BW - __999__

AGENDA, PRESENTATIONS & NOTES

BRINE WELL WORK GROUP

3/26/09 - Present

New Mexico Oil Conservation Division
UIC Class III Brine Well Evaluation Work Group
Porter Hall (Wendell Chino Bldg.)
1220 South St. Francis Drive, Santa Fe, NM 87505
March 26-27, 2009
(8:00 a.m. – 5:00 p.m.)

FINAL AGENDA

Thursday, March 26, 2009

8:00 - 8:10 a.m.	**Welcoming remarks:** OCD Environmental Bureau Chief Wayne Price.
8:10 - 8:15 a.m.	**OCD introduction:** OCD Environmental Bureau Jim Griswold states purpose and goal of the work group.
8:15 - 8:30 a.m.	**Work group members' introduction:** Members briefly state interest in serving on the work group; and what he/she hopes to bring to the table.
8:30 - 8:50 a.m.	**Shallow geology & hydrology of the Delaware/Permian Basin in SE NM (Glenn von Gonten- OCD/ Richard Beauheim- SNL)**
8:50 - 9:05 a.m.	**A history of brine well operation & regulation in NM (Jim Griswold- OCD)**
9:05 - 10:00 a.m.	**Recent brine well collapses in NM & case studies (Jim Griswold- OCD)** Jims Water Service SE of Artesia on 7/16/2008 & Loco Hills Disposal E of Artesia on 11/3/2008
10:00 – 10:15 a.m.	**Break**
10:15 – 10:35 a.m.	**Federal discussion (Ray Leissner- EPA)** EPA oversight capacity and scope of the federal Class III program. First impression federal perspective on suggestions/topics that may arise during the discussions and will identify to the group if an idea

at hand would likely have implications on program approval or revision and what that effort would include. More discussion as needed.

10:35– 11:15 a.m.	**Potential impacts to the WIPP Site? (Chuck Byrum- EPA & Russ Patterson- DOE)** Slide show of subsurface facilities relative to the oil field activities in the region; associated regulatory requirements; and any other relevant issues.
11:15 – 11:45 a.m.	**Sonar Testing in Bedded Salt (Jason McCartney- SOCON Sonar Well Services, Inc.)**
11:45 - Noon	**Developing a research plan to evaluate existing brine wells & to assess potential risk of collapse (George Veni (NCKRI)**
Noon – 1:00 p.m.	**Lunch (on your own)**
1:00 – 1:30 p.m.	**Potash Well Siting, Construction & Operation (Richard Miller- Intrepid Potash)**
1:30 – 2:00 p.m.	**Class II Hydrocarbon Storage Wells- Western Refining L.P.** Siting, construction & operation. Should these types of wells be considered similar to Class III brine wells for potential collapse?
2:00 – 3:00 p.m.	**Current OCD discharge permits requirements for Class II HC Storage & Class III Brine Wells (Carl Chavez- OCD)** Display of OCD discharge permits and current requirements
3:00 – 3:15 a.m.	**Break**
3:15 – 4:00 p.m.	**Brine well strategy/talking points (Carl Chavez- OCD)** Brainstorming
4:00 – 4:30 p.m.	**Miscellaneous (Work Group)**
4:30 – 5:00 p.m.	**Work Group Summary**

BRINE WELL WORK GROUP MEETING SIGN-IN SHEET

26-Mar-09

NAME	AGENCY/COMPANY	ADDRESS	CITY	STATE	PHONE	E-MAIL
Carl Chavez	NMOCD	1220 South St. Francis Dr.	Santa Fe	NM	505-476-3490	Carl J.Chavez@state.nm.us
DAVID HUGHES	WRES	1518 MUSCATEL AVE	CARLSBAD	NM	575-234-7342	DAVE.HUGHES@wipp.ws
Chuck Byrum	US EPA	1445 Ross Ave	Dallas	TX	214-665-7555	byrum.charles@epa.gov
Dennis Powers	Con. Geologist	140 Heml[illegible] Rd	Anthony	TX	915 877-3929	dwpowers@evaporites.com
Lynn Sockwell	Basic Energy Serv.	500 W. Illinois	Midland	TX	432-571-810[illegible]	lyn.sockwell@basicenergyS[illegible].com
Ron Weaver	Wester Ref.		Bloomfield	NM	505-632-4165	ron.weaver@wnr.com
Jim Rutley	BLM-CFO	913 FOUNTAIN DR	CARLSBAD	NM	575-234-5904	james_rutley@blm.gov
Ken Parker	Western Ref	PO Box 1345	JAL	NM	575-395-263[illegible]	Ken.Parker@wnr.com
Richard Miller	Intrepid Mining	707 17th St Ste 4200	Denver	CO	303-881-5440	Richard.Miller@intrepidpotash.com
Jason McCartney	SOCON	1133 I-45 S. Ste. E Conroe, TX 77302	Conroe	TX	936-441-5801	mccartney@socon.com
Allen Hains	WESTERN REFINING		BLOOMFIELD	NM	915-775-5554	allen.hains@wnr.com
Mark Cartwright	TEXAS BRINE	4800 SAN FELIPE ~~Houston~~	HOUSTON	TX	713-877-2634	MCARTWRIGHT@TBM.COM
Courtney Herrick	Sandia Nat'l Labs	4100 National Parks Hwy	Carlsbad	NM	575-234-0176	cgherri@sandia.gov
Ross Kirkes	Sandia Labs	4100 Nat'l Pks Hwy	Carlsbad	NM	575 234 0187	grkirke@sandia.gov
George Veni	NCKRI	1400 COMMERCE DR.	CARLSBAD	NM	575-887-5517	GVENI@NCKRI.ORG
Veronica Waldram	Navarro Research + Engineering	4021 National Parks Hwy	Carlsbad	NM	575 234-8449	Veronica.Waldram@wipp.ws
Jim Snyder	OCD	NMOCD	SF	NM	476-3484	jim.snyder@state.nm.us
Dan Snow	Lotus LLC	PO Box 1277 Andrews TX 79714			432 661-5828	dwsnow@lotusllc.com
Rick Beauheim	Sandia Nat. Labs	4100 Natl. Parks Hwy	Carlsbad	NM	575-234-0006	rlbeauh@sandia.gov
THADDEUS KOSTRUBALA	NM STATE LAND OFFICE	310 Old Santa Fe Trail	SF	NM	505-827-5723	~~ttko~~ tkostrubala@slo.state.nm.us
LOREN MOLLEUR	Key ENERGY	1514 HERITAGE BLVD	ANDREWS	TX	432-638-9023	lmolleur@keyenergy.com
Ray Leissner	EPA Region 6	1445 Ross Ave, Dallas	Dallas	TX	214-665-7183	rleissner@hotmail.com
Glenn von Gonten	OCD		SF	NM	505-476-3488	GLENN.VONGONTEN@STATE.NM.US

Friday, March 27, 2009

8:00 – 9:00 a.m. **Siting Criteria (Work Group)**
Proximity of populated development
Proximity of public roadways
Proximity of utilities including water supply wells
Oil & gas production
Potash mining (Hugh Harvey)
Other brine wells/caverns
Easements
WIPP (Chuck Byrum)
Other infrastructure
Disposition of protectable ground water
Thickness of salt ore layer
Interbedding

9:00 – 9:30 a.m. **Construction Characteristics (Loren Molleur)**
Re-entry of former oil and gas wells
Thickness and lithology of overburden
Borehole geophysical logging
Well Materials
Casing penetration into salt
Cementation of casing
Multi-well operation

9:30 – 10:00 a.m. **Operations (Mark Cartwright)**
Tubing placement
On-site pumping of fresh water
Modes of fresh water injection/brine extraction
Production pressures and rates
Operational lifetime
Closure including possible backfilling of cavern with solid materials

10:00 – 10:15 a.m. **Break**

10:15 – 10:45 a.m. **Monitoring (Work Group)**
Subsidence monitoring
Mechanical integrity testing of casing and cavern (Wayne Price)
Surface assessment

	Geophysical methods for determination of cavern size and geometry (Andreas Reitze) Groundwater quality monitoring
10:45 – 11:15 a.m.	**Plug & Abandonment (Work Group)** Fill brine cavern w/ brine water & cement casing to surface
11:15 – Noon	**Collapse Response (James Rutley- BLM)** Pre-positioning of emergency materials Immediate public safety Longer term restriction of access Property damage (Thaddeus Kostrubala) Groundwater contamination Backfilling
Noon – 1:00 p.m.	**Lunch (on your own)**
1:00 – 1:30 p.m.	**NM Class III Brine Well Regulations (Carl Chavez- OCD)** WQCC 20.6.2 NMAC
1:30 – 2:00 p.m.	**TX Class III Brine Well Regulations (Jim Griswold- OCD)** Chapter 3: Oil and Gas Division, Rule 3.81
2:30 – 3:00 p.m.	**KS Class III Brine Well Draft Regulations (Jim Griswold- OCD)** Article 46 - Underground Injection Control Regulations
3:00 – 3:15 p.m.	**Break**
3:15 – 3:45 p.m.	**Suggestions for NM Regulations or Guidelines (WQCC 20.6.2 NMAC) based on KS & TX Regulations**
3:45 – 4:00 p.m.	**Industry perspective**
4:00 – 4:15 p.m.	**Federal perspective**
4:15 – 5:00 p.m.	**State perspective** Work Group members who provided e-mail addresses will be included on any draft electronic draft documents, regulations, reports, etc. that may follow from our meeting. All work drafts will be posted on "BW-999" on OCD Online.

BRINE WELL WORK GROUP MEETING SIGN-IN SHEET

27-Mar-09

NAME	AGENCY/COMPANY	ADDRESS	CITY	STATE	PHONE	E-MAIL
Carl Chávez	NMOCD	1220 S. St. Francis Dr.	Santa Fe	NM	505 476 3490	carlj.chavez@state.nm.us
DAVID HUGHES	WRES-	1518 S MASCOTEL AVE	CARLSBAD	NM	575-234-7342	DAVE.HUGHES@WIPP.WS
Veronica Waldram	Navarro Research & Environmental	4021 National Parks Hwy	Carlsbad	NM	575-234-8449	Veronica.Waldram@wipp.ws
JIM RUTLEY	BLM	620 EAST GREENE ST	CARLSBAD	NM	575-234-5904	JAMES_RUTLEY@BLM.GOV
Chuck Byrum	US. EPA	1445 Ross Avenue	Dallas	TX	214 665 7555	byrum.charles@epa.gov
LOREN MOLLEUR	KEY ENERGY	1514 HERITAGE BLVD.	ANDREWS	TX	432-638-9023	lmolleur@keyenergy.com
Lyn Sockwell	Basic Energy	500 W. Illinois	Midland	TX	432-238-9519	lyn.sockwell@basicenergyservices.com
Russ Patterson	DOE	DOE-Carlsbad	Carlsbad	NM	575-234-7457	russ.patterson@WIPP.ws
RAY LEISSNER	EPA Region 6	1445 Ross Ave	Dallas	TX	214-665-7183	leissner.ray@epa.gov

New Mexico Energy, Minerals and Natural Resources Department

Oil Conservation Division

Governor's Office Inquiry
Who, Where, What, When

WHY ?

Mandates Prevention

Focus on

Establish Effective Tools
&
Set Appropriate Goals

PURPOSES

- To discuss effective tools for evaluating the collapse potential of historic closed and presently operational brine wells along with LPG storage caverns in NM.

- To discuss siting, construction, and operational criteria for future operations.

GOAL

- Listen to technical and experiential input such that future OCD guidelines and/or rules relating to salt caverns will reflect the current state-of-the-art while allowing for the incorporation of future innovation.

New Mexico Energy, Minerals and Natural Resources Department

Oil Conservation Division

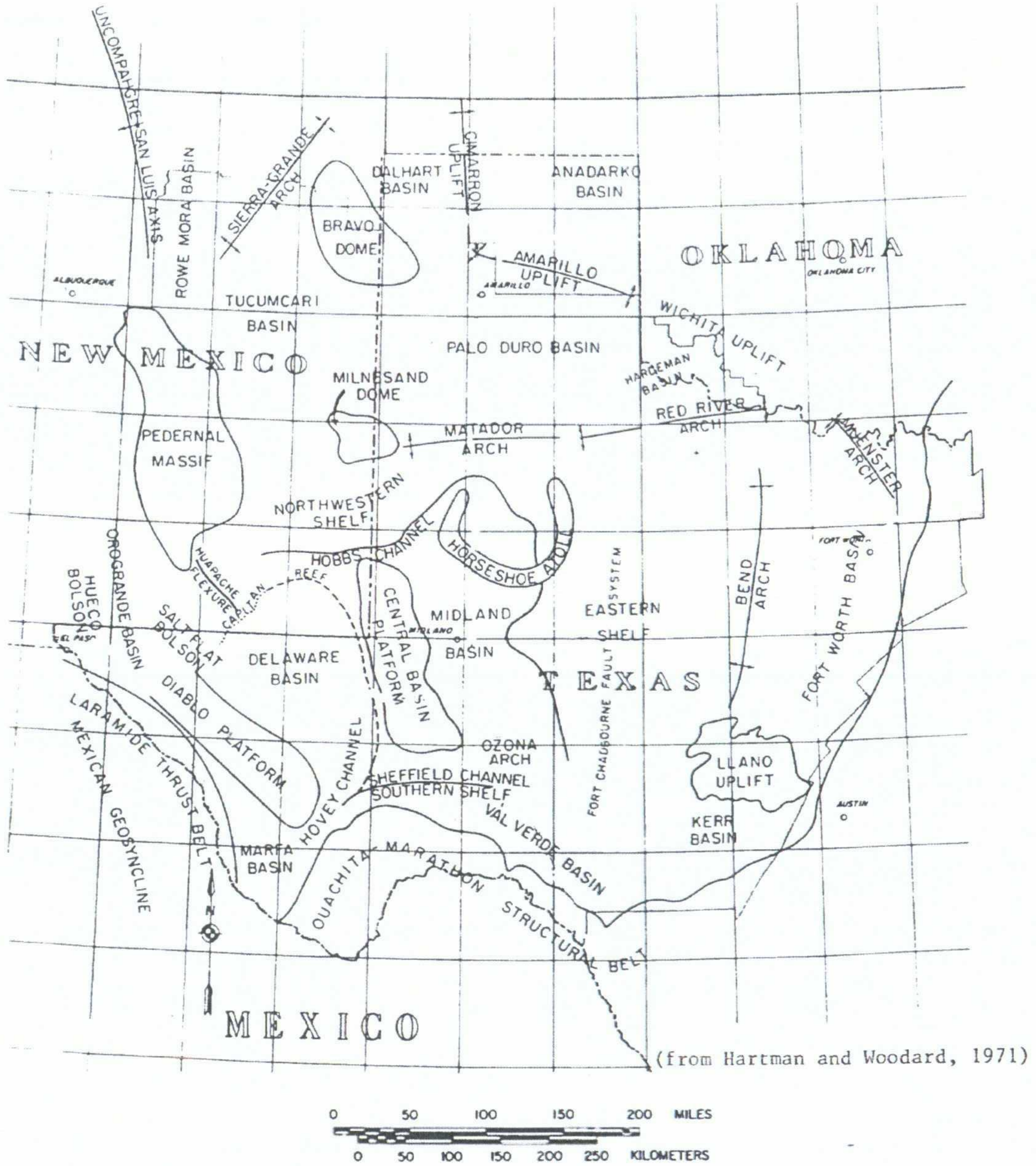
Purpose and Goals (5 minutes)

- Discuss effective tools for evaluating the collapse potential of historic closed and presently operational brine wells along with liquid hydrocarbon storage caverns in NM under the regulatory purview of the OCD.

- Discuss siting and operational criteria for future operations.

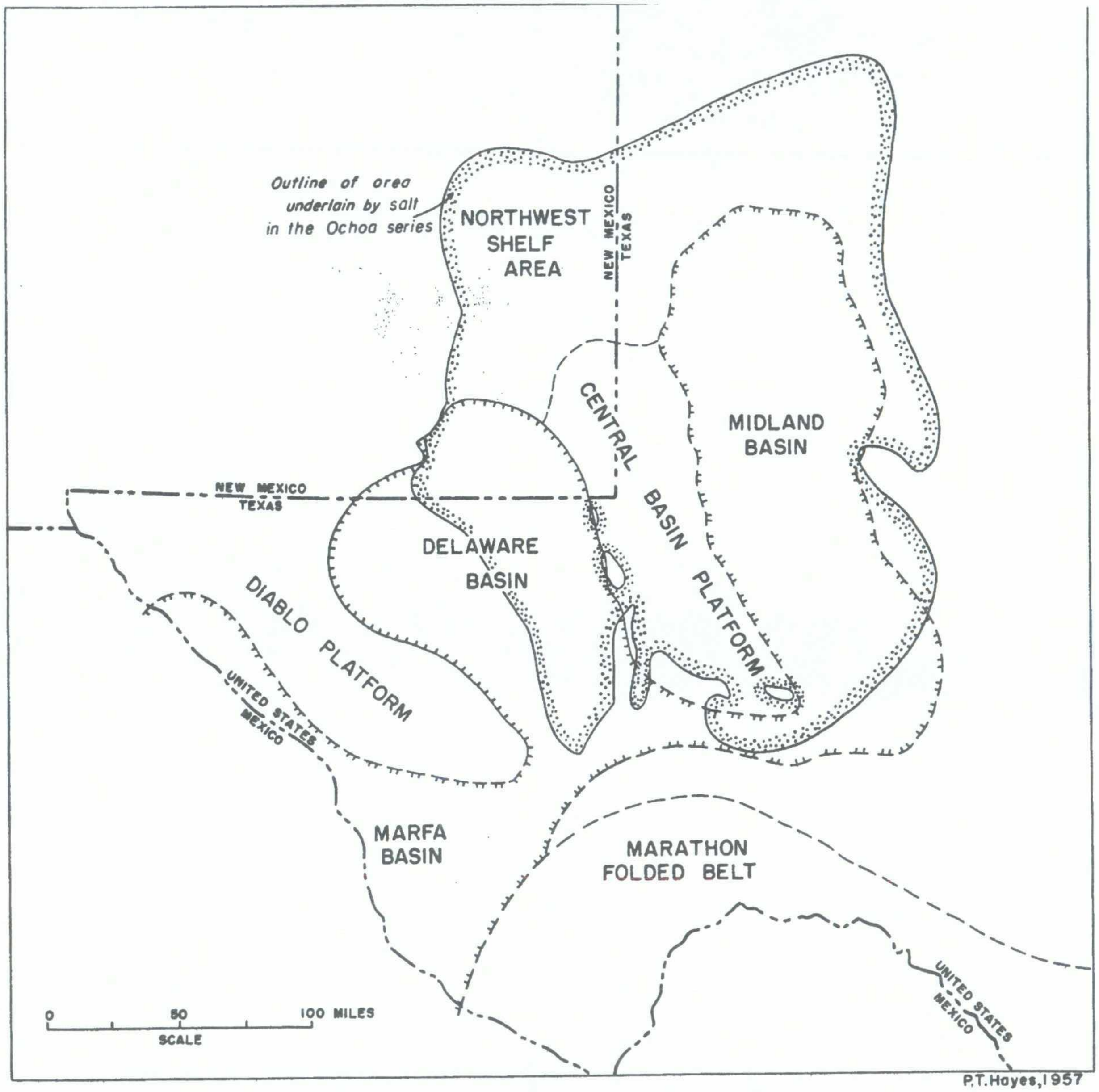
- Listen to technical and experimental input such that future OCD guidelines and/or rules relating to salt caverns will reflect the current state-of-the-art while allowing for the incorporation of any future innovations.

LOCAL GEOLOGY



(from Hartman and Woodard, 1971)

Fig. 5–Index map showing significant geologic features.



P.T. Hayes, 1957

Fig. 1. Index map showing outline of area underlain by salt in the Ochoa series in relation to late Permian basins and shelf areas. (Adapted from King, 1948).

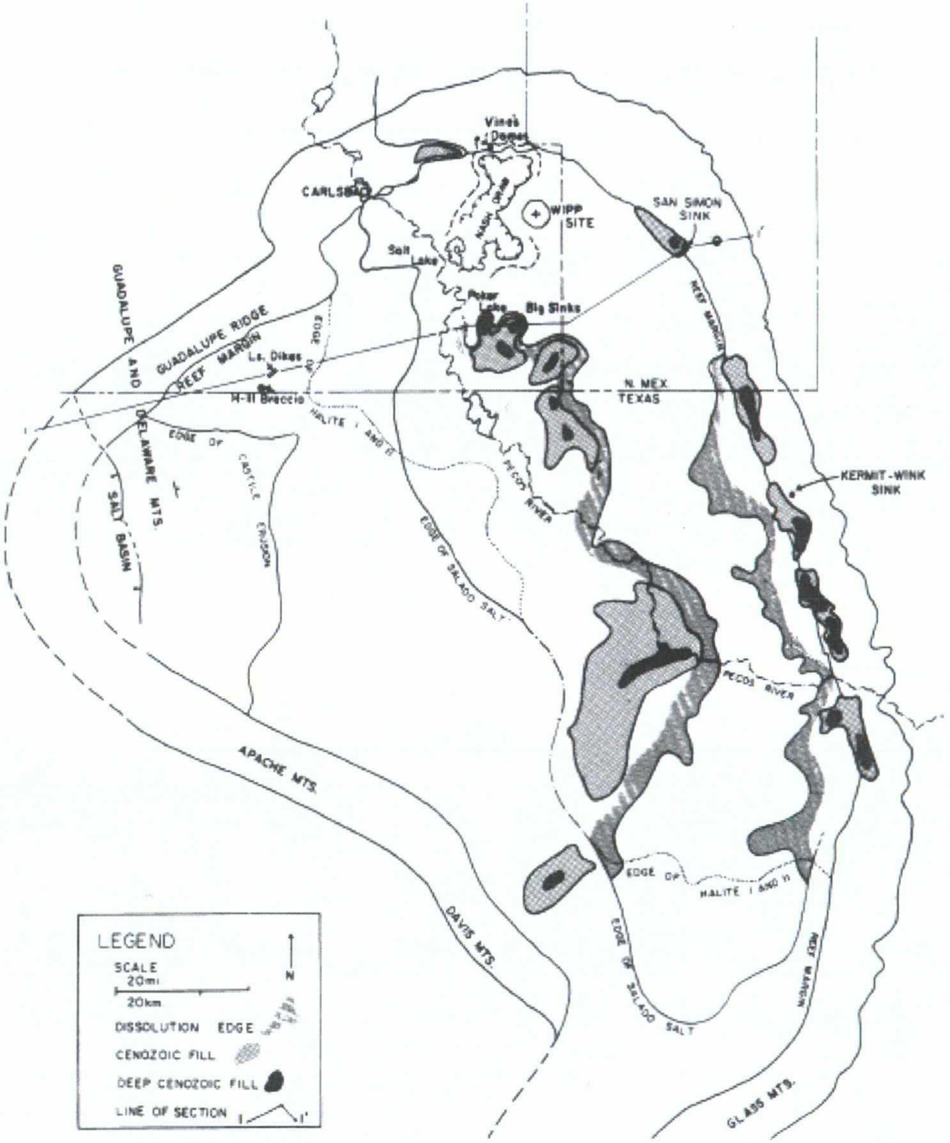


Figure 2. Map of Delaware Basin showing location of Capitan reef, major dissolution depressions, and western dissolution edge of evaporites and of major salt units.

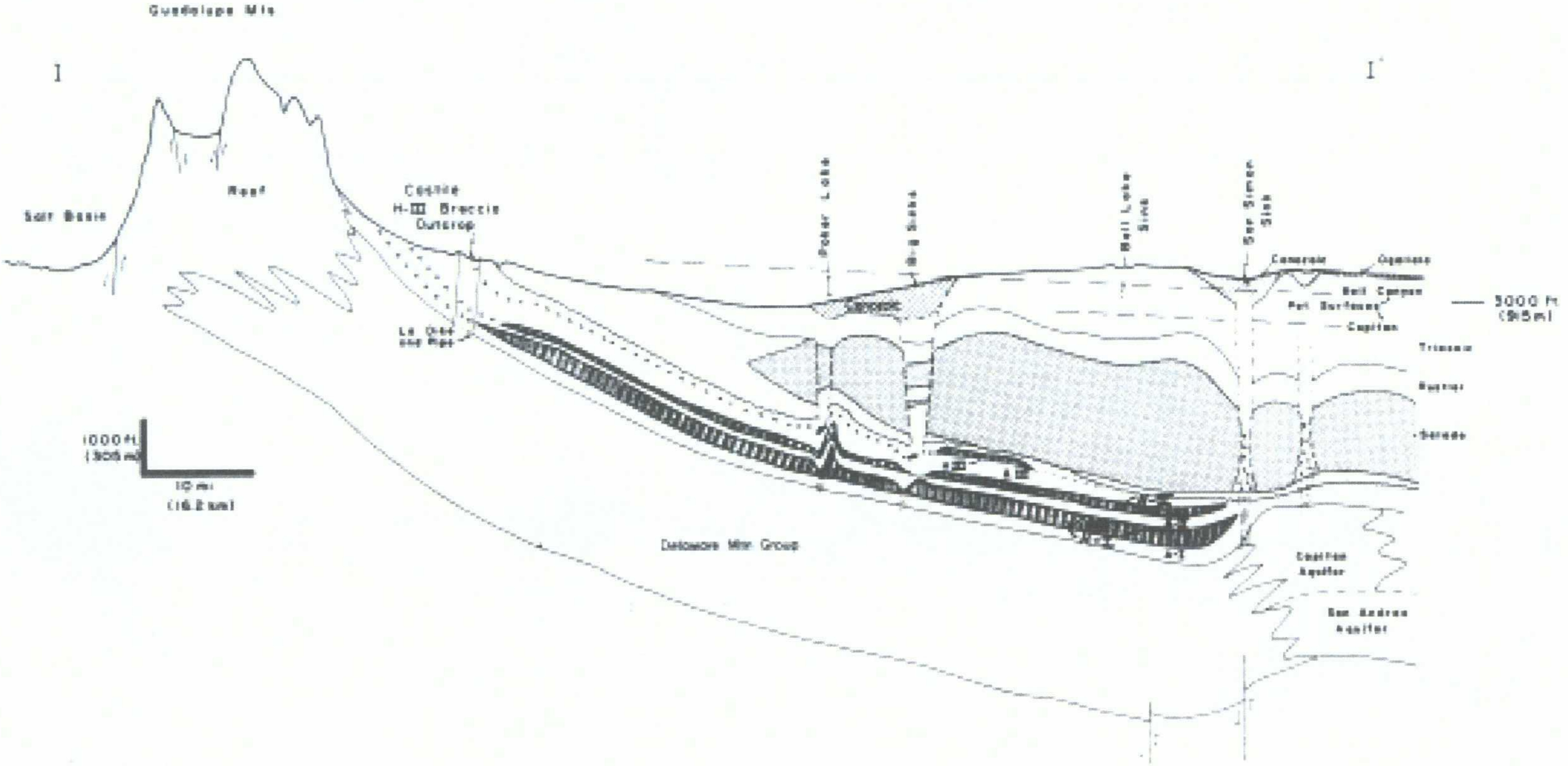
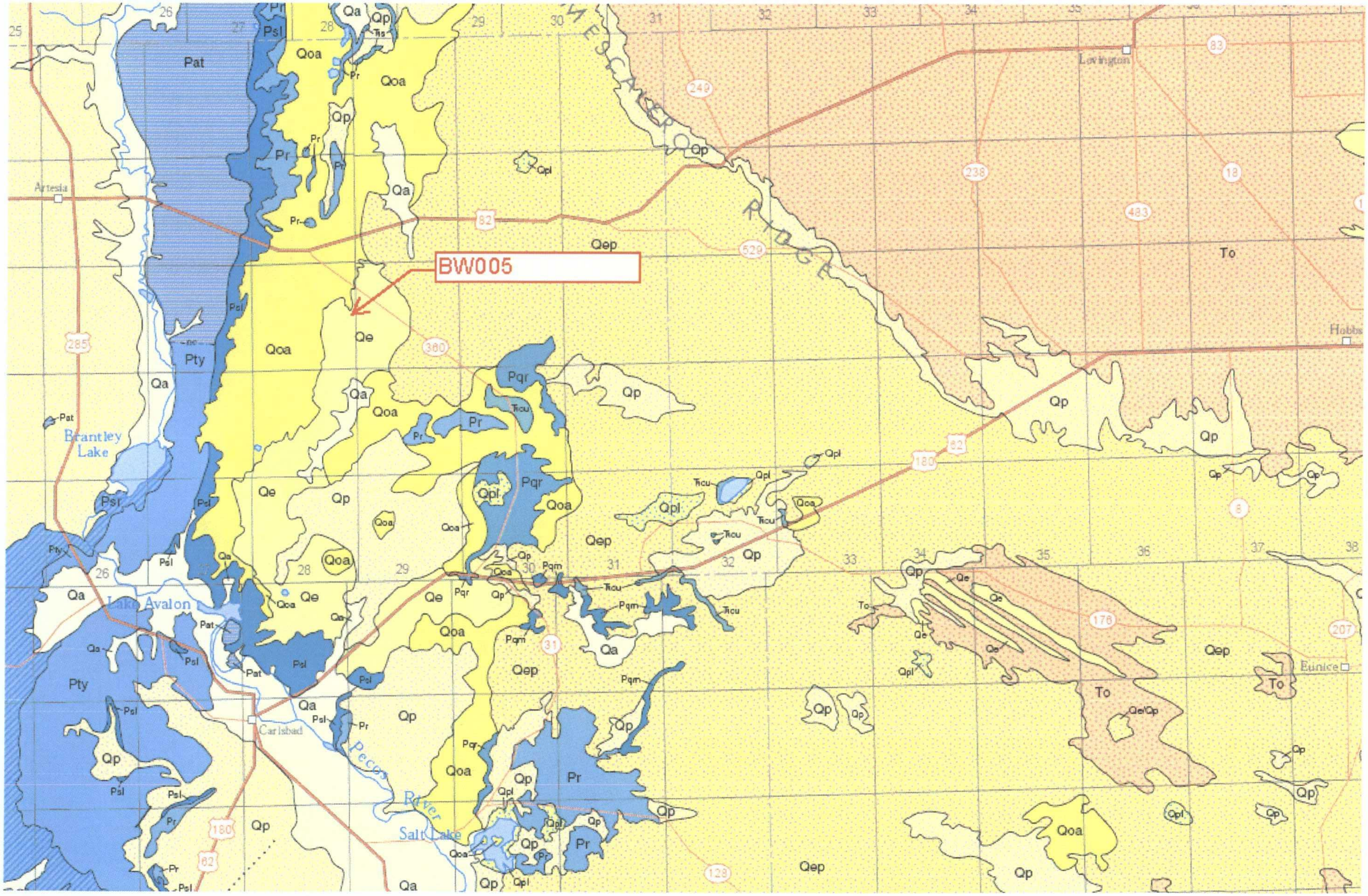
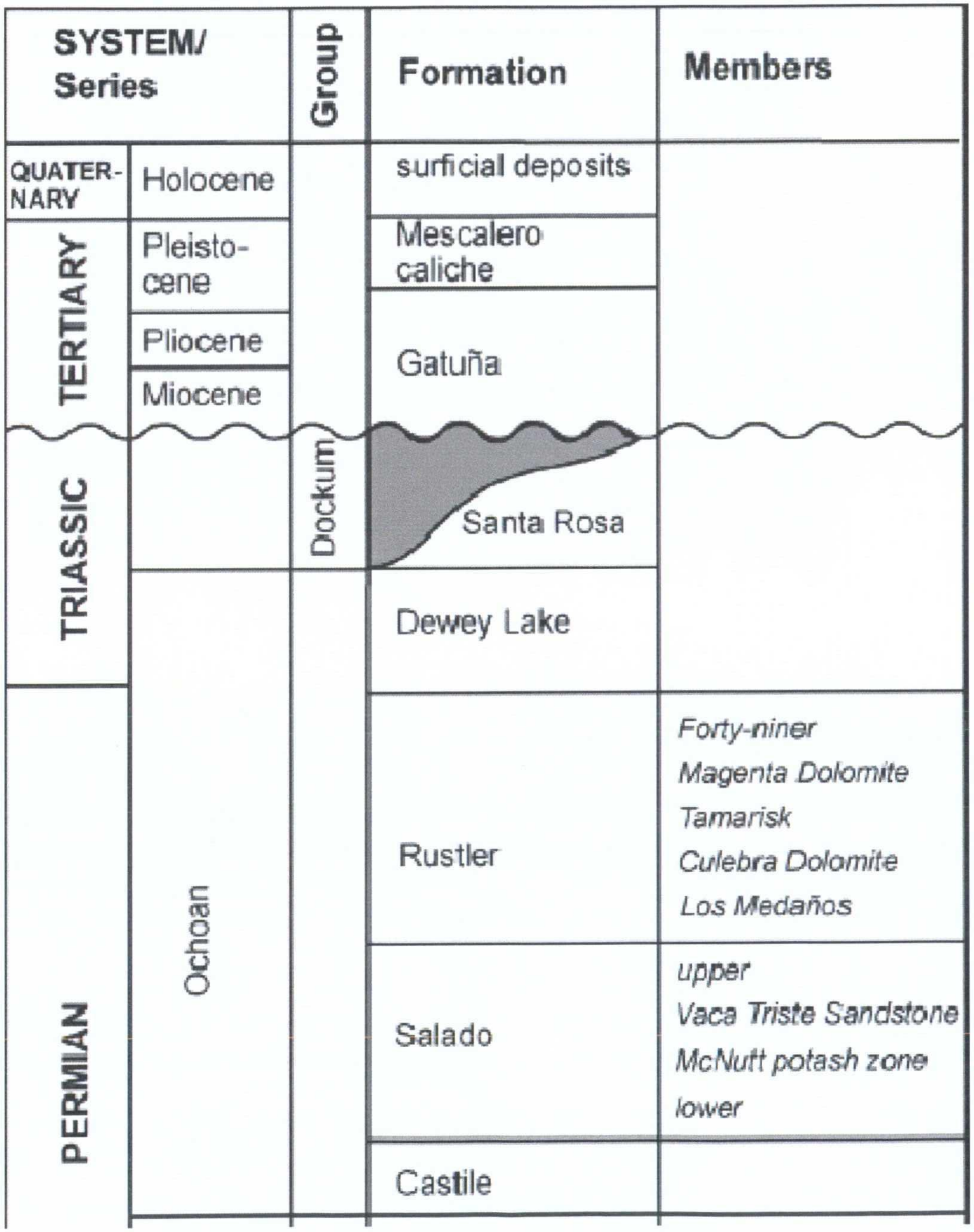


Figure 4. Diagrammatic cross section across Delaware Basin showing approximate thickness of major stratigraphic units and position of potentiometric surfaces (pot. surface) for the Bell Canyon and Capitan aquifers (line of section I-I' in Figure 2); modified from Hiss (1975).


BW005
Artesia
Brantley Lake
Lake Avalon
Carlsbad
Pecos River
Salt Lake
Lovington
Hobbs
Eunice
MESCALERO RIDGE
Pat
Pty
Psl
Pr
Qa
Qoa
Qe
Qp
Qpl
Qep
Pqr
Pqm
Ticu
To
Qe/Qp
285
82
380
529
249
238
483
18
83
180
62
31
176
128
8
207
25
26
27
28
29
30
31
32
33
34
35
36
37
38

Qe	Eolian deposits (Holocene to middle Pleistocene)	
Qoa	Older alluvial deposits of upland plains and piedmont areas, and calcic soils and eolian cover sediments of High Plains region (middle to lower Pleistocene)—Includes scattered lacustrine, playa, and alluvial deposits of the Tahoka, Double Tanks, Tule, Blackwater Draw, and Gatuña Formations, the latter of which may be Pliocene at base; outcrops, however, are basically of Quaternary deposits	
To	Ogallala Formation (lower Pliocene to middle Miocene)—Alluvial and eolian deposits, and petrocalcic soils of the southern High Plains. Locally includes Qoa	
TRs	**Santa Rosa Formation** (Carnian)–Includes Moenkopi Formation (Middle Triassic) at base in most areas	Dockum Fm.
TRcu	**Upper Chinle Group, Garita Creek through Redonda Formations, undivided**	
Pqm	**Quartermaster Formation** (Upper Permian)–Red sandstone and siltstone	
Pqr	**Quartermaster and Rustler Formations** (Upper Permian)	Dewey Lake Redbeds
Pr	**Rustler Formation** (Upper Permian)–Siltstone, gypsum, sandstone, and dolomite	
Psl	**Salado Formation** (Upper Permian)– Evaporite sequence, dominantly halite	
Pc	**Castile Formation** (Upper Permian) – Dominantly anhydrite sequence	
Pat	**Artesia Group** (Guadalupian)–Shelf facies forming broad south-southeast trending outcrop from Glorieta to Artesia area; includes Tansill, Yates, Seven Rivers, Queen and Grayburg Formations (Guadalupian). May locally include Moenkopi Formation (Triassic) at top	



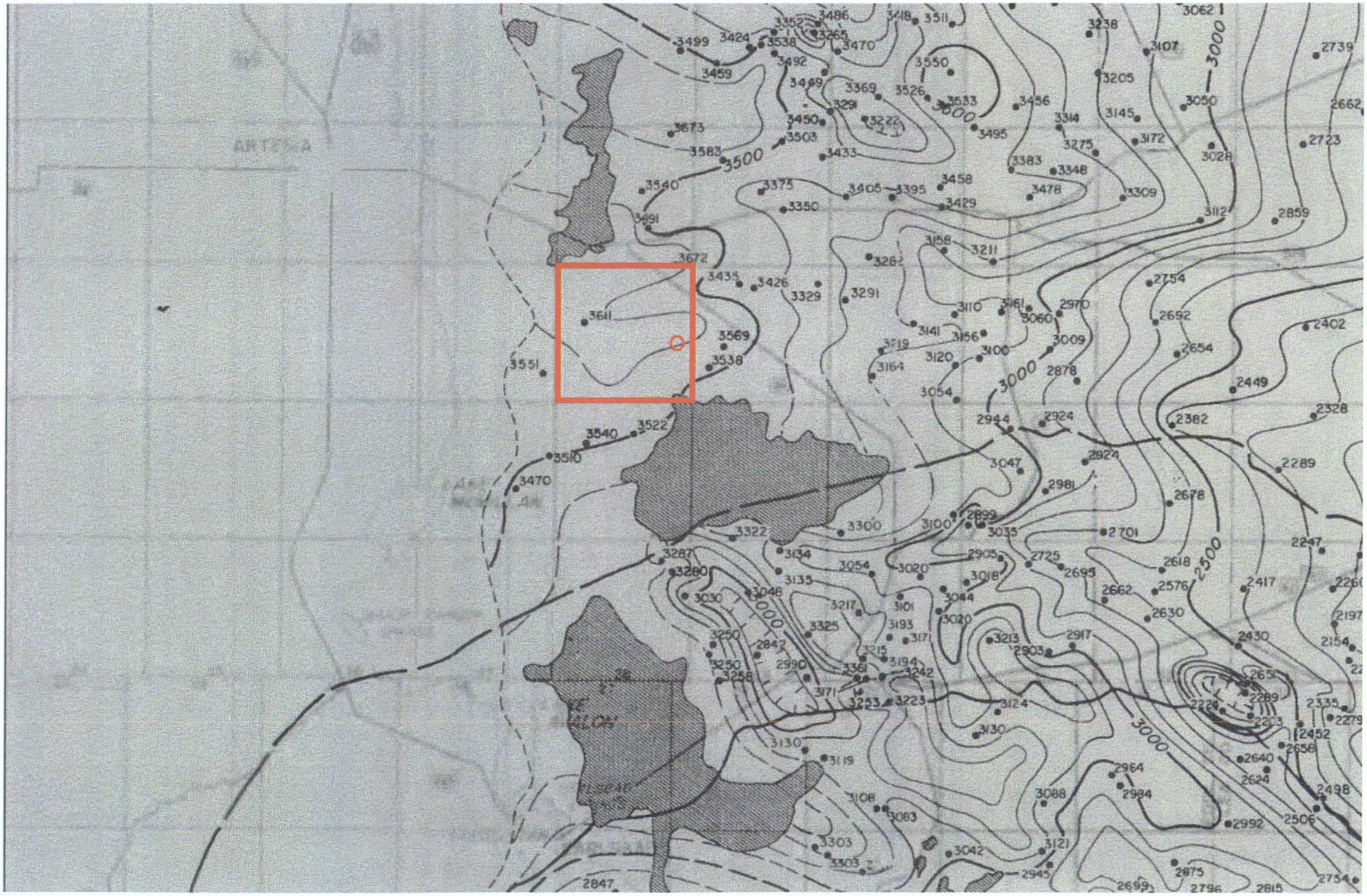
SYSTEM/ Series		Group	Formation	Members
QUATER-NARY	Holocene		surficial deposits	
TERTIARY	Pleistocene		Mescalero caliche	
	Pliocene		Gatuña	
	Miocene			
TRIASSIC		Dockum	Santa Rosa	
	Ochoan		Dewey Lake	
PERMIAN			Rustler	*Forty-niner* *Magenta Dolomite* *Tamarisk* *Culebra Dolomite* *Los Medaños*
			Salado	*upper* *Vaca Triste Sandstone* *McNutt potash zone* *lower*
			Castile	

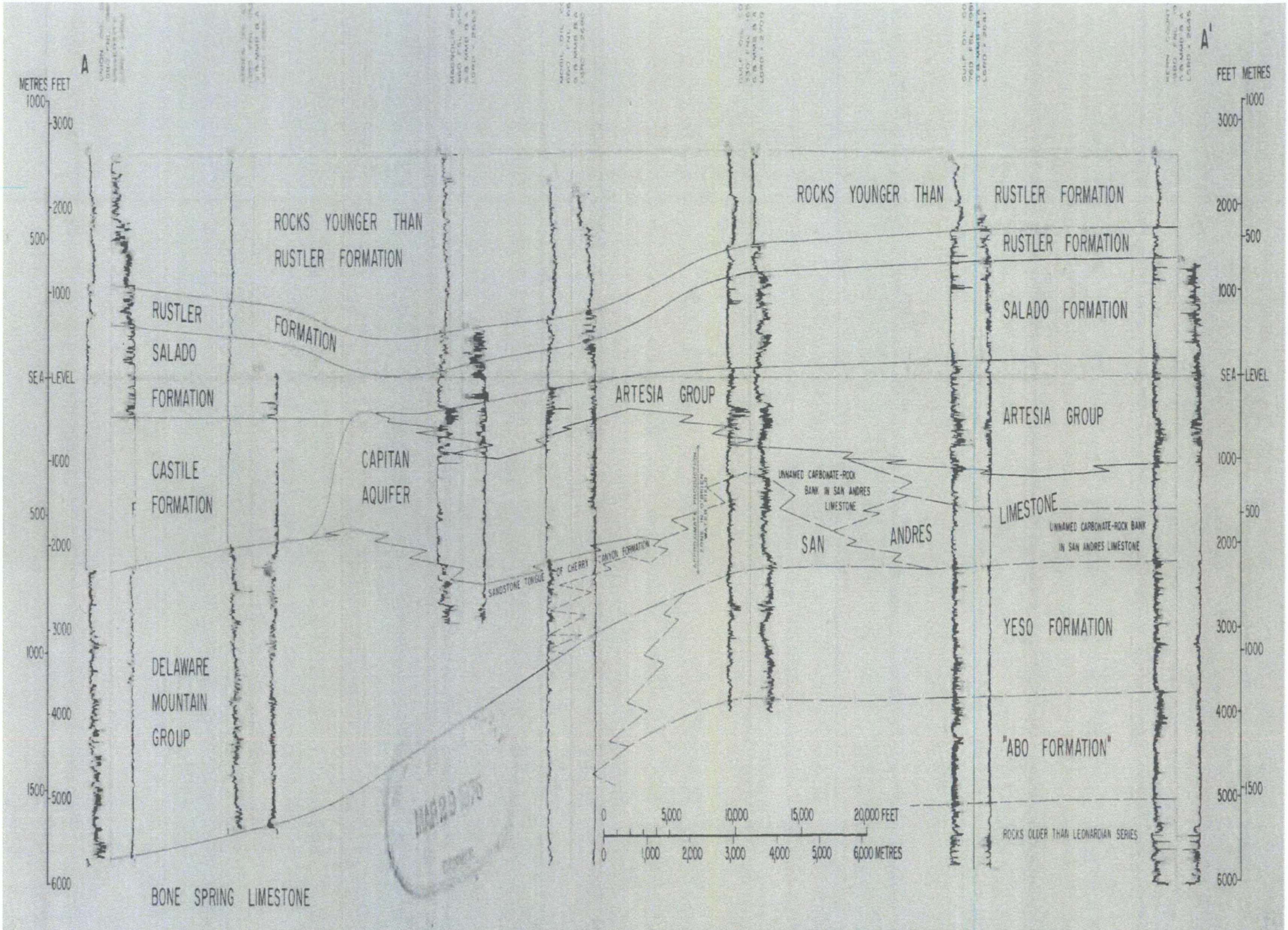
Table 1. Summary of rock units of Permian (Ochoan and Guadalupian) and younger age, Eddy and Lea Counties, New Mexico (from Mercer and Orr, 1977).

Age		Rock Unit		Thickness (meters)	Description
Quaternary	Holocene	Sand of Mescalero surface		0-4.6	Dune sand, uniformly fine-grained, light-brown to reddish-brown
					UNCONFORMITY
		Alluvium		0-91	Sand, silt, and conglomerate
		Caliche		0-1.5	Limestone, chalky, includes fragments of underlying rock
					UNCONFORMITY
	Pleistocene	Gatuna Formation		0-114	Sandstone and siltstone, poorly indurated, dominantly reddish-orange
					UNCONFORMITY
Tertiary	Miocene	Ogallala Formation		7.6-53	Sandstone, fine- to medium-grained, tan, pink, and gray, locally conglomeratic and typically has resistant cap of well-indurated caliche
					UNCONFORMITY
Triassic	Late Triassic	Chinle Formation		0-244	Mudstone, shaly, reddish-brown and greenish-gray, interbedded lenses of conglomerate, and gray and reddish-brown sandstone
		Santa Rosa Sandstone		42.7-91	Sandstone, medium- to coarse-grained, commonly cross-stratified, gray and yellowish-brown, contains conglomerate and reddish-brown sandstone
					UNCONFORMITY
Permian	Ochoan	Dewey Lake Red Beds		61-183	Siltstone and sandstone, very fine- to fine-grained, reddish-orange to reddish-brown, contains interbedded reddish-brown claystone, small-scale lamination and cross-stratification common
					UNCONFORMITY
		Rustler Formation		61-183	Anhydrite and rock salt with subordinate dolomite, sandstone, claystone, and polyhalite
		Salado Formation		442-632	Rock salt with subordinate anhydrite, polyhalite, potassium ores, sandstone, and magnesite
		Castile Formation		396-610	Anhydrite and rock salt with subordinate limestone
	Guadalupian	Delaware Mountain Group	Capitan Limestone	488 ±	Limestone, massive, with dolomitized reef breccia
			Bell Canyon Formation	305 ±	Sandstone, gray and brown, with limestone and minor shale
			Cherry Canyon Formation	305 ±	Sandstone, gray and brown, with limestone and minor shale
			Brushy Canyon Formation	305 ±	Sandstone, gray, with brown and black shale and brown limestone

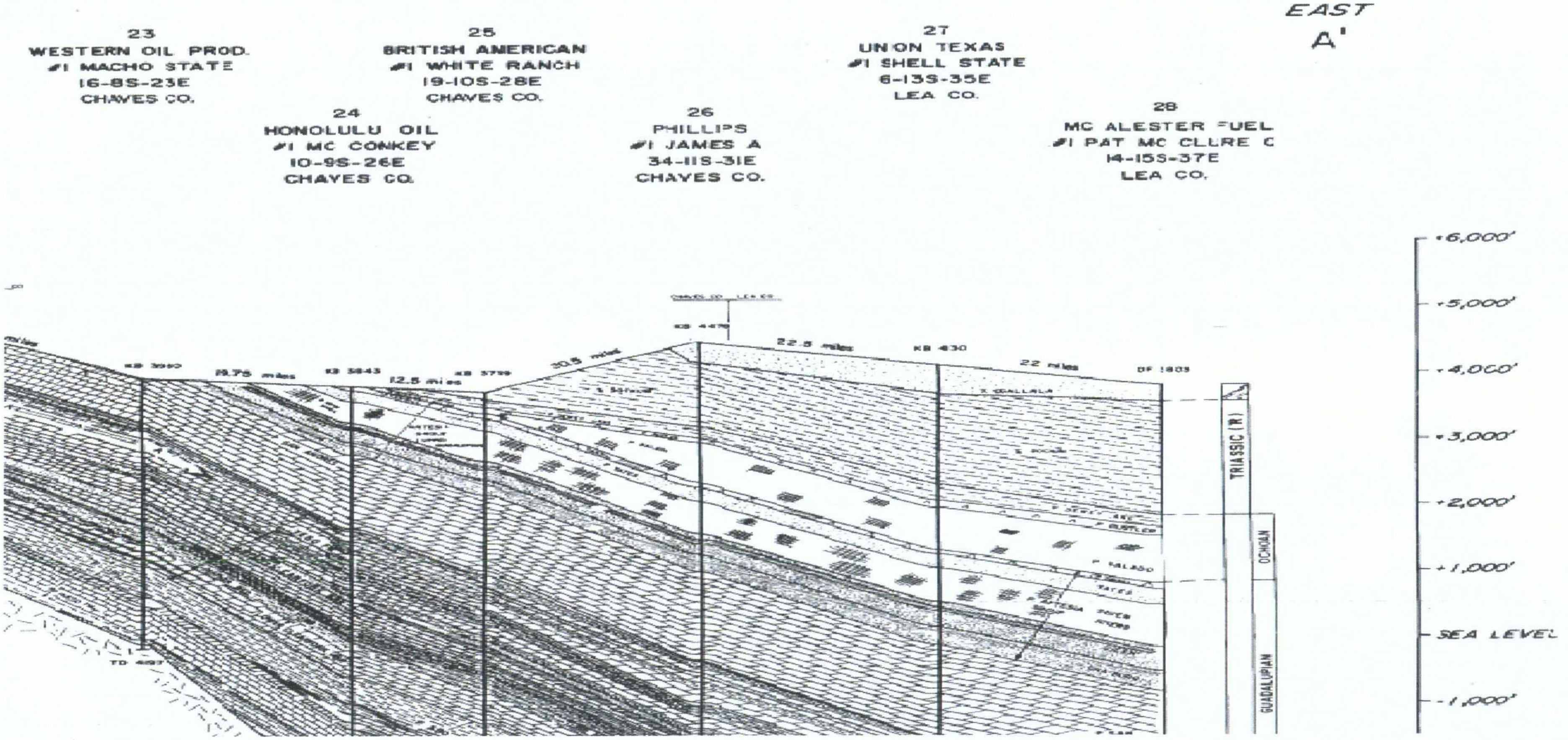
New Mexico Geological Society, Special Publication No. 10, 1981, pp. 133–145.

TOP OF RUSTLER FORMATION

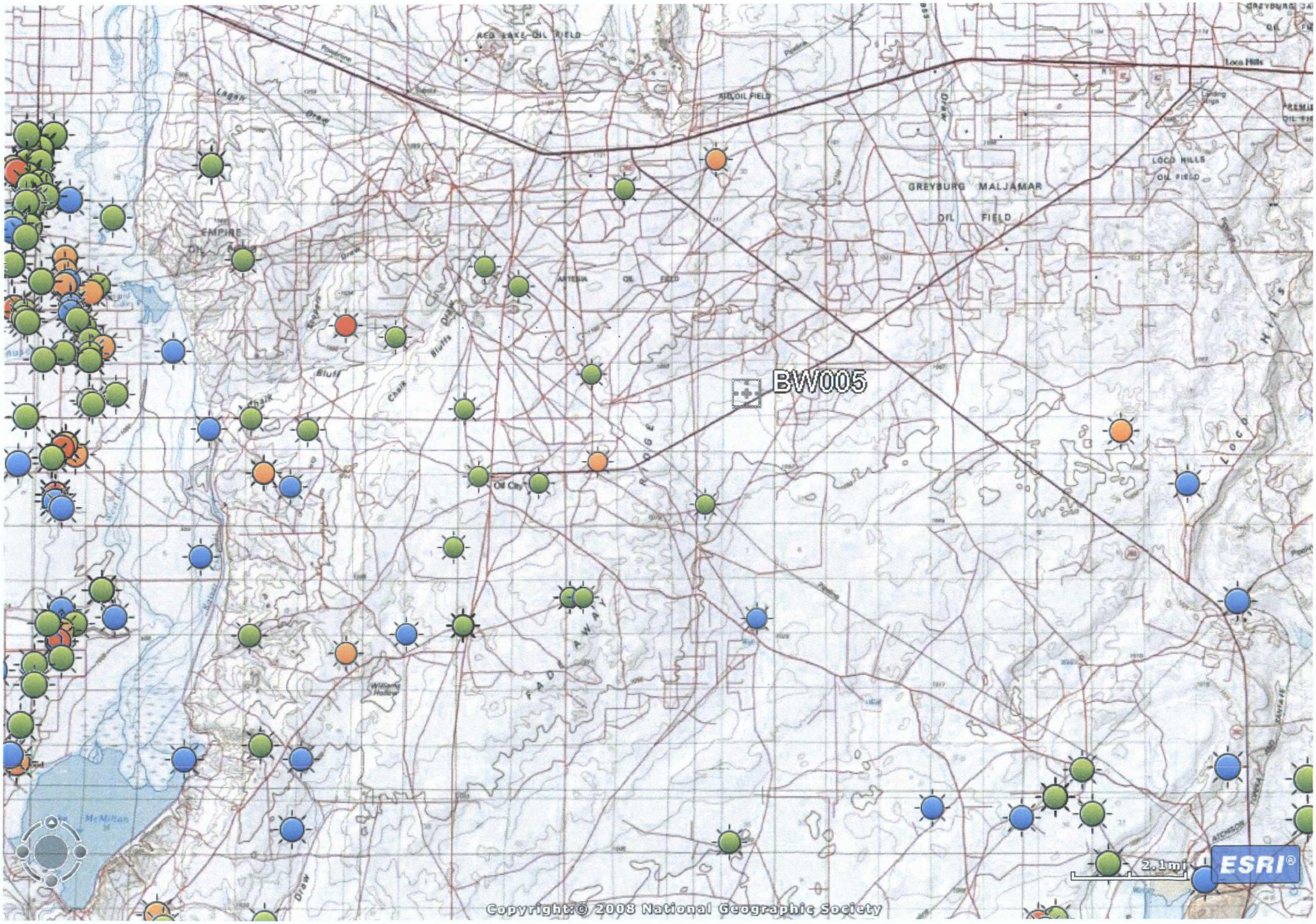




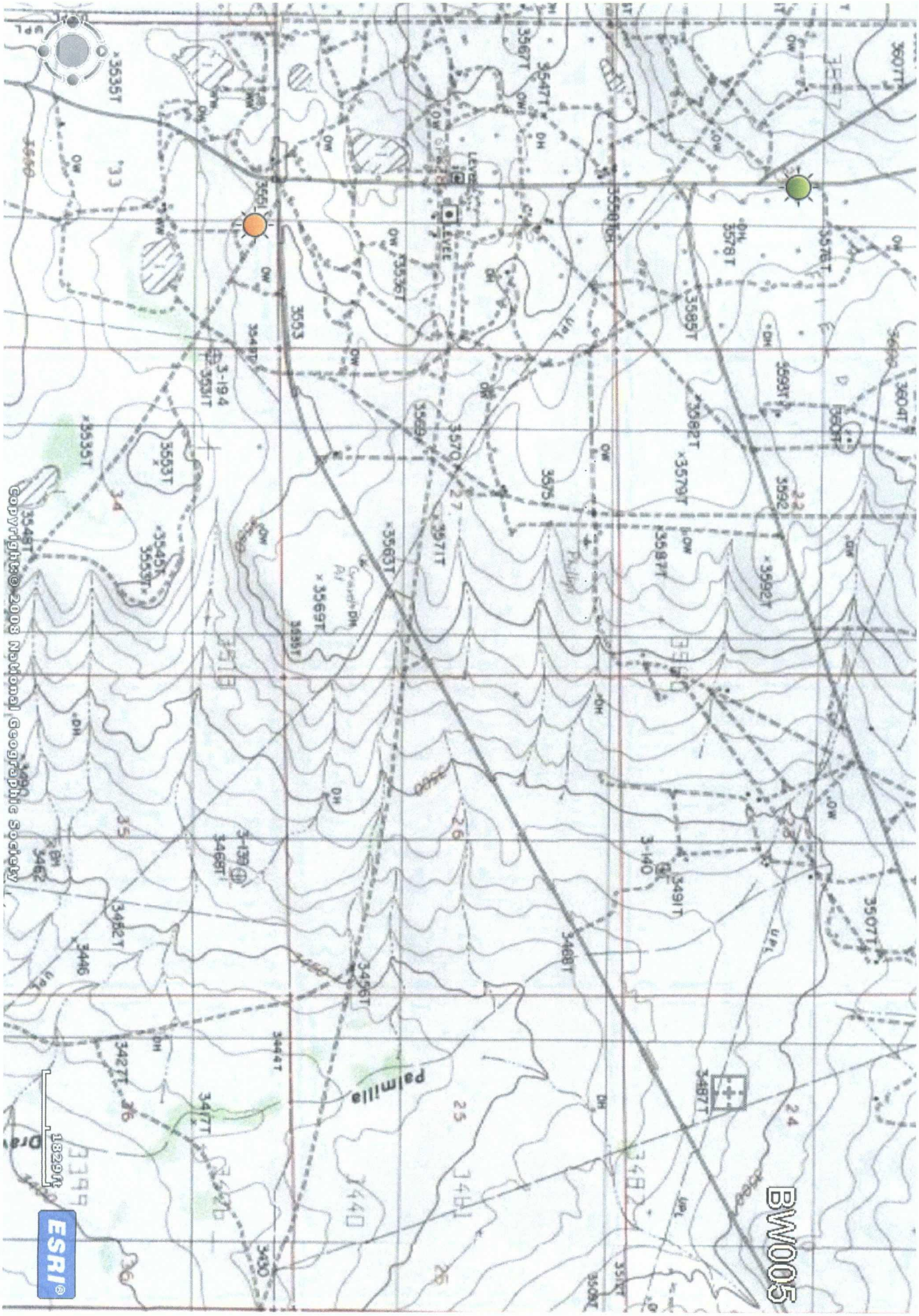
TRANSVERSE STRATIGRAPHIC SECTION A-A' SHOWING THE POSITION OF THE CAPITAN AQUIFER ALONG THE EAST MARGIN OF THE DELAWARE BASIN


EAST
A'
23
WESTERN OIL PROD.
#1 MACHO STATE
16-8S-23E
CHAVES CO.
24
HONOLULU OIL
#1 MC CONKEY
10-9S-26E
CHAVES CO.
25
BRITISH AMERICAN
#1 WHITE RANCH
19-10S-28E
CHAVES CO.
26
PHILLIPS
#1 JAMES A
34-11S-31E
CHAVES CO.
27
UNION TEXAS
#1 SHELL STATE
6-13S-35E
LEA CO.
28
MC ALESTER FUEL
#1 PAT MC CLURE C
14-15S-37E
LEA CO.
KB 3990
19.75 miles
KB 3843
12.5 miles
KB 3799
30.5 miles
CHAVES CO. LEA CO.
KB 4479
22.5 miles
KB 4030
22 miles
DF 3803
OGALLALA
SALADO
YATES
ARTESIA
TRIASSIC (R)
OCHOAN
GUADALUPIAN
+6,000'
+5,000'
+4,000'
+3,000'
+2,000'
+1,000'
SEA LEVEL
-1,000'

PROTECTABLE GROUND WATER



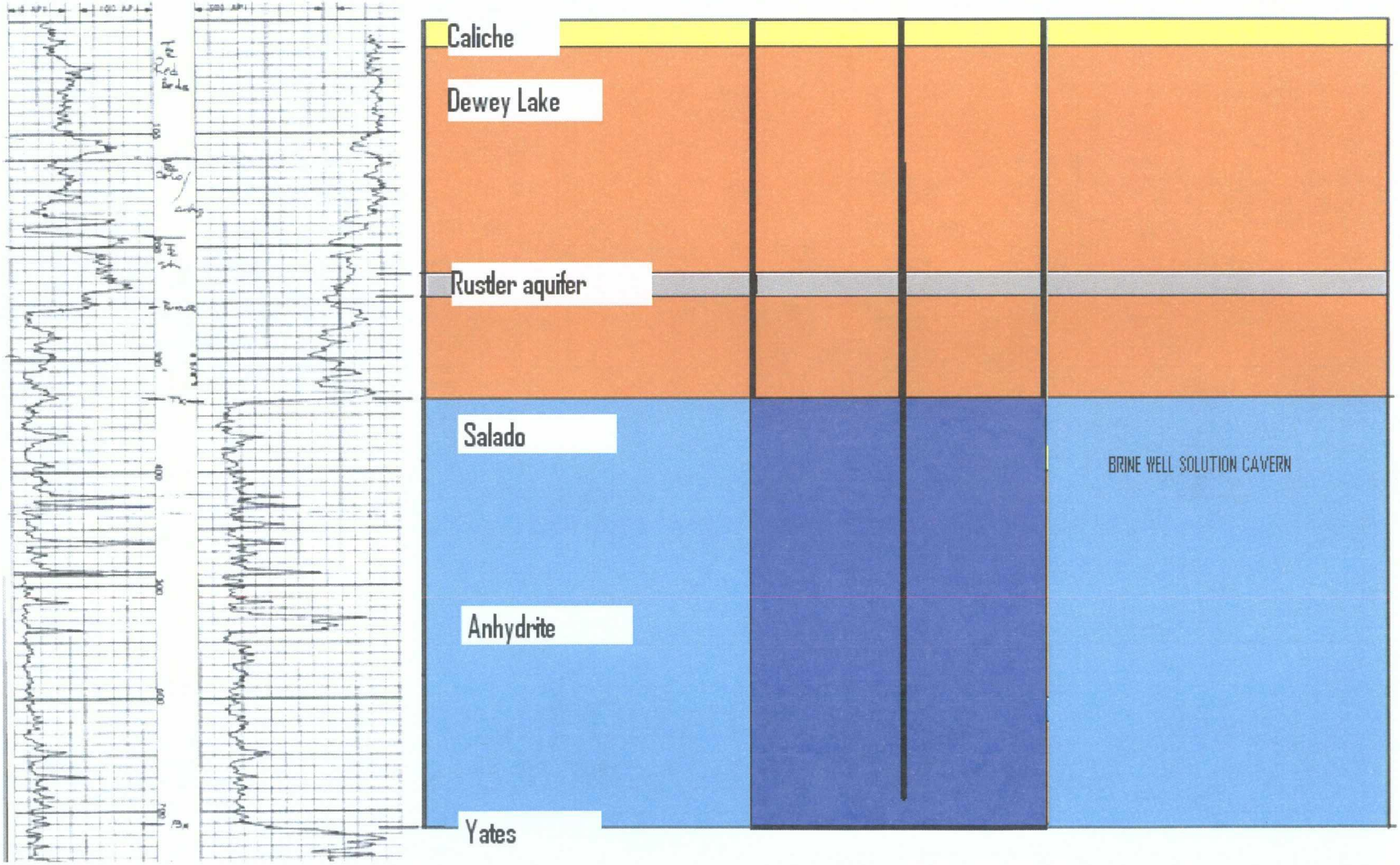
RED LAKE OIL FIELD
AID OIL FIELD
EMPIRE
OIL
ARTESIA OIL FIELD
GREYBURG MALJAMAR
OIL FIELD
LOCO HILLS
OIL FIELD
Loco Hills
Logan Draw
Chalk Bluffs Draw
Bluff
Chalk
Oil City
RIDGE
FADEAWAY
LOCO HILLS
Willow Hollow
McMillan
Draw
BW005
2.1mi
ESRI®
Copyright:© 2008 National Geographic Society



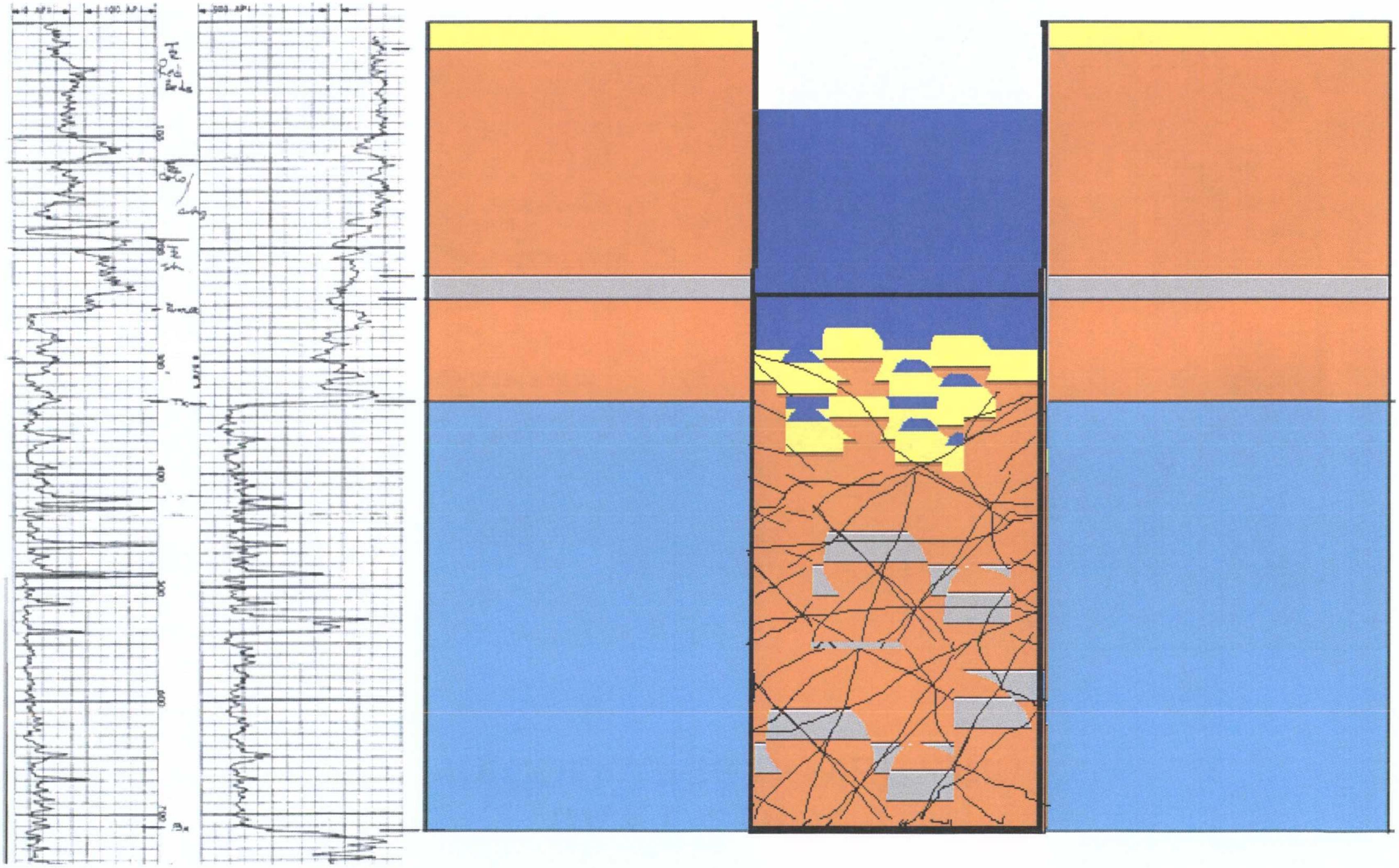
BW005

INTERIM MODEL FOR BW005 COLLAPSE

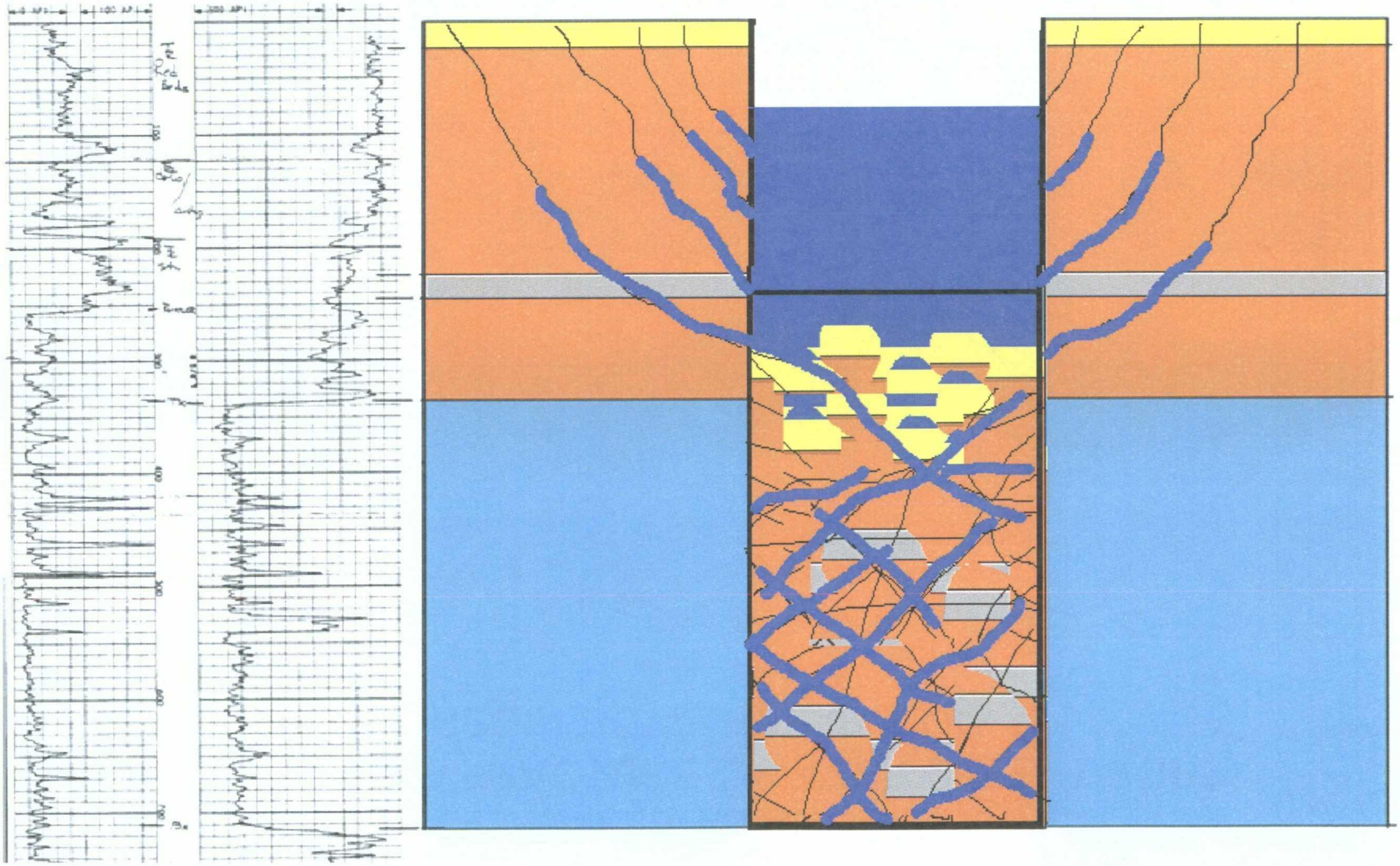
DAY 1: STAGE 0
PRECOLLAPSE CONDITIONS



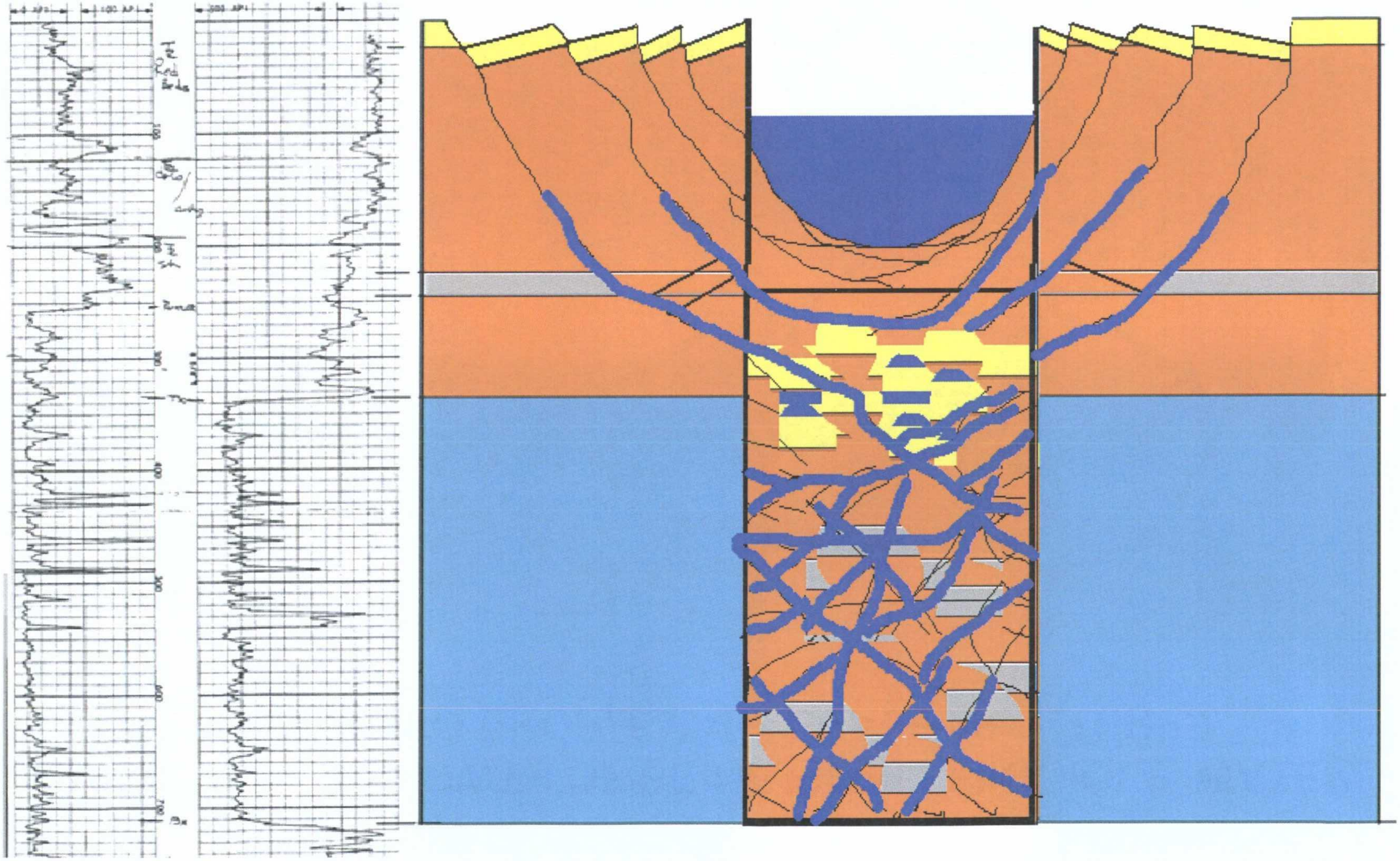
DAY 1 – JULY 16, 2008: STAGE 1
CATASTROPHIC VERTICAL COLLAPSE
BRINE FILLED SINKHOLE



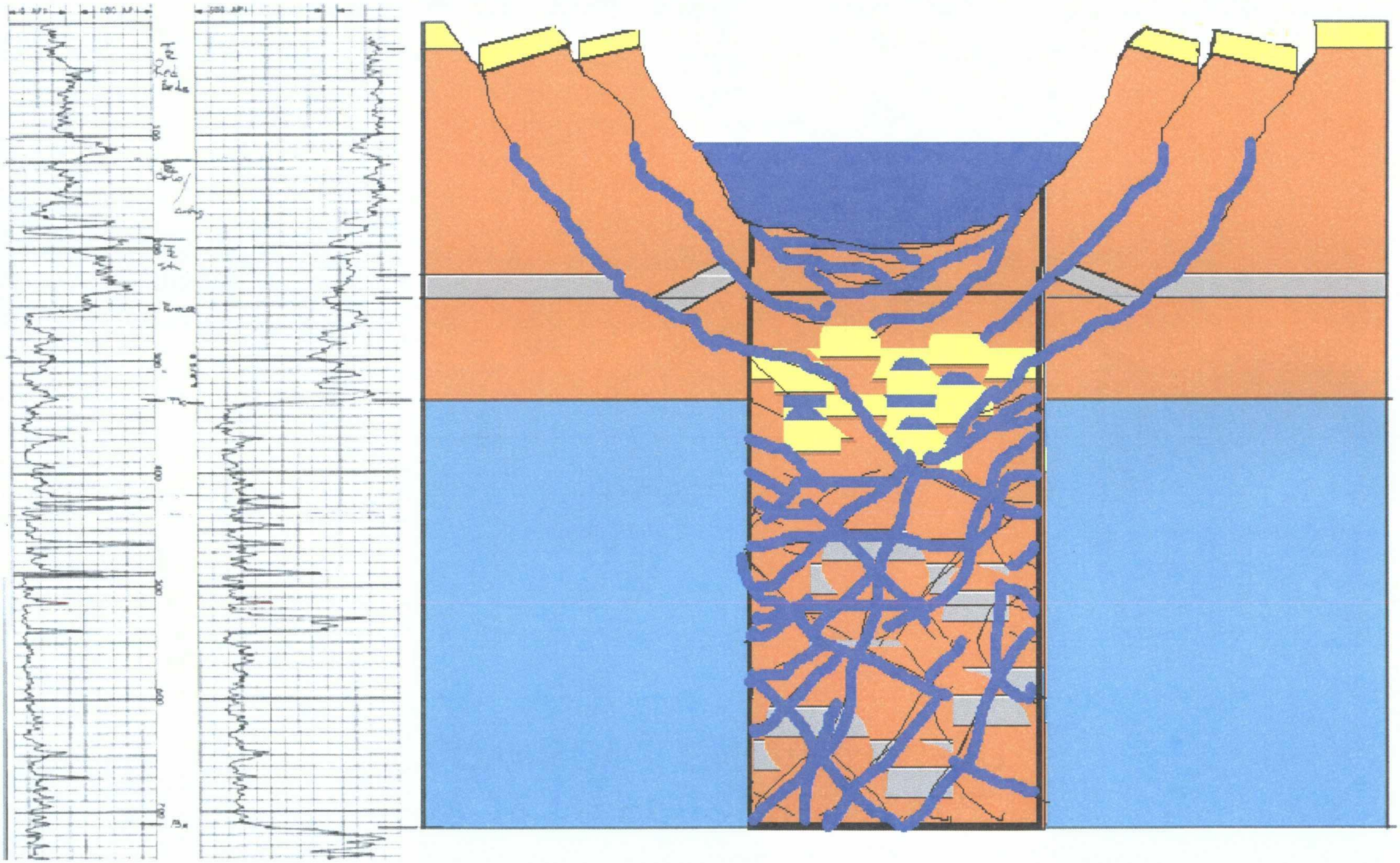
DAY 8 – JULY 24, 2008: STAGE 2
CONTINUED GROWTH OF BRINE FILLED SINKHOLE, WATER BEGINS TO DROP, SMALL SCALE FRACTURES



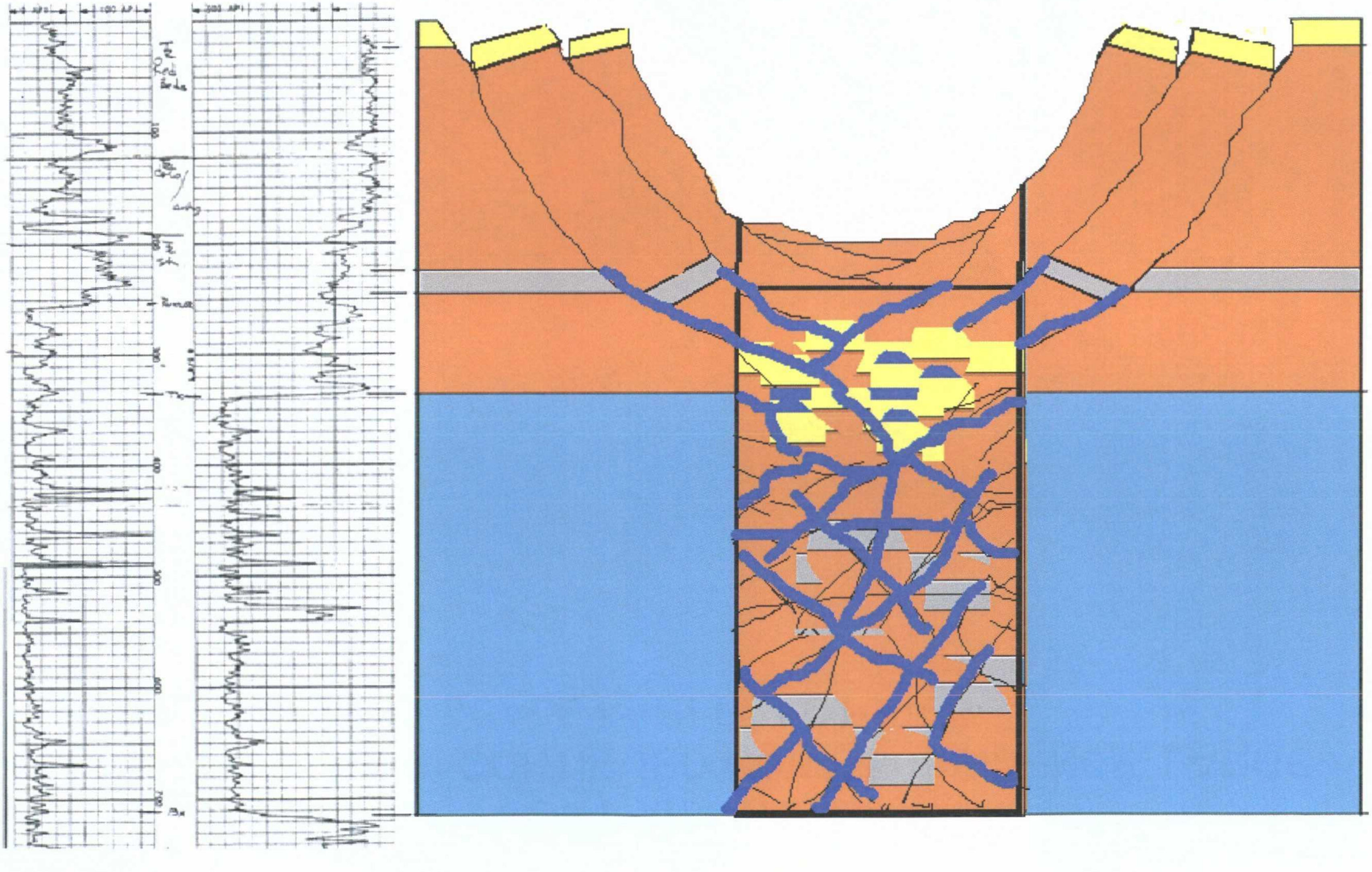
DAY 10: STAGE 3
MAJOR RING FRACTURES, WATER LEVEL DROPS, BEGIN BOWL FORMATION



DAY 11: STAGE 4
WATER DRAINS, CONTINUED BOWL SUBSIDENCE, LARGE SCALE RING FRACTURES



DAY 12 TO PRESENT: STAGE 5
SLOW BOWL ENLARGEMENT



HISTORY OF BRINE WELL
OPERATIONS & REGULATION
IN NEW MEXICO

A quick word about units…

1 barrel (bbl) = 42 gallons (159 liters) = 5.6 ft^3 (0.159 m^3)

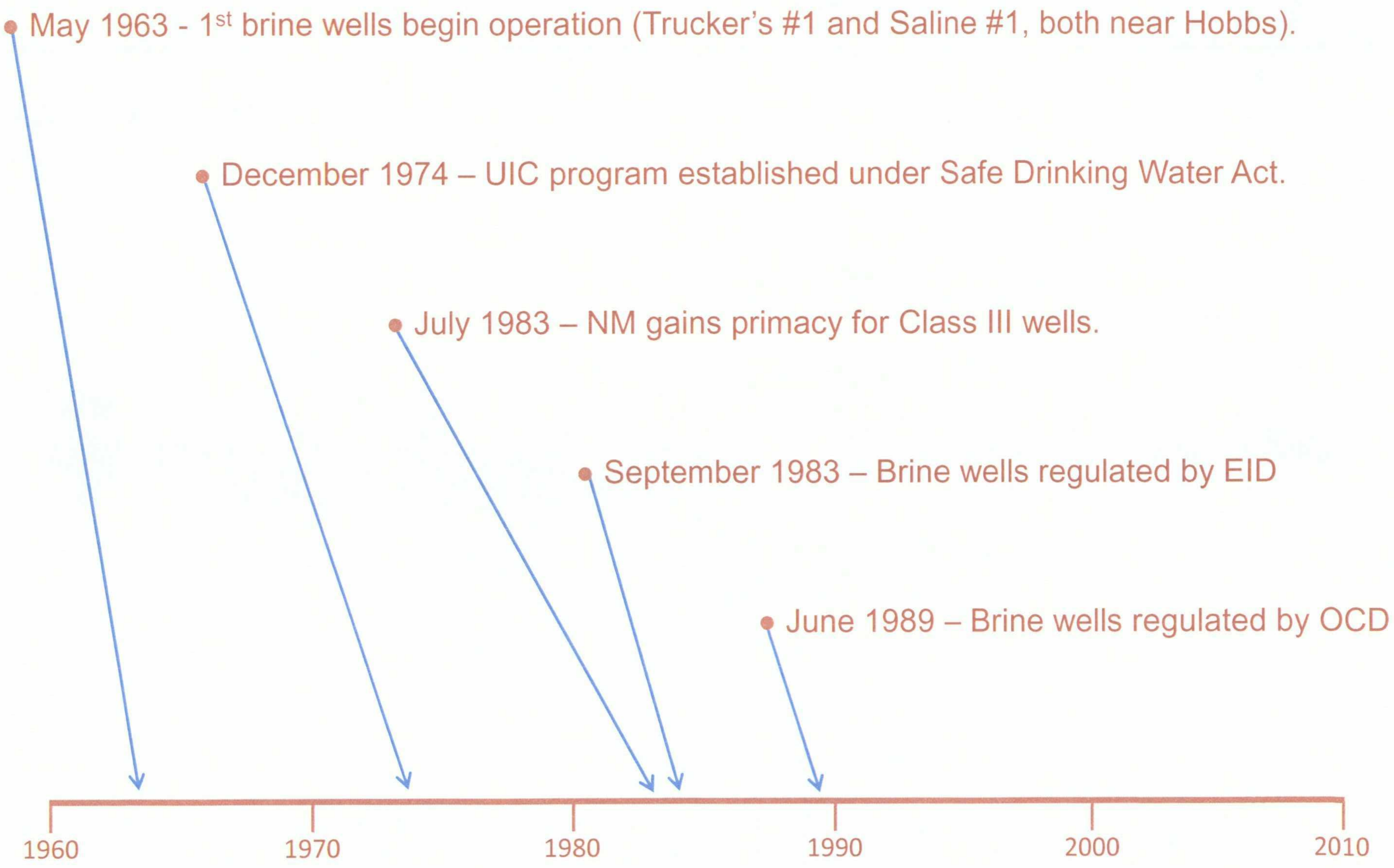
Use of the phrase “10 pound brine”

Refers to a saltwater density of 10 lbs/gallon

Uses for Brine in the Oil & Gas Industry

- Additive to drilling mud to provide weight and minimize borehole dissolution (washouts) when drilling thru salt-rich lithology

- “Kill” fluid used during workover activities to mitigate downhole pressures



May 1963 - 1st brine wells begin operation (Trucker's #1 and Saline #1, both near Hobbs).

December 1974 – UIC program established under Safe Drinking Water Act.

July 1983 – NM gains primacy for Class III wells.

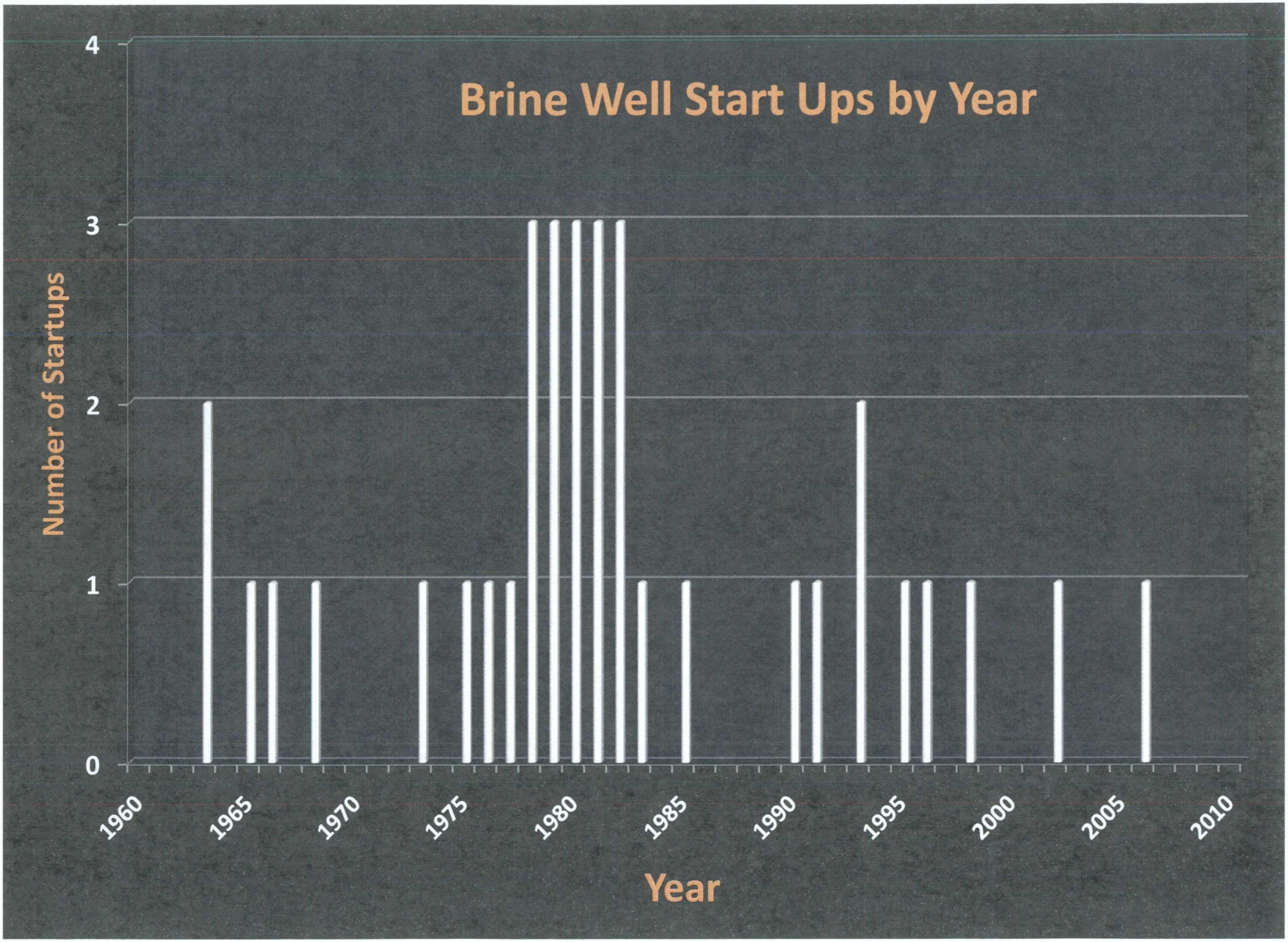
September 1983 – Brine wells regulated by EID

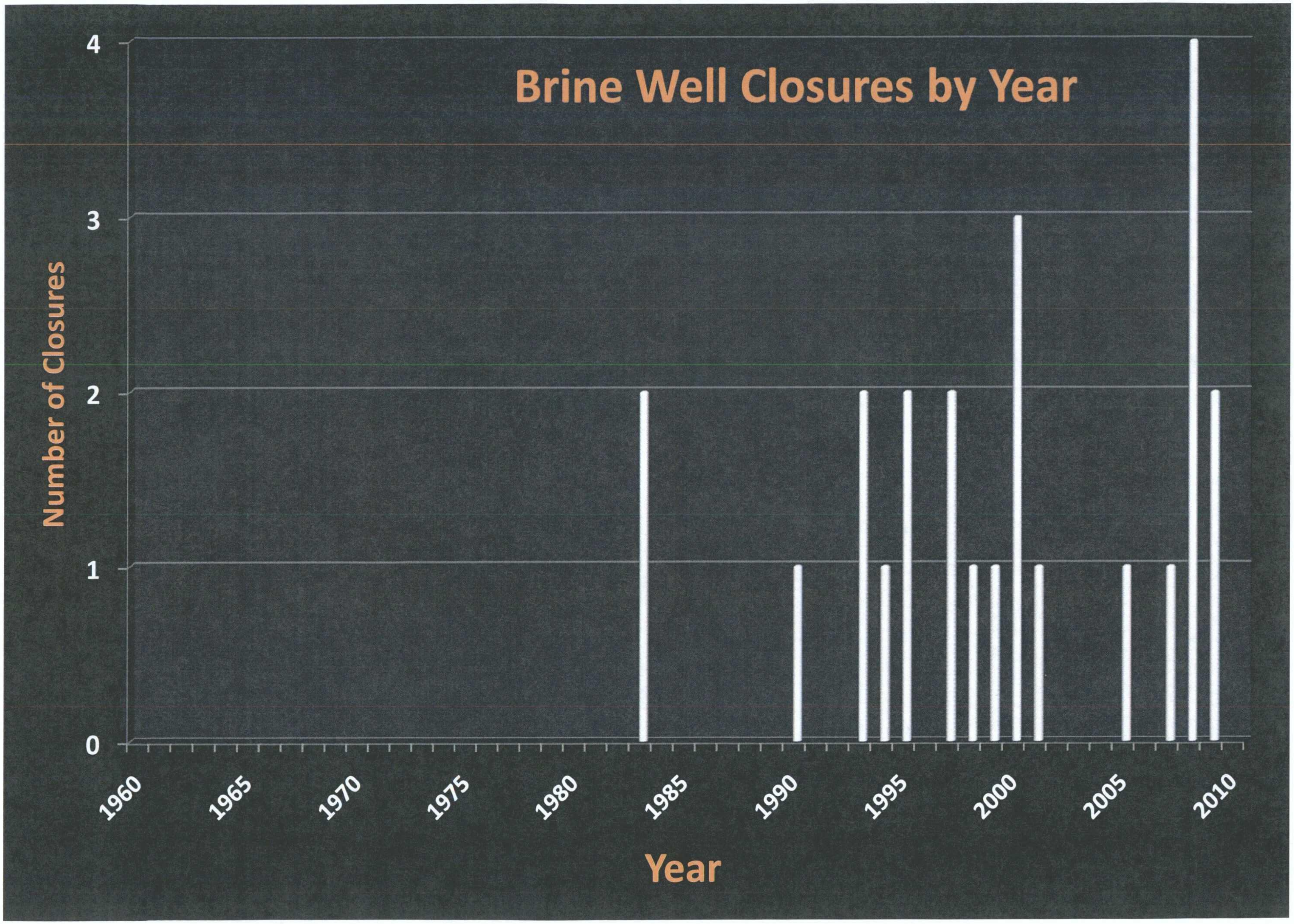
June 1989 – Brine wells regulated by OCD

Discharge permits are issued for brine operations under provisions of the NM Water Quality Act in conjunction with the Oil & Gas Act with conditions focused toward the protection of ground and surface waters with a TDS of <10,000 mg/l.

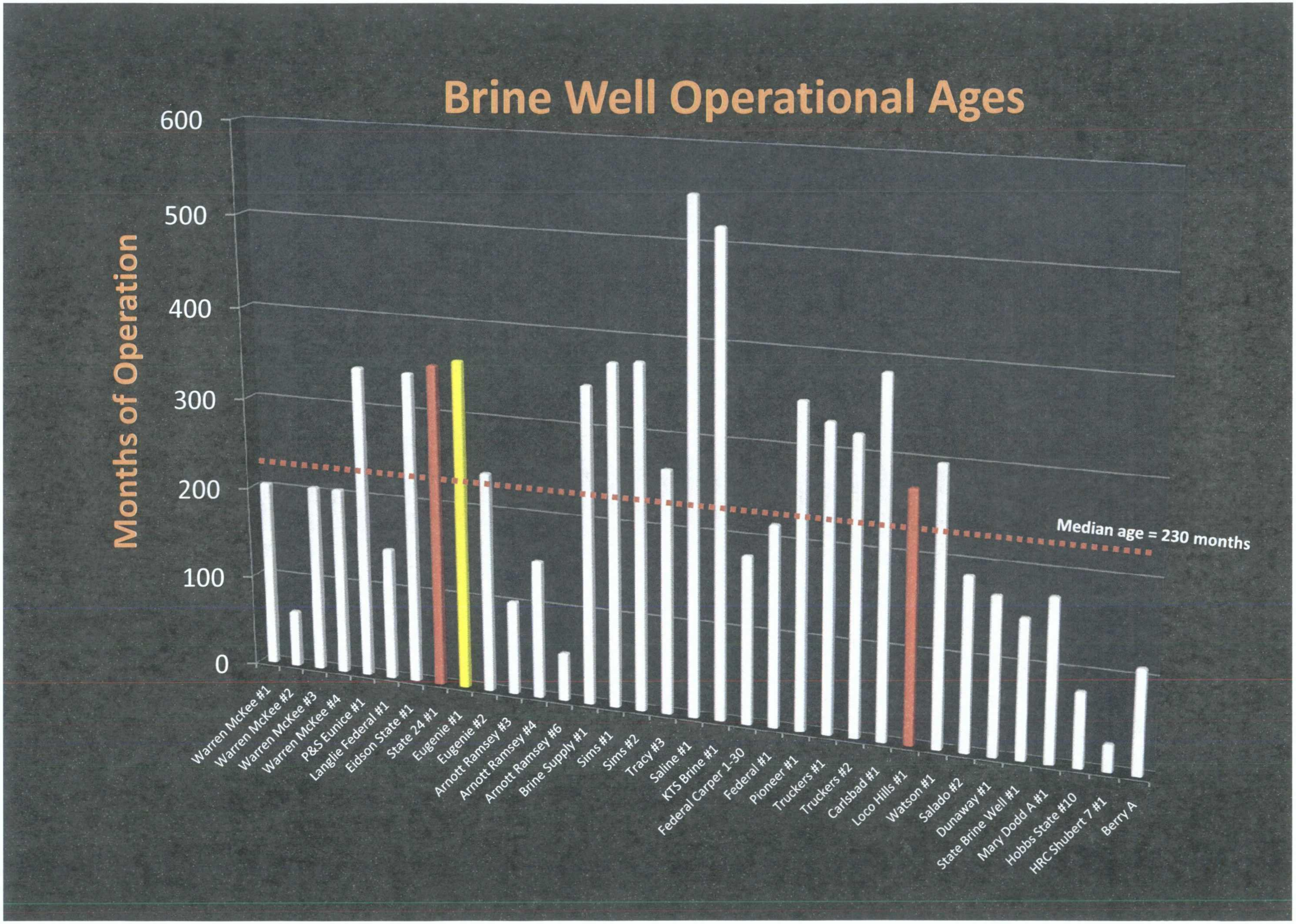
OCD Permit	EID Permit	Most Recent Operator	Well Name	API#	ULSTR	Latitude (deg)	Longitude (deg)	County	Nearest Town	Distance (miles)	Private, State, or Federal Land?	1 or 2 Well Operation?	New Well or Re-entry?	Original Well Name	Current Status	Start Date	End Date	Duration of Operation (months)	Depth to fresh water (ft bgs)
BW-1	DP-318	Conoco	Warren McKee #1	30-025-25836	M-2-20S-38E	32.596863	-103.126668	Lea	Nadine	1	State	1	New		Plugged	2/26/78	3/14/95	205	
			Warren McKee #2	30-025-30707	N-2-20S-38E	32.596712	-103.121413	Lea			State	1	New		Plugged	1/26/90	3/15/95	62	
			Warren McKee #3	30-025-32745	M-2-20S-38E	32.595812	-103.126480	Lea			State	1	New		Plugged	12/1/82	1/24/00	206	
			Warren McKee #4	30-025-32746	N-2-20S-38E	32.595812	-103.121794	Lea			State	1	New		Plugged	12/1/82	1/26/00	206	
BW-2	DP-319	Basic Energy	P&S Eunice #1	30-025-26884	O-34-21S-37E	32.429850	-103.150136	Lea	Eunice	0.3	Private	1	New		Active	7/21/80	–	343	45
BW-3	DP-320	Salado Brine Sales	Langlie Federal #1	30-025-35701	P-14-25S-37E	32.123376	-103.127539	Lea	Jal	3	Federal	1	New		Plugged	1/1/81	1/25/93	145	80
BW-4	DP-321	Gandy Corp.	Eidson State #1	30-025-26883	M-31-16S-35E	32.873056	-103.505202	Lea	Lovington	9	State	1	New		Active	8/21/80	–	342	75
BW-5	DP-322	Jim's Water Service	State 24 #1	30-015-02036	J-24-18S-28E	32.731990	-104.127910	Eddy	Loco Hills	10	State	1	Re-entry	Nix & Curtis Gulf State #2	Collapsed	3/1/79	7/16/08	353	225?
BW-6	DP-323	I & W	Eugenie #1	30-015-22574	M-17-22S-27E	32.388128	-104.218116	Eddy	Carlsbad	0	Private	1 and 2	New		Plugged	8/1/78	7/22/08	360	40
			Eugenie #2	30-015-23031	L-17-22S-27E	32.388982	-104.218438	Eddy			Private	2	New		Plugged	11/22/79	1/14/00	241	40
BW-7	DP-324	P & S Brine	Arnott Ramsey #2	--	P-16-25S-37E	32.123542	-103.159885	Lea	Jal	1.5	State	1	Unknown		Plugged	pre-1974	7/7/83		50
			Arnott Ramsey #3	--	P-16-25S-37E	32.123615	-103.160876					1	New		Plugged	1/1/75	7/7/83	103	
			Arnott Ramsey #4	30-025-26999	P-16-25S-37E	32.124492	-103.159655					1	New		Plugged	3/10/81	10/19/93	151	
			Arnott Ramsey #6	30-025-31279	P-16-25S-37E	32.124674	-103.159604					1	New		Plugged	12/28/93	6/8/98	53	
BW-8	DP-325	PAB Services	Brine Supply #1	30-025-26307	J-5-19S-36E	32.688427	-103.374346	Lea	Hobbs	11	Private	1	New		Active	5/7/79	–	346	60
BW-9	DP-326	Key Energy Services	Sims #1	30-025-22727	A-32-21S-37E	32.441954	-103.177186	Lea	Eunice	0		2			Plugged	10/1/68	9/29/97	372	
			Sims #2	30-025-25525	A-32-21S-37E	32.441483	-103.177203					2 and 1			Active	5/5/77	–	375	
BW-10	DP-351	Broom Transporting	Tracy #3	30-015-20331	M-3-22S-27E	32.416127	-104.184128	Eddy	Carlsbad	1	Private	1	Re-entry	Union Oil Tracy #3	Plugged	12/23/78	2/13/01	265	
BW-11		Salty Dog Inc.	Hobbs #1			32.735600	-103.167366	Lea	Hobbs	0		1			Never Constructed				
BW-12	DP-354	Plains Marketing	Saline #1	30-025-12803	M-36-18S-37E	32.698234	-103.210488	Lea	Hobbs	0		1			Plugged	5/1/63	3/19/09	550	50
BW-13	DP-355	John R Stearns	KTS Brine #1	30-025-35702	P-27-9S-35E	33.498447	-103.340169	Lea	Crossroads	1	State	1			Plugged	1/1/66	3/9/09	519	140
BW-14		I & W	Federal Carper 1-30	30-025-35715	O-30-17S-32E	32.799288	-103.802580	Lea	Maljamar	4		1	Re-entry	Federal Carper 1-30	Plugged	12/1/82	2/3/97	182	
BW-15		CW Trainer	Federal #1	30-025-35703	P-25-19S-34E	32.625859	-103.507231	Lea	Hobbs	19	Federal	1	Re-entry		Plugged	8/11/81	10/4/99	218	
BW-16	DP-369	Calico	Pioneer #1	30-025-35705	J-34-21S-37E	32.434133	-103.150619	Lea	Eunice	0		1			Plugged	1/17/65	2/23/94	350	50
BW-17	DP-370	Key Energy	Truckers #1	30-025-03154	A-1-19S-35E	32.693848	-103.405525	Lea	Hobbs	13		1	re-entry	Ralph Lowe Ohio State #1	Plugged	5/15/63	12/1/90	331	70
BW-18	DP-371	Key Energy	Truckers #2	30-025-07551	K-33-18S-38E	32.702056	-103.155644	Lea	Hobbs	0		1	re-entry		Plugged	7/1/80	4/3/07	321	60
BW-19		Key Energy	Carlsbad #1	30-015-21842	H-36-22S-26E	32.348974	-104.237857	Eddy	Carlsbad	0.5		1	new		Plugged	8/20/76	10/22/08	386	
BW-20		Agua	French Drive Brine #1	30-025-07426	E-28-18S-38E	32.720232	-103.159919	Lea	Hobbs	0		1			Never Re-entered				
BW-21		Loco Hills Water Disposal	Loco Hills #1	30-015-32068	M-16-17S-30E	32.828963	-103.984737	Eddy	Loco Hills	0.6	State	1	New		Collapsed	12/18/85	6/19/08	271	750
			Loco Hills #2	30-015-36119	L-16-17S-30E	32.831313	-103.984877					1	New		Plugged	4/15/08		0	750
BW-22		Gandy Corp.	Watson #1	30-025-28162	M-20-12S-36E	33.258655	-103.332884	Lea	Tatum	0		1	New		Active	4/17/83	–	299	30
BW-23		Carter & Son	Maljamar Brine #1	30-025-35716	A-9-17S-32E	32.853351	-103.764931	Lea	Maljamar	0.1		1			Never installed				
BW-24		Scurlock Permian	Tracy #1	30-015-26733	J-33-21S-27E	32.435295	-104.190869	Eddy	Carlsbad	1					No salt, plugged				
			Tracy #2	30-015-26734	J-33-21S-27E	32.435888	-104.191503								No salt, plugged				
BW-25		Basic Energy	Salado #2	30-025-32394	A-20-25S-37E	32.119510	-103.176553	Eddy	Jal	0.4		1			Active	9/6/93	–	187	
BW-26		Salado Brine Sales	Salado #3	30-025-32395	A-32-23S-33E	32.268216	-103.586120	Lea	Eunice	27		1			Never installed				
BW-27		Mesquite SWD	Dunaway #1	30-015-28083	F-23-22S-27E	32.381607	-104.162101	Eddy	Carlsbad	2		2	new		Active	1/30/95	–	170	180
			Dunaway #2	30-015-28084	F-23-22S-27E	32.381705	-104.163300					2	new		Water injection				
BW-28		Key Energy	State Brine Well #1	30-025-33547	E-15-21S-37E	32.482466	-103.158375	Lea	Eunice	2	State	1	new		Active	10/4/96	–	150	
BW-29		Marbob	Mary Dodd A #1	30-015-31998	N-22-17S-29E	32.813654	-104.065225	Eddy	Loco Hills	4	Federal	1	new		Plugged	4/29/91	12/16/05	175	70
BW-30		Liquid Resource	Hobbs State #10	30-025-35915	F-29-18S-38E	32.718630	-103.171685	Lea	Hobbs	0		1	new		active	7/1/02	–	81	60
BW-31		HRC	HRC Shubert 7 #1	30-025-36781	J-7-19S-39E	32.673851	-103.083629	Lea	Hobbs	2		1	re-entry		Active	10/1/06	–	30	80
BW-32		Mack Energy	Berry A		E-21-17S-30E	32.822395	-103.982524	Eddy	Loco Hills	0.15	Federal	1	new		Plugged	6/26/98	10/9/07	112	

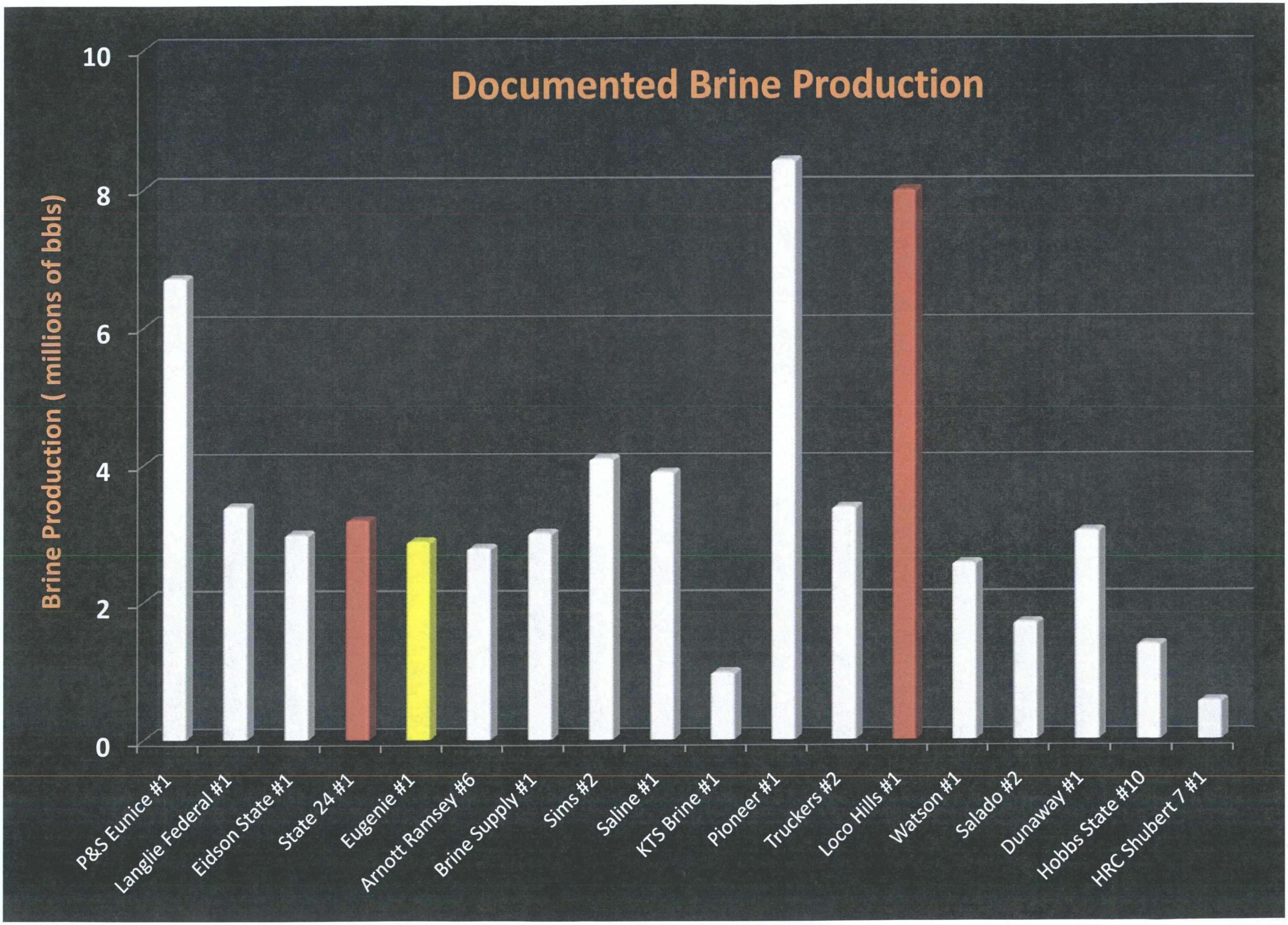
Roof Formation	Salt Formation	Depth to Top of Salt (ft bgs)	Depth to Bottom of Casing (ft bgs)	Casing Diameter (in)	Tubing Depth (ft bgs)	Tubing Diameter (in)	Total Drilled or Plugged Depth (ft bgs)	Fresh water into annulus? (Y or N)	Injection Pressure (psi)	Total Injection (bbls)	Total Production (bbls)	Date of last Sonar	Average Radius (ft)	Maximum Radius (ft)	Radius near casing (ft)	Volume of cavern (bbls)	Method of volume estimation
Rustler	Salado	1650	1456	9.625	2400	8.75	2400	Y									
Rustler	Salado	1680	1580	7		2.375	2770										
Rustler	Salado	1663	1650	7	2800		2800										
Rustler	Salado	1663	1645	7	2800		2800										
Rustler	Salado	1245	1200	7	1718	2.875	1816	Y			6,700,000	2/4/09				1,139,000	17% of production
Rustler	Salado	1040	970	7	2105	2.5	2105	Y	250		3,384,446					575,356	17% of production
	Salado	1865	1895	7	2461	2.875	2555	Y	375		2,977,968					506,255	17% of production
Rustler	Salado	397	416	8.625	660	2.375	740	N	137		3,190,284					542,348	17% of production
	Salado	456	456	5.5	574	2.875	663	Y	238			8/30/07	30	86	30	47,823	partial sonar of 8/30/07
		456	285	5.5	583	2.875	583										
			1229	7				N									
			1223	7			1860	N									
Rustler	Salado	1269	1269	5.5	1582	2.875	1591	N	180								
		1235	1000	7	1500		1500				>2,779,676					>472,545	17% of known production
Rustler	Salado	2000	1847	5.5	2534	2.5	2958	Y			3,000,000+	2/5/09				510,000+	17% of minimum production
		1375	1373	7	1680	2.875	2125	N									
			1204	7	1690	2.875	2434		100		4,085,353					694,510	17% of production
		1060	1031	5.5	1224		1274	Y									
Rustler	Salado	1810	1720	5.5	2650	2.875	2700	Y			3,883,459					660,188	17% of production
Rustler	Salado	1960	2000	5.5	2800	2.875	2800	Y	290		975,000						
Rustler	Salado	1911	1902	5.5	2400	2.5		y									
		1259	1300		1912						8,400,000						
		2140			2260												
		2045									3,378,602						
Rustler	Salado	715	710	5.5	764	2.875						4/2/08					
Rustler		470	415	5.5	900	2.875	1045	Y	125	9,148,000	7,978,000	2/7/01		178.4		753,993	sonar of 2/7/01
Rustler		520	521		1020			Dual string		0	0						
Rustler	Salado	2290	2249	5.5	2870	2.375	2905	Y	300		2,561,250	8/19/08		59.4		435,413	17% of production
			1220		1385		1420				1,700,000						
		1060	1064								3,028,788						
		1390	1390	8.625	2074	2.875											
			350	7.625			800										
		1645	1700	7	2300		2400				1,382,450						
		1800	1865		2300						561,110						
			425				646										


Brine Well Start Ups by Year
Number of Startups
4
3
2
1
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

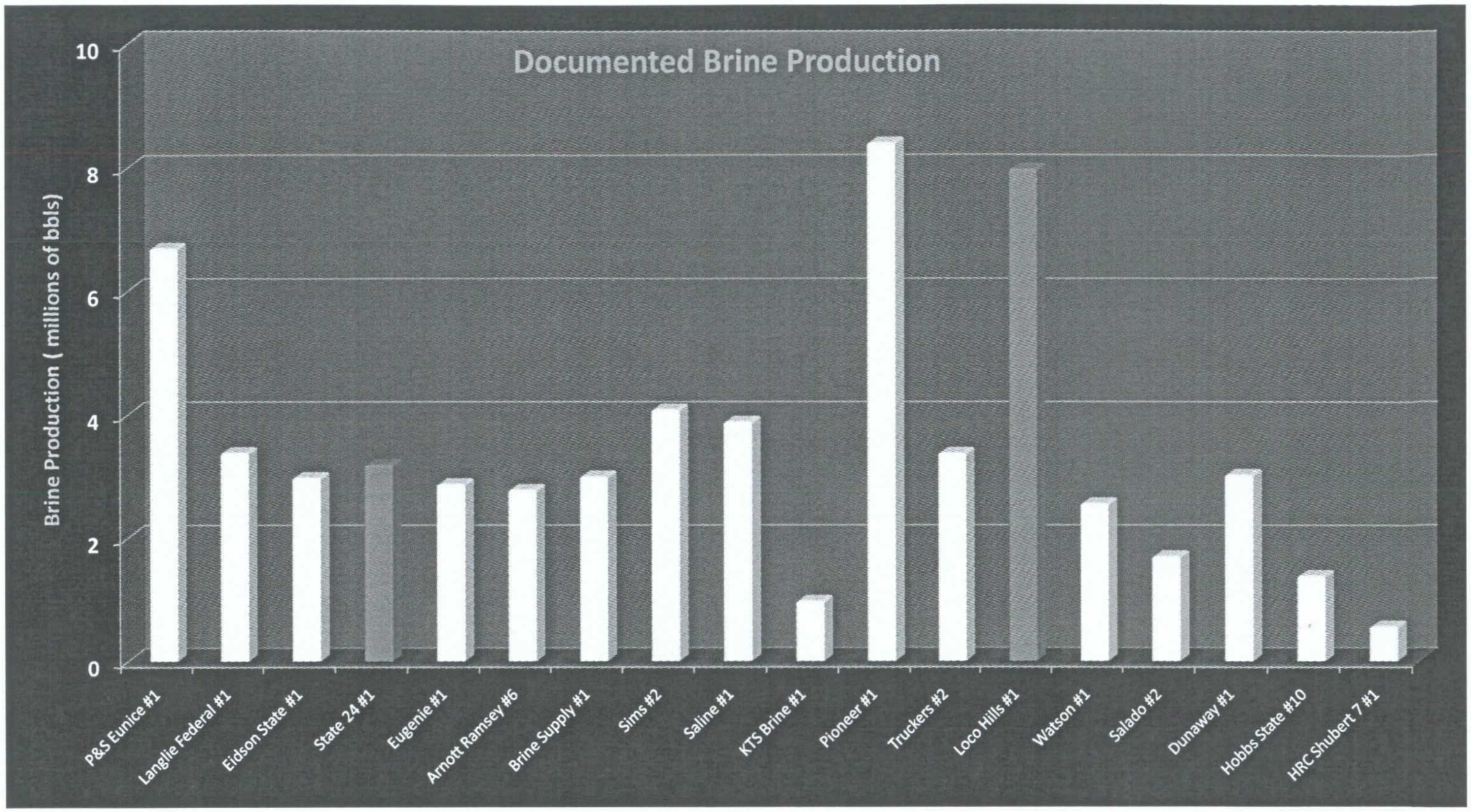

Brine Well Closures by Year
Number of Closures
0
1
2
3
4
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

Brine Well Operational Ages




Documented Brine Production
Brine Production (millions of bbls)
0
2
4
6
8
10
P&S Eunice #1
Langlie Federal #1
Eidson State #1
State 24 #1
Eugenie #1
Arnott Ramsey #6
Brine Supply #1
Sims #2
Saline #1
KTS Brine #1
Pioneer #1
Truckers #2
Loco Hills #1
Watson #1
Salado #2
Dunaway #1
Hobbs State #10
HRC Shubert 7 #1

Well Name	Production
P&S Eunice #1	6.700
Langlie Federal #1	3.384
Eidson State #1	2.978
State 24 #1	3.190
Eugenie #1	2.874
Arnott Ramsey #6	2.780
Brine Supply #1	3.000
Sims #2	4.085
Saline #1	3.883
KTS Brine #1	0.975
Pioneer #1	8.400
Truckers #2	3.379
Loco Hills #1	7.978
Watson #1	2.561
Salado #2	1.700
Dunaway #1	3.028
Hobbs State #10	1.382
HRC Shubert 7 #1	0.561



Jim's Water Service (BW-5) Collapse of July 16, 2008

The Jim's Water Service brine facility (re-entry of Nix & Curtis Gulf State #2) is situated approximately 10.6 miles SW of Loco Hills and 17 miles ESE of Artesia in Eddy County at an altitude of ~3500 fmsl. (ULSTR J-24-18S-28E) The brine well, now known as State 24 #1, was only 400 feet NW of Hagerman Road (CR 217) on state trust land otherwise used for the grazing of cattle. The facility consisted of the brine well, supplied with freshwater via pipeline from the NW, and a brine pond (100 x 100 x 8 ft w/ 10,000 bbl capacity) situated along the road approximately 900 feet east of the well. There are four operating natural gas wells within ½ mile of the brine well.

The original prospective oil well was drilled via cable tool in Spring of 1955 and salt was encountered at depths from 397 to 680 ft bgs with intermittent layers of anhydrite and shale. Shallowest groundwater in the area is thought to reside at a depth of about 225 ft. in a water sand to a depth of 245 ft. Water was not encountered again until 2300 ft. There are no water wells within 3 miles of the facility. TD on the well was ~3000 ft. The hole wasn't considered viable despite a minor gas show and was immediately abandoned. Cement plugs were said to have been set from 3009 to 2965, 2350 to 2320, and 420 to 390. The well was re-entered in December of 1978 by B&E Inc. and Permian Brine Sales, a surface plug was cleared but the shallowest plug was not found, and the first plug was encountered at 1540. New plugs were set at 1540 to 1400, and 1000 and 740 ft bgs. Used 8-5/8" 24# casing was set from surface to 416 ft. A hole was found in the casing @ ~42 ft, so a squeeze job was undertaken, and then 2-7/8" tubing was hung w/o a packer to a depth of 660 ft.

Freshwater was initially injected down the tubing at the pipeline pressure (75 to 80 psig) and brine returned to the surface thru the annulus at about 25 psig and a flow rate of 30 gpm. A booster pump was available to up the injection flow to 75 gpm at a max pressure of 125 psi. The brine was piped to the pond where it was sold. The injection water was metered along with the sale of brine. Flow direction switched in ~1986.

OCD first approves a discharge permit for the facility (GWB-4) in Dec 1982. In September 1983 B&E buys out Permian. Jim's Water Service of Colorado buys facility in January 1992. JWS is now owned by KP Kaufmann Co.

Unverified total brine production from 1979 thru 1982 of 1.62 Mbbls. Quarterly brine production figures exist starting in the 1st Quarter of 1983 thru 1991, with a total production over this interval of another 1.28 Mbbls. Records are spotty thereafter but OCD is working to compile that information but could approach 300,000 bbls per year. This may account for another 5 Mbbls, putting total historic production at just under 8 Mbbls.

If the average brine density were 10 lbs/gallon, the volume of the cavern could have been 1.3 Mbbls. No sonar data exists. The last 5-year EPA casing integrity test was completed and passed in December 2006. The last cavern nitrogen pressure testing was in December 2007. Both tests were passed.

On the morning of July 16, 2008 one of the JWS employees was approaching the brine well in his pickup to perform a site check, entering along the unpaved service road from the northeast. When he reached within ~200 feet of the well, he noticed a dust cloud in the area of the well. He stopped and exited the truck, but thankfully left the engine running. He then noticed a surface crack open and progress toward him. He thought it was an earthquake, immediately jumped back into the truck, threw it in reverse and backed up the road at full throttle. The initial hole was perhaps 40 feet wide.

By that afternoon, the surface collapse was ~180 ft in diameter with a depth to water of perhaps 45 feet. Within 3 days, by the 19th, the hole was 240 ft across and water at a depth of ~75 ft.

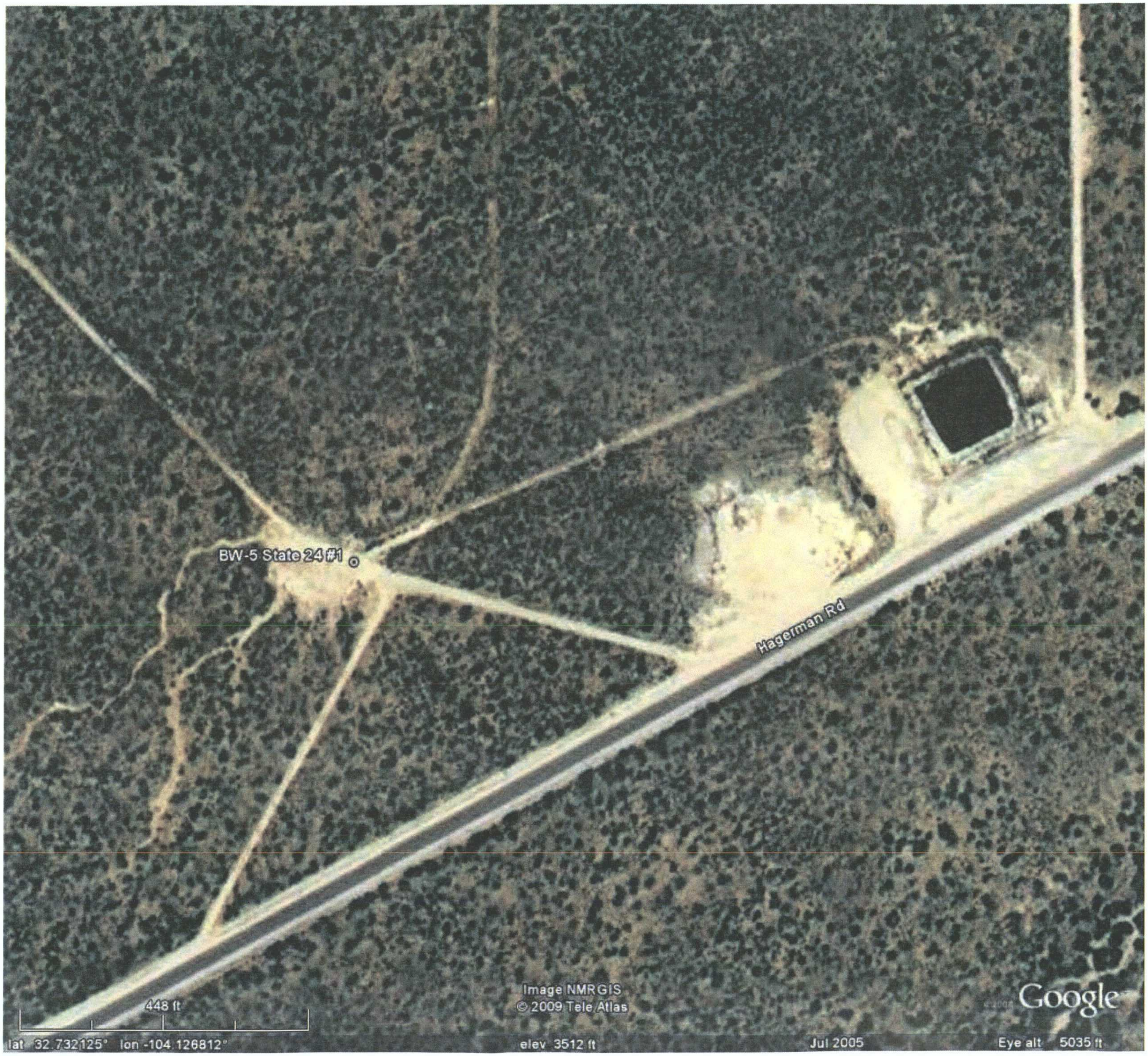
The OCD got in contact with Dr. Rick Aster at NM Tech in Socorro to inquire if any of their seismic instrumentation may have detected the collapse. Fortunately, a 3-component broadband seismograph (TA126) part of the Earthscope USArray Transportable Seismic Array is situated ~8.4 miles southeast of the brine well near the old Eddy Potash Mine. About 6 hours before the sink appeared at the surface, seismic signals were noted at the station most likely the result of the failure of the cavern roof.

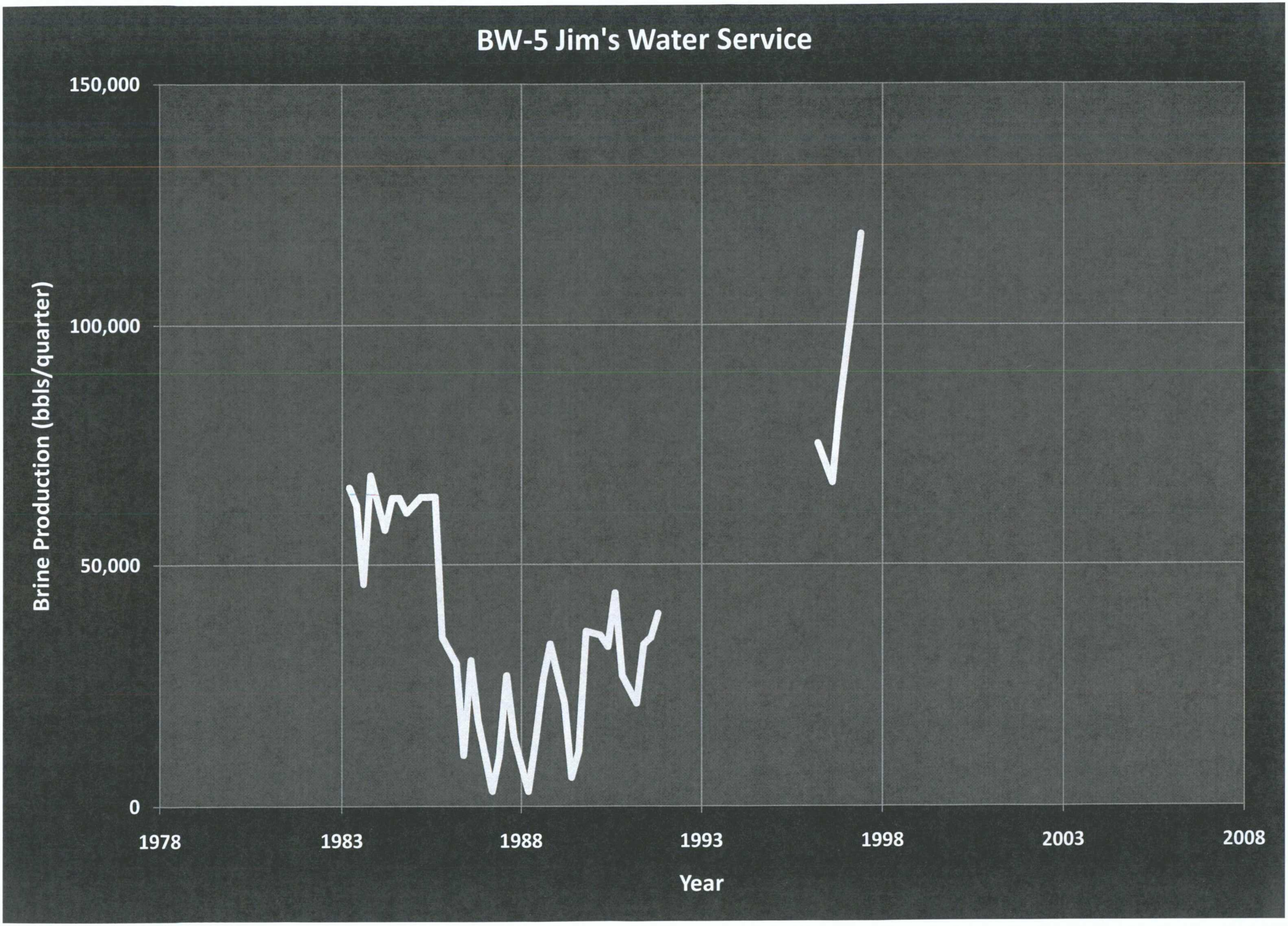
Initial fencing of the area was completed by July 25th.

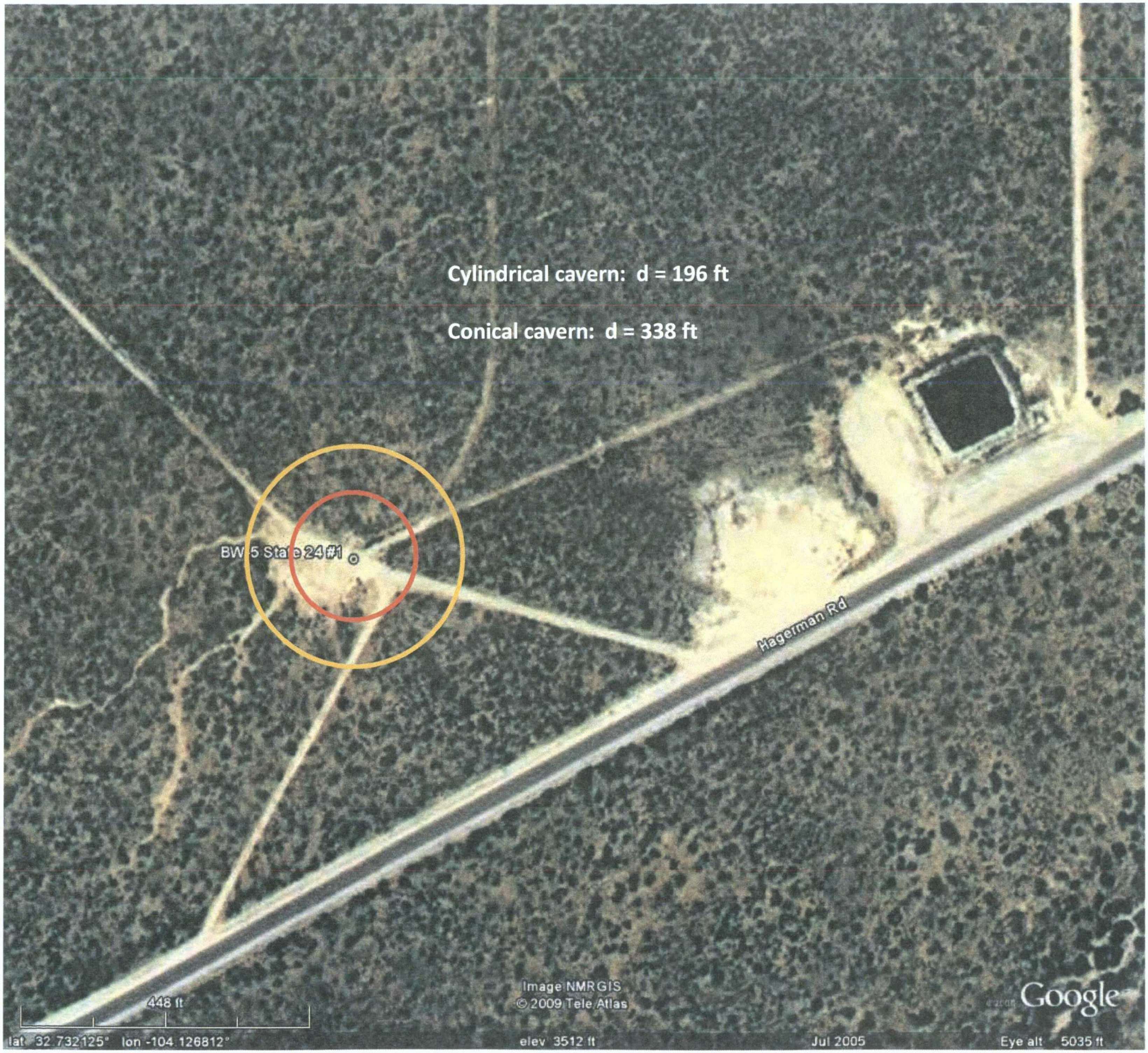
On August 30, 2008 OCD personnel undertook a preliminary radiation survey using a Ludlum with a scintillation probe. Readings were taken within or immediately above visible concentric soil cracks equidistant (40 ft) from the edge. No readings appreciably above background (0.40 milliRoentgens/hr) were noted.

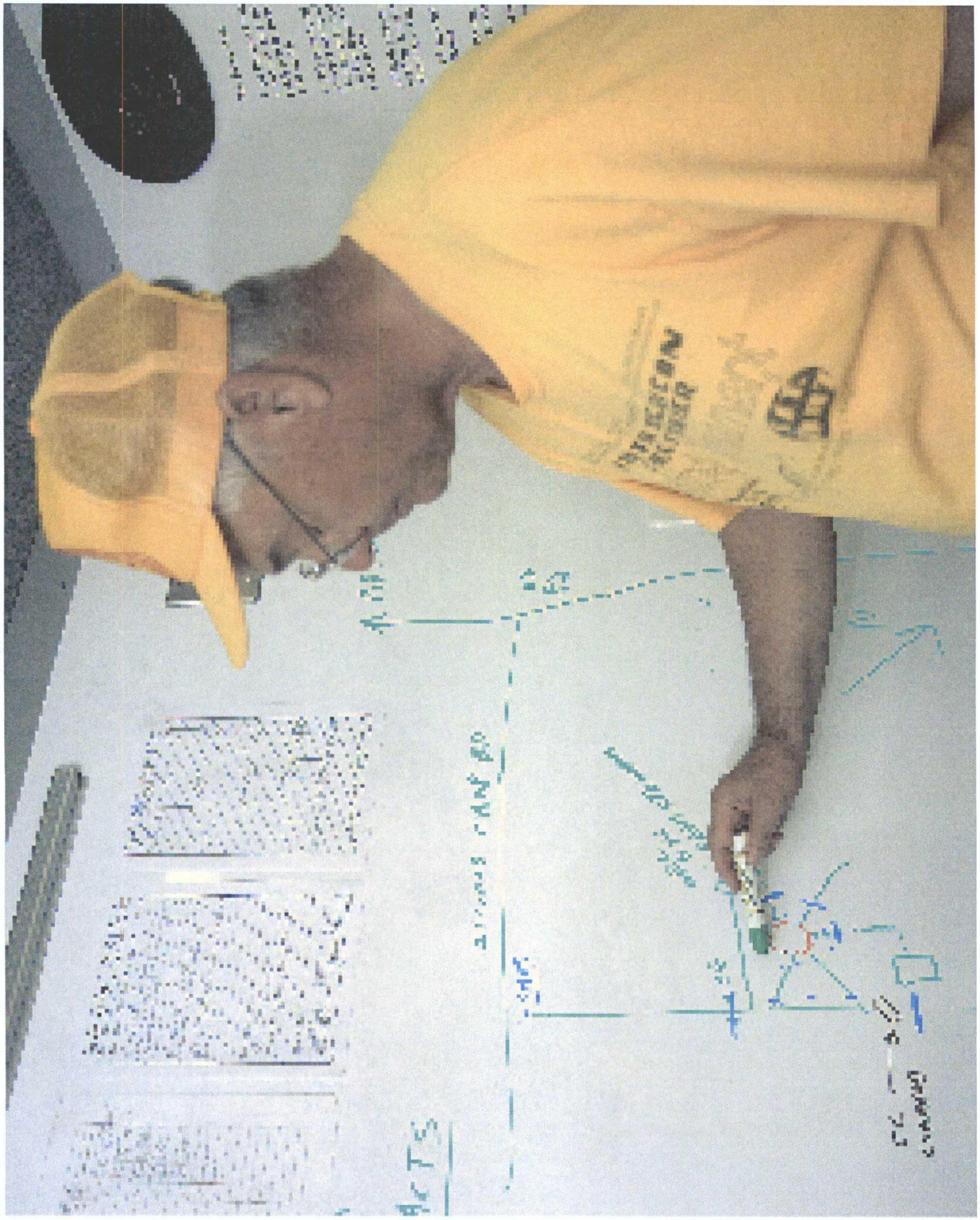
An 8-foot chainlink fence w/ concertina wire is now surrounding the larger area to restrict access. The brine pond is in the process of being closed after proper investigation beneath the liner and an initial series of groundwater monitoring wells are to be installed for verification of groundwater flow direction along with the possibility of brine upwelling into freshwater resulting in dissolved-phase contamination. Continued growth of the hole and vertical subsidence as well as the propagation of surface cracks is being monitored via survey on a regular basis to continually determine if closure of the nearby road might be warranted.

COLLAPSE OF STATE 24 #1
BRINE WELL
JIM'S WATER SERVICE (BW-5)
JULY 16, 2008

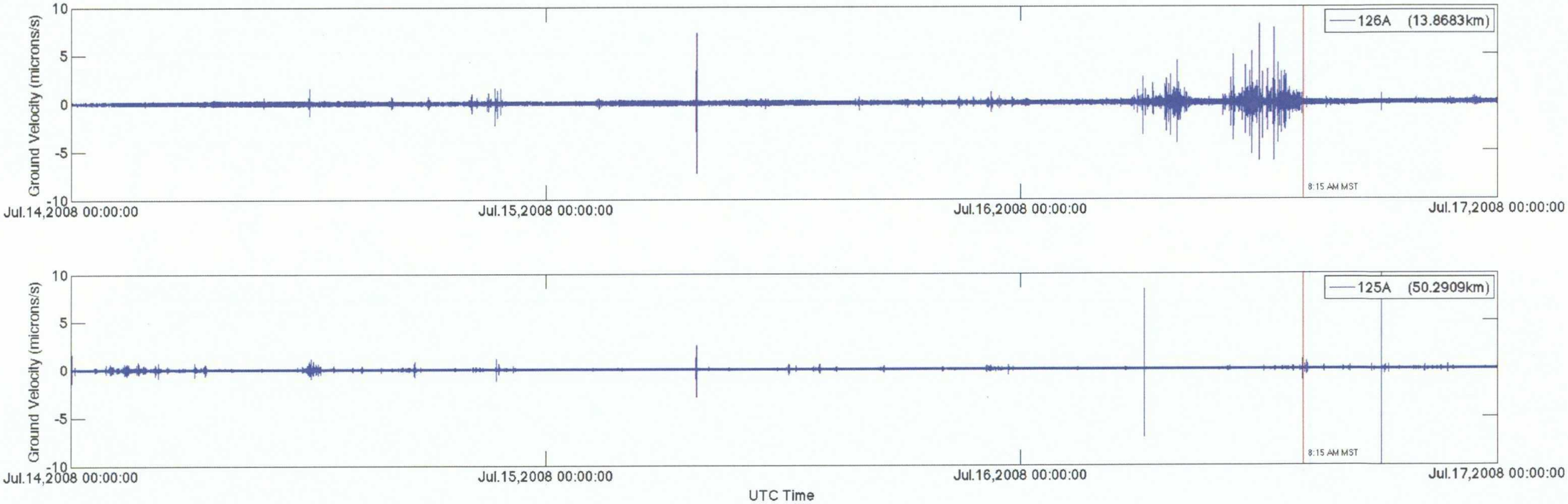

BW-5 State 24 #1
Hagerman Rd
448 ft
Image NMRGIS
© 2009 Tele Atlas
Google
lat 32.732125° lon -104.126812°
elev 3512 ft
Jul 2005
Eye alt 5035 ft


BW-5 Jim's Water Service
Brine Production (bbls/quarter)
150,000
100,000
50,000
0
1978
1983
1988
1993
1998
2003
2008
Year


Cylindrical cavern: d = 196 ft
Conical cavern: d = 338 ft
BW 5 State 24 #1
Hagerman Rd
448 ft
Image NMRGIS
© 2009 Tele Atlas
Google
lat 32.732125° lon -104.126812°
elev 3512 ft
Jul 2005
Eye alt 5035 ft

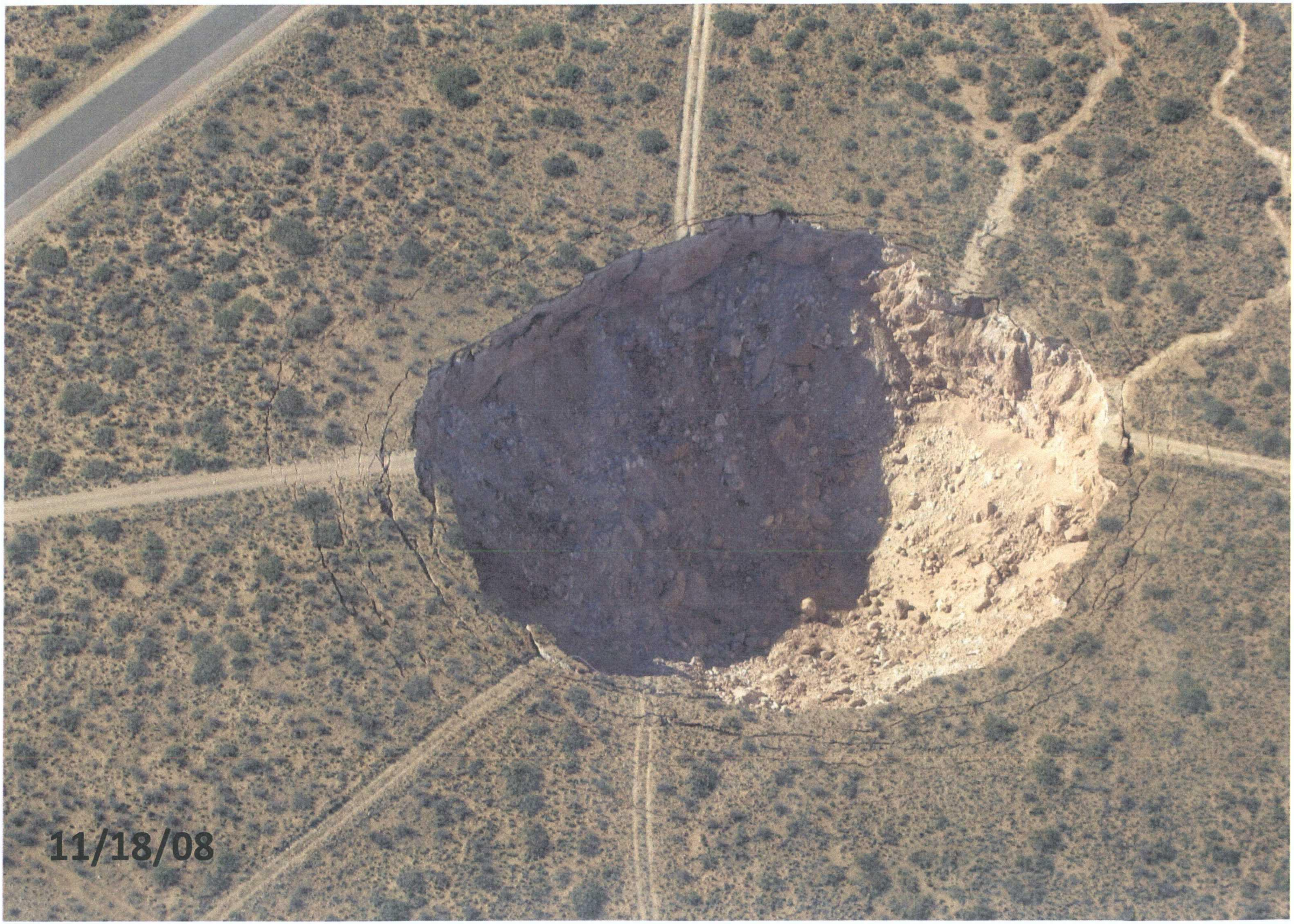

ACTS


82
BW-5 State 24 #1
TA-126 Seismograph
Image © 2009 DigitalGlobe
Image NMRGIS
© 2009 Tele Atlas
Google
4.68 mi
lat 32.695409° lon -104.079994°
elev 3413 ft
Jul 2005
Eye alt 16.81 mi


10
5
0
-5
-10
Ground Velocity (microns/s)
126A (13.8683km)
8:15 AM MST
Jul.14,2008 00:00:00
Jul.15,2008 00:00:00
Jul.16,2008 00:00:00
Jul.17,2008 00:00:00
10
5
0
-5
-10
Ground Velocity (microns/s)
125A (50.2909km)
8:15 AM MST
Jul.14,2008 00:00:00
Jul.15,2008 00:00:00
Jul.16,2008 00:00:00
Jul.17,2008 00:00:00
UTC Time

7/24/08

DANGER
STATE LAND TRUST
NO TRESPASSING
YOU WILL BE PROSECUTED
NMSA STATUTES 19-6-3 AND 19-6-



11/18/08

12/1/08

1/20/09

1/20/09

1/20/09

Loco Hills Disposal (BW-21) Collapse of November 3, 2008

The Loco Hills Water Disposal facility is situated just 0.6 miles North of Loco Hills and immediately adjacent to CR 217 about 10.7 miles NE of the JWS collapse in ULSTR M-26-17S-30E and is also on state trust land.

The brine well was drilled in the latter part of 1985 solely for the purposes of brine production. The depth to the top of salt is about 470 ft bgs. The 5-1/2" casing shoe was set 415 ft bgs and 2-7/8" tubing to a depth of ~900 ft. TD on the well (bottom of salt) was 1045 ft. Freshwater provided from a nearby pipeline servicing the area has always been introduced thru the annulus between the casing and tubing at a pressure of less than 125 psig with brine produced up the tubing and stored for sale in a lined pond immediately north of the well.

As you can see, there is a high level of O&G activity in the area. Fresh groundwater does not appear to exist in the area at a depth less than the solution cavern. The larger facility functions for the disposal of exempt liquid wastes via evaporation and infiltration.

Freshwater injection and brine production information is more complete for this facility, but not entirely verified. From 1986 thru 2002, approximately 3.47 Mbbls of brine were produced.

A sonar log was completed of the brine cavern during February 2001 indicating a mined volume of 753,993 bbls. It is presently estimated that more than 7 Mbbls of brine were produced over the life of the well, which could place the cavern at a volume of 1.2 Mbbls before collapse.

The last casing integrity test of the well was undertaken in June 2008 which failed. The well was plugged the following day by ensuring the cavern was full of brine, setting a bridge plug at a depth of 402 feet within the casing and circulating cement all the way to surface.

The area was monitored visually by facility personnel on a daily basis. Upon returning from lunch on November 3rd, 2008 they noticed cracks in the ground adjacent to the well and immediately notified the Eddy County Sheriff's Office and the OCD. CR 217 was closed as a precaution. Within 2 hours, an opening appeared on surface. By that afternoon the shed housing the triplex water injection pump had been consumed. The next day the wellhead disappeared into the hole along with a nearby storage tank which typically held freshwater. The berm integrity of the pond to the north of the well was in jeopardy, so it was drained. Eventually this berm was breached and at least half the pond consumed. Electrical power was terminated and rerouted.

By mid-January of this year the asphalt in the nearby road had begun to buckle.

The surface hole has become fairly stabilized with an estimated average diameter of 270 feet and the hole a depth greater than 100 feet. The area has been fenced off, a section of the road closed and CR 217 realigned to the west and reopened to traffic. The operator recently submitted a proposal to the OCD for backfilling of the sinkhole with earthen materials.

A review of available seismic data (nearest seismograph [same TA126] located 12.5 miles to the SSE) did not indicate any detection of the event.

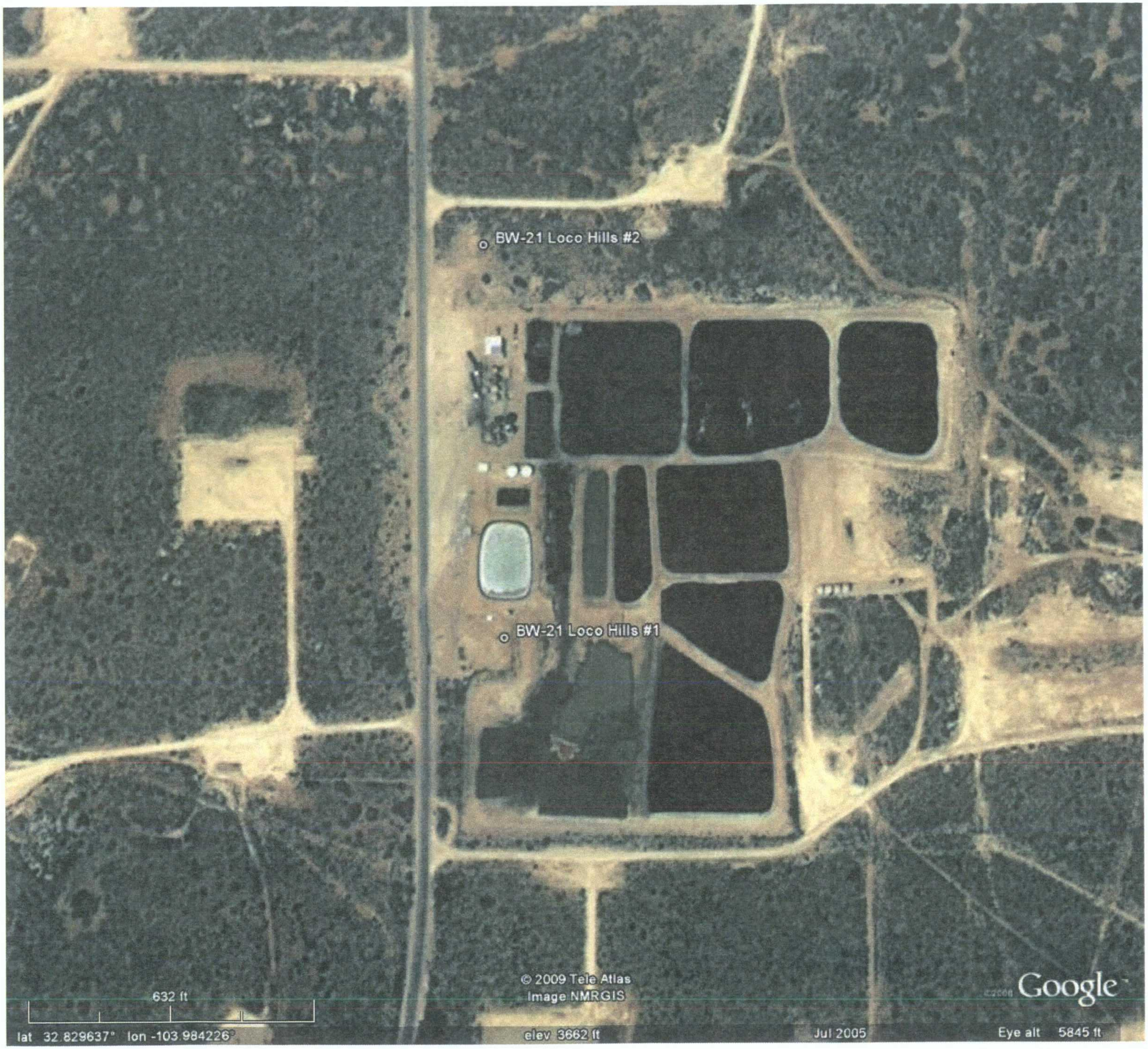
Texas Brine Well Regulations

Kansas Brine Well Regulations

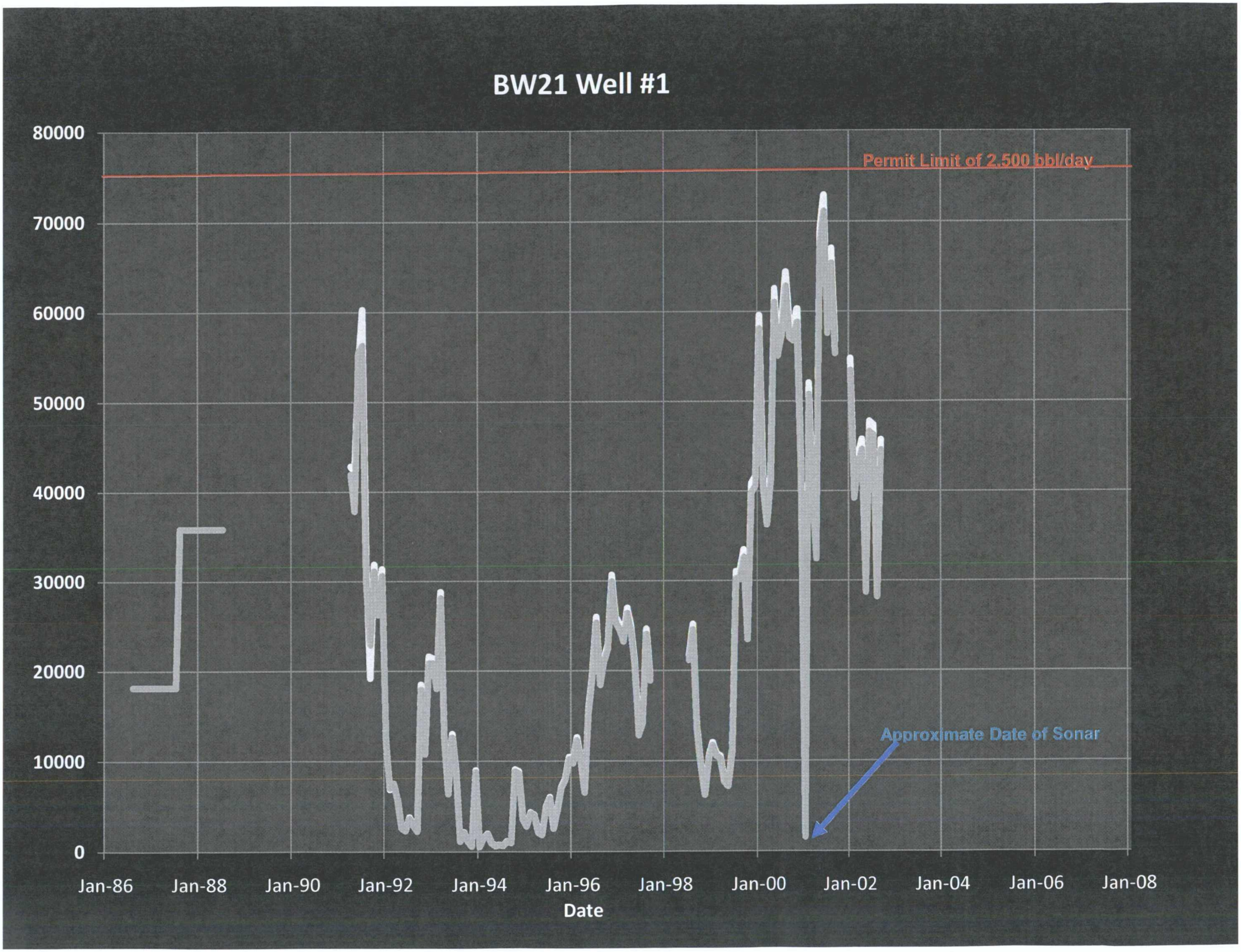
COLLAPSE OF LOCO HILLS #1
BRINE WELL
LOCO HILLS WATER
DISPOSAL SERVICE (BW-21)

NOVEMBER 3, 2008

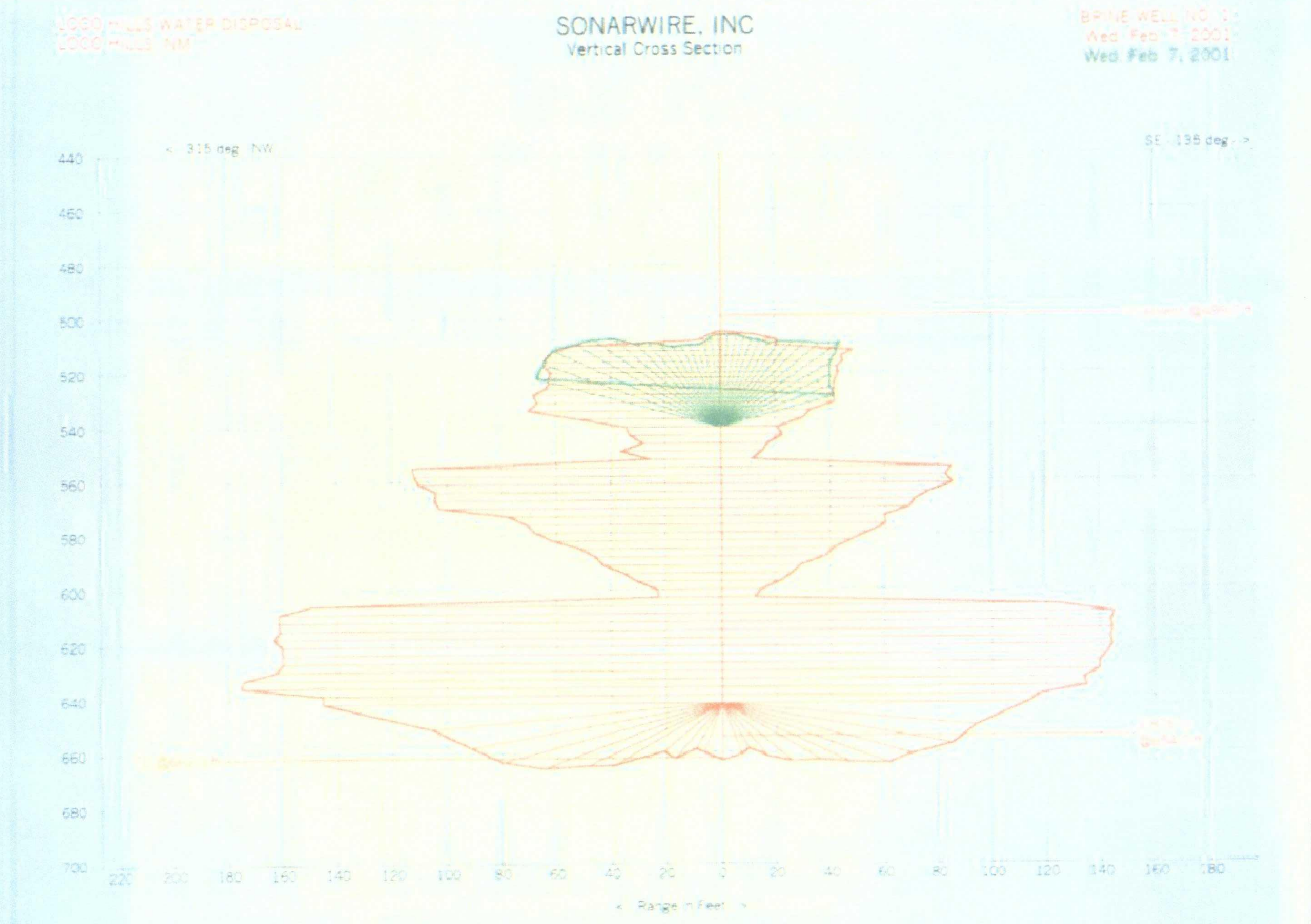

BW-21 Loco Hills #1
82
Loco Hills
© 2009 Tele Atlas
Image NMRGIS
Google
2479 ft
lat 32.825939° lon -103.983693°
elev 3653 ft
Jul 2005
Eye alt 12197 ft


BW-21 Loco Hills #2
BW-21 Loco Hills #1
© 2009 Tele Atlas
Image NMRGIS
Google
632 ft
lat 32.829637° lon -103.984226°
elev 3662 ft
Jul 2005
Eye alt 5845 ft

BW21 Well #1



80000
70000
60000
50000
40000
30000
20000
10000
0
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Date
Permit Limit of 2,500 bbl/day
Approximate Date of Sonar



LOCO HILLS WATER DISPOSAL
LOCO HILLS, NM

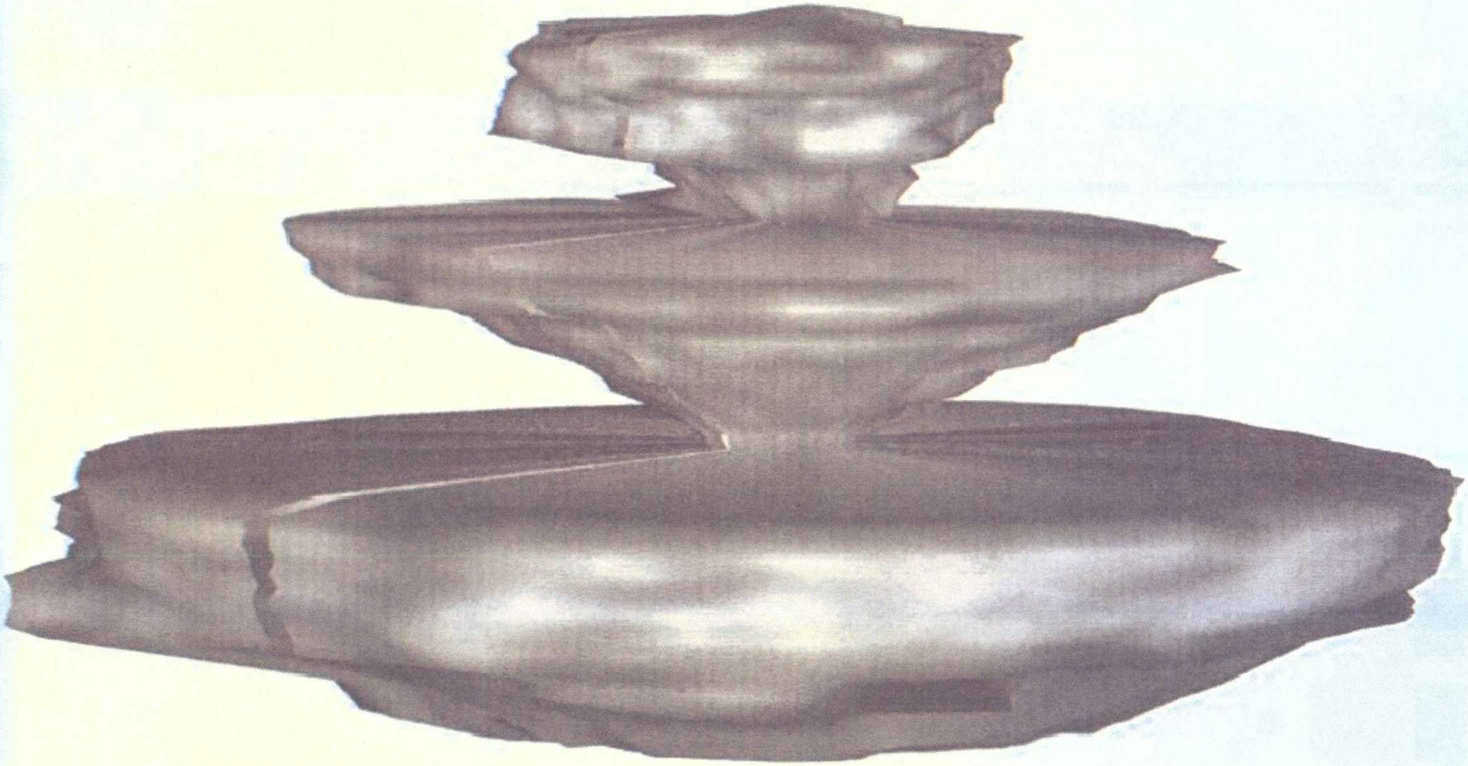
SONARWIRE, INC
Vertical Cross Section

BRINE WELL NO. 1
Wed Feb 7, 2001
Wed Feb 7, 2001

LOCO HILLS WATER DISPOSAL
LOCO HILLS, NM
BRINE WELL NO. 1
WED, FEB 7, 2001

3D SHADE PLOT

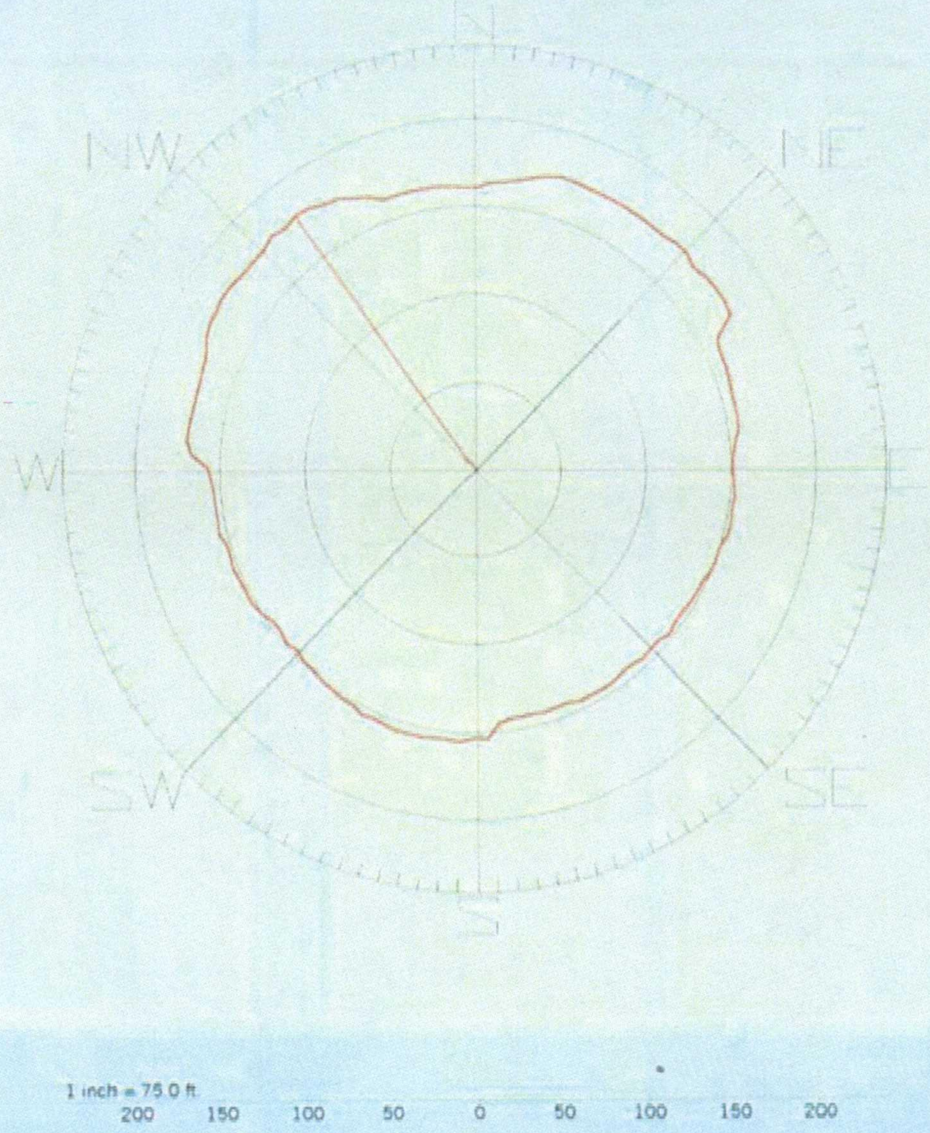
VIEWING AZIMUTH: 45
AXIS TILT: -5 DEGS.



LOCO HILLS WATER DISPOSAL
BRINE WELL NO. 1
LOCO HILLS, NM

SONARWIRE, INC
Max Range vs Bearing

Max Radius=178.4 ft @ 323.9 deg
Depth= 642 ft. Wed. Feb. 7, 2001

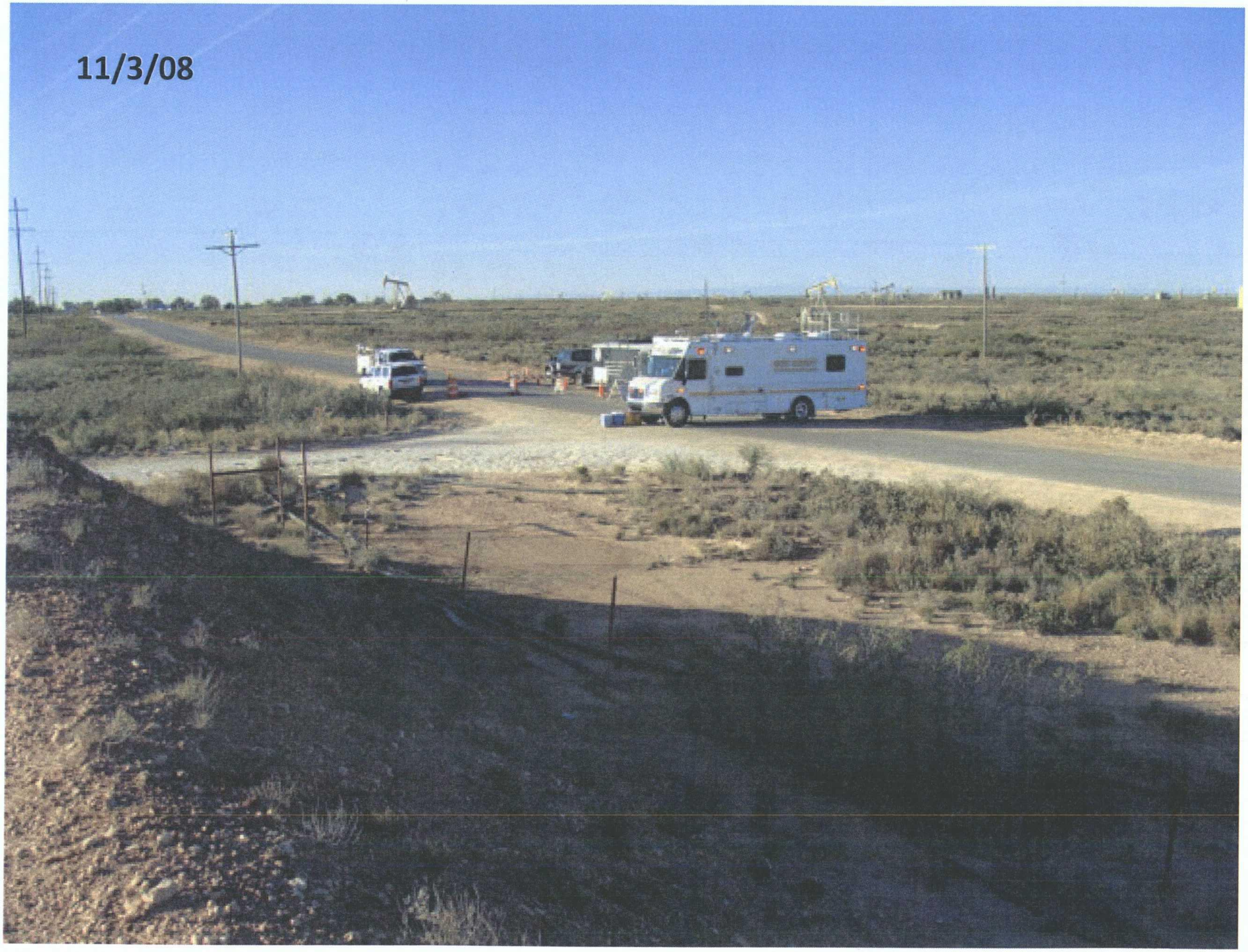



BW-21 Well #1

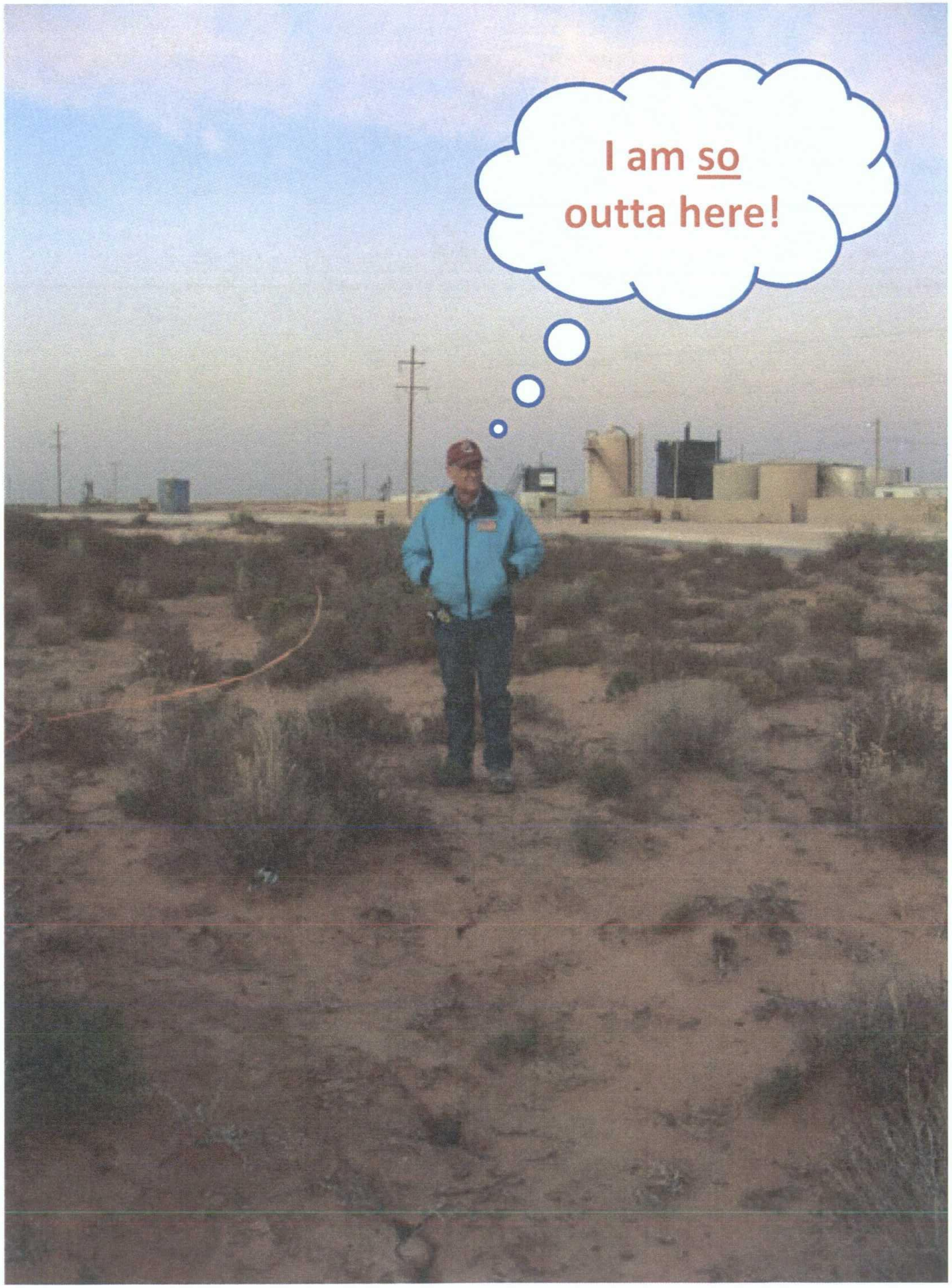
11/3/08

11/3/08

11/3/08

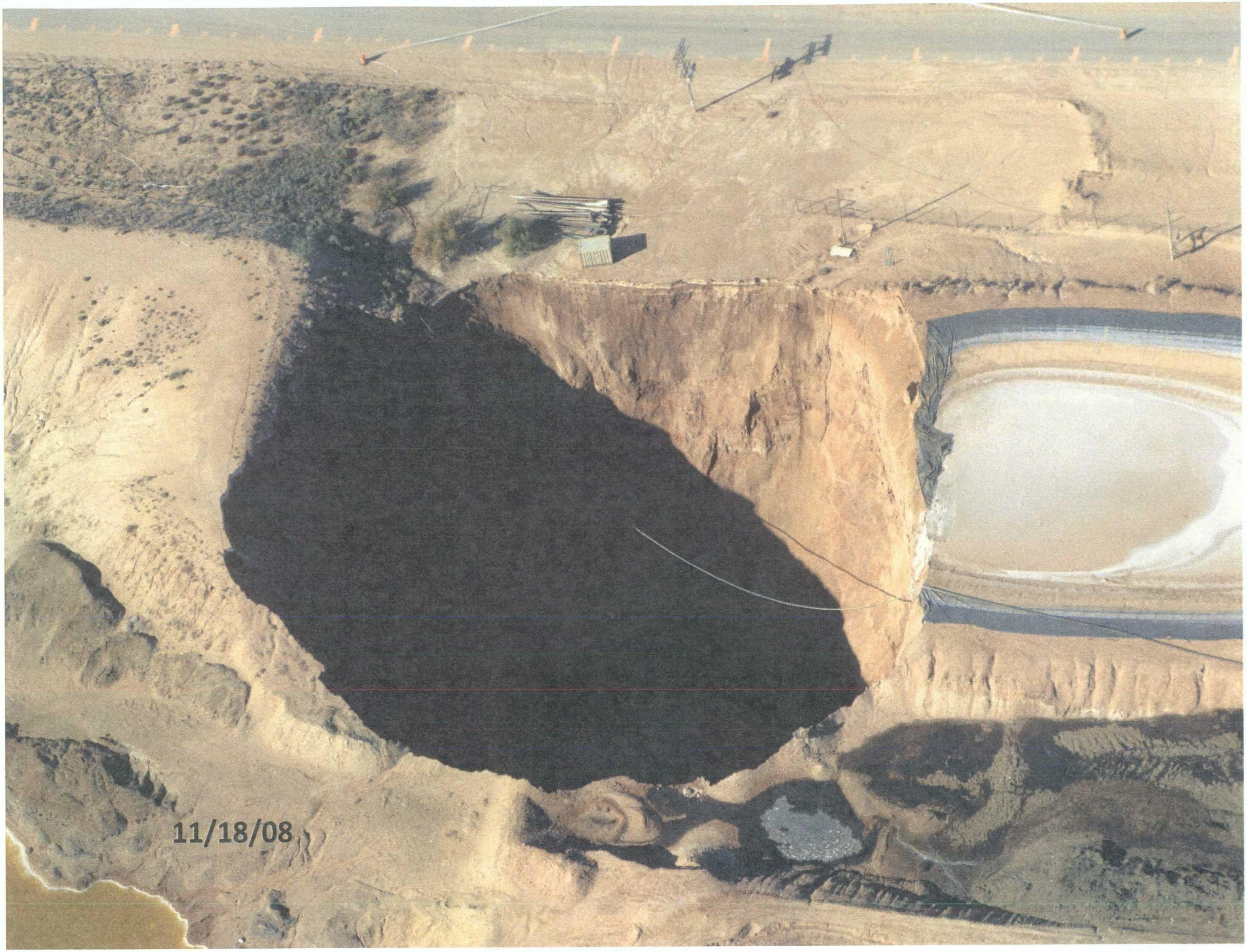


11/3/08


I am so outta here!

11/3/08

03/25/2216



11/18/08

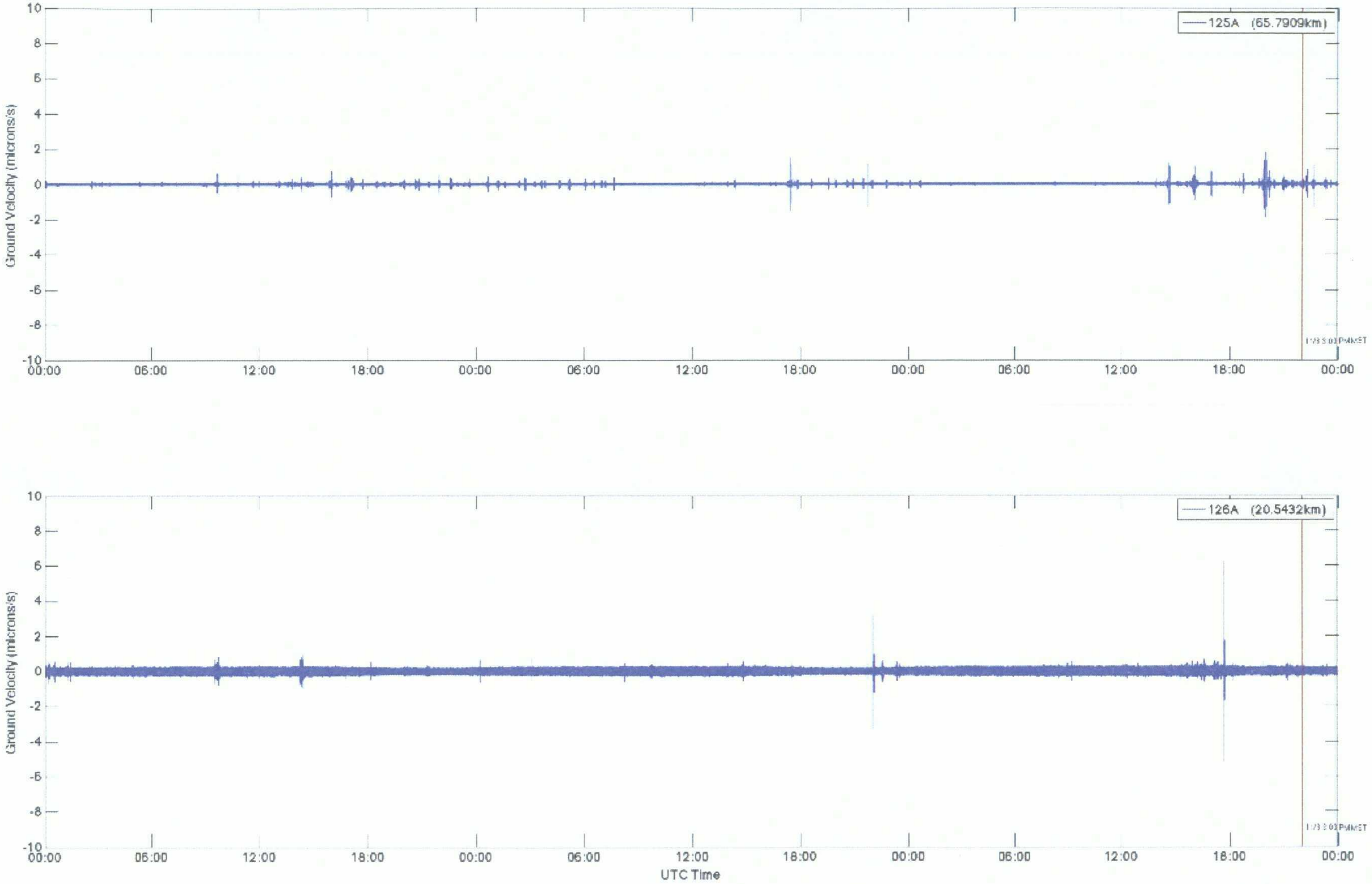
11/18/08

12/12/08

1/22/09

1/22/09


BW-21 Well #2
BW-21 Well #1
N
Image NMRGIS
© 2008 Tele Atlas
©2008 Google
547 ft
lat 32.829190° lon -103.984261°
elev 3660 ft
Jul 2005
Eye alt 5546 ft

125A (65.7909km)
Ground Velocity (microns/s)
10
8
6
4
2
0
-2
-4
-6
-8
-10
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
1/23 5:03 PM MST
126A (20.5432km)
Ground Velocity (microns/s)
10
8
6
4
2
0
-2
-4
-6
-8
-10
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
1/23 5:03 PM MST
UTC Time

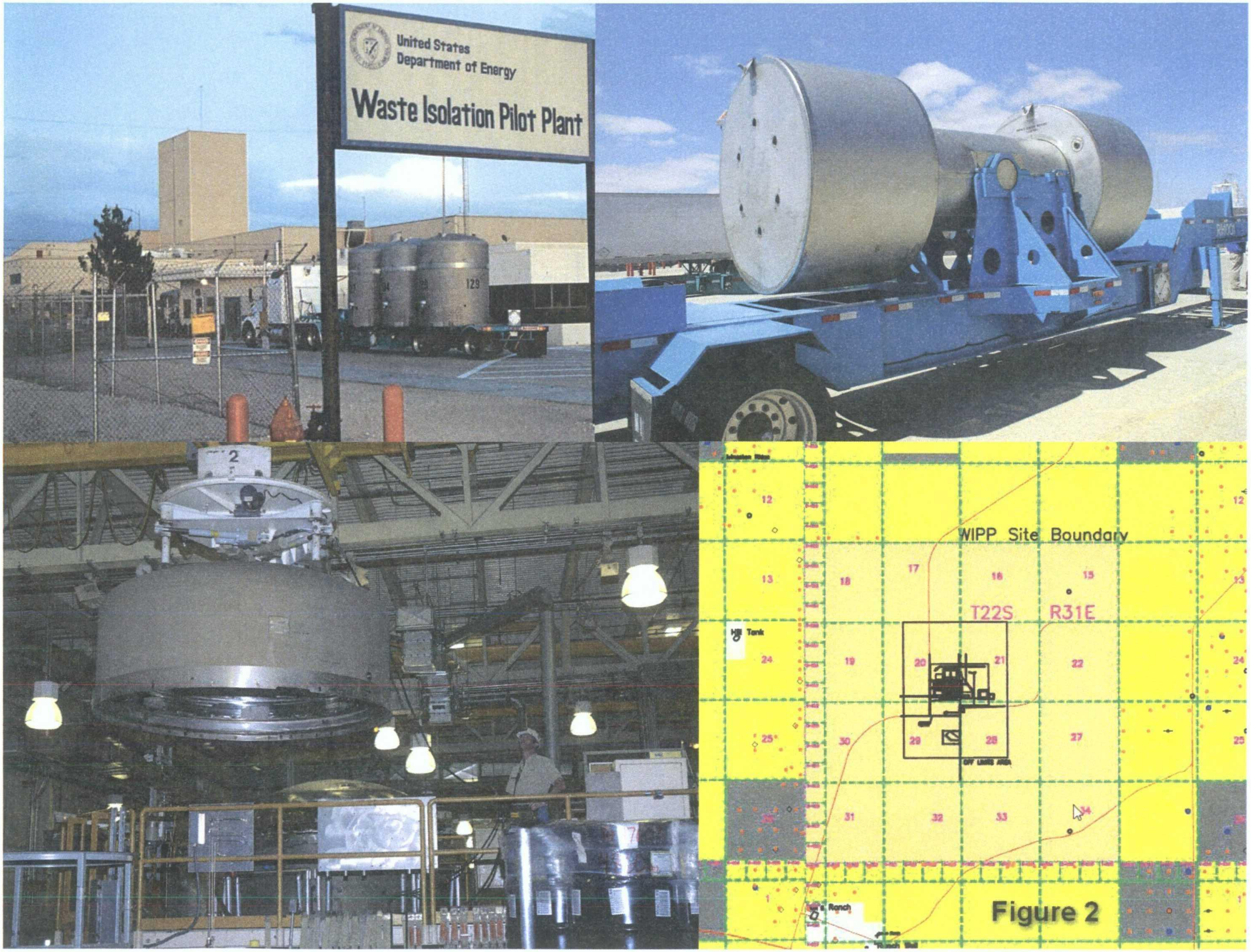
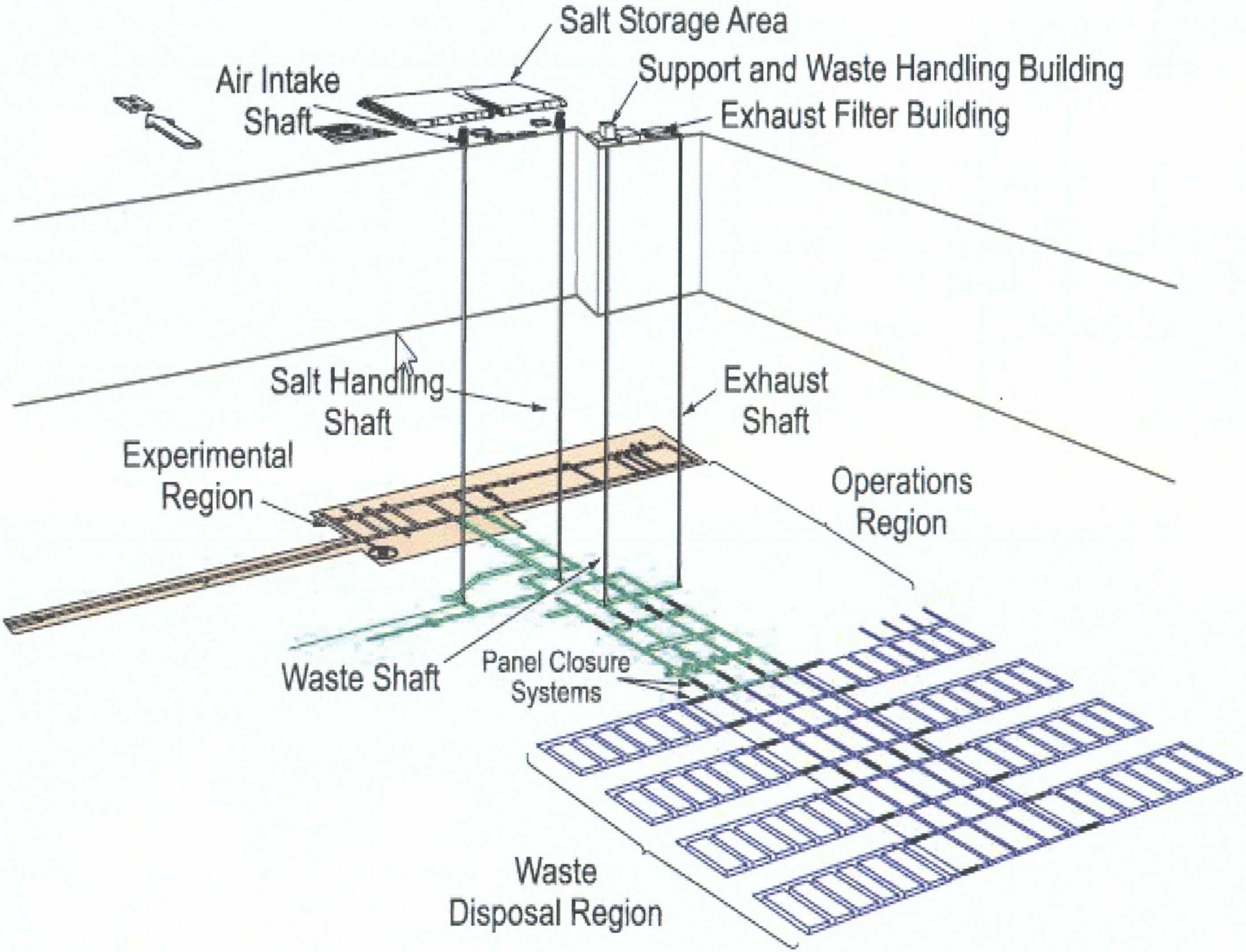
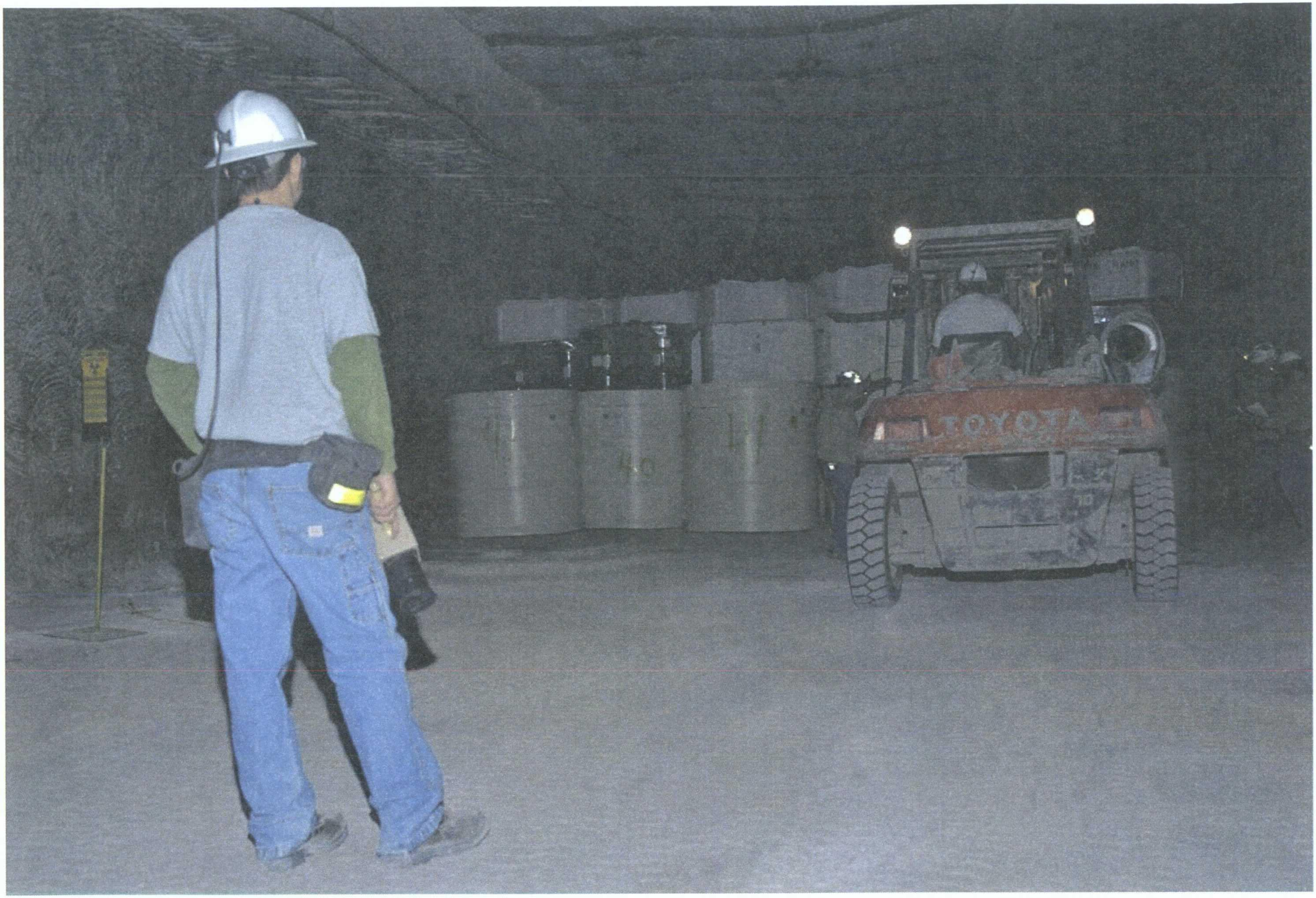


Figure 2

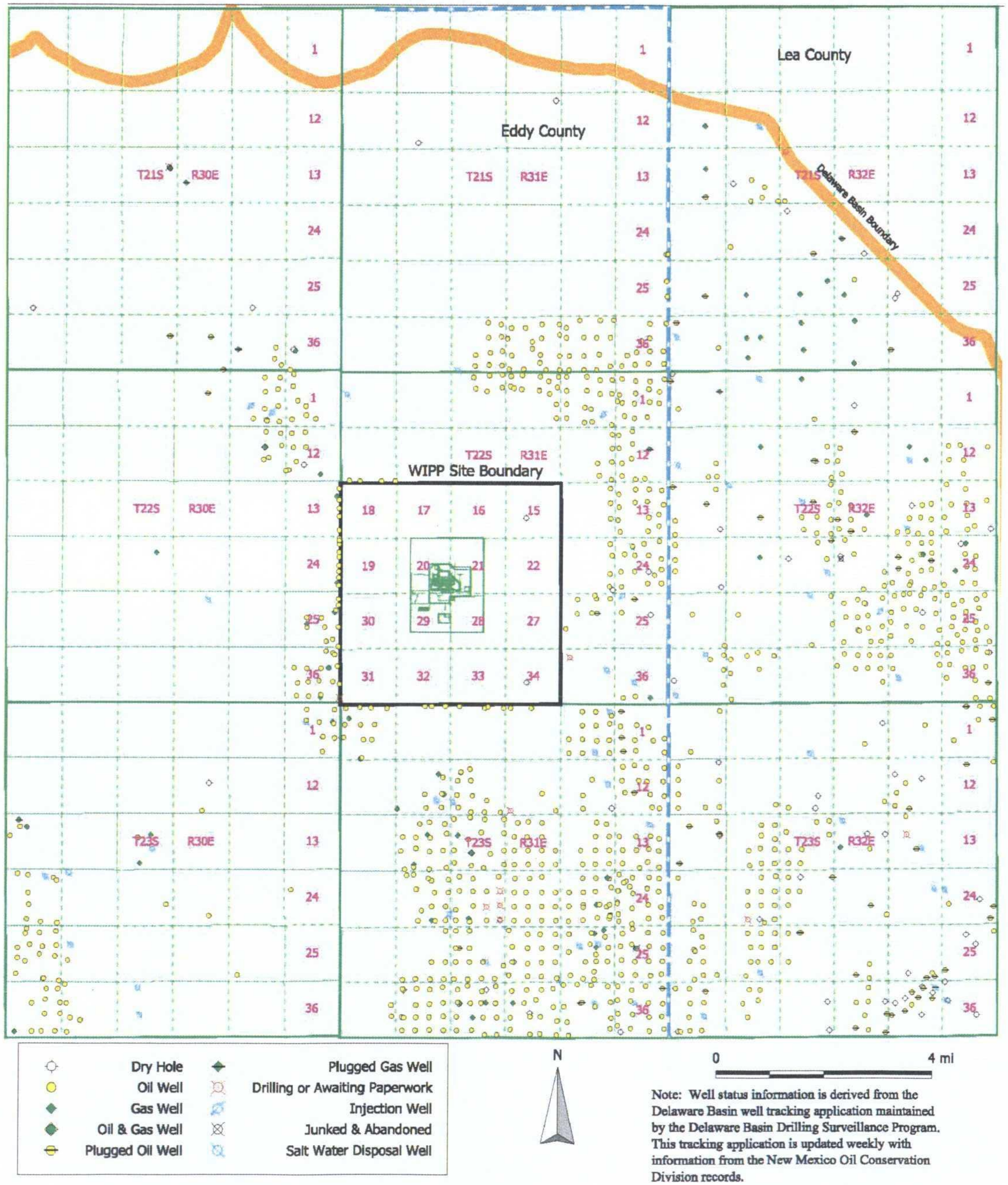
United States
Department of Energy
Waste Isolation Pilot Plant
129
2
WIPP Site Boundary
T22S
R31E
12
13
18
17
16
15
Hill Tank
24
19
20
21
22
25
30
29
28
27
OFF LIMITS AREA
31
32
33
34
1
Ranch


Salt Storage Area
Air Intake Shaft
Support and Waste Handling Building
Exhaust Filter Building
Salt Handling Shaft
Exhaust Shaft
Experimental Region
Operations Region
Waste Shaft
Panel Closure Systems
Waste Disposal Region


TOYOTA

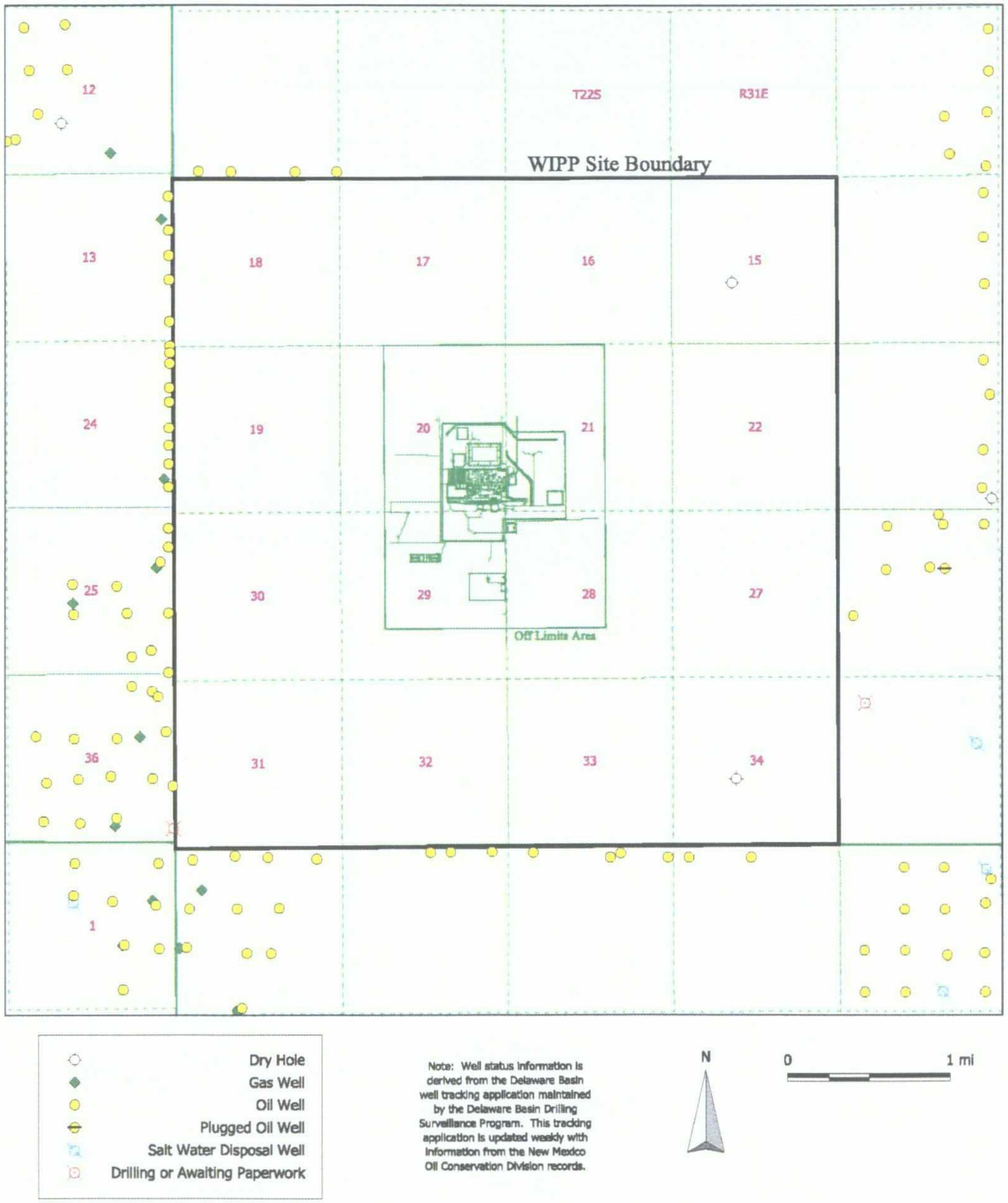

NEW MEXICO
HOBBS
62
180
LEA
SBAD
WIPP SITE
NINE-TOWNSHIP AREA
285
DELAWARE
CAPITAN REE
LOVING
A

Status of Hydrocarbon Wells in the Nine Township Area
March 16, 2009



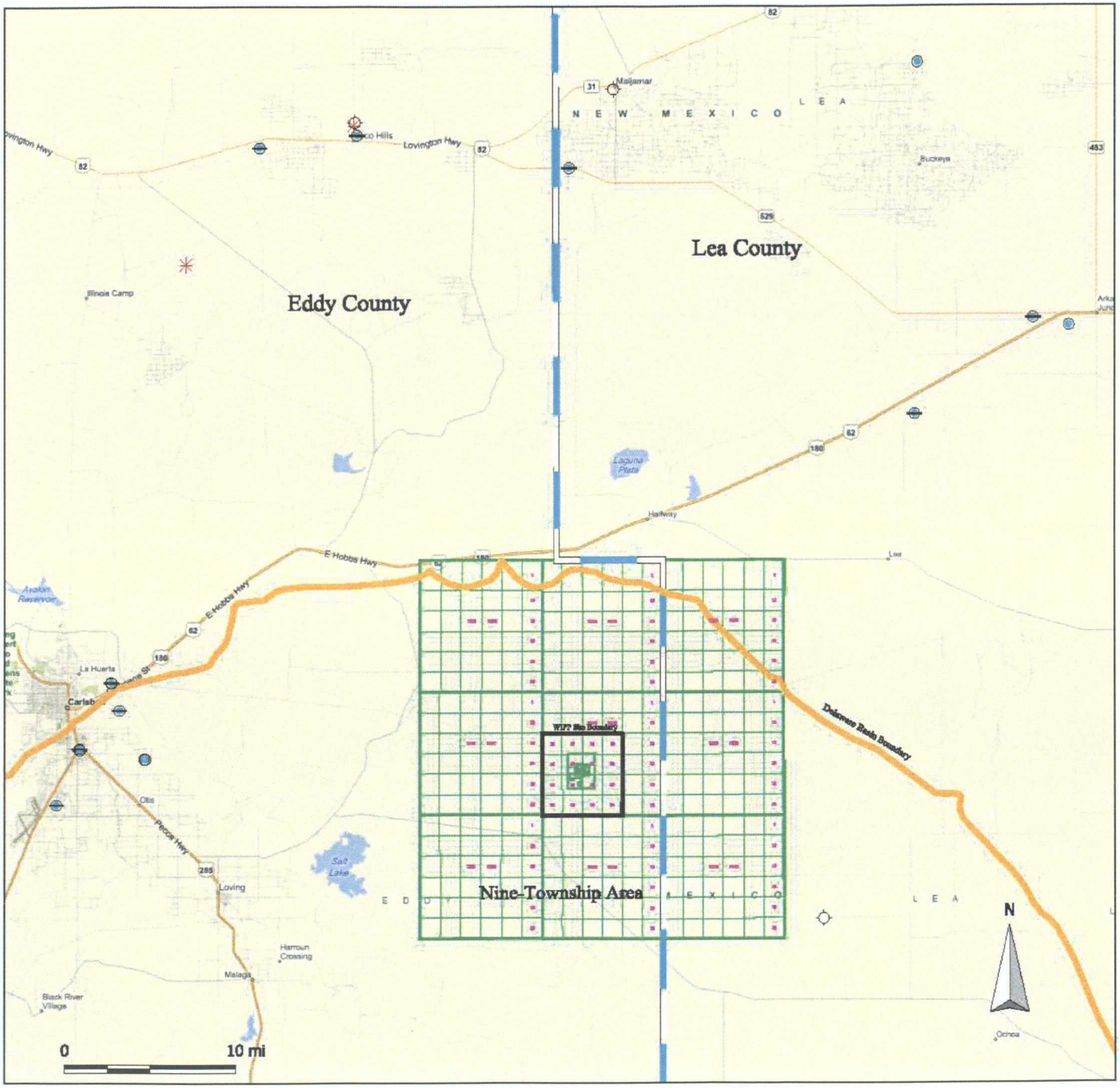
Note: Well status information is derived from the Delaware Basin well tracking application maintained by the Delaware Basin Drilling Surveillance Program. This tracking application is updated weekly with information from the New Mexico Oil Conservation Division records.

STATUS OF HYDROCARBON ACTIVITY
WITHIN ONE MILE OF THE WIPP SITE
MARCH 16, 2009



Note: Well status information is derived from the Delaware Basin well tracking application maintained by the Delaware Basin Drilling Surveillance Program. This tracking application is updated weekly with information from the New Mexico Oil Conservation Division records.

Brine Well Status in the Vicinity of the WIPP Site



● Active Brine Well
◎ Inactive Brine Well
⊖ Plugged Brine Well
○ Never Drilled
✳ Sinkhole

Delaware Basin Outline
WIPP Site Boundary
County Boundary

Note: Brine Well information collected through New Mexico Oil Conservation Division and status verified in the field by the Delaware Basin Drilling Surveillance Program.

Collapsed Brine Wells in the Vicinity of the Delaware Basin

Washington Regulatory and Environmental Services	Delaware Basin Drilling Surveillance Program

Modeling & Geophysics for EPA, DOE & WIPP

(Courtney Herrick-

Sandia National Labs)

9

Ground investigation in sinkhole terrains

In karst or any other terrain, a thorough site investigation precedes construction to assess the suitability of locations and appropriate designs for buildings and engineered structures; it involves the acquisition of all necessary information on the characteristics of the sites relevant to design, construction and the security of neighbouring land and structures (British Standards, 1999). Each investigation should be designed to meet the requirements of the building or construction to be carried out. A preliminary stage of the investigation involves a desk study and reconnaissance survey; this is followed by the main stage of detailed field exploration and ground investigation; data review then continues during the construction activities when ground excavations expose more details of the ground conditions.

In karst terrains, prior to any development and construction operations, a geohazard assessment of the possibility of sinkholes or subsidences occurring at any specific sites is necessary to determine its overall suitability for development (Chapter 10). Where a site is designated suitable, this assessment should help evaluate the risk of damage occurring to any of the buildings or structures that are erected subsequently. It should also help in design of any precautionary or mitigating measures that are required to reduce or eliminate this risk. However, an accurate assessment of the likelihood of sinkhole development is usually difficult where there is incomplete data relating to the potential sinkhole processes. Karst ground conditions are so highly variable that every site on karst can be regarded as unique. An overall description of karst ground conditions at a given site might prove of value in terms of the scale of anticipated foundation difficulties, but a full description should consider not only the karst class (Figure 2.11) but also the mean sinkhole density, typical cave size and rockhead relief (Waltham and Fookes, 2003).

Particularly important in sinkhole terrains, a feasibility study should be carried out before any development plans are drawn up, and this must evolve into a full ground investigation prior to final layout of a site and the design of its buildings and structures. A ground investigation in karst should not only attempt to determine the locations of any voids or caves in the ground, but should also determine the properties and character of the relevant soil and rock masses, the rockhead configuration and the hydrogeological conditions. Rock structure is important as dissolution voids are normally enhanced along fracture zones and at the intersections of discontinuities, while soil properties can indicate the susceptibility and characteristics of potential subsidence sinkholes (Figure 9.1). As sinkholes frequently make their appearance after periods of heavy seasonal rainfall or prolonged water table decline, long-term information on local meteorological conditions should be gathered, as should data on the location and status of water pipelines and drains. In terms of geotechnical engineering, the depth and relief of the carbonate rockhead may influence excavation and foundation design. The final evaluation also has to identify any restrictions on land use and the type of development that is suitable. Examination of ground conditions should continue during excavation and foundation works, as many of the details and peculiarities of the karst ground are unlikely to be revealed by cost-effective site investigation.

9.1 PRELIMINARY STAGES

A desk study is the first stage in gathering data for a site investigation. Its purpose is to make an initial assessment of the ground conditions and to identify, if possible, any potential geotechnical problems (Herbert *et al.*, 1987). The desk study includes a search for, and review of, appropriate maps, documents, archival records, literature, imagery and photographs relevant to the area or site concerned (possibly including those gathered on the initial site visit), to ascertain a general picture of the existing ground conditions prior to field investigations. This begins the process of constructing an adequate geological model for the site, presented in one or more conceptual block diagrams (Fookes, 1997). The model should present all relevant aspects and terrain components within the karst, and may appear comparable to any one of the diagrams in Figure 2.11, but will normally have more details that are site-specific. Subsequently, and dependant on potential interaction between the proposed construction and the geological model, a ground investigation will be designed and implemented. Alternatively, a desk study can be undertaken to determine the factors that affect a proposed development, as an aid to feasibility assessment and project planning. In all cases, the terms of reference for a desk study need to be defined clearly in advance of its implementation. The amount of effort expended in a desk study should relate to the type of project, the geological and geotechnical complexity of the area or site, and the availability of relevant information.

A desk study for the planning stage of a project can encompass a range of appraisals from the preliminary rapid response to the comprehensive statement. There are some common factors within this spectrum that always need to be taken into account. Whether preliminary or exhaustive, an appraisal report should include a factual and interpretative description of the surface and geological conditions, information on previous site usage, a preliminary assessment of the suitability of the site for the planned development, an identification of potential constraints, and provisional recommendations with regard to ground engineering aspects. However, a desk study is a component of a site investigation, and should not be regarded as an alternative to adequate ground exploration prior to a construction project.

During or at around the same time as the desk study, preliminary work should include a site inspection that constitutes a reconnaissance or a walkover survey of the ground. This involves noting, where possible, distribution of soils and rocks, surface relief, surface drainage and associated features, locations and dimensions of any actual or likely sinkholes, ground cover and obstructions, and any signs of earlier uses of the site such as tipping or previous construction. The inspection should not be restricted to the site, but should examine adjacent areas to see how they affect or will be affected by construction on the site in question and also to recognise features significant to the concepts of karst development.

As water movement is the main process behind the development of subsidence sinkholes, it is essential that the groundwater conditions are properly understood at any potential development site on karst. Much of this understanding will normally develop during the preliminary stage from a thorough desk study and a perceptive walkover survey. An effective site investigation must determine the depth to the water table, its relationship to rockhead and how this changes with

Figure 9.1. New subsidence sinkholes in thick soils are the most widespread hazard in karst terrains, and the likelihood or potential for their development is one of the prime tasks of ground investigations in karst.
TW.

time in relation to rainfall, seasons and any abstraction. It may also need to estimate the direction and scale of groundwater flow, and perhaps the chemistry of the groundwater.

The ultimate importance of the preliminary investigation is that it should assess the suitability of a site for any proposed works. If the site appears suitable, the data from the desk study and the walkover survey will form the basis upon which the site exploration is planned. The walkover survey also allows a check to be made on some of the conclusions being developed within the desk study.

9.2 GROUND INVESTIGATION FIELDWORK

Investigation methods fall into two groups, those that are intrusive (probing, augering, boring, drilling, pitting, trenching, sampling and testing) and those that are non-intrusive (geophysics and aerial or satellite remote sensing). Some extent of drilling and sampling is a component of almost every ground investigation. It is employed most effectively when combined with, or following up, comprehensive desk study and appropriate non-intrusive investigations, especially in the complex, variable and unpredictable ground conditions that typify karst (Section 9.6).

The use of most remote sensing imagery and aerial photography is restricted where sinkhole subsidence features may be just a few metres across, but satellite imagery is becoming increasingly sophisticated, including radar measurement of millimetric ground movements in urban areas (Section 9.4). Over the past thirty years, the use of geophysical surveys has developed considerably for the location and delineation of voids and bedrock surfaces (Section 9.3). However, no one geophysical method has yet been developed that resolves all the problems of sinkholes and cavities in karst terrain. A variety of surface traversing techniques provide readings at close station intervals, mostly for the location of shallow voids with lateral dimensions that exceed the depth of burial. Borehole to borehole geophysical methods can be particularly useful in determining the shape and dimensions of open or infilled voids, and there is continuous evolution of useful new techniques, but cost is increased where they rely on the drilling of boreholes (Section 9.3.8).

Hydrogeological investigations may continue into the fieldwork stages of a site investigation in karst. Depth to the water table can be refined from observations in investigation boreholes, which subsequently may need to be screened if they are to be used for monitoring purposes. Multiple monitoring points are required to determine the direction of flow by constructing groundwater level contours, where flow is approximately in the direction of the steepest gradient. Groundwater movement can also be monitored by use of tracer dyes, including those that are collectible in sub-visible concentrations and fluoresce under ultraviolet light. Monitoring may be from boreholes or sinkholes to others of the same or to one or more springs. The design of a groundwater dye-tracing programme needs to be carried out by a specialist, as the results can be extremely complicated in karst terrain (Quinlan and Ewers, 1989). It is a characteristic of karst aquifers that flow is through discrete conduits, and flow destinations may change significantly where high-level conduits become active at high stage, perhaps generating flow to different suites of springs during summer and winter (Crawford and Ulmer, 1993). The selected dye, the locations, timing and methods of dye injection, the sampling strategy used and the analytical methods used are all critical to the success of a tracing programme. The results can be especially critical where there is the potential for underground transmission of pollutants, notably from stormwater run-off from new highways across karst (Bednar and Aley, 2001).

9.3 GROUND-BASED GEOPHYSICAL SURVEYS

One of the major advantages of geophysical investigations over intrusive explorations is that information is obtained for much larger volumes of ground at lower cost (McDowell *et al.*, 2002). This is an important consideration in sinkhole terrains, because the probability of finding a small target sinkhole or cave within a large volume of ground is very low using point-sampling methods. The probability of finding a target of $10\,\mathrm{m}^2$ using 15 sampling points in a site of 0.5 ha is 3%, and this falls to 1.7% with 85 sampling points in a site of 5 ha (Hobson, 1992). That example is essentially 2-D, so uncertainty is further increased when the vertical dimension also has to be considered. However, geophysical surveys are not a replacement for drilling boreholes within ground investigation for engineering projects. They should be viewed as complimenting the boreholes, and perhaps guiding the borehole locations. Geophysical surveys are valuable because they provide an overview of ground conditions, of areas that may be small in specific applications, but are still large compared to the $0.005\,\mathrm{m}^2$ of a site area that is examined in a typical borehole. Because the gathered geophysical data relates to variations in the physical properties of a volume of ground as a whole, it must be processed and then interpreted in the light of a previously created conceptual ground model. Data processing has been vastly improved by modern computer capacity and software, and has been responsible for the major recent advances in geophysical applications. However almost all geophysical surveys still require confirmation by drilling into their detected anomalies (ground control, or ground truthing).

In general, geophysical methods involve the identification of anomalies – where there are spatial changes in physical properties. These changes may relate to changes in the soil or rock (in lithological variations, structure or fracture densities), or to extreme anomalies (including voids wholly or partially infilled with air, water or soil), or to changes with time caused by groundwater movement (including the growth of pollution plumes). Whether or not a particular geophysical method is inherently capable of detecting a change in physical properties is dependent upon a number of factors:

- the required depth of penetration into the ground;
- the vertical and horizontal resolution required for the anticipated targets;
- the contrast in physical properties between the target and its surroundings; and
- signal-to-noise ratio for the physical property being measured at the site.

As an example, a spherical, air-filled cave 2 m in diameter would be detected by a gravity survey if buried at a depth of 2 m, but not if it were at a depth of 10 m (McCann *et al.*, 1997). The magnitude of the anomaly diminishes with depth, and in this case is close to measuring accuracy of the instrument where the cave lies 10 m deep. If the cave is infilled with soil having a density close to that of the surrounding rock, the cavity would probably not be observed at all because the gravity anomaly would be below the resolution of the instrument. Environmental noise can also reduce the effectiveness of geophysical methods; seismic measurements might be difficult to make near to a busy highway due to vibrations from the traffic, and electromagnetic surveys are affected by proximity to buried, or overhead, electrical transmission cables.

Selection of the most appropriate geophysical method, or methods, for the detection of a likely karst cavity relates to various factors (McCann *et al.*, 1987):

- The physical properties of the cavity and the surrounding rock should be known to within an order of magnitude, so that the contrast in physical properties can be assessed. The necessary data may be available from the literature or from initial site investigation boreholes.
- Other effects due to the presence of likely cavities such as changes in drainage patterns should be considered. In such cases, the altered properties of the rock mass are likely to be detected.
- When the depth of burial of the cavity is more than two to three times its diameter, surface methods may not work and cross-hole techniques are likely to prove more useful.

Two examples of the selection procedure are presented in Table 9.1.

While selection of the most appropriate geophysical method, or methods, is important, this aspect forms only a part of the planning and execution of a geophysical survey as part of the overall site investigation. Too often, geophysical investigations have failed to satisfy the expectations of the engineer, not because geophysical techniques are inherently poor, but because they have been wrongly applied or poorly managed. Fortunately, the complexities of geophysical science have reached a stage where nearly all engineering geophysics is carried out by specialist sub-contractors, but it is still important to have the appropriate team involved at all stages, from planning through execution to reporting, of a site investigation that involves a geophysical survey.

9.3.1 Geophysical methods

Geophysical techniques can be divided into two principal types:

- Passive geophysics, that make use of the earth's inherent physical properties – its gravitational, magnetic, electrical, electromagnetic and thermal fields.
- Induced geophysics, that utilise artificial sources whereby signals are transmitted into the ground from seismic, electrical or electromagnetic sources.

Table 9.1. Assessment of the most appropriate geophysical methods for cave detection. After McCann *et al.* (1987).

Geophysical method	Example A *Air-filled cave, 5 m in diameter, at a depth of 5–10 m, in dry limestone above water table*	Example B *As in Example A, but in seasonal wet temperate climate, under clayey alluvium 1–2 m thick*
Electrical resistivity	Very little resistivity contrast	* Should be a large contrast in physical properties due to moisture in the limestone and drainage in the alluvium. Should detect cave by resistivity array; and delineate rockhead under alluvium by low-frequency electromagnetic survey
Seismic	*P*-wave surveys may be limited by attenuation. *S*-wave surveys possible but the wavelengths may be too long	* Closely spaced *P*-wave seismic refraction should show velocity and amplitude perturbations. Wave lengths for *S*-wave refraction may still be too long
Gravity	* May be a detectable anomaly if the host rock is homogeneous	Variation in overburden thickness may obscure any anomaly due to the cave
Ground penetrating radar	* Penetration of radar pulses would be >5 m and the cavity may be resolved	Radar pulse would be highly attenuated in the alluvium and saturated limestone
Magnetic	Only detectable if cave is part of old mine workings, with iron or brick debris	As for Example A

* Methods most likely to detect the cave under the specified conditions.

In both cases, the geophysical survey measures the vertical and/or lateral variation in a physical property in the ground. The data gathered must then be interpreted in terms of the ground conditions that are likely to give rise to the measured data set. A small void near the surface may create a gravitational anomaly of the same magnitude as that created by a larger void at greater depth. A conceptual model of the ground may help to resolve the interpretation. Alternatively, a more sophisticated data analysis, perhaps of an increased data set, may be able to distinguish the anomalies on the basis of their wavelength and profile revealed by Fourier analysis.

Table 9.2. Usefulness of geophysical methods for the detection of cavities.
After British Standards (BSI) (1999) and ASTM (1999a).

	Usefulness of method		
Geophysical method	BSI (1999)	ASTM (1999a)	Physical properties measured
Seismic refraction	1	B	Seismic velocity; largely related to variations in rock mass strength
Seismic reflection	2		
Cross-hole seismic	3		
Electrical resistivity sounding	2	B(A)	Electrical resistivity or conductivity; related to variations of porosity, fluid conductivity, degree of saturation
Electrical resistivity profiling	3		
Induced polarisation (IP)	0		
Electromagnetic profiling (EM)	3	A	
Ground probing radar (GPR)	3	A	*Same as electrical*
Gravity and microgravity	2	A	Density; related to lithology and fissuring
Magnetic	1		Magnetic field of ground materials
Downhole self potential	1		*Same as electrical*
Downhole resistivity	0		
Downhold neutron/gamma logs	0		Radioactivity; porosity, density, moisture
Downhole fluid conductivity	2		*Same as electrical*
Downhole sonic velocity	2		Seismic velocity (*see above*)

0 = not applicable; 1 = limited use; 2 = used, or could be used, but not the best approach, or has limitations; 3 = excellent potential but not fully developed.
A = primary method; B = secondary method.

It is essential that the geophysical interpretation be calibrated against information from previous investigations, boreholes and other sources, and efficiency is greatly improved if the survey is correctly targeted on the basis of an adequate geological model.

The usefulness of different, commonly available, geophysical methods can be summarised with regard to ground cavity detection, excluding lava tubes (Table 9.2). Within an overview of geophysical surveys in site investigation, none was generally considered as "excellent, with the technique well developed" for the specific task of cavity detection (British Standards, 1999). Overall, the most useful methods applicable in limestone karst are cross-hole seismic, microgravity, resistivity or

Table 9.3. Recommended methods for the geophysical location of specific dissolution features in karst.

After McDowell *et al.* (2002).

Karst feature	Dimensions	Recommended methods	Factors to consider
Pipes and hollows, with clay fill	Depth : diameter $< 2:1$	Conductivity traversing	Coil separation, *cf* depth
	Depth < 30 m	Magnetic	Local magnetic gradient
Pipes and hollows, with sand fill	Depth < 5 m	Ground penetrating radar	Conductivity of cover and fill, and cover thickness
Small open caves	Depth : diameter $< 2:1$	Conductivity traversing	Coil separation, *cf* depth
	Depth < 30 m	Microgravity	Density and nature of fill
	Depth > 30 m	Cross-hole seismic	Borehole spacing
Large open caves	Depth < 10 m	Ground penetrating radar	Ground conductivity
		Conductivity traversing	Cavity infill
	Depth > 10 m	Gravity and microgravity	Cavity infill, terrain relief
		Cross-hole seismic	Borehole spacing

conductivity profiling and ground penetrating radar. Some other methods could be used but may have serious limitations. Most of the same methods were recommended for cavity detection twenty years ago (Owen, 1983), except ground probing radar that was not then well developed. Other methods generally are considered to be inappropriate for cavity detection. More detailed guidance has been provided on the suitability of geophysical methods to locate dissolution features that include both caves and soil-filled pipes (Table 9.3). The principles that lie behind each of these methods, including theory, instrumentation and data processing, are considered in detail in available publications on geophysics (Telford *et al.*, 1990; Hoover, 2003; Reynolds, 2005).

9.3.2 Surface seismic surveys

Surface seismic methods involve measuring the velocity of transmission of vibrational energy from a hammer, falling weight, air gun, explosive or other similar source to an array of geophones, usually placed in a line across the area of interest. The calculated seismic velocities are functions of the density and elastic properties of the transmitting soils, rocks or rock masses, and are therefore broadly indicative of strength. Intact rock, fractured rock masses and weak soils are readily distinguished. Repeated measurements at the same site create strong signals that stand out from random noise, but seismic surveys may not work well in urban areas or on sites where heavy equipment is being used. The transmitted signal may arrive at the geophones via a number of routes depending upon the elastic properties of the rocks and soils and the position of the water table, having travelled along the ground surface or by a range of refracted and/or reflected paths through multi-layered ground structures.

Surface seismic refraction methods have a depth of penetration around one-third of the geophone spread (Hoover, 2003). Generally on their own they are unlikely to detect limestone pinnacles, steep-sided buried sinkholes and voids in bedrock, unless features are near the surface and greater than about 6 m across (McCann *et al.*, 1987). However, they may successfully identify the profiles of sinkholes that have flatter sides and a large velocity contrast between the rock and the infilling soil, as where soft alluvium overlies strong limestone; they provided excellent results in the investigation of features in the chalk at the Mundford site, U.K. (Grainger *et al.*, 1973). Also, rockhead pinnacles have been profiled where a pilot conductivity survey enabled the seismic lines to be located directly across the suspected pinnacles (Jansen *et al.*, 1993).

Seismic reflection methods that use a high frequency source may detect cavities at greater depths. This use of surface seismic surveys for cavity detection and rockhead mapping is a relatively new field and only a few experiments have been carried out (Luke and Chase, 1997; Harrison and Hiltunen, 2003).

9.3.3 Electrical resistivity surveys

Electrical geophysics measures the resistance of the ground to the passage of an electric current. Resistivity is increased, or conductivity is decreased, by the presence of air-filled voids, but opposite characteristics are created where bedrock voids are filled by wet clay soils. The objective, therefore, is to identify and interpret areas of anomalous apparent resistivity, but surveys may not work well in developed sites where buried metal or electrical cables are present.

A resistivity survey is carried out by placing electrodes in or on the ground surface. Usually, a current is passed between two input electrodes while the induced voltage is measured between two others. The ratio of voltage to current gives the resistance and the apparent resistivity is derived by multiplying this by a factor that accounts for the electrode spacing. Modern equipment allows multiple electrodes to be placed on a grid, where sequences of input and measurement electrodes can be selected. Depth profiles are produced by increasing separation of the measuring electrodes, lateral variations are mapped by traversing with constant electrode separation, and a combination of measured patterns produces an apparent resistivity image along a section through the ground. There are many variants on the electrode configurations used.

Electrical surveys may have poor resolution that is no better than around 10% of the depth (McDowell *et al.*, 2002). On karst, they cannot readily distinguish between individual large dissolution features and zones of ground broken by multiple narrow fissures, as is demonstrated by the variable situations revealed by drilling into identified anomalies. Perhaps more significantly, a zone of hazardous dissolution cavities, where some are open and dry while others are filled with clay, may not create an anomaly because the electrical survey lacks the resolution to identify the individual features with opposing resistivity characteristics.

Resistivity surveys have been used to locate buried and incipient sinkholes in soils overlying the chalk in southern England, and there has been variable success with different electrode arrays in different situations (Case study #9). A site with 1–10 m of silty clay overlying limestone in Pennsylvania was surveyed with a traversing dipole–dipole electrode array, where success was influenced by the orientation of the electrode array, by the electrode spacing and by the line spacing (Roth *et al.*, 2002). Voids in the limestone were not detected, and anomalies associated with sinkhole formation were not clearly defined, but the rockhead surface could be mapped with moderate accuracy. It is clear that the selection of electrode array and its spacing requires detailed understanding of the various methods and how these will affect the results from any particular site. Some knowledge of the site conditions, competent interpretation and appropriate boreholes for ground truthing are all essential to electrical surveys.

9.3.4 Electromagnetic conductivity surveys

Ground conductivity surveying involves the energising of a transmitter coil with an alternating current, so that its generated electromagnetic field induces small currents in the ground, which are then sensed by a receiver coil located a fixed distance away. It is described as non-contacting because it avoids the use of ground electrodes. Coil spacing and operating frequency are selected so that a direct reading of the apparent ground conductivity is obtained. Depth penetration of 6 m is achieved with a coil spacing of 4 m, but depth can be increased to about 30 m by increasing coil separation. Electromagnetic conductivity traverses can be carried out very rapidly, as a single instrument with a 4 m coil spacing can be operated by one person carrying it in use. Equipment with larger coil separations is more efficiently operated by two people. The method is most appropriate on undeveloped ground, as electrical cables, wire fences and most buildings can provide interference, reducing or distorting the signal. The output of a survey is a conductivity map. Positive or negative anomalies may be correlated with the location of buried or incipient sinkholes, depending upon the nature of any infill material; clay has a higher conductivity than sand, and most limestone has very low conductivity. Soil moisture increases its conductivity, and sinkholes may be wetter where they collect drainage or drier where they efficiently drain the soil. Data interpretation compares to that of resistivity surveys, but the method cannot be extended to greater depth penetration.

A pilot conductivity survey used vertical coils with a separation of 10 m to attempt mapping anomalously shallow rockhead and buried pinnacles at a site in Wisconsin where dolomite is overlain by 6–12 m of clay-rich, residual soil (Jansen *et al.*, 1993). Profile lines were at 15 m separations with every 10 m along each line, on a grid that was designed as a compromise between cost and the likelihood of detecting the anticipated anomalies. Some areas of low conductivity were found and were interpreted as shallow or pinnacled rockhead (Figure 9.2), and some of these were subsequently proved by drilling. However, it was decided that the grid spacing was too coarse for the final survey, so the profile and station separations should be halved and different coil separations should be used to try to locate pinnacles more accurately.

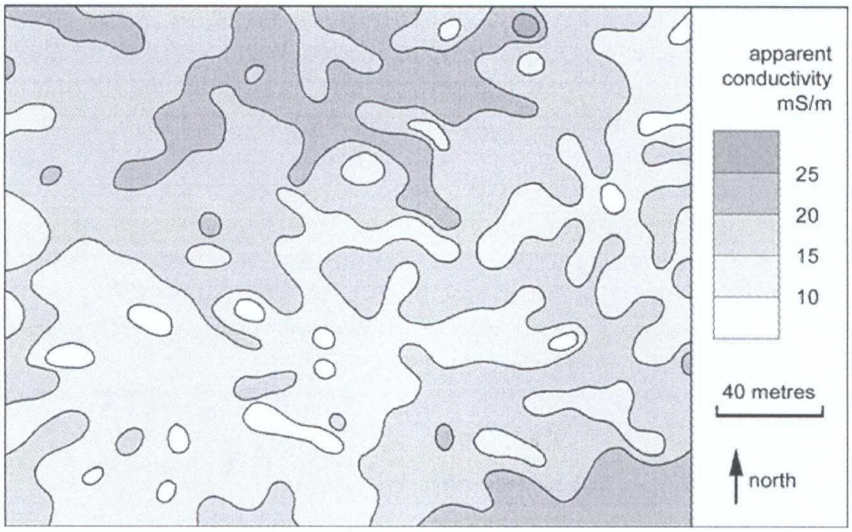


Figure 9.2. Apparent conductivity mapped over a site 250 m by 200 m in the covered karst of Wisconsin; areas of low conductivity, with light shading, are over shallow rockhead and dolomite pinnacles, while high values, shaded dark, relate to deep soil cover and buried sinkholes.
After Jansen *et al.* (1993).

9.3.5 Ground penetrating radar

The application of ground penetrating radar (GPR) involves the transmission of short pulses of high-frequency electromagnetic energy (25–1,000 MHz) into the ground through an antenna. Variations in the ground's electrical impedance produce reflections that are detected at the surface by the same or another antenna. A survey may trace a single line, as along a highway where the equipment can be conveniently towed behind a slowly moving car, or may cover a grid pattern of traverses. Variations in electrical impedance are mainly due to variations in the dielectric constant of the ground. Reflection of the input electromagnetic energy takes place where there are impedance contrasts. The radar signal is attenuated more in wetter materials that have higher conductivity, where depth penetration is therefore reduced. Similarly, clay soils have lower electrical impedances, and generally limit depth penetration to 6 m where dry or to only 2 m where saturated. The limited depth of penetration is one of the main drawbacks of GPR, though it is not always necessary to penetrate to bedrock; soil disturbance by movement or arching at shallow depths, that may precede development of a subsidence sinkhole, can create anomalous radar reflections that are identifiable. Soil cavities were detected at depths of 1 m in gravel overlying chalk in southern England, but the GPR could not detect voids at greater depths, probably due to the wet conditions (Case study #9).

In contrast, depth penetration reached 7 m in dolomitic limestone beneath a road in north-east England (Cuss and Beamish, 2002), and radar surveys have reached depths of 30 m in dry sandy soils in Florida. In profiling a site in central

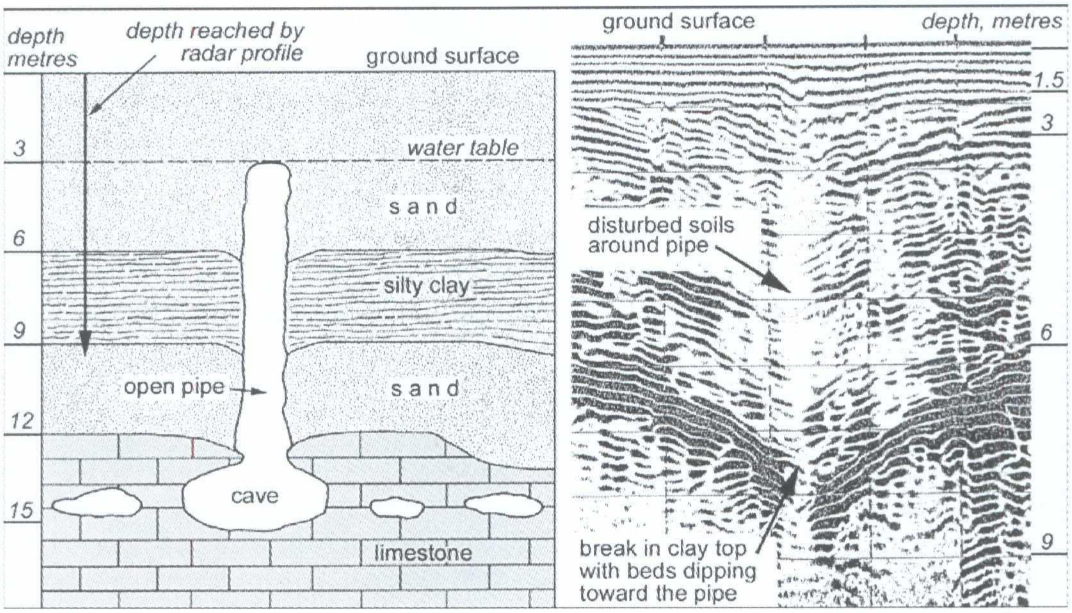


Figure 9.3. Profiles of pipes developing through soil over limestone in North Carolina; on the left, a conceptual geological section; on the right, an image from ground probing radar that could not reach below the clay; note that the ground section reaches deeper than the radar profile, on which the vertical scale is not linear, as it is time-dependant.
After Benson and Yuhr (1987).

Florida, where silty to clayey sands overlie 3 m of clay on top of rockhead 12 m deep on thick limestones, a GPR survey was able to identify both buried sinkholes and potential cavities in the limestone (Stangland and Kuo, 1987). At a site in North Carolina, limestone rockhead lies at a depth of about 12 m, but is overlain by a shelly sand and then by a silty clay with its top surface at a depth of about 6 m, beneath more sand (Benson and Yuhr, 1987). Strong reflections were only obtained from the top of the silty clay, but this allowed identification of small vertical piping features by depressions of this boundary and by disturbance of the overlying sands (Figure 9.3).

9.3.6 Microgravity surveys

Gravity and microgravity involves the measurement of small changes in the Earth's gravitational field that are caused by localised changes in soil and rock mass and density. They are particularly valuable investigations of karst, because negative anomalies represent "missing mass" which can then be interpreted either as open or water-filled ground cavities or as caves or sinkholes filled with soils of lower density than the surrounding rock. Measurements are made using extremely sensitive gravity meters, normally at a sequence of locations on a predetermined grid.

Early gravity surveys had very low resolution and were only applicable to large structures. The classic example in karst was the mapping of the very large buried sinkholes in the South African dolomite, whereby negative anomalies hundreds of metres across were, and still are, regarded as zones of hazardous ground (Kleywegt and Enslin, 1973). Subsequently, improved instrumentation and hugely refined computer analysis of the data has allowed the evolution of much more sensitive microgravity surveying. Stations spaced as closely as 1.5 or 2.0 m have been used in microgravity surveys, and yield increased benefits in that they provide a data bank from which cavity depths can be interpreted from the anomaly profiles. A gravity survey of a residential area in Kuwait used readings on a grid spacing of 7 m, as housing units were 14 m wide and readings could then be taken both inside houses and in their gardens (Bishop *et al.*, 1997). The search was for incipient sinkhole structures in 35–40 m of gravels and sands overlying the Dammam Limestone, but measurement stations on a 3-m grid were required in the areas of recorded sinkhole collapse.

Gravity measurements made at each station have to be corrected for a number of factors, including elevation (because the distance from the centre of the Earth varies), location (because the Earth is not a true sphere), ocean and Earth tides, drift in the calibration of the instrument and the gravitational attraction of nearby terrain features. Microgravity surveys can be carried out inside or outside buildings, and also in areas where electric cables and metal conductors limit the use of electrical and electromagnetic surveys. Along with GPR, they offer the only practical method for investigations in most urban environments. However, gravity surveys can become impracticably complicated by the excessive relief corrections that may be needed in mountainous regions.

A gravity survey was the best method of assessing flooded cavities beneath a limestone platform on Grand Bahama prior to grouting to stabilise the ground for construction of a container terminal (Case study #10). On a smaller scale, microgravity traverses around and beneath a building in Bowling Green, Kentucky, revealed the causes of structural distress arising from suffosion of the soil mantle into the karstic limestone bedrock 10–15 m down (Figure 9.4). The ground profile interpreted from the gravity data was confirmed with boreholes, and remedial grouting to fill the voids and compact the soils was directed to the negative gravity anomalies (Crawford *et al.*, 1999). A buried sinkhole in the gypsum at Ripon, England, was detected by a gravity low of −70 µgals. It was found in an area where bedrock is generally 11–14 m deep, and drilling encountered a sinkhole fill of loose sands, silts and clays that reached a depth of more than 40 m (Patterson *et al.*, 1995). However, there is no guarantee that a gravity anomaly will necessarily relate to a sinkhole. At a site with numerous fresh sinkholes in soils over strong limestone in North Wales, U.K., gravity anomalies were found, and were coincident with seismic refraction anomalies. However, drilling intersected only massive limestone, and the anomalies were thought to relate to either rockhead undulations or to variable lithologies in the drift cover (Nichol, 1998).

9.3.7 Magnetic surveys

Magnetic measurements record local variations and distortions in the Earth's magnetic field caused by the presence of underlying rocks with different magnetic

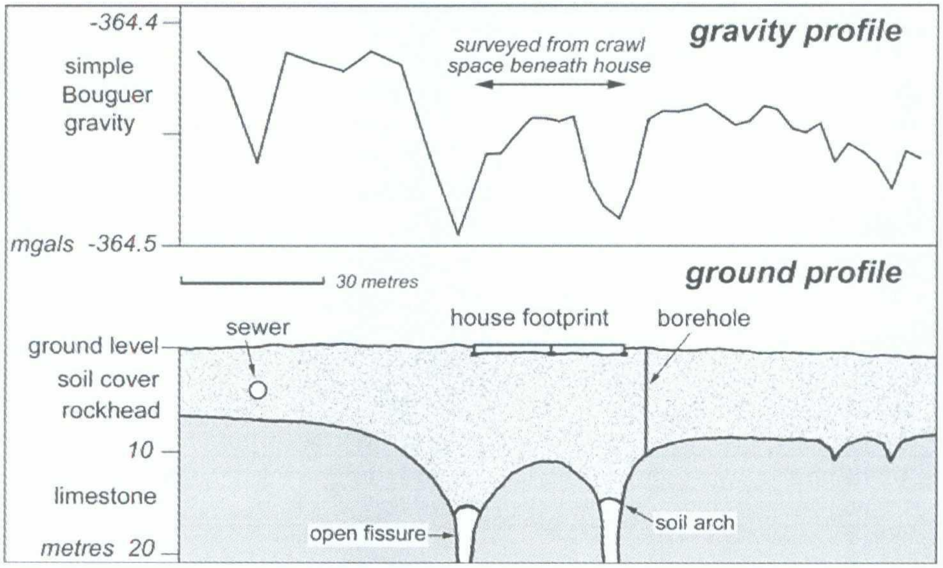


Figure 9.4. One profile from a microgravity survey, carried out in order to assess the subsidence sinkhole developing beneath a house in Kentucky; survey stations were at intervals of 1.5 or 4.5 m, and the data was calibrated and confirmed by boreholes to rockhead. After Crawford *et al.* (1999).

properties. They are quick, simple and economical, and the field data only requires corrections for diurnal variations in the Earth's field, normally monitored on site during the survey, though their integrity is reduced by nearby electrical and ferrous structures. Magnetic surveys are widely used for the detection of old and capped mineshafts, which usually have magnetic contrasts in their fill or lining. However, they are generally unsuitable for the detection of natural cavities and sinkholes, where magnetic contrasts are low or absent in limestones and soils. The exception is where small clay-filled buried sinkholes can be identified in pure limestone or chalk (McDowell, 1975).

Magnetic surveys have been used to detect lava tubes in magnetically conductive basalt. They have proved very effective at mapping systems of open tubes beneath rough terrain on the lava fields of Iceland (Wood *et al.*, 2002). GPR surveys on the same site were far less efficient, except that they could measure roof thickness over the tubes. Magnetic surveys have also been used to follow the evolution of tubes within active lava flows on the Etna volcano in Italy, but the detection of tubes containing hot flowing lava is barely applicable to most engineering sites (Budetta and Del Negro, 1995).

9.3.8 Cross-hole tomography

Most surface geophysical surveys can only be completed where the ground surface is not obstructed or disturbed by buildings, foundations, services or construction activity. Development of cross-hole geophysical methods, especially the technique of 3-D tomographic imaging, overcomes most of these problems, and can also provide far superior ground data. They do however require boreholes that are either available or purpose-drilled, though some costs can be saved by carrying out surface to borehole imaging. Pairs of boreholes are normally used to scan, electrically to seismically, from a transmitter in one borehole to receivers in another. A series of measurements are made by moving source and receiver up or down each borehole by a predetermined amount (usually 0.25 or 1.0 m) so that every possible ray path is scanned. Data manipulation then derives a physical property value for each of a grid of ground cells between the boreholes, and from these creates a 2-D tomography image in a vertical plane (Jackson and McCann, 1997). Multiple boreholes allow scans between every available pair, and the results can be combined into 3-D tomography; this has only become possible with advances in computer processing of the vast amount of data generated within a single survey. Most ground tomography is on seismic data, and the wavelength of the seismic signal

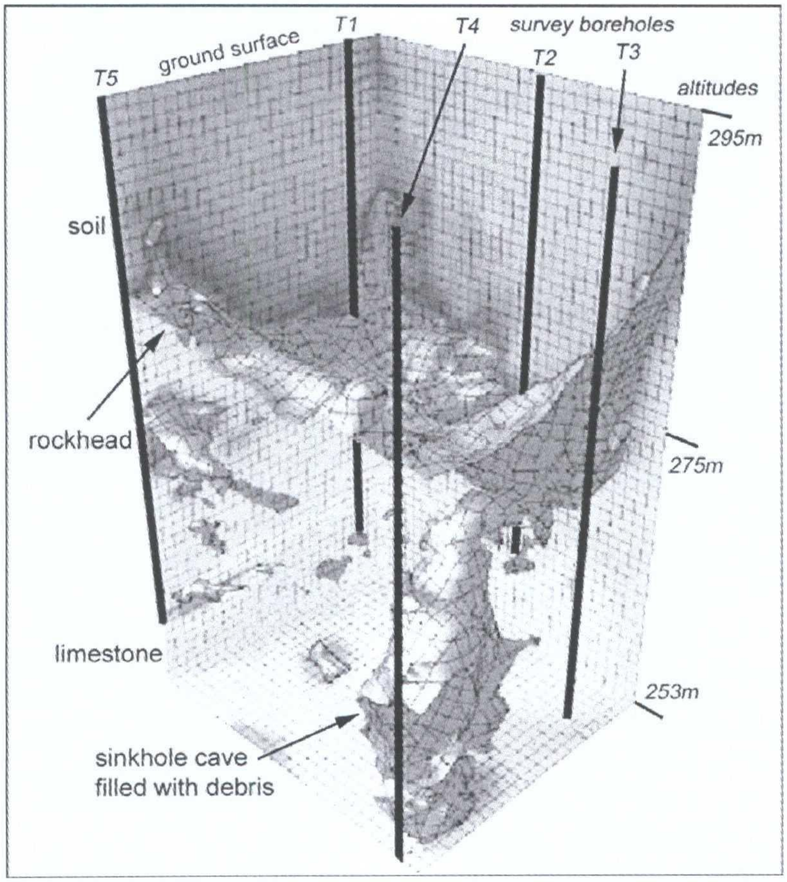


Figure 9.5. Image of a sinkhole beneath a road in Pennsylvania, produced by 3-D seismic tomography between five boreholes; the soil-filled cave that drains the floor of the sinkhole was verified by subsequent drilling.
Courtesy of 3dT/NSA Engineering.

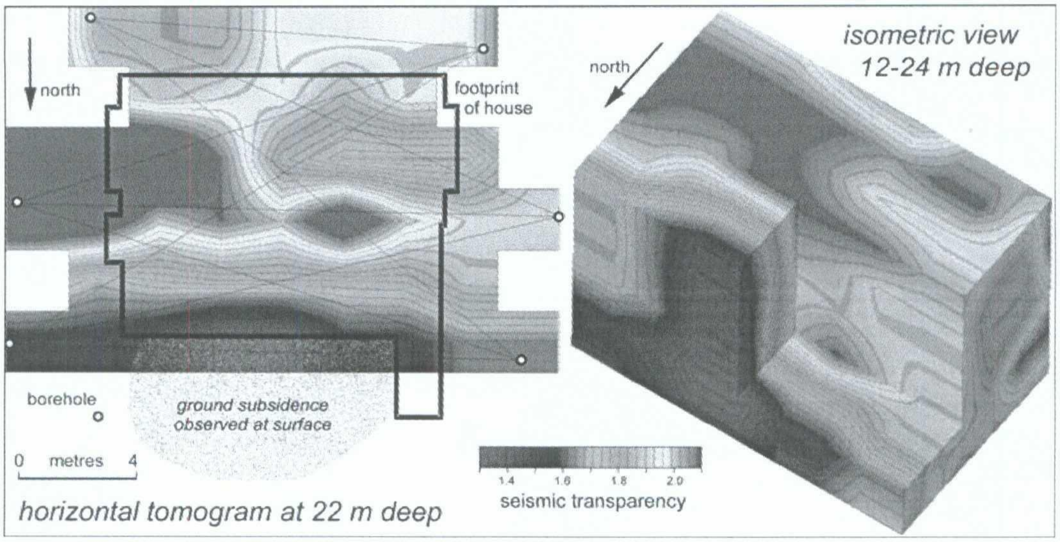


Figure 9.6. Seismic transparency tomography for ground beneath a house on soil-mantled chalk in southern England; both in the horizontal tomogram at 22 m below ground level and in the isometric projection of the 3-D tomography image covering depths between 12 and 24 m, the dark tones keyed to low seismic transparency show the zones of disturbed soil that are related to sinkhole subsidence.
After Jackson *et al.* (2001).

needs to be less than the average dimensions of the sinkhole target (McDowell and Hope, 1993). Comparable tomography can be based on electric resistivity measurements, and has been developed successfully beneath buildings threatened by sinkhole subsidence in karst terrains (Case study #16).

The quality of the tomography is a function of the nature of the ground, in particular contrasts in the physical properties, the number of borehole pairs, the distances between the boreholes and their location in relation to the target. In sinkhole investigations, tomography is usually only feasible where boreholes already form part of the site investigation or where a building or structure of sufficient value is so located that investigation from the surface is too difficult. Some 3-D seismic tomography has proved excellent, and the technique is perhaps the most useful, and most promising, that is currently applicable to sinkhole investigations where borehole access is available (Simpson, 2001). A ground image calibrated and presented in seismic velocities can provide a realistic model where intact bedrock limestone, open fissures, soil-filled caves, buried sinkholes, rockhead topography and disturbance zones in the soil cover are all identifiable (Figure 9.5). In the Chiltern Hills karst of southern England, a house 160 years old had suffered damage over a five-year period. It stands on sands and clays that overlie chalk, and the damage was caused by subsidence into a buried sinkhole. Ground conditions beneath the house were investigated by a 3-D seismic tomography survey (Figure 9.6), in which over 5,000 rays were scanned between 17 pairings among 7 boreholes that were sunk around the building (Jackson *et al.*, 2001). Because the ground was so disturbed, seismic amplitude was used, rather than velocity data, to create tomograms of empirical seismic (or acoustic) transparency. Observed surface subsidence had been at the north side of the house, where the tomography identified a deep zone of ground that is seismically opaque (of low transparency), and this was interpreted as the disturbed soil within or over a buried sinkhole in the chalk (Figure 9.6).

9.4 AIRBORNE AND SATELLITE REMOTE SENSING

Remote sensing data from both aeroplane and satellite platforms has been used as a part of site investigation for many years, but its use in the detection of sinkhole subsidence is mainly restricted to rural areas, and scale is then a critical factor. The resolution necessary for the detection of relatively small subsidence features (1.5–3.0 m across) is provided by aerial photographs with scales between 1 : 25,000 and 1 : 10,000. Colour photographs may be more useful than black and white ones since they can reveal subtle changes in vegetation related to subsidence and changes in moisture conditions. However, tones on monochrome photography are generally darker on healthy vegetation and wet ground, and these tonal contrasts can sometimes prove to be valuable indicators of soil water movement. False-colour infrared photography maps thermal emission, and has been used for both the identification of stressed vegetation, which might indicate problematical ground conditions, to locate wetter or drier areas, and also to detect hot or cold spots that might relate to cave entrances. Detail obtained from all aerial photographs should normally be represented on a site plan at a scale of 1 : 2,500 or larger.

False-colour infrared and black-and-white aerial photographs were used for hazard mapping of a freeway corridor across karst in Florida that is prone to solution and subsidence sinkholes (Padgett, 1993). On the infrared images at a scale of 1:40,000, vegetation around sinking streams appeared bright red and around active sinkholes it appeared dark red. Tonal variations could be used to determine the extent of enclosed drainage features associated with relic sinkholes and recharge zones. However, black-and-white photographs at a similar scale were not useful for determining the extent of closed drainage basins. At scales nearer to 1:10,000, aerial photographs can be used as stereoscopic pairs to identify subtle variations in the morphology of the ground surface, particularly if photography was in a season when vegetation is reduced and a low sun angle creates clear shadows to accentuate even the smallest of surface depressions (Figure 4.17). On false-colour infrared film, bright or deep red colours represent growing, healthy vegetation, probably related to wetter areas of poorer drainage that might be associated with sinkhole depressions that have a soil cover. However, if these soils are freely drained or absent, and vegetation is stunted or absent, the image shows pinkish to yellow and grey colours.

Radar and laser sensors on airborne platforms are being used to produce high-resolution (centimetre to metre) digital terrain models that are already finding application in floodplain studies, but may also be applicable for locating topographic lows associated with sinkholes where the depth of the depression is within the resolution of the technique. The LIDAR (LIght Detecting And Ranging) system sends a laser pulse from an airborne platform to the ground and measures the speed and intensity of the returning signal, in order to map ground elevation. Radar systems can produce results similar to those from laser. Satellite imagery has gradually improved in its resolution over time so that its use has extended into detailed geomorphological mapping and geohazard identification. The original LANDSAT images were limited by their low resolution, but new satellite imagery is more applicable to sinkhole studies in the style of airborne photography.

Satellite radar measurements are becoming increasingly sophisticated, and a technique known as PSInSAR or PSI (Permanent Scatterer Interferometry) uses radar data collected by satellites 800 km out in space. The PSInSAR method exploits a dense network of natural reflectors that can be any hard surface such as a rock outcrop, a building wall or roof or a road kerb. These reflectors are visible to the radar sensor over many years, typically in urban regions but also in partially developed rural areas, and are known as permanent scatterers. They are derived from the analysis of a stack of 30 or more radar scenes derived from repeated satellite passes, and the density of recognised permanent scatterers is about 1 per hectare in urban areas. Using this dense network of points common to all 30 images, corrected for contemporary atmospheric conditions, PSInSAR produces maps showing rates of displacement, accurate to a few millimetres per year and over extensive time periods. Data since 1992 is available from three satellites launched by the European Space Agency.

The PSInSAR process provides the millimetric displacement histories for each reflector point across the entire time period analysed, as calculated at every individual radar scene acquisition. Small incremental ground movements, that might be caused by gradual sinkhole subsidence, can therefore be detected. There are some disadvantages with the technique. If movement of a permanent scatterer is too great, coherence between one image and the next is lost, as the reflection point effectively vanishes because it has moved too much. Also, the full time series of movement since 1992 can only produce data along the line of sight from the satellite, which is at an angle of 20–30° to the vertical. It is possible to resolve movement only into vertical and north–south components, but this requires utilising both forward and backward images of the point on different passes of the satellite and requires a greater degree of computer processing. PSInSAR is currently too expensive for use in most site investigations, but it is likely that cost will come down as processing software improves and larger computers become available.

9.5 DIRECT INVESTIGATIONS

No single method of investigation is appropriate for locating and quantifying sinkholes in all circumstances. The most effective approach to a site investigation on karst is a combination of methods, usually involving those that are both indirect and direct. Some extent of drilling and probing is always likely to be required, and is also critical to confirming almost all geophysical surveys. Pinnacled rockheads and highly cavernous ground, in karst of classes kIV or kV, can require very large numbers of boreholes to adequately define ground able to bear construction loadings. In the notoriously difficult ground of Kuala Lumpur, Malaysia, geophysical surveys may not be successful in defining a founding surface for the piles for high-rise building foundations (Tan, 1987; Bennett, 1997). It is not uncommon to drill as many as 100 boreholes for each high-rise building to map out the variation in the limestone rockhead profile (Figures 5.3 and 5.7); this borehole density is ten times what would be expected to locate rockhead on schist or sandstone.

With particular regard to buried, suffosion and dropout sinkholes, the aim of an intrusive investigation is normally to provide evidence of ground truth in relation to the bedrock profile, particularly the shape and dimensions of the sinkhole and any ravelling zone, the geotechnical and hydrogeological properties of the soil and bedrock, and the groundwater conditions that may alter the character of the sinkhole in the future. Selection from the available techniques should be appropriate to the scale and nature of the immediate situation.

Among the various methods of direct investigation, there is an extra option that is specific to karst, because its ground voids are commonly large enough to be physically explored by a person. Though cavities in soil may be so unstable that direct entry is unsafe, caves in bedrock limestone may be perfectly safe for exploration by competent cavers, preferably by those with experience in exploration, mapping, geology and engineering (Figure 9.7). Physical examination and mapping are undoubtedly the most cost-effective means of investigating any mature cave passage or cave system that happens to lie beneath a construction site.

Pitting and trenching are commonly used in shallow soil investigations, to allow block sampling and visual inspection. Reachable depths are limited by safety considerations, and rarely can be adequate for useful investigation of sinkholes. However, a backhoe can often dig a hole that does not have to be descended to locate bedrock at depths of up to 4 m for less cost than deploying a drill rig.

9.5.1 Soil probing

Because the most widespread sinkhole hazard is the development of new subsidence sinkholes entirely within the soil profile, a large proportion of ground investigations on karst focus on the stability or potential failure of the soil cover. One concern is to locate soil cavities (referred to by the regolith arches over them in most of the American literature), that may migrate upwards to form a dropout sinkhole. The second concern is to find ravelling zones, where soil is disturbed and unstable due to losses into limestone fissures beneath, and may evolve into either a suffosion or a dropout sinkhole.

Soil voids can be located by the simplest form of probing, involving the manual pushing of steel rods, usually 12 mm in diameter, into the ground. Penetrations of as much as 6 m have been achieved in Florida, and these could be increased by use of a drop hammer, but results of such probing may be regarded as subjective (Handfelt and Attwooll, 1988). Conventional soil probing uses a light percussion rig with

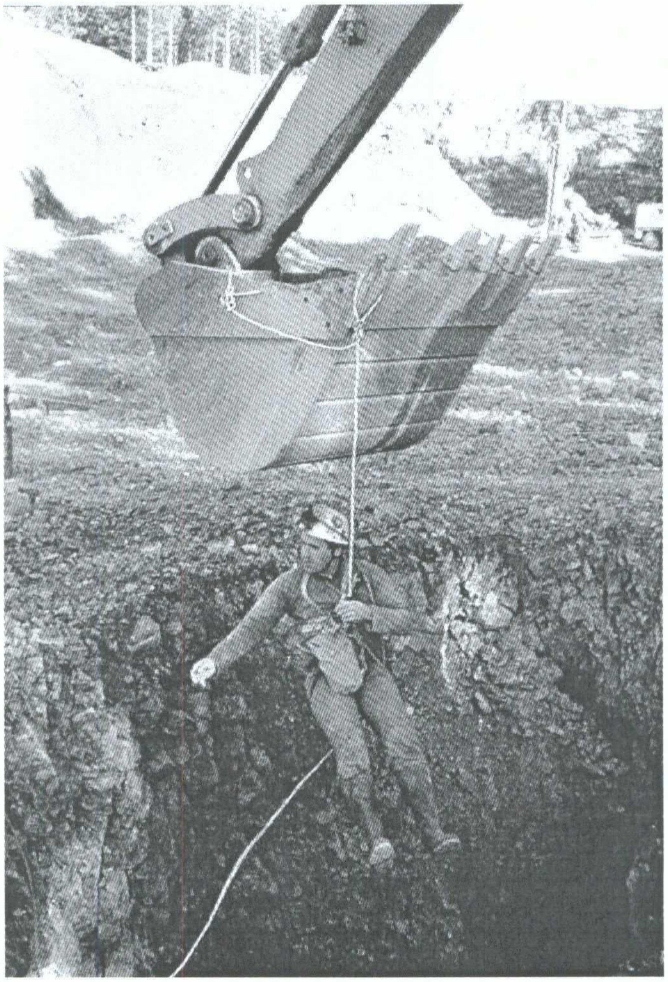


Figure 9.7. Direct exploration: an engineering geologist, who is also an experienced caver, abseils from an excavator bucket into a sinkhole that collapsed into an open cave during road construction in Slovenia.
Photo: Martin Knez.

capability of either driving a shell or turning an auger. Soil voids may also easily be recognised during a probing operation, either by the loss of end resistance, or by complete or partial loss of circulating fluid. However, the loss of flush return can be disastrous, as increased water flow through the soil profile is the most effective means of inducing sinkhole activity (Chapter 8). There have been multiple cases in Florida alone, where drill rigs deployed on sinkhole investigations have created their own subsidence sinkholes and thereby self-destructed. In the worst cases, drilling investigations at sites of modest ground subsidence under or adjacent to houses have created large new sinkholes, and thereby have caused major damage to the buildings under investigation. Where a potential hazard is recognised, by appropriate desk study, dry augering or air drilling becomes appropriate when direct investigation is essential.

The main type of probing in the less cohesive soils is the standard penetration test (SPT). A split sample tube is driven into the ground by means of a fixed weight dropping a fixed distance onto a drive head connected directly to the drilling rods (British Standards, 1999; A.S.T.M., 1999b). The number of blows to drive 300 mm is recorded and quoted as the N-value, usually measured at depth intervals of 1.5 m. The method is crude but effective. It is widely used, so test results are well understood, and the split sampler also produces a disturbed sample. Ravelling zones are widely identified by their lower N-values that reflect the disturbed and unstable nature of the soil. In the soil-mantled karst of Florida, ravelling is described as an isolated, continuous vertical zone of cohesive soil having N-values of 2 or less, or non-cohesive soil having N-values of 4 or less, and this zone forms a pipe surrounded by firmer, stiffer, or denser soil, to distinguish it from a laterally continuous layer of very soft or very loose soil (Zisman, 2003). This move towards a more specific definition of a sinkhole in Florida has been driven by the inclusion of sinkhole coverage in homeowners' insurance policies (Chapter 9) and by an increase in the number of disputes over whether damage has been caused by a sinkhole or by another process. Significantly this represents a narrowing of the definition of a sinkhole, by greatly reducing the threshold N-values from those cited previously by the same author (Zisman, 2001). However, some practitioners still regard the use of SPT in the recognition of sinkhole hazards as potentially misleading (Kannan, 1999).

More appropriate to investigations of cohesive soils, the Dutch cone or cone penetrometer test (CPT) involves continuously pushing a so-called friction cone into the ground by means of hydraulic rams (A.S.T.M., 1998). The cone resistance (Q_c) and the friction (F_s) on a sleeve immediately behind the cone are both measured to produce a continuous graphic log with depth. The cone can also be fitted with a porous sensor to measure fluid pore pressure. The ratio F_s/Q_c is known as the friction ratio (R_f), which can be used to recognise changes in soil lithology and density. Ravelling zones are indicated by low cone resistance, high friction ratio and negative values of a corrected pore pressure measurement (Wilson and Beck, 1988). The CPT is relatively cheap and easy to carry out because full-time supervision is not required, and results are simple to interpret with respect to identifying the depths to voids and associated weak zones. At a site of 200 ha in Pennsylvania, over 300 CPT soundings were completed as they were considered to be the most effective intrusive technique for investigating small sites for proposed building foundations (Pazuniak, 1989).

SPT and CPT results were compared at four sinkhole sites in Florida (Bloomberg *et al.*, 1988). The conclusion was that CPT is a superior technique because it produces more information, is sensitive to minor lithological variations and is particularly useful for detecting potential conduits and piping failures. For these reasons it may be regarded as a more cost effective method for sinkhole investigation. However, it does have a significant drawback in that progression of the cone can be stopped by relatively small stones or pieces of rock. With the SPT, run on a conventional light percussion rig, boring could remove the obstruction so that further tests could continue at greater depths.

9.5.2 Rock probing and boring

Rock is only penetrated by rotary drilling. This can produce an intact core inside a bit armoured with diamond or tungsten carbide. Alternatively, probing (or destructive drilling) simply bores a hole without retaining any rock core, and relies on flushed cuttings and penetration rates to interpret the ground conditions. Probing is quicker and cheaper, and is generally adequate for simple cavity searches in karst bedrock, once strata control has been established by a smaller number of cored holes. All rock drilling requires the use of a flushing medium to cool the drill bit and to bring cuttings to the surface. Loss of drilling fluid can be a valuable indicator of sinkholes or caves, especially where the fluid escapes through a narrow fissure that drains into an adjacent cave missed by the borehole. Uncased boreholes can be inspected by means of cameras or echo-sounders, especially where they penetrate a void. Rotary holes that breach an open or water-filled cave may have to be terminated where a steeply inclined cave floor prevents the drill biting in to continue the hole; if deeper exploration is required, it is often cost-effective to drill a second hole. Flush loss does not create a hazard in limestone, as it may only wash loose sediments out of any caves and is unlikely to induce any sinkhole failure. However, care is needed when drilling in salt due to the possibilities of very rapid dissolution, either by the normal water flushes or by chemically aggressive groundwater that is able to flow from another aquifer via the new borehole. Drilling in salt can use a brine flush, and all boreholes in salt and gypsum should be sealed after use; failure to complete the latter may lead to new sinkhole development shortly afterwards (Figure 9.8).

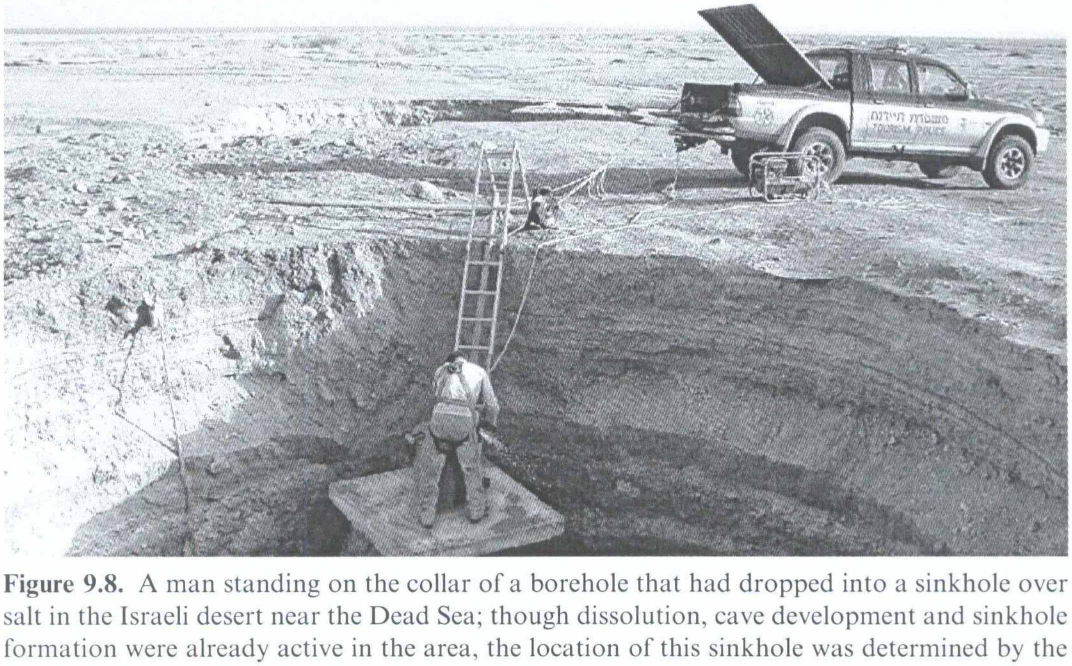
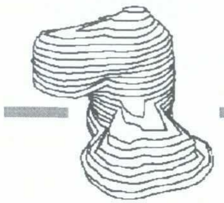


Figure 9.8. A man standing on the collar of a borehole that had dropped into a sinkhole over salt in the Israeli desert near the Dead Sea; though dissolution, cave development and sinkhole formation were already active in the area, the location of this sinkhole was determined by the borehole that was drilled to investigate the subsidence problem.
Photo: Mark Talesnik.

The optimum spacing and depths of investigation boreholes is particularly difficult to prescribe for the extremely variable ground conditions of karst. With respect to rock boring, both parameters must relate to potential cavity size and hazard. Minimum borehole depths are defined in terms of rock roof stability over caves (Table 7.1). Borehole spacing must be appropriate to specific site conditions relating to the potential cave size and the unsupported span that can be safely bridged by any proposed construction, and economies can usually be made where boreholes can target recognised geophysical anomalies. The frustrations of cavity searches were demonstrated by the unfortunate case of the Remouchamps Viaduct in Belgium (Waltham *et al.*, 1986). The five pier sites on limestone were investigated by 31 boreholes, all of which missed two caves at critical locations only found during excavation for the footings; the project was then halted to allow a second phase of investigation, but 308 new probes found no more caves. Minimising risk is one of the hardest tasks for the geotechnical engineer working on karst.

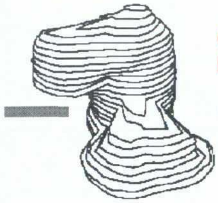


Sonar Testing in Bedded Salt Caverns and 3D-Presentations of Cavern Fields

Jason McCartney

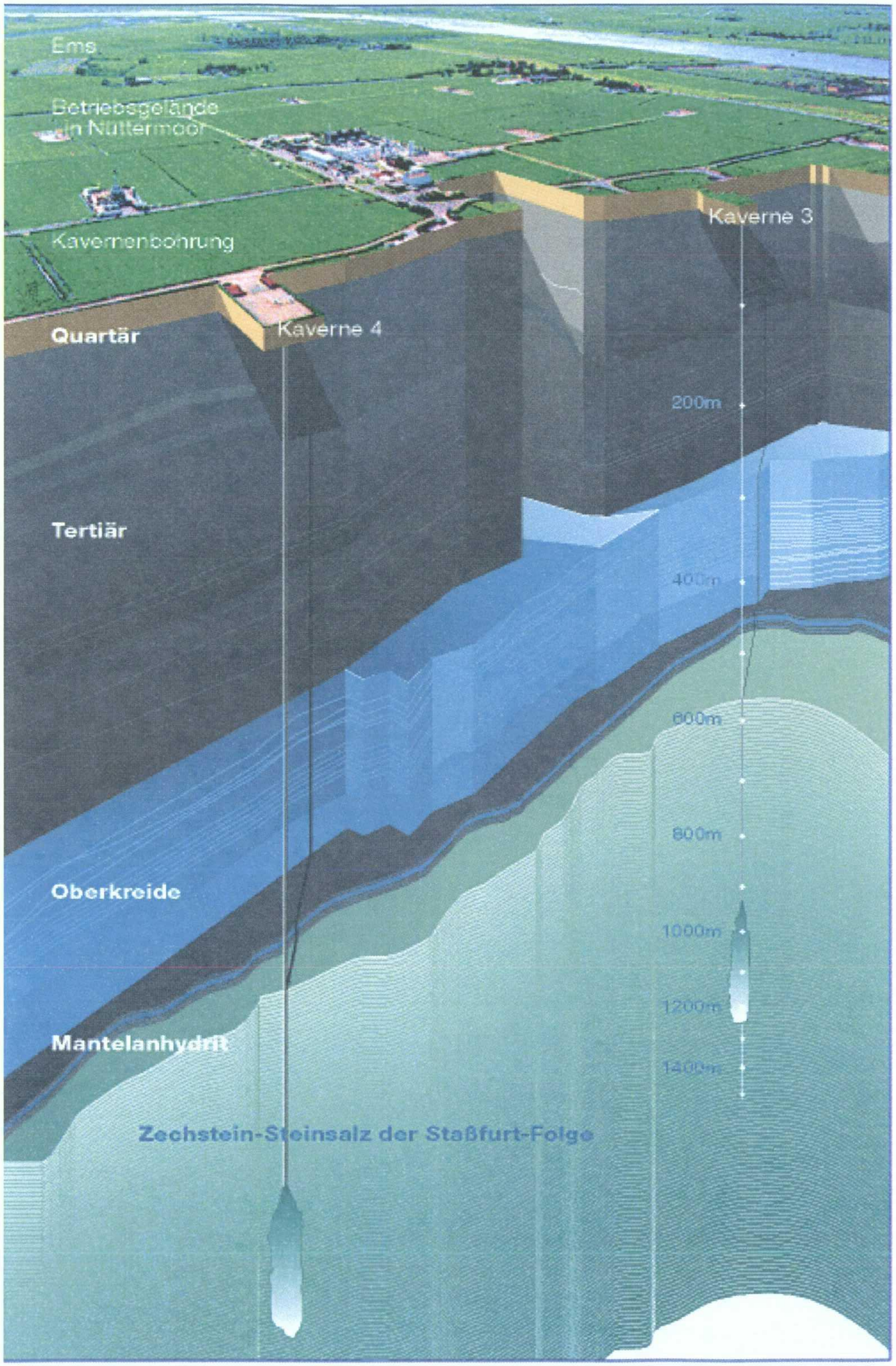
SOCON Sonar Well Services, Inc.
Conroe, Texas

NMOCD, Santa Fe, New Mexico
March 26-27, 2009

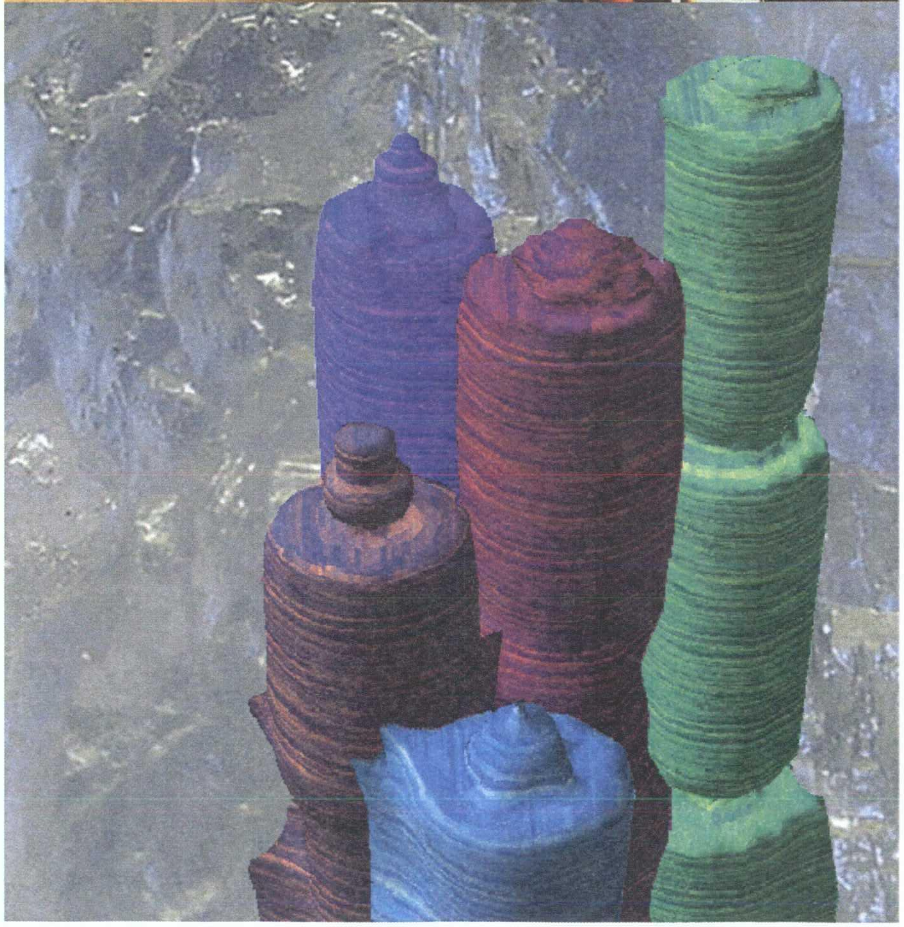


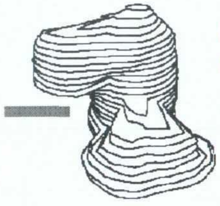
Structure

1. Introduction of SOCON Sonar Well Services, Inc.
2. Sonar surveying of bedded salt caverns
   - Problems and situations while working with bedded salt caverns
   - Possible surveying techniques on old and new caverns.
3. 3D-Presentation of cavern survey results
4. Conclusions



Thomas Piter





Services

SOCON

Cavern and Cavity surveys

- Ultrasonic and laser
- Blanket interface
- Logs
- sampling

Geodetic surveys and mapping

Software development

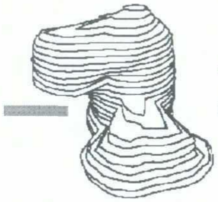
Thomas Piter

Own R&D department

Development and construction of geophysical survey tools

Client seminars

Patented tool technology

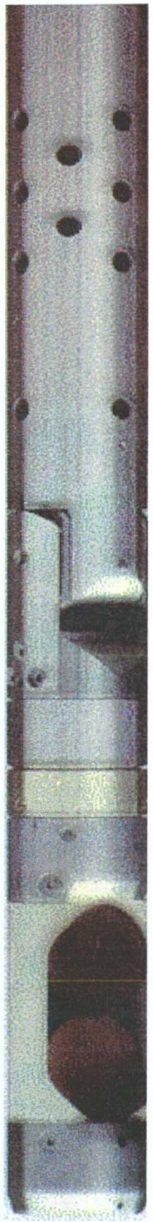


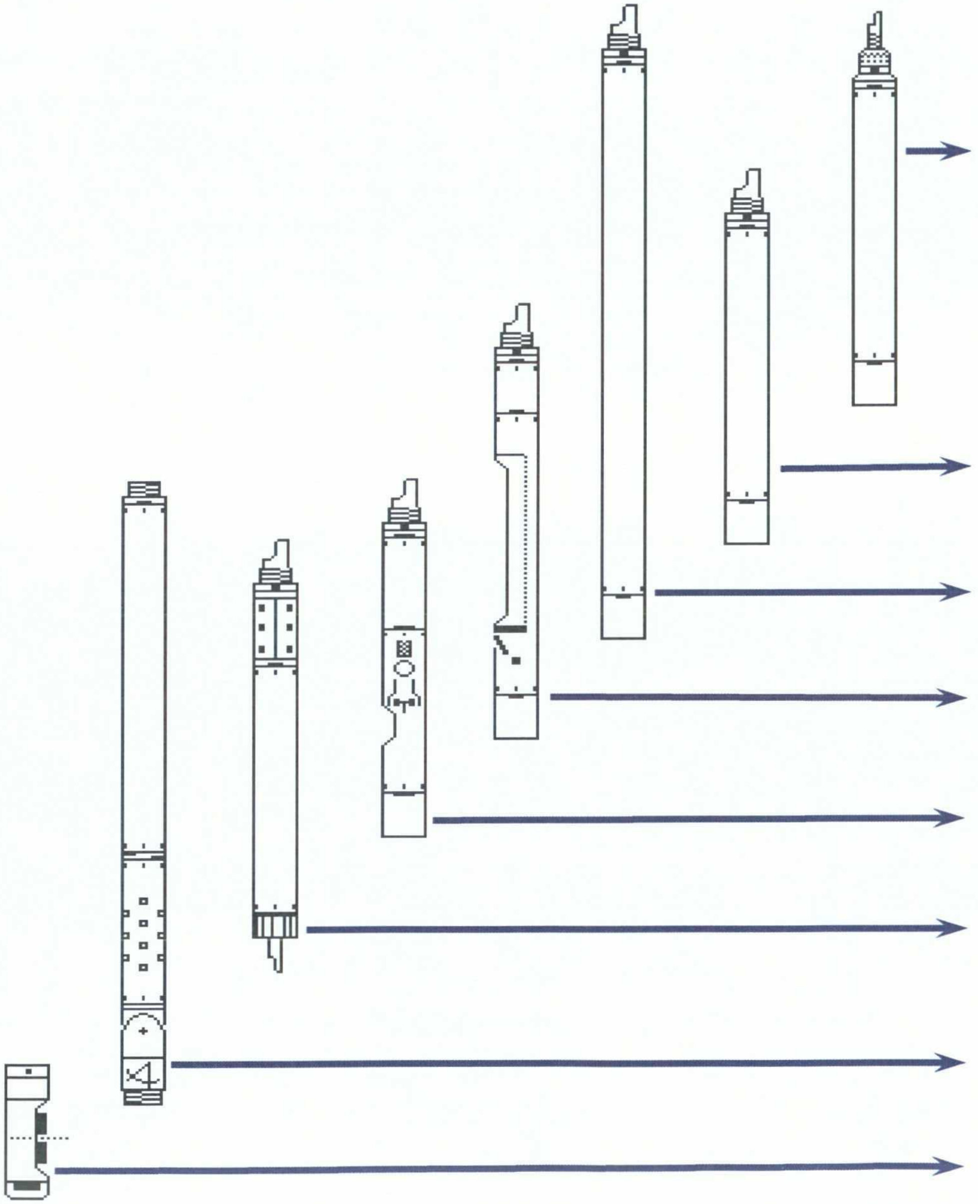
Applications for salt caverns

- **Crude oil and product storage**
- **Brine/Salt production**
- **Natural gas storage**
- Power plant
  (Compressed Air Energy Storage)
- Waste disposal

BSE echo tool

SOCON

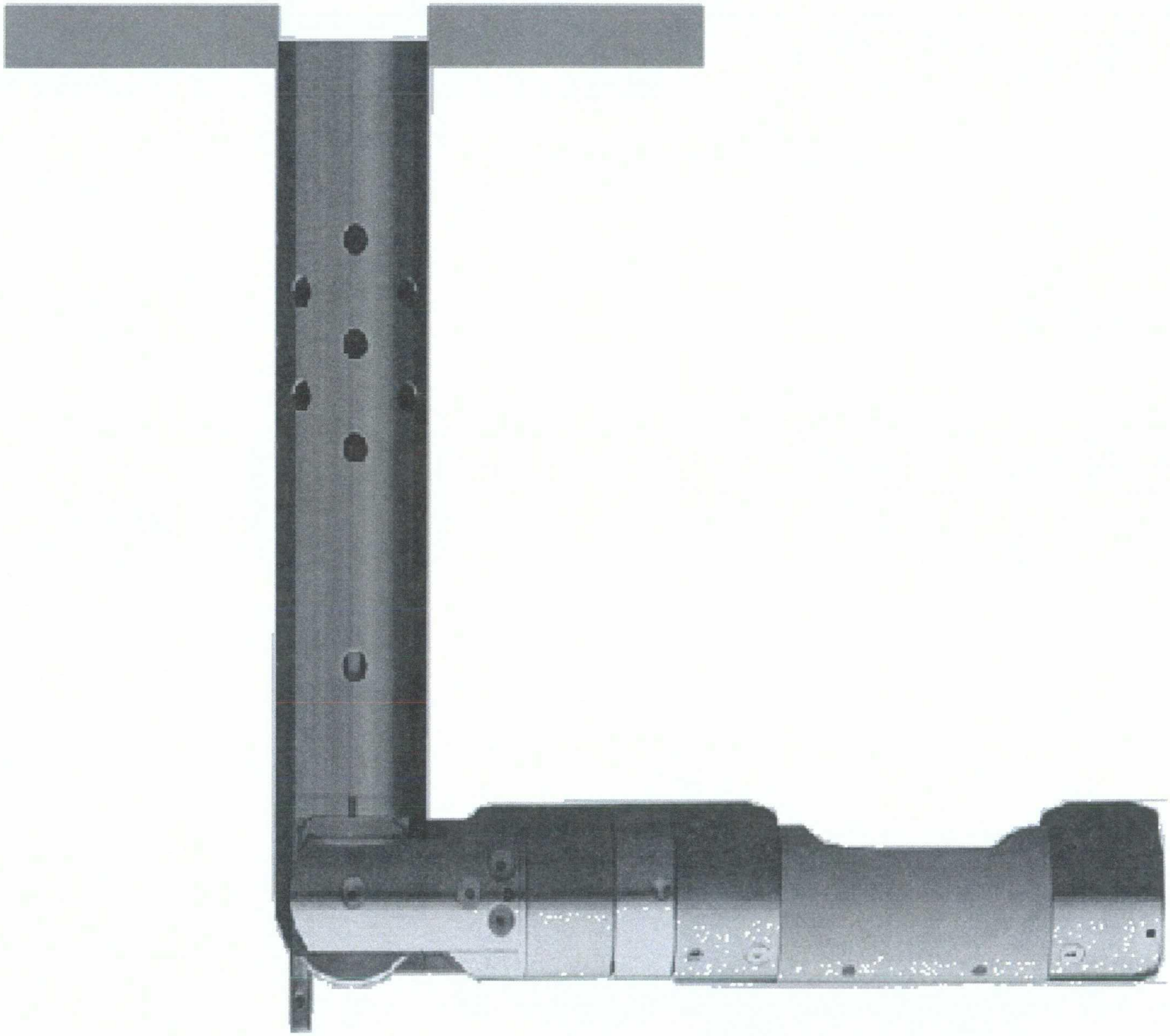




- power supply,

  gyro stabilizers
- fiber-optic gyro
- CCL, S-CCL, gamma
- acoustic velocity, pressure, temperature
- dew point
- rotation drive, pressure compensation
- compass, tilt drive
- ultrasonic transducers

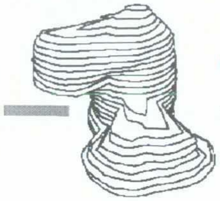
BSE tilt head



Technical data

SOCON

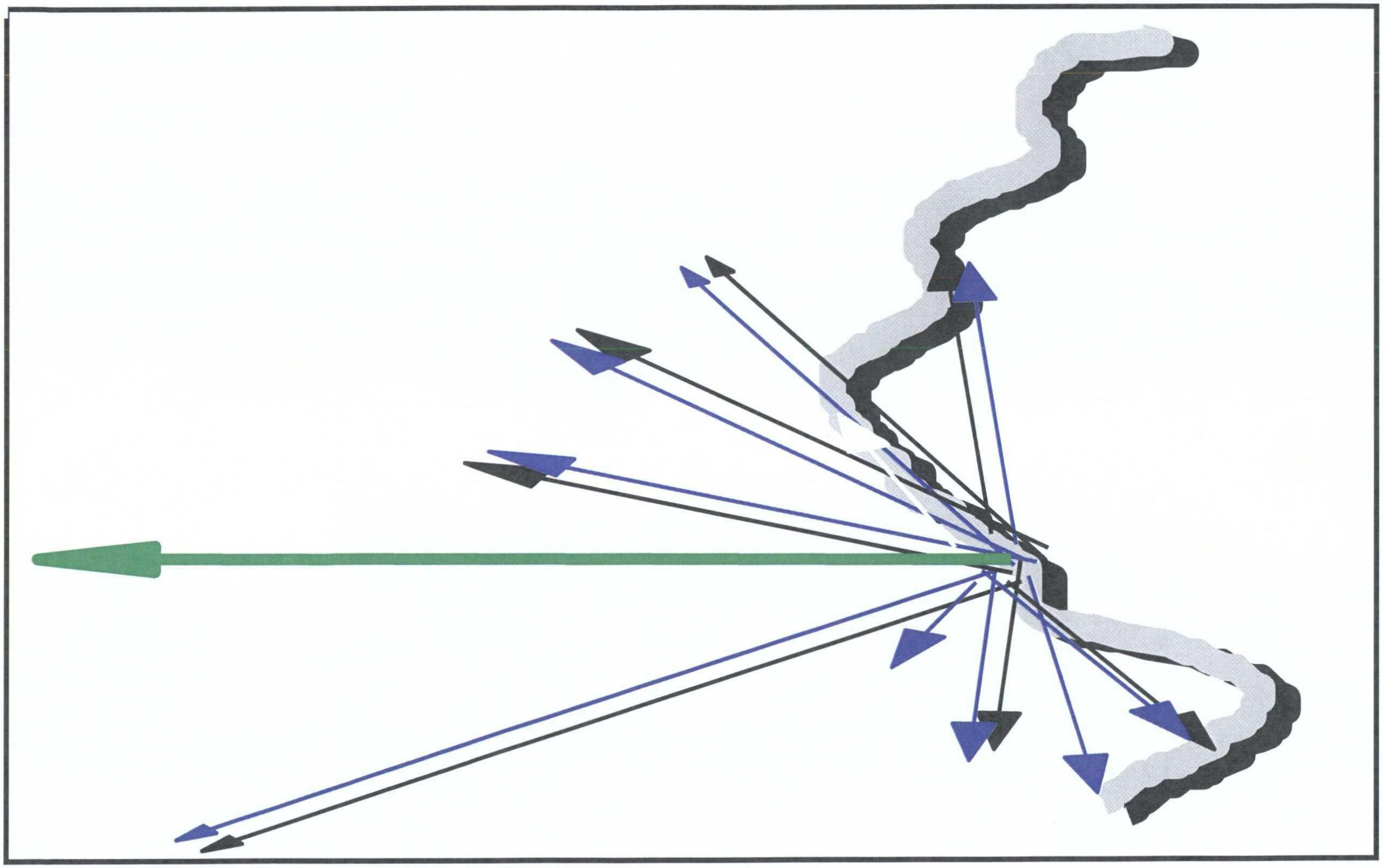
• Diameter	2,8" (3,7")
• Length/Weight	min: 19 ft. / 88 kg max: 28 ft. / 120 kg
• Cable	4-conductor
• Temperature range	32° - 170°F
• Pressure range	up to 4500 psi



Survey parameters (brine)

Acoustic velocity (ft/sec)	5740 - 6070
Angle of beam (°)	
minimum	0,4
normal	0,9
maximum	3,0
Maximum range (ft)	
no casing	~800
single casing	~220
double casing	~160

Reflection on the cavern wall



Reflections on the cavern wall

green = direct

black and blue = ricochet

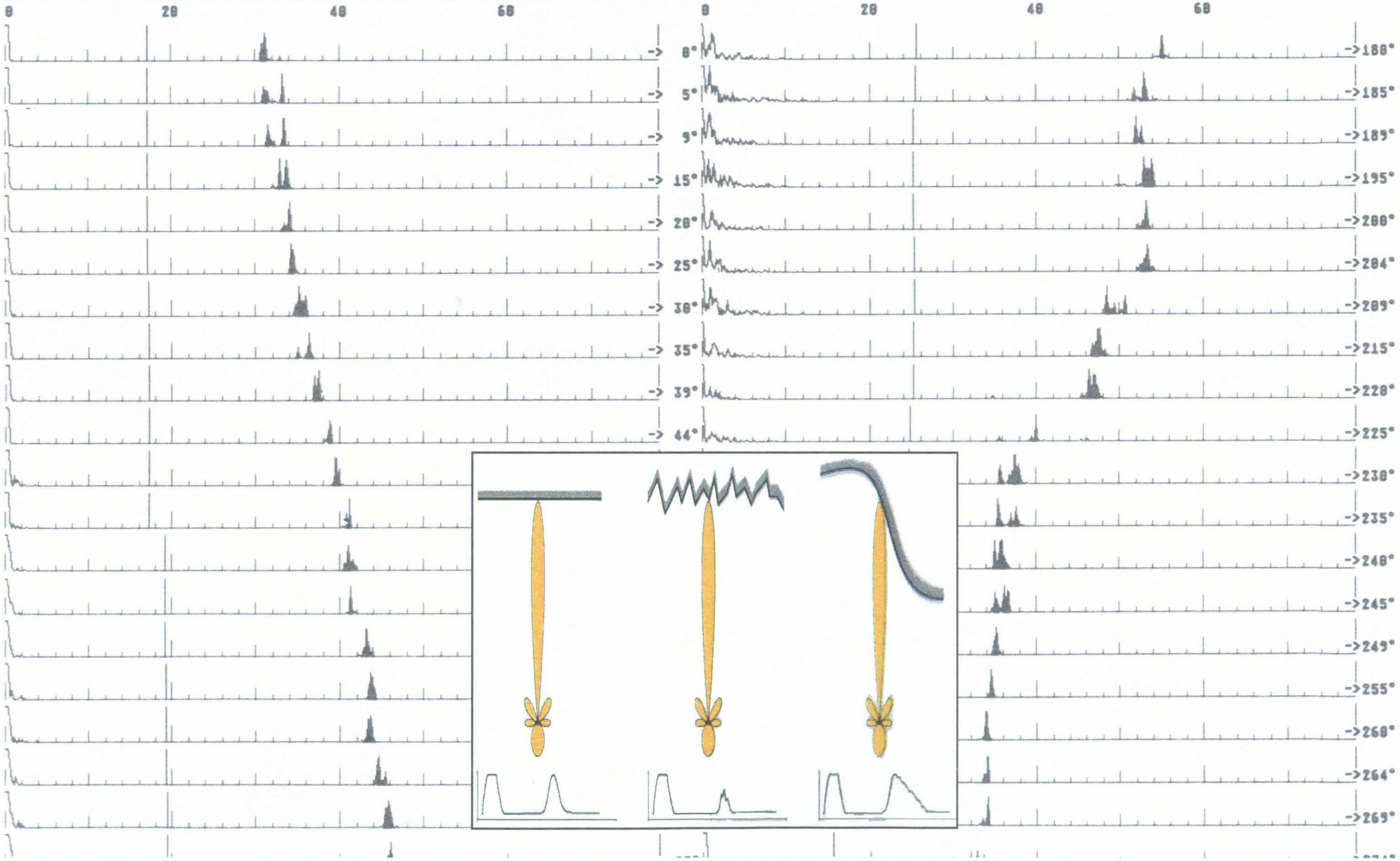
26.08.1997 14:35:34 - 14:37:40

E-D 150µs / Puls 99.4µs / SW -50% / TVG 0

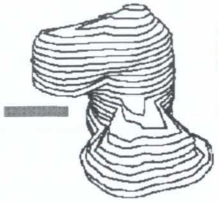
SOCON

NÜTTERMOOR K 16 Auftrag: 971080 26.08.1997 Prtk: 40 / 1

BSE13 Kopf13/9553 1810.0 m/s MAG H[2>-<2] 48° Tiefe 1029.00 m



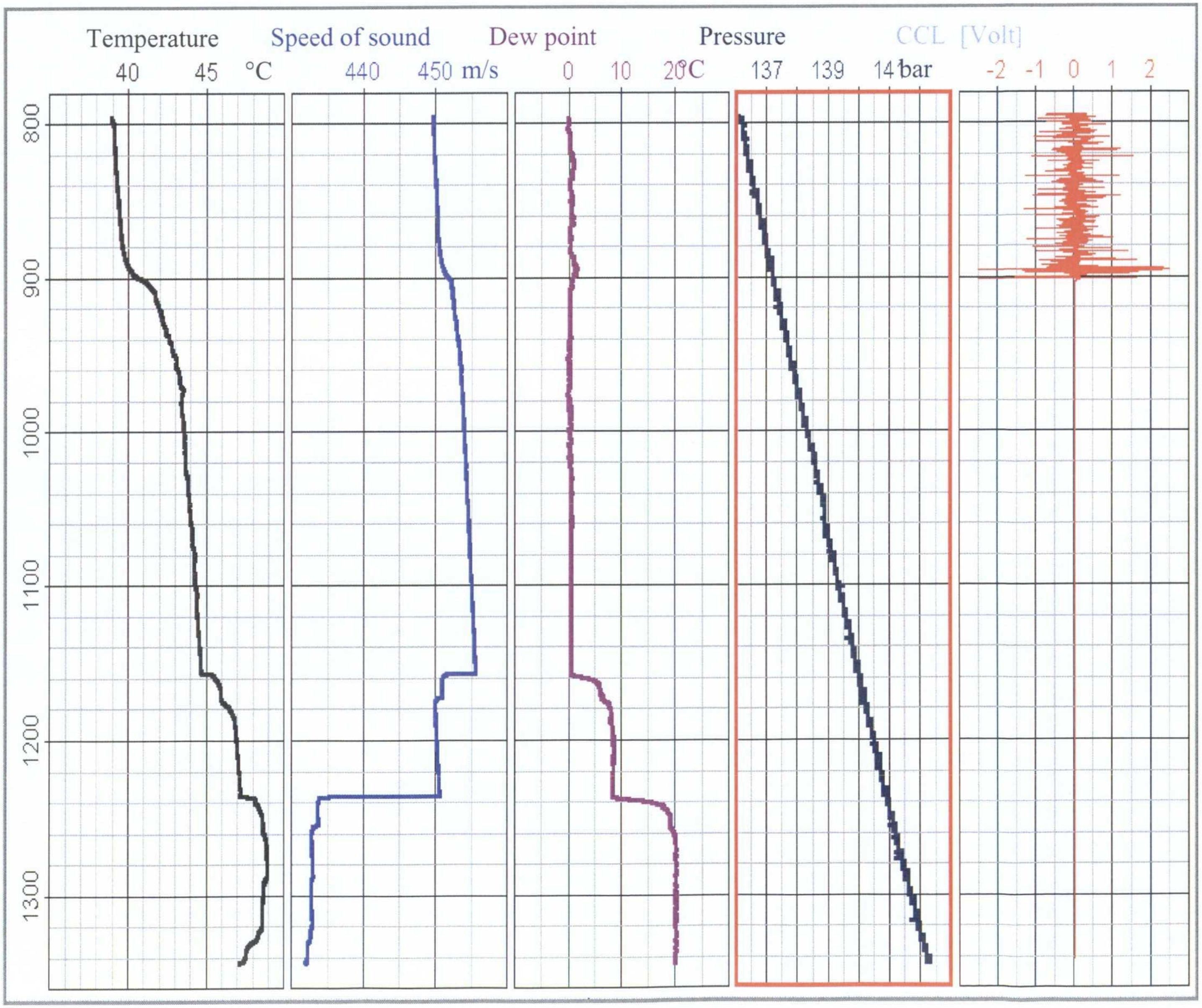
Surveying procedure (1)



S T A R T

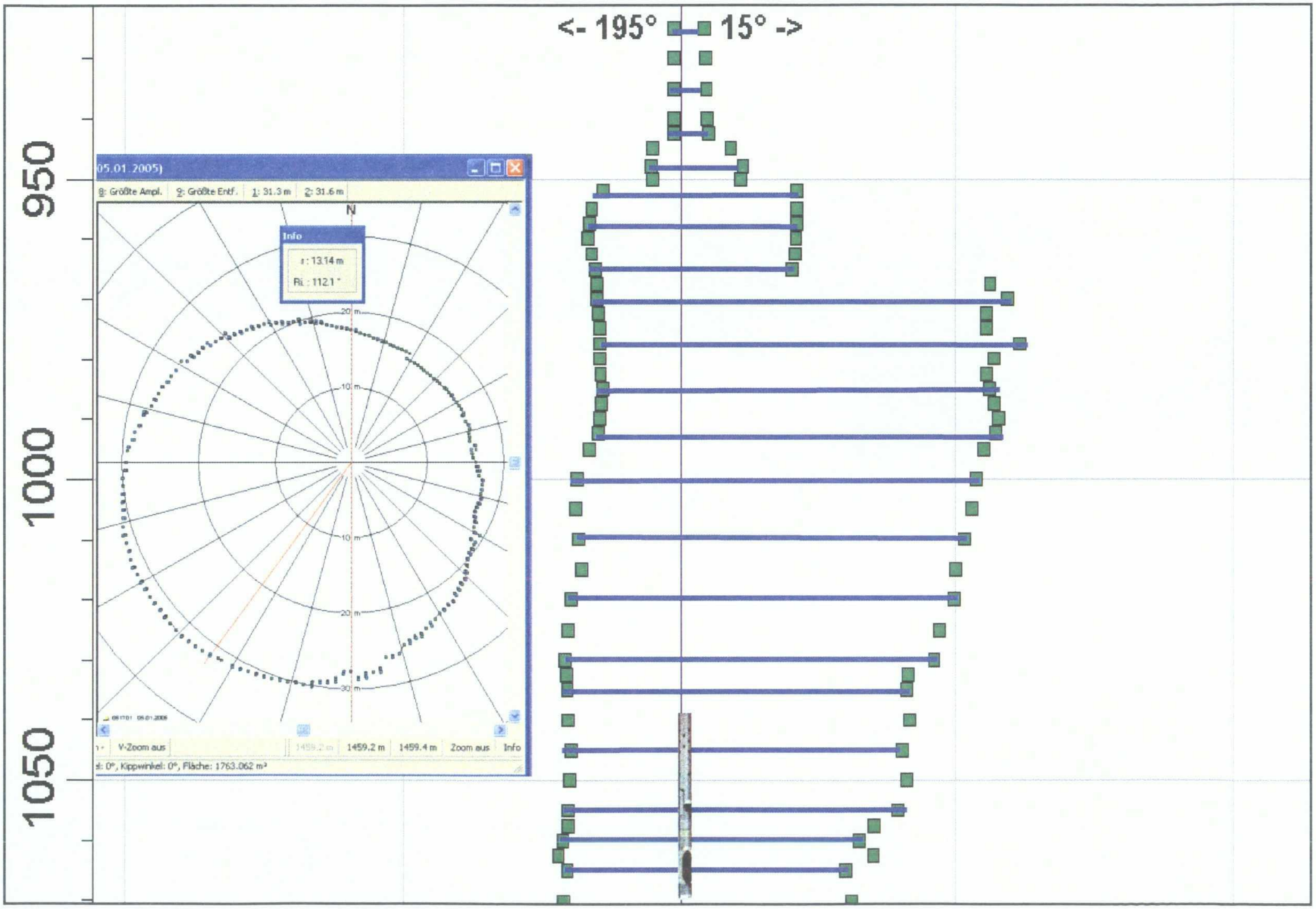
1. depth determination
temperature
velocity of sound
pressure (gas)

→ determination of parameters



Surveying procedure (2)

→ horizontal sections



1: 31.3 m

2: 31.6 m

r: 13.14 m

Ri: 112.1 °

1459.2 m

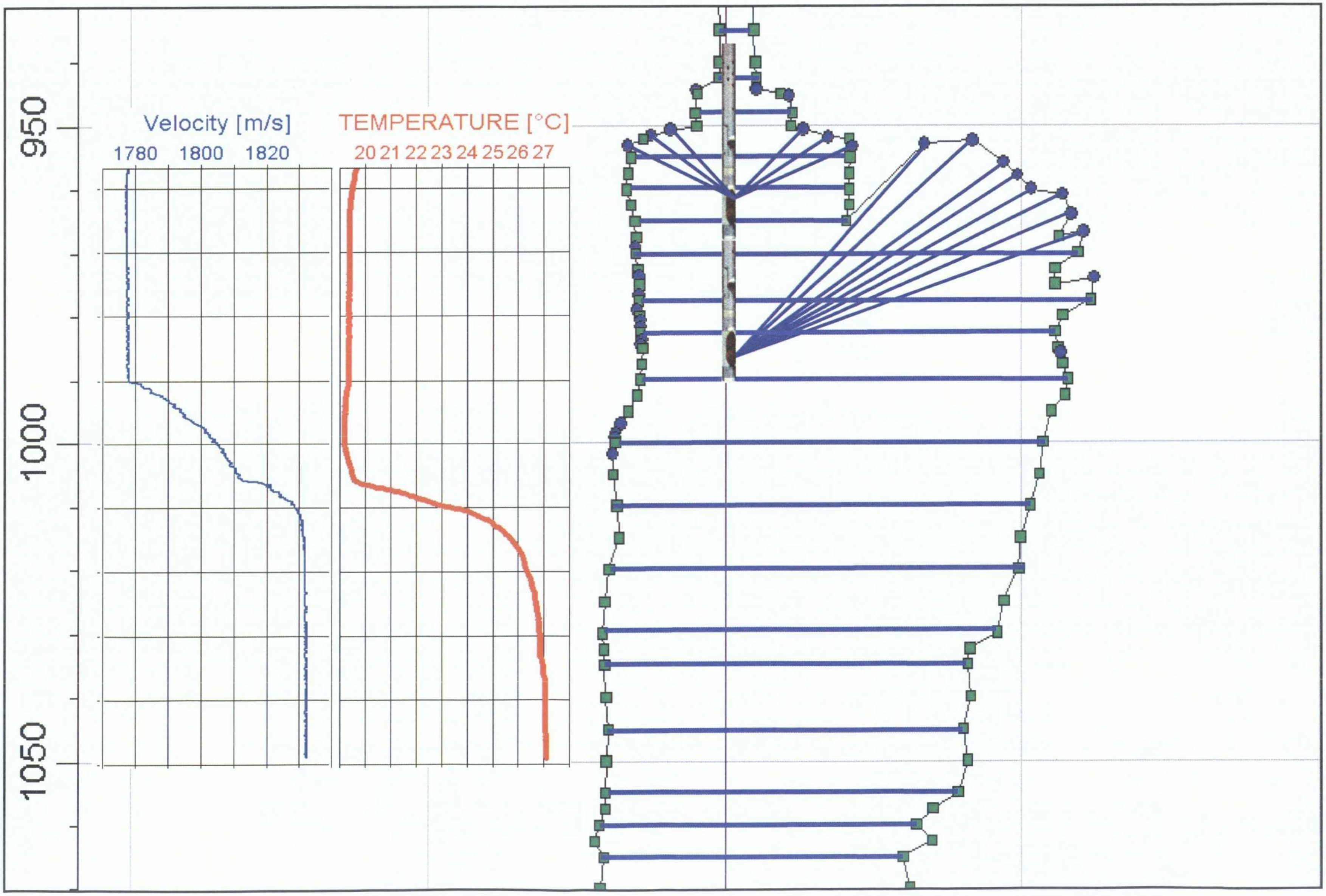
1459.2 m

1459.4 m

:l: 0°, Kippwinkel: 0°, Fläche: 1763.062 m²

Surveying procedure (3)

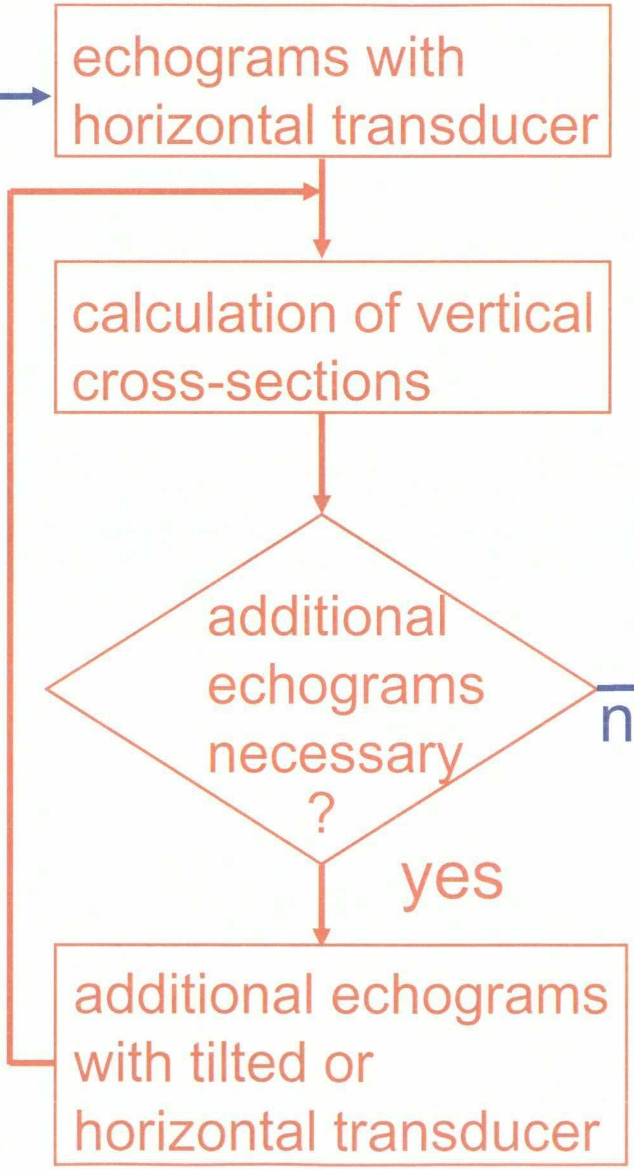
→ tilted sections



Surveying procedure (4)

START

1. depth determination
temperature
velocity of sound
pressure (gas)



echogram with horizontal transducer

calculation of vertical cross-sections

additional echograms necessary ?

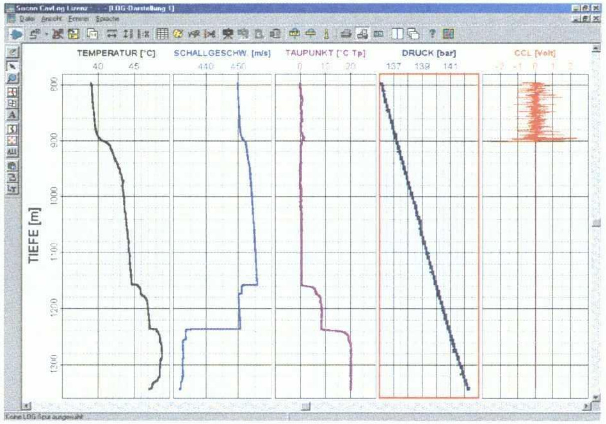
yes

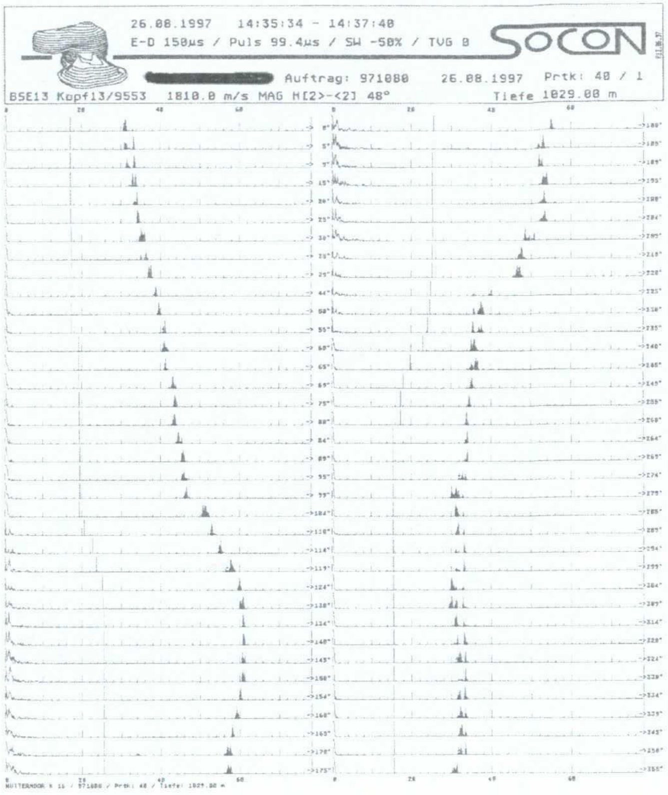
additional echograms with tilted or horizontal transducer

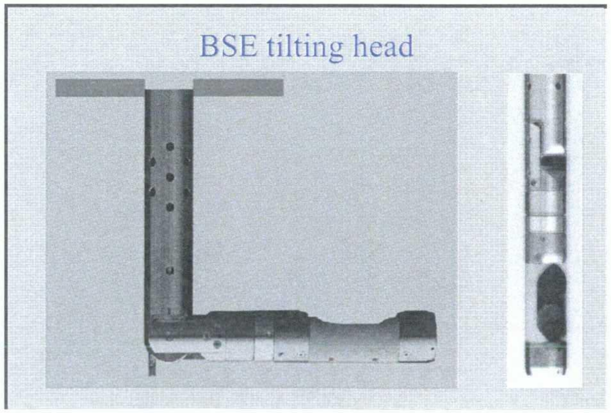
no

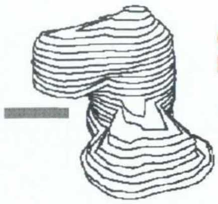
2. depth determination

END




26.08.1997   14:35:34 - 14:37:40
E-D 150µs / Puls 99.4µs / SW -50% / TVG 8
[redacted] Auftrag: 971080   26.08.1997   Prtk: 40 / 1
BSE13 Kopf13/9553   1810.0 m/s MAG H[2>-<2] 48°   Tiefe 1029.00 m


BSE tilting head



Structure

SOCON

1. Introduction of SOCON Sonar Well Services, Inc.
2. Sonar surveying of bedded salt caverns
   - Problems and situations while working with bedded salt caverns
   - Possible surveying techniques on old and new caverns.
3. 3D-Presentation of cavern survey results
4. Conclusions

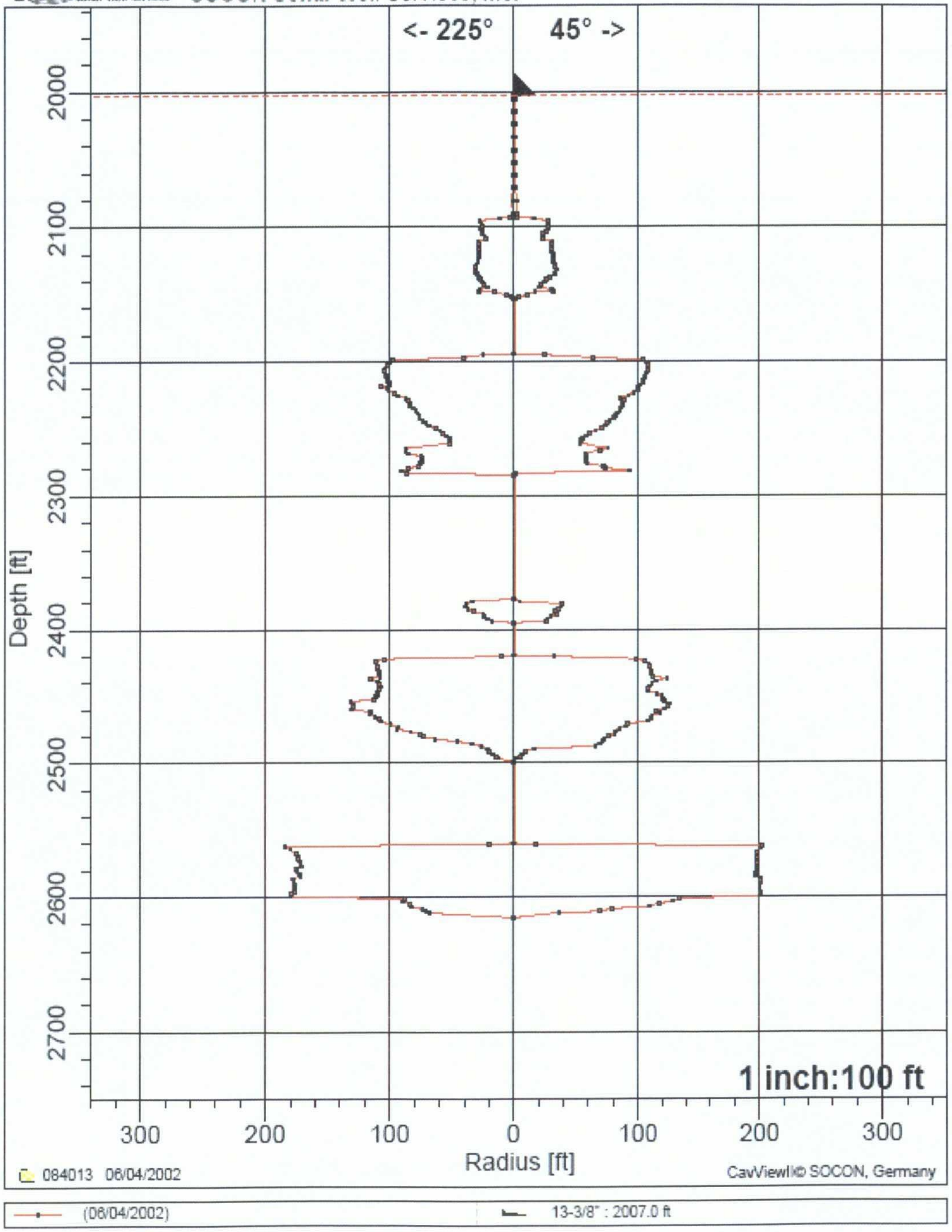
Problems and Situations

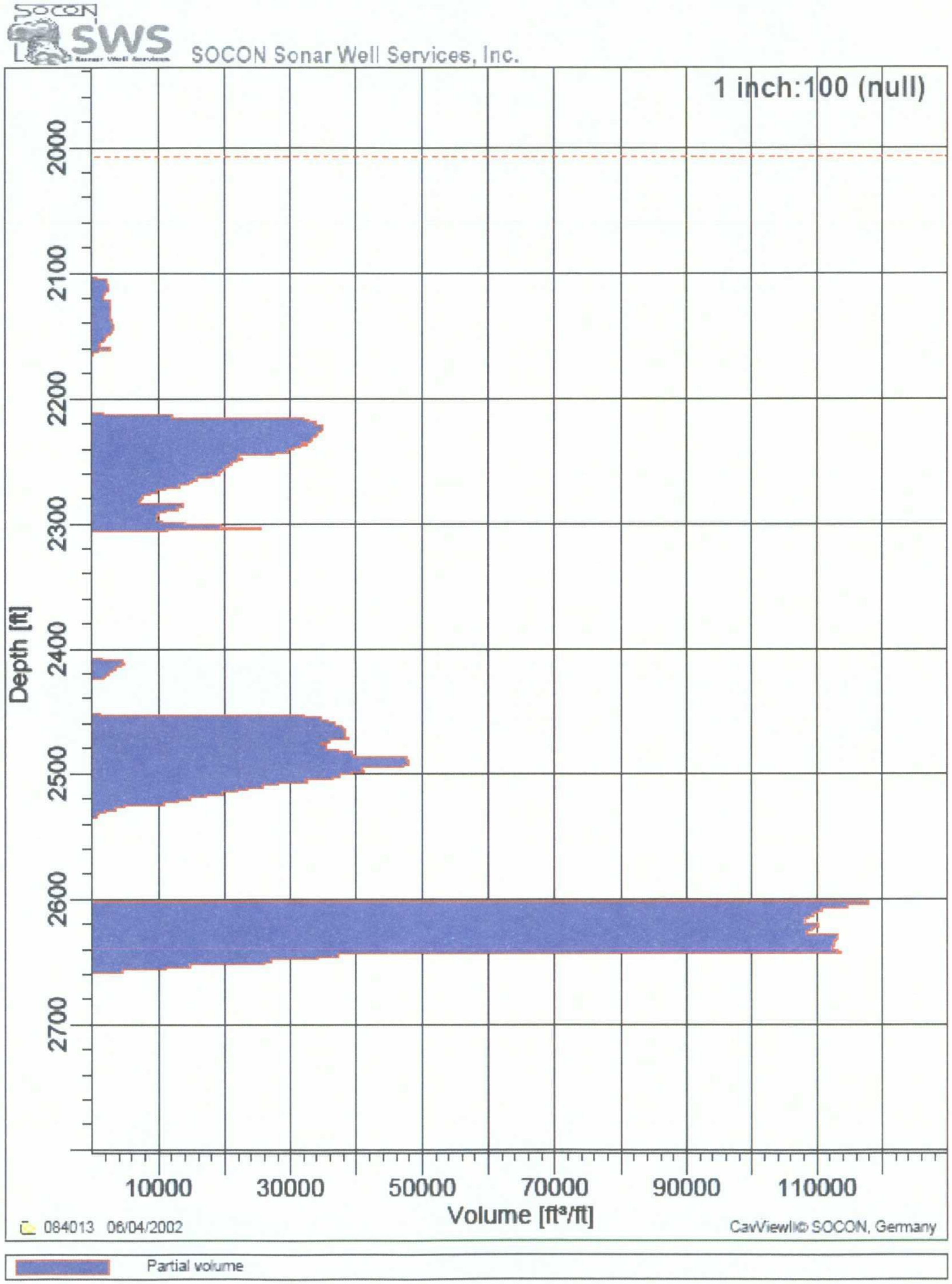
1. Tubing size is smaller in diameter (2-7/8”) than the standard sonar tool (3.5”).

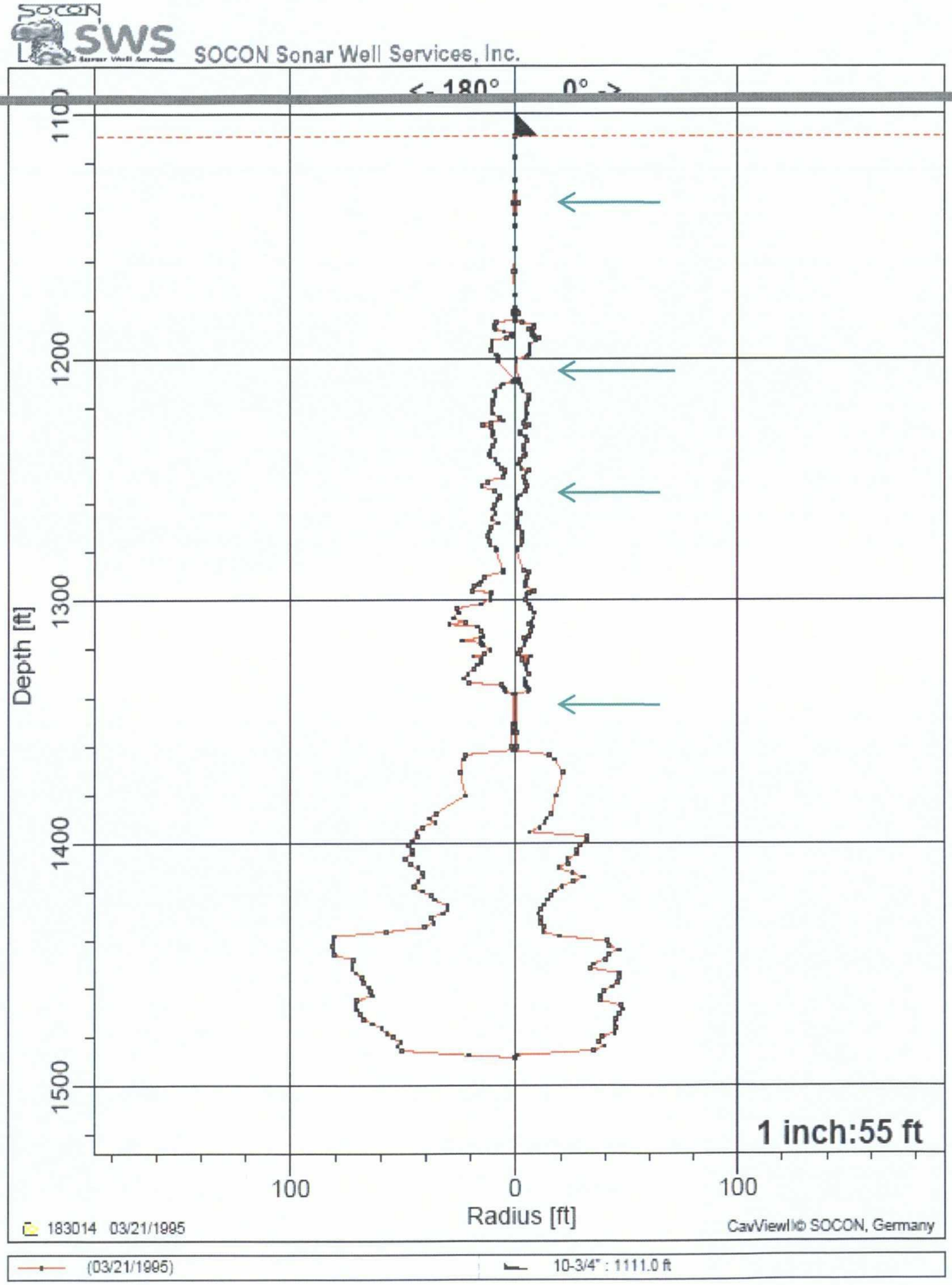
2. Once the tubing is pulled it is very difficult to re-enter the cavern to survey.

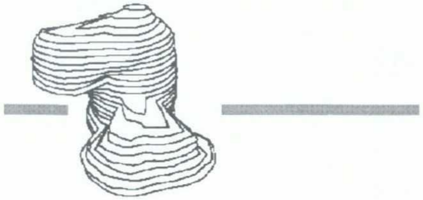
3. Possible collapse and bends in the casing prevent tools from exiting the end of the tubing and make it impossible to proceed to require depths.

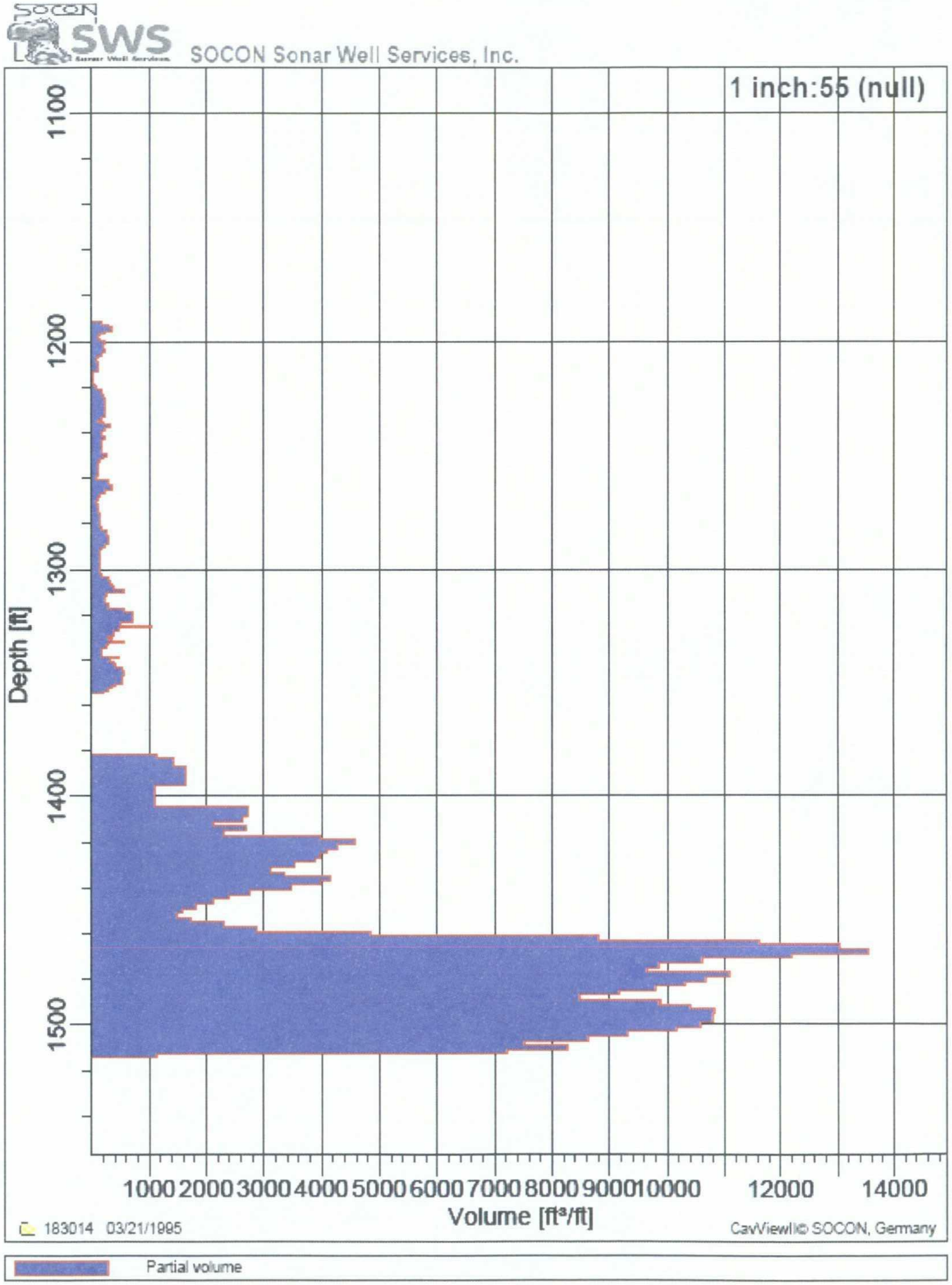
SWS SOCON Sonar Well Services, Inc.

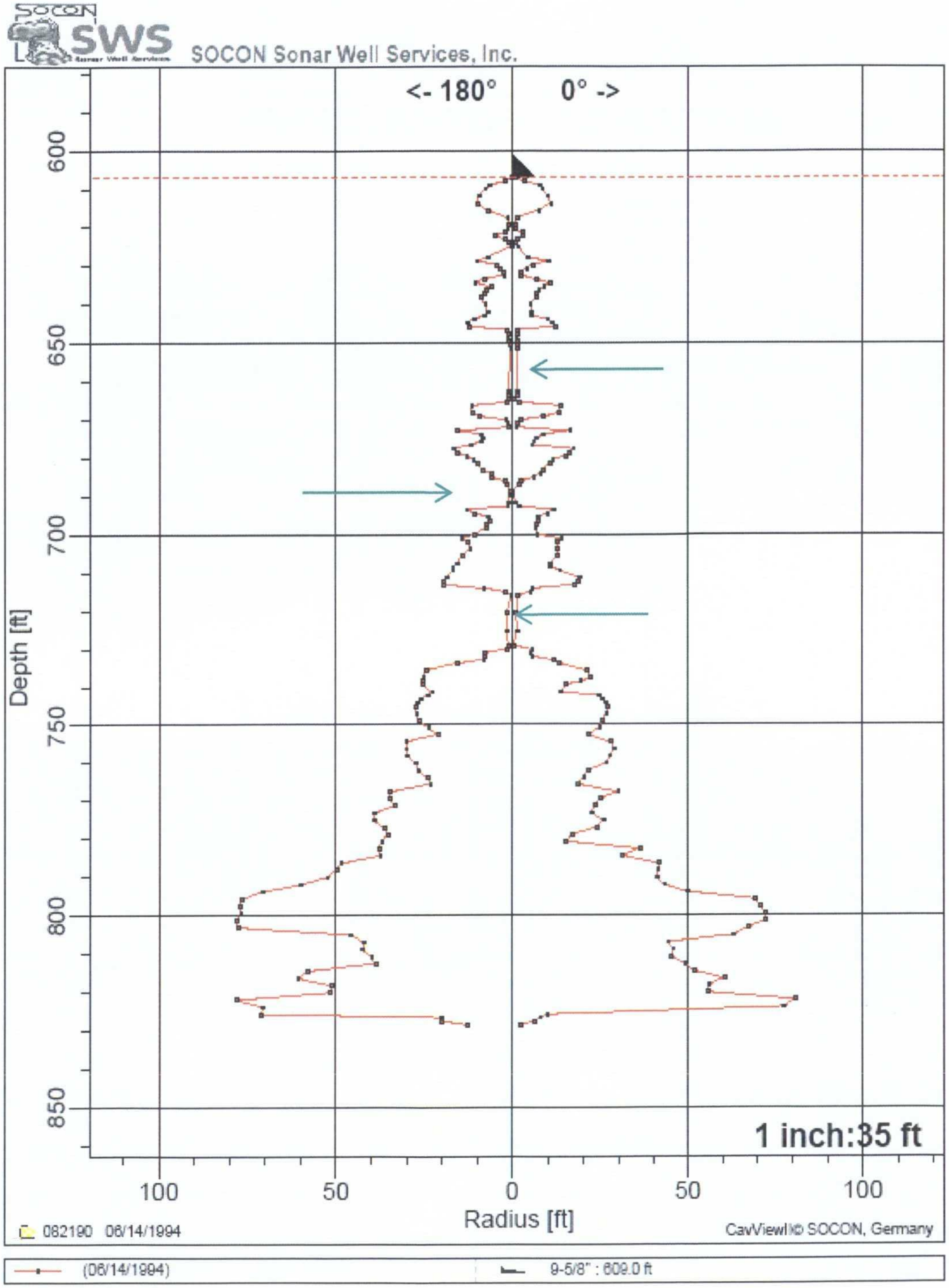


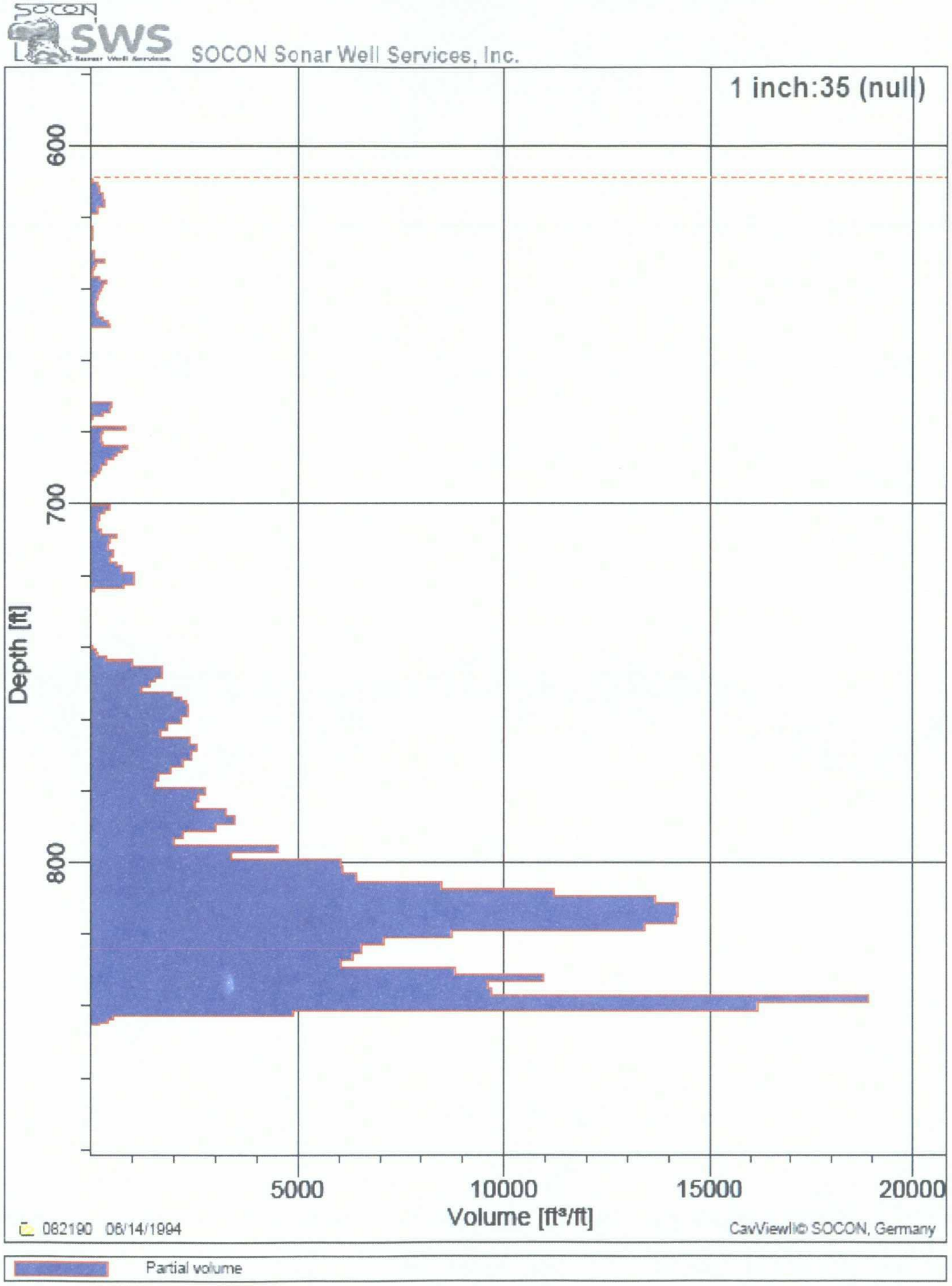

SOCON SWS
SOCON Sonar Well Services, Inc.
1 inch:100 (null)
Depth [ft]
2000
2100
2200
2300
2400
2500
2600
2700
10000
30000
50000
70000
90000
110000
Volume [ft³/ft]
084013 06/04/2002
CavViewII© SOCON, Germany
Partial volume

SOCON SWS Sonar Well Services
SOCON Sonar Well Services, Inc.
<- 180°
0° ->
Depth [ft]
1100
1200
1300
1400
1500
1 inch:55 ft
100
0
100
Radius [ft]
183014 03/21/1995
CavViewII© SOCON, Germany
(03/21/1995)
10-3/4" : 1111.0 ft




SOCON SWS Sonar Well Services
SOCON Sonar Well Services, Inc.
1 inch:55 (null)
Depth [ft]
1100
1200
1300
1400
1500
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
12000
14000
Volume [ft³/ft]
183014 03/21/1995
CavViewII© SOCON, Germany
Partial volume

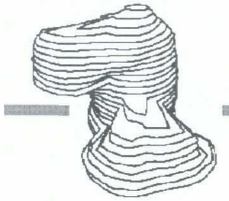
SOCON
SWS
Sonar Well Services
SOCON Sonar Well Services, Inc.
<- 180°
0° ->
Depth [ft]
600
650
700
750
800
850
1 inch:35 ft
100
50
0
50
100
Radius [ft]
082190 06/14/1994
CavView!© SOCON, Germany
(06/14/1994)
9-5/8" : 609.0 ft


SOCON SWS Sonar Well Services
SOCON Sonar Well Services, Inc.
1 inch:35 (null)
Depth [ft]
600
700
800
5000
10000
15000
20000
Volume [ft³/ft]
082190 06/14/1994
CavView!© SOCON, Germany
Partial volume

Possible surveying techniques on old and new caverns.

1. Use a density tool to “Map” the ledges/salt formations before removing the pipe.

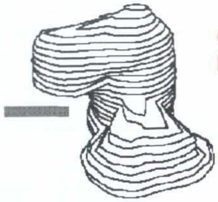
2. Poking out of the end of the tubing to survey section, then pull some pipe and re-enter to survey next section.



3. On new wells – Insert larger diameter tubing which would allow entry of larger logging tools and also slow down the drilling process to prevent "cork screwing" allowing a less deviated pipe.

4. On old wells – use a smaller sonar tool which could run inside a 2-7/8" tubing such as SOCONS 42mm sonar tool.

- ➢Cannot see through pipe
- ➢Cost for survey

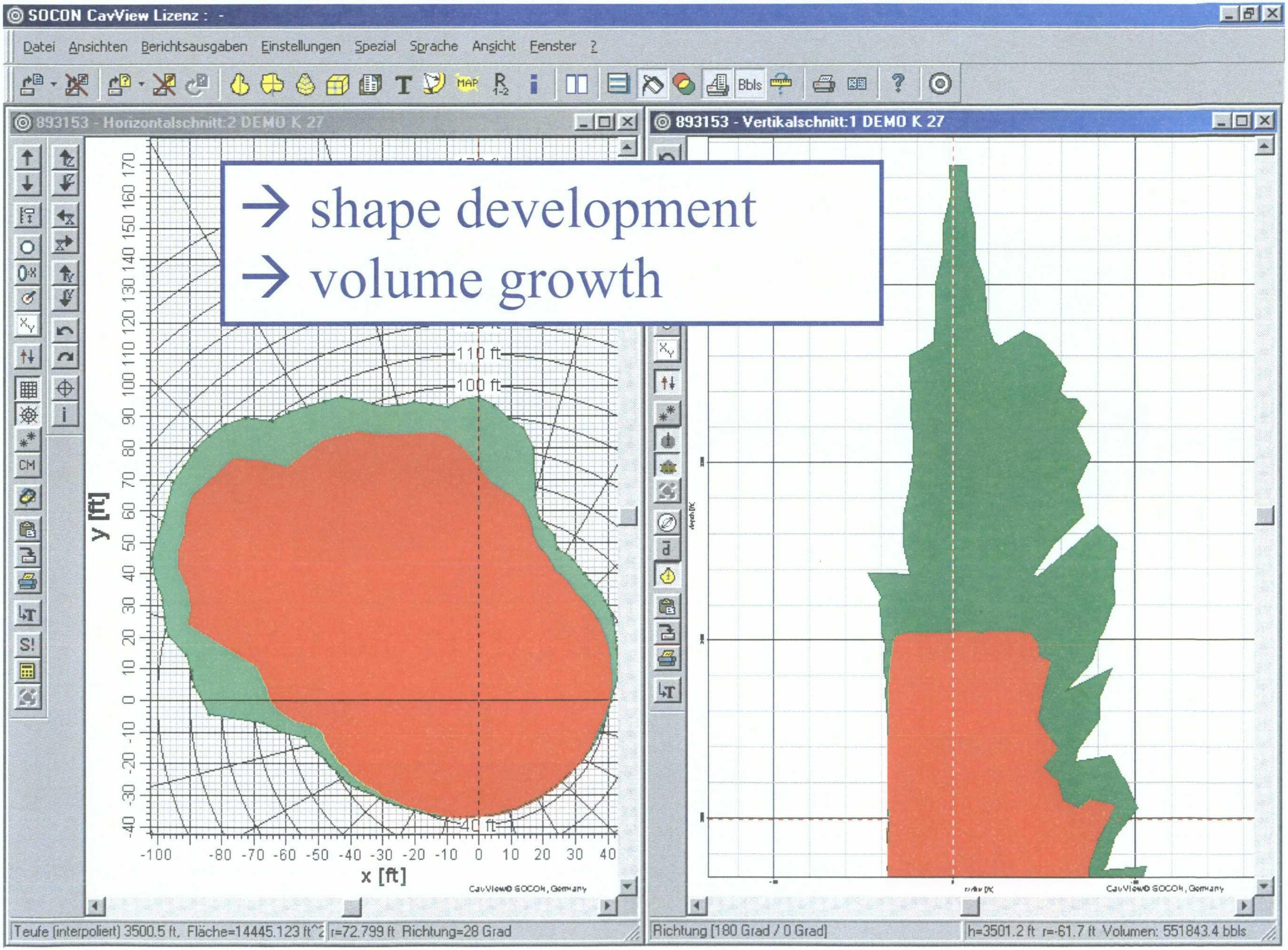


Structure

SOCON

1. Introduction of SOCON Sonar Well Services, Inc.
2. Sonar surveying of bedded salt caverns
   - Problems and situations while working with bedded salt caverns
   - Possible surveying techniques on old and new caverns.
3. 3D-Presentation of cavern survey results
4. Conclusions

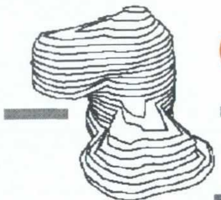
Cavern surveys during leaching



Teufe (interpoliert) 3500.5 ft, Fläche=14445.123 ft^2 r=72.799 ft Richtung=28 Grad

Richtung [180 Grad / 0 Grad] h=3501.2 ft r=-61.7 ft Volumen: 551843.4 bbls

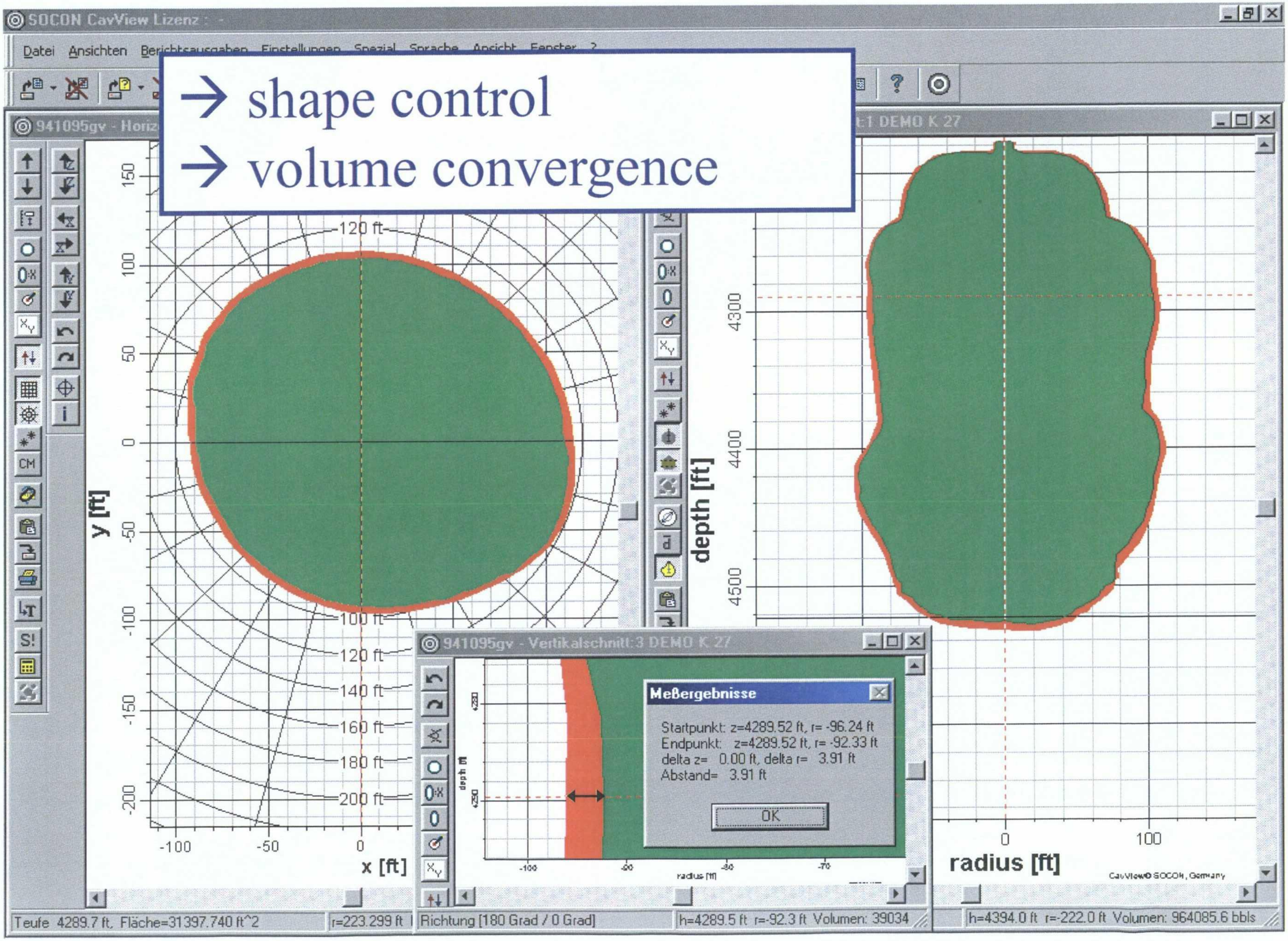
- → shape development
- → volume growth



Cavern surveys - storage phase

→ shape control

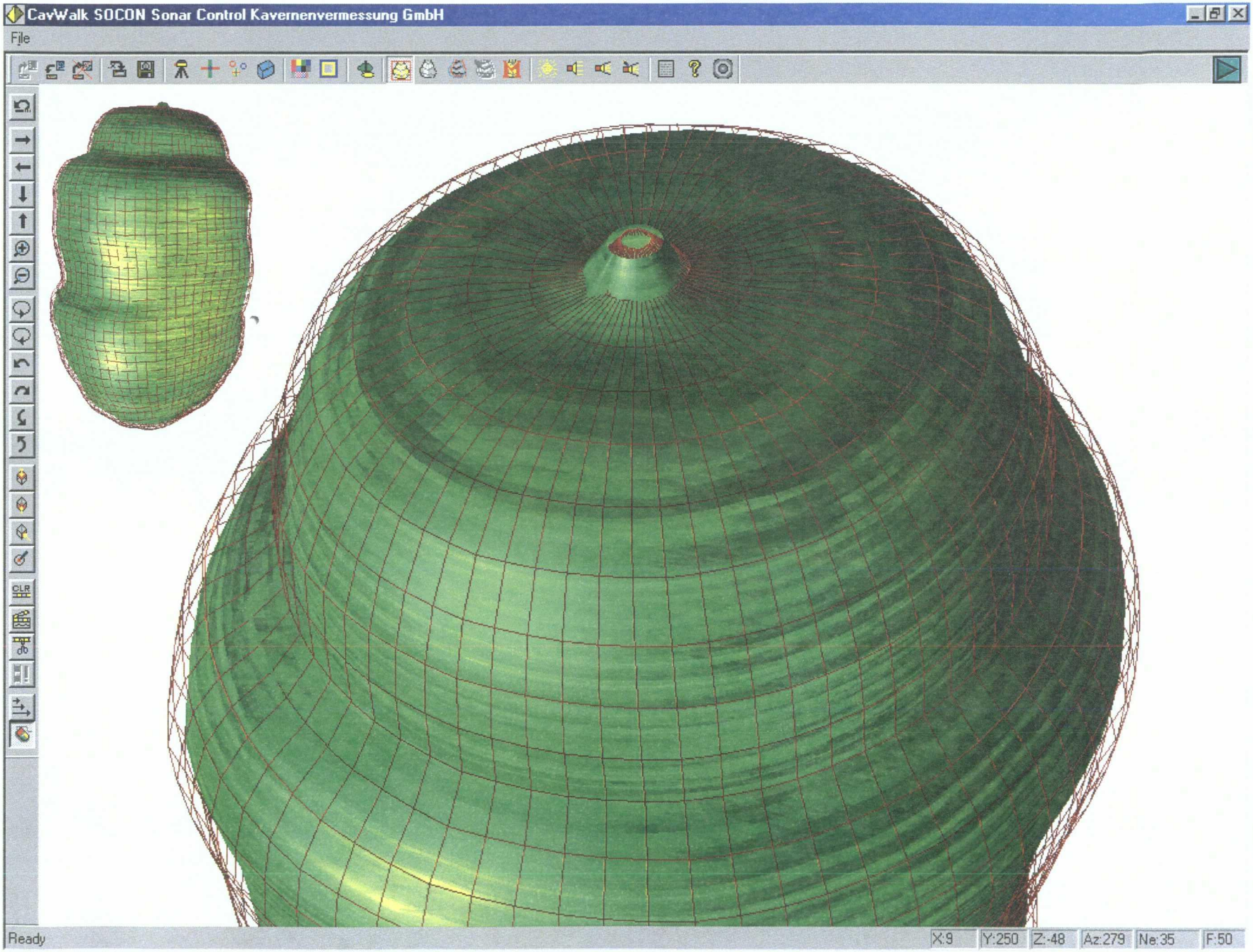
→ volume convergence



Startpunkt: z=4289.52 ft, r= -96.24 ft
Endpunkt: z=4289.52 ft, r= -92.33 ft
delta z= 0.00 ft, delta r= 3.91 ft
Abstand= 3.91 ft

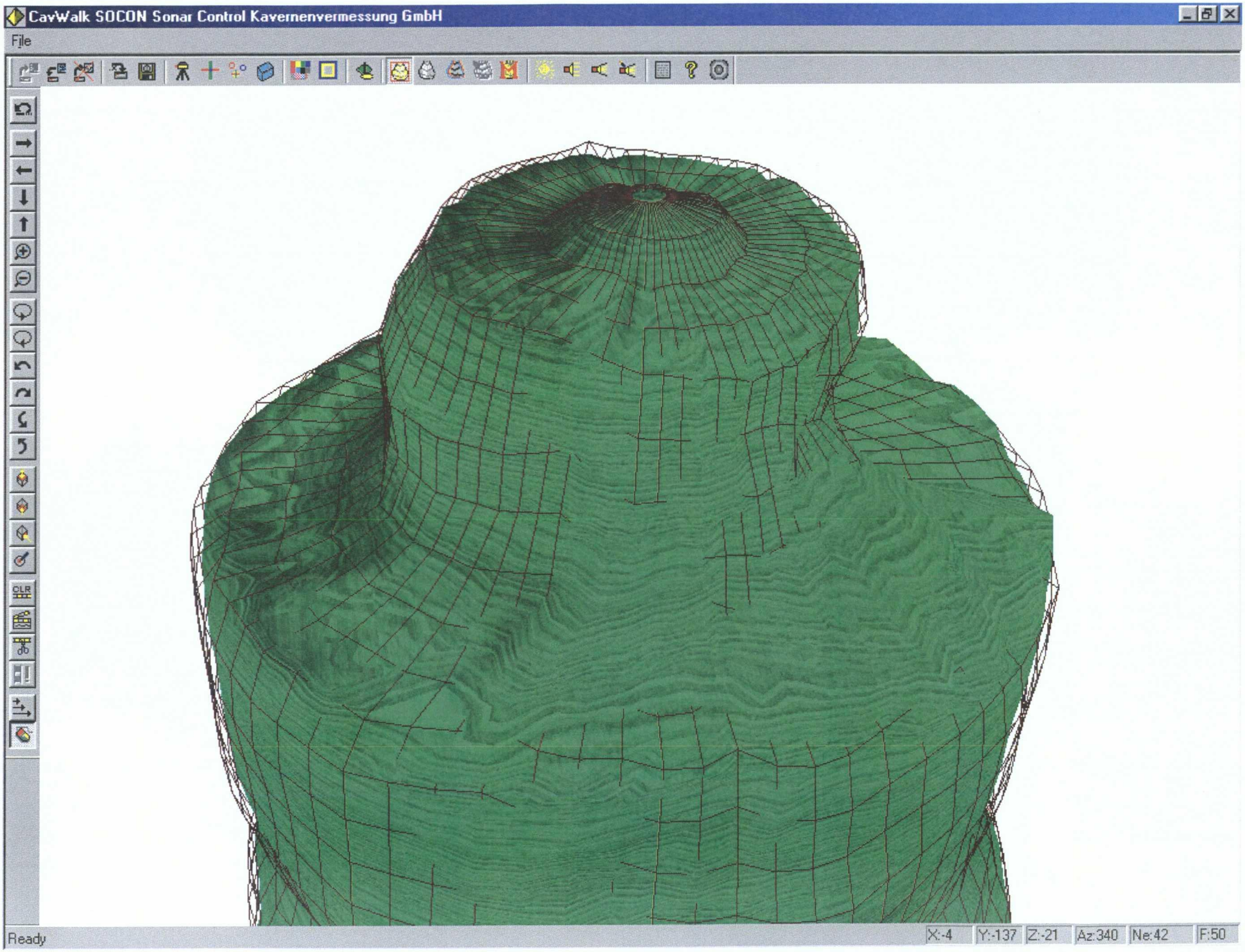
Teufe 4289.7 ft, Fläche=31397.740 ft^2 | r=223.299 ft | Richtung [180 Grad / 0 Grad] | h=4289.5 ft r=-92.3 ft Volumen: 39034 | h=4394.0 ft r=-222.0 ft Volumen: 964085.6 bbls

Storage cavern convergence

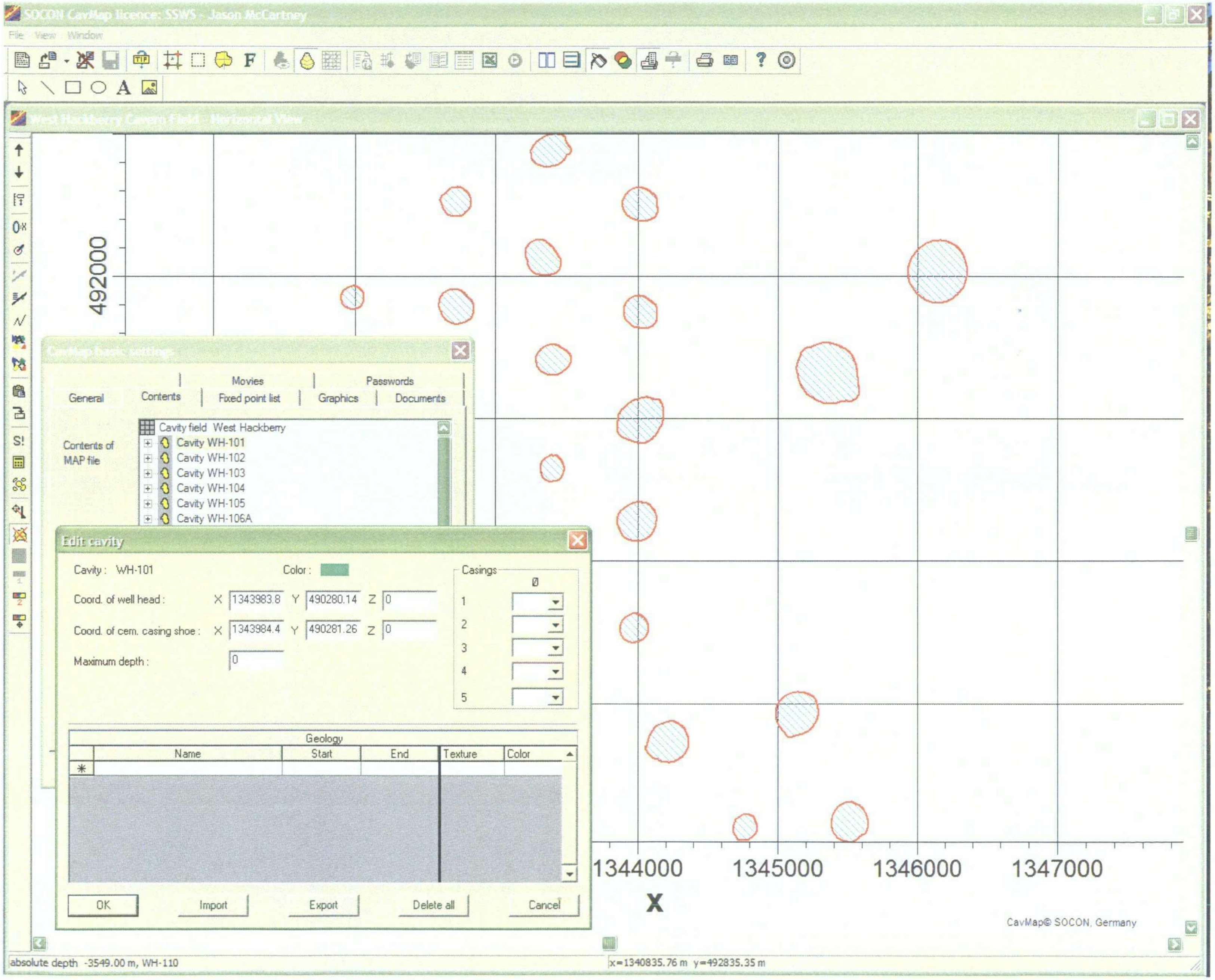


X:9 Y:250 Z:-48 Az:279 Ne:35 F:50

Storage cavern convergence



Cavern field mapping (CavMap)



Contents of MAP file:

- Cavity field West Hackberry
  - Cavity WH-101
  - Cavity WH-102
  - Cavity WH-103
  - Cavity WH-104
  - Cavity WH-105
  - Cavity WH-106A

Cavity: WH-101

Color:

Coord. of well head: X 1343983.8 Y 490280.14 Z 0

Coord. of cem. casing shoe: X 1343984.4 Y 490281.26 Z 0

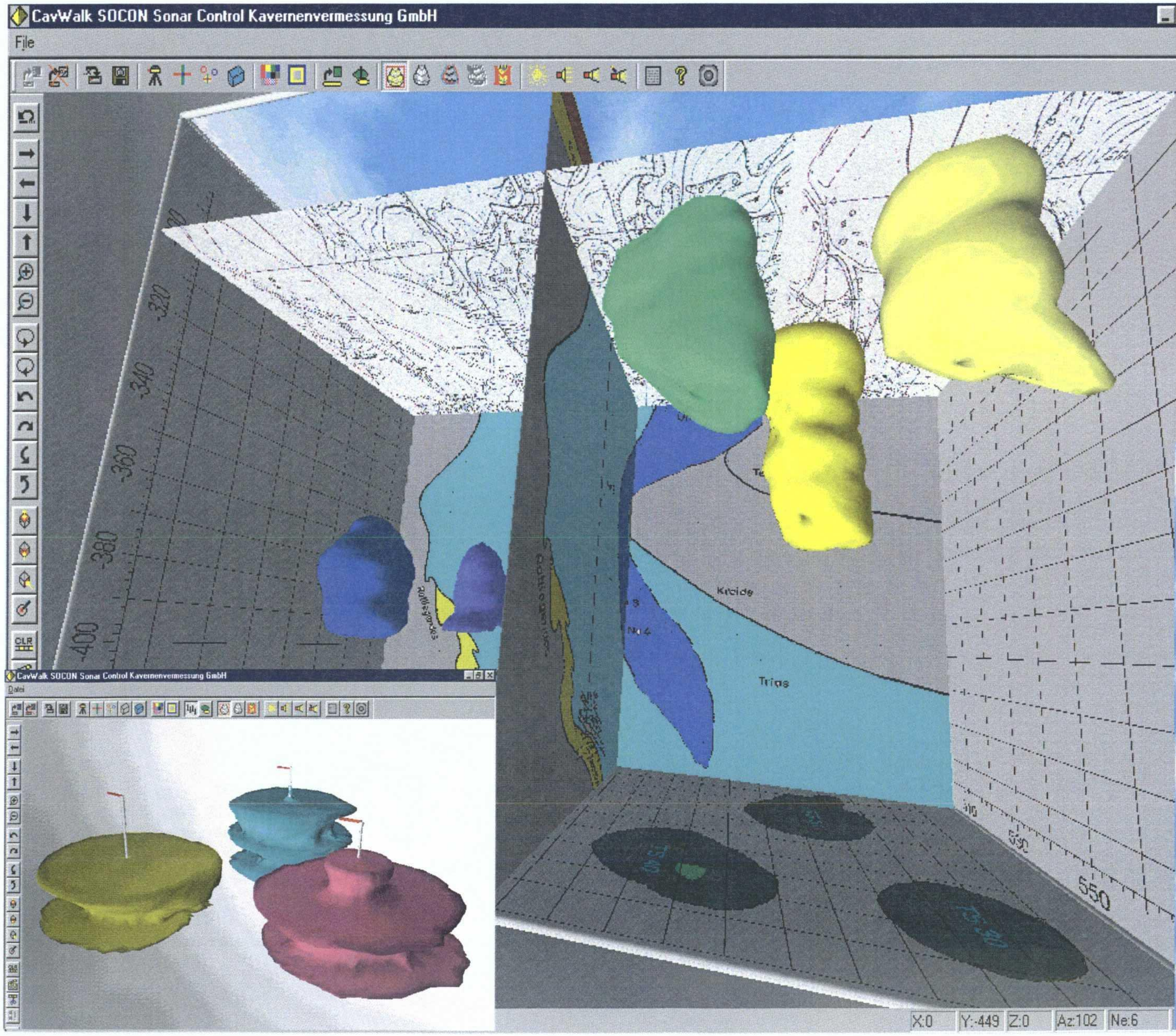
Maximum depth: 0

absolute depth -3549.00 m, WH-110

x=1340835.76 m y=492835.35 m

3D-Presentation

SOCON

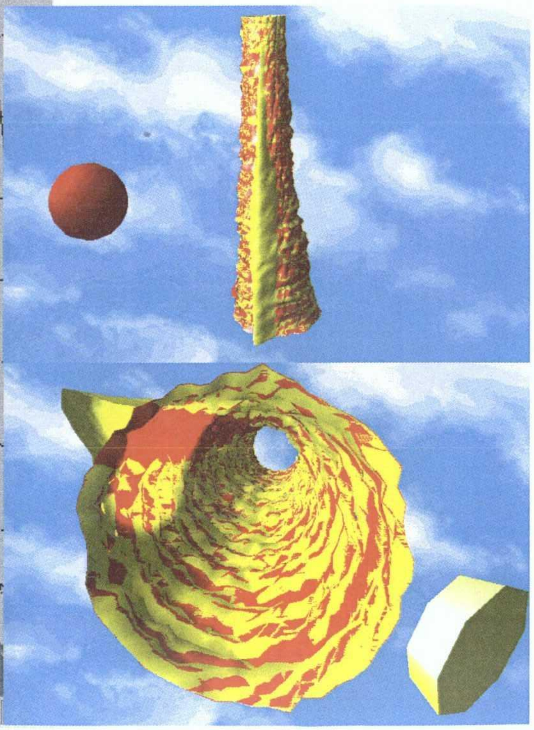


Cav*Walk*

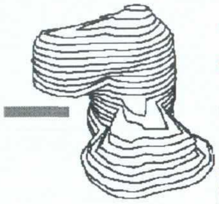
Three-dimensional display and animation of caverns and cavern fields

Cav*Movie*

3D-movies

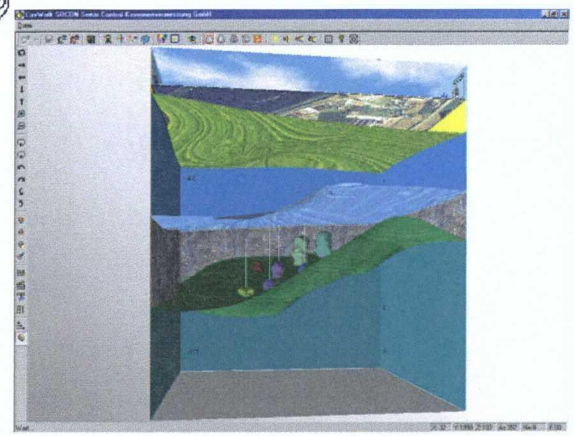


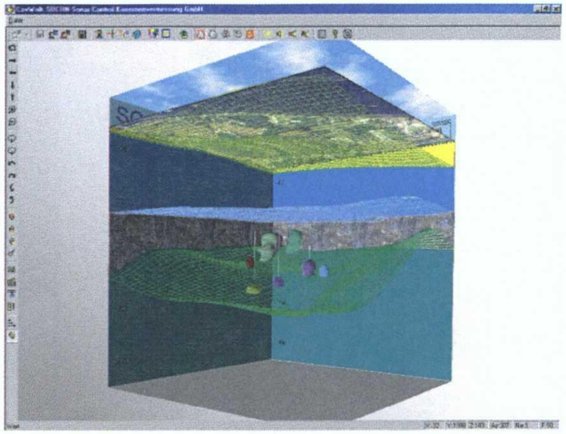
CavWalk® - Geology

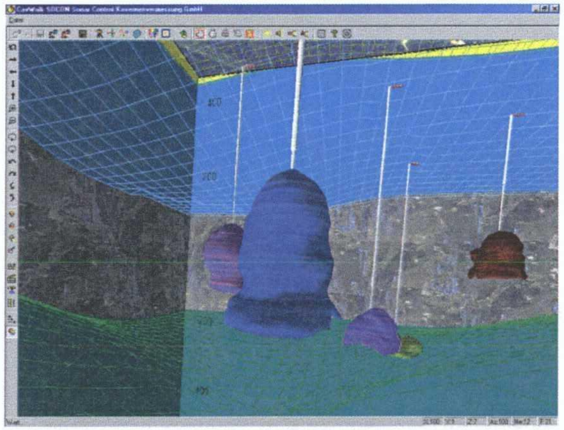


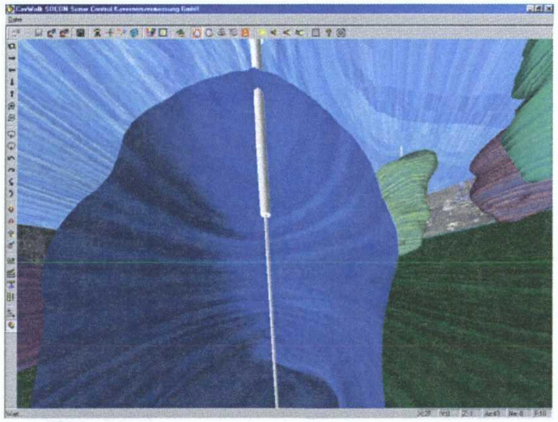
3D-animation

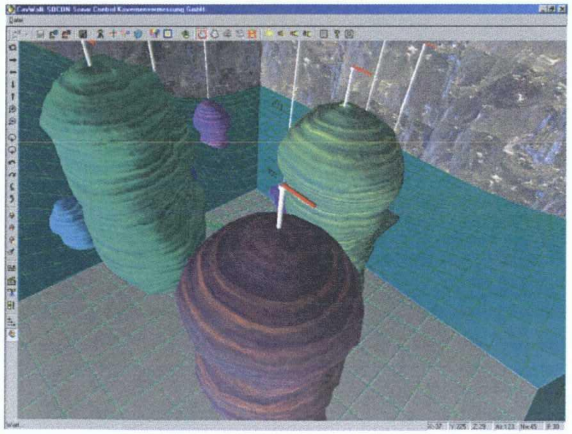
SOCON

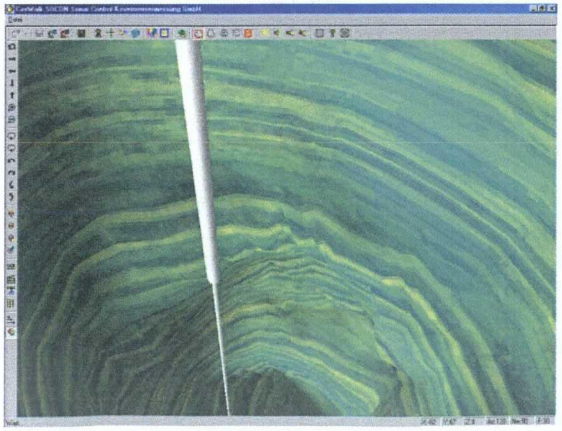


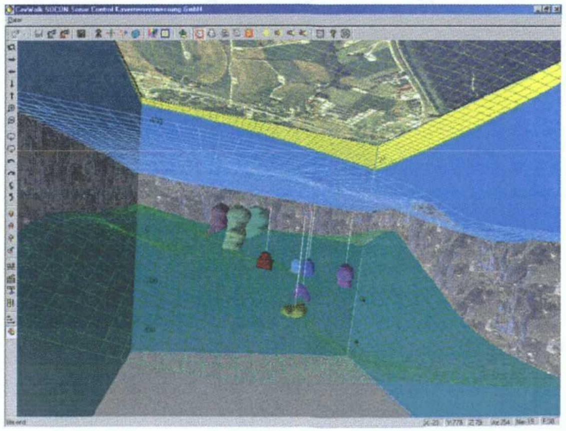






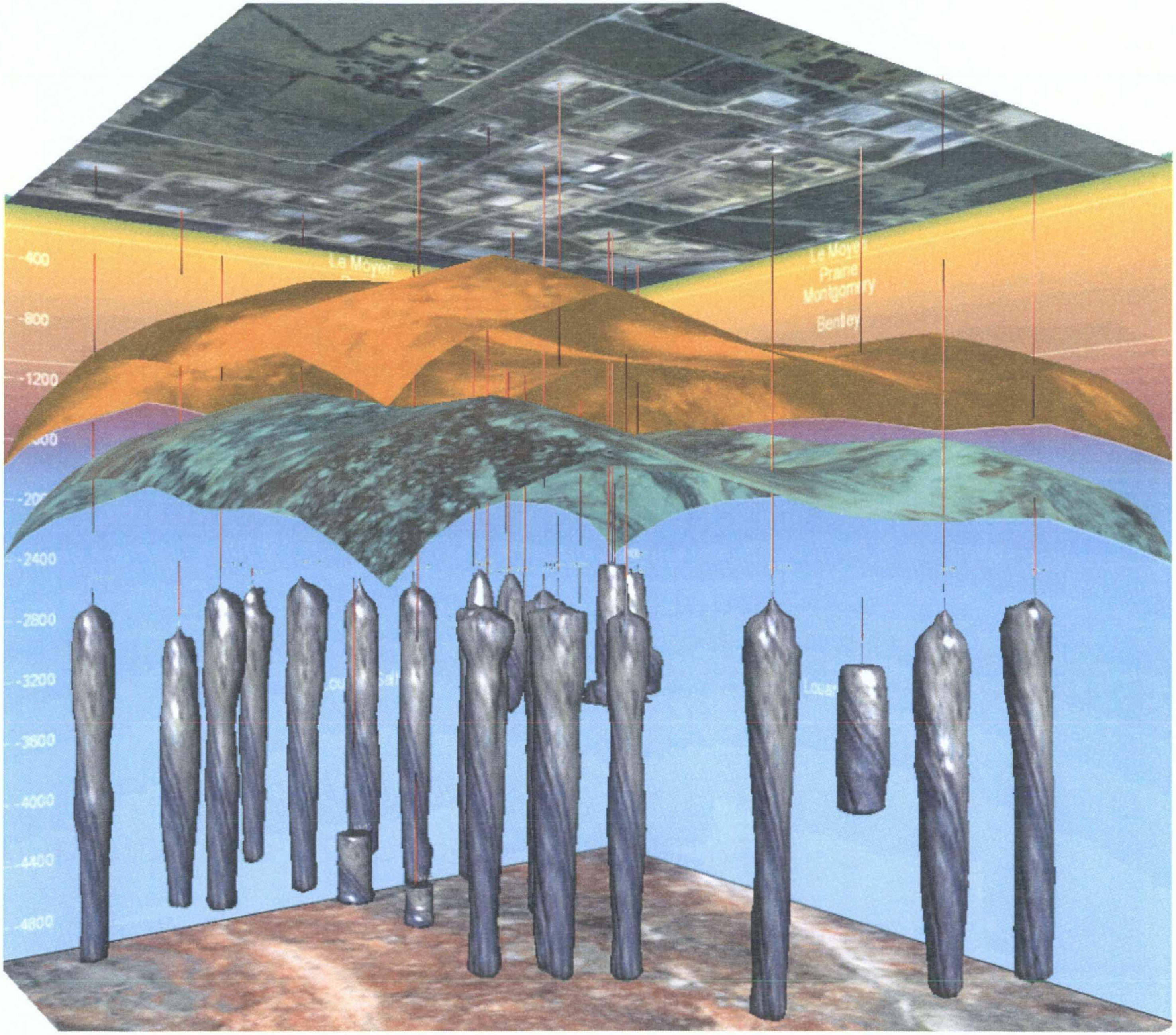


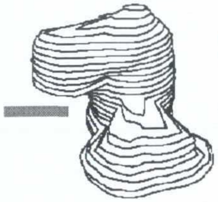




3D-Animation

SOCON





Conclusions

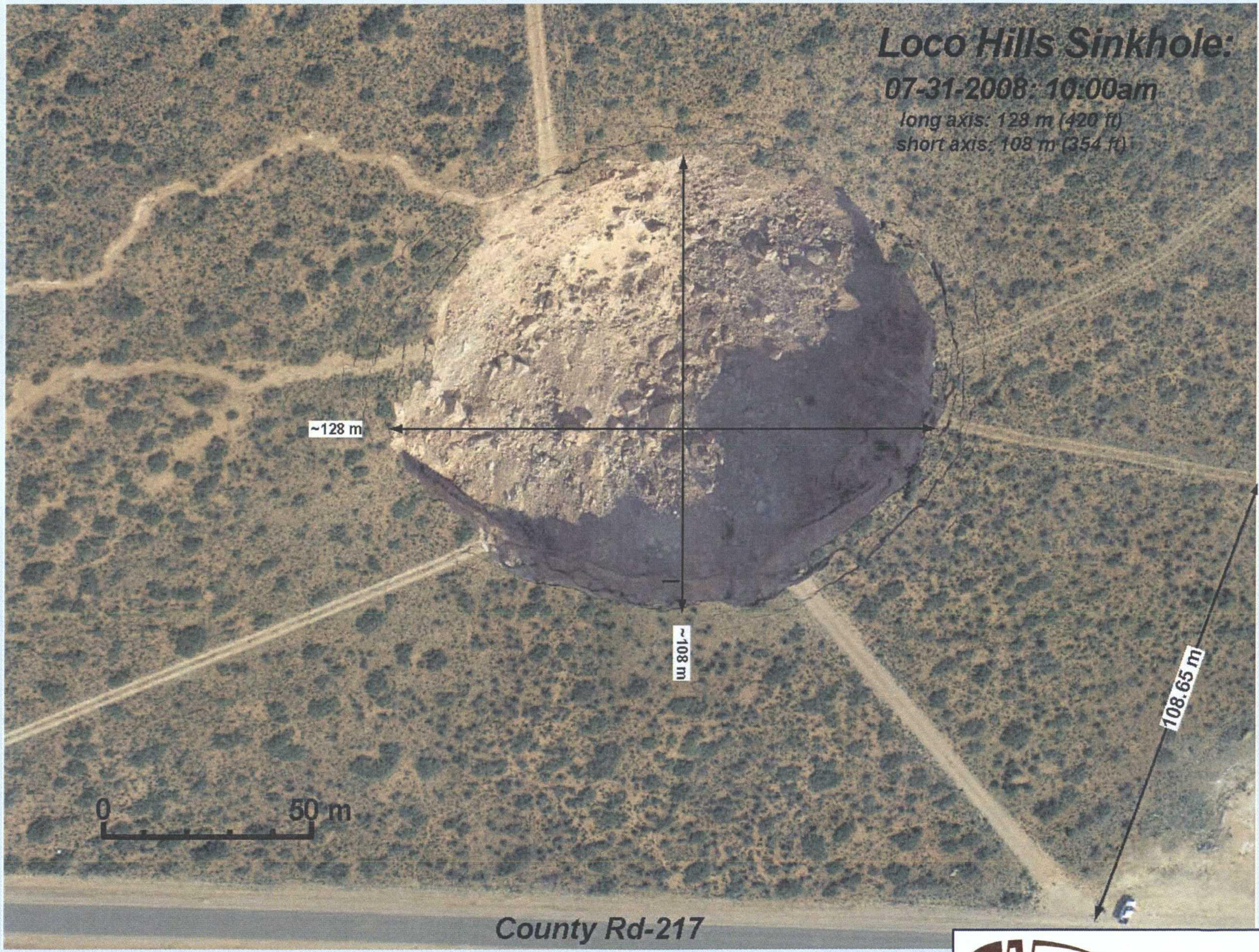
Applying state-of-the-art sonar survey and software technology …

- ➢ guarantees an accurate control of cavern development during leaching
- ➢ may improve salt extraction
- ➢ guarantees an accurate control of storage cavern behavior
- ➢ is an essential part of safe and sustainable cavern operations

Brine Well Collapse Research Proposal: Prediction, Risk Management, Prevention

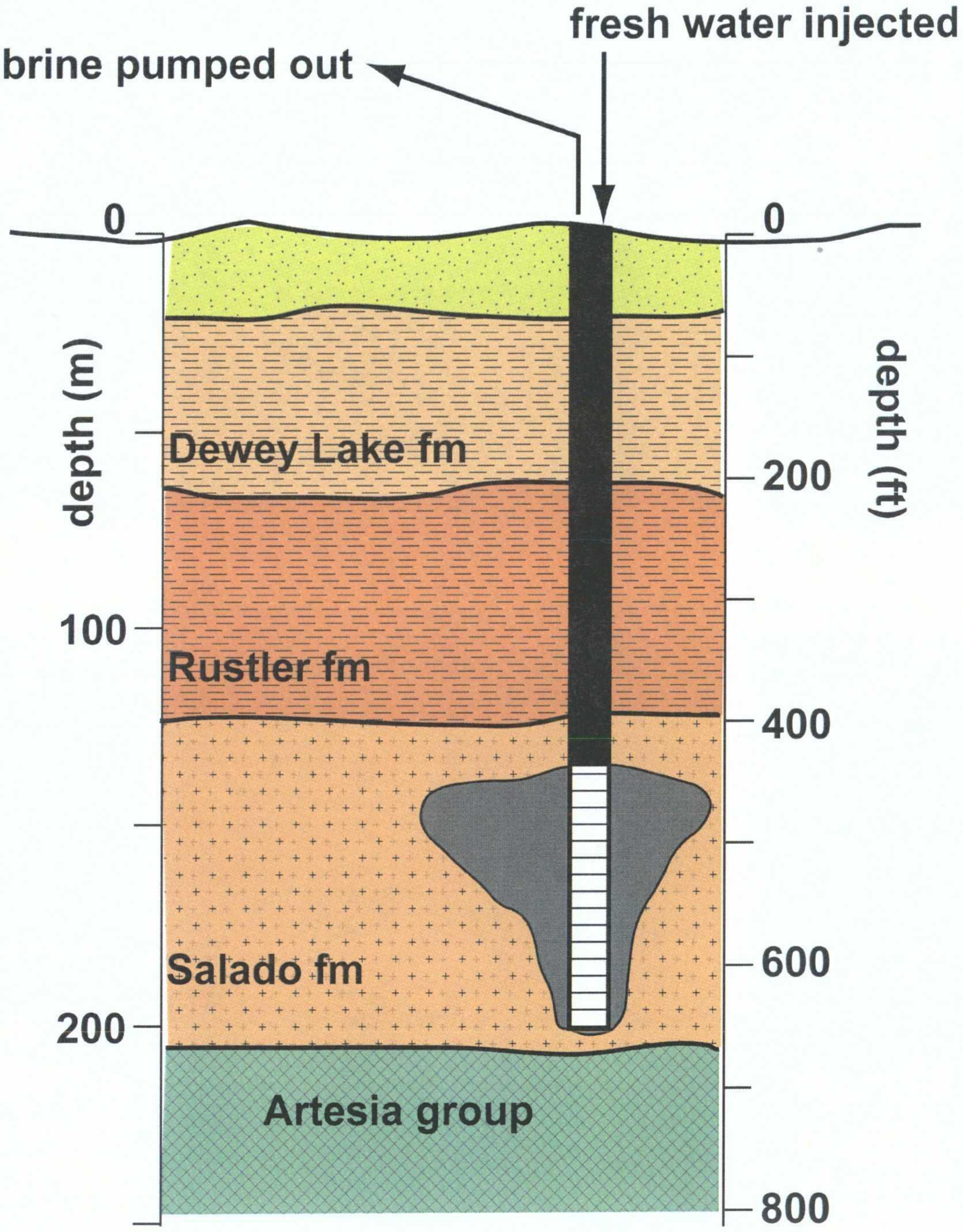
George Veni
Executive Director

National Cave and Karst
Research Institute



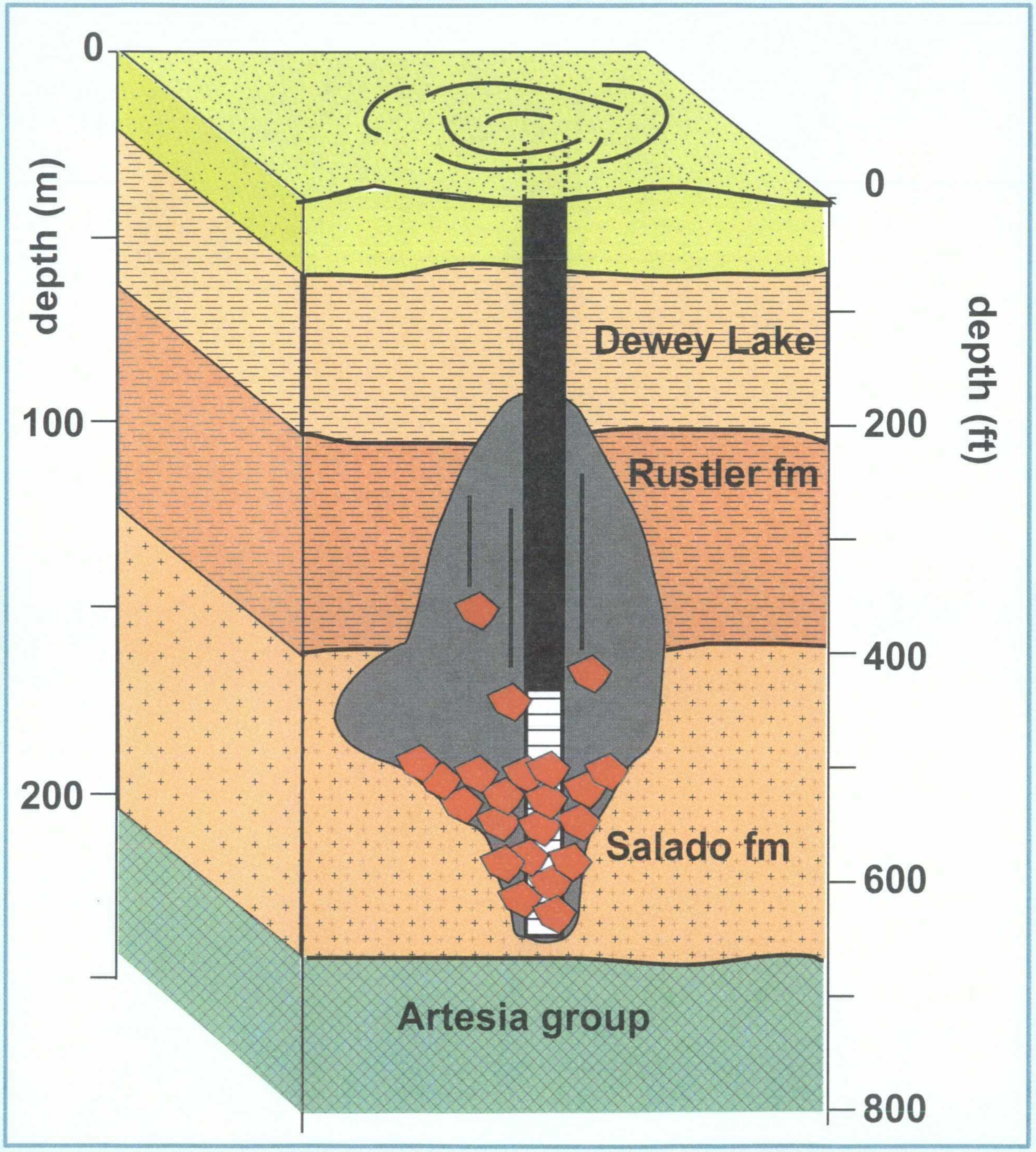
National Cave and Karst Research Institute

National Cave and Karst
Research Institute



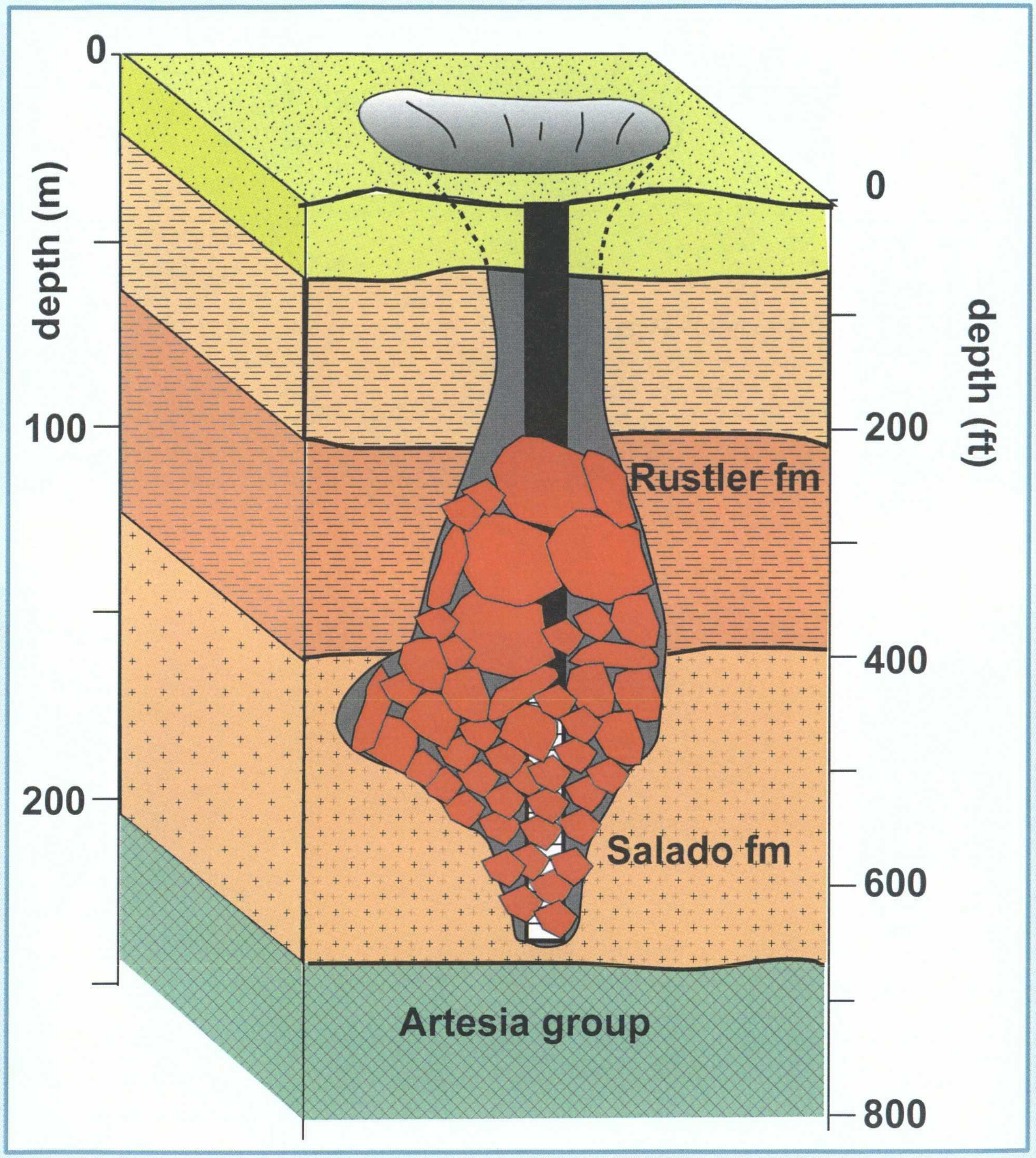
Sinkhole origin: Solution mining in the Salado Formation

National Cave and Karst
Research Institute



Basic origin: known

National Cave and Karst
Research Institute



Basic origin: known

Specific triggers for predictive analysis: unknown

National Cave and Karst Research Institute

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision
- Identify all active and inactive brine wells in a selected test area and analysis their data with the predictive model to determine risk

National Cave and Karst
Research Institute

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision
- Identify all active and inactive brine wells in a selected test area and analysis their data with the predictive model to determine risk
- Conduct detailed study of high risk wells to evaluate model

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision
- Identify all active and inactive brine wells in a selected test area and analysis their data with the predictive model to determine risk
- Conduct detailed study of high risk wells to evaluate model
- Refine model if needed

National Cave and Karst
Research Institute

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision
- Identify all active and inactive brine wells in a selected test area and analysis their data with the predictive model to determine risk
- Conduct detailed study of high risk wells to evaluate model
- Refine model if needed
- Apply results broadly to all known sites for monitoring, risk management decisions, and preventive action as required

National Cave and Karst
Research Institute

Research proposal:

- Detailed analysis and modeling of known collapses in New Mexico and in similar geologic settings in other states
- Broad approach builds partnerships, funding, and model precision
- Identify all active and inactive brine wells in a selected test area and analysis their data with the predictive model to determine risk
- Conduct detailed study of high risk wells to evaluate model
- Refine model if needed
- Apply results broadly to all known sites for monitoring, risk management decisions, and preventive action as required

National Cave and Karst
Research Institute