Seismic Delineation of Solution Cavities

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ABSTRACT

For engineering management of solution cavities in bedded salt or other evaporites, knowledge of cavity outlines is needed from time to time. Down-hole methods are not fully successful in surveying the thin, lenticular cavities common in bedded evaporites. A new type of surface seismic-reflection surveying has been tested for this purpose; in principle, large seismic amplitude anomalies should be found above flooded solution cavities. Two years of research on the proposed method have been supported by the Brine Cavity Research Group. Results from the majority of the field experiments performed were negative, mostly because of unfavorable geology. Nevertheless, in the final study, excellent cavity indications were obtained using the "seismic shadow" technique and normalized amplitudes: Solution cavities at a depth of 1,500 feet were apparently delineated with a lateral precision of around 15 feet. Further testing and development of this powerful method is recommended.

INTRODUCTION

The research reported here had the aim of finding a practical method of defining the outlines of solution cavities from the surface of the ground. In bedded evaporites, such cavities tend to be thin and lenticular, with obstructions and probably tortuous connecting passages. Such cavities cannot be explored fully with down-hole sonar. A seismic method was chosen for testing rather than any other surface geophysical method for the following reasons:

1. The geometry of the typical solution cavity (width less than 400 feet, depth greater than 1,000 feet) is unfavorable for any of the force field methods: electric, magnetic, gravity, and strain fields (Jakosky, 1950). Such force fields spread out with distance, seriously "smearing" the details of the geophysical patterns at distances larger than the source dimensions.[1] On the other hand, a field of waves can theoretically form an image of the cavity at any distance, with a sharpness limited only by the diffraction effect (perhaps one-quarter wave length in an ideal case).

2. Only two kinds of waves are known which are capable of appreciable penetration through the earth: seismic waves and very low-frequency electromagnetic waves. However, absorption and reflection of the latter are too large to permit their use at depths greater than a fraction of a wave length in typical earth materials, so that electromagnetic images cannot be formed. Seismic waves do not suffer from this limitation: they can travel many hundreds of wave lengths through the earth. They are routinely used for petroleum prospecting at depths as great as 30,000 feet under favorable geological conditions.

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[1] Recent success reported in delineating cavities with near-surface strain measurements do not appear to contradict this prediction; the cavity boundaries so indicated are said to be vague and only the shape of the cavity is accurately given.

3. Underground cavities should produce strong anomalous effects on seismic waves. The boundary between the contained brine or air and the surrounding solid rock reflects seismic waves much better than boundaries between solids such as salt and dolomite. Therefore the seismic reflection from an evaporite bed can be expected to be much stronger where the bed is replaced locally by liquid or gas. Furthermore, reflections of deeper beds, where they must pass through such a cavity, should be greatly weakened. This may be called the "seismic shadow effect."

This paper reports three preliminary tests of the seismic-reflection-amplitude method of delineating underground solution cavities, made in the period 1961-63. This work has been largely reported previously elsewhere (Cook, 1964 and 1965). All tables and figures are taken from these earlier publications. The work was conducted by the writer at the Southwest Research Institute and was supported by the Brine Cavity Research Group, an association of eleven chemical and salt-producing companies, which has since been absorbed into the Solution Mining Research Institute. Unfortunately, most of the results obtained in the seismic research project were negative: by the time positive results of encouraging quality were obtained, the decision had already been made to discontinue seismic work. It is recommended that this research be continued; the seismic method continues to have the greatest theoretical potential for outlining solution cavities accurately, particularly at great depths.

THEORY

Initial inquiries showed that conventional seismic methods, involving measurements of times between reflecting horizons or the use of refracted waves, probably would not work in this problem. However, measurements of amplitude should provide definitive anomalies from fluid-filled underground caverns. This should be particularly so for shear waves, since these cannot travel through liquids or gases at all. In particular, horizontally-polarized (SH) shear waves striking a horizontal interface between a solid and a liquid would be completely reflected. Initially, it was thought that many of the solution cavities of interest would have reasonably flat tops (Fig. 1). Therefore, the seismic reflection amplitude anomalies expected would be of the form indicated by reflection "a" in the seismogram at the upper left of Fig. 1. Later, it was seen that the "shadow" type of anomaly would also occur where reflected waves from the deeper horizons ("b" in Fig. 1) were obstructed by the fluid-filled cavity.

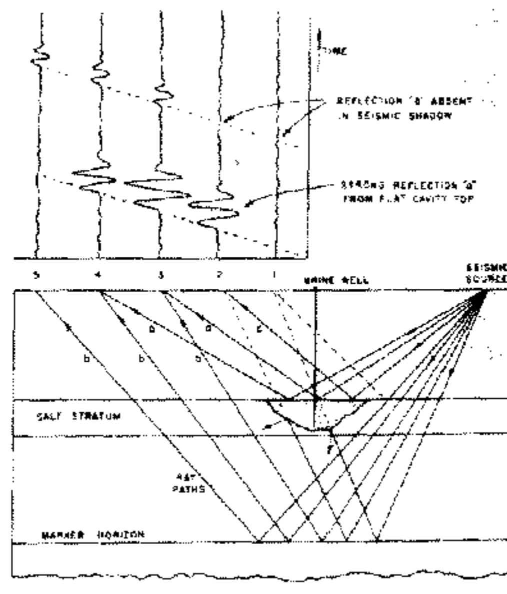

Figure 1. Idealized seismogram and solution-cavity, showing expected results.

Upon more careful quantitative study, the expectation that these two effects would be found was reinforced. The amplitude of a reflected seismic wave from a given horizon depends largely upon the contrast in the "seismic impedances" of the two geologic formations above and below the reflecting interface. The seismic impedance of each formation is given by the product of the density and seismic velocity in that formation. It can be seen in Table 1 that salt, gypsum or similar evaporites closely resemble typical rocks in seismic impedance, so that the reflection coefficients from the top and bottom interfaces of an evaporite stratum are normally small, especially for ordinary compressional (P) waves. On the other hand, a cavity of sufficient size filled with brine has a much lower density ρ, acoustic velocity V, and impedance, hence a large reflectivity r. The large lateral contrast between the brine and the solid evaporite should produce a large, clearly distinguishable, localized geophysical anomaly.

Table 1. Typical Amplitude Reflection Coefficients For Seismic Waves*

	Density ρ' gm/cm^3	For P-Waves: Velocity V_p' km/sec	For P-Waves: r_p	For S-Waves: Velocity V_p' km/sec	For S-Waves: r_s
A. Paleozoic Formations					
shale	2.3	4.0		2.0	
			> -0.06		> -0.02
salt, gypsum, etc.	2.1	5.0		2.3	
			> -0.153		> -0.17
dolomite	2.6	5.5		2.6	
			> +0.81		> +1.0
brine	1.0	1.5		-	
			> -0.72		> -1.0
shale	2.3	4.0		2.0	
B. Tertiary Formations					
salt, gypsum, etc.	2.0	4.5		1.8	
			> +0.20		> +0.24
sand or shales	2.2	2.8		1.1	
			> +0.60		> +1.0
brine	1.0	1.5		-	

* Note: densities and velocities used are representative values from the literature.

FIELD METHODS

For practical seismic-reflection-amplitude surveys in the field, as well as for experimental research purposes, two things are required: a source of seismic energy and a set of receiving equipment. The sources used so far in this work have been of two types: hammer-trucks and explosives. In order to test the feasibility of using horizontally-polarized (SH) shear waves, much of the field work so far has been done with sources giving a horizontal thrust to the earth. Figs. 2 and 3 illustrate respectively, a hammer-truck and an explosive-disc source. The hammer-truck had a heavy pendulum pivoted to an A-frame. The pendulum was hoisted by a winch and was electrically released, striking horizontally against the end of a small trench dug at the rear of the truck. The explosive-disc source consisted of a spiral of large primacord wound on the surface of a steel disk. It was buried in a vertical plane in contact with the end of a trench. Upon detonation, it produced an unsymmetrical horizontal thrust on the end of the trench. In addition to these

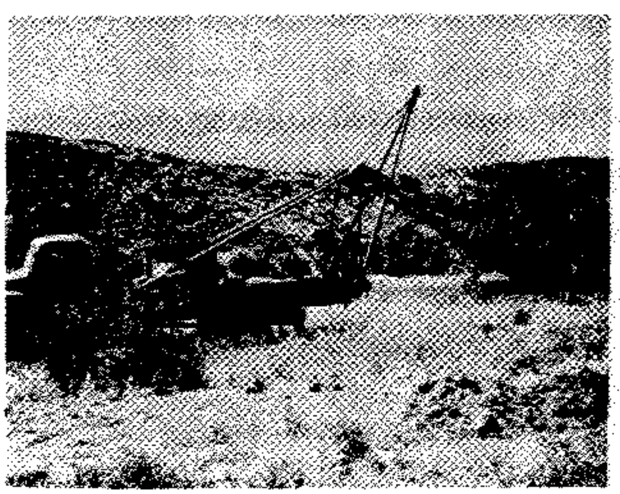

Figure 2. Hammer-truck SH-wave source in action at brinefield in North Texas.

Figure 3. Explosive-disc source for SH waves.

sources, used to generate SH (horizontally-polarized shear) waves, ordinary explosive seismic sources consisting of charges buried in drilled holes were used to generate P (compressional) waves.

The receiving equipment consisted of the following elements: 24 short arrays of geophones, which could either be oriented vertically for P waves, or horizontally and transverse to the axis of the geophone spread for SH waves; cables leading to the recording truck (Fig. 4) and amplifiers and recorders within the truck. The resulting records show motion of the ground vs. time as wiggly lines, and are called seismograms. The seismograms were recorded not only in visible form but on multichannel magnetic tape, for subsequent data-processing operations. The magnetic tapes were subsequently reprocessed by some of the most sophisticated methods available to the petroleum exploration industry: These included several kinds of frequency-filtering, compositing of several successive records, common-reflection-point stacking, and velocity filtering. These efforts to improve the record quality were not entirely successful.

On the basis of observed costs during these experiments, and on petroleum-prospecting experience, it appears likely that routine seismic field work would cost of the order of $700 per day, per crew, with a productivity of the order of one cavity in two days for each crew.

FIRST EXPERIMENT

The first major field experiment undertaken after the initial theoretical, literature, and model studies were completed, consisted of a test survey over a group of solution cavities some 500 feet in depth below the surface in North Texas. Of some 200 seismograms produced in this experiment, only one illustration will be given here. Figure 5 shows one of the layouts of equipment with relation to three interconnected brine wells and the cavities assumed to be associated with them. Figure 6 illustrates one of the corresponding seismograms obtained. The clear reflection "b" obtained is sharply limited in lateral extent, and is interpreted to mean that a strong reflector exists at point "b" in Fig. 5. This result has since been corroborated in qualitative fashion by the brinefield owners, by mechanical means. Unfortunately, the general quality of the seismic results obtained in this area was poor, results were not consistent, and clear outlines of the solution cavities and their connecting channels could not be drawn. The poor record quality prevailing was attributed to excessive absorption of seismic energy by the loose surface sands. The inconsistencies were attributed to confused dips in near-surface beds, perhaps as a result of differential solution of interbedded evaporites during geologic time. It was recommended that a site with simpler geology be found for another experiment.

Figure 4. Seismic recording truck in the field.

SECOND EXPERIMENT

A site of apparently ideal geology was found in the Great Lakes region. From numerous drill holes, it was known that the strata from the surface down to the salt were of simple, flat form and consisted principally of dolomite with an overburden of dense glacial clay, both of which are good media in which to produce and transmit seismic waves. A series of over 100 seismic records were made in an area containing a large solution cavity at a depth of about 1,100 feet. By analogy to nearby cavities which had been surveyed by down-hole sonar, this cavity was expected to be flat-topped and of essentially round shape. Figure 7 shows a cross section (with true vertical scale) of the geometry involved in this experiment. The receiving instruments were laid out in a line with an array of explosive wave sources at its center ("split spread").

In one particular position of this line, the record shown in Fig. 8 was obtained. This record has been selected for illustration because a seismic reflection at approximately the right depth to represent the cavity top was seen, despite severe reverberation interference. The reflection entitled "North Cavity Reflection" in Fig. 8 is interpreted to mean that seismic energy followed the paths shown by the shaded section in Fig. 7, and was strongly reflected from a body presumed to be a liquid-filled cavity. This reflection was apparently confined to channels 1 to 12 on the seismogram; the reflector positions deduced from this are plausible, as shown in Fig. 7.

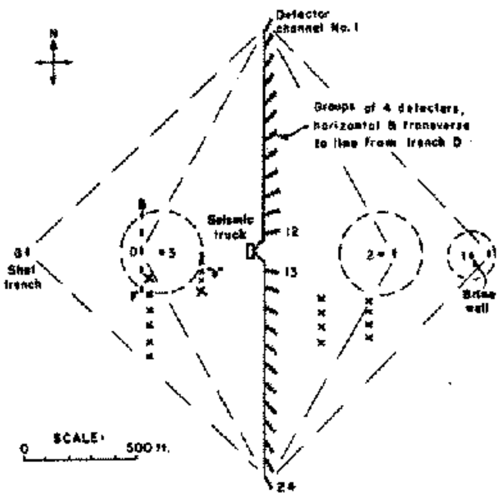

Figure 5. Map of North Texas brinefield and deduced reflectors "x."

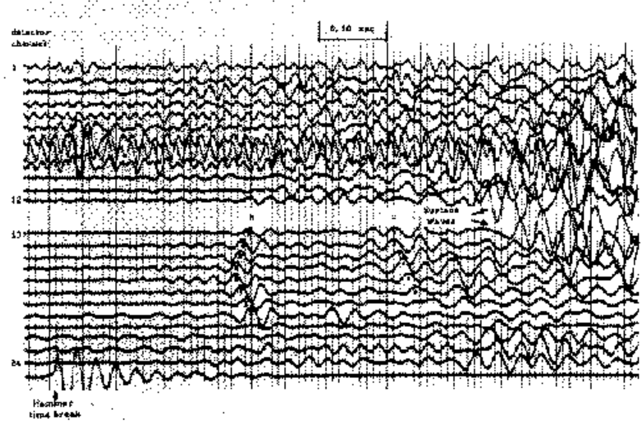

Figure 6. Seismogram from North Texas showing localized reflection "b."

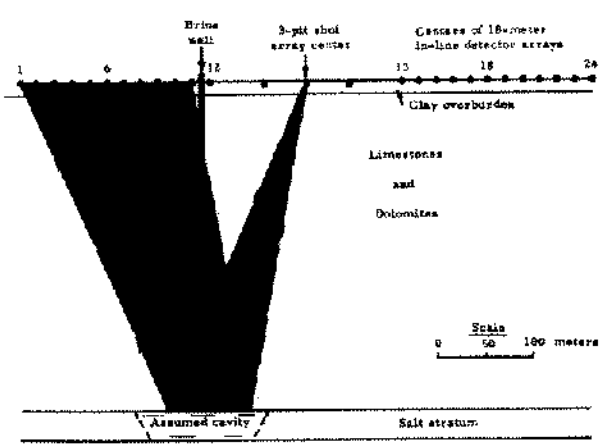

Figure 7. Cross section of Great Lakes experiment.

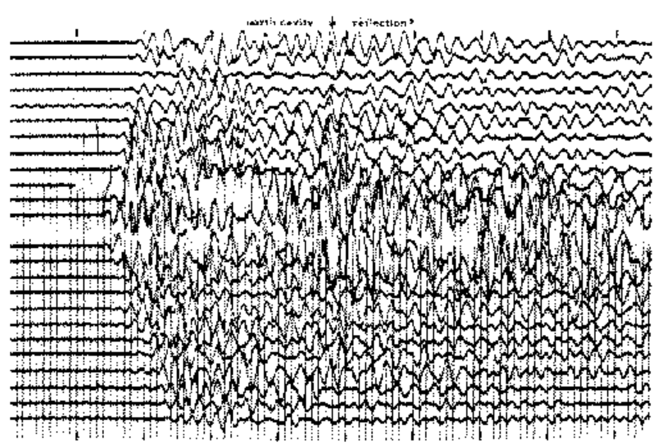

Figure 8. Example of filtered seismogram from Great Lakes experiment.

Unfortunately, the high reverberation noise level in this test area required severe frequency-filtering before the reflections could be seen at all. Despite the use of a variety of seismic techniques in the field, and the use of advanced data-processing techniques in the laboratory, seismograms better than Fig. 8 could not be obtained. The agreement between records taken with different spread positions was not good. It was concluded that the method had again not been proven, principally because of the unexpected reverberation noise. It is possible that future seismic experiments in the Great Lakes area will succeed, because favorable results have recently been obtained by others (Brinker, 1963) using special shooting techniques.

THIRD EXPERIMENT

One of the principal requirements of the seismic-amplitude-reflection method for delineating solution cavities evidently is that good seismic reflections can be obtained. Fortunately, good seismic reflection data were available from another solution-mining area where the evaporite was about 1,500 feet below the surface. A typical record from this area is shown in Fig. 9. Three clear and consistent reflections were found throughout this group of records, which were called A, B, and C. Reflection B was identified as coming approximately from the evaporite horizon; reflection A is from a stratum some distance above the evaporite, and reflection C was from a "marker horizon" (see Fig. 1) some distance below the horizon of interest.

In the first attempt to use these reflections, the absolute amplitude of reflection B for each trace of each seismogram was plotted at a position corresponding to the presumed position of the underground reflector for that trace along the linear traverse, as shown in Fig. 10. It is seen that the amplitude of B varies greatly and without apparent pattern. It was expected that a large increase in average amplitude would be seen near the solution-mining well (shown by a block at shotpoint 4). This was not the case. It was concluded that there are numerous uncontrolled factors affecting the amplitude of the reflection. Among these could be, the random variability in coupling between various geophones and the soil, and the difference in intensity between different explosive shots.

To control these variables, one could use reflection A as a "standard." Therefore, the ratio A/B was tabulated for two records, shot # 3 in the vicinity of the well and its solution cavity, and shot # 10 a great distance away, to give the "background." Table 2 shows that the average ratio A/B was the same for both records, whether recordings were made with or without automatic gain control (AGC). This was a most unexpected result, and means that, despite normalization of reflection B, it does not change, or perhaps reverses sign while remaining the same in magnitude, when the evaporite horizon is replaced with fluid in this particular area.

Finally, a search for the seismic shadow effect was made. Reflection C from beneath the evaporite horizon was normalized by taking the ratio A/C as shown in Table 3. It was immediately

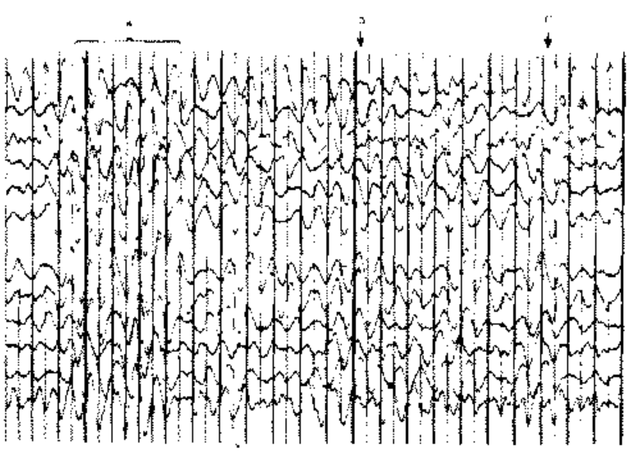

Figure 9. Typical seismogram used in third experiment, with reflections.

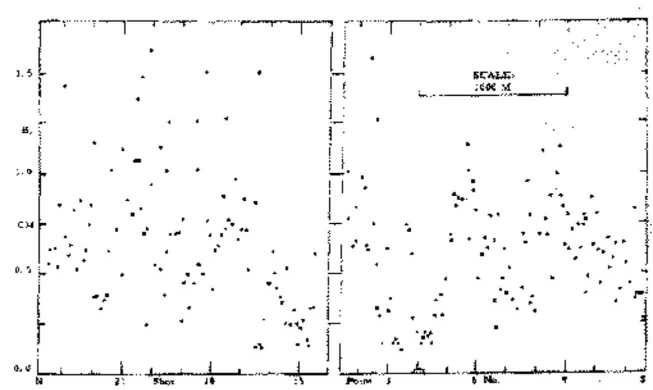

Figure 10. Amplitudes of evaporite reflection vs. traverse position.

Table 2. Normalized Reflection Amplitude Results for Contrasting Records

Ratio A/B for AGC-off Records

	Trace:	1	2	3	4	5	6	7	8	9	10	11	12	average ratio
Shot No. 3	A, mm	(25.4)	27.9	16.3	(34.5)	6.60	6.60	6.60	3.56	4.06	6.10	10.2	7.11	2.66
	B, mm	10.2	12.2	7.11	5.08	3.05	1.27	2.79	1.52	2.03	2.03	3.05	3.56	±.67*
	A/B	2.50	2.30	2.30	6.8	2.16	5.2	2.16	2.34	2.0	3.0	3.33	2.0	
Shot No. 10	A, mm	23.9	13.2	14.0	20.3	14.7	6.86	(17.8)	(5.08)	10.7	8.89	10.2	(14.0)	2.63
	B, mm	8.13	5.59	5.08	10.2	6.35	4.06	8.38	2.54	4.06	3.56	4.32	2.54	±.51*
	A/B	2.94	2.36	2.76	2.0	2.32	1.69	(2.12)	(2.0)	2.62	2.50	2.35	(5.50)	

Ratio A/B for Records with AGC

	Trace:	1	2	3	4	5	6	7	8	9	10	11	12	average ratio
Shot No. 3	A, mm	21.8	31.5	18.8	21.8	34.5	26.4	19.8	18.3	17.8	15.2	26.4	16.3	1.76
	B, mm	22.9	14.2	13.7	13.2	15.2	10.2	16.8	7.62	8.89	10.2	13.2	15.7	±.46*
	A/B	0.96	2.22	1.37	1.66	2.27	2.6	1.12	2.4	2.0	1.50	2.0	1.03	
Shot No. 10	A, mm	11.4	22.4	21.6	17.8	16.5	19.1	16.5	17.8	19.1	22.4	23.4	8.13	1.76
	B, mm	41.4	12.8	9.65	12.7	10.2	12.2	13.2	12.7	13.2	10.7	11.7	10.7	±.46*
	A/B	0.72	1.76	2.23	1.40	1.62	1.56	1.25	1.40	1.44	2.10	2.0	0.76	

Note: Numbers in parentheses are from doubtful, noisy readings.
* mean deviations

Table 3. Normalized Shadow Amplitude Results for Contrasting Records

Ratio A/C for Records with AGC

	Trace:	1	2	3	4	5	6	7	8	9	10	11	12	average ratio
Shot No. 3	A, mm	21.8	31.5	18.8	21.8	34.5	26.4	19.8	18.3	17.8	15.2	26.4	16.3	1.27
	C, mm	21.8	18.8	18.3	21.3	18.0	21.3	18.8	12.7	12.7	11.2	13.7	18.3	±.29*
	A/C	1.0	1.67	1.03	1.02	1.95	1.23	1.05	1.44	1.40	1.36	1.92	0.89	
Shot No. 10	A, mm	11.4	22.4	21.6	17.8	16.5	19.1	16.5	17.8	19.1	22.4	23.4	8.13	.708
	C, mm	19.1	18.8	18.0	29.2	26.9	23.4	30.5	17.8	21.3	23.1	21.8	20.8	±.22
	A/C	0.60	1.19	1.20	0.61	0.61	0.82	0.54	1.0	0.89	0.96	1.08	0.39	

* mean deviations

found that the average ratio was significantly different for record # 3 and record # 10. Also, the sign of the difference was such as to indicate a weaker reflection arriving through the solution cavity, as is expected in the seismic shadow effect (A/C is larger in the vicinity of the cavity). This was considered a significant, positive result.

The test summarized in Table 3 was made with records having AGC. In order to increase the effect and eliminate chance variations caused by the AGC itself, the same study was repeated using records made without AGC. Figure 11 shows the result for a traverse crossing two solution-mining wells and their associated cavities. It can immediately be seen that in the "background" area far from the wells, the ratio A/C is reasonably smooth, low, and reasonably constant in value. In the vicinity of the solution cavities however, the ratio becomes large and highly variable, as would be expected. The variability may be due in part to diffraction effects.

Especially noticeable is the sharp discontinuity at each side of the anomaly; the edge of the anomaly, indicating the edge of the solution cavity, is definite to within perhaps 15 feet. This is essentially the result expect from theory, and supports our original expectation that seismic-wave methods should give sharp resolution of cavity edges.

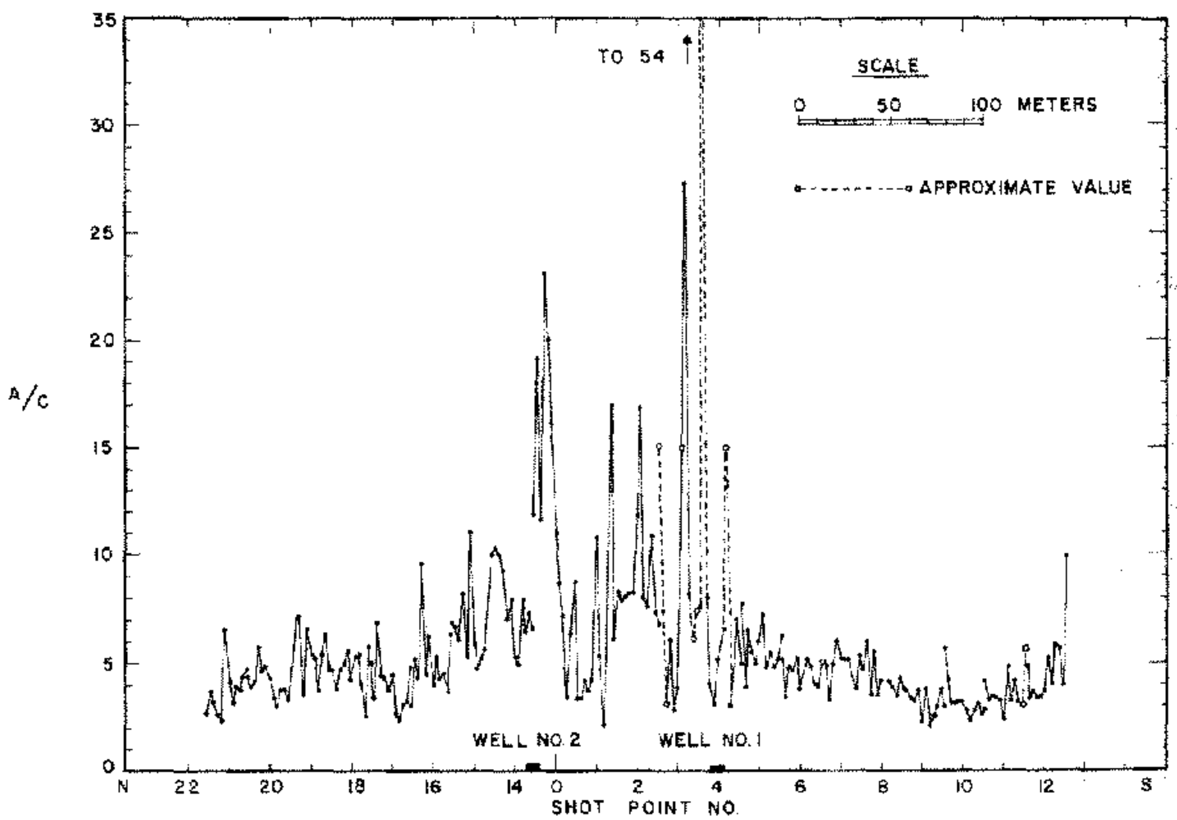

Figure 11. Normalized marker-horizon reflection amplitudes vs. traverse position, showing shadow anomaly near wells.

SUMMARY

1. Some evidence of successful seismic-reflection-amplitude cavity delineation has been shown in each field experiment performed so far. However, the best and most consistent support of the theory comes from data taken in an area where good seismic reflections occur.

2. The theoretical resolution of the order of 1/4 of a seismic wave length (perhaps 15 feet) has apparently been demonstrated in one case. Similar sharp resolution is theoretically

possible with the seismic-reflection-amplitude method at depths of many thousands of feet, that is, any depth from which good seismic reflections can be obtained.

3. Successful use of amplitude information from seismic reflections requires a normalization process to correct for amplitude variations occurring at and near the surface of the ground. As presently conceived, the method requires a reference reflector somewhat above the stratum of interest.

4. In certain geologic situations, strong reflectivity contrasts can be seen between solution cavities and the neighboring undissolved evaporite. However, the seismic shadow technique, which requires an additional seismic reflecting horizon below the evaporite stratum, may be more reliable where it is feasible, since two to four passages through fluid-solid interfaces occur in forming the shadow.

5. For successful development of the potentialities of this method, additional practical field research will be required. Thirty years of development on the seismic reflection method of prospecting for oil are available as a starting point.

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