SOLUTION MINING RESEARCH INSTITUTE
3336 Lone Hill Lane
Encinitas, California 92024, USA

Telephone: 619-759-7532 ◆ Fax: 619-759-7542
www.solutionmining.org ◆ smri@solutionmining.org

Meeting Paper

Solution Void Cavity Definition Using the Suface Based Z-Scan High Resolution Magnetotelluric System

by

Daniel A. Woods, President
Digital Magnetotelluric Technologies
Tulsa, Oklahoma, USA

and

Stephen A. Marinello, Ph.D.
Newpark Resources
Metairie, Louisiana, USA

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SOLUTION VOID CAVITY DEFINITION USING THE SURFACE-BASED Z-SCAN HIGH RESOLUTION MAGNETOTELLURIC SYSTEM

Daniel A. Woods, President – Digital Magnetotelluric Technologies
Stephen A. Marinello, Ph.D. – Newpark Resources, Inc.

ABSTRACT

A new high-resolution magnetotelluric remote sensing system was used to survey a salt solution mining operation located in Fort Stockton, Texas. The system was used to determine the depth, geometry, and estimated capacity of the three main solution caverns in the bedded salt. The results compared favorably with those of a previously run borehole sonar survey of the uppermost cavern. The system technology, known as the **Z-SCAN** technology, has been accepted by the Railroad Commission of Texas for the evaluation of underground caverns. It is completely portable and non-invasive, and was unintrusive to daily area operations at the Fort Stockton site. Survey station layouts are adaptable to the varying goals of different projects and can be easily modified throughout the procedure in order to meet evolving needs.

INTRODUCTION

After attempts to run a downhole sonar survey succeeded only in delineating the upper most void within the bedded salt solution cavern, it was decided to test a different non-invasive technology in an attempt to measure overall cavern size and shape. This was necessitated by regulations required for new and modified permits by the Railroad Commission of Texas, and by the fact that attempts to drill in larger tubing to bottom in order to allow sonar tool usage were not successful.

The method chosen was the **Z-SCAN**, a magnetotelluric technology using remote sensing at the surface. Based on previous estimates of cavern volume and size, a survey grid pattern was chosen to enable a staggered step-out procedure to determine lateral extent of the cavern voids in all directions.

A high resolution magnetotelluric survey was performed at the Fort Stockton facility in Pecos County, Texas. A depth interval for the survey was assigned which encompassed the salt section. Three cavernous porosity features (V1, V2, and V3) were defined within this section which were individually analyzed to determine thickness, depth profile, and boundary limits.

Data acquisition was conducted from September 25, 1998 to October 3, 1998. To contain costs, data collected was field interpreted and the results were reviewed with the office geophysicist for coordination of continued sampling. Additional stations needed to define the salt void limits were re-assigned to the field geologist for acquisition, and the procedure repeated until the void limits were defined.

THEORY

Natural electromagnetic energy comprises the source for the **Z-SCAN** system. The source is “many orders of magnitude greater than the strengths of fields that can be generated with man-made sources on the surface of the earth” [1]. The energy originates in particle form as “solar wind”, and is transduced into wave energy as it passes through the Ionosphere and Magnetosphere. Very low frequency (.0005-100Hz) carrier waves subsequently enter the earth, and the amplitude and phase of individual frequencies are modified at resistivity interfaces from which they are reflected back to the surface. This system varies from classical magnetotelluric methods by analyzing a secondary set of higher frequency harmonics (100Hz-22Khz) generated by the large impedance contrast at the air-ground interface. These frequencies carry the same relative amplitude data as the returning carrier frequencies, but facilitate a significant improvement in resolution, allowing for detailed vertical subsurface sampling with depth errors of <20’, in most areas, with proper calibration.

The **Z-SCAN** technology employs the simultaneous recording of the electric (E) and magnetic (H) components of the telluric field to tape. Through processing, the arrays of amplitudes of their frequency series can be measured separately, or as ‘Z’ ratios (Z=E/H). The results are displayed in log format as relative apparent resistivity profiles of the subsurface. The conversion from frequency to depth is accomplished using a modification of the well-established ‘skin depth’ equation.[2] The tapes can be processed in analog form (**Z-SCAN** system) using an analog computer and a trained audio interpreter, or in digital form (**DIGILOG** system) via computer, using signal processing techniques.

This system yields valuable information on subsurface porosity-bearing zones, whether they are cavernous or dominated by matrix or secondary porosity. Since electromagnetic energy seeks the least resistive travel path, the amounts of connate waters dramatically effect the apparent resistivity. The more the porosity, the more bound water, and the lower the resultant apparent resistivity curve, yielding an excellent set of log-form data for point-to-point correlation as well as diagnostic information about subsurface porosity zones. With calibration, mapping of contaminant solids, fluids, and gases within these cavernous or porosity-bearing zones (including, in some cases, plumes of impacted subsurface soils) can be accomplished.

[1] Mag. Sounding Method, Kaufman & Keller, Chapter 1, pg. 1, Elsevier, 1981.

[2] Magnetotelluric Exploration for Hydrocarbons, Arnold S. Orange IEEE, Vol. 73, #2, Feb. 1989.

METHODOLOGY

In the field, each station location was surveyed using a hip-chain and a Brunton compass. **Z-SCAN** data collection was conducted during optimally dry field conditions. Each day, field data collection commenced with a calibration at the cavern well location (Stations #0, R1 through R5) to determine signal conditions, which were good in every case. A total of 45 stations were interpreted.

All stations were recorded in a straight line along an eight arm star, except for Station #46 which was offset slightly south, due to a surface salt water pit. The procedure used for **Z-SCAN** surveying worked well, with one exception. Interior data stations were not recorded at first, but later it became obvious they were needed to enhance the accuracy of the volume calculations.

After **Z-SCAN** analysis was complete, calibration was confirmed by tying to the top of salt as defined by the gamma-ray, Neutron log from the well, and by comparison to the sonar survey conducted in the Upper Salt Void interval (V1). The sonar survey was also used to confirm the correction used to minimize the effect of the subsurface image overlap known to exist with the **Z-SCAN** electromagnetic technology. This overlap occurs in accordance with physical phenomena described in Fresnel's equations[3]**,** and is similar to the "Fresnel zone" effect observed in the seismic geophysical method. The calculated correction factor verified at V1 was applied to V2 and V3. All data are presented in corrected form for this report. A sufficient density of **Z-SCAN** stations was run to allow for virtual full coverage, as well as to maximize the accuracy of volumetric calculations.

Each solution void was defined using the **Z-SCAN** by depth intervals of low apparent resistivity, with strong "water" signature phase disturbances, in a surrounding matrix of higher apparent resistivity and quieter phase disturbances.

Vertical depth bulk shifts of a maximum of 20' were noted on a few stations. These shifts were corrected on the raw data set.

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[3] Electromagnetic Methods In Applied Geophysics, Ward and Hohmann, Chapter 4, pp. 187-191 (ed. Misac N. Nabighian), 1988.

RESULTS

The results of the survey clearly define the three primary voids leached out of the bedded salt. Isopachs and sections of the voids are shown in the following displays:

- ***V-1 Void Isopach – corrected data with sonar outline – Figure 1***
- ***V-2 Void Isopach – corrected – Figure 2***
- ***V-3 Porosity Zone Isopach – corrected – Figure 3***
- ***E-W Section Voids V-1, V-2, V-3 – Figure 4***
- ***N-S Section Voids V-1, V-2, V-3 – Figure 5***

Void limits were defined for eight compass directions using the corrected data sets. To aid in the evaluation of void limits, the distance from the injection well is used as the header data for each **Z-SCAN** log on the section displays (Figures 4 and 5).

The total volumes were computed for each void or porosity zone. While uncorrected volume estimates might have been in excess of 900,000 barrels, the application of the “image overlap” correction yields a total volume of just under 750,000 barrels. The total and individual cavity volumes are noted below.

- **Total Void 1 – 242,596 bbls**
- **Total Void 2 – 186,282 bbls**
- **<u>Total Void 3 – 319,950 bbls</u>**
  Grand Total: 748,828 bbls

DISCUSSION

The evaluation of the areal extent and volume of the Ft. Stockton caverns was initiated after mechanical difficulties complicated the use of the downhole sonar tool to evaluate all but the uppermost void (V-1). This provided an opportunity to compare the **Z-SCAN** magnetotelluric results to the downhole sonar results. The first comparative review of **Z-SCAN** and sonar was done after preliminary **Z-SCAN** results were compiled and reported.

Each solution void was defined by depth intervals of low apparent resistivity, with strong “water” signature phase disturbances, in a surrounding matrix of higher apparent resistivity and quieter phase disturbances.

V-1 Void

The Void V-1 Isopach (Fig. 1) is a combination of two closely connected voids. Void 1 was very important for the confirmation of the accuracy for the overall calibration of this **Z-SCAN** project. As anticipated, the raw **Z-SCAN** data overcalled the limits and volume of the void as compared to the sonar data.

However, using the “image overlap” corrected **Z-SCAN** data set, the volume compared closely to the sonar volume. A volume of 242,596 barrels was calculated using **Z-SCAN**, which compares with the 247,710 barrels indicated by the sonar data. To calibrate the volume calculation methods used by DMT, the sonar results were input to the Rockworks 98®’s, a registered trademark of Rockware, Inc., 2D-volume program on a 20’ station interval used by DMT. Sonar volume reports indicated a V-1 volume of 247,710 while Rockworks calculated 241,517, a very close tie of 2.5%.

The corrected **Z-SCAN** data continues to see the void extent past the limits seen by sonar, with one exception. The south leg of the data set is shorter on the **Z-SCAN** data. This may indicate that the bottom location of the sonar tool (the borehole) is 15’ to 20’ south of the surface location. Shifting the sonar outline to the north-northeast to correct this possibility would cause the two surveys to become more in register. It is interesting to note that the raw **Z-SCAN** data overcalled or tied the sonar limits of the void in every case, and therefore, would error in the proper direction. This provides useful safeguards where exceeding certain boundaries are the main concern. The most accurate data are the image overlap corrected **Z-SCAN** data set.

The cross-section data is an aid in visualizing the shape of the two voids, as defined by **Z-SCAN**. A small ledge is seen on a few stations which separates the voids in certain locations, but the data indicates these are connected for overall volume considerations.

V-2 Void:

The total V-2 Void Isopach (Figure 2) is a combination of the three voids. Small ledges separate these on a few stations, but data indicate that they are also all interconnected and contribute to the total V-2 volume. Void 2 is unusual in that thicknesses increase away from the injection well in several directions, with a maximum thickness of 92’ indicated.

V-3 Porosity Zone or Void:

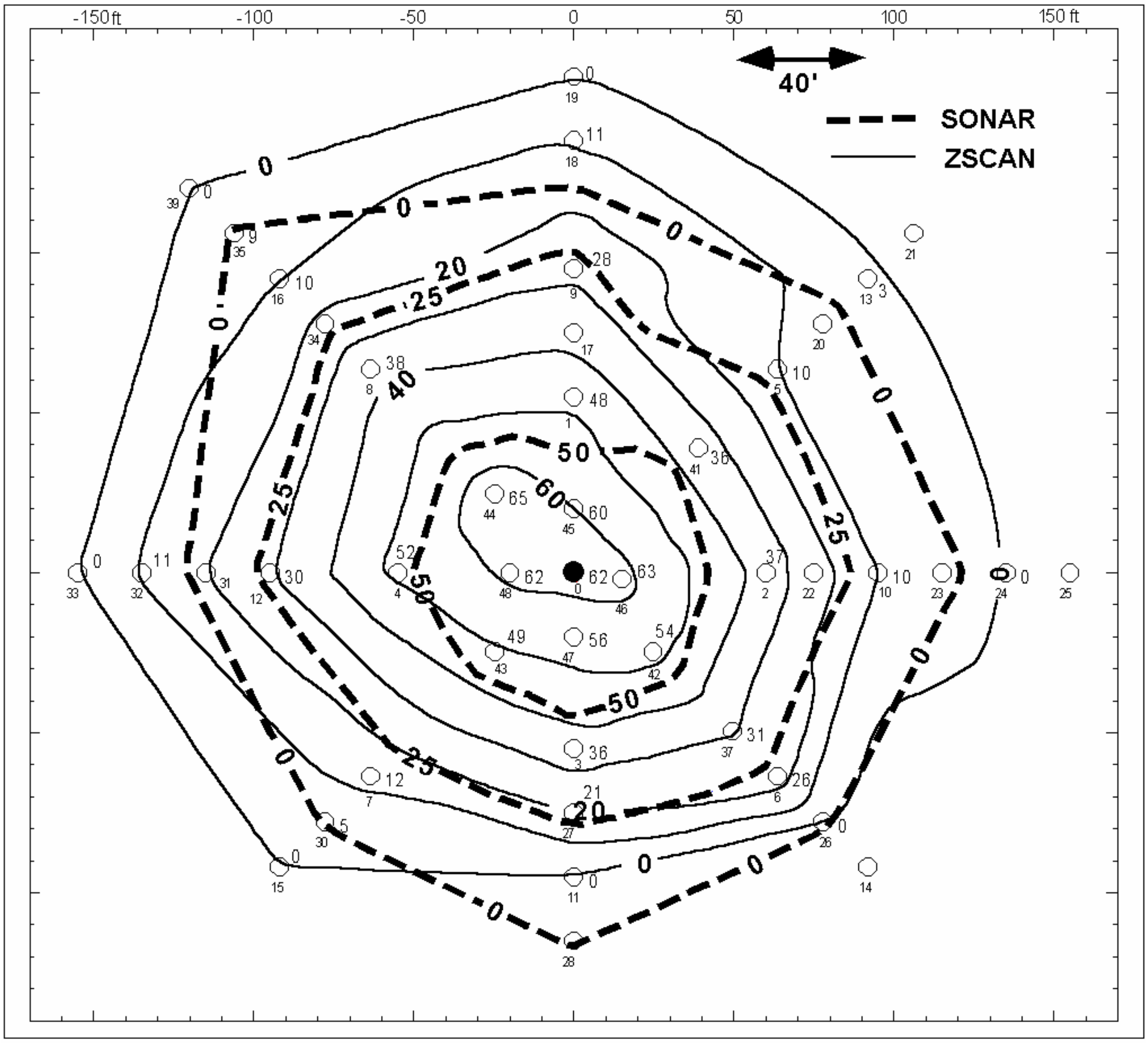
Originally, some questions existed from past information and interpretation of the electric log data on the depth and nature of the V-3 porosity interval. This was based on the interpreted depth of the salt versus anhydrite. Because the low indicated resistivity and the observed identical fluid response to Voids 1 and 2, the initial interpretation was that the **Z-SCAN** data indicated good porosity which was either a salt solution void or a collapsed anhydrite void. After coordinating all the data, it became apparent that V-3 is a salt solution void. One station indicated a thin member of the void under a substantial ledge, but it was ignored for these analyses. Void 3 has not been completely closed in several of the northern radial components. Data has been recorded but not analyzed in all needed directions, except for the NE, at the client’s request. To complete the sections, V-3 was interpolated on stations where the interval was not available. Actual **Z-SCAN** control is noted by thickness values on the V-3 Isopach map (Figure 3).

If horizontal void limits are the main concern through time, future re-checks of the active site can be less costly, as fewer stations will be needed. However, if volume and vertical limit definition are still required, the same number of stations will be necessary on future re-checks.

CONCLUSIONS

In review, **Z-SCAN** survey results offer a close tie to the limits and volumes defined by the sonar technique for Void 1. Volumes and limits for cavern V-2 are considered accurate, and should be used for total volumes. Zone V-3, though not completely closed with 0’ void values, is anticipated to close; interpolated data used in volume calculations is considered reliable. Overall volumes for V-1, V-2, and V-3 yields a total of 748,828 barrels. Results of the study indicate **Z-SCAN** to be viable technology for determining the depth, geometry, and estimated capacity of underground voids.

V-1 VOID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-50
0
50
100
150 ft
40'
SONAR
ZSCAN
0
20
25
40
50
60
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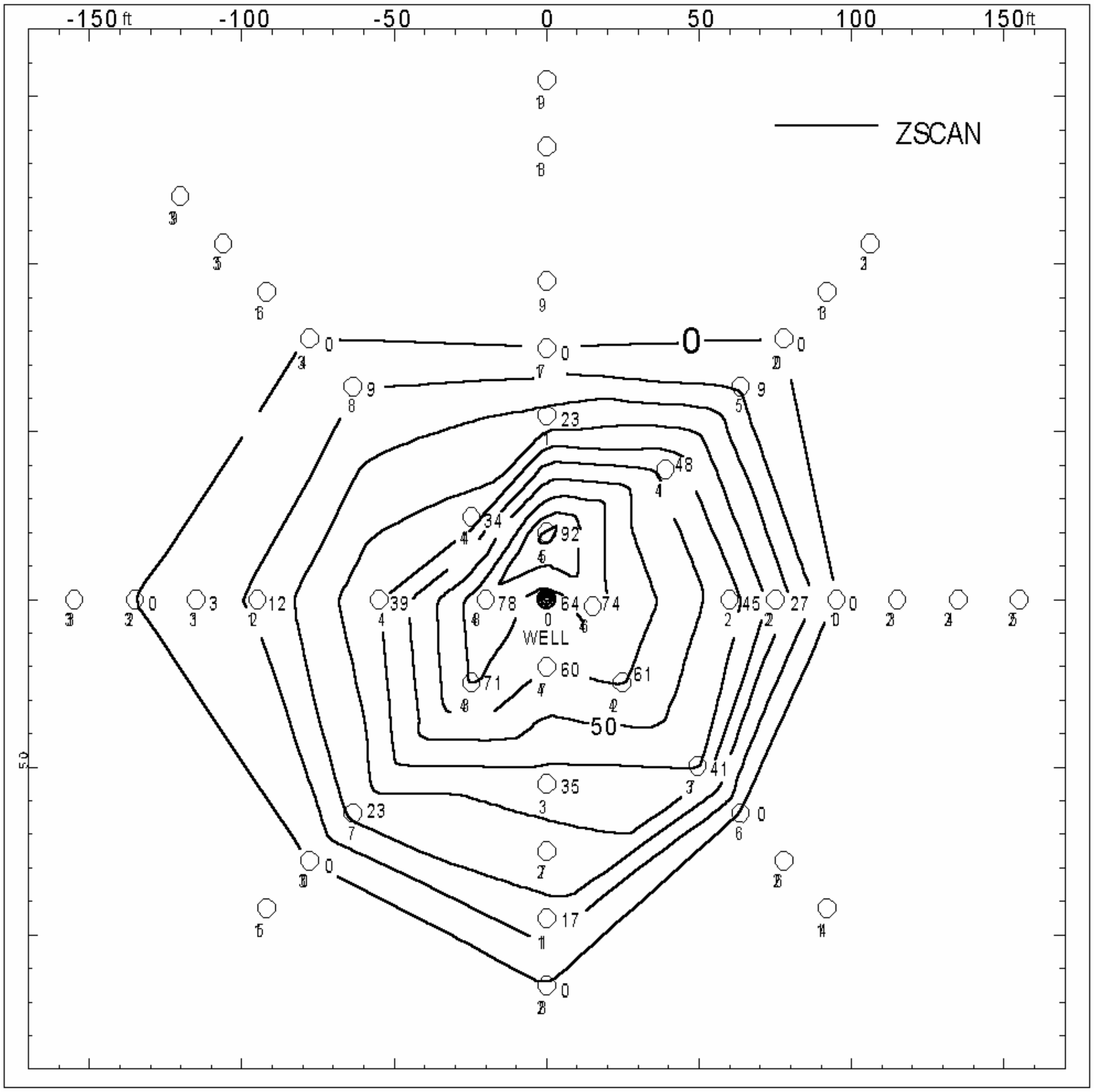
18
39
35
16
34
8
9
17
1
41
44
45
48
46
4
12
31
32
33
2
22
10
23
24
25
43
47
42
37
3
7
6
27
30
26
15
11
14
28
21
13
20
5
65
62
63
52
49
56
54
36
38
30
37
26
11
10
3

fig. 1

V-2 Void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-100
-50
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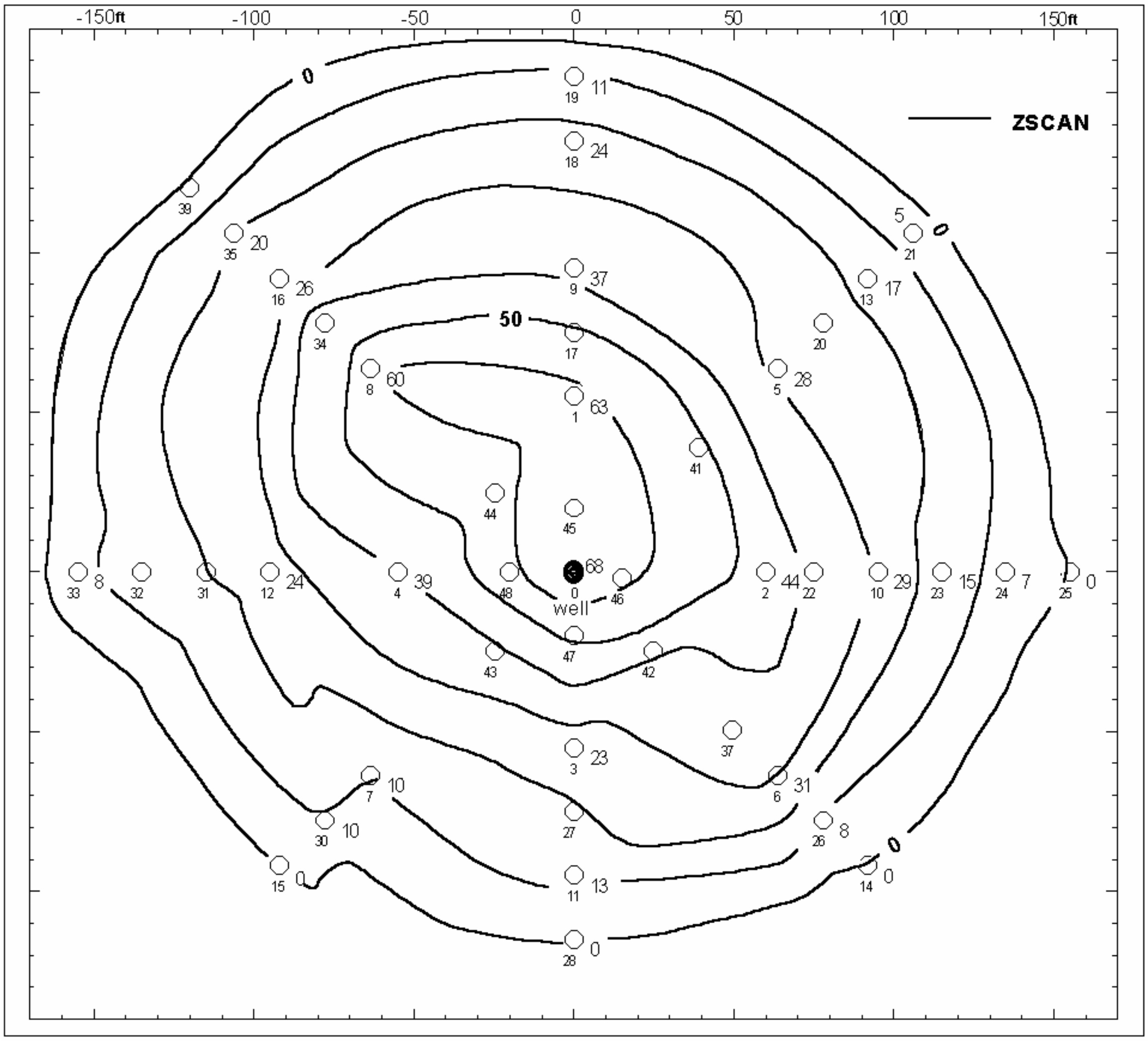
100
150 ft
ZSCAN
0
50
WELL
0
9
23
48
34
92
39
78
64
74
45
27
12
3
60
61
71
41
35
23
17

fig. 2

V-3 VOID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0
50
100
150ft
ZSCAN
0
50
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18 24
39
35 20
5
21
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9 37
13 17
34
17
20
8 60
1 63
5 28
41
44
45
33 8
32
31
12 24
4 39
48
68
0
well
46
2 44
22
10 29
23 15
24 7
25 0
43
47
42
37
3 23
6 31
7 10
30 10
27
26 8
0
15 0
11 13
14 0
28 0

fig. 3

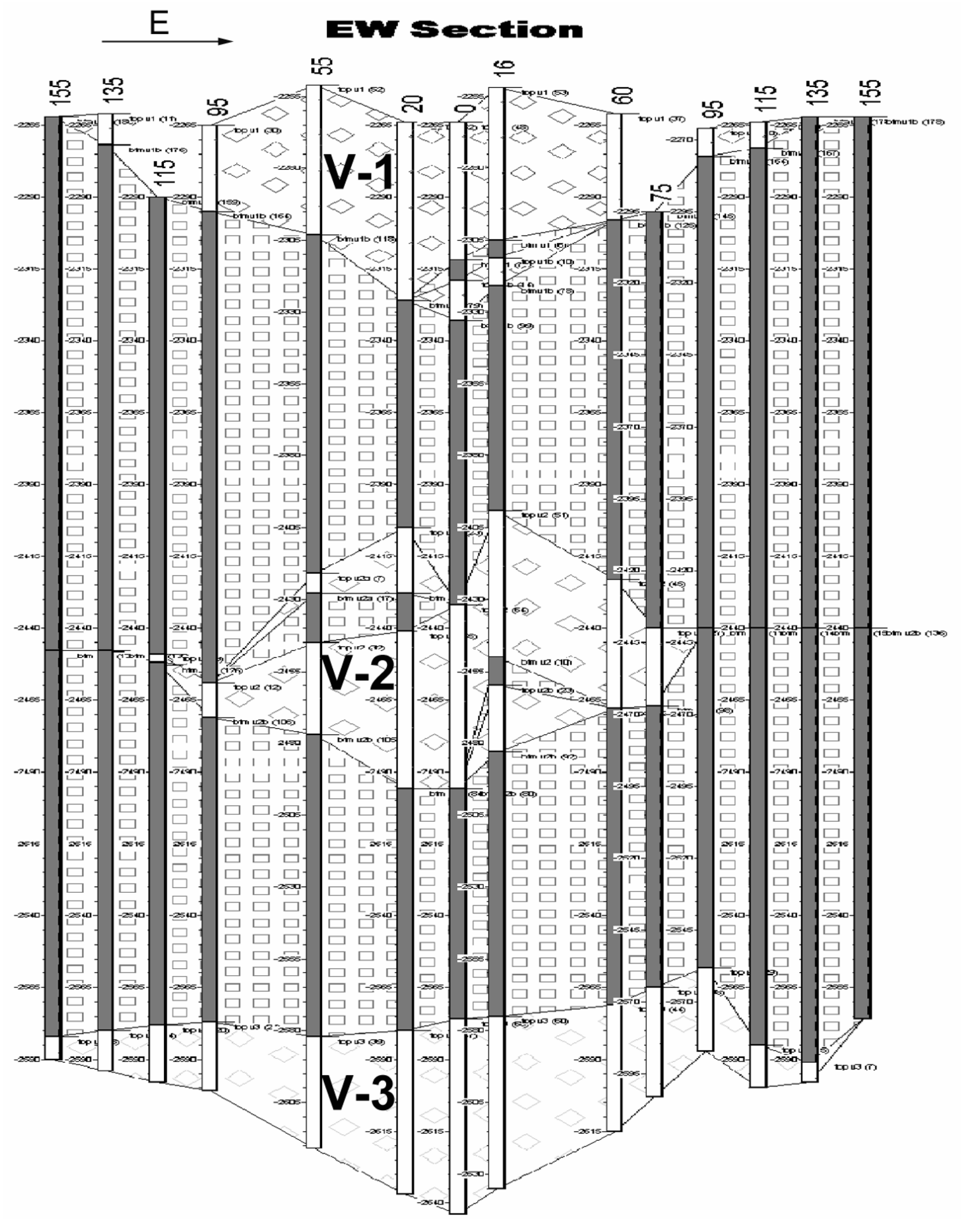
E
EW Section
155
135
115
95
55
20
0
16
60
75
95
115
135
155
V-1
V-2
V-3
-2265
-2290
-2315
-2340
-2365
-2390
-2415
-2440
-2465
-2490
-2515
-2540
-2565
-2590
top u1
btmu1b
top u2
btm u2b
top u3

Fig. 4

NS Section

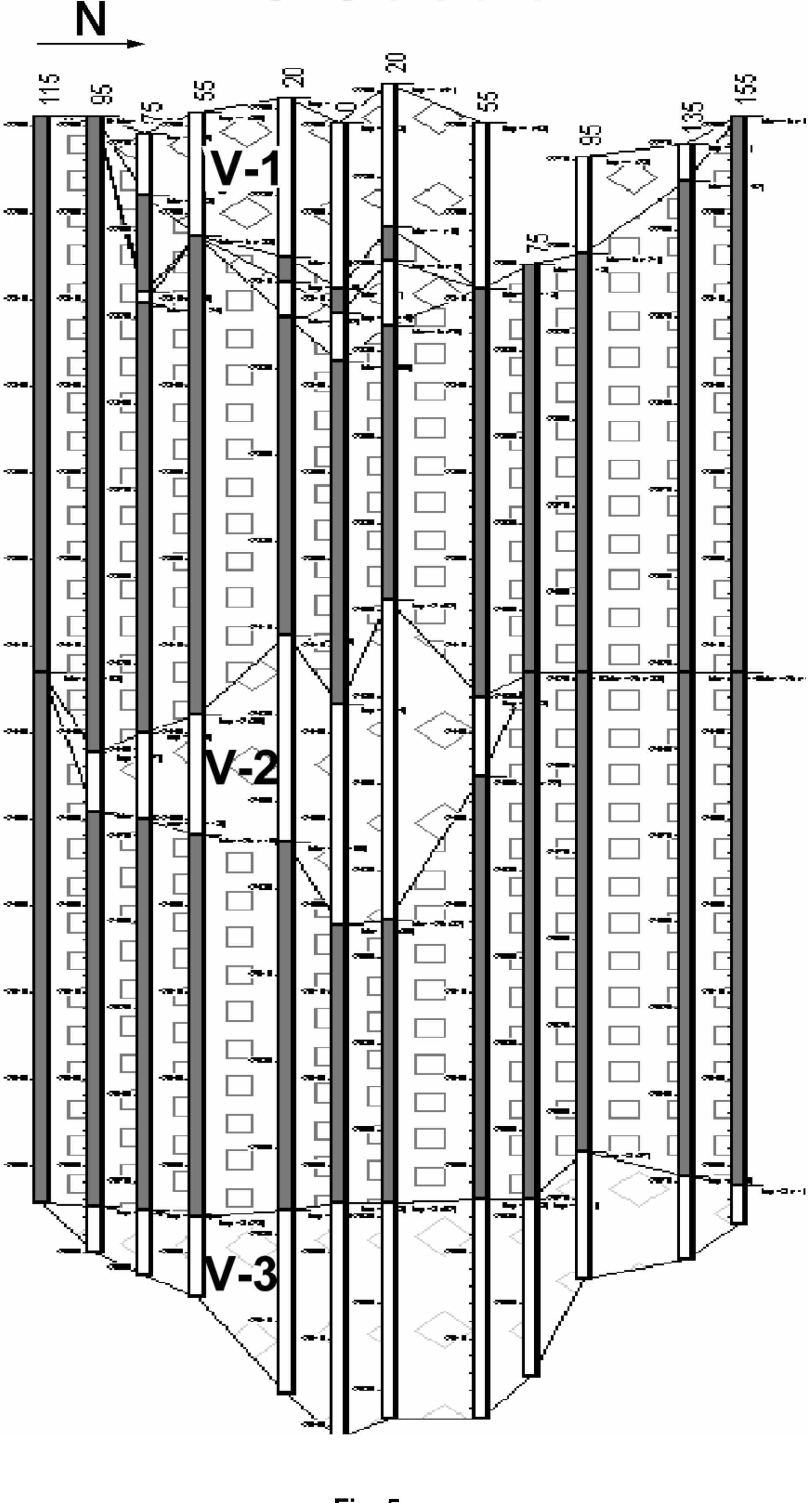

Fig. 5