can resolve a conductive layer as thin as 30 m at 1 km; maximum depth possible is about 5 km in optimum circumstances (e.g., high-resistivity surface layers).
Electromagnetic (EM) methods	Brines and water-filled fractures.	Time domain EM can detect good conductors to 1-km depths; Slingram to 150 m. Detectibility is strongly controlled by resistive contrast and depth.
Magnetotelluric and telluric profiling	MT, regional crustal structures, layering; TP, magma chambers, conductive fracture systems, vertical offsets of layers in some cases.	Magnetotellurics can pick up to five layers in 10 km of depth with a maximum depth of investigation limited mainly by the length of the time series being sampled; the telluric profile method can pick out fracture zones but would probably miss a conductive fracture narrower than the traverse wire dipole width (typically 100 m at 27 Hz or 500 m at 0.03 Hz) at depths of more than two dipole widths and could not locate it closer than a dipole width.
Borehole methods (electrical, neutron, acoustic logs)	Locations of fractures, presence of water in fractures, permeability.	Electrical normal log cannot penetrate more than 75 cm from the borehole wall; most other tools cannot penetrate more than 15–20 cm, with the exception of neutron gamma (about 1 m).
Borehole gravity	Primarily in situe density measurements.	Measurements to 0.01 MGal can be made; density resolution less than 0.1 g/cm^3 depends on accurate terrain corrections.
Borehole radar	Water- and clay-filled fractures in salt or low-porosity rock, brines in salt.	Can resolve a high-dielectric-contrast seam a few centimeters wide, as far away as 400 m in salt or 50 m in crystalline rock.
Hole-to-surface electrical methods	Water-filled fractures, some sulfides, brine pockets in salt.	Maximum detectible distance from hole is 2 times the depth of the hole, the best zone being roughly above a 45° line from source to surface. Body resolution is extremely variable, as in EM methods. Object sizes less than 0.2 times the source object distance are generally undetectable.
Heat flow	Vertical component of groundwater movement, geothermal systems.	Vertical motion of groundwater as little as a few millimeters per year can be detected under the most optimum circumstances.
Hydrofrac measurements	In situ stress.	Provides stress information around the drill hole; can be extrapolated to stress for the tectonic province.
Local seismicity	Location of active faults.	Can provide source location to within 0.5 km of the source vertically and 1 km horizontally.
P wave residuals	Deep crustal structures, low-velocity zones.	Resolution of the order of the network spacing; typically 30 km vertically and 15 km horizontally.
Remote sensing	Possible fracture zones and regional-scale structures.	Landsat 1, 2, and 3 pixel size is 79 m; for Landsat 4 it is 30 m. There is no significant vertical penetration.
Seismic refraction	Presence of magma chambers and vertical offsets; continuity of layered formations, low-velocity zones.	For sharp velocity contrasts, can resolve layers and vertical offsets to 1% of depth up to 20 km; in volcanic terrains this becomes 5–10% at best.
Seismic reflection	Geologic structures, especially horizontal ones. Continuity of layered formations.	Can resolve layers as thin as 15 m, or normal fault offsets of 20 m at 1000 m depth (for 30 Hz and a high-reflection coefficient).

Optimal penetration/sensitivity column is added here to give a rough idea of the best penetration and target resolution possible with the given method in the most optimum circumstances. The typical examples used here are chosen to emphasize the strength of the given method to applications in high-level radioactive waste disposal, with emphasis on the nine possible repository site of Figure 1. With some methods (e.g., gravity and magnetics) the maximum resolution can be improved by increasing the density/precision of measurements and consequently the financial resources expended. With all geophysical methods, resolution decreases with increasing depth no matter what the measurement spacings might be. With electrical methods especially, the variables controlling resolution and depth penetration are many and complex. Detailed resolution of penetration and sensitivity questions must be resolved by computer modeling tuned to the local geologic environment. This table shoud be used with caution, since penetration, and particularly resolution. are dependent upon a large number of variables and considerations beyond the scope of this or any single paper brokered commercial seismic data were acquired around each dome to assist in defining edges. At the Richton dome nearly 12 km of high-resolution seismic data (Mini-Sosie) were also acquired and, though noisy, were able to help in outlining the dome in three dimensions [*U.S. Department of Energy*, 1984*c*; M. Gibbons, personal communication, 1985].

Vertical electrical soundings (VES, or Schlumberger) were carried out over the domes and assisted in identifying areas of subsidence over the Vacherie dome. A microseismic network has been recommended at the Gulf Coast sites but has not been installed as of this writing.

Permian Basin, Texas

The Permian Basin is an area of relatively flat-lying sediments, and interest in potential repositories has centered around Swisher and Deaf Smith County, Texas. To date, the prime focus is on the Deaf Smith County site [*U.S. Department of Energy*, 1984*d*]. This site has had 10 deep and three shallow wells drilled in it, with full tool suites run in each well. No holes were drilled in the potential repository site itself: six holes drilled within 10–15 km were used instead. Brokered commercial gravity data and regional scale aeromagnetics have been acquired and used principally to map regional structures.

Nearly 1000 line kilometers of older brokered and some new reflection seismic data were acquired in this area. There is not a great deal of acoustic contrast between basement rocks and overlying sediments (including the Ogalalla aquifer), and the older data are useful mainly for mapping broad-brush structures. Even with high-frequency, modern vibroseis data, information on the upper 300 m of sediments cannot be obtained because the data are too broken-up (M. Gibbons, personal communication, 1985).

A 15-station microseismic network was set up in 1983 and picked up events in a faulted, oil-producing area about 30 km north of the potential repository site. Little microseismic activity has been observed in the Amarillo Uplift or the axis of the Permian Basin.

Paradox Basin, Utah

The Paradox Basin of southeastern Utah hosts a complex sequence of layered salt and other sediments. Several holes were drilled in Salt Valley in the northern Paradox, but the complex structures encountered in the potential repository horizons of the salt units there lead to abandonment of this area. A single drill hole in the Gibson Dome site was extensively logged, and hole-to-surface electrical studies were carried out to identify any through-going structures there. Elsewhere in the Paradox Basin, VES and electromagnetic (ground and airborne) profiles were carried out to look for conductors that might suggest brines or active dissolution processes in salt. The current prime site in the Paradox is Davis Canyon [*U.S. Department of Energy*, 1984*a*].

About 4000 gravity stations were acquired in the Paradox Basin from several sources, along with over 1100 km of aeromagnetic data, and these were used to map regional structures in the underlying basement. Some initial two-dimensional gravity model attempts proved unsatisfactory, and three-dimensional modeling is planned. A microseismic network has been active in the Paradox since 1979 and has picked up events associated with active solution potash mining taking place on the edges of the basin west of Moab, Utah (J. Hileman, personal communication, 1985; M. Gibbons, personal communication, 1985).

Seismic data acquired from a number of sources in the Paradox Basin suggest that faulting in basement rocks rarely extends up into the overlying salt formations. Resolution problems with older data have lead geophysicists working at the Paradox to plan additional high-resolution three-dimensional seismic acquisition. Vertical seismic profiling (VSP) data have been acquired for velocity control, and attempts to use the seismic data to map facies changes in the sedimentary sequences will follow.

Hanford Reservation (BWIP) Site

The Hanford Nuclear Reservation lies in the Pasco Basin in Washington State and presents unique problems to geophysicists with 200–300 m of unconsolidated sediments overlying a series of basalt flows, which in turn are structurally controlled by the Yakima Fold Belt expressed in the underlying basement rocks [*Rockwell International*, 1983; *U.S. Department of Energy*, 1984*e*]. Extensive logs were carried out in a limited number of drill holes in the vicinity of the potential repository site, including less common techniques such as borehole magnetics (used to provide parameters for magnetic modeling), borehole gravity (used to provide density data on the unconsolidated sediments), and VSP (to provide the velocity control necessary to extend the utility of the reflection seismic data into the underlying basalt layers).

Aeromagnetic and gravity data acquired in the area have been used principally to map basement structures including faults, strike direction changes in fold axes, and flow pinch-outs. Heat flow studies were carried out at Hanford, and the data indicate that there is no convective heat flow, but instead that heat transfer takes place within flowing groundwater systems. Existing data suggest that there are no shallow crustal heat sources present in the area (A. Tallman, personal communication, 1985).

Magnetotelluric (MT) data have been used to map resistivity variations and identify large-scale structures in the deep crust, but resolution limitations precluded any useful data from shallower depths. The principal value of the MT data was to determine the style of folding and tectonics in the Yakima Fold Belt. Resistivity data have proven useful only in mapping the water table. A single large-scale seismic refraction line was acquired and provided information useful in processing reflection data, but difficulties were encountered with velocity inversions causing gaps in the record.

An initial 200 km of brokered seismic reflection data acquired in 1979 were not successful in penetrating to the basalts due to strong attenuation of seismic energy by the overlying unconsolidated sediments. Data acquired in 1981, however, were successfully used to map the top of the basalt layer. This holds out hope that with VSP and potential field data (to provide control of the overlying sediments), seismic data will prove useful in mapping structures within the underlying basalts.

Nevada Test Site

Site exploration at the Nevada Test Site (NTS) has focused on Yucca Mountain in the southwestern corner of the reservation [*Roseboom*, 1983; *U.S. Department of Energy*, 1984*b*]. The target volume consists of welded volcanic tuffs in the unsaturated zone above the water table at depths of approximately 250 m as well as overlying and underlying volcanic rocks. A number of holes have been drilled around the perimeter of Yucca Mountain, and extensive logging suites and hole-to-surface electrical work carried out in them.

Extensive gravity and ground and airborne magnetic data acquisition have been carried out at the NTS, along with detailed three-dimensional modeling. A broad range of resistivity, telluric profiling, and time and frequency domain electromagnetic measurements have also been made, with modeling follow-up to identify potential faults and other water-channeling structures in the Yucca Mountain block. These methods have proven particularly useful in mapping steep faults hidden by alluvium in surrounding valleys and pediments.

A natural seismicity network has been in place since 1979, and *P* wave residual studies to look for deep basement structures and magma reservoirs have been carried out utilizing underground nuclear tests from the northern and central parts of the NTS. Several reflection seismic studies have been carried out in the Yucca Mountain vicinity, but despite use of unusually rigorous field acquisition and processing procedures, the efforts were disappointing largely due to the extreme attenuation of seismic energy by the volcanic tuffs.

ISSUE OF SENSITIVITY OF GEOPHYSICAL METHODS

Table 1 shows most of the ways in which geophysical methods have been used at the various sites. All of these methods have been used at the Nevada Test Site, and most of them have been used at the Hanford site and the Paradox Basin. Less than half of the techniques have been used at the Deaf Smith County site: only reflection seismics, seismicity networks, borehole logging, and regional scale gravity/magnetics have been used in the Permian Basin as of this writing. Reflection seismic, borehole logging suites, VES data, and potential field geophysics are the only data acquired at the salt domes in the southeastern United States (M. Gibbons, personal communication, 1985).

Geophysical parameters being measured vary tremendously with the geologic and geohydrologic environment. The lithologic and structural features being sought vary greatly also, even within the present limited set of candidate sites for the first repository. It is not unreasonable that a sequence of geophysical surveys could be carried out that showed no significant anomalies yet missed a significant feature that would later be encountered in drilling or mining. A large brine pocket found at the WIPP site would be an example, though no electrical geophysical surveys, which might have found it, were carried out there. We must, therefore, be able to determine the sensitivity and resolving power of the methods listed in Table 1 and be able to answer such questions as what size and what kinds of inhomogeneities will they detect and at what distances? In order to meet the requirements of quality assurance programs, we need to know the size of geological features that might slip through the geophysical seine.

The penetration and resolution examples shown in column 3 of Table 1 are specific (and by no means complete) to problems being studied at the sites shown in Figure 1. They are nevertheless put here to provide some overall sense of the capabilities and limitations of geophysical methods in the disposal of high-level radioactive wastes. For each site, and each particular geologic/geohydrologic question needing answers, extensive computer modeling is required to ascertain the resolution of each method. This kind of detailed analysis, quite beyond the scope of this paper, is only summarized in Table 1. For further information, the reader is directed to other papers in this and other issues of the *Journal of Geophysical Research*.

Some specific comments about how each group of geophysical methods applies to the disposal problem of high-level radioactive wastes follows:

Regional scale gravity and magnetic methods can provide information about lithology and structure of the crystalline rocks underlying sedimentary sequences but usually can provide little information about the sedimentary layers themselves. Borehole gravity can give in situ densities for the overlying individual sedimentary layers, and three-component borehole magnetic tools can provide information on natural remanent magnetization and polarity reversals for stratigraphic correlation and dating purposes. These potential fields methods have proven especially helpful toward understanding what underlies the thick volcanic sequence at Yucca Mountain at the NTS [*Snyder*, 1981, *Kane et al.*, 1982], as well as in suggesting the structures underlying the bedded salts of the Paradox Basin in Utah [*Hildenbrand and Kuchs*, 1983], and the sediments overlying the Pasco Basin at the Hanford Reservation [*Rockwell International*, 1983].

Electrical geophysical methods used at the surface are of special interest because they can provide information on the presence of water or brine in the underlying rocks. In a salt environment the presence of brine is very significant, as it raises the question of whether the salt might be undergoing active dissolution. The Schlumberger method has worked well in investigating dissolution in the bedded salt in the Paradox Basin [*Watts*, 1982, 1983]. Electrical methods, however, cannot penetrate very far into a high-resistivity salt sequence, unless that sequence is interrupted by a solution feature or a fault. Newly developed time domain electromagnetic (TDEM) methods have identified conductors as deep as 1 km at the NTS. There is some indication that TDEM could be more effective in evaluating thick, highly resistive bedded salt units where galvanic current systems do not easily penetrate.

The magnetotelluric (MT) method, while useful in providing deep crustal resistivity information to supplement regional scale gravity and magnetics, has relatively poor resolution compared to other geophysical methods that have been used to study potential disposal sites, and this resolution gets worse with increasing depth. It is best used in deep layered-earth situations where adequate seismic data are not obtainable. Its maximum resolution under optimum conditions is five layers for the first 10 km of depth (W. D. Stanley, personal communication, 1985); MT has been used at the Hanford site [*Rockwell International*, 1979]. Audiofrequency magnetotellurics could be used at potential disposal sites, but the typical lowest frequency of about 7 Hz limits its penetration to less than 500 m or less, depending on the resistivity of the underlying rocks.

The telluric profiling method, an offshoot of the MT method, can resolve fault systems to great depths if they are large enough and conductive enough. The minimum target width that can be resolved (for a conductive target) is the dipole length, (typically 100–500 m) though conductive fracture zones narrower than this can be recognized readily enough. Below one or two dipole lengths depth, the conductor would have to be a minimum of one dipole length wide to be seen.

Standard borehole logging methods [*Nelson et al.*, 1982] are used for correlation purposes in layered sediments and volcanic rocks and also for identification of water-filled fractures and otherwise anomalous zones in crystalline rocks as well as salt. The neutron gamma method can do actual elemental identification and can effectively penetrate about a meter from the borehole wall. The log normal (single-electrode electrical) method can penetrate (on the average) about 75 cm, while most other tools can penetrate no more than 15–20 cm from the borehole at most. One additional logging tool, the

Post-it® Fax Note 7671		Date 12-13-96	# of pages ▸ 1
To Steve Castor		From H. Ross	
Co./Dept. UNR-NBMG		Co. EGI/UU	
Phone # (702) 784-6691		Phone # (801) 581-5184	
Fax # (702) 784-1709		Fax # (801) 585-3540	

Stephen Castor
Nevada Bureau of Mines and Geology
University of Nevada, Reno

ADDITIONAL REFERENCES NEEDED FOR YUCCA MOUNTAIN GEOPHYSICS

Yes ✓ Baldwin and Jahren, 1982 - Magnetic properties of drill core and surface samples, Calico Hills area.., USGS OFR-82-536, 27p.

Yes ✓ Bath and others, 1983 - Magnetic investigation of Climax stock intrusive..,USGS OFR-83-377, p.40-77.

Yes ✓ Saltus, 1988 - Bouguer gravity anomaly map of Nevada: NBMG map M94B (1:750,000)

Yes ✓ Ackerman and others, 1988 - Prelim. Interp. of seismic refraction and gravity at Yucca Mtn.. In Carr and Yount, eds, USGS Bull. 1790, p.23-34

No? Carr and Yount, eds, 1988 - Investigation of the geology and geophysics.. at Yucca Mtn, USGS Bull. 1790, 152 p. (DO NOT COPY - DOYOU HAVE AN EXTRA COPY?)

✓ Greenhaus and Zablocki, 1982 - A Schlumberger resistivity survey of the Amargosa Desert - USGS OFR 82-2897, ~~150 p.~~ (ONLY COPY SUMMARY AND AVG RESISTIVITY SECTION) 13+ pg.

Yes Hoover and others, 1982, Electrical studies at the proposed Wahmonie and Calico Hills areas .., USGS OFR-82-466, 45p.

Yes Hoover and others, 1982, Geophysical studies of the Syncline Ridge area, NTS - USGS OFR-82-145, 55p.

Yes Kauhikaua, 1981, Interpretation of TDEM at Calico Hills, NV, USGS-OFR-81-988, 13p.

? ✓ Senterfit and others, Resistivity soundings by the Schlumberger method, Yucca Mtn., USGS OFR-82-1043 (HOW BIG IS THIS OFR?)

LET'S DICSU~~SS~~SS THESE ON THE PHONE BEFORE YOU GO TO THE TROUBLE OF COPYING ALL THIS MATERIAL!!!

Langenheim & Ponce (1995), Depth to Pre-Cenozoic Basement in SW Nevada
→ missing pgs. 2, 4, 6 Abstract.

Refs p.3 Corbett, J.D., 1991
G & O Dep of Gt Basin, v. 2, p.1237-1251

Wynn, JC & Roseboom, 1987
JGR-B, v. 92, n. 8, p. 7787-7796.

Refs, p.5 Blakeley and Jahren, 1991,
G & O D of Gt. Basin, v. 1, p. 185-192

Post-it® Fax Note 7671	Date 12-13-96 # of pages ▶ 1
To Steve Castor	From H. Ross
Co./Dept. UNR - NBMG	Co. EGI / UU
Phone # (702) 784-6691	Phone # (801) 581-5184
Fax # (702) 784-1709	Fax # (801) 585-3540

Stephen Castor
Nevada Bureau of Mines and Geology
University of Nevada, Reno

ADDITIONAL REFERENCES NEEDED FOR YUCCA MOUNTAIN GEOPHYSICS

Baldwin and Jahren, 1982 - Magnetic properties of drill core and surface samples, Calico Hills area.., USGS OFR-82-536, 27p.

Bath and others, 1983 - Magnetic investigation of Climax stock intrusive..,USGS OFR-83-377, p.40-77

Saltus, 1988 - Bouguer gravity anomaly map of Nevada: NBMG map M94~~B~~A (1:750,000)

Ackerman and others, 1988 - Prelim. Interp. of seismic refraction and gravity at Yucca Mtn.. In Carr and Yount, eds, USGS Bull. 1790, p.23-34

Carr and Yount, eds, 1988 - Investigation of the geology and geophysics.. at Yucca Mtn, USGS Bull. 1790, 152 p. (DO NOT COPY - DOYOU HAVE AN EXTRA COPY?)

Greenhaus and Zablocki, 1982 - A Schlumberger resistivity survey of the Amargosa Desert - USGS OFR 82-2897, 150 p. (ONLY COPY SUMMARY AND AVG RESISTIVITY SECTION)

Hoover and others, 1982, Electrical studies at the proposed Wahmonie and Calico Hills areas .., USGS OFR-82-466, 45p.

Hoover and others, 1982, Geophysical studies of the Syncline Ridge area, NTS - USGS OFR-82-145, 55p.

Kauhikaua, 1981, Interpretation of TDEM at Calico Hills, NV, USGS-OFR-81-988, 13p.

Senterfit and others, Resistivity soundings by the Schlumberger method, Yucca Mtn., USGS OFR-82-1043 (HOW BIG IS THIS OFR?)

LET'S DICSUSS THESE ON THE PHONE BEFOR YOU GO TO THE TROUBLE OF COPYING ALL THIS MATERIAL!!!

DD 12:20pm:

12/13/96

Jeff
Geology and Ore
Deposits of the Great
Basin - V1, V.2
NBMG ??

~~USC Database cost = $~~ $1.8M/yr ~~onge.~~

12/13/96

Steve Castor

① Status of report / study — mag + grav indicate some

② Time used — & saved — 2 days for visit/trip + wrap up

③ 10 pgs text — no figures yet

④ Schedule for draft report — Rep ✓

" " near final rept.

⑤ Report Format info — citations (— and others ✓✓✓) or (— et al.)

references ✓ — — same as 1977 reports

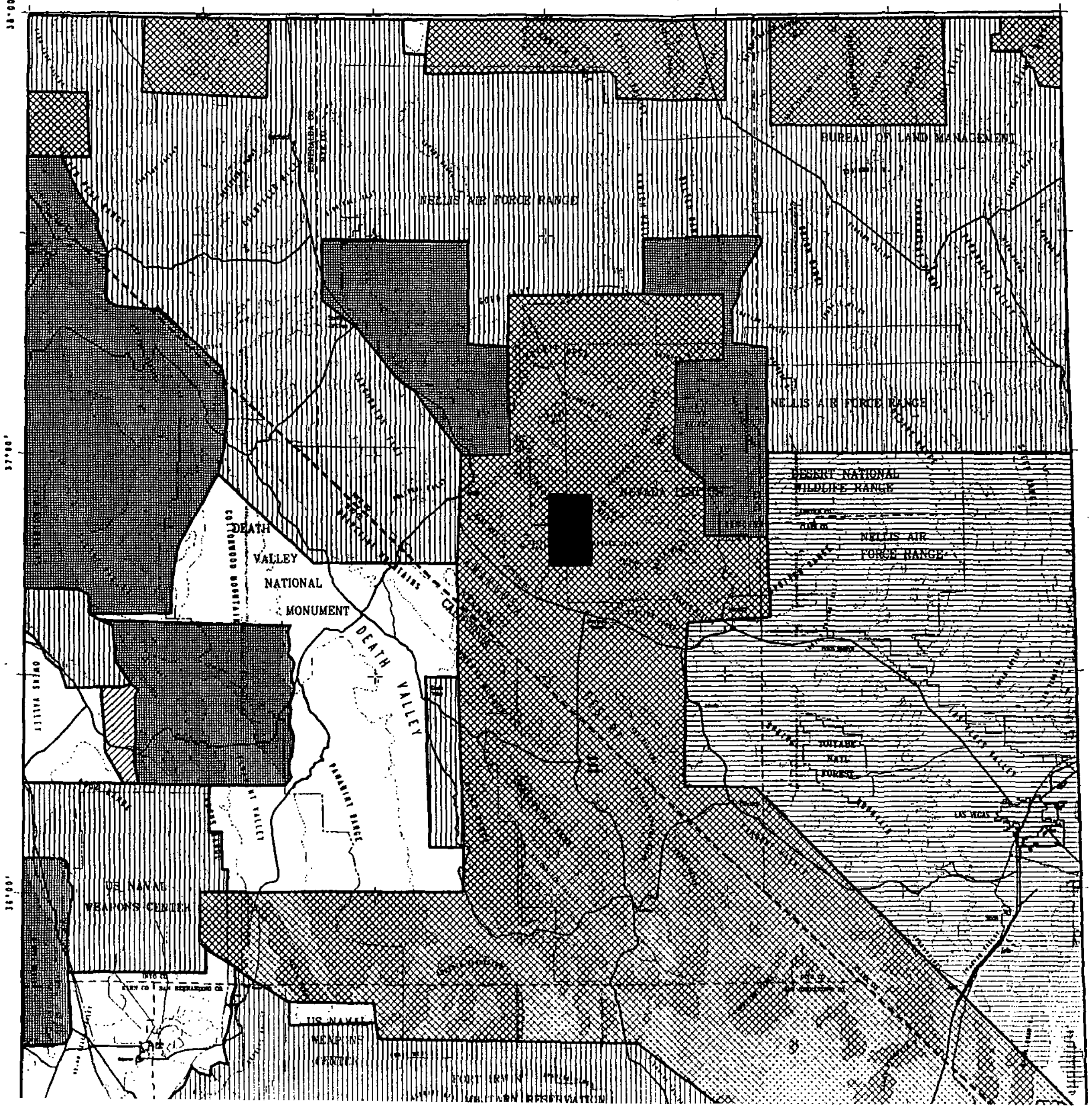
⑥ Christmas schedule 23 - 30th

Rept. deadline by Feb. 15th to M&O; March 28

⑦ Remote sensing & aerial γ-ray : Tom Lagarkin :

⑧ email #


NELLIS AIR FORCE RANGE
BUREAU OF LAND MANAGEMENT
NELLIS AIR FORCE RANGE
DESERT NATIONAL WILDLIFE RANGE
NELLIS AIR FORCE RANGE
DEATH VALLEY NATIONAL MONUMENT
NEVADA
CALIFORNIA
LAS VEGAS
NAVAL WEAPONS CENTER
FORT IRWIN MILITARY
38° 00'
30'
37° 00'
30'
36° 00'
35° 30'
118° 00'
30'
117° 00'
30'
116° 00'
30'
115° 00'



YUCCA MOUNTAIN PROJECT

FIGURE 2.2–1. Aeromagnetic Index Map of Regional Study Area Showing Flight Line Spacing of Available Data.

MILES 0 20 40
0 20 40 60 KILOMETERS

LEGEND

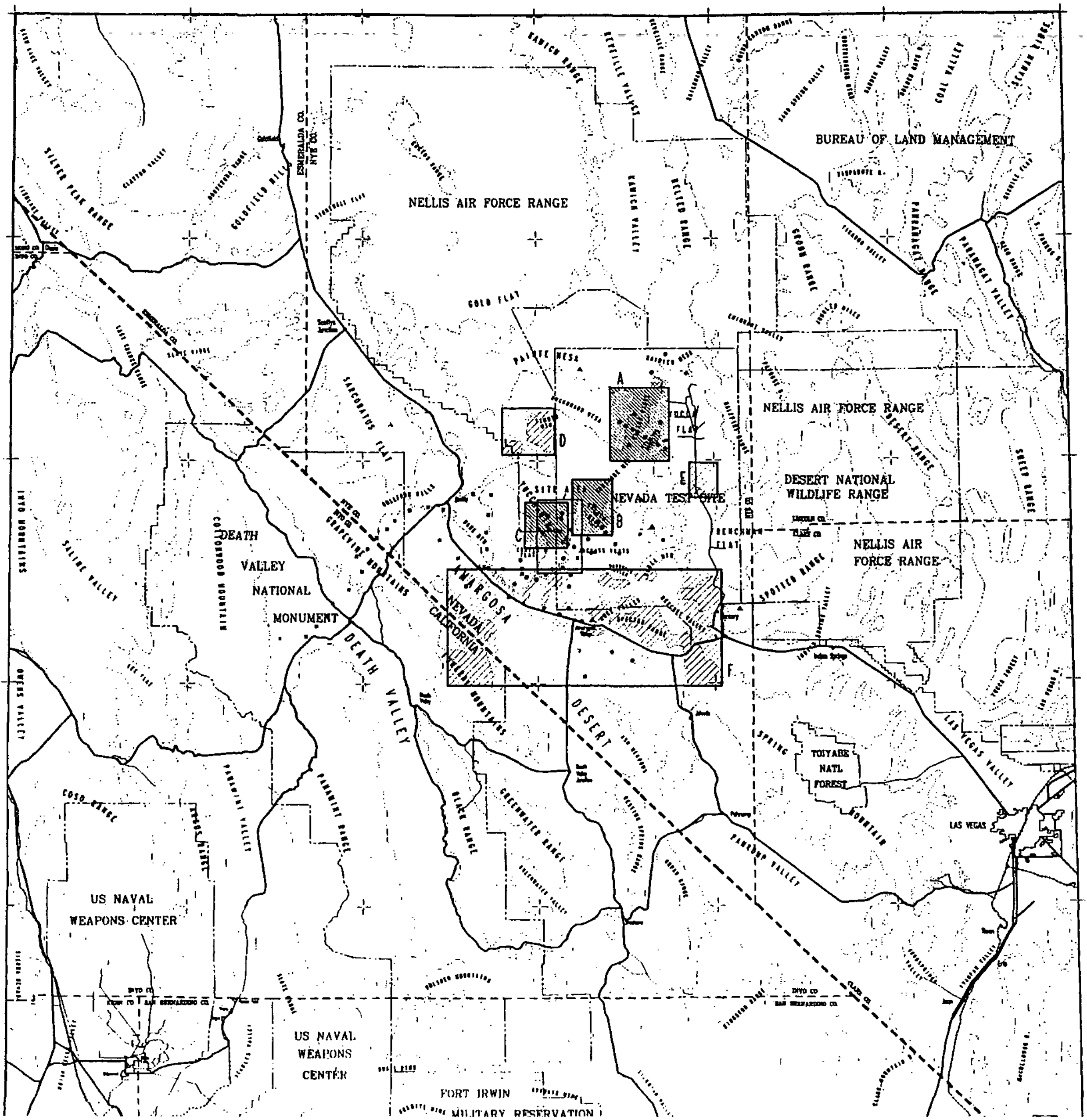
⊠ 1/4 & 1/2 MILE SPACING DRAPED Constant Elev.
▦ 1/2 MILE SPACING BAROMETRIC
⊟ 1 MILE SPACING DRAPED
▥ 1 MILE SPACING BAROMETRIC
▨ 2 MILE SPACING BAROMETRIC
☐ 1 & 3 MILE SPACING NURE (Entire map area covered)
■ SITE AREA

HIGHWAY
IMPROVED ROAD
RAILROAD
STATE BOUNDARY
COUNTY BOUNDARY
ADMINISTRATIVE BOUNDARY

NEVADA
CALIFORNIA
UTAH
N

EG&G YMP-89-068.1

[redacted] Table of Geoelectric
Survey [redacted] [redacted]



YUCCA MOUNTAIN PROJECT

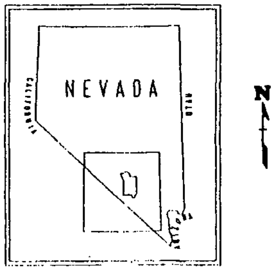
FIGURE 2.3-1. Location of Geoelectric Surveys in the Yucca Mountain Region, Including the Nevada Test Site, Southern Nevada.

MILES
0 20 40
0 20 40 60
KILOMETERS

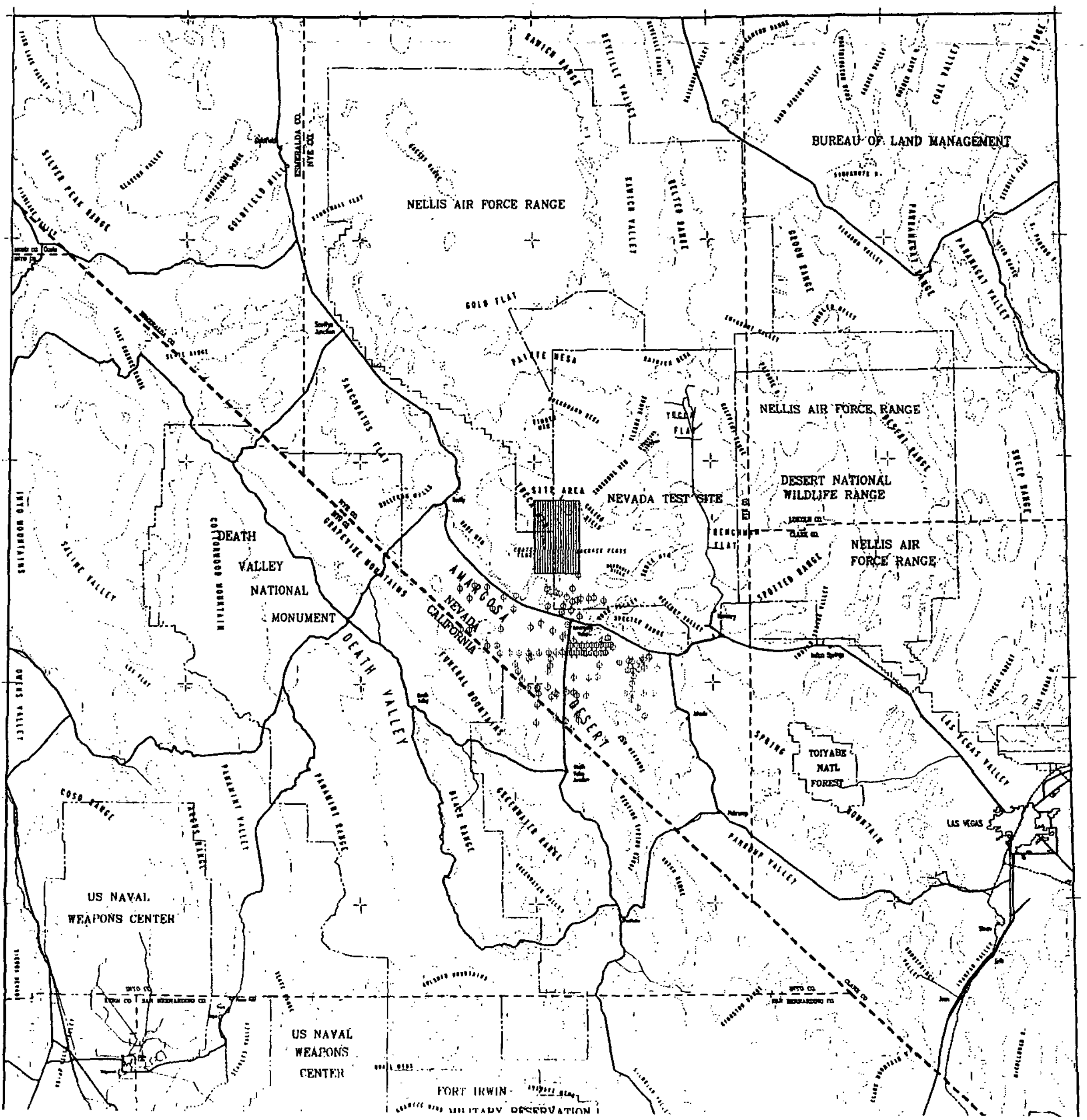
LEGEND

MAGNETOTELLURIC SOUNDINGS
DATE OF REPORT OR DATA ACQUIRED

·	1966
`	1977
●	1979
▲	1982
▪	1985
▨	A, B, C AREAS OF MULTIMETHOD GEOELECTRIC STUDIES
☐	D, E, F SPECIAL PURPOSE GEOELECTRIC STUDIES
╱╲╱	HIGHWAY
╱╲╱	IMPROVED ROAD
╱╲╱	RAILROAD
╱╲╱	STATE BOUNDARY
╱╲╱	COUNTY BOUNDARY
╱╲	ADMINISTRATIVE BOUNDARY



EG&G YMP-89-030.1



YUCCA MOUNTAIN PROJECT

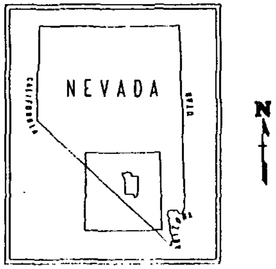
FIGURE 2.3-3. Location of Schlumberger Resistivity Soundings Acquired by Greenhaus and Zablocki (1982).

MILES 0 20 40

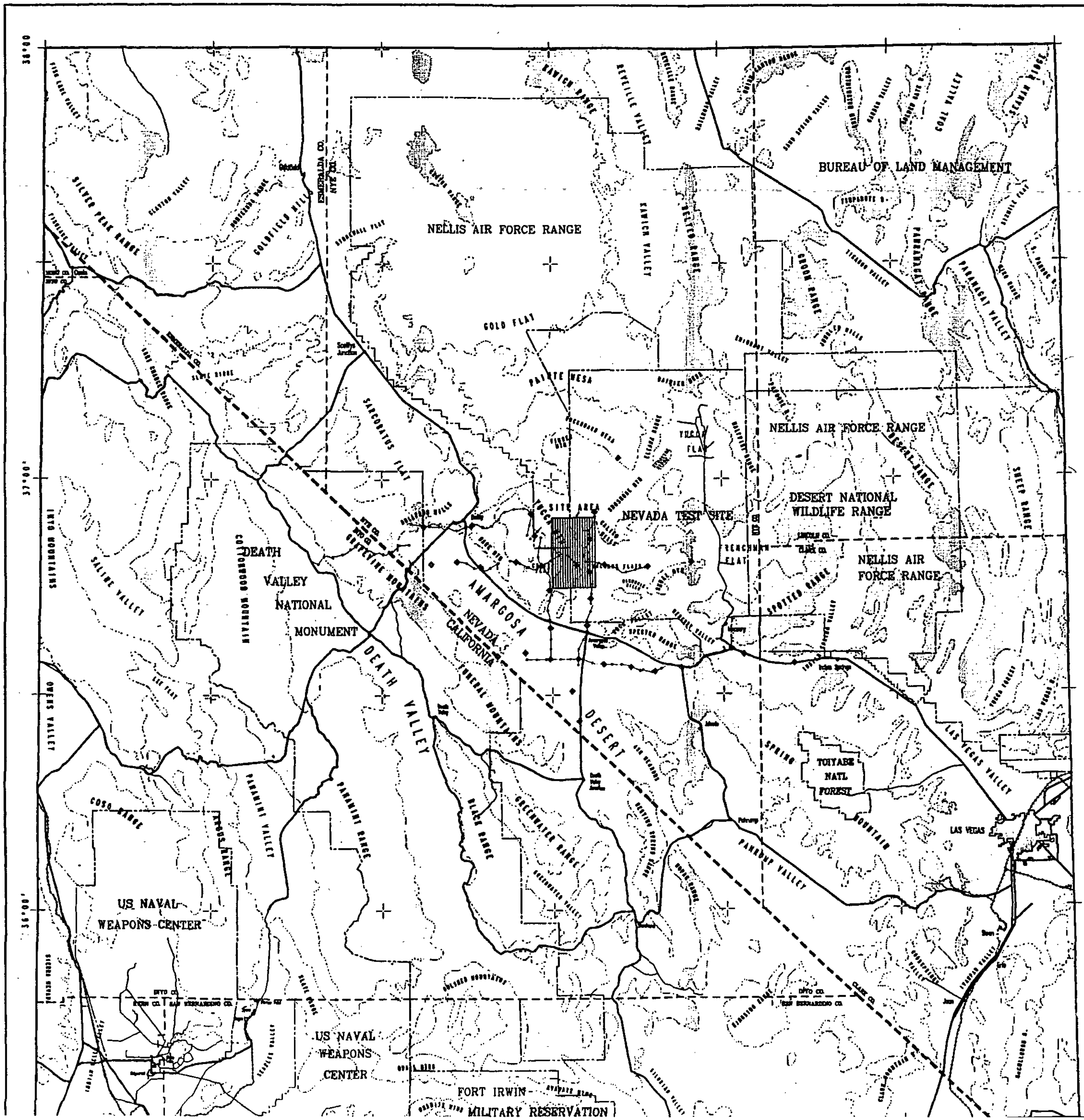
KILOMETERS 0 20 40 60

LEGEND

- ⌽ SOUNDING LOCATIONS (Azimuths not indicated)
- HIGHWAY
- IMPROVED ROAD
- RAILROAD
- STATE BOUNDARY
- COUNTY BOUNDARY
- ADMINISTRATIVE BOUNDARY



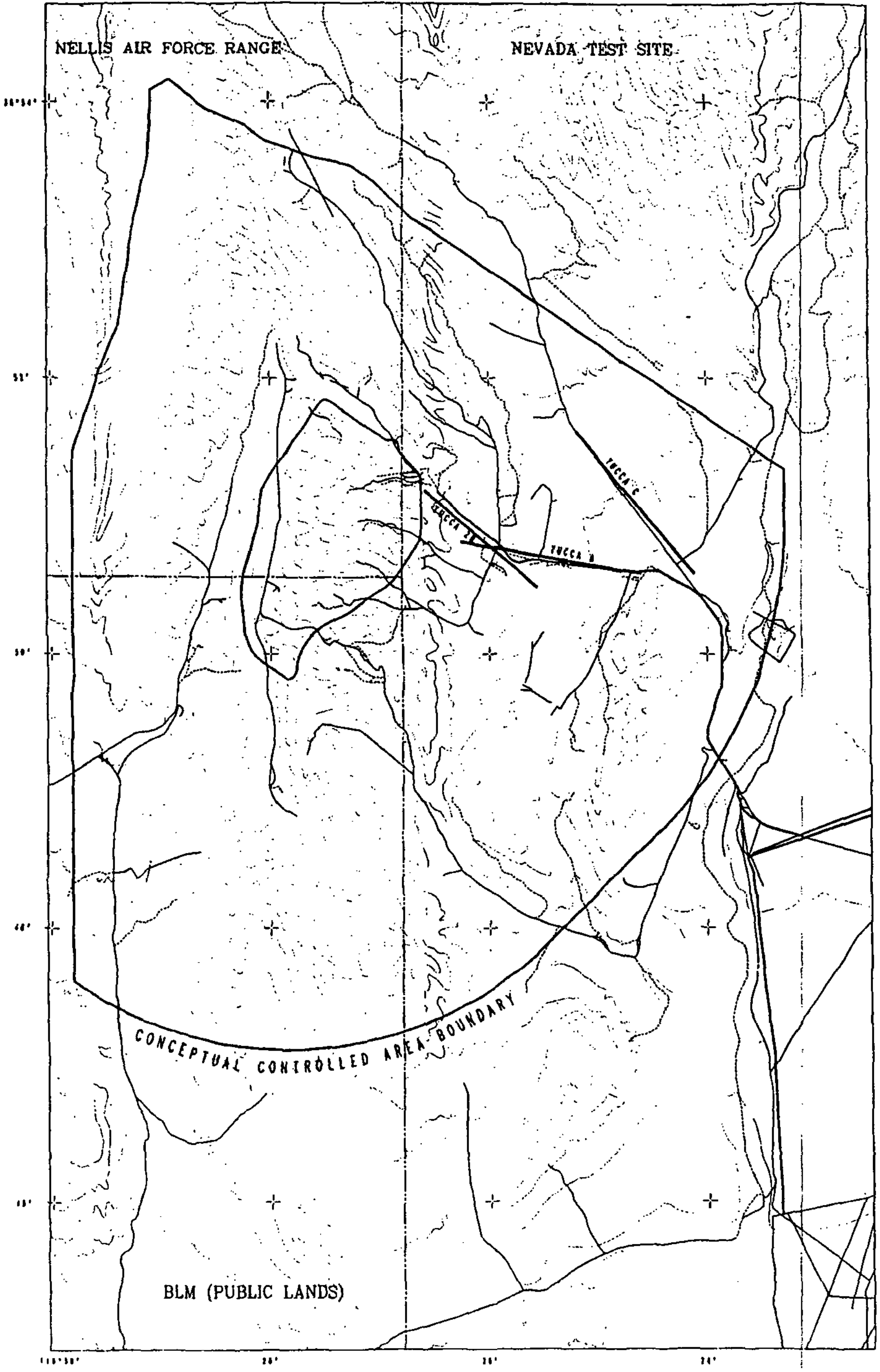
EG&G YMP-89-064.1



YUCCA MOUNTAIN PROJECT

FIGURE 2.4–2. Map of Yucca Mountain Region Showing the Locations of Five High Resolution Upper-Crustal Seismic Refraction Profiles. The Three Profiles that Trend East–West are Referred to as the Beatty, Yucca Mountain, and Amargosa Profiles. The Two Profiles that Trend North–South are Referred to as the Crater Flat and Fortymile Wash Profiles. Diamonds indicate Shot Points. The Location of the Proposed Repository is Shown in the Center of the Figure by a Shaded Rectangle.

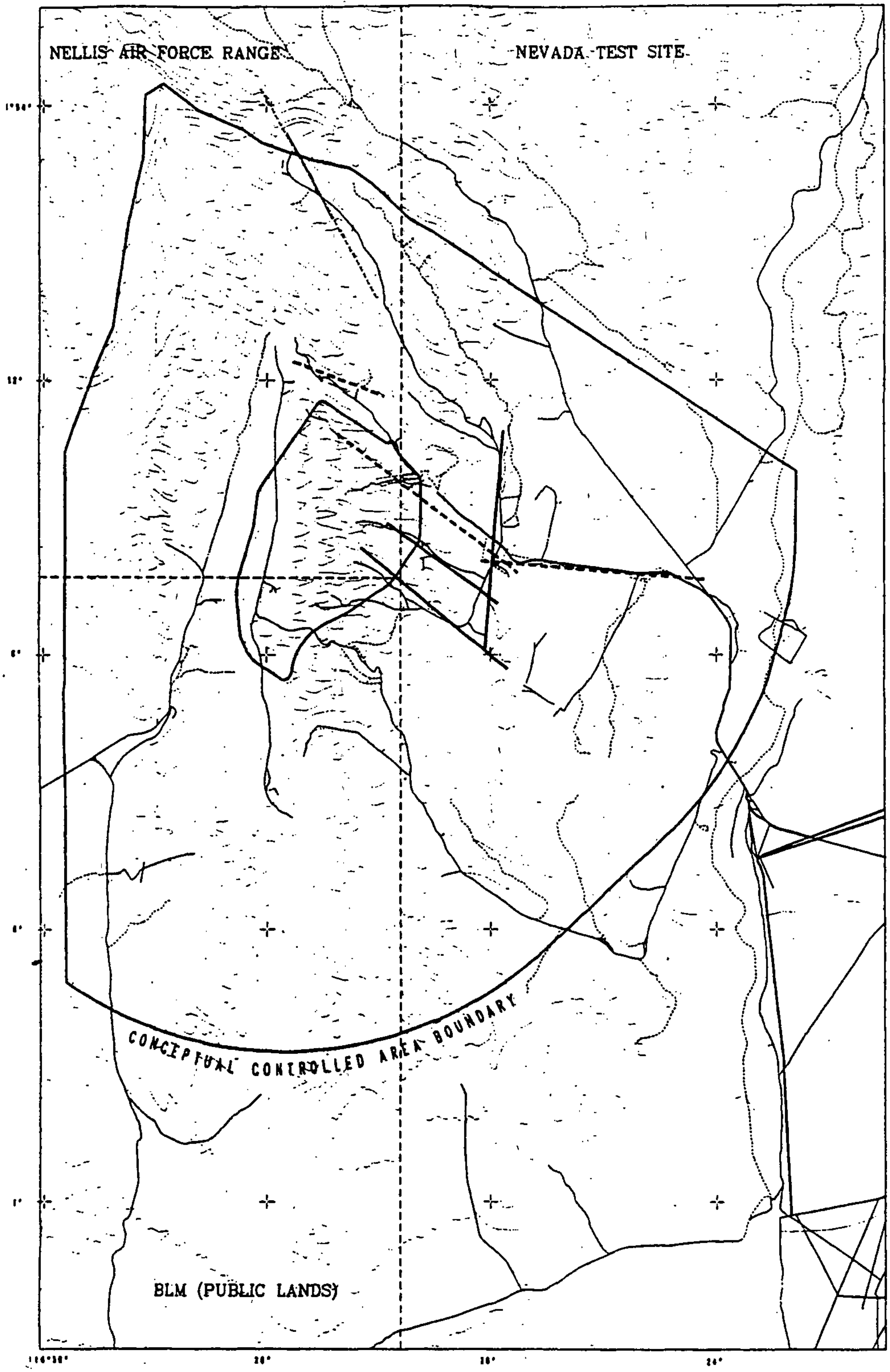
EG&G YMP-89-038.2



YUCCA MOUNTAIN PROJECT

FIGURE 2.4-1. Map of Yucca Mountain Refraction Lines from Pankratz (1982)

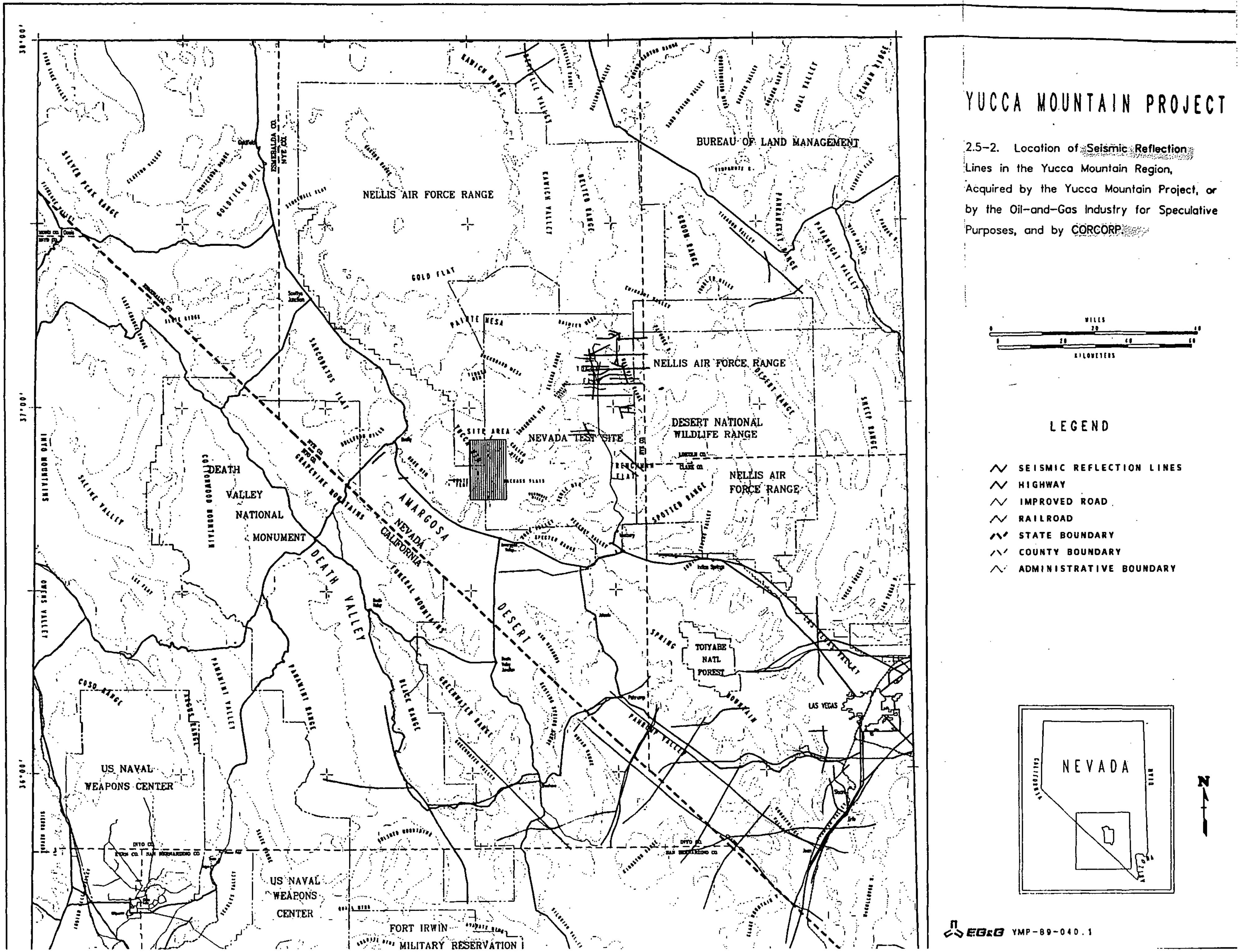
EG&G YMP89072.2



YUCCA MOUNTAIN PROJECT

FIGURE 2.5-1. Location of Seismic Reflection Surveys Reported by McGovern (1983) for the Yucca Mountain Site Area

EG&G YMP89071.2



YUCCA MOUNTAIN PROJECT

2.5-2. Location of Seismic Reflection Lines in the Yucca Mountain Region, Acquired by the Yucca Mountain Project, or by the Oil-and-Gas Industry for Speculative Purposes, and by CORCORP.

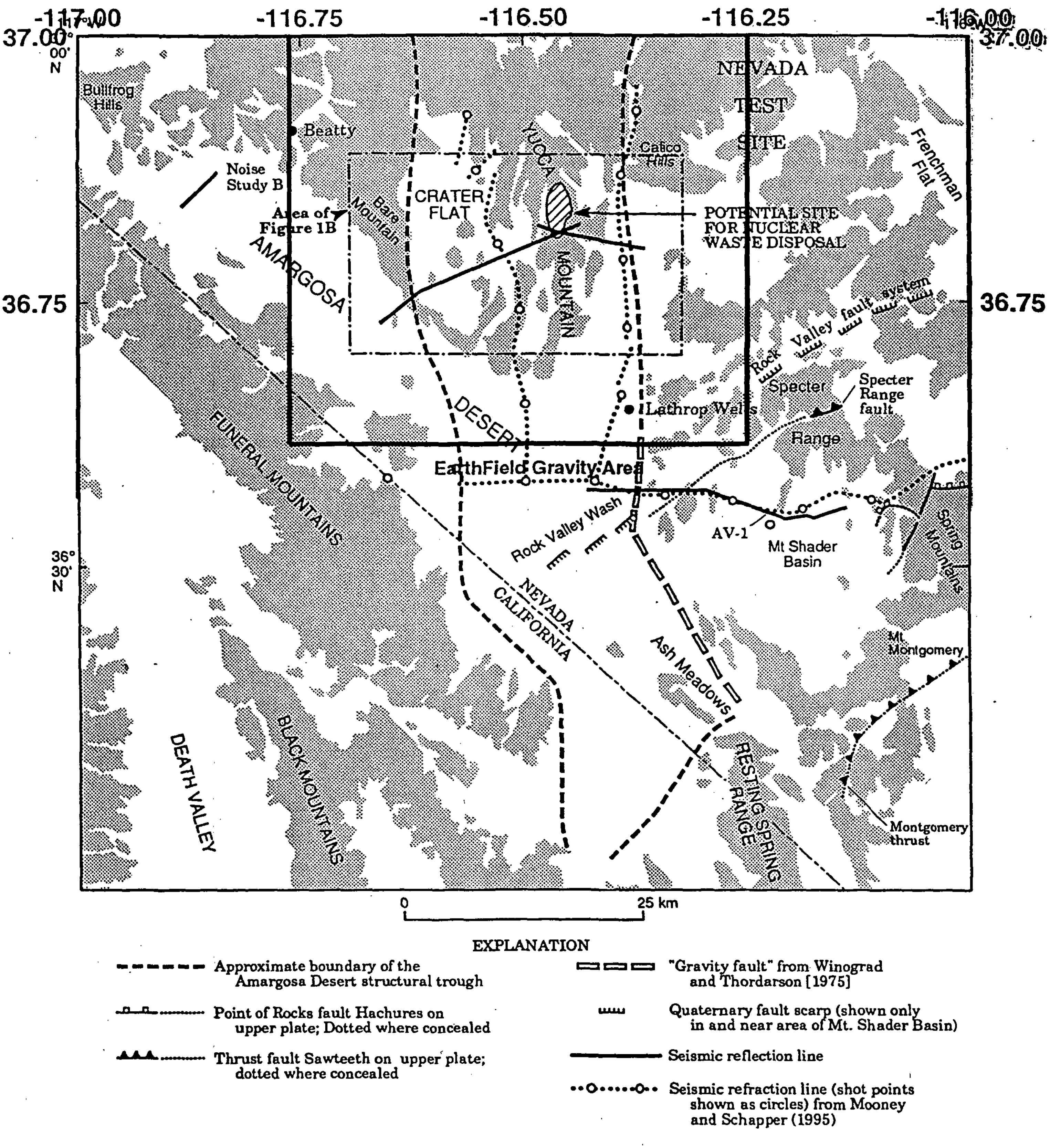


Figure 1a. Regional map of Yucca Mountain area, Nevada, showing seismic lines 2 and 3 and line AV-1 in the Amargosa Desert relative to Yucca Mountain and other structures described in the text. Map modified from Brocher and others [1993]. Outcrops of pre-Pliocene rocks are shaded.

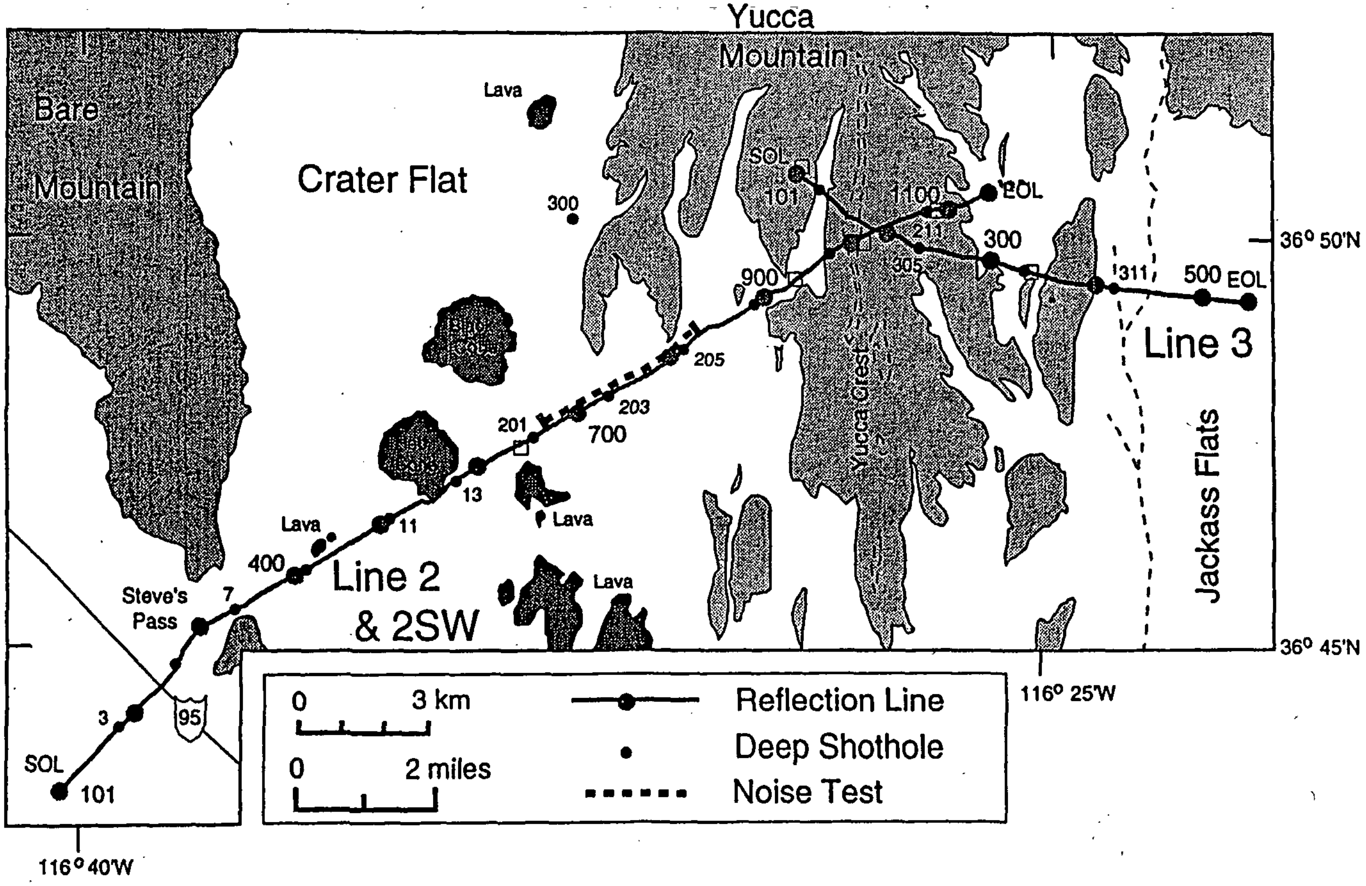


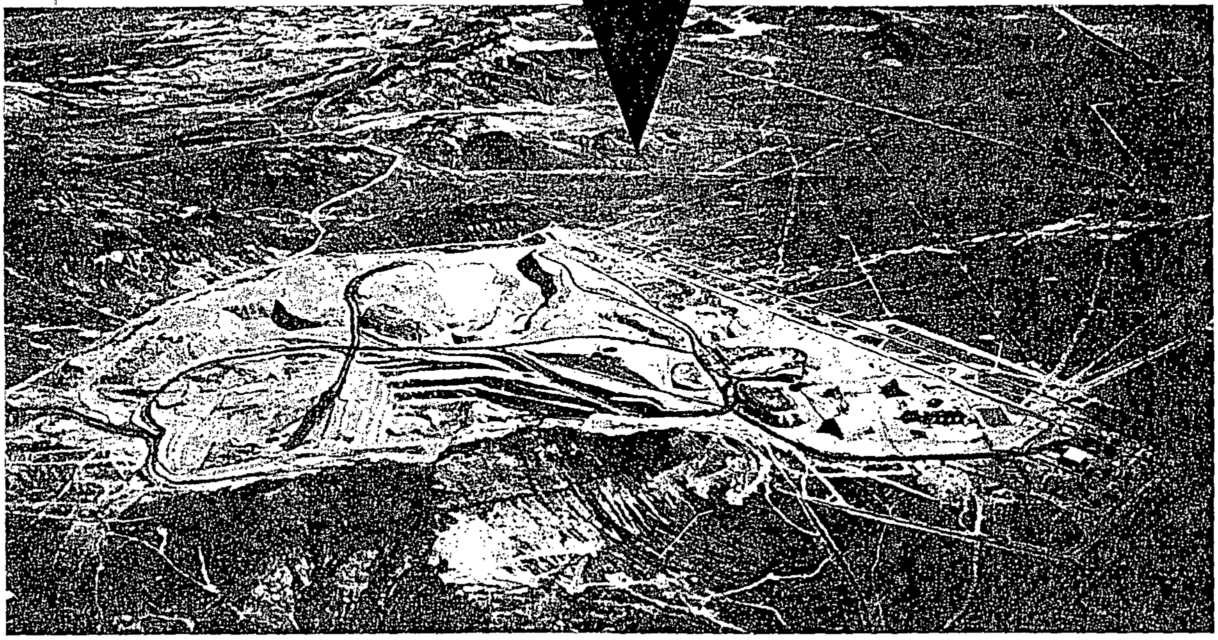
Figure 1b. Map of the vicinity of Yucca Mountain showing location of seismic lines 2 and 3. Larger numbers along lines provide station numbers, smaller numbers provide shothole locations. Dark shaded features in Crater Flat show lava flows and basaltic cones.

p.16 Eleana Fm

Bond-Bullfrog Mine near Beatty, Nev., is only 18 miles west of Yucca Mountain and in 1990 produced more than 220,000 ounces each of gold and silver. The volcanic rock that hosts gold and silver ore here is also present at Yucca Mountain.

COVER STORY

YUCCA MOUNTAIN NEVADA


FRANCIS DUBOIS ©

NUCLEAR WASTE OR RESOURCE RICH

The greatest uncertainty in assessing the suitability of the nation's single candidate site for a high-level nuclear waste repository may be the potential for human intrusion in search of valuable natural resources. The undisturbed natural geologic characteristics of the site must provide the primary assurance that the site can isolate the wastes from the environment for thousands of years.

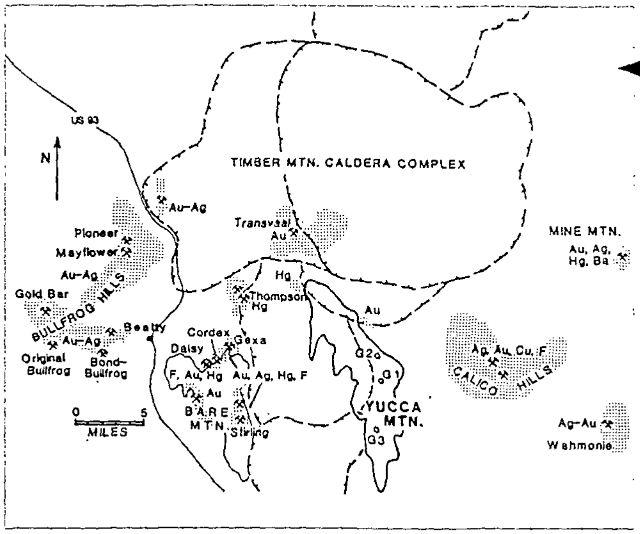
Studies of the Yucca Mountain region by Nevada geologists and hydrologists continue to show more evidence and generate more questions about the dynamic and complex nature of the geologic setting. But, unanswerable questions remain: How will future generations of humans interact with the geologic setting, and will their actions disturb the site and result in the loss of waste isolation?

I have discussed the major geotechnical uncertainties that require investigation before considering Yucca Mountain as a suitable repository for isolating highly radioactive waste and spent nuclear reactor fuel (Johnson, January 1989 Geotimes). It is likely that uncertainties inherent in southern Great Basin geologic complexity cannot be fully resolved. They include the effects of future volcanism on the site: the potential for contamination of the regional aquifer beneath the proposed repository horizon; the effect of future climate variation and resulting changes in the hydrologic regime; the nature of moisture and gas movement through the unsaturated zone at the site; and finally, the potential for future human intrusion, associated with the search for extractable natural resources.

The U.S. Department of Energy has focused the least attention on evaluating the Yucca Mountain site and surrounding area for the potential of recoverable valuable natural resources.

The potential for human activity disrupting a waste-disposal system's effectiveness has been considered throughout the conceptual development of a geologic disposal of highly radioactive wastes. The 1980 U.S. Department of Energy Generic Environmental Impact Statement on Radioactive Waste Management compared potential disposal concepts for their post-operational radiological integrity. Among the factors considered was "compromise of repository integrity by inadvertent human activity." The impact statement presumed that efforts would be made to avoid siting repositories in areas having known or potential resource value, thus reducing the motivation for human intrusion.

The U.S. Environmental Protection Agency in promulgating the environmental standards for the management and disposal of spent nuclear fuel, and high-level and transuranic radioactive wastes (40 CFR Part 191) concluded that geologic disposal sites should be selected to avoid places where resources have been mined, where it is reasonable to expect to explore for scarce or easily accessible resources, or where a significant concentration of a material is not otherwise available. The DOE, in its general guidelines for the recommendation of sites for nuclear-waste repositories (10 CFR Part 960), discussed the need for "reducing the incentive for post-closure human interference by avoiding sites containing natural resources that would invite potentially disruptive human activities." Can we reconcile the Yucca Mountain site with the clear warnings about avoiding sites for nuclear-waste repositories that are attractive for resource exploration and extraction?

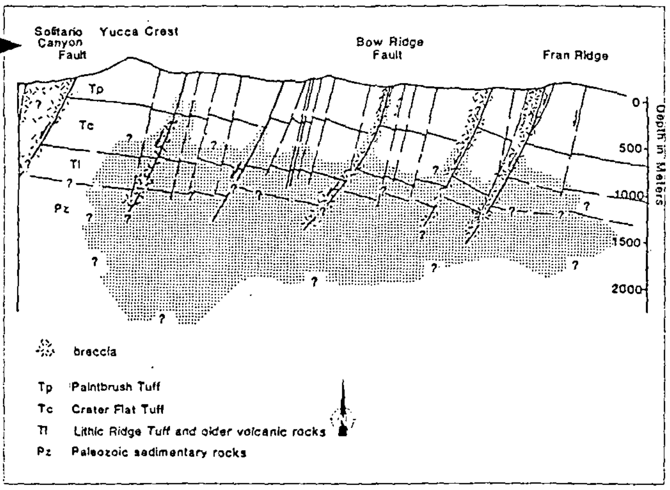


MACKAY SCHOOL OF MINES, UNIVERSITY OF NEVADA, RENO

Casual rejection of Yucca Mountain's resource potential is refuted by the proximity of mines, prospects and areas of hydrothermal alteration. Stippled areas indicate general distribution of hydrothermal alteration.

MINING

Mining base and precious metals has been a large part of Nevada's history since before statehood. Gold and silver have played a significant role in the state's contribution to the prosperity of the nation. In 1990, Nevada contained 87 active significant mines, which produced six million ounces of gold and 22 million ounces of silver, as well as other metallic minerals such as mercury, lithium, copper, lead, zinc, and molybdenum.



MACKAY SCHOOL OF MINES, UNIVERSITY OF NEVADA, RENO, FROM A DIAGRAM BY USGS.

Stipple pattern on a general cross section through Yucca Mountain shows distribution of hydrothermal alteration inferred or proven from drill holes and surface information. Alteration minerals include albite, potassium, montmorillonite, zeolites, iron oxides, manganese oxides, fluorite, calcite, quartz, pyrite, illite, and chlorite.

Numerous Nevada ore deposits show common geologic features, and many exist in the Yucca Mountain area. These features include certain types of rock alteration, and a distinct geochemical signature (gold, silver, arsenic, mercury, antimony, molybdenum, zinc, barium, and fluorine). Also these ore deposits commonly are found along and within faults and breccia zones, and are often associated with felsic or granitic dikes, plugs, sills, and stocks. Barite (with or without fluorite) is common. All of these features exist in the immediate Yucca Mountain area.

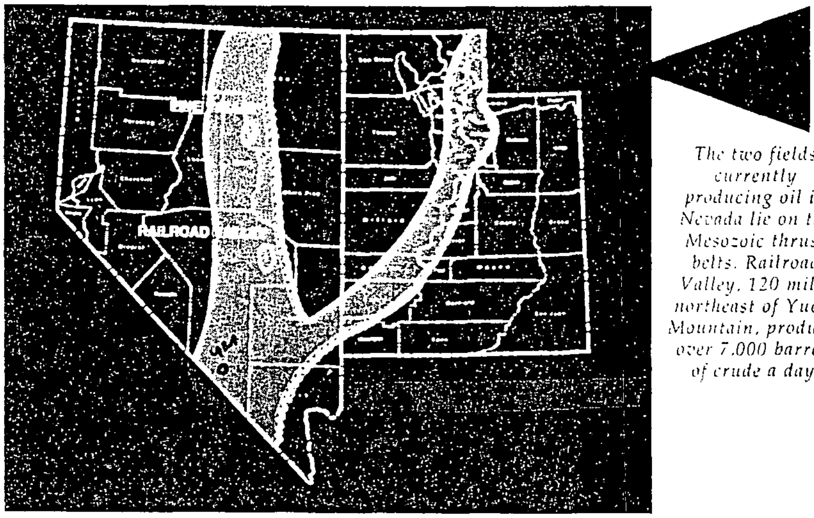
The Yucca Mountain geologic environment is favorable for hydrothermal mineral deposits. Hydrothermal activity resulted from repeated magmatic and volcanic activity. The area has abundant faults and a complex structural history. Gold Bar, Sterling, Daisy, Mother Lode, and Bond-Bullfrog are currently or recently producing mines in the vicinity of Yucca Mountain. Other areas, such as the Cordex deposits on Bare Mountain, Transvaal area and Thompson Mine northwest of Yucca Mountain, and the Calico Hills, Wahmonie, and Mine Mountain areas within the Nevada Test Site are areas with rock alteration geochemistry and other geologic conditions favorable to mineral exploration.

Yucca Mountain has features that suggest mineral potential:

- Hydrothermal alteration of the type associated with epithermal mineralization is evident even in the very limited published data of the subsurface of Yucca Mountain.
- In the subsurface, hydrothermal mineral assemblages include quartz, illite, albite, K-feldspar, chlorite, calcite, pyrite, fluorite, and barite.
- Available data show elevated concentrations of fluorine, barium, zinc and gold in the subsurface.
- Elevated concentrations of arsenic, antimony, mercury, zinc, molybdenum, lead, and gold are present in altered rocks in a trench, less than a mile from the repository site.
- Elevated arsenic, mercury and gold concentrations have been measured in rocks from the surface of Yucca Mountain in the Prow Pass and Claim Canyon areas.
- The elevated concentrations of one or more of those elements at various locations show that the hydrothermal system or systems were metal bearing. Radiometric dating and stratigraphic relations show that the same volcanic rock units that compose Yucca Mountain host gold and silver ore in Gold Bar, Bond-Bullfrog, Cordex, and the Mother Lode deposits.

- Yucca Mountain has numerous high-permeability channels such as faults and breccias, which could have been favorable conduits for hydrothermal fluid circulation and mineral deposition.
- In summary, the information from existing drill holes does not suggest that the presence of economic deposits at Yucca Mountain should be ruled out.

The recent discoveries of mineral deposits in areas near and even adjacent to Yucca Mountain, reflect increased and successful mineral exploration in the region. Such discoveries make hydrothermally altered areas of the southern part of the southwestern Nevada volcanic field much more attractive for exploration than before. All this information suggests that the potential for valuable mineral resources in the immediate area surrounding Yucca Mountain must be recognized, along with the potential for resulting human interference and intrusion at the site.



CEDAR STRAT CORP., DENVER

The two fields currently producing oil in Nevada lie on the Mesozoic thrust belts. Railroad Valley, 120 miles northeast of Yucca Mountain, produces over 7,000 barrels of crude a day.

OIL AND GAS

Although Nevada is not thought of as a major oil-producing state, about 31 million barrels of oil have been produced since 1954. Producing fields are located in Pine Valley (central Nevada) and Railroad Valley (eastern Nevada). The Grant Canyon 2 well field, in Railroad Valley, 120 miles northeast of Yucca Mountain, produces over 7,000 barrels of crude per day, with the Grant Canyon #3 well producing more than 4,200 barrels per day from 4,000 feet — the most barrels a day from a conventionally drilled onshore well in the continental United States.

In southern Nevada, wildcat drill holes have encountered oil and gas shows, but no producible quantities. Nevertheless, wildcat drilling persists, including at least one recent well in Oasis Valley, 20 miles northwest of the site.

All of Nevada's current production is from relatively shallow fault plays at depths of 4,000 to 7,000 feet. The reservoirs are Tertiary volcanics and Paleozoic carbonate rocks. The hydrocarbon source rocks are organic-rich, fine-grained sediments that were shed eastward into a deep-water foreland basin from the Antler Mountains, the result of a late Mississippian orogeny in central Nevada, which interrupted the normal carbonate margin deposition. Devonian reefs, similar to the Canadian Devonian reefs that have produced billions of barrels of oil, were deposited along the carbonate margin in Nevada.

Recent detailed stratigraphic data suggests that the Mississippian Antler Basin is similar to the Cretaceous foreland basin of the interior seaway. Both foreland basins contain valley fill sequences interbedded with margin strata. The Cretaceous foreland basin has generated billions of barrels of oil. The Antler foreland basin may have had a similar generating capacity for hydrocarbons.

Later, Sevier/Laramide age thrusting trapped the Mississippian hydrocarbons. All the oil produced in Nevada is found along the Sevier/Laramide thrust belt. The current producing fields in Nevada may be the result of hydrocarbons migrating from deep thrust plates into shallow fault-block traps resulting from Tertiary extensional tectonics. However, the presence of deeper thrust-belt reservoirs has been suggested, similar to the model of the highly prolific overthrust belt in western Wyoming.

Mississippian-age clastic rocks extend southwestward across Nevada (including Yucca Mountain) and into Southern California. In southern Nevada, the Eleana Formation is thought to be the equivalent of these Mississippian-age source rocks. The Eleana Formation crops out in the Eleana Range and the Calico Hills northeast and east of Yucca Mountain, and to the west of Yucca Mountain at Bare Mountain. Several lines of evidence suggest that the Eleana is present beneath the Tertiary volcanic rocks at Yucca Mountain. Samples of the Eleana less than 50 miles northeast of Yucca Mountain indicate thermal maturation conditions appropriate for oil generation.

Thrust faults occur at Bare Mountain, in the Calico Hills and in the Eleana Range and can be reasonably projected beneath Yucca Mountain. The only drill hole to penetrate the Tertiary volcanic section in the vicinity of Yucca Mountain found Silurian carbonates immediately below the Tertiary. However, these Silurian rocks are probably in the upper plate of a thrust fault.

Interpretations of aeromagnetic data from the vicinity of Yucca Mountain reflect the presence of the Eleana Formation at depth. This supports the interpretation that the Eleana Formation underlies a thrust beneath the repository site, and therefore the potential for hydrocarbons is postulated.

INTRUSION A "CERTAINTY"?

In planning for site characterization at Yucca Mountain, the Department of Energy has argued that the natural-resource potential is low for both minerals and hydrocarbons. DOE asserts that the metallic-mineral potential is low because no obvious surficial signs indicate hydrothermal activity typically associated with mineral deposits, and the oil and gas potential is low because all the potential source rocks have been heated beyond the oil and gas generating window.

There is a paradox in these arguments: if the rocks were heated enough to drive off the hydrocarbons, then the potential for hydrothermal minerals may be higher; conversely, if the deeper rocks never were heated significantly by hydrothermal fluids, then the potential for hydrocarbon resources may be higher. The geologic evidence suggests both resources may be present. It is DOE's responsibility to resolve the paradox and document the potential for natural resources, if Yucca Mountain is to remain candidate for a high-level nuclear waste repository.

Intense exploration and development is occurring in all areas surrounding Yucca Mountain that are open to entry. Historically, where known or perceived natural resources exist, exploration and the resulting human intrusion have taken place. It must be assumed that this will be the case here, and that human intrusion will affect the Yucca Mountain site in the future — and certainly during the prescribed 10,000 to 100,000 years of isolation.

Carl Johnson
Nevada Agency for Nuclear Projects. Nuclear Waste Project Office, Capitol Complex, Carson City, Nevada 89710

Peter Hummel
Nevada Commission on Mineral Resources, Capitol Complex, Carson City, Nevada 89710