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MICROFRACTURING IN POSTSHOT GASBUGGY CORE GB-3

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Abstract

Microfracturing in the shocked rock of the Ojo Alamo, Picture Cliffs, and Lewis formations has been examined microscopically in core samples. The amount of fracturing observed is small and shows little correlation with distance from the shot point, but it does show qualitative correlation with permeability measurements on the same cores. Fractures are short-lived in the sandstones and terminate within individual grains or die out in the semiductile cementing clays and micas. The finer-grained sediments show extensive dilation on bedding and other compositional boundaries that results in open breaks ranging in width from less than $1\ \mu$ to greater than $50\ \mu$. At overburden pressure, it is questionable whether bedding dilations in fine, grained shales would appreciably increase the permeability over time intervals measured in years.

Calculated peak radial, tangential, and mean stresses for the core samples indicate that the maximum stresses seen by the rocks are in the 6 to 8 kb range and are somewhat below the yield strengths of the rocks as measured in laboratory triaxial tests. Exact behavior of any rock below its ultimate strength is largely unknown, but it probably includes incipient fracture and ductility (slip or cataclastic flow) in the case of the transitional-type failure expected for Gasbuggy rocks. Comparisons of shock effects in brittle granodiorite and in the semibrittle Gasbuggy rocks at the same peak radial stresses indicate that matrix fracturing in the granodiorite is many times greater than that observed in Gasbuggy rocks. It points up the important role that weak cementing minerals in the Gasbuggy rocks have had in determining the mode of yielding of the whole.

Introduction

Project Gasbuggy was designed to determine to what extent an underground nuclear explosion could stimulate gas flow. The experiment was conducted in an unproductive portion of a gas field within the San Juan Basin in New Mexico. General information concerning the pro-

ject and the joint effort of participating agencies, including the El Paso Natural Gas Company, the Bureau of Mines, the United States Department of the Interior, and the Lawrence Radiation Laboratory, has been summarized by Holzer^{1,2,3} and Rawson et al.⁴ Some of the particulars

relevant to the explosion are given in Table 1.

The success of the experiment depends on the extent and magnitude of the changes in permeability in the gas-bearing strata surrounding the explosion. Hence, study of the nature and extent of fracturing on all scales is germane to the assessment of the experiment and to the interpretation

of changes in permeability and postshot production data. Fracturing on a gross scale was monitored by cliper cable and casing breaks.⁵ Microfracturing has been studied in postshot cores GB-2RS and GB-3.⁶ The present report constitutes a resume of microfracturing as seen in samples taken from the GB-3 core.

Table 1. General data on the Gasbuggy Event.

Date	December 10, 1967	Radius of vaporized and melted rock	39 ft (11.9 m) ⁸
Place	55 mi east of Farmington, New Mexico	Chimney height	333 ft (101.5 m) ⁵
Environment of explosion	Within Lewis shale, 40 ft below the contact with the gas-bearing Picture Cliffs sandstone.	Apical void	None or small
Yield	29 ± 3 kt (from evaluation of all effects) ³	Time of collapse	30 sec after detonation ²
Depth of burst	4240 ft (1292 m) or 2964 ft mean sea level	Overburden pressure at the working point (W. P.)	~0.32 kb
Cavity radius	84.6 ft (25.8 m) — SOC calculation GB-22 based on 25 kt yield; ⁷ 80 ± 2 ft (24.4 m) — from krypton concentrations corrected for porosity ³		

GB-3 Core

The collar on the GB-3 hole was located 250 ft NW of the top of the emplacement hole (1430 ft from south line and 1636 ft from west line of Section 36, T29N R4W, elevation 7200.4 ft) and was 4809 ft long. Figure 1 is a plot of distance from the working point (W. P.) as calculated from a Sperry-Sun Directional Sur-

vey of the hole. The closest approach of the core to the W. P. is 197.6 ft (60.2 m) at 4243 ft slant hole distance (SHD).

Specimens collected for study are listed in Table 2. Figure 2 is the stratigraphic column for the core as compiled by El Paso Natural Gas geologists.⁶

Fig. 1. Postshot radial distance from the shot point of core GB-3.

Stresses Generated by the Explosion

Some idea of the stress levels seen by the GB-3 rocks can be had from the SOC calculations of Cherry et al.,^{7,9} which are based on a 25-kt yield. Peak radial, tangential, and mean pressure are given in Fig. 3 as a function of pre- and post-shot radial distance. Calculated permanent displacements are given in Fig. 4, and a plot of preshot vs postshot radial distances is shown in Fig. 5. The preshot positions and pressures seen by the core samples studied are tabulated in Table 2.

The maximum radial pressure experienced by the recovered core rocks is about 8 kb with a mean pressure of 6 kb. At this point the stresses are close to the compressive strength of the Lewis shale as determined from laboratory triaxial tests (see Fig. 6). Higher up in core, within the Picture Cliff sandstone, the calculated stresses are somewhat below

Fig. 2. Stratigraphic column from core GB-3.⁶

Table 2. Description of Gasbuggy samples from Core GB-3.

Formation	Slant hole distance GB-3 (ft)	Postshot radial distance to W. P.		Δr (ft)	Preshot radial distance to W. P.		SOC calculation GB-22			No. fractures/ft of core ^a	Degree of matrix micro-fracturing ^b	Postshot permeability/porosity at 1 atm ^c		
							Peak radial stress (kb)	Peak tangential stress (kb)	Peak mean stress (kb)			Horiz mD	Vertical mD	%
		(ft)	(m)		(ft)	(m)								
Tertiary (undifferentiated)	2947	1310	399.3	0	1310	399.3	0.40	0.25	0.30	3	D	—	—	—
Ojo Alamo	3509	759	231.3	0.2	759	231.3	0.80	0.46	0.58	(?)	3	~1.15	~1.55	11.4
Ojo Alamo	3618	654	199.4	0.3	654	199.4	0.98	0.64	0.75	2	2	0.66	0.47	12.2
Kirtland	3693	583	177.7	0.4	583	177.7	1.2	0.74	0.90	4	0+	—	—	—
Kirtland	3783	499	152.3	0.7	498	151.8	1.5	0.98	1.2	6	D	—	—	—
Upper Picture Cliffs	3915	382	116.5	1.0	381	116.2	2.3	1.5	1.8	2	1	0.07	0.04	13.6
Upper Picture Cliffs	3957	347	105.8	1.5	346	105.5	2.7	1.8	2.1	3	0+	0.01	<0.01	8.1
Lower Picture Cliffs	4108	239	72.9	3.4	236	72.6	5.4	3.6	4.2	4	1-	0.07	0.01	10.5
Lower Picture Cliffs	4140	223	67.9	4.0	219	66.8	6.1	4.0	4.7	50	1	0.02	0.01	4.5
Lower Picture Cliffs	4167	212	64.5	4.5	207	63.1	6.6	4.4	5.1	4	1-2	0.15	0.08	14.2
Lewis shale	4233	198	60.3	5.0	193	58.8	7.6	5.1	5.9	8	1,D	—	—	—
Lewis shale	4404	256	78.0	3.0	253	77.1	4.9	3.2	3.8	4	D	—	—	—
Lewis shale	4503	327	99.7	1.8	325	99.1	3.0	2.0	2.3	10	D	—	—	—
Lewis shale	4594	407	124.1	1.0	406	123.8	2.1	1.4	1.7	4	D	—	—	—
Lewis shale	4800	506	181.7	0.4	596	181.7	1.1	0.74	0.86	3	0+	—	—	—

^aSee Ref. 6.^b0 — no fracturing; 1 — low; 2 — low-moderate; 3 — moderate; D — dilation on bedding.^cCore Laboratories, Inc. data courtesy El Paso Natural Gas Co.

Fig. 3. Stresses as a function of distance from the shot point for the Gasbuggy Event (SOC calculation GB-22 based on 25-kt yield).

Fig. 4. Permanent displacement of rock surrounding the Gasbuggy shot point (SOC calculation GB-22 based on 25-kt yield): displacement vs preshot radial distance.

those required to cause gross failure in triaxial strength tests; however, assuming that failure of shocked rock approximates failure in the laboratory, the stresses are probably sufficiently high to produce a small amount of permanent strain in the form of incipient plastic or cataclastic flow. The latter term implies crushing, granulation, or intergranular slip for which friction is important. In the present instance, the high clay-mica content of the matrix material suggests operation of the last-mentioned mechanism.

Information at hand indicates that loading under shock conditions does not exactly parallel that associated with triaxial tests. Specifically, the increase in differential stress ($\sigma_1 - \sigma_3$) with increase in mean stress is not as great in the shock experiment. Under these circumstances,

Fig. 5. Permanent displacement of rocks surrounding the Gasbuggy shot point (SOC calculation GB-22 based on 25-kt yield): preshot vs postshot distance.

Fig. 6. Strength of Gasbuggy rocks from triaxial laboratory tests.⁷

$$Y/2 = \frac{\sigma_1 - \sigma_3}{2}; \quad \bar{P} = \frac{\sigma_1 + \sigma_3}{2}.$$

using compressibility data instead of triaxial tests as a guide, onset of fracturing on loading is assumed to occur at lower stress levels than would be predicted from Fig. 6. The threshold is largely unexplored for most rocks, and fracture-radii predictions are weakened by the lack of information on behavior at low stress levels on loading as well as on unloading. In the case of shocked rock, unloading involves simultaneous decrease of both mean and differential stress. Thus, either brittle or ductile-brittle yielding may eventually occur in rock whose ultimate strength was not exceeded by the peak pulse.^{*} Additional uncertainties in predicting the degree of fracturing as a function of distance from the W. P. are the as yet unassessed roles played by (1) volume dilation under triaxial compres-

sive loading and (2) relaxation phenomena upon passage of a shock wave through porous material, where one or more of the stresses can locally become truly tensile. When we add the uncertainties in our knowledge of the pressures generated by the shock to those discussed above concerning the nature of the response of the rock, we should be circumspect in our treatment of the formation summarized in Figs. 3 through 6.

^{*} This type of failure has been called "tension cracking" in predictions of fracture radii, even though all principal stresses are compressive. Fractures so produced are normal to the least of the three compressive stresses and are equivalent to extension fractures of static tests. If one or more of the principal stresses are tensile, i.e., of the opposite sign, fractures produced normal to the least principal stress are called tensile fractures.

Microfracturing

Standard thin sections (22 × 35 mm) of the GB-3 core samples were examined microscopically. Core samples were impregnated with epoxy under vacuum in order to minimize fracturing during the subsequent sectioning and grinding process. All sections were parallel to the core axis and hence approximately normal to the bedding of the Gasbuggy rocks. In the descriptions that follow, fracturing implies recognizable loss of cohesion irrespective of the nature of the break. The questions addressed by the examination are: How extensive is the fracturing on a microscopic scale? Are fractures through-going, i.e., once initiated, are breaks propagated across the specimen for any distance? Is the position of the crack influenced by grain boundaries, mineral cleavages, or other preexisting discontinuities? How does failure in the Lewis shale differ from that of the Picture Cliffs sandstone? Is there any sign of plasticity in the ubiquitous carbonate minerals of the sediments?

MINERALOGY

A summary of the mineralogy and petrology at the Gasbuggy site has been prepared by J. E. Fassett, USGS (see Ref. 6) and by L. D. Ramspott¹⁰ from GB-1 preshot core samples. Results of quantitative x-ray analysis of weight percent of three constituents, quartz, calcite, and dolomite, are⁸: Picture Cliff sandstone (P-43, 3970-ft depth) — 54, 1.3, and 5%; (P-24, 4095-ft depth) — 56, <1, and <1%; (P-47, 3946-ft depth) — 65, <1, and <1%; Lewis shale

(4218 to 4280-ft depth, av 14 samples) — 51, 3, and 7%. The remainder of the rocks consist of feldspar and fine-grained minerals such as micas and clays. The important observation related to failure is the high proportion of mechanically weak minerals (micas, clays, and calcite) in both rock types. They comprise an estimated 15 to 25% by volume of the Picture Cliffs sandstone and 25 to 30% of the Lewis shale. Photomicrographs of the rocks show the individual quartz and feldspar grains floating in the matrix. Quartz-quartz or quartz-feldspar grain contacts, which are potential sites of local stress concentration on loading, are rare. By contrast, the Ojo Alamo sandstone has a lower proportion of matrix material and consequently a larger number of such contacts within a given volume.

DEGREE OF FRACTURING

A microscopic survey of the samples indicates a low level of matrix fracturing. The most highly fractured samples examined come from the Ojo Alamo, 650 to 750 ft from the W. P. Several samples of the Picture Cliffs sandstone are virtually unfractured. In these, the quartz and feldspar grains are clear and unbroken; no dilation is visible on the bedding or at grain boundaries, even at the highest magnifications. In order to compare the degree of fracturing in the various samples, a semiquantitative scale was arbitrarily set. Four degrees of matrix fracturing were recognized: moderate, low-moderate, low, and no fracturing. Examples from the sandstone studied are shown in Fig. 7.

(a)

(b)

(c)

(d)

Fig. 7. Degrees of matrix fracturing in postshot Gasbuggy core GB-3: (a) moderate - Ojo Alamo sandstone (3509 ft SHD); (b) low-moderate - Ojo Alamo sandstone (3618 ft SHD); (c) low - Picture Cliffs sandstone (4167.8 ft SHD); (d) none - Picture Cliffs sandstone (4167.3 ft SHD). Scale bar = 100 μ . Doubly polarized light.

The samples have been assigned to one of these categories on the basis of the overall amount of fracturing observed (refer to Table 2). There does not seem to be a correlation between radial distance and degree of fracturing in the samples examined. However, this may in part reflect the selectivity in the initial sampling. In general, highly fractured core is not recovered; moreover, any study involving additional specimen preparation (cutting or recoring) fosters unconscious selection of coherent core samples.

Permeabilities measured in core samples at 1 atm and macrofracture counts along the core length are included in Table 2.⁶ These show little correlation to each other; however, the permeability measurements do correlate well with the assessment of microfracturing in this study. The order of increased amount of macrofracturing is the same as the order of increased permeability irrespective of distance from the W. P.

NATURE OF THE FRACTURES

Healed, preexisting fractures can be distinguished from fresh shock-induced fractures on the basis of the discoloration, precipitation, or alteration typically seen along the former. Preexisting fractures are not conspicuous in the core samples, and there is no convincing evidence that shock-induced fracturing preferentially occurs parallel to them.

Typically, the fractures in the coarse-grained sandstone are "short lived," i. e., they fail to traverse a single grain or grain boundaries. As the overall amount of fracturing increases, they tend to be individually longer and extend across

several large grains if these are contiguous (see Fig. 7(a)). Commonly the subangular quartz and feldspar grains are surrounded by weaker clay and micaceous minerals. In this case, through-going fractures in quartz die out in the matrix (refer to Fig. 9(d)).

Separation at grain boundaries in the coarse-grained sandstones is rare; however, as the grain size becomes finer, e. g., in siltstones of the Kirtland and Lewis formation, dilation or partings parallel to bedding become more conspicuous (see Fig. 8). In some cases, the through-going partings are parallel to local compositional inhomogeneities that transgress the normally flat bedding. They vary in width from 1 to 50 μ in the samples studied. The broadest parting shown in Fig. 8(a) is 33 μ wide; Fig. 8(c) shows one 7 μ wide. These breaks have the character of strictly extension (or tension) phenomena, as they are open; they characteristically follow grain boundaries, and they have propagated without involving the fracture of the larger grains of quartz and feldspar in the sample. Samples showing dilation are noted in Table 2.

BEHAVIOR OF OTHER MINERAL COMPONENTS

Evidence of plasticity in the form of kinking in the coarser micaceous materials and mechanical twinning in calcite is infrequently observed in the suite of rocks. No mechanical twinning at all was seen in dolomite, the more abundant of the two carbonate minerals, as might be expected from the higher resolved shear-stress, τ_c , necessary to initiate it (2000 bars in dolomite vs 30 to 60 bars in calcite, at

(a)

(b)

(c)

Fig. 8. Dilation in postshot Lewis shale: (a) open partings (up to $33\ \mu$) parallel to bedding (4574 ft SHD); (b) and (c) position of partings in the matrix ($7\ \mu$) with respect to coarse-grained components (4503 ft SHD). Scale bar = $100\ \mu$. Bedding vertical. Doubly polarized light.

(a)

(b)

(c)

(d)

Fig. 9. Comparison of behavior of Picture Cliffs sandstone and Piledriver granodiorite at comparable peak radial stresses; (a) Picture Cliffs sandstone (3915 ft SHD) - 2.3 kb; (b) Piledriver granodiorite (BL-225-2) - 2.6 kb; (c) Picture Cliffs sandstone (4167.8 ft SHD) - 6.6 kb; (d) Piledriver granodiorite (P-2-60) - 7.1 kb. Scale bar = 100 μ . Doubly polarized light.

temperatures below 400°C and a 5-kb confining pressure¹¹). In some specimens, cleavages in the carbonates are more conspicuous than in comparable unshocked GB-1 core; however, the effect on permeability is insignificant.

COMPARISON WITH BEHAVIOR OF GRANODIORITE AT COMPARABLE STRESSES

The observations suggest that failure of these sedimentary rocks at low mean pressures is transitional, as opposed to purely brittle or ductile failure. The strength or yield point is equated with the onset of appreciable cataclastic flow in the matrix cement and with some as yet unknown amount of fracturing of the brittle components. In order to emphasize the difference in behavior of two materials

that have undergone transitional and purely brittle failure, photomicrographs of the Picture Cliffs sandstone are juxtaposed with those of the shocked Piledriver granodiorite (see Fig. 9). Peak radial stresses seen by the two types of rocks (2.3 and 2.6 kb, and 6.6 and 7.1 kb, as shown in Fig. 9) are comparable. Clearly the fracturing is more extensive and the cracks are wider in the granodiorite. Specimen preparation was identical for both rock types. Fractures in the Gasbuggy sandstone would not be seen in photomicrographs taken at the same (lower) magnification as used for the granodiorite. A conscious effort was made to photograph representative portions of the thin sections, rather than highly fractured sectors, in the case of the granodiorite and lightly fractured sectors of the sandstones.

Discussion

The most impressive feature of the rocks examined is the generally low degree of fracturing. This is consistent with the preliminary data on the changes in permeability produced by the explosion on these samples^{3,12,13}; however, it is difficult to reconcile this finding with the observations and calculations that led to statements such as "This region of the reservoir evidently was intensely fractured to at least 375 ft from the shot. Similar evidence plus gas production data indicate that intense fracturing took place in the Lewis formation to at least 400 ft."⁴ These conclusions stemmed primarily from examination of caliper logs of post-shot holes and from the positions of casing and cliper cable breaks. Moreover, pre-

shot SOC calculations (predictions) seemed to be consistent with such an interpretation,^{4,9} since "tensile cracking" was anticipated to extend beyond the limit for compressive failure, which is now estimated to be approximately 60 m from the W. P.⁷ In view of the absence of pervasive microfracturing 60 to 80 m from the shot point, distant failure in cables, etc., would appear to be due to extension or tensile failure associated with collapse or dilations — perhaps along preexisting discontinuities such as bedding. Closer in, within the Picture Cliffs sandstone located 60 to 70 m from the shot point, compressive stresses were not sufficient to cause brittle failure of the matrix. This is not to say that the rock did not yield under the

applied load, or during unloading, but that the deformation mode was largely flow with incipient fracture. The behavior of the rock at low stress levels in laboratory tests is not sufficiently well known to have predicted the results. From the standpoint of increased gas production, this portion of the behavior history of a deformed rock is of greatest interest since the volume of surviving rock that has been subjected to low mean stresses is several times the volume that sees mean stresses greater than 10 kb.

Volume expansion on loading or unloading (dilation), plays a role in deformation that has not been assessed in either

laboratory or field experiments. The results of dilation are most evident in fine-grained members of the suite of postshot rocks examined, the Lewis shale and the Kirtland siltstones. At 1 atm confining pressure, there are wide ($>33 \mu$), "long-lived" openings parallel the bedding planes and boundaries of compositional changes. At overburden pressures of 0.3 kb, they are probably closed, and their effect on the permeability may be small. Moreover, minor adjustments in the positions of the very-fine-grained clay and micaceous matrix minerals, as well as chemical cementing processes, may reseal the breaks within a few years.

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