Yes, We *Can* Locate Solution Cavity Boundaries

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ABSTRACT

Ten years ago, after two years of brining-company-sponsored research, solution cavities were clearly located from the surface at a depth of 1600 feet by seismic reflection. That result has been thoroughly ignored. The method has not yet been tested further by the industry, despite a persisting need to map cavity boundaries. During the past decade, seismic techniques have been improved by another order of magnitude; even seismically difficult areas can now be worked. Cavity mapping from the surface by the seismic method is needed, is feasible and is overdue. Suitable techniques are recommended and the costs of applying them are estimated.

INTRODUCTION

Solution cavities developed by brining bedded deposits would ideally be circular and flat. Actually, they tend to develop as broad inverted cones, elliptical or fingered in plan view, with the brining well off-center. This is a consequence of density stratification in the brine, curved and dipping beds, gas pads, and fractures. Where wells become interconnected, as through hydrofracturing and washing, the route of the connection may be tortuous and is usually unknown. For many years the brining industry has sought some method of locating the cavity boundaries, for control and management purposes. This search has recently been discontinued because of repeated disappointments; the technological problems are not straightforward, and the research has been expensive. It is my purpose, in this paper, to show that cavity delineation in bedded deposits is indeed possible, that the means to do it may now be at hand, and that such means may be within the financial capability of the brining industry.

BACKGROUND

Two classes of cavity-delineation methods: access and non-access have been distinguished by Piper (1971). The chief access method is down-hole sonar, which has adequately solved the delineation problem for the tall, narrow cavities usual in dome salt. It can also map simple cavities in bedded deposits. It cannot delineate the gently sloping walls and feather-edges often occurring with cavities in bedded deposits; it cannot trace fingering or interconnecting passages, and it cannot "see" beyond the piles of debris which may occur in such cavities in their maturity. Evidently it must be supplemented by a future down-hole "robot," or by non-access methods. The non-access methods are chiefly those which may be operated on the surface of the ground. The Solution Mining Research Institute and its predecessor, the Brine Cavity Research Group, have supported research on the following non-access ("geophysical") methods:

1. Electrical resistivity; particularly employing the cavity as one of the current electrodes. (See First Symposium on Salt.)
2 Seismic reflection; particularly employing shear waves (Cook, 1964, 1966).
3. Strain field variation; strain-gage measurements in near-surface rocks with changes of cavity size (Emery, 1966).
4. Gravity surveys; preferably changes occurring with cavity development (Speed, 1970).

The results in all four studies were essentially negative, and the reasons are in each case highly technical.

PHYSICAL CONSTRAINTS

It is generally agreed (Piper, 1971) that most solution cavities occur at depths greater than their widths. In fact, most occur at depths between 1,000 and 8,000 ft. Typically, widths do not exceed 600 ft and thicknesses are 50 to 200 ft. The cavity boundaries must be delineated with a horizontal precision of 50 to 100 ft initially; greater precision is desired. Several cavities may be "stacked" where there are several evaporite beds. The surface environment may be urban or industrial. Portions of cavities may be completely filled with caved debris and insoluble residue. A suitable delineation method must eventually operate within the majority of these constraints. However, more nearly ideal conditions are available in some brine fields for the development and testing of a fledgling technique.

The usual geometry of the cavity problem immediately discourages the use of the entire class of geophysical methods based upon "potential fields." Such methods include gravity, magnetism, electrical resistivity, heat flow, gas diffusion, and mechanical strain (or stress) fields. All such methods are inherently "blunt" tools having a horizontal resolution of the same order of magnitude as the depth to the target (where this exceeds the target width, as it does here). All potential fields are smooth, simple, weak, and essentially featureless at a distance from the "source" (the target) large compared to its dimensions. There is not, and there never was, any chance that such methods could delineate the edges of a solution cavity with the necessary precision. This conclusion is an inevitable consequence of the basic laws of physics, without regard to the practical engineering problems or the "noise" interferences created by near-surface topography, conductors, jointing, etc.; the potential-field methods are by their nature incapable of resolving source details at a large distance, absolutely and forever.

The only remaining method tried to date, seismic reflection, is in a quite different class. Methods employing waves *are* capable of resolving details at a distance; otherwise the reader could not distinguish the words on this page by means of light waves. In the wave methods, resolution is determined by the wavelength of the radiation employed, in combination with the geometry of the problem. The laws of physics do not preclude adequate seismic resolution of cavity boundaries; past failures have resulted merely from inadequate technology and from the sins and errors of the experimenter. These can be remedied.

Only two kinds of waves are known to exist which can be used for geophysical exploration to depths of 1,000 feet or more: seismic body waves, and electromagnetic waves. The latter, unfortunately, cannot travel through the overburden or through porous wet rocks to any useful degree if short enough waves are used to delineate solution cavities (Yost, 1952). They *can* be so used for exploration in salt, anhydrite, limestone and other massive rocks of low porosity (Holzer et al., 1972; Cook, 1972). Brine cavity edges, even sharp feather edges, should be defineable by "meter wavelength radar" equipment operated within the evaporite bed, either in an adjacent mine or in a borehole drilled from the surface. Location accuracies of the order of 3 feet are theoretically possible (Cook, 1973).

Similar accuracy should be possible with short seismic waves; the writer has obtained 1000-Hz seismic echoes from a distance of 600 ft through salt, using a small hammer as a source. Rechtien (1970) has developed a downhole seismic source capable of generating 4,000 Hz seismic waves in competent rock. The waves from this source would have a wavelength of only 4 ft in salt. Unfortunately, such short seismic body waves cannot traverse the overburden; Rechtien (1970) recommends that all cavity delineation be done in boreholes. This should not be necessary initially, as we shall see. Because of the high cost of such boreholes, only the all-surface methods will be considered further in this paper.

SURFACE SEISMIC METHODS

The seismic reflection method originally proposed for cavity delineation (Cook, 1964) is illustrated in Figure 1. Seismic rays reach the detectors 1, 2, 3, 4, 5 by reflection both from the "salt stratum" and the marker horizon (the first set arrives earlier in time than the second set). The solution cavity should produce distinct differences in received seismic wavelet amplitudes by two processes:

(a) Reflection from the gas or liquid at the cavity top is more efficient than from un-mined solid evaporite. See Table I, reproduced from Cook (1964).

(b) The cavity fluid obstructs and diverts rays which would have to pass through it to reach the detectors on the surface.

The two seismic field experiments performed in 1961–63 were designed to observe effects (a) and (b). They were largely unsuccessful because of poor seismic record quality, which resulted from two unfortunate choices of test areas. Years afterward, Figure 2 compiled by Lyons (1951) was discovered by accident. It is a summary of the seismic record quality observed by oil companies throughout the United States. With its aid, more suitable test areas could have been selected in 1961. Today, it may not be needed.

The causes of poor seismic record quality are numerous: overburden ringing, high attenuation, multiples, "ghosts," velocity variations, complex structure, etc. In its continuing efforts to open up new areas, the petroleum industry has developed major improvements in seismic technique to overcome many of these problems. Since 1963 there has been a major revolution in exploration seismology, with the introduction of the digital computer and the methods of communication theory (Schneider, 1971). Most of the "poor" and "no reflection" areas shown in Figure 2 can now be successfully prospected; digital seismic data enhancement methods can produce records one to two orders of magnitude clearer than those

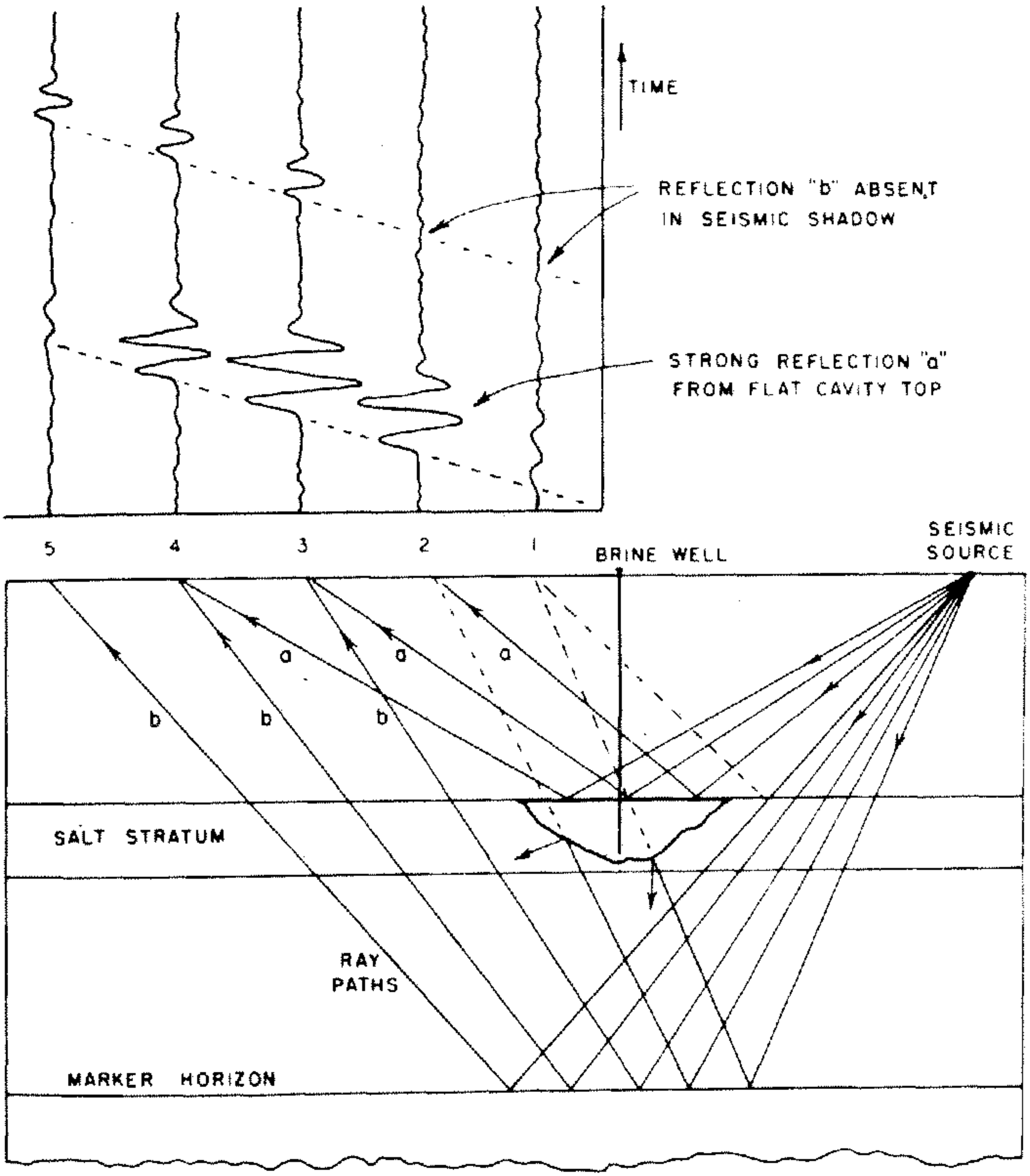

Figure 1. Idealized seismogram and solution cavity, showing expected results (reproduced from Cook, 1964).

TABLE I

Typical Amplitude Reflection Coefficients For Seismic Waves*

	Density ρ' gm/cm³	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	> -0.06	2.0	> -0.02
salt, gypsum, etc.	2.1	5.0	> -0.153	2.3	> -0.17
dolomite	2.6	5.5	> +0.81	2.6	> +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	> +0.20	1.8	> +0.24
sand or shales	2.2	2.8	> +0.60	1.1	> +1.0
brine	1.0	1.5		-	

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

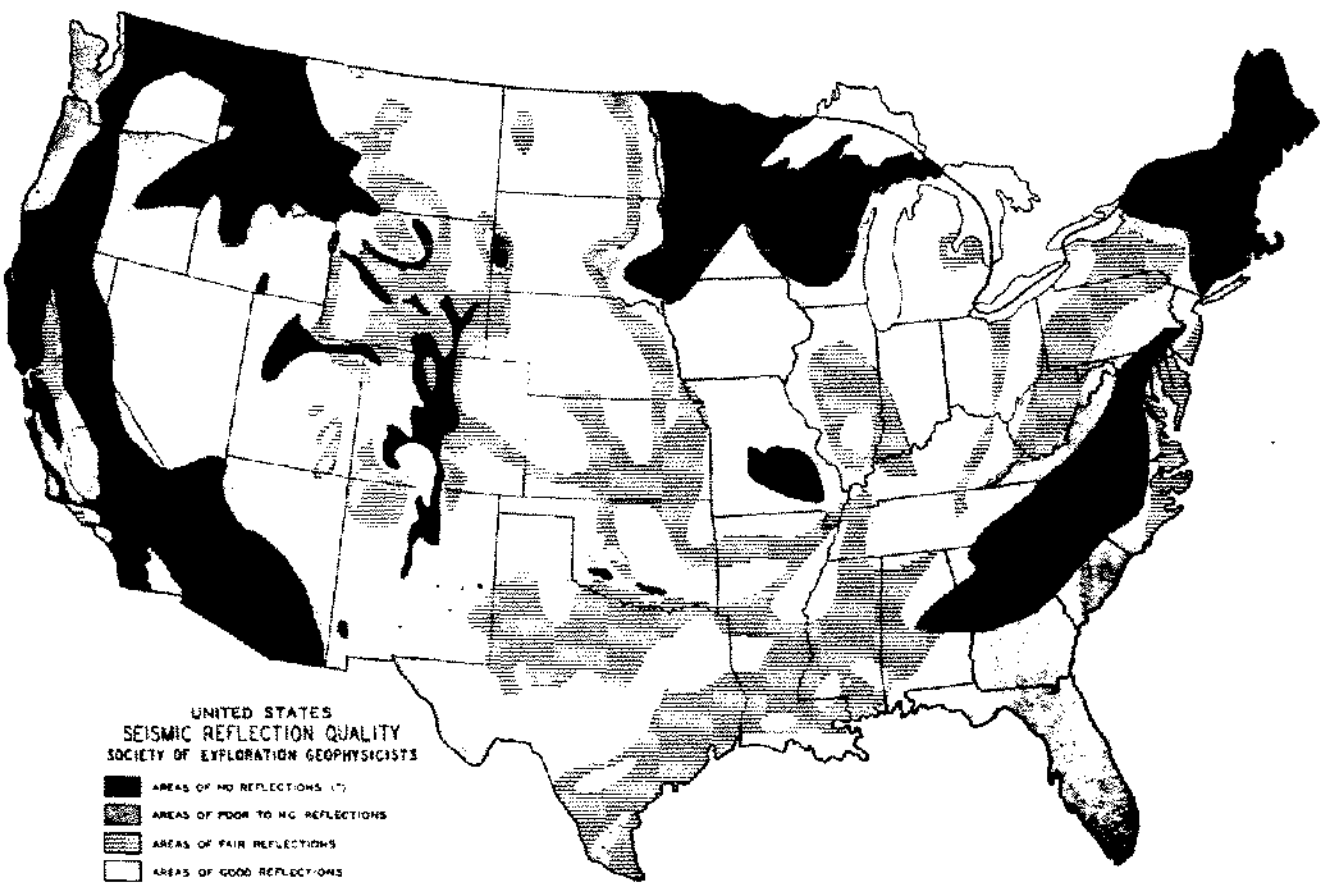

Figure 2. Map showing probabilities of good seismic results in 1951-1961.

typically available in 1963 (Schugart, 1973). "Dinoseis" and "Vibroseis" exciter trucks have eliminated the need for drill holes and explosives, and can operate even on city streets at night. There is much justification for believing that practical seismic surveys of brinefields can be carried out today in nearly all the locations where they are needed.

Subsequent to the two seismic experiments performed for the BCRG, the writer had the opportunity to study seismic reflection data of good quality from a third solution-mining area, under private sponsorship. To overcome variable near-surface effects, it was found necessary to normalize all the reflection amplitudes of type (b) seismic rays (figure 1) by means of a third flat reflecting horizon considerably above the evaporite. The result, shown in Figure 3 (from Cook, 1964), was a striking success and a confirmation of the process proposed in Figure 1. The tall "spikes" in the data near the wells are the expected seismic shadow of the solution cavity. Figure 3 alone proves that a solution cavity 1,600 ft deep can be located by the seismic reflection method. This favorable result, published 10 years ago, has been repeatedly brought to the attention of solution mining personnel, without appreciable effect. Reconsideration of seismic methods is now overdue.

DIFFRACTION-LIMITED RESOLUTION

As was previously mentioned, the accuracy with which the edges of a solution cavity can be delineated depends upon the seismic wavelength employed and upon the geometry. In Figure 1, considering only the seismic-shadowing rays of type (b), the cavity edges may be treated as diffracting straight-edges. The resulting Fresnel diffraction pattern to be expected is shown in Figure 4. The "width" w of the left-hand shadow edge, as defined in that figure, is given approximately (Burnett, et al., 1958) by:

$$w \approx \sqrt{\frac{\lambda}{2}\left(\frac{R_1 R_2}{R_1+R_2}\right)} \qquad (1)$$

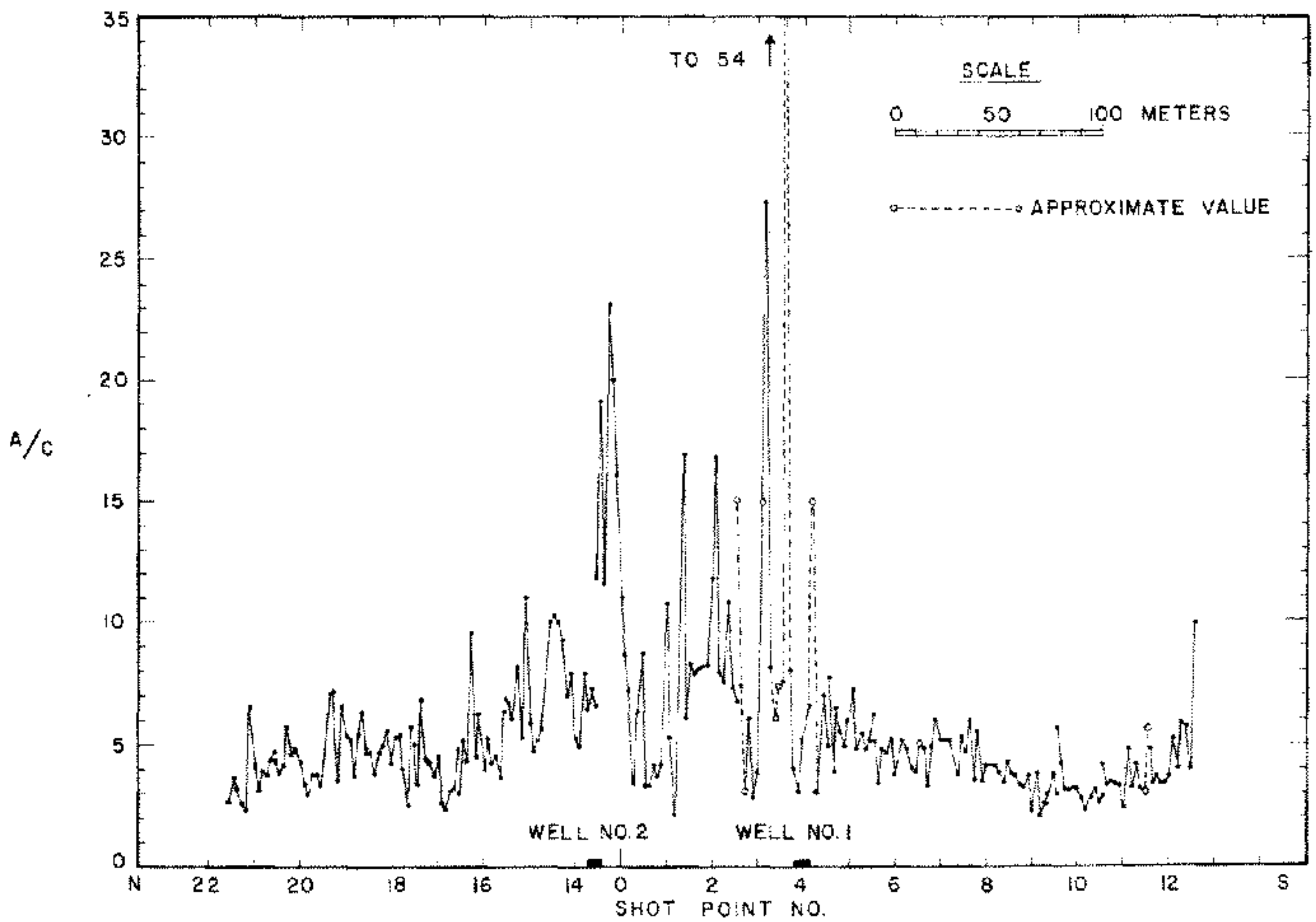

Figure 3. Seismic shadow effect confirmation; from an actual cavity survey.

Here R_1 is the ray-length from the source to the edge, R_2 is the ray-length from the edge to detector No. 2 or 3, and λ is the seismic wavelength in the vicinity of the edge. The uncertainty with which the cavity "edge" is defined is also approximately w. It is apparent that the uncertainty should increase as the square root of the cavity depth. Actually, if the seismic amplitude transition curve at the shadow edge is well-defined by several detectors, the position of the edge can be interpolated to a precision of about (1/6) w.

Good resolution requires the shortest possible seismic wavelengths; that is, high frequencies. Unfortunately, propagation losses, especially in the overburden, increase rapidly with frequency, and frequencies above 100 Hz are little-used in deep exploration for petroleum. While frequencies as high as 200 Hz may be usable in certain areas and to delineate the shallower cavities, there is no assurance that anything above 100 Hz will be generally available.

An example of the attainable seismic resolution, on the basis of all the foregoing, can now be estimated. The situation from which Figure 3 was obtained will be used. Here the seismic velocity v = 8,000 ft/sec, the dominant frequency f = 80 Hz, and the seismic wavelength $\lambda = v/f =$ 100 ft. With $R_2 = 1,600$ ft and $R_1 = 2,000$ ft, the shadow-edge width should be w$\sim$ 210 ft = 63 meters. The edge could presumably be located to a precision of about 10 meters or 35 ft. This would be acceptable.

In actual appearance, Figure 3 does not much resemble Figure 4. The causes may lie in cavity or near-surface complexities, the effect of which is not now understood. The mystery may be resolved when additional seismic cavity-delineation results become available.

Diffraction effects are well-known in seismic exploration for petroleum, and have been exploited to identify and locate faults (Krey, 1952) and formation lensing or pinch-outs (Schenck, 1963). The problems are very much akin to that of locating the boundaries of solution cavities. The theoretical basis is fairly sound (Krey, 1952) and automatic fault-plotting is now possible with a digital computer (Schneider, 1971). Model experiments have been performed (Harper, 1965) which appear to confirm the general shape of Figure 4 and the applicability of Fresnel optical theory to seismology. Recent model studies in seismic holography (Hoover, 1972) confirm the feasibility of accurately locating a fault edge, despite diffractive scattering of seismic energy in all directions by the edge. Examples are given in Table II.

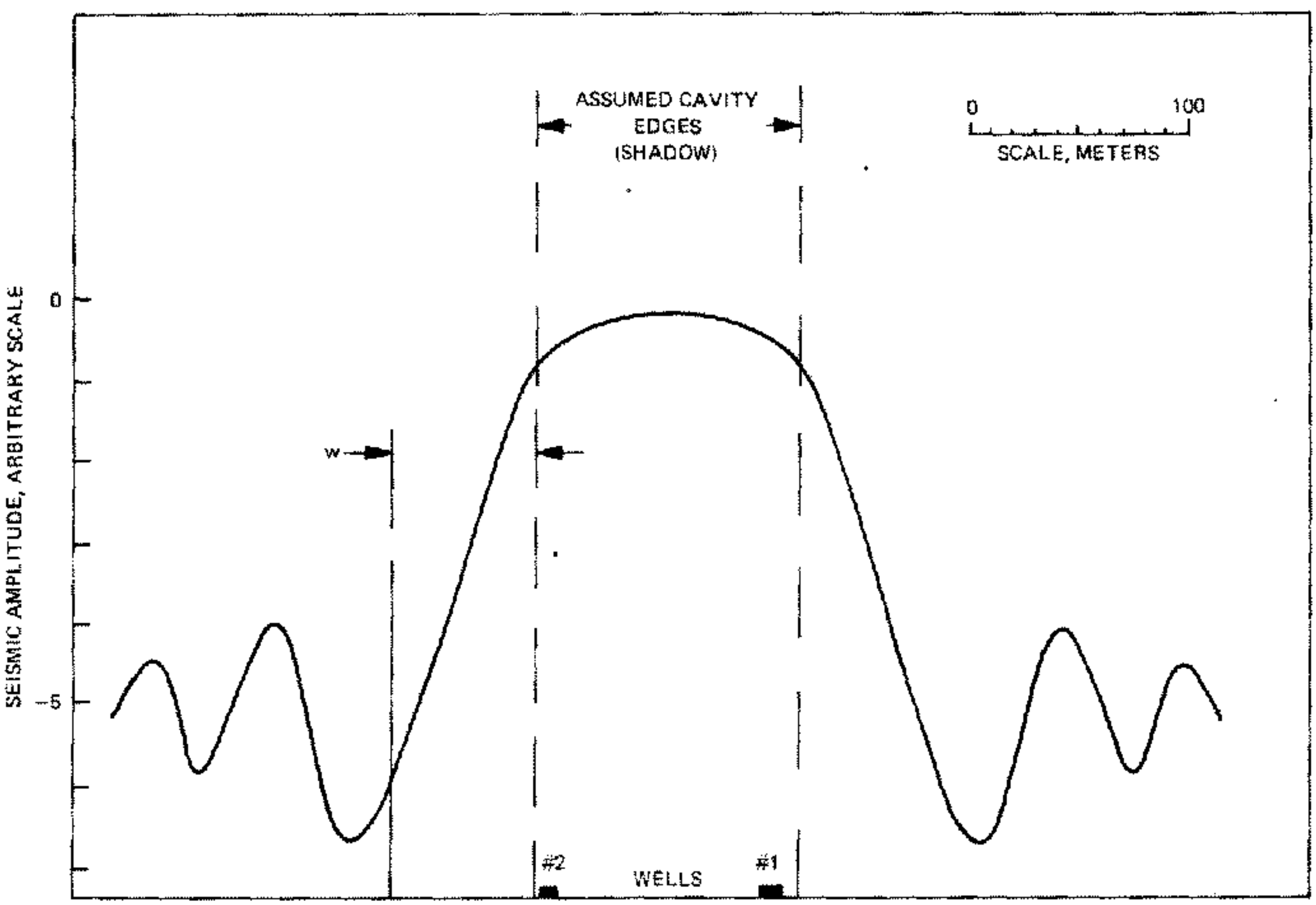

Figure 4. Expected shadow and Fresnel diffraction pattern for Figure 3.

TABLE II
Some edge location accuracies (δx)

Experiment	R	λ	δx	Δx	w
Holographic model	80 in.	2.1 in.	0.8 in.	3.5 in.	6.5 in.
	50 in.	6.3 in.	1.0 in.	6.4 in.	8.9 in.
Hypothetical field tests	1000 ft.	120 ft.	(20 ft.?)	120 ft.	173 ft.
	8000 ft.	120 ft.	(20 ft.?)	120 ft.	490 ft.

Here the depth of the (cavity) edge is taken as $R = R_1 = R_2$ for the computation of the shadow edge width w by means of formula (1). Hoover (1972) calculates the edge location accuracy or resolution Δx from the formula:

$$\Delta x \cong \lambda \ R/A \tag{2}$$

This formula comes from the Rayleigh criterion for the resolution of two points separated by Δx at a distance R by an instrument of aperture A. In the holographic model, information from detectors distributed over a line 48 inches long was combined coherently in the computer, so that the concept of an "instrument aperture" is valid. Equation (2) should perhaps be adjusted for diverging incident rays and other departures from classical optical conditions.

The location accuracies δx observed in the holographic experiments were 4 to 9 times better than either of the calculated quantities w or Δx. This appears to have been made possible by computer-contouring of the diffracted wave-intensity pattern, which facilitated interpolation.

If similar interpolation is assumed to be possible in a full-scale brine-cavity survey, and if coherent processing of data from a line of detectors equal in length to the cavity depth is assumed (lines 1000 ft and 8000 ft long for the two cases shown in Table II), then location accuracies of the order of 20 ft should be feasible for cavity edges 1000 to 8000 ft deep. It must be realized that this might be possible only in a simple, homogeneous earth. Then, despite smearing by the diffraction effect, the seismic amplitude technique of delineating solution cavity edges, as proposed in Figure 1 and confirmed by Figure 3, appears to be capable of providing adequate resolution.

SUGGESTIONS ON PRACTICAL FIELD SURVEYS

The depths of solution cavities, between 1000 and 8000 ft, are intermediate between "shallow" and "deep" in relation to customary seismic prospecting depths. The cavities are too deep to encourage the use of low-cost man-portable field equipment. Yet they are in the upper range of depths for which oil prospecting equipment is designed; it may be more sophisticated, unwieldy and expensive than necessary.

There has heretofore been no great demand for seismic equipment engineered especially for the 1000–8000 ft depth range, and it is unlikely that any exists. Under these circumstances, it would doubtless be wise to employ advanced digital oil-prospecting equipment for further definitive testing of the seismic reflection method in delineating solution cavities. Another consideration leading to the same conclusion is, that some of the advanced digital computer programs designed for data enhancement and recovery in oil prospecting may be required to obtain good seismic data, at certain brine fields which occur in "poor seismic areas" (Figure 2). A final consideration is, that computer programs already prepared for the delineation of pinch-outs, faults and similar discontinuities may be applicable to cavity delineation without change (Schugart, 1973).

For best resolution of cavity edges, seismic sources and recording equipment should operate at the highest available frequencies, up to 200 Hz if possible. Unfortunately, deep petroleum prospecting relies mainly upon lower frequencies around 30 to 70 Hz; equipment is seldom designed for higher frequencies. To provide adequate dynamic range and to preserve phase and amplitude information, recording must be fully digital. A large detector spread, as long or longer than the cavity depth, should be used for adequate array "aperture." There should be 24 or more detectors, preferably in a tapered array with 20 ft spacings near the expected cavity-edge seismic shadow. All channels should be composited or otherwise combined in processing, to achieve best resolution of the cavity edges. Near-surface variations must be overcome, either by adjusting the channel gains to equalize average amplitudes, or by the process which led to Figure 3: normalizing the amplitudes of the cavity and sub-cavity reflections against a persisting reflection from an overlying stratum (Cook, 1966). Seismic spread lines should be laid radially across the cavity edges, in as many azimuths as edge locations are desired; a minimum of six lines is recommended for each cavity.

The cost of experimental surveys is bound to be high, because a certain amount of cut-and-try will be needed and because of moving costs. Advanced seismic equipment is currently operating in several eastern states, and is normally engaged in major surveys of several months' duration each. A full scale, "production" seismic survey system includes a digital recording truck, three cable trucks, four or five seismic source trucks ("Dynoseis," "Vibroseis" or equivalent), and one or two service trucks: a total of 10 to 12 vehicles requiring a crew of 20 to 30 men (Belknap, 1973). Each crew can run 1 to 2 miles of line per day at a cost between \$1,000 and \$3,000 per day. Data reduction costs begin at around \$20 per line mile. The equipment represents an investment of over \$200,000; moving and idle time is expensive. An operating digital system and crew could be obtained for a short experimental brine-field survey only in a slack season or during a move from one major oil project to another.

An effort of such magnitude may appear formidable; however, relief is in sight. The 10 vehicles and 20 men may normally be required in prospecting for petroleum to depths of 20,000 ft or so; but they probably are not needed for cavity delineation at more modest depths. Three vehicles and a crew of 5, able to survey 1 mile of line per day at around $500 per day, are probably all that is needed. After the technique has been perfected, routine seismic delineation of solution cavities should be possible at a cost of $600 to $6000 per cavity, depending on the depth. Whole brine-fields could be delineated at substantially less cost per cavity.

SUMMARY

1. The seismic reflection method is the only known "non-access" method of delineating solution cavities in bedded deposits from the surface of the ground, which is physically capable of the needed resolution. Accuracies of the order of 20 ft appear to be feasible for all cavity depths.

2. Revolutionary improvements in seismic technique during the past decade have made possible, successful surveys in formerly "bad" or "poor" areas, including those where seismic tests failed in 1961–63.

3. The seismic "shadowing" technique, using normalized reflection amplitudes, was proven in 1963 with private support. It is suggested as the basis for future seismic delineations of solution cavities.

4. Seismic delineation costs as low as $600 per cavity are expected in routine surveys. Research and capital equipment funds would be required in addition.

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