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GASBUGGY
POSTSHOT INVESTIGATIONS IN GB-ER

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Abstract

Postshot reentry of the emplacement hole began on December 12, 1967, and terminated at a total depth of 3,916 ft on January 10, 1968. The hole below 3,000 ft was drilled with water and gel because of wet hole conditions.

Two voids (from 3,856 to 3,862 ft and from 3,907 to 3,916 ft) and a number of casing breaks and offsets were encountered. Subsequent geophysical logging and short term flow tests suggests that the lower void could be considered part of the "chimney," but that it is only poorly connected with the major void volume. It is also felt that the chimney geometry is strongly influenced by horizontal fracturing, so that the chimney top is a poorly defined region of sags, or slump blocks. It must be recognized, however, that these conclusions are based on minimal data, and new information may alter them.

Introduction

The Gasbuggy explosive was detonated at 1230 (MST) on Sunday, December 10, 1967. Confirmation of the expected yield of approximately 26 kt by radiochemical techniques has not been made as postshot exploration has not yet provided adequate samples. Indications are, from seismic data and device diagnostics, that the explosive performed satisfactorily and the yield is probably between 20 and 30 kt.

Postshot investigations of the effects of the detonation, by reentering the emplacement hole, began on December 12, when Brinkerhoff Drilling Company started rigging up over GB-E. Assembly of the high pressure gas recirculation system, furnished by LRL, had begun on December 11.

The objectives to be accomplished by reentering the emplacement hole were:

1. Determine the height and character of the chimney.
2. Determine, by sampling, the composition of the cavity gas and its associated radioactivity, as a function of time and production history.
3. Provide access for production testing.
4. Determine, by geophysical logging, the changes in the physical character of the emplacement hole.

Results

The following is a summary of the more pertinent data obtained from postshot reentry drilling of the emplacement hole. The Appendix is a detailed, chronological discussion of the reentry so that the full context of the data is available.

1. Reentry drilling inside the 7-in. casing proceeded with difficulty to 3,000 ft. The difficulty was mainly a result of a failure to stem the hole with cement all the way to the surface preshot. The stemming plan actually used is shown in Fig. 1. This plan was chosen because of concern for the possibility of additional preshot cable failures.

2. The cement was moist below 3,029 ft, and continued drilling with gas circulation was risky. Drilling proceeded with caution to 3,260 ft, but the hole remained moist. It was suspected that the moisture came from a leak at a depth of 3,550 ft where there was a preshot leak in the cement staging tool. Drilling then proceeded to 3,600 ft, using water and some bentonite gel as a drilling fluid.

3. The water leak was determined to be at a depth of 3,550 ft, through the first section of slots, and below the cement staging tool used in cementing in the 20-in. casing (Fig. 2). The rate of entry was about 15 gal/hr (Fig. 3), and chemical analysis of the water confirmed that it was from the Ojo Alamo formation. A water sample taken from this depth appeared to show tritium at about twice background.

4. The leak was so small that it was judged difficult and expensive to fix; and even if fixed, the cement below was probably moist and could not be drilled with gas. Drilling proceeded with water circulation until a void was encountered in the interval between 3,856 and 3,862 ft. At that time, circulation of the drilling fluid

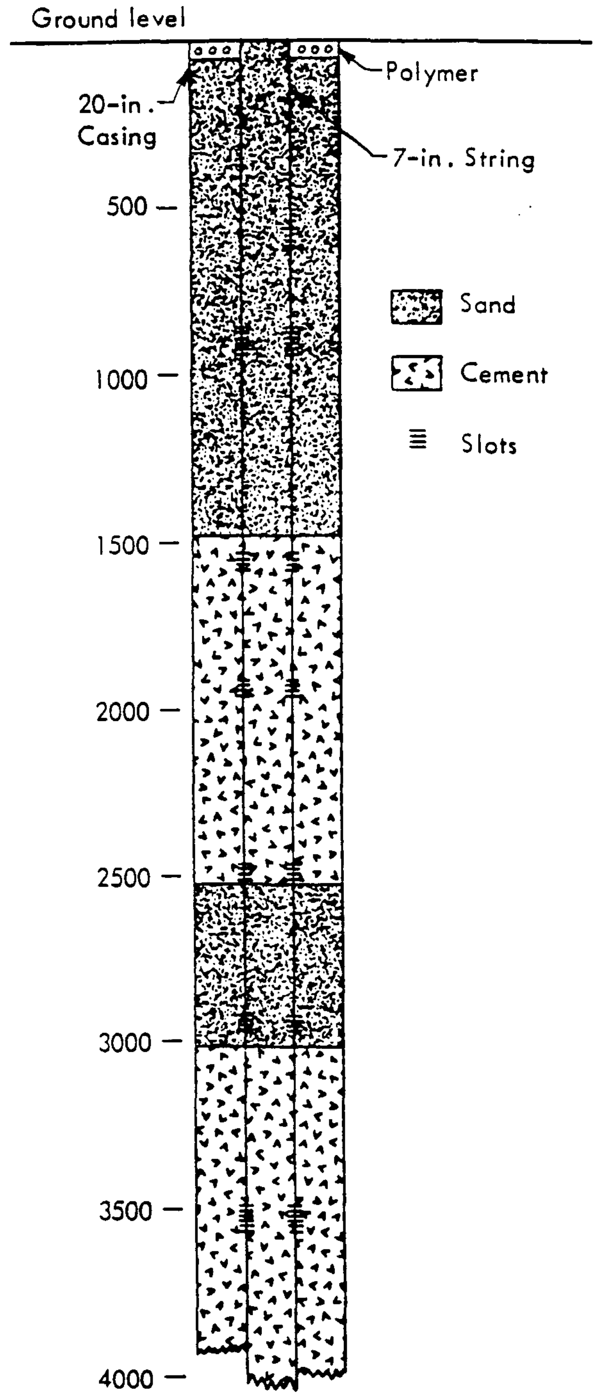

Fig. 1. Emplacement string, 7-in. (preshot configuration).

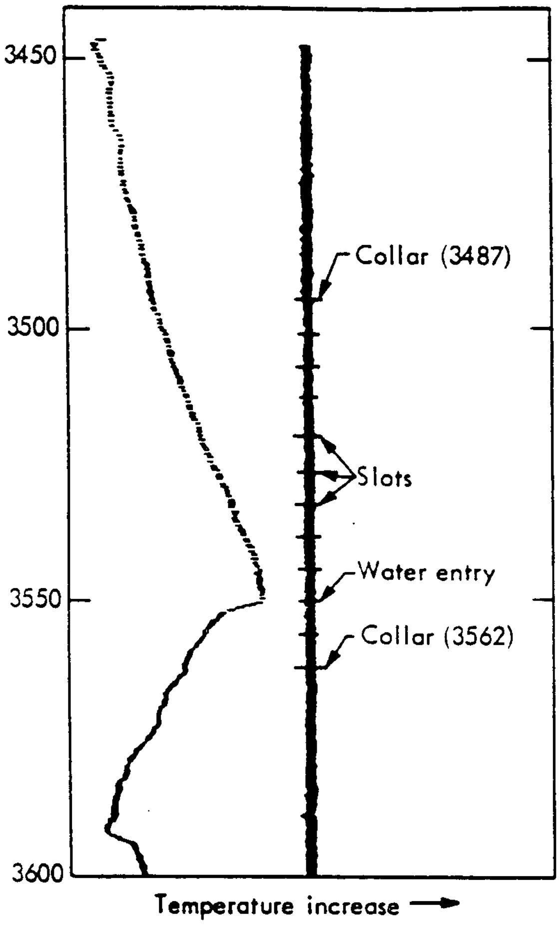

Fig. 2. GB-ER temperature log (1-8-68).

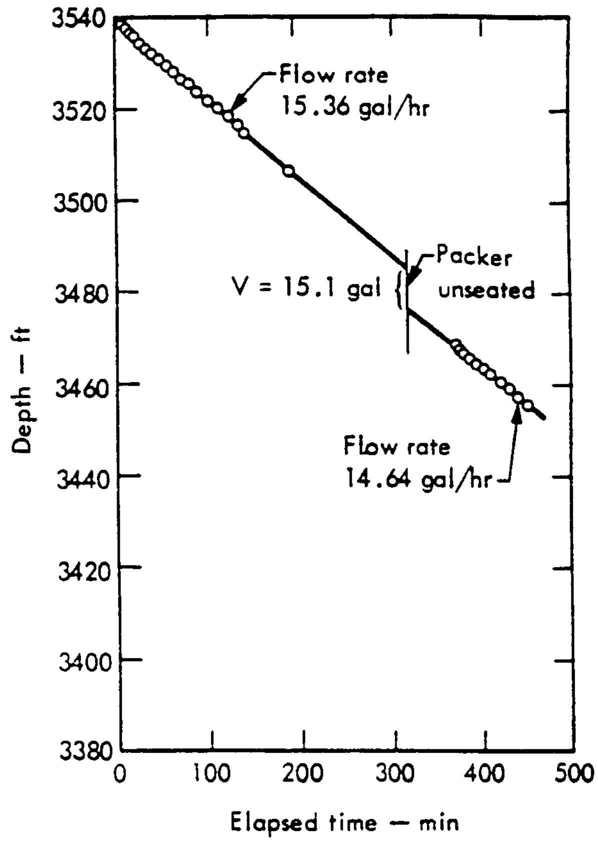

Fig. 3. GB-ER Water level recovery (1-6-68).

was lost. Subsequent geophysical logging and testing indicated that the drilling fluid dropped to approximately 1,748 ft below the surface. The addition of approximately 30 barrels of water raised the water level only 9 ft, indicating the column was held by a supporting fluid pressure of approximately 930 psig. The logging also revealed four breaks in the casing above the void with radioactive gas pockets in gaps in the cement between the 7 and 20-in. - casing strings (see Fig. 4). Slight lateral offsets in the casing occurred at these breaks. The caliper log indicates both the 7 and 20-in. casings parted in the region of the void (3,856 to 3,862 ft).

5. Drilling then proceeded with water in the hole, but without circulation. Some water was added to cool the bit while drilling. Occasionally, the bit milled on metal, but good progress was made until another void was encountered in the interval of 3,907 to 3,916 ft. At the bottom of the void, the bit was on metal and further drilling was not possible. A total of 500 barrels of water was added while drilling. Soon after encountering the void, water was blown back up the hole to the well head, the well was shut in, and the well head pressure was monitored until fluid in the pipes to the gauge froze. The monitoring gauge was relocated at the well head, the

system thawed out, and pressure monitoring continued. The pressure rose to 830 psig in a period of 27 hr after encountering the void. Logging revealed no standing water in the hole. Additional geophysical logs were run and the results are shown in Fig. 4. The irregular bore hole prohibited logging to the full depth of the hole. About five more casing breaks with slight offsets were found between the two voids. Bore hole photography confirmed the water leak at 3,550 ft, but the presence of water caused poor visibility below that depth (Figs. 5 and 6).

6. Gas sampling was carried out both at the well head and in the bore hole. Results indicate that insignificant amounts of I^{131} and about 5% of the tritium produced were in the cavity gas (if the samples represent "typical" cavity gas). Table I compares radiochemical analyses on samples from the cable leak at +1 day with samples from reentry exploration (+1 month), and with calculated estimates of expected concentrations.[1] The bulk chemistry of these samples is shown in Table II. A companion report by A. Sherwood is being written that covers, in detail, the results of the gas sampling and pressure buildup.[2]

7. Several short term, low volume gas flow tests were conducted under adverse conditions to determine something of the nature of the communication between the reentry hole and the chimney. The rapid pressure decline during the short term production indicates the possibility that

TABLE I. Preliminary radiochemical results on Gasbuggy (from Floyd Momeyer—3/5/68).[1]

	μCi per cubic foot (STP) of cavity gas		
	Kr^{85}	HT	$CH_3T^{(b)}$
Preshot estimates[a]	2.0	200	0.6
Current estimates[a]	3.0	390	0.9
+1 day samples—2	2.91 ± 0.11	91 ± 4	8.8 ± 0.4
+1 month samples—5	3.11 ± 0.08	4.4 ± 0.1[c]	11.8 ± 0.7

[a]Both estimates assume 350 Ci of Kr^{85} in the gas, 4 g of T total, and 2.0×10^6 ft^3 cavity volume. Preshot estimates assumed the cavity at 84 atmospheres and 25°C. Current estimates use the values of 66 atmospheres and 67°C measured at about 35 days after detonation.

[b]The amount of CH_4 in the cavity is very sensitive to temperature of the equilibrium. Preshot estimates arbitrarily assumed a temperature of 1700°C. Using the same set of thermodynamic calculations, the observed CH_3T in the early samples corresponds to equilibrium at 1200°C. However, there is not yet enough information to justify the assumption that all the initial conditions actually correspond to equilibrium at 1200°C, so the estimates have not been altered in this respect.

[c]This large uncertainty reflects an irregular variation in DPM* of T per cc STP of H_2 from sample to sample. This is surprising but repetition of determinations indicates it is real.

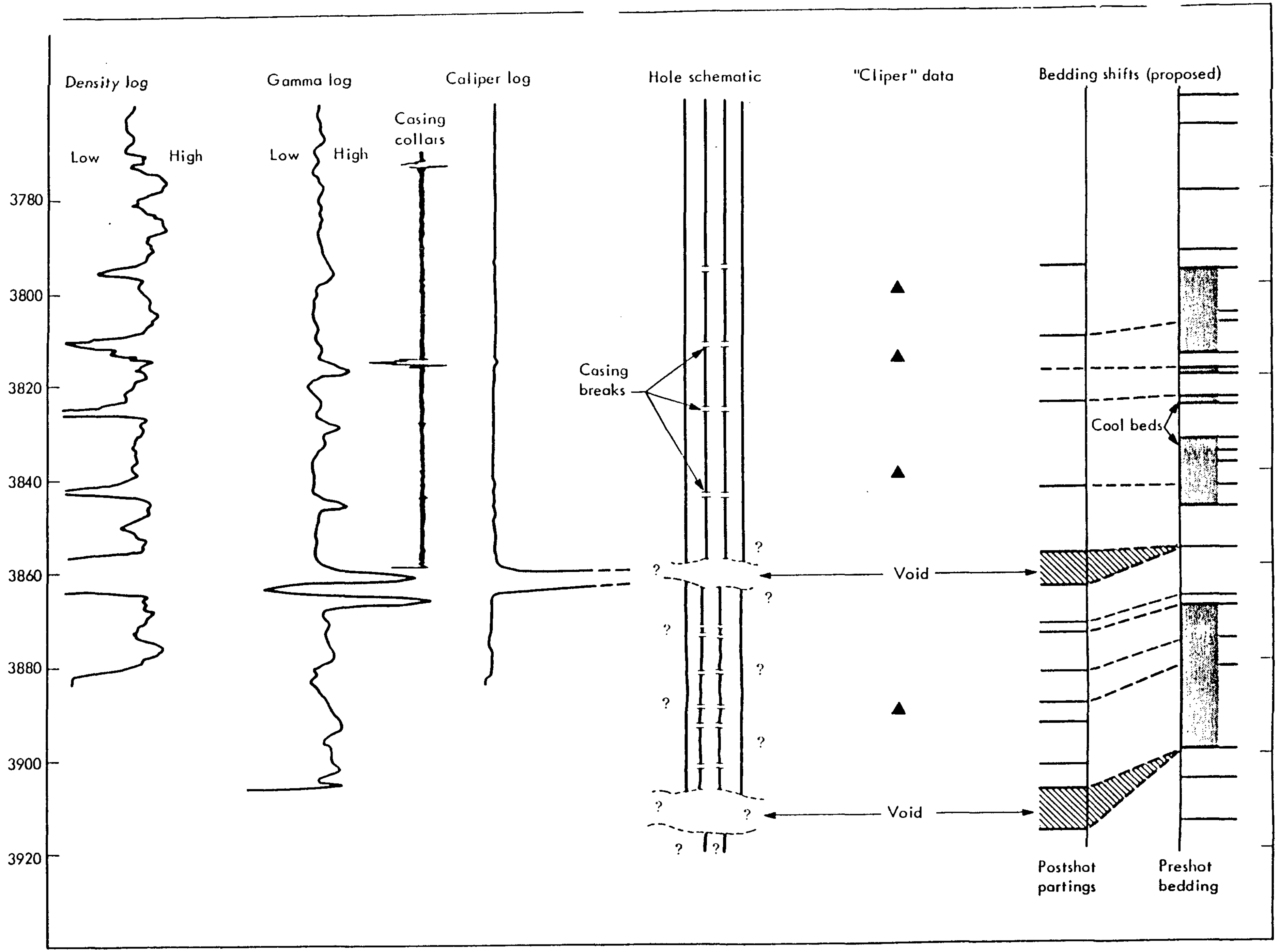

Fig. 4. Postshot characteristics. 15a

Fig. 5. Laval borehole photograph in GB-ER showing result of water leak from 3,550 ft. Depth = 3,828 ft. The linear feature in the upper left is a rope ladder for scale. The wood sticks are 2 in. apart.

communication with an assumed chimney of near infinite permeability is restricted.[2] During flaring, Xe^{133} (the dominant radionuclide in the gas) was monitored in the gas stream. The decline in concentration with time of this relatively short-lived nuclide was quite apparent during the sampling period.

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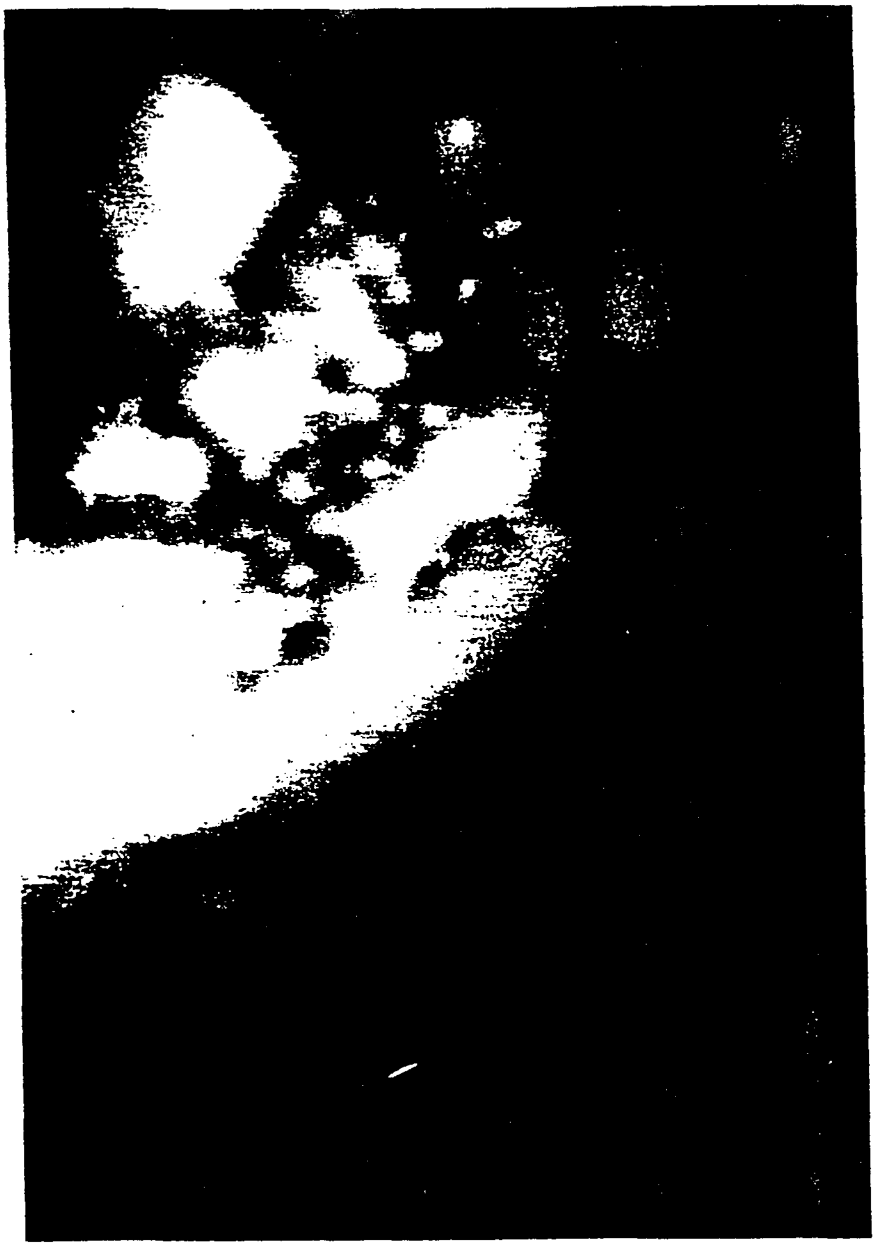

Fig. 6. Laval borehole photograph in GB-ER. Depth = 3,870 ft. The camera is sitting on a ledge or bottom of a void, with the drilled hole off to the upper left.

8. The reentry hole was left with 2-7/8 in. tubing stabbed through a packer to isolate the water leak from the chimney. The pressure at the well head is being monitored daily—by El Paso Natural Gas (EPNG) personnel—and periodic downhole gas sampling (by LRL personnel) is continuing.[2]

TABLE II. Gasbuggy cavity gases (from Floyd Momeyer— 3/5/68).[1]

	Totals in Units of 10^6 ft^3 STP[(a)]		
	Preshot Gas	+1 day (2 samples)[(b)]	+1 month (5 samples)[(b)]
CO_2	0.32	12.3 ± 0.4	40.6 ± 0.8
CO	<0.01	27.1 ± 0.9	4.43 ± 0.30
H_2	<0.01	28.5 ± 1.5	19.2 ± 0.7
CH_4	97.6	53.7 ± 1.3	41.9 ± 1.5
C_2H_6	8.48	2.17 ± 0.06	4.07 ± 0.10
C_3H_8	4.73	–	1.33 ± 0.14
$C_{\geq 4}H_x$	3.13	–	1.26 ± 0.60
N_2	0.70	–	0.62 ± 0.23
	114.96	123.77	113.41

[a]For comparison, contents of the cavity at 66 atmospheres and 67°C (measured conditions at about 35 days after the detonation) are given in the first column for original formation gas composition. Totals in the last two columns were calculated using observed Kr^{85} concentrations and assuming a total of 350 Ci of Kr^{85}, all of which is in the gas phase. There is as yet no information bearing on actual total Kr^{85} or on actual yield and cavity-chimney volume.

[b]Results for these samples should be taken with reservation. They were about 85% air. "Normal air" was assumed not to be truly present in the cavity. All mass spectrometric results were treated by removing air based on O_2 to get at "true cavity gas composition." For the 5 later samples, this was not serious as air found ranged from only 1 to 4%. Blanks for the early samples indicate minor components which could not be analyzed accurately.

Discussion

EMPLACEMENT HOLE INTEGRITY

At about 8 hrs after the detonation, a small amount of radioactivity was detected at the ground surface because of leakage in the explosive arming and firing cable.[3] Breaks in this cable could have allowed leakage of radioactive gas to porous portions of the stemmed emplacement hole. This is the likely source of radioactivity found in the water sample from the Ojo Alamo at 3,550 ft and the radiation spikes, where the casing parted, in the interval 3,790 to 3,870 ft (Fig. 4). In cementing off the slotted sections where there was sand stemming (Fig. 1), the cement did not bond to the casing such that it was gas and water tight. It is likely that a finite permeability existed, preshot, in the stemming as well. Water apparently was able to migrate from the leak at 3,550 ft up to at least 3,260 ft and possibly up as far as

3,029 ft. Considering the pressure head of approximately 1,000 psig in the Ojo Alamo, it would not take much permeability for upward migration. The possibility exists that the explosion caused failure of the grout, or grout bonds, with rock, casing or cables; but the exploration was unable to distinguish between pre-existing or explosion-produced effects above 3,770 ft.

No severe offsets or constrictions in the casing were found above the total depth of 3,916 ft that prohibited drilling inside the casing. The most distant casing break was at 3,796 ft or 444 ft above shot point. In Hole GB-1, the most distant cable break was at about the same elevation, but laterally displaced approximately 190 ft from GB-ER. This is a radial range of 480 ft. Since the bottom of the casing in Hole GB-2 is at a radial range of 475 ft, it is possible that reentry drilling in GB-2 will encounter a casing break or offset at the contact of the Fruitland coal with the Pictured Cliffs formation at about 20 ft above the casing bottom. The chances for encountering a break are enhanced if there should be significant lateral channeling of the explosion energy, because of the velocity discontinuity at that boundary.

CHIMNEY DEVELOPMENT

The geophone evidence indicates that the chimney formed during the first minute following the explosion.[3] The "cliper" data on cable breaks in Hole GB-1 indicated failure out to a radial range of 480 ft which occurred at about the time of passage of the outgoing stress wave from the explosion.

Figure 4 illustrates the casing breaks found in GB-ER and a proposed correlation of these breaks with preshot bedding plane "weaknesses" interpreted from the density log of the emplacement hole. The correlation is not conclusive, but is suggestive of breaks due to slight shifts or tensional openings along the boundaries of rock with different densities. Also shown are the breaks of the "cliper" cables in Hole GB-1. The extent, location, and frequency of the breaks also suggests failure along rock boundaries. Figure 7 is a plot of the "cliper" data with density log in GB-E. This further illustrates the correlation between breaks and the locations of major density changes or bedding plane boundaries. The relative depth uncertainty of the cable breaks is about ±1 ft, the absolute depth is uncertain to ±10 ft.

Prior to the shot, it was the author's judgment that if chimneying propagated through the Pictured Cliffs formation, such propagation would continue through the coal section to a depth of approximately 3,800 ft.[4] We now postulate that sufficient bulking in the chimney occurred within the Pictured Cliffs formation so that there is no large apical void and the overlying material has sagged and parted along pre-existing weaknesses. This overlying material was further weakened by the stress wave at shot time and failed in tension with the chimney development. With this hypothesis, the upper portion of the chimney is different from previous experience; it is a broad transitional zone from rubble with nearly infinite permeability to rock with very little increase in permeability. We suspect that GB-ER was not drilled deeply enough to get into chimney rubble with nearly infinite permeability. Figure 8 is a schematic drawing of this concept.

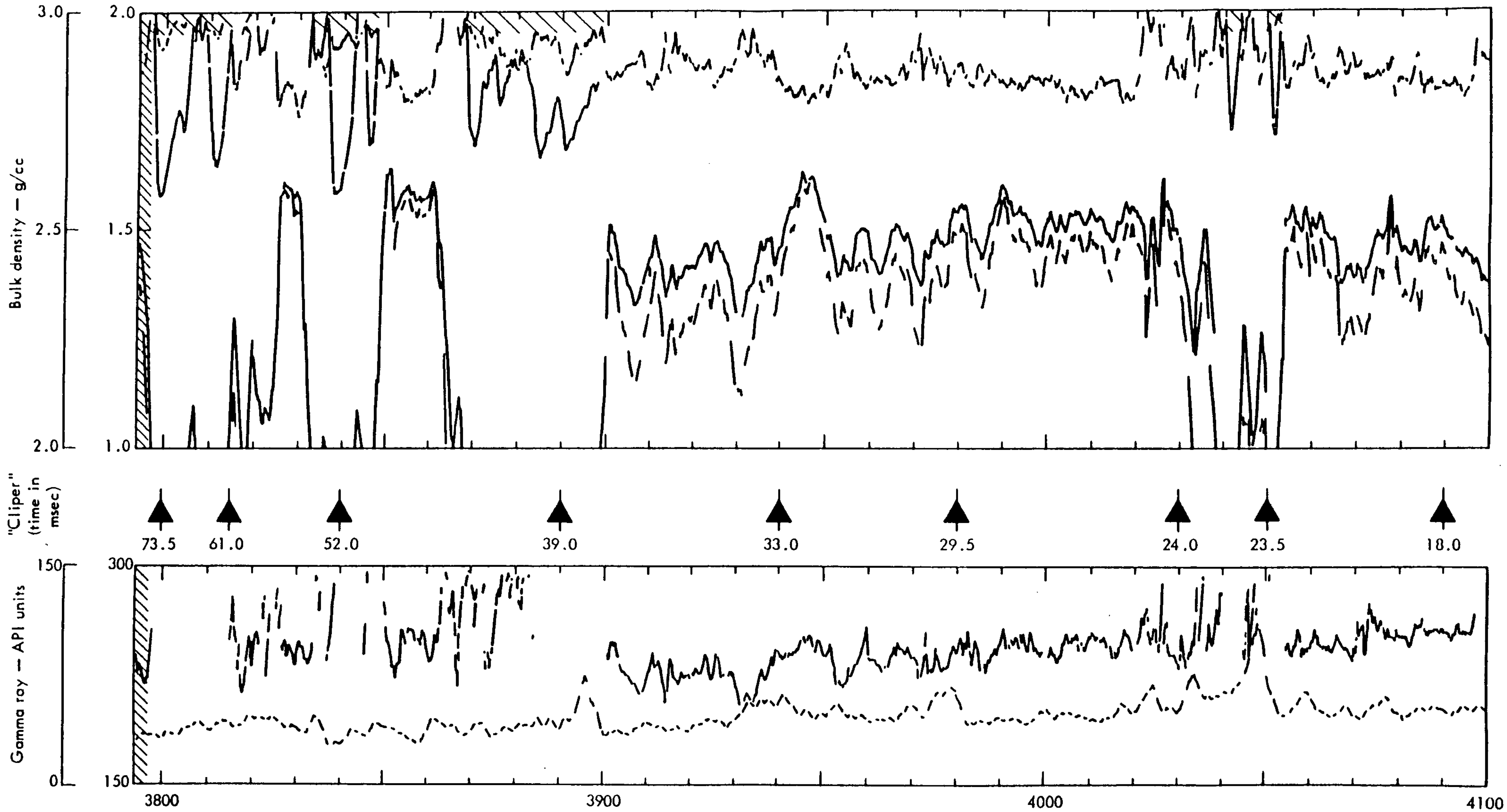

Fig. 7. "Ciper" data (GB-1) plotted with density (GB-E).

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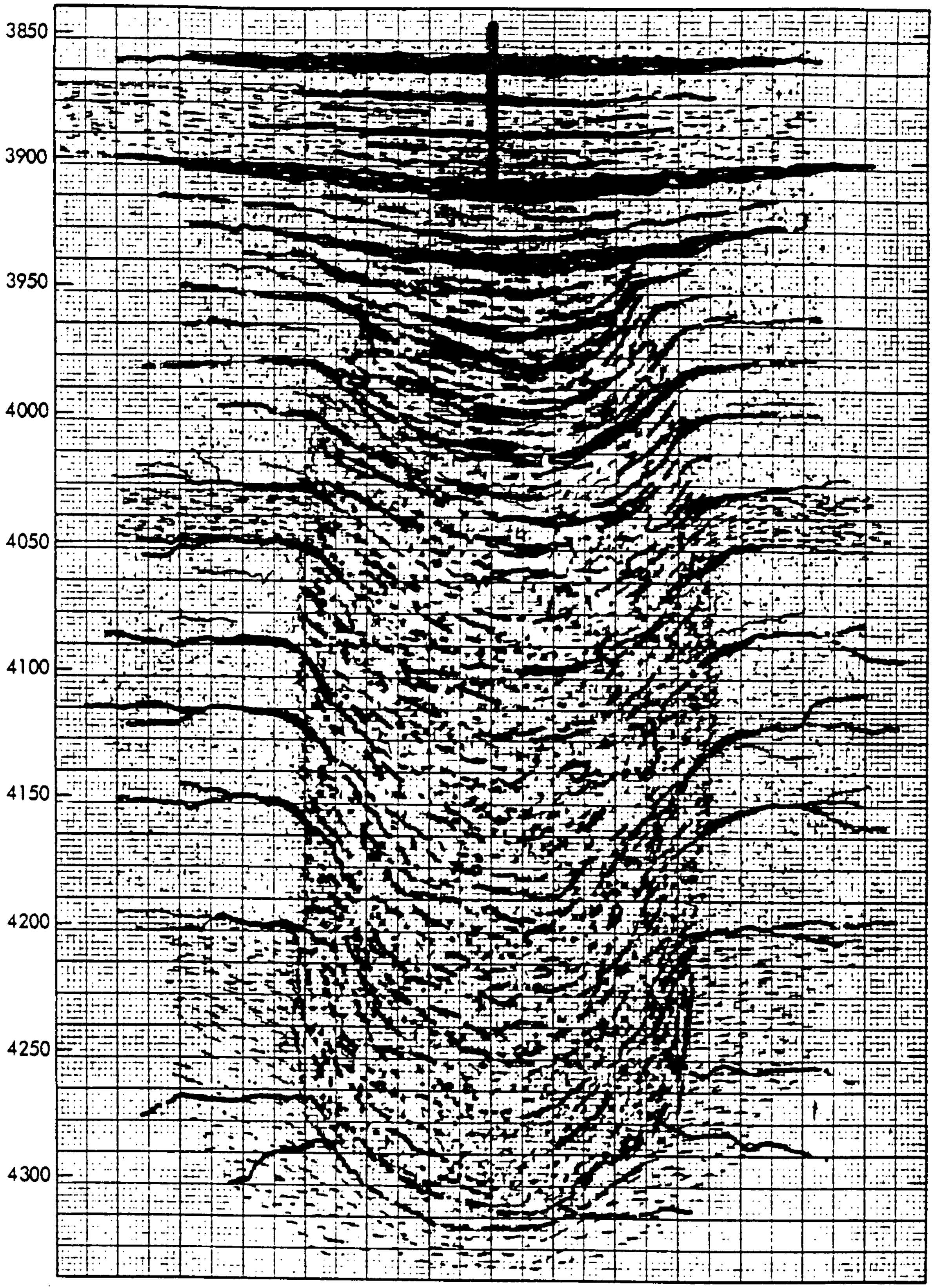

Fig. 8. Gasbuggy—proposed chimney.

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The predicted radius of fracturing of 425 ft is close to the 480-ft radius (cliper data GB-1) and the furthest casing break in GB-ER of 444 ft. The chimney was expected[5] to terminate at a distance of 334 ft above shot point, or in the region of the lower void found in GB-ER. This is, indeed, where communication with the chimney occurred, and it could be very near the chimney top.

CHIMNEY GAS

A major question is whether or not GB-ER is in good communication with the chimney. It is reasonable to assume that the void encountered at 3,858 to 3,864 ft is probably not in good communication with the large void volume expected to be associated with the chimney. Otherwise a water block, such as existed there, would not have been expected to form. On the other hand, no such persistent water block was formed on penetrating the lower void (3,907 to 3,916 ft). The geometry of that void was apparently such that the water and gas could exchange places. Water was first blown back to the well head and then fell into the void after the well was shut in. The initial reaction was that this lower void was the top of the chimney.

The early history of the well head pressure showed a pressure buildup from something less than 338 psig to 830 psig in a period of approximately 27 hrs, after which it was relatively constant. The calculated downhole pressure was approximately 950 psig, which is less than the maximum pressure in the preshot reservoir (1,050 psig), calculated by extrapolating well pressure buildup data. The early time rise is attributable to the unloading of the water in the hole. The final pressure (830 psig at the well head, approximately 950 psig downhole) may be representative of the pressure in the chimney at that time. Subsequent long-term monitoring has shown that the pressure is rising toward the preshot value, at a rate of about 1.3 psig/day. (The well head pressure on February 27, 48 days after drilling stopped, was 885 psig.)

Seven days after drilling stopped and after several short term gas flow tests, a maximum downhole temperature of 152°F was recorded. This is probably not an equilibrium temperature of the rock beyond the reentry hole, but it at least indicates that gas from the chimney is significantly above ambient temperature (125 to 132°F).

The short term flow tests[2] were inconclusive, but the results suggest that communication between GB-ER and the chimney is poor. The flow tests, under the best conditions of measurement (a partial bottom hole pressure record), showed a 3-psig drop in 45 min of flow at a restricted rate of $\sim 1.5 \times 10^6$ ft^3/day. A chimney with nearly infinite permeability in good communication with GB-ER would probably not have shown that large a pressure drop.[2]

It can be inferred that the restricted communication with the "chimney" could be the result of GB-ER terminating in a transitional "sag zone" in the upper portion of the chimney; the result of induced permeability restrictions caused by casing or the loss of drilling water; the result of misleading flow analyses; or the fact that the "chimney proper" has not yet been encountered.

Examination of the preliminary chemical analyses of gas samples (Tables I and

II) may provide some clues as to whether the gas is chimney gas or a mixture of gas from the chimney with gas directly from the rock near GB-ER. The similar concentrations of Kr^{85} between the samples at 1 day and those at 1 month (if taken at face value) could indicate that no appreciable natural gas dilution has occurred since the first day after the explosion. This thesis of course needs to be viewed in the light of very limited samples, poor sampling conditions (for the cable samples), and the assumption that the samples represent typical chimney gas.

The large amount of CO_2 in the downhole samples needs explanation. A source of CO_2 is the decomposition of carbonate minerals by the explosion. R. Taylor[6] estimates that enough CO_2 is liberated from the minerals, calcite, aragonite, and dolomite, in the Lewis shale to account for the observed CO_2 content. He also postulates that the postshot chimney pressures were high due to the presence of CO_2 such that methane could only flow into the chimney as water condensed. The preshot chemical analyses of the Lewis shale, sampled to represent material that would be decomposed, vaporized, or melted by the explosion, now appear to be suspect. The samples were taken from core from GB-1, with the explosion center at 4,240 ft. Correlating the natural gamma radiation log from GB-ER with GB-1 indicates that the projected center for the explosion which may be equivalent with rock in GB-1, would be at a depth of approximately 4,260 ft. The carbonate content is expected to be higher than the previous estimate.[3] Further work is in progress to define the shot-time chemistry to compare with gas analyses.[6]

From this limited data it appears credible that the gas samples are reasonably representative of chimney gas and that methane flow into the chimney was retarded due to existing high CO_2 pressures in the chimney. This model also allows time for more tritium to combine with water, reducing the amount in the gas. This is also consistent with results shown in Table I, that total tritium as HT or CH_3T is down by about a factor of 14 from preshot predicted levels.

EXPLORATION DIFFICULTIES

The difficulties encountered during reentry drilling caused substantial delays in the schedule and added significantly to the cost of the program. One difficulty, which was unavoidable, was the extreme weather conditions. Heavy snow hampered the movement of equipment and personnel to and from the site. Low temperatures (-20°F) froze equipment, pipe lines, and valves. Many of the non-weather related difficulties, on the other hand, might have been avoided.

The choice of reentry drilling in GB-ER was, in the planning phase, thought to be the most economical. With the stemming of GB-E with sand plugs, reentry of that hole probably should have been reconsidered since it was recognized that a better stemming plan (to minimize postshot drilling problems) would have been to cement to the surface. Now with "hindsight" it might have been less expensive and more would have been learned about rock deformation and the chimney, if a new exploratory hole had been drilled. Also, it is likely that chimney penetration could have been done with gas rather than water, as the cement in GB-E failed to seal completely the pre-existing leak.

Conclusions

With respect to the objectives outlined at the beginning of this report, the postshot investigations in GB-ER have been only partially successful. Limited funds, coupled with unexpected difficulties and misjudgments resulted in the failure of the exploration to meet fully these objectives. As a result, only tentative conclusions can be reached, and the acquisition of new data may require that these conclusions be altered.

Since there is considerable uncertainty about the nature of the communication between the chimney and GB-ER, the first objective, that of determining the height and character of the chimney cannot be considered completely fulfilled. Moreover, without this determination, it becomes difficult to assess the significance of the results of the logging and sample analyses. The evidence suggests that either the chimney region has not been penetrated or that communication between this region of the chimney and the rest of the chimney is not well developed. If the latter case is correct, this poor communication may either have existed since the time of collapse, or may have developed as a result of discharging more than 700 barrels of fluid into the formation.

The authors are of the opinion that the lower void penetrated by GB-ER could be considered part of the "chimney," but that it is only poorly connected with the major void volume, at least partly caused by "water blockage." It is also felt that the chimney geometry is strongly influenced by horizontal fracturing, so that the chimney top is a poorly defined region of sags, or slump blocks.

If it is assumed that this model is somewhat correct, and that the gas analyses represent chimney gas, then the following is indicated:

1. The pressure in the chimney remained high because of CO_2 from decomposed carbonate minerals, retarding the flow of natural gas into the chimney.
2. This retardation of gas flow into the chimney probably helped reduce the amount of tritium as HT and CH_3T. Presumably there was more tritium in the form of HTO than expected.
3. Kr^{85} occurred in concentrations in the gas approximately as expected; I^{131} was conspicuously absent.

In retrospect, it would probably have been both less costly and more would have been learned, if a new exploratory hole to the chimney top had been drilled, rather than re-entering GB-E.

The remaining postshot program should be designed, not only to determine the changes in the productivity and deliverability of the stimulated reservoir, but also to provide an understanding of the physical mechanisms responsible for these changes. The investigations in GB-ER have revealed very little about these mechanisms. Deter mining, as well as possible, the vertical extent of the chimney or the permeability distribution, is most vital to understanding the geometry of the stimulated region. Without this information, data on the chimney radius and extent of fractures is of limited value.

From reading this report, it is obvious that further work is needed. Our understanding of the postshot environment is, to a large degree, conjectural, as a result of the investigations in GB-ER.

Acknowledgments

The material contained in this report is the product of the efforts of many people. We would like to thank particularly Floyd Momyer, and Charles Smith for the data on the gas analysis, and Ken Kase and Bill Silver for their information on radiation detection. Thanks are also due to those personnel of LRL, El Paso Natural Gas Co., and the U. S. Bureau of Mines in Bartlesville, Okla. who participated in the collection and interpretation of the postshot data.

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Appendix

[Detailed Reentry Chronology (GB-ER)]

SURFACE TO 1,474 FEET

The reentry plan called for the gas drilling and blowing out of the sand and cement plugs constituting the stemming material inside the 7-in. casing on which the explosive was emplaced. (See Fig. 1.) After installing the blowout preventer (BOP) containment stack and the blooie line, the first sand plug in the 7-in. casing and 7 × 20-in. annulus was cleaned out to 956 ft. This took place on December 14-15. The first set of slots in the 7-in. casing (864 to 949 ft) were then sealed off with cement. (The reason for blanking off the slots in the 7-in. casing in the sand-filled intervals was to prevent drilling returns from accumulating in the space between the 7- and the 20-in. casing.) After drilling through this plug, the hole was cleaned out to the top of the first cement plug at 1,474 ft.

1,474 TO 2,536 FEET

Drilling of this plug began on December 17. Difficulties were encountered while drilling from 1,474 to 1,686 ft because of wet hole conditions and cement buildup on the drill pipe. Because of the extremely cold weather conditions, the separator on the gas dehydrater for EPNG's gas supply line had frozen, allowing the accumulated liquids to be blown down the hole. The problem was solved by thawing out the separator and switching the supply line to a drier gas at higher pressure. Drilling began again on December 18 and continued to the bottom of the plug at 2,536 ft.

2,536 TO 3,029 FEET

The second sand plug from 2,536 to 3,029 ft in the 7-in. casing and the 7 × 20-in. annulus was then cleaned out.

In the attempt to cement the slots at the bottom of this sand plug (2,932 to 2,975 ft), the drill pipe became stuck. This was on December 20. The hole was mudded up and attempts were made to retrieve the drill string. The last three joints were finally retrieved on December 28. The hole was evacuated of mud and a new cement plug was set to seal off the slots.

3,029 TO 3,102 FEET

After waiting for the cement to set, the plug was drilled from 2,491 to 2,991 ft, but not before having to mud up again, because the hole could not be dried out. The hole from 2,991 to 3,031 ft was not cement filled. Drilling continued to 3,102 ft, and another attempt was made to dry up the hole. The attempt was unsuccessful.

Schlumberger then ran a density log on December 31 inside the 7-in. casing from the surface to 3,102 ft. The log gave the following information about the 7 × 20-in. annulus:

From the polymer plug at 50 ft to approximately 800 ft the annulus is gas filled.

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From approximately 800 ft to approximately 934 ft is water (?) filled and the slots from 934 to 944 ft are not cemented.

From approximately 944 to 1,440 ft is a sand/water mixture.

From 1,440 to approximately 1,473 ft is a "concrete" (sand and cement) plug.

From approximately 1,473 to approximately 2,523 ft is neat cement.

From approximately 2,523 to approximately 2,585 ft is gas filled.

From approximately 2,585 to approximately 2,866 ft is mud, possibly gas cut.

From approximately 2,866 to approximately 2,945 ft is neat cement.

From approximately 2,945 to 2,956 ft the slots are not cemented off.

From approximately 2,945 to approximately 2,978 ft is possibly water cut cement.

From approximately 2,978 to 3,102 ft is neat cement.

The density log clearly indicated that at least a large part of the difficulty in drying up the hole was due to water and/or mud draining from the annulus through the slots, which were only partially cemented. Consequently, on January 1, 1968 two sets of perforations, one at 2,797 ft and one between 2,858 and 2,860 ft, were made in the 7-in. casing in order to drain the annulus.

3,102 TO 3,260 FEET

The hole was dried up sufficiently for drilling to reach 3,177 ft by January 3.

The high pressure recirculation system was connected to the well and on January 4 about 5 ft of hole was drilled with it. The system did not perform well, because of continuing wet hole conditions and the fact that it was designed for a larger hole (GB-3).* The difficulties because of hole size have now been corrected[7] and, should further work be done in GB-ER, the system should operate more efficiently.

Attempts were made to continue drilling with gas, but because the cement continued to be wet, increasing the probability of getting stuck, drilling was stopped at 3,260 ft. Although the annulus had been drained through the perforations, it could not be determined whether fluid was still coming from this source or whether the cement was being wetted from a source further down the hole. The decision was made, therefore (Jan. 5), to switch to mud as a circulating medium. This "mud" was water with a few sacks of bentonite gel added to increase the viscosity.

3,260 TO 3,600 FEET

The plan called for mud drilling to approximately 3,600 ft, then stopping to determine the source of the fluid in the hole. It was suspected that there might be a leak at about 3,550 ft, where water from the Ojo Alamo had been entering the hole through an open staging tool prior to stemming. Drilling to 3,600 ft took place on January 6, and the mud was displaced out of the hole with gas.

After circulating the mud out of the hole, the hole was blown with gas until essentially no water came back. Blowing stopped at 1:50 p.m. on January 7 and a Baker

*Also, the compressor did not meet specifications.

packer was set on the drill pipe at 3,439.5 ft. Water level measurements were taken, starting at 5:25 p. m., when the water level was 3,538.0 ft, indicating a significant water entry below the packer. The water level change was recorded until 8:35 p. m. when the water was 3,506.0 ft.

The packer was then unseated, while water level measurements continued. The purpose was to see if another water entry was occurring through the upper slots near 950 ft. A slight jump in the water level was noted when the packer was unseated at 10:42 p. m. The rate of rise in the water level, however, did not change from what it had been prior to unseating the packer. The indications were then, that there was no significant leak from the upper slots and that the water coming in was water left behind from drilling. In fact, the flow rate computed from the water rise after unseating the packer was 14.64 gal/hr, whereas the flow rate before unseating was 15.36 gal/hr. The amount of fluid added to the hole when the packer was unseated was about 15.1 gal. Fluid levels were recorded after unseating, and continued until 12:57 a. m. on January 8. The final level recorded was 3,455.0 ft. Figure 3 is a plot of the data, showing water level as a function of time.

Following the water level measurements a differential temperature log was run in an attempt to ascertain the water entry point. Three runs were made and it was judged that run No. 1 gave the most reliable results. The absolute temperature curve on run No. 1 shows the water entry at 3,550 ft, based on the assumption that the formation water is at a higher temperature than the water in the hole. This is the same point at which water was entering the hole before stemming. This log (run No. 1) is reproduced in Fig. 2. A density log was run from approximately 3,000 to 3,600 ft which indicated that there was good cement in the annulus. Finally, a sample of the water was taken and chemically analyzed by EPNG. Comparison of the analysis of this sample with that of water taken from the Ojo Alamo in GB-1 confirmed that the water was coming from the Ojo Alamo.

The inflow rate, while making it essentially impossible to continue drilling with gas, was not considered to be enough of a problem to warrant trying to seal it off. Moreover, it was not thought to be sufficient to compromise any of the logging or testing which was planned for later in this hole.

3,600 TO 3,862 FEET

Drilling was resumed from 3,600 ft at 3:00 p. m. on January 8. At 10:45 p. m. the bit dropped into a void at 3,856 ft and mud circulation was lost. After determining that the void extended from 3,856 to 3,862 ft, the well was shut in.

A Heise pressure gauge had been connected to the annulus between the drill string and the 7-in. casing, and when the well was shut in at approximately 10:48 p.m. the gauge read -8 psig, i.e., a negative gauge pressure. At 11:30 p. m. the gauge reading was 0 psig. The drill string was then stripped out of the hole.

The pressure in the hole continued to rise, measuring 19.0 psig at 4:05 a.m. (January 9). The pressure was monitored until 6:45 a. m., although it had stabilized at 48.0 psig by 5:13 a.m.

A natural gamma log was run from 1,750 to 3,862 ft. Three radiation peaks could be discerned on this log, one at 3,817, one at 3,829, and one at 3,846 ft. A radiation peak in the void from 3,856 to 3,862 ft might have been seen, except that the detector was some 6 ft above the bottom of the tool. In fact, if it is assumed that the bottom of the tool reached the bottom of the hole at 3,862 ft, the detector reached 3,856 ft and the beginning of a radiation rise can be seen at this point on the log.

A density log, run later in this interval (3,500 to 3,862 ft), showed low density spikes at the following, approximate depths: 3,817, 3,826, 3,843, and 3,851 ft. These spikes can be interpreted as breaks in the 7-in., and possibly in the 20-in. casings. A caliper log run simultaneously with the density log showed small offsets in the 7-in. casing at approximately 3,815, 3,826, and at 3,843 ft. At 3,857 ft the caliper measured a hole at least 14 in. in radius. Also, since a magnetic collar locater, which was run in the area of the water leak showed the casing slots so well, the locator was run again here to see if it would show casing breaks. The log performed well in showing the casing irregularities (see Fig. 4).

Because of a lack of understanding of the pressure measurements, which showed only 48 psig in the hole, and a sharp change in intensity at approximately 1,760 ft on the gamma log, the presence of water and/or mud in the hole was suspected. The water level locater was run in and the top of a water and/or mud column was found at 1,748 ft.

One of two situations could account for the mud (?) in the hole. Either the void at 3,856 ft, into which the mud column fell, had a finite volume approximately equal to the volume of the 7-in. casing from the surface to 1,748 ft (approximately 350 ft^3), or the mud column in the hole was being supported by gas pressure in the formation equal to the weight of the mud. In the latter case, and assuming that the mud column extends from 3,862 to 1,748 ft, the gas pressure would be approximately 930 psig.

To test which of these two situations might be the case, about 30 barrels of water were added to the hole. The water level locater was run back in again and showed that the top of the column was at 1,739 ft, a rise of 9 ft. Evidently, from these results, the latter situation, that of a mud column being supported by formation pressure, was the more likely.

Under these conditions, one would expect that, since the weight of the column is balanced by the pressure, the gauge pressure in the hole above the mud would be zero. As was reported, however, the gauge readings showed first a partial vacuum (-8 psig at 10:48 p.m.) and then a steady rise to 48 psig at 5:13 a.m.

The following model is suggested to explain this behavior. When circulation was lost and the mud fell into the void (3,856 to 3,862 ft) a partial vacuum was created above the column by the momentum of the moving column. This vacuum disappeared as the system came to equilibrium. In the meantime, gas which was trapped in the annulus above the open slots at approximately 944 ft during earlier gas drilling, began to leak into the 7-in. casing. Since the well was still shut in and the gas pressure in the annulus might have been as high as 100 psig or more, a positive gauge pressure developed. Approximately 6-1/2 hr elapsed between the -8 psig reading and the +48 psig reading, indicating that the connection through the slots at approximately 944 ft was a poor one.

The model of a "water block" was generally agreed upon and, although it would be impossible to regain circulation, it was decided to attempt to drill further.

3,862 TO 3,916 FEET TOTAL DEPTH (TD)

Drilling resumed from 3,862 ft on the evening of January 9. There were no fluid returns, although water was added during the drilling to cool the bit. Drilling went relatively fast except for a few places where the casing was apparently broken, shifted, or bent. Drilling was slow since the casing had to be partially milled. The bit was milling at about 3,907 ft when it suddenly broke through into another void. This occurred at 12:54 a.m. on January 10.

The void extended from 3,907 to 3,916 ft, where more metal was encountered. This time milling was impossible and drilling stopped. A total of about 500 barrels of water had been added during the drilling from 3,862 to 3,907 ft, with no returns. Where this water went is not known, but it is reasonable to assume that a large part of it was lost to the upper (3,856 to 3,862 ft) and lower 3,907 to 3,916 ft) voids.

At 1:18 a.m. (24 min after penetration at 3,907 ft), while the bit was still on bottom, fluids began coming back up the annulus and into the mud tanks. The well was immediately shut in, and monitoring of the pressure gauge on the annulus was commenced.

The pressure at 1:25 a.m. was 338.0 psig and rising steadily. At 1:38 a.m. the pressure jumped from approximately 350 to approximately 400 psig in less than 10 sec, then slowed down again. By 2:00 a.m. the pressure was 433 psig. After this it stopped rising and wavered between 431 and 432 psig.

Because of the abrupt stop in the pressure rise, it was suspected that fluid had gotten into the 1/4-in. gauge line running from the well head to the gauge, and since the outside temperature was below zero, had frozen. This was verified when the valve on the bleed off line from the gauge was opened and only a small volume of gas escaped. Attempts were made to thaw out the line with steam hoses, but since the line was several hundred ft long, this project was abandoned. The gauge was, instead, relocated under the rig floor within a few ft of the well head. At this new location the first reading of 674.5 psig was taken at 7:22 a.m.

Pressure monitoring continued throughout the day (Jan. 10), while the drill pipe was being pulled up through the rotating head to 2,000 ft. By 4:00 a. m. on January 11 the pressure was 830.0 psig and had stopped rising. Monitoring of the pressure gauge ceased at about 8:00 a.m. The Otis high pressure stripping equipment was installed on the well head, and the last 2,000 ft of drill pipe was pulled.

The water level locater was run in the hole (Jan. 12) to determine if a fluid column still existed. The tool, however, behaved erratically and the results were uninterpretable.

A gamma radiation log was run next, but because of the very irregular hole below 3,862 ft, the detector on the tool was able to go only to 3,906 ft. As a result the radiation levels in the void (3,907 to 3,916 ft) were undetermined. In addition to the three radiation peaks observed on the previous gamma log (Jan. 9), the following peaks could be seen; two in the upper void at 3,862 and 3,866 ft, one probable at 3,878 ft, one at 3,893 ft, one at 3,902 ft, and one at 3,906 ft (?).

A formation density log was run, but as with the gamma log, the bad hole conditions below 3,862 ft prevented the tool from going lower than 3,886 ft. As can be seen in Fig. 4, the low density areas on this log correlate well with the high radiation areas on the gamma log.

Several attempts were made to take down-hole black and white pictures of the voids with the Laval stereo camera. Although the large diameter of the camera (5-1/2 in) and the irregularity of the hole precluded going lower than 3,870 ft, the few pictures that were taken provide some clues to the down-hole conditions.

Specifically, the hole below 3,550 ft was quite wet. Water was leaking in through the uncemented slots in the 7-in. casing and forming a steady rain in the hole. This would explain the erratic behavior of the water level locater when it was last used. The pictures also showed that there was no standing water in the hole at least down to 3,870 ft. Pictures taken above 3,550 ft show a damp, foggy hole, but no falling water drops. Also, the pictures at 3,550 ft appear to show the slots through which the water from the Ojo Alamo was leaking. Unfortunately, the wet conditions in the hole make it difficult to see much of anything else. Moreover, unless the slots seen in the picture at 3,550 ft are those which are leaking, the accuracy of the depth measurement cannot be determined.

If the assumption is made that the slots in the picture at 3,550 ft were the slots through which the water was leaking, then the camera depth was essentially correct.

The camera stopped at 3,869 (?) ft, where the line lost weight, indicating that the camera was caught on something. A picture was taken at this point, the camera was raised 1.5 ft, and another picture was taken. The picture at 3,869 (?) ft shows that the camera was sitting on a ledge or offset in the hole, with the drilled hole off to the upper left. Whether this ledge is the bottom of the void at 3,858 to 3,864 ft or an offset farther down cannot be accurately determined. A possible casing break does occur at approximately 3,872 ft and, on the other hand, the bottom of the second radiation spike in the upper void occurs at approximately 3,869 ft. The hole below the upper void is quite irregular, and it becomes difficult to determine exactly where the camera stopped.

In retrospect, it would have been desirable to have taken more pictures at more intervals, but this was only intended to be a trial run to check exposures. Because of the many delays which had already occurred in the postshot schedule and because of the poor quality of the photos, it was decided not to make another run. Two of these photos are reproduced in Figs. 5 and 6.

On Friday afternoon, January 12, after logging, but before the downhole camera runs, the well was flowed for 10 min to determine whether there was still water in the hole. The results indicated that there was no water column in the hole, and that during the test there was essentially no pressure drop at the well head. It had not been expected that any meaningful amounts of gas could be produced at this early time, since it was thought that activity levels, particularly for I^{131}, would be too high. It turned out, however, that the levels were low enough to allow at least moderate flows of gas. I^{131}, in fact, has not been found in any significant amounts in any of the later samples taken either uphole or downhole. It has been reported that "an upper limit of 10^{-4} of the total I^{131} residing in the gas appears very conservative. Eventual careful analysis of the data could lower this level by orders of magnitude."[1]

Several attemps to obtain downhole gas samples were made but, because of weather-induced mechanical difficulties, no samples were obtained until the morning of January 13. There followed another flow test of about 1 hr Saturday night (Jan. 13). The results of these flow tests, the flow tests made subsequent to setting tubing, and the gas sampling program are covered in a companion report by A. Sherwood.[2]

Following the downhole photography and gas sampling with the 3-1/2 in. bottles (Jan. 13), a Baker packer with an expandable plug was set in the 7-in. casing at 3,791 ft. On January 14, 2-7/8 in. tubing was run into the hole and stabbed through the plug in the packer. After removing the BOP's and installing the tubing head, the drill rig was demobilized (Jan. 15). This concluded the reentry drilling program for GB-ER.

Further flow testing and gas sampling through the tubing took place on January 16 and 17. All technical activities, except for daily monitoring of the well head pressure (by EPNG personnel), and periodic (monthly) downhole gas sampling ceased on January 17. Resumption of the postshot program is now awaiting the availability of funds.

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SUMMARY OF GEOLOGIC DATA OBTAINED FROM BOREHOLE GB-1, PROJECT GASBUGGY[1]

By

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INTRODUCTION

On a clear sunny day, Sunday, December 10, 1967, about 300 people were standing, momentarily hushed, on a small mesa in northwestern New Mexico awaiting the detonation of a 26-kiloton nuclear explosive at a depth of 4,240 feet. For a few seconds after the countdown reached zero nothing happened; then suddenly the ground was rocked by a double shock wave and a low rumbling roar was heard in the distance. The explosion completed the most dramatic phase of Project Gasbuggy—an experiment designed to determine the practicability of increasing gas production by fracturing low permeability sandstones with nuclear explosives.

Project Gasbuggy is a joint venture of the U.S. Atomic Energy Commission, the El Paso Natural Gas Co., and the U.S. Bureau of Mines. The site chosen by the participants for the experiment is in sec. 36, T. 29 N., R. 4 W., New Mexico principal meridian, Rio Arriba County, N. Mex., about 55 miles east of Farmington, N. Mex. (fig. 1). This site was chosen because (1) the Pictured Cliffs Sandstone, the target formation, is thicker (nearly 300 feet) than in any other part of the San Juan Basin, (2) the Pictured Cliffs Sandstone is gas-bearing but it does not have sufficient permeability to yield commercial quantities of gas, (3) the formations above the Pictured Cliffs do not contain large amounts of water, and (4) the area is far from population centers.

BOREHOLE GB-1

Borehole GB-1 (Gasbuggy 1) was the first test hole drilled for Project Gasbuggy. The primary purpose of drilling the hole was to obtain for laboratory analyses core samples of the rocks which would be affected by the nuclear explosion. The test hole is located 1,324 feet from the south line and 1,614 feet from the west line of sec. 36 at a surface elevation of 7,200.19 feet. Drilling was begun on February 11, 1967, and a depth of 3,436 feet was reached on February 21, 1967. All depths herein referred to were measured from the Kelly bushing whose elevation was 7,210.09 feet. The hole was cored from 3,436 feet to 4,316 feet; 5¼-inch core was cut from 3,436 to 3,880 feet, and 3½-inch core was cut from 3,880 to 4,316 feet. Coring was completed on March 16, 1967. The hole was mud-drilled from the surface to 3,880 feet and gas-drilled from 3,880 feet to the total depth.

Coring started in the lowermost part of the Paleocene Nacimiento Formation and continued, in descending order, into the Paleocene Ojo Alamo Sandstone and the Upper Cretaceous Fruitland Formation, Pictured Cliffs Sandstone, and upper part of the Lewis Shale. The author examined and described the core segments (Fassett, 1968) as they were brought to Farmington from the well and later examined in detail chips of the cores with a stereomicroscope. The core chips were subsequently sent to R. S. Tschudy of the U.S. Geological Survey for pollen and spore analyses.

1. Publication authorized by the Director, U.S. Geological Survey.

GEOLOGY

The electric log and a lithologic column based on the core description from the cored portion of borehole GB-1 are shown in figure 2. Each of the units shown is discussed below in ascending order. The brief discussion of the environment of deposition and the regional relationships of each of these units is based on data accumulated by the author and J. S. Hinds during several years of study of these units, on the surface and in the subsurface, throughout the San Juan Basin. The results of this study are soon to be published.

Lewis Shale.—The upper part of the Lewis Shale, which

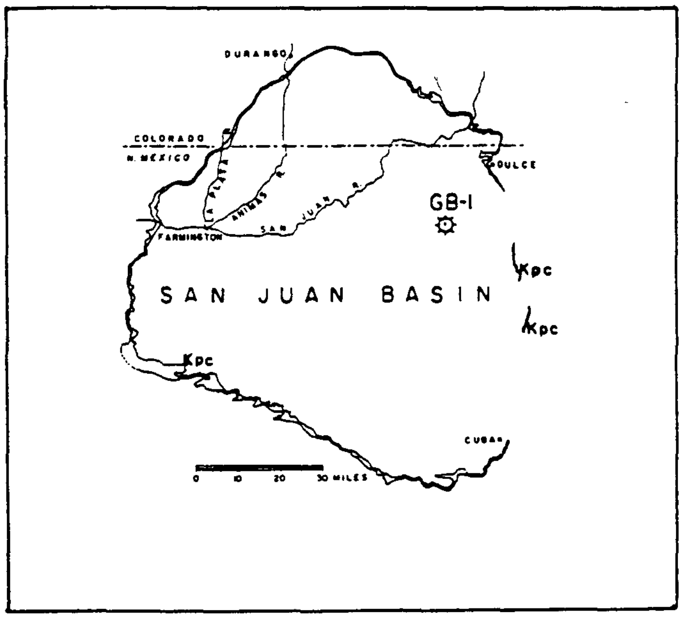

FIGURE 1.
Index map of the San Juan Basin showing the location of borehole GB-1; Kpc, Pictured Cliffs Sandstone.

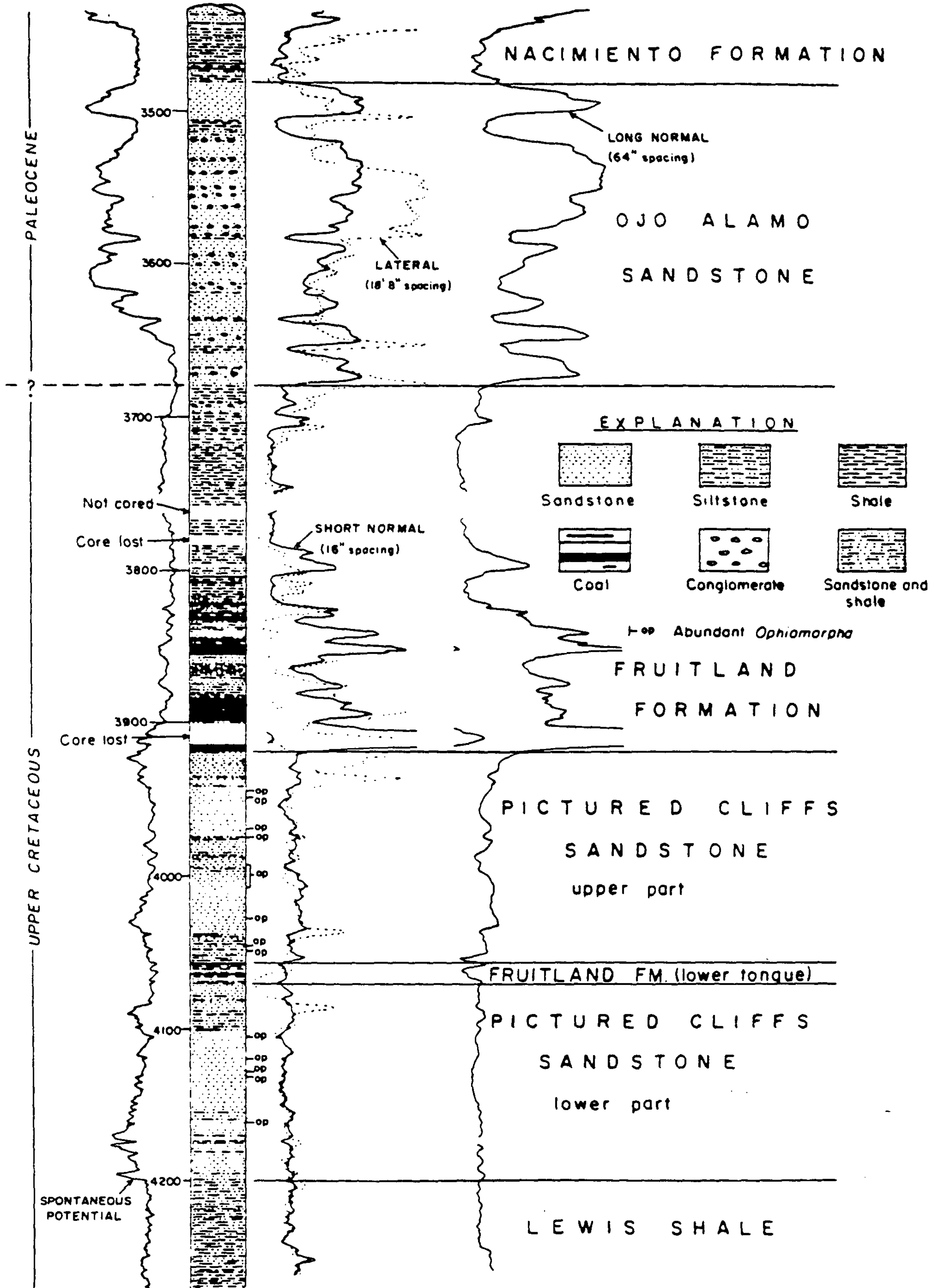

FIGURE 2.
Electric log and lithologic column of the cored portion of borehole GB-1.

was cored from 4,200 to 4,316 feet, is composed of interbedded very fine grained sandstone, siltstone, shale, and silty shale. The amount of sandstone decreases and the amount of black silty massive brittle shale increases downward. The grain size decreases downward from very fine sandstone to siltstone. The lowermost shale units contain a relatively high amount of silt-size material and many cylindrical bodies of sandstone and siltstone about dime-size in cross section.

The portion of the Lewis Shale cored was deposited in a shallow marine environment; the finer grained material at the base of the core represents the deepest water and the greatest distance from the shore.

Pictured Cliffs Sandstone, lower part.—The lower part of the Pictured Cliffs Sandstone, which occurs between 4,072 and 4,200 feet, primarily consists of very fine grained to fine-grained sandstone composed of fairly well sorted quartz grains and a small amount of dark grains which include glauconite, mica, and carbonaceous shale. The dark grains give the sandstone a salt-and-pepper appearance. The average grain size of the sandstone decreases downward from fine to very fine at the top to very fine at the base. Many black shale interbeds as much as 0.65 foot thick are present in the lower part of the unit but the interbeds become fewer and thinner upward to about 4,170 feet where they disappear. Thin papery streaks of carbonaceous material occur at the top and decrease in number downward to about 4,100 feet where they disappear. The entire sequence contains casts and molds of *Ophiomorpha* (fig. 2). The lower part of the Pictured Cliffs fingers out into the Lewis Shale to the northeast.

The lower part of the Pictured Cliffs Sandstone represents a regressive shoreline environment of deposition. The uppermost part of the formation was deposited at or near the beach, whereas the lower part was deposited seaward of the beach in somewhat deeper water. At the time of deposition of the sandstone, the Pictured Cliffs shoreline trended northwest.

Fruitland Formation, lower tongue.—A thin tongue of the Fruitland Formation is present between 4,055 and 4,072 feet. It is composed of interbeds of coal, siltstone, shale, carbonaceous shale, and carbonaceous sandstone. The thickest coal bed is at the top of the sequence and is 1.15 feet thick.

The lower tongue of the Fruitland was deposited in a coastal swamp environment. It wedges out into the Pictured Cliffs Sandstone to the northeast and thickens southwestward where it merges with the main body of the Fruitland Formation.

Pictured Cliffs Sandstone, upper part.—The upper part of the Pictured Cliffs Sandstone occurs between 3,918 and 4,055 feet (fig. 2) and is primarily composed of fine to very fine grained sandstone similar to the lower part of the Pictured Cliffs. The lower part of this unit contains thin shale interbeds up to about 4,038 feet. Between 3,970 and 3,995 feet thin black shale interbeds as much as 0.65 foot thick are present. In the upper part another interval of very thin shale and carbonaceous sandstone partings occurs between 3,935 and 3,943 feet. There does not seem to be a consistent gradation in grain size throughout the sandstone of the upper part of the Pictured Cliffs as there is in the lower part. Casts and molds of *Ophiomorpha* occur throughout most of this unit.

The sediments of the upper part of the Pictured Cliffs were deposited in a marine littoral and beach environment. Because this unit is both underlain and overlain by coal beds of continental origin, it must represent a transgressive phase at the bottom and a regressive phase at the top. The shale interbeds just above 4,000 feet may represent deeper water deposition after maximum transgression, followed by the final regression of the sea. Several other relatively minor cycles of transgression and regression probably occurred during the time that the upper part of the Pictured Cliffs was being deposited.

The upper part of the Pictured Cliffs Sandstone was deposited along a northwest-trending shoreline. It thins and wedges out into Fruitland rocks toward the southwest where the main body and the lower tongue of the Fruitland Formation merge. To the northeast the lower part of the upper part of the Pictured Cliffs fingers out into the Lewis Shale.

Fruitland Formation.—The main body of the Fruitland Formation occupies the interval of rock between 3,680 and 3,918 feet and is composed of sandstone, siltstone, shale, claystone pebble conglomerate, coal, and carbonaceous shale, siltstone, and sandstone. The coal beds are chiefly in the lowermost part of the formation. Thin coal beds occur as high as 3,716 feet. The lowermost coal zone which includes a few thin partings of silty shale has an aggregate thickness of 34 feet. This thickness includes 10 feet of lost core which from interpretation of the electric log seems to be coal. A coal bed 6.4 feet thick above the lowermost coal zone is between 3,858 and 3,884.4 feet. Most of the other rocks in the Fruitland are thinly laminated and intermixed. The thickest discrete unit, other than coal, is a 6.1-foot-thick bed of siltstone and fine-grained sandstone located between 3,837.9 and 3,844 feet. Based on the core information, the most abundant lithologic rock type in the Fruitland is siltstone. Sandstone grain size ranges from very fine to very coarse. The claystone pebbles in the upper part of the Fruitland are as much as 1 inch or more in diameter. Most of the pebbles are flattened; they are gray, green, and red-brown.

The Fruitland was deposited in a coastal swamp environment which graded to a river and flood-plain environment farther landward. The largest and longest enduring swamps were closest to the shore.

Ojo Alamo Sandstone.—The Ojo Alamo Sandstone is present between 3,480 and 3,680 feet. It is composed of poorly sorted arkosic sandstone and a few thin shale interbeds and papery carbonaceous partings. Beds of claystone pebbles as much as 0.3 foot in diameter occur at random throughout this unit. A few chert pebbles as much as 0.1 foot in diameter were seen. Grain size of the sandstone ranges from very fine to very coarse. Some parts of the formation contain as much as 20 percent feldspar.

The Ojo Alamo Sandstone was deposited by streams of relatively high energy. The streams may have had a source to the northwest or west. Basinwide subsurface studies (J. E. Fassett and J. S. Hinds, unpublished data, 1968) indicate that the Ojo Alamo Sandstone was deposited on an erosion surface from which possibly thousands of feet of sediment were removed. The sediment thickness between the Ojo Alamo Sandstone and the Pictured Cliffs Sandstone on the outcrop in the northwestern part of the basin is more than 2,000 feet. This same interval is only 238 feet thick at GB-1. The Cretaceous-Tertiary boundary is shown with a query on figure 2 because, although this boundary is believed to be located at the base of the Ojo Alamo Sandstone throughout most of the San Juan Basin, in some areas it has been located in the shales below the base of the Ojo Alamo.

Nacimiento Formation.—The lowermost part of the Nacimiento Formation occupies the interval from 3,436 feet to 3,480 feet. This part of the Nacimiento is composed of interbedded poorly sorted arkosic sandstone, siltstone, shale, and carbonaceous shale. The sandstone contains as much as 40 percent feldspar and ranges from very fine to very coarse.

The rocks comprising the Nacimiento in this part of the basin are probably mainly fluvial in origin and had a northern source. These fluvial beds grade southward into lake-bed deposits.

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