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INFLUENCE OF SITE-SPECIFIC GEOLOGY ON OIL SHALE FRAGMENTATION EXPERIMENTS AT THE COLONY MINE, GARFIELD COUNTY, COLORADO

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ABSTRACT

The Los Alamos National Laboratory executed 19 intermediate scale cratering experiments in oil shale at the Colony Mine in Garfield County, Colorado. These experiments have led to a better understanding of fracture characteristics and fragmentation of *in situ* oil shale by use of a conventional high explosive. Geologic site characterization included detailed mapping, coring, and sample analyses. Site-specific geology was observed to be a major influence on the resulting crater geometry. The joint patterns at the experimental site frequently defined the final crater symmetry. Secondary influences included vugs, lithology changes, and grade fluctuations in the local stratigraphy. Most experiments, in both the b and floor, were conducted to obtain data to investigate the fragmentation results within the craters. The rubble was screened for fragment-size distributions. Geologic features in proximity to the explosive charge had minimal effect on the rubble due to the overpowering effect of the detonation. However, these same features became more influential on the fracture and rubble characteristics with greater distances from the shothole. Postshot cores revealed a direct relationship between the grade of the oil shale and its susceptibility to fracturing. The Colony Mine experiments have demonstrated the significant role of geology in high explosive/oil shale interaction. It is probable that this role will have to be considered for larger applications to blast patterns and potential problems in retort stability in the future of oil shale development.

INTRODUCTION

The importance of shale oil was recognized with the first recorded production in Austria in 1350 (EPA, 1979). Since the first installation of oil shale retorts by France in 1838, the greatest activity of oil shale industries took place in the decade encompassing World War II. Generally, development has occurred only under unusual localized conditions where supplies of coal or crude oil were absent or inadequate. As conventional petroleum resources continue to rise in costs, the significance of this resource will come into focus.

This peculiar rock occurs, by one name or another, on all continents and is known to exist in nearly three dozen countries. However, the Green River Formation in Colorado, Utah, and Wyoming contains the largest single known concentration of hydrocarbons in the world (Russell, 1980). Resource estimates range from 111.3 billion m^3 (700 billion barrels) of synthetic crude (Yen and Chilingarian, 1976) to 636 billion m^3 (four trillion barrels) of oil equivalent (EPA, 1979). The perspective of what is economically recoverable is the main factor for difference in the estimates. The Piceance Creek Basin of western Colorado (Fig. 1), alone, may yield approximately 190.8 billion m^3 (1.2 trillion barrels) of shale oil (Newton, 1982). Regardless of which reserve estimate is accepted, the resource is extensive.

A primary influence on economic feasibility has been the lack of adequate technology addressing certain problems in oil shale industry development. The problems are numerous and cover a broad spectrum of disciplines ranging from environmental impact to process chemistry. However, one problem is frequently mentioned in oil shale literature and has been assigned high priority by several investigators (McCarthy et al., 1978; Peil and Humphrey, 1978; Berry, 1978; and Simon, 1979). That problem is rock fragmentation, sometimes termed rubblization or rubble bed preparation. The solution of that problem could represent a key step toward economic feasibility by circumventing the costly operations of mining, surface handling, and surface retorting. Rubblization is oriented toward a process known as modified <u>in situ</u> (MIS) retorting. This method may introduce additional technical problems, but it does present a viable alternative for oil shale development. It is particularly suited for deeper lying shale beds such as those in the Piceance Creek Basin of Colorado. Modified <u>in situ</u> (MIS) processes, by mining some of the oil shale for surface processing prior to explosive fracture, allow the damaged rock to expand into the mined-out volume. This increases the permeability of the resultant rubble pile sufficiently to allow pyrolysis and removal of retorted products. The void volumes achieved can be controlled by the amount of mining performed. Representative numbers for void volume range from 20 to 30%. This form of fractured bed, permeable openings around nonporous blocks, is a desirable goal for <u>in situ</u> retorting because of minimum mining cost (Simon, 1979).

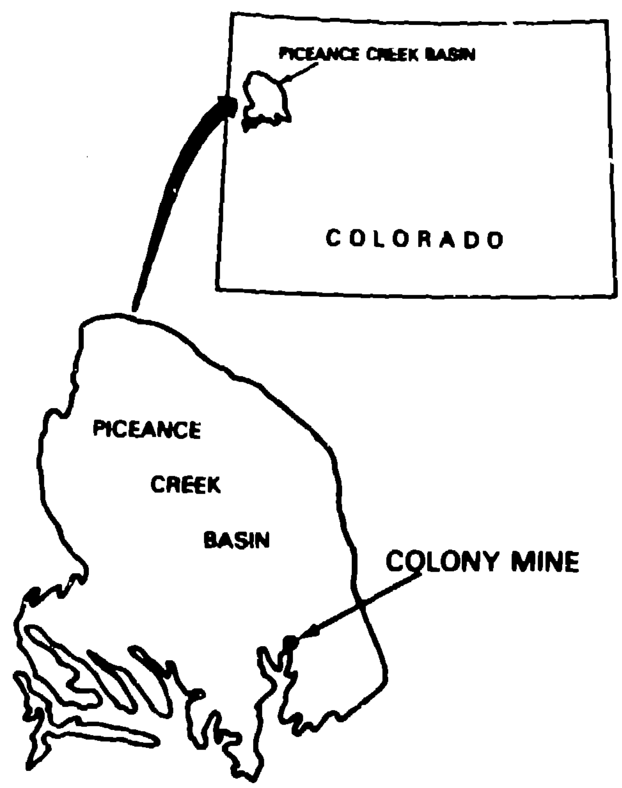

Fig. 1. Location of the Colony Mine within the Piceance Basin of western Colorado.

Other mining techniques have been considered as alternatives to MIS retorting or as modifications to the MIS approach. The mining system used must be capable of excavating large quantities of shale at a very low cost. One technique with great economic potential is block caving, which uses gravity to fracture the shale into manageable sizes. However, Reynolds (1975) points out that it is not at all clear that oil shale will fracture under a natural caving action even though joint spacing prerequisites appear favorable. A detailed study by Hoskins et al. (1975) considered six mining systems adaptable to large-scale mining of oil shale. Three systems were prioritized above block caving, with room and pillar being the most favorable. Allsman (1968) proposed a modified block caving system using blasting to enhance rubblization and propagating subsidence to the surface for disposal of spent (retorted) shale. The surface disturbance is severe, however, and this method is feasible only for uninhabited and undeveloped areas (Sladek, 1975). Since the U.S. Bureau of Mines tried room and pillar mining in the 1940's and 1950's, that mining system appears to be an attractive method, and several private firms have successfully operated room and pillar mines safely. The rubble-size for processing remains a problem, however, and handling for surface retorting is costly considering the tonnage to be moved.

The Los Alamos National Laboratory is involved in a research effort primarily directed toward the explosively produced fracture of oil shale in preparation for a MIS retort. The oil shale fragmentation is produced by use of conventional high explosives. The initial objective is to develop the capability of predicting various rubble bed characteristics from an explosive emplacement design. The ultimate goal is to define a design plan that will produce a rubble bed suitable for retorting.

The approach taken at Los Alamos is a combination of numerical calculations to analyze and predict certain physical phenomena, laboratory experiments to provide basic information, and field verification experiments. The field experiments were performed in the Colony Mine and, more recently, the Anvil Points Mine. This discussion will be restricted to the Colony Mine experiments. The Colony Mine (room and pillar) is located approximately 25 km north of Parachute (previously named Grand Valley), Colorado in Section 7, Township 5 South, Range 95 West (Fig. 2).

The field verification experiments have three basic purposes: (1) to provide field data for the calibration and evaluation of computer codes that model various phenomena; (2) to identify major factors that influence the fracturing of oil shale; and (3) to analyze the field results in a quantitative manner and determine the applicability of scaling laws. During the program of field verification experiments, site geology clearly established its impact on experimental results. Site-specific geology was documented during the Colony experiments as an integral parameter that will require characterization for applications to design of blast patterns and potential problems in retort stability.

GEOLOGIC SETTING

Regional Geology

Geomorphology in this area of the Piceance Basin shows that a high table-land, known as the Roan Plateau, is bounded by steeply sloping cliffs (Roan Cliffs) of the Green River Formation on the south and the Grand Hogback monocline to the east. The Roan Cliffs rise several hundred meters above steep talus slopes which, in turn, rise 900 to 1200 meters above the Colorado River to the south. The plateau is frequently dissected by tributaries of the Colorado River drainage which flow through steep-walled canyons contributing to an intricate topography.

The Piceance Basin margins present many opportunities to observe the stratigraphic section. In most areas the dip of the beds is negligible and allows a close approximation of the thickness of any member of interest. The outcrops of early Tertiary (Eocene) rocks are assigned to the Wasatch and Green River Formations that overly a thick section of Mesozoic and Paleozoic sedimentary rocks. The Green

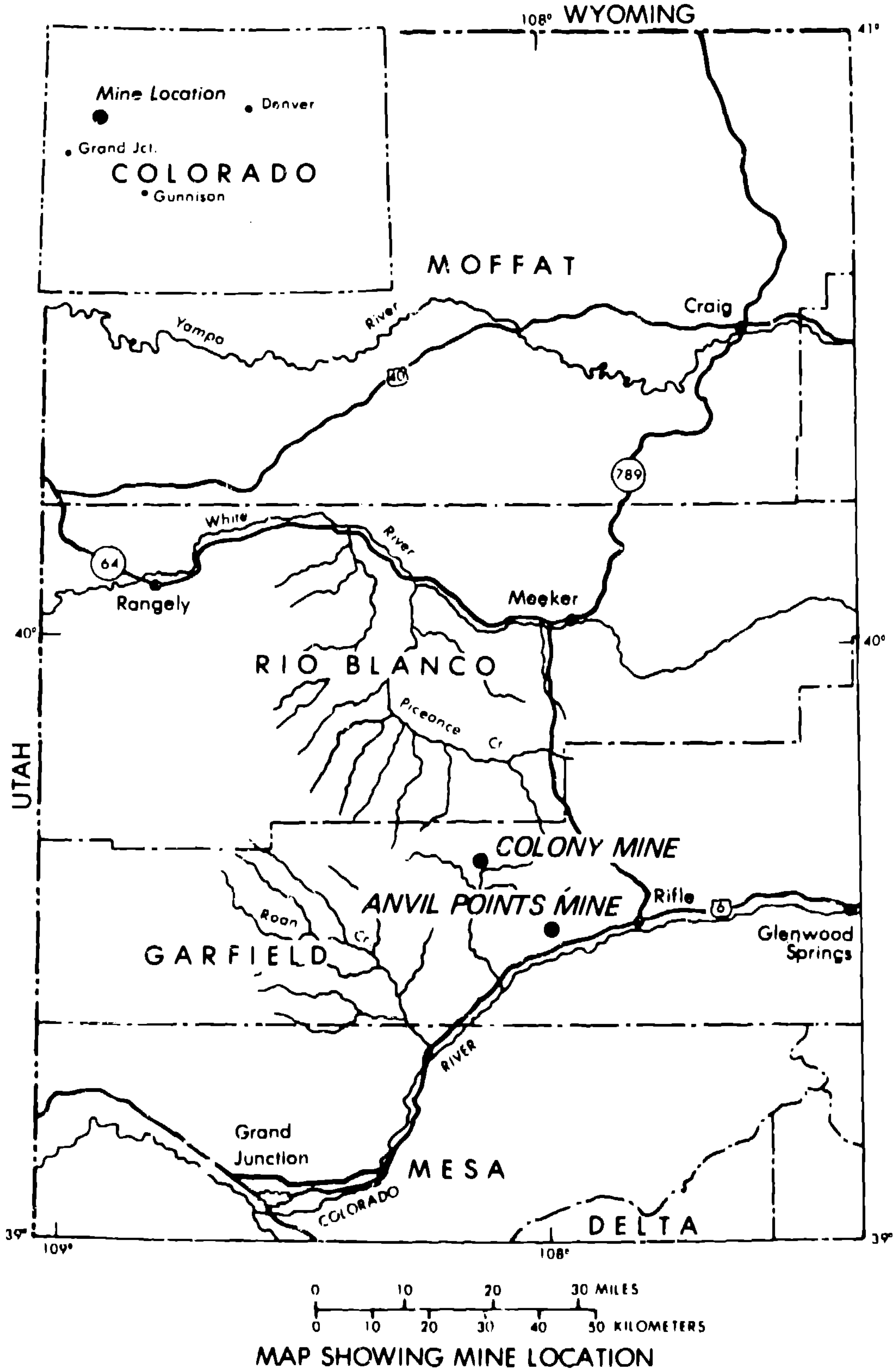

Fig. 2. Location of the Colony Mine and Anvil Points Mine.

River Formation primarily consists of tan to gray sandstone and shale in the upper and lower thirds, and gray to black thin-bedded marlstone in the middle third, with a total thickness of about 975 m. The marlstone portions of the formation contain the "oil shale." There are four local members in the Green River Formation: (1) Evacuation Creek Member; (2) Parachute Creek Member; (3) Garden Gulch Member; and (4) Douglas Creek Member. Proceeding east, the Douglas Creek Member and the Garden Gulch Member become the Lower Sandy Member. Further east the Lower Sandy Member begins to interfinger with the Parachute Creek Member. A generalized description of the Wasatch Formation and the respective members of the Green River Formation may be reviewed in Fig. 3. These descriptions and specified thicknesses are general and may vary substantially over the extent of the basin. Figure 3 also represents a compendium of works by many authors (as noted on the figure) addressing the unique stratigraphy of this region.

The general consensus credits algal organisms as the principal contributor to oil shale source materials (Yen and Chilingarian, 1976). The organic content of oil shale generally ranges from less than 1 weight-percent of total weight to 40 weight-percent of the total weight. The organic content of the rock greatly influences the inherent mechanical properties of the rock and their response to explosive fracturing. The rich Mahogany Zone of the Green River Formation averages about 16 weight-percent organic content. The Mahogany Zone is the best known interval of rich oil shale and most of the test mining has been performed within this zone. The organic content of oil shale is generally translated into "grade" quantitatively expressed in ℓ/tonne (gallons per ton)* oil yield. Figure 4 presents a histogram showing oil yield typical of the upper Parachute Creek Member of the Green River Formation.

Regional structures show a marked tendency toward northwest orientation and include faults, anticlines, and synclines. The nearest major structure to the Colony Mine is the Crystal Creek Anticlinal Nose approximately 14 km southwest. An azimuth frequency plot of the regional structures, shown in Fig. 5, shows very similar distributions to those measured on specific sites in the Colony Mine. The data plotted in that figure also shows the orientation of the two closest major structures to demonstrate their influence on site-specific parameters.

Colony Mine Geology

The Colony Mine is located in the southern part of the Piceance Basin (Fig. 1), but well within a geologic environment representative

*General use of the terms "gallons per ton" (oil yield) and barrels continues in the oil shale industry. The following conversion factors (Dickson, 1981) may be used: to convert ℓ/tonne to gal/ton, multiply by 0.2396; to convert m^3 to barrels, multiply by 6.29.

System	Series	Geologic Unit		Thickness Meters	Physical Character
TERTIARY	EOCENE	GREEN RIVER FORMATION	EVACUATION CREEK MEMBER	~ 306	FINE GRAINED, GRAY AND BROWN SANDSTONE WITH TUFFACEOUS SILTSONES AND MARLSTONES WITH A FEW THIN BEDS OF OIL SHALE. THE UPPER ~ 61 METERS CONTAINS MASSIVE SANDSTONES THAT MAY BELONG TO THE LOWER SECTION OF THE BRIDGER FORMATION THAT RESTS CONFORMABLY ON THE EVACUATION CREEK MEMBER. (BRADLEY, W. H., U.S.G.S. PROFESSIONAL PAPER NO. 168, 1931). WEATHERS TO ROUNDED SLOPES.
			PARACHUTE CREEK MEMBER	~ 122 - 366	BLACK, BROWN, TO GRAY ORGANIC MARLSTONE, INCLUDES THE PRINCIPAL OIL SHALE UNITS AND THIN PERSISTENT ALTERED TUFFS. IN DRILL SECTIONS, UNIT IS 382 TO 512 METERS THICK. MOST DRILL CUTTINGS ARE DOLOMITIC. TUFFS ARE IN MOST CASES ALTERED TO ANALACITE, A ZEOLITE. THIS MEMBER CONTAINS THE MAHOGANY LEDGE WHICH HAS A VERY HIGH OIL YIELD. WITHIN THIS LEDGE IS THE MAHOGANY MARKER, AN ANALCITIZED TUFF APPROXIMATELY ~ .15 m THICK. WEATHERS TO LIGHT GRAY & LIGHT BROWN CLIFF.
			GARDEN GULCH MEMBER	~ 192 - 219	SERIES OF DARK GRAY, BROWN AND BLACK SHALES AND MARLSTONES. THIS MEMBER CONTAINS ORGANIC MATTER IN SUFFICIENT QUANTITY TO YIELD ~ 15 GALLONS PER TON. RELATIVELY LOW RESISTIVITY AS COMPARED TO THE PARACHUTE CREEK MBR. DUE TO THE LOW CARBONATE CONTENT IN THE SEDIMENTS. WEATHERS TO SMOOTH STEEP SLOPES.
			DOUGLAS CREEK MEMBER	~ 131 - 232	ALTERNATING BEDS OF SANDSTONES, DARK GRAY SHALE, SANDY SHALES & GRAY MARLSTONES. CORE IS SOMETIMES OIL STAINED WHEN RECOVERED. WEATHERS TO BUFF SLOPES & LOW CLIFFS.
		WASATCH FORMATION		~ 1035 - 1585	ALTERNATING VARICOLORED (RED, DRAB, GRAY AND MAROON) SHALES WITH LENTICULAR SANDSTONES. TOP OF FORMATION IS USUALLY THE HIGHEST RED OR VARICOLORED SHALE. WEATHERS TO VARICOLORED SLOPES W/DISCONTINUOUS SANDSTONE LEDGES.

Unit	Thickness	Physical Character
LOWER SANDY MEMBER	355 TO [illegible] m	STRATIGRAPHIC EQUIVALENT OF THE COMBINED DOUGLAS CREEK AND GARDEN GULCH MEMBERS AND INCLUDES YOUNGER BEDS THAT INTERFINGER WITH THE LOWER OIL SHALES OF THE PARACHUTE CREEK MEMBER. BEDS OF FINE GRAINED SANDSTONES WITH SHALES AND MARLSTONES, BROWN TO LIGHT GRAY IN COLOR.

MODIFIED STRATIGRAPHIC COLUMN AFTER: (COFFIN, WELDER, AND GLANZMAN, 1971)
(DUNCAN AND BELSER, 1980)
(DUNCAN AND DENSON, 1949)
(BRADLEY, 1931)

Fig. 3. Generalized descriptions of oil shale strrtigraphy in the vicinity of Colony Mine.

of the potential oil resource of the region. The Colony Mine portal is located in the middle fork of Parachute Creek canyon within the Parachute Creek Member of the Green River Formation (Fig. 6). More important, however, is its location within the rich Mahogany Zone. All of the Colony Mine cratering experiments were executed in the relatively rich 12 m interval below the Mahogany Marker. The Mahogany Marker is a thin (10- to 20-cm) bed of sandy textured

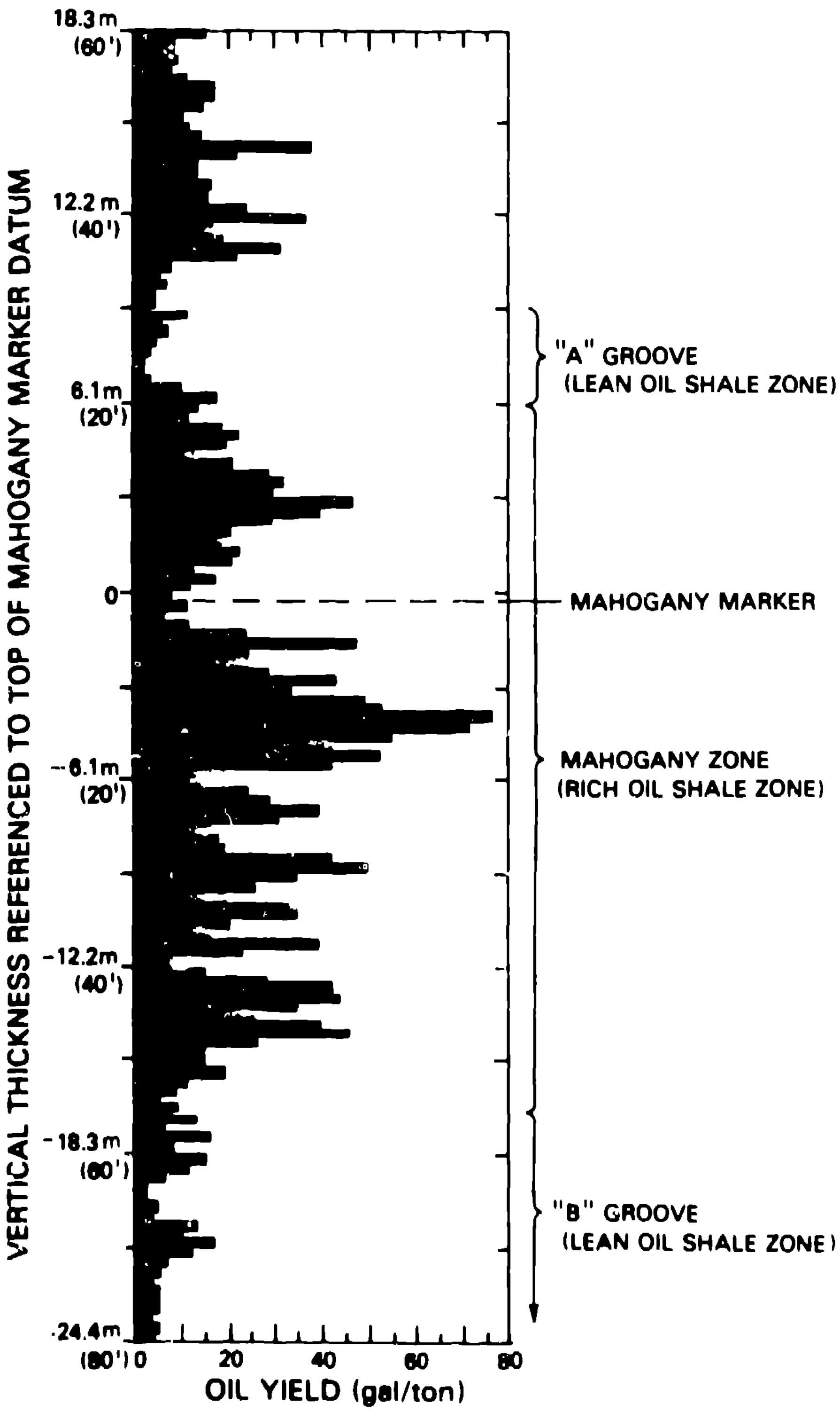

Fig. 4. Histogram showing oil yield variations typical of the upper Parachute Creek Member test beds in the Colony Mine.

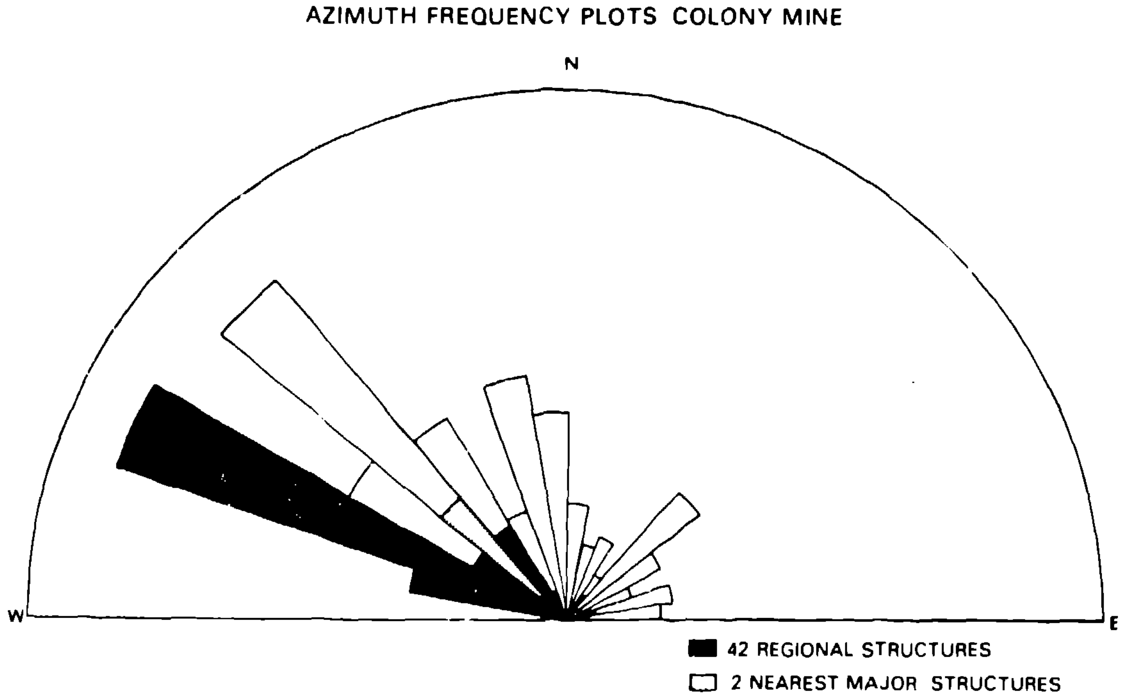

Fig. 5. Joint azimu'h frequency plot comparing data from experiment 79.03 to regional structure orientations.

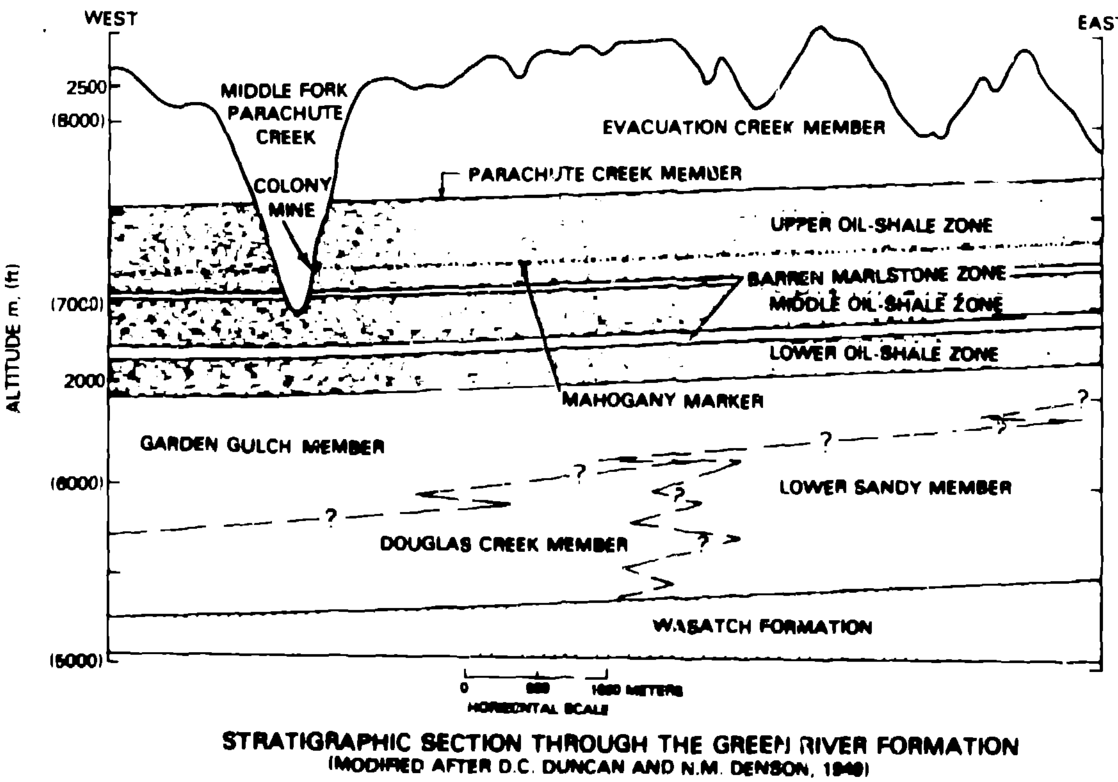

Fig. 6. Idealized stratigraphic cross section through the Green River Formation near Colony Mine.

analcitized volcanic tuff. It is used as a standard reference bed in detailed correlations of the oil shale within the Mahogany Zone.

The structure in the Colony Mine is primarily expressed in two joint sets oriented near 90° to each other. The major joint system generally trends N80°E and the conjugate set strikes approximately N20°W. The joints are usually closed and occasionally contain mineralization precipitated out of the ground water or filling comprised of volcanic tuff. The joint systems within the mine are a primary influence on fracture experiments. Laboratory tests have shown that jointing may reduce the compressive strength of the rock by a factor of four (Agapito, 1972). Reaction of the joint system to the explosives often produced unstable conditions in the mine pillars and ribs necessitating postshot scaling for safety. Joint spacing and orientation is variable and sometimes sensitive to particular stratigraphic horizons. In certain locations in the Colony Mine joints sometimes dissect as much as 12 m of mine rib and continue into the back as seen in Fig. 7. Dips on the joint systems were found to usually be 60° or greater, and most often close to vertical. This joint posture is important because studies by Horino and Hooker (1971) found critical joint orientation, along which failure takes place at low strength values, to lie between 4° and 55° from the vertical. No evidence of faulting was identified in the mine.

COLONY MINE EXPERIMENTS

Results of the Colony Mine experiments, like most others, were defined by factors that could be controlled interacting with factors that could not be controlled. The controllable factors were elements that could be manipulated on each experiment. The uncontrollable factors were essentially elements of the site-specific geology. The geologic elements could be identified through site characterization but their basic disposition could not be altered.

Young et al. (1978), contended that explosive fracturing to produce void volume, a major obstacle to development of *in situ* processing, would require a great deal of site-specific information. Tailoring the controllable elements of explosive fracture to site-specific information will represent a positive step toward removing that obstacle. Table 1 summarizes those two categories pertinent to the Colony Mine experiments.

Agapito (1972) cited overcore measurements as evidence that the stability in the central part of the mine is marginal. The fracture experiments were located well away from the unstable center of the mine and their locations are shown on the map in Fig. 8. Most of the instability problems encountered were associated with the pillars northwest of the experiments in Room 5 which are closer to the center of the mine.

Fig. 7. Vertical continuity of joints frequently extended through mine ribs into the floor and back. These particular joints greatly influenced the resulting crater of experiment 79.03.

The explosive used in these experiments was ammonium nitrate/fuel oil (ANFO). The ANFO contained approximately 6 weight-percent fuel oil with density ranging from 0.79 g/cm^3 to 0.89 g/cm^3 (Edwards et al., 1981). The detonators used varied from commercial blasting caps to exploding bridgewires (EBW). Each experiment was designed to blast to a free face with the ANFO detonated from the bottom of the explosive column. Above the ANFO, the borehole was stemmed to the surface with either grout or oil shale fines. Schematics for typical experiment configurations are illustrated in Figs. 9 and 10.

Table 1. Factors identified as important elements in the Colony Mine experiments.

Controllable Factors	Uncontrollable Factors
1. DOB (depth of burial)	1. grade
2. powder (type)	2. joints
3. C_d (charge diameter)	3. vugs (and associated permeability)
4. C_L (charge length)	4. inhomogeneities
5. C_o (charge orientation)	5. *in situ* stresses
6. C_p (charge pattern)	6. bedding features
7. stemming (type)	
8. timing (multiple shotholes)	

EXPERIMENT RESULTS

The interaction of the factors itemized in Table 1 leads to experimental results expressed as observable and measureable parameters that are of direct interest to Los Alamos researchers. The following data sets are certainly not exclusive but have consistently demonstrated a relationship to site geology.

Fragmentation

Modified *in situ* oil shale technology depends on effective rubblization of large volumes of shale deposits. Certain important characteristics of the rubblization process include fragment sizes and void/permeability distributions. The larger the shale particles, the less efficient the oil extraction process is (Galloway, 1979). But in contrast, Reynolds (1975) asserts that a minimum amount of fines is desirable. Therefore an essential characteristic of a rubblization plan is its ability to produce a predictable and reproducible particle-size distribution within a certain range of sizes. The particles comprising a heterogeneous bed have different sizes (from dust to blocks) and the permeability channels between particles have different resistances to fluid flow (Travis, 1982).

The size distribution of the rubble from experiments performed at the Colony Mine can be used to compare the effects of different experimental designs on the overall fragmentation results (Harper and Oliver, 1981). The rubble was separated into various size ranges by passing the fragments through screens of sequentially smaller sizes.

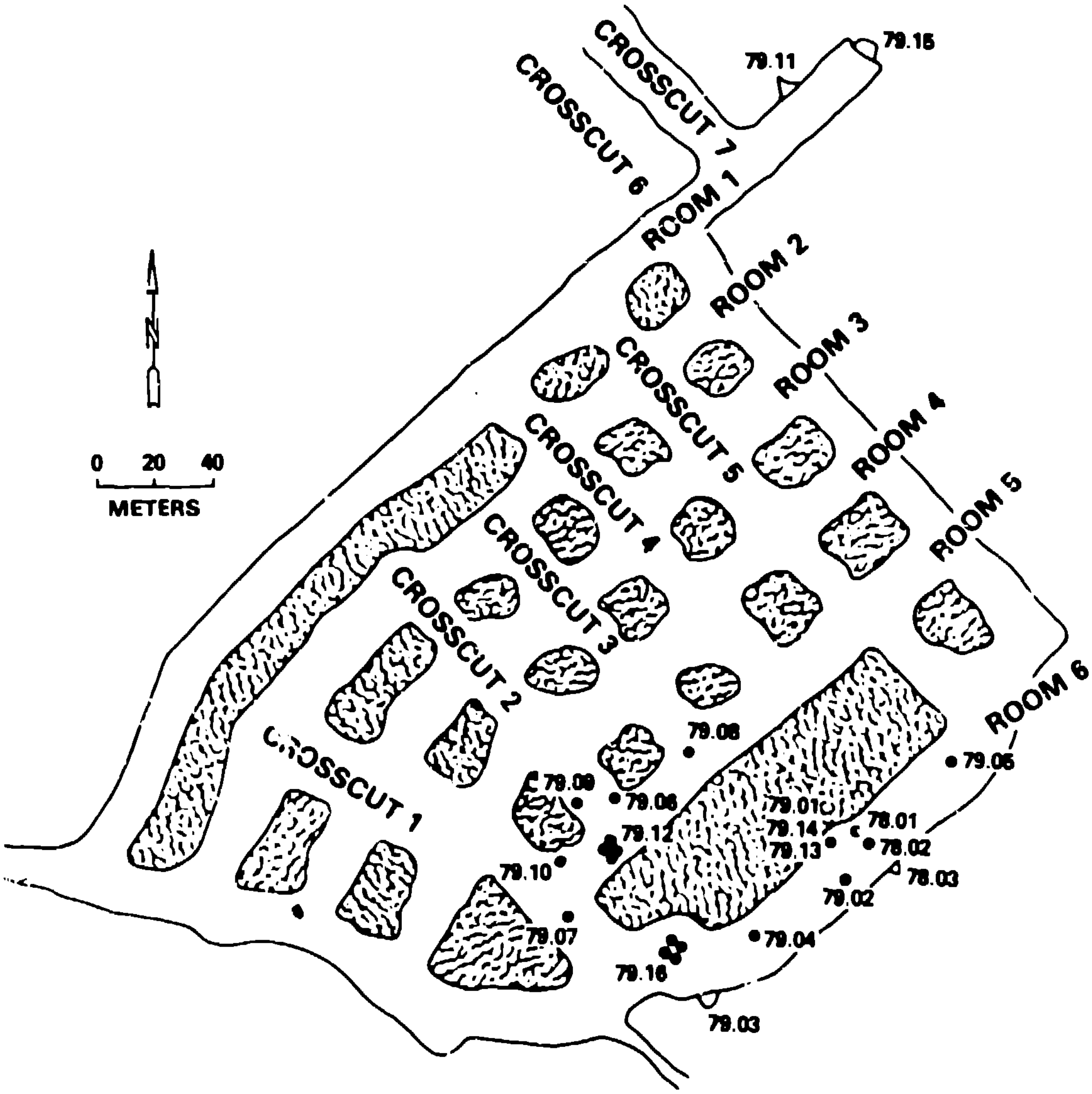

Fig. 8. Map of Colony Mine showing location of the intermediate scale experiments.

The larger fragments were screened by dumping the excavated rubble through three static screens. The remaining rubble that passed through the 26 cm (8 in.) screen was then run through a portable screening unit (Fig. 11), which contained three smaller screen sizes. Inclination toward slab-shaped fragments such as those formed by jaw, gyratory, or toothed-roll crushers (Baughman, 1978) was not apparent in any of the size ranges.

Certain experiments were excavated in progressive stages to allow separate treatment of the resulting data from zones within the crater interior. This procedure was introduced to specifically address concerns for rubble distribution (e.g., Berry, 1979) within the fragmented test bed. Zones identified during excavation of the Colony

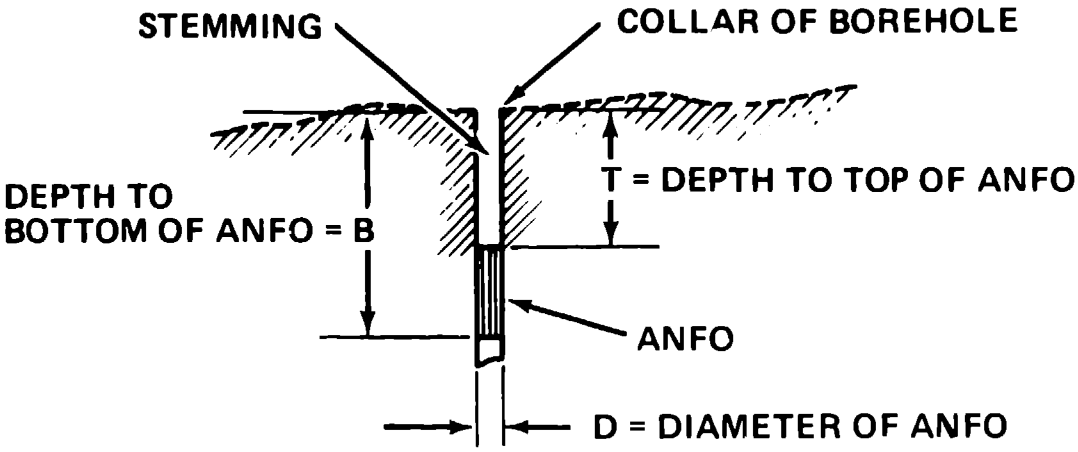

Fig. 9. Design parameters for single explosive borehole experiments.

Mine experiments can generally be categorized under one of the following: (1) fines immediately adjacent to the explosive charge (ANFO); (2) flyrock ejected from the crater; (3) surface spall above the crater but most often preserved at the crater periphery as surface heaving; (4) fractured and tumbled (or rotated) rubble remaining in the crater interior; and (5) the portion of the host bed which has

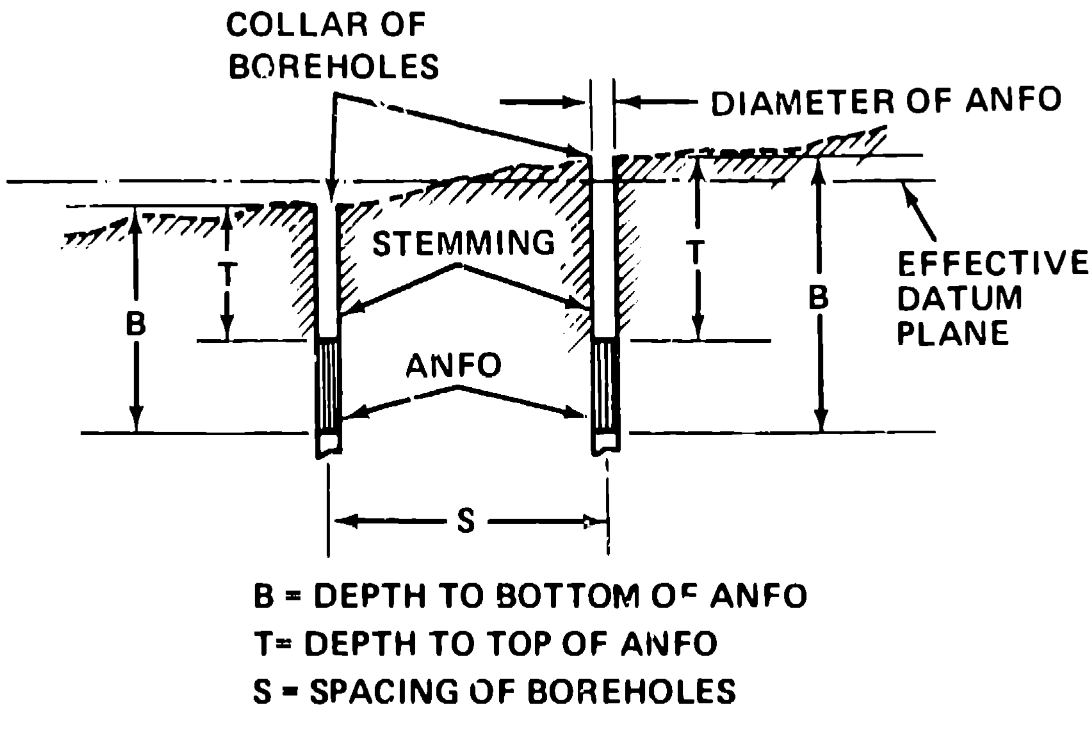

Fig. 10. Design parameters for four explosive borehole experiments.

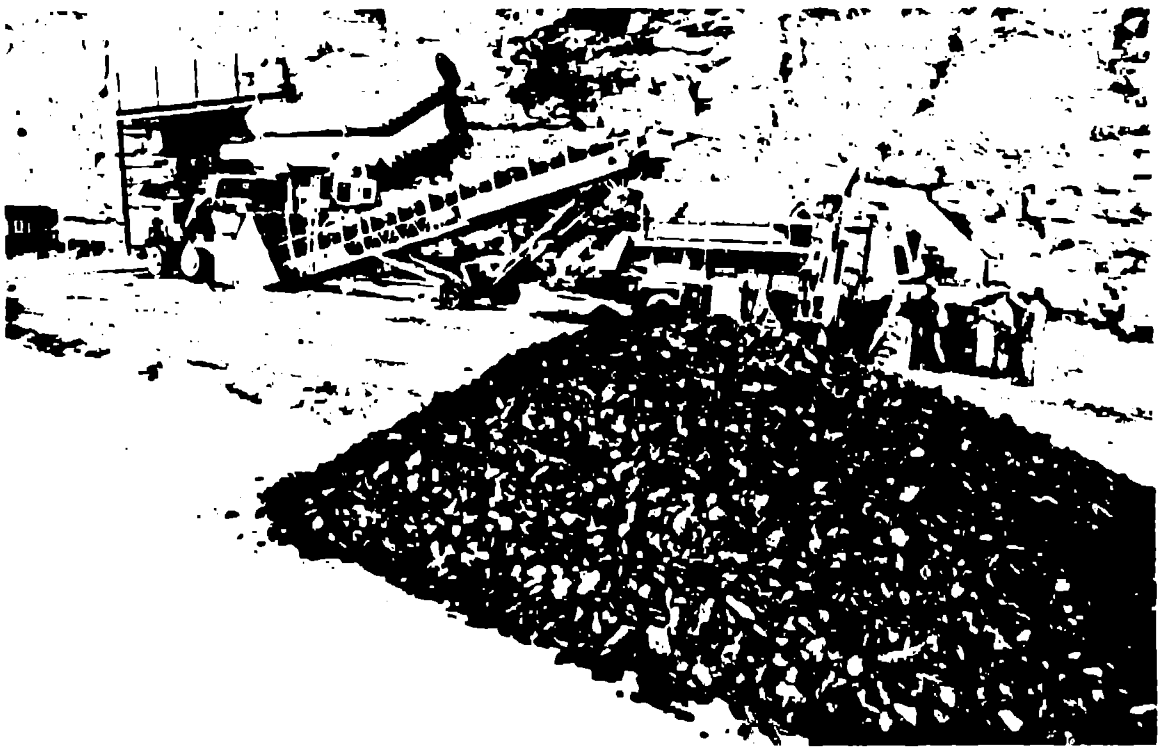

Fig. 11. Rubble screening operations using the portable screening unit outside the Colony Mine portal.

been fractured, but not rotated, and remains essentially in its original position. These zones are schematically illustrated, relative to a typical charge, in Fig. 12.

Adams and Keller (1982) performed a detailed comparison of crater damage on a single shot-hole experiment and a multiple shot-hole experiment. These experiments were performed at the Colony Mine and were designated 79.10 and 79.12 respectively. Adams and Keller concluded that the effect of having four charges, spaced in a square pattern as in experiment 79.12, did not appreciably increase the total extent of fracture, but rather the total volume of loose and tumbled rubble. Their conclusions were strongly influenced by a comparison of the crater profiles. The increase in total volume is to be expected, but inspection of the screen-size distributions for these two experiments reveals an interesting contrast. The screening data for 79.10 is plotted in Fig. 13 with data from two other single experiments for comparison. The curve for 79.10 shows an unusually high percentage of fines for a single borehole experiment. The screening data for 79.12 is presented in Fig. 14. The volume of rubble bounded by the four-hole pattern in this experiment was screened separately and, as expected, shows a significantly greater volume of fines than the rubble from the crater periphery. The percentage of smaller rubble produced in 79.10 compares best with the data from the center of the crater from 79.12. However this

SCHEMATIC OF RUBBLE ZONES IN TYPICAL CRATER

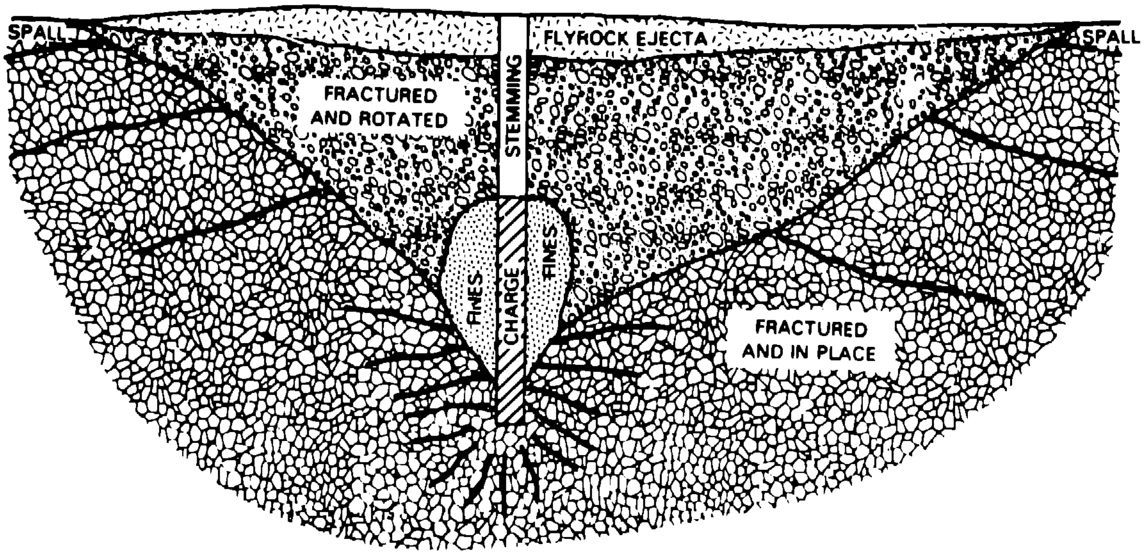

Fig. 12. Schematic of the zonal relation of rubble identified during crater excavations.

comparison for these two experiments is valid only for the screened rubble <5 cm. The 79.10 distribution for rubble greater than 5 cm is very similar to the other single borehole experiments.

The volume inside a four-hole shot pattern was treated differently on another experiment designated as 79.16. The rubble volume inside the pattern was subdivided into a zone above the top of the charges and a zone below the top of the charges. The data from this screening process, seen in Fig. 15, shows no appreciable change in the distribution of the rubble inside the pattern. The zones inside the multiple shot patterns on 79.12 and 79.16 appear to follow an approximate log-linear scale curve while the rubble external to the shot pattern can be approximated by a linear curve (Edwards et al., 1981). The difference in fragment-size distributions for zones inside and outside of multiple-shot patterns makes a significant statement about the influence of crater edge-effects on the rubble process.

One common basis for comparison of single and multiple borehole experiments is the scaled depth of burial (SDOB), the depth of burial divided by the cube root of the weight of the explosive. The SDOB values for 79.10 and 79.12 show the lowest values of all the experiments with screening data plotted in Fig. 16. This figure documents the relationship of SDOB to fragment size produced by explosive fracture in the Colony experiments. The plot integrates computed SDOB values from experiments for which there is screening data with

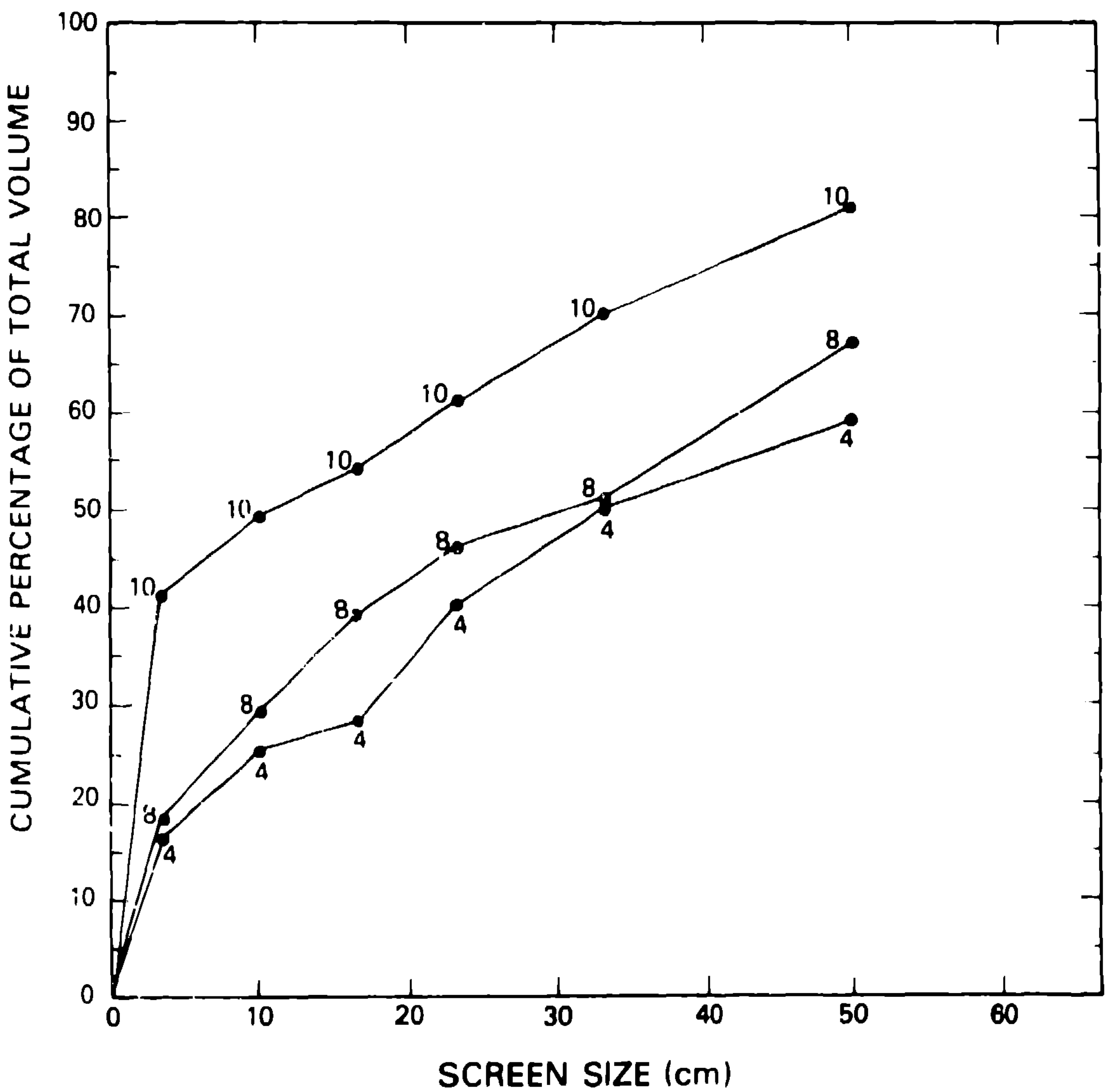

Fig. 13. Cumulative percentage of the volume of rubble screened from experiments 79.04, 79.08, and 79.10.

the resulting percentages for two extremes of rubble size. The explosive has a greater tendency to produce fines (<5 cm) with a correspondingly lower SDOB value. The percentage of large rubble (>45 cm) increases with those experiments having a larger SDOB value. The two rubble sizes considered in Fig. 16, bracket the range required for maximum extraction efficiency as determined by chemical kinetics and process studies (Schmidt et al., 1979). It is notable that these two curves intersect at 7.6 SDOB, slightly less than the value of 8.5 SDOB used as optimal depth (conducive to maximum crater volume) for the experiments, but within reasonable agreement. The relatively small overall change in percentage for either curve in Fig. 16 (∿20%) implies that pattern and spacing parameters may be more critical to rubblization than SDOB.

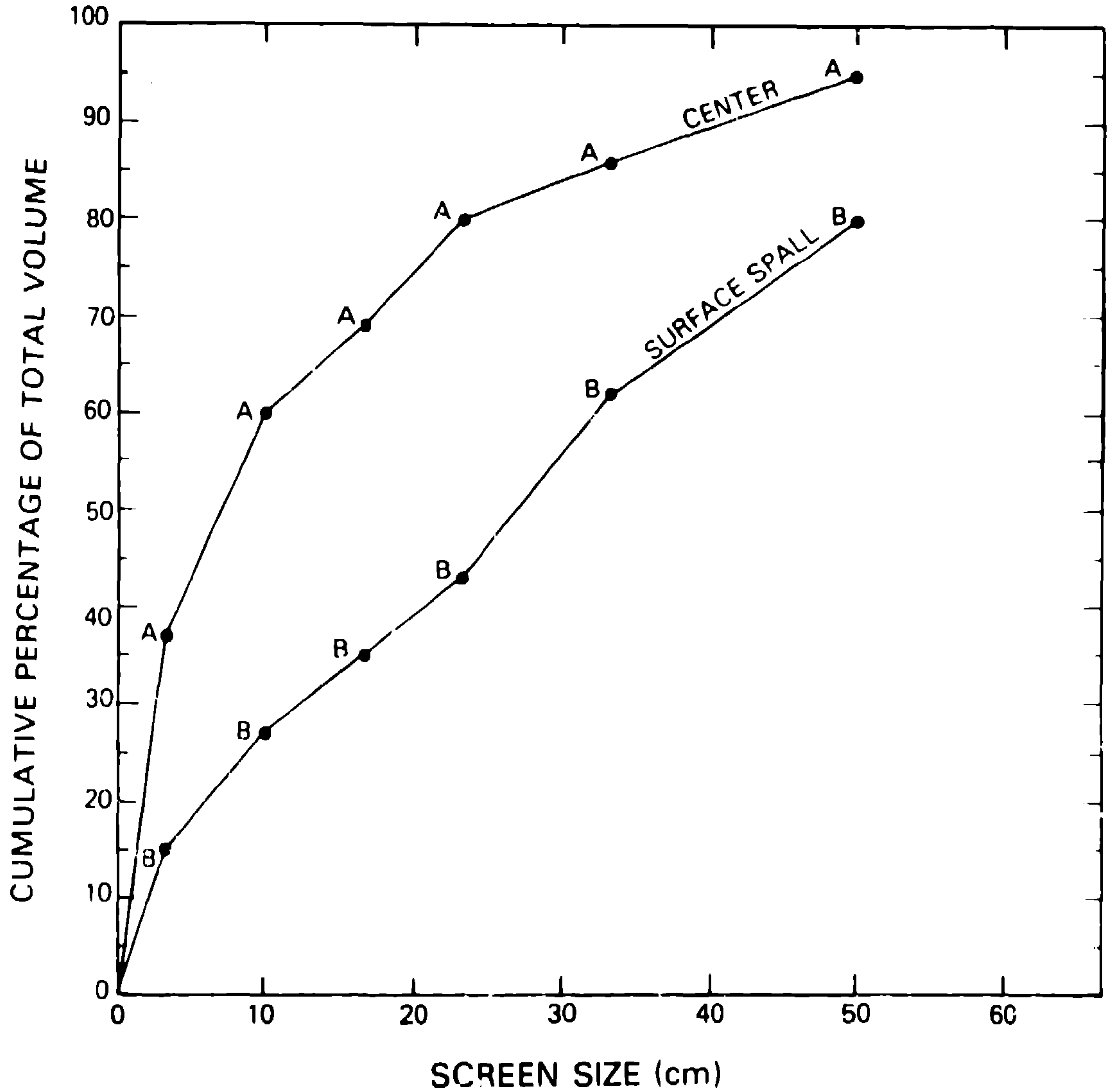

Fig. 14. Cumulative percentage of the volume of rubble screened for zones A (center) and B (surface) from experiment 79.12.

Geologic Influences

The geologic influences parallel the uncontrollable factors listed in Table 1 and may generally be considered either a stratigraphic or structural feature.

Principal stratigraphic influences include oil shale grade (kerogen content), inhomogeneities, bedding features, and vugs (voids). The stratigraphic variations in oil shale fracture properties must be understood if *in situ* rock fracture is to be controlled and optimized for specific processes. Olinger (1977) reported wave velocities for five propagation modes relative to the bedding orientation through Green River oil shale. The velocity data demonstrated considerable

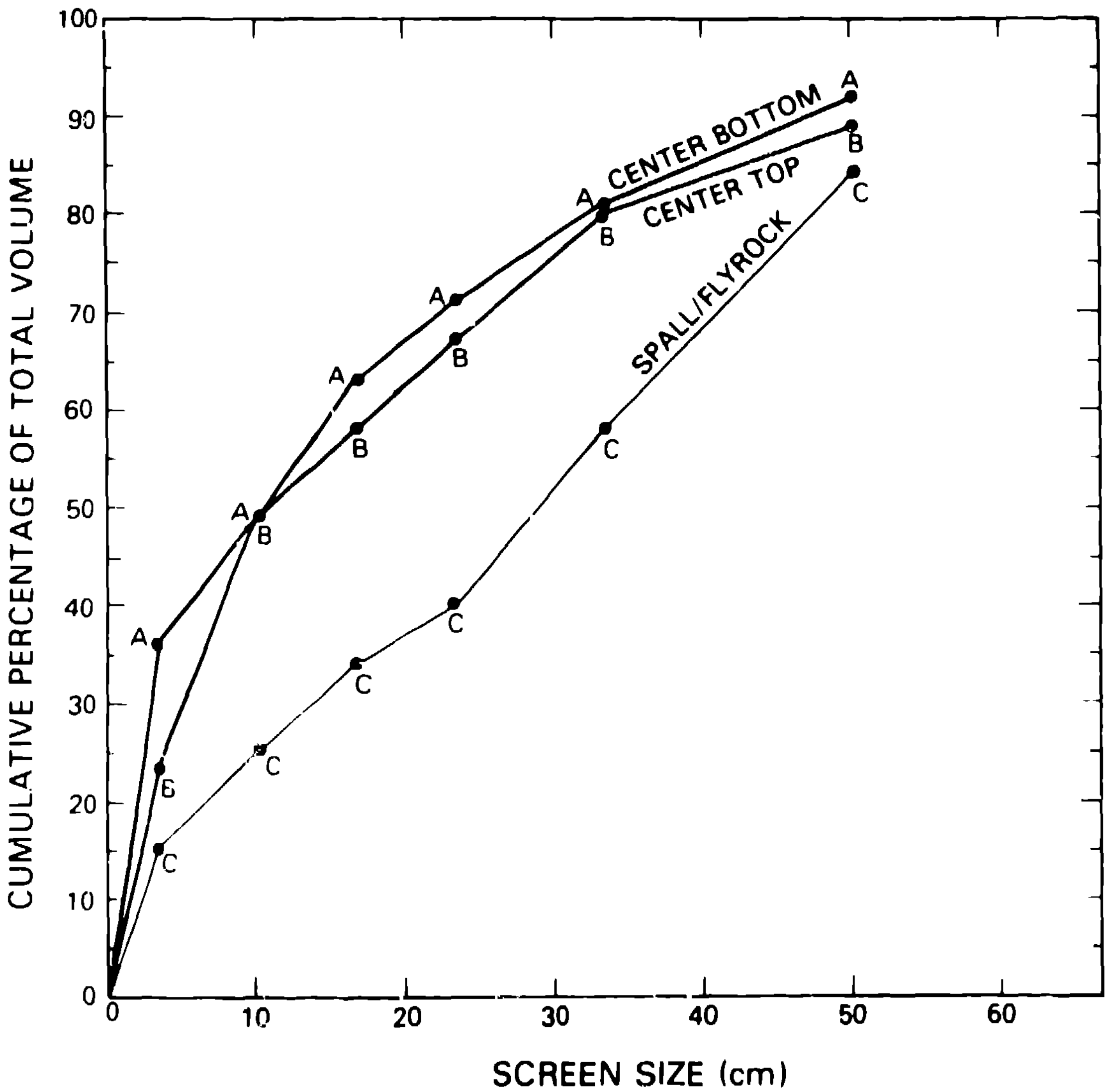

Fig. 15. Cumulative percentage of the volume of rubble screened for zones A, B, and C (as labeled) from experiment 79.16.

dependence on the oil shale density and documented the nontransverse isotropic nature of the shale. The density is sensitive to the kerogen content, or oil yield (Smith, 1976 and Trent et al., 1981), as seen in Fig. 17. Young and Smith (1979) caution that this variability underscores the risks that re taken when rock, and particularly oil shale, is treated as a homogeneous isotropic engineering material in the design and analysis of field experiments. This concern is reiterated by Adams et al. (1981) and Margolin (1981) regarding its impact on predictive computer modeling of fracture. In each case, the detailed assessment of site-specific geologic parameters is advocated.

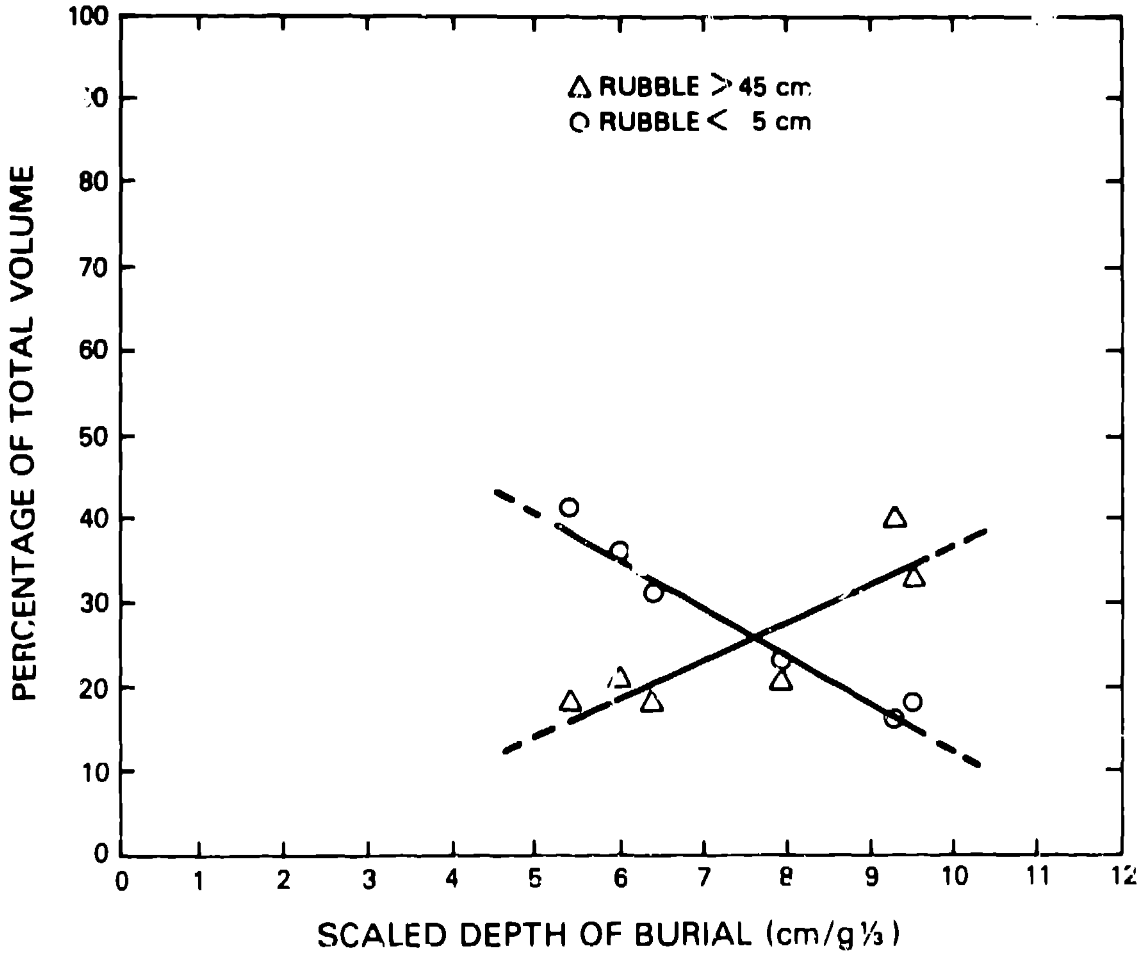

Fig. 16. Relationship of fragment sizes <5 cm and >45 cm vs scaled depth of burial (a critical shot design parameter).

Experiment 79.02 in the Colony Mine presented a unique opportunity to observe the influence of oil shale grade on fracture frequency. Cores were retrieved during site characterization prior to execution of the experiment and again after the single borehole charge had been detonated. The postshot cores were possible because extensive rubblization and cratering did not occur on this experiment. The relative location for cores 1 and 2 with respect to the shothole are presented on the site schematic in Fig. 18. The histograms in Fig. 19 allow comparison of the frequency distribution of interval lengths of competent, or unbroken, core from each of the four core holes. Similar information is presented in Fig. 20 that graphically shows the lengths of competent core relative to cumulative percentage. The data plotted in these two figures disregards oil shale grade. Since the Fisher Assay grade analyses were determined from core site 2, the postshot core fractures at that site were tabulated and the frequency was plotted relative to grade as seen in Fig. 21. Several fractures logged in the core were obviously associated with inhomogeneities, sedimentary structures, and/or lithology changes but their occurrence

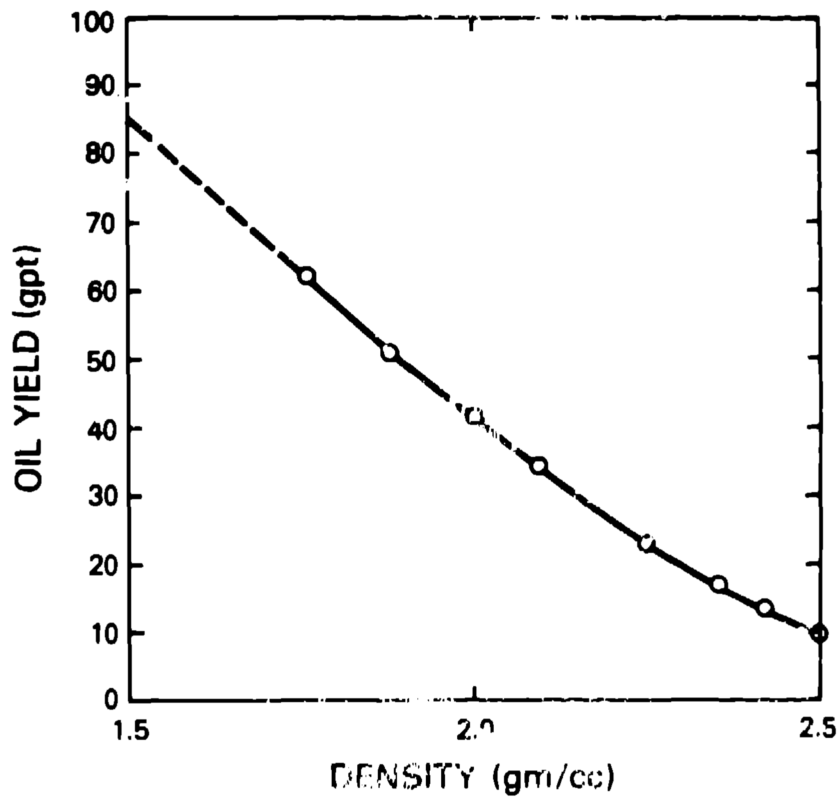

Fig. 17. Graphical illustration of interdependence between density and kerogen content (data from Smith, 1976 and Trent et al., 1981).

was relatively infrequent. The largest values of fracture frequency correspond to the lowest grades of oil shale. The same data from postshot core 2 is presented differently in Fig. 22. A percentage of the total sample of fractures represented by this core may be compared directly to any specific oil shale grade identified at this site. The curve shows, for example, that shale with a grade of 167 ℓ/tonne (40 gallons per ton) or greater contained approximately 12% of the total number of fractures logged in this core. Although Fig. 22 is site specific it documents the relationship of oil shale grade to fracture propensity.

Mineral lined voids, known as vugs, were also influential on the 79.02 experiment. Two vug zones were identified in the core and during the grouting process. The interpreted position of the two zones is illustrated in the schematic cross section in Fig. 23. Communication between holes by way of the vug zones was noted during grouting operations. The void characteristic of a vug does not necessarily represent a problem to siting explosive experiments. However, the fracture permeability channels frequently associated with vugs (shown in Fig. 24) can greatly influence the role played by the high pressure gases produced from the explosive. Careful excavation of experiment craters has provided evidence that the zone

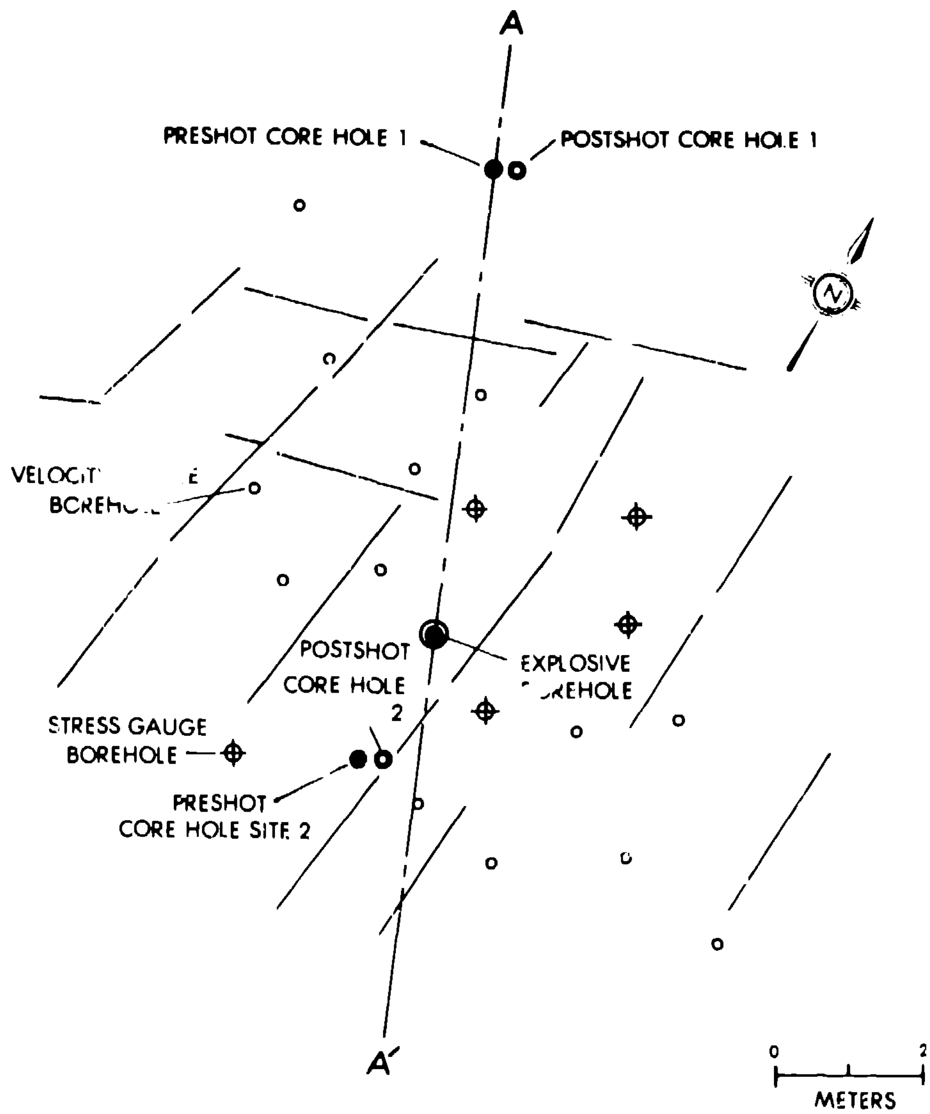

Fig. 18. Plan view of experiment 79.02 site with borehole locations. Dashed lines schematically indicate the primary joint pattern identified at this site.

of effective rubblization (i.e., rotated and tumbled fragments) closely coincides with the region of gas penetration. It is probable that the vug zones, especially the upper zone, channeled the explosive energy from the shothole in 79.02. Two points of evidence for energy dissapation through the vug zones are: (1) no crater was formed by this shot which had a relatively low SDOB value of 7; and (2) significant increases in the frequency of horizontal fracture occurred at the 5 m and 10 m depths in both core 1 and core 2. Although this increase is possibly due to the effect of late time gas drive (Craig et al., 1981), it is more likely a product of the two vug zones which correspond to those depths.

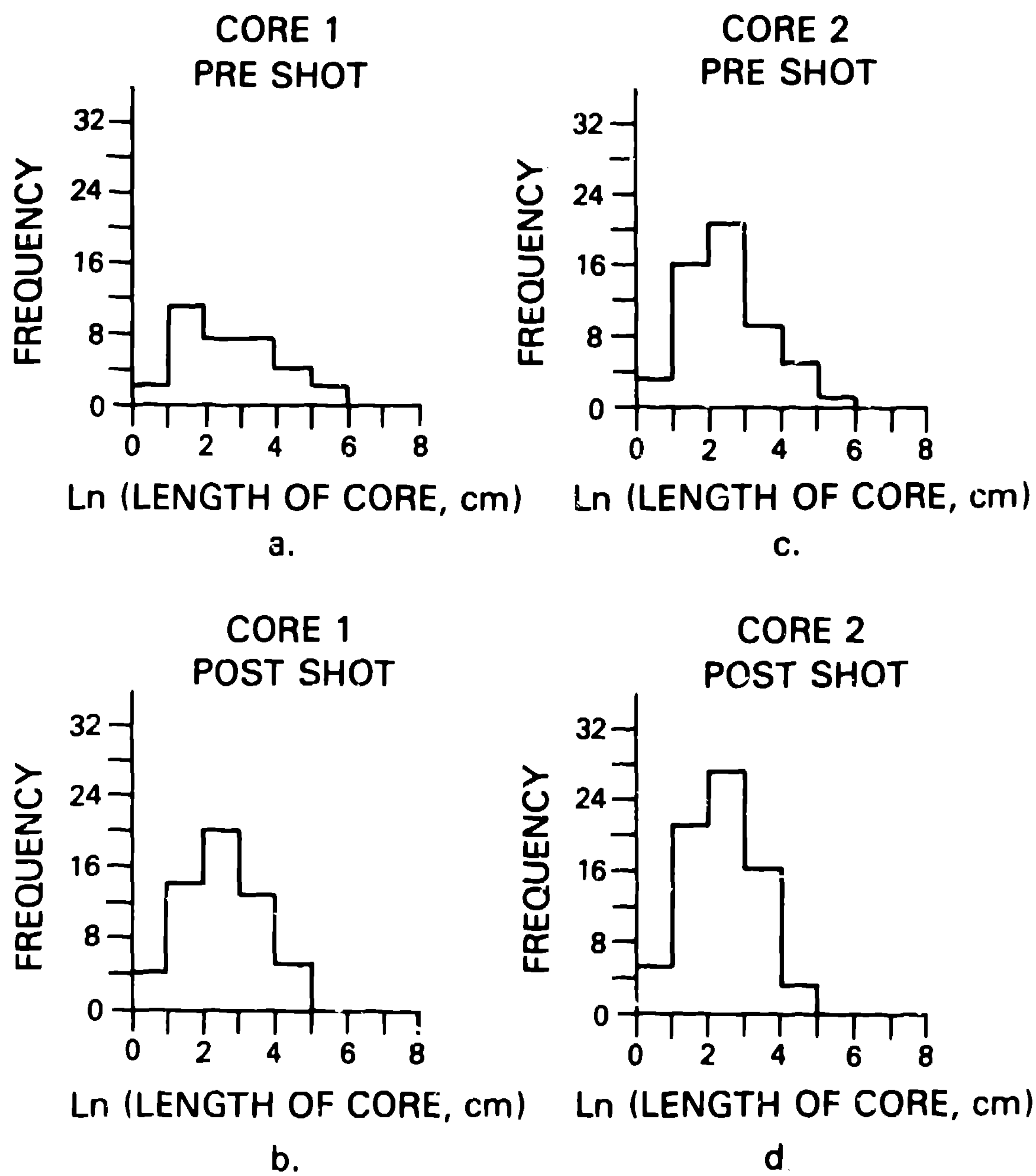

Fig. 19. Histograms showing frequency of various lengths of competent core from four core holes on experiment 79.02.

Influence of geologic structures on the Colony Mine experiments was dominated by joint systems. Two major joint sets are present in the Colony Mine and generally strike NW and NE consistent with other sections of the Green River Formation. Both joint sets appeared to be tight but normally showed signs of being water transmissive. This evidence for joint permeability is particularly important when considering the scenario of gas drive and its contribution to the

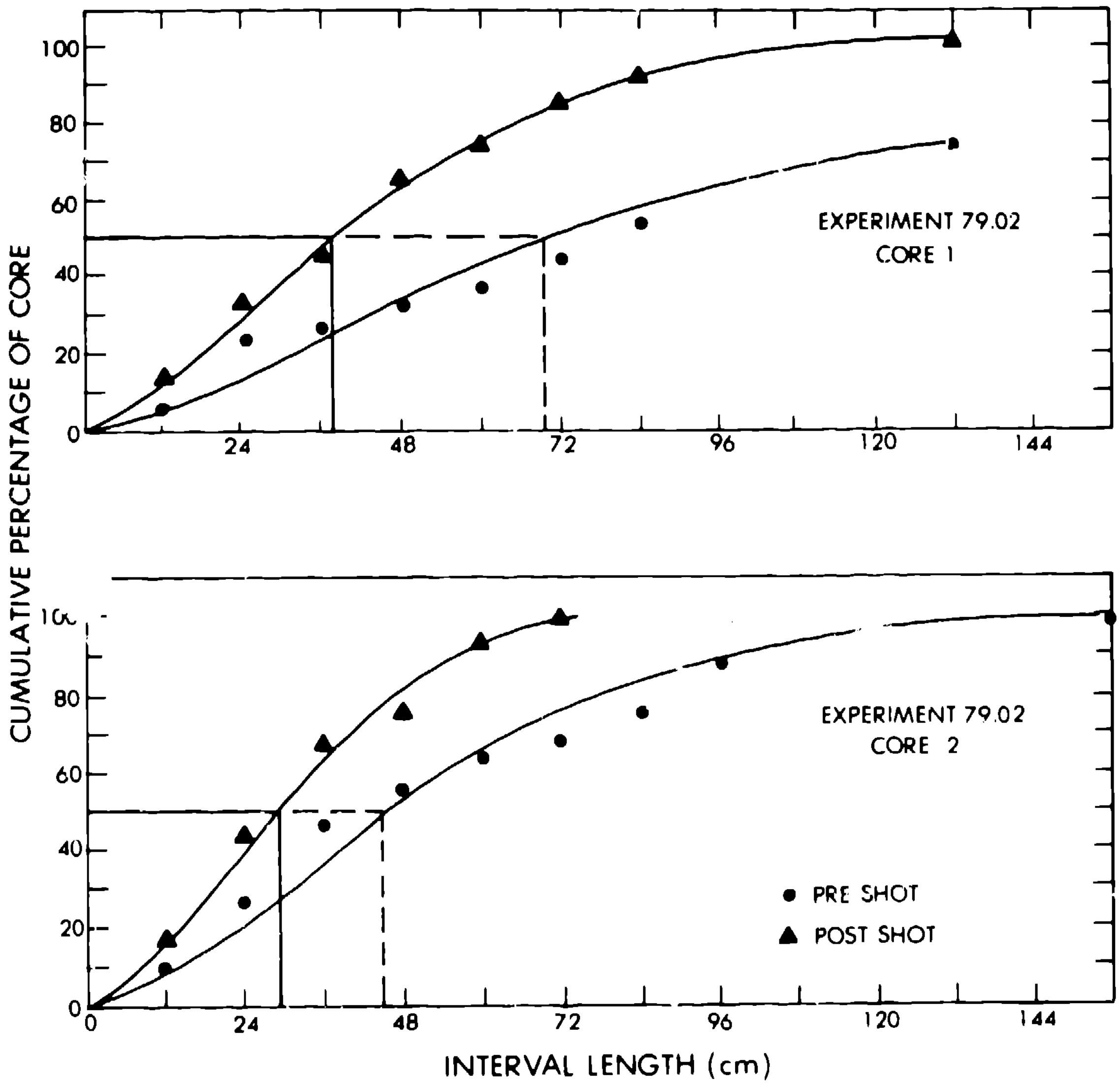

Fig. 20. Differences in cumulative percent of preshot and postshot core for experiment 79.02.

fracturing process. The mineralization or volcanic tuff occasionally observed in the joints gives evidence of previous voids.

Experiment 78.01 was exhaustively investigated for postshot fractures to determine the general trends expected for the Colony Mine experiments. The histogram in Fig. 25 displays the azimuth frequency distribution for those measured fractures. This figure quantifies the tendency toward specific fracture orientations with respect to strike but does not consider dip components. The planar faces and fractures in the 78.01 crater interior that survived the explosive detonation were measured for strike and dip. This data was needed to provide information regarding the survivability of joints and their contribution to rubblization. One approach considered fragmentation

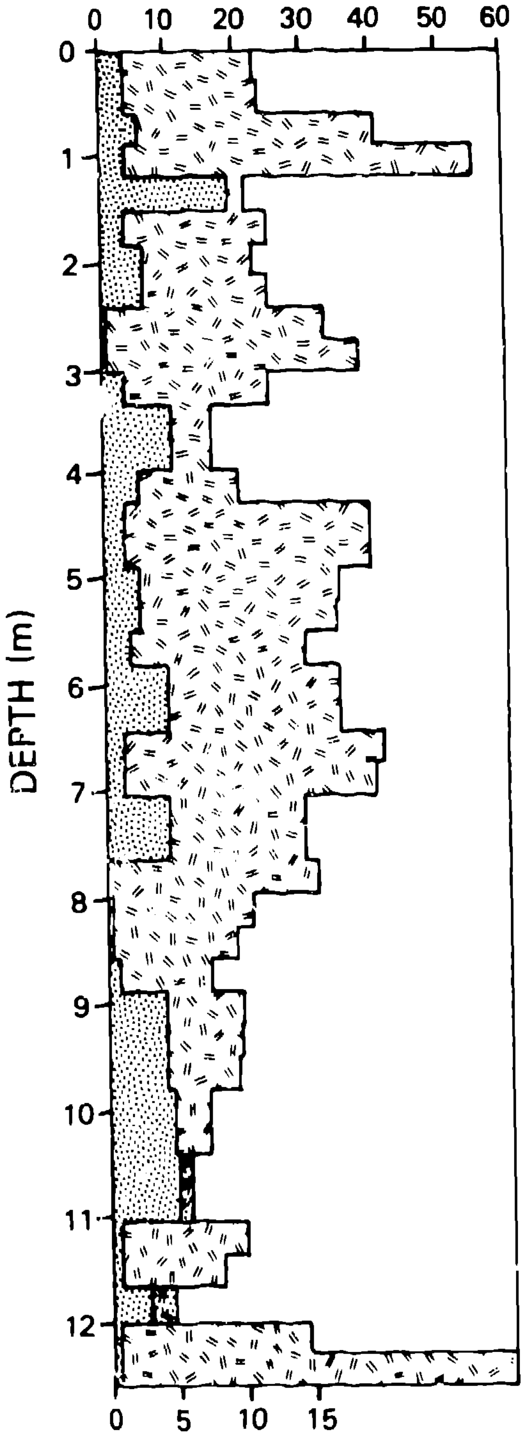

Fig. 21. Fracture frequency relative to oil shale grade from core site 2 on experiment 79.02.

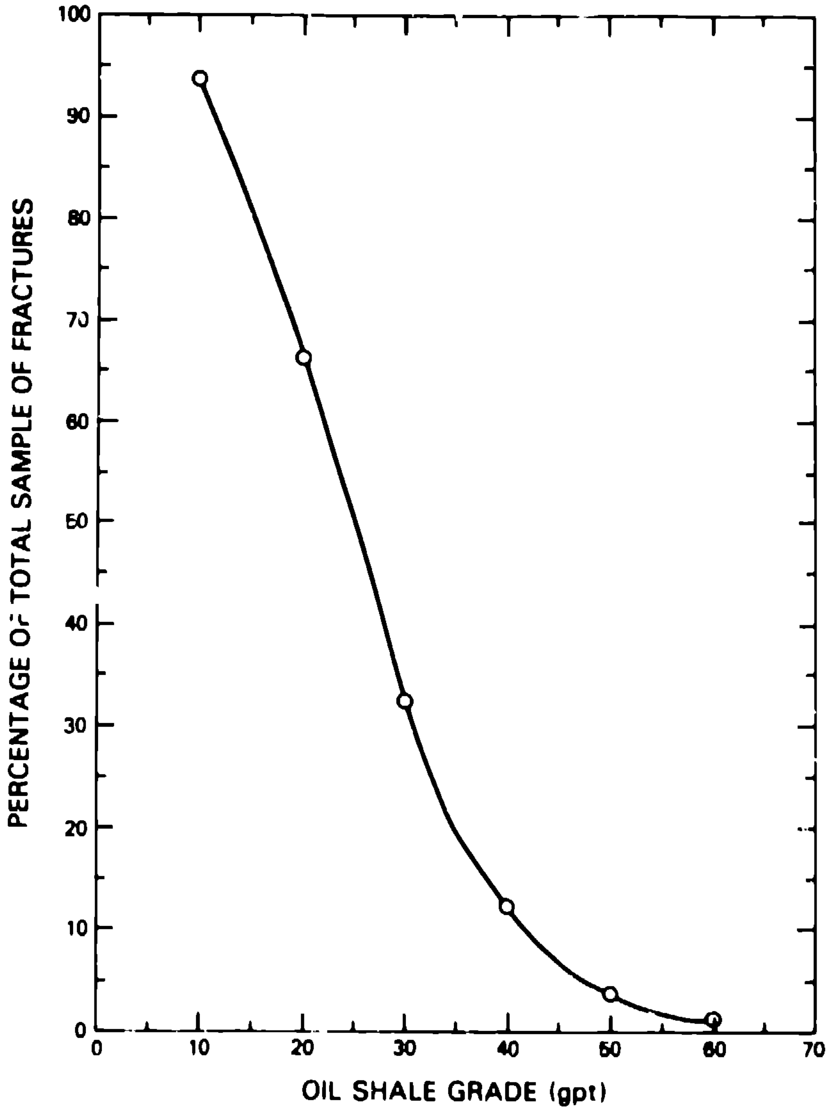

Fig. 22. Relative percentage of the total fractures logged compared to specific oil shale grade values for postshot core 2 on experiment 79.02.

results to be greatly influenced by bedding planes and to occur irrespective of the natural joints which would be subjected to overpowering effects of the explosive. However, inspection of the resulting rubble found very few fractures along the bedding planes and most often the breaks were high angle with respect to bedding (consistent with the joint geometry).

To address the influence of the three-dimensional joint orientation, inclusive of strike and dip, a polar plot was constructed on a stereo net. The polar plot in Fig. 26 represents density contours of polar axes perpendicular to both the dip and the strike of the

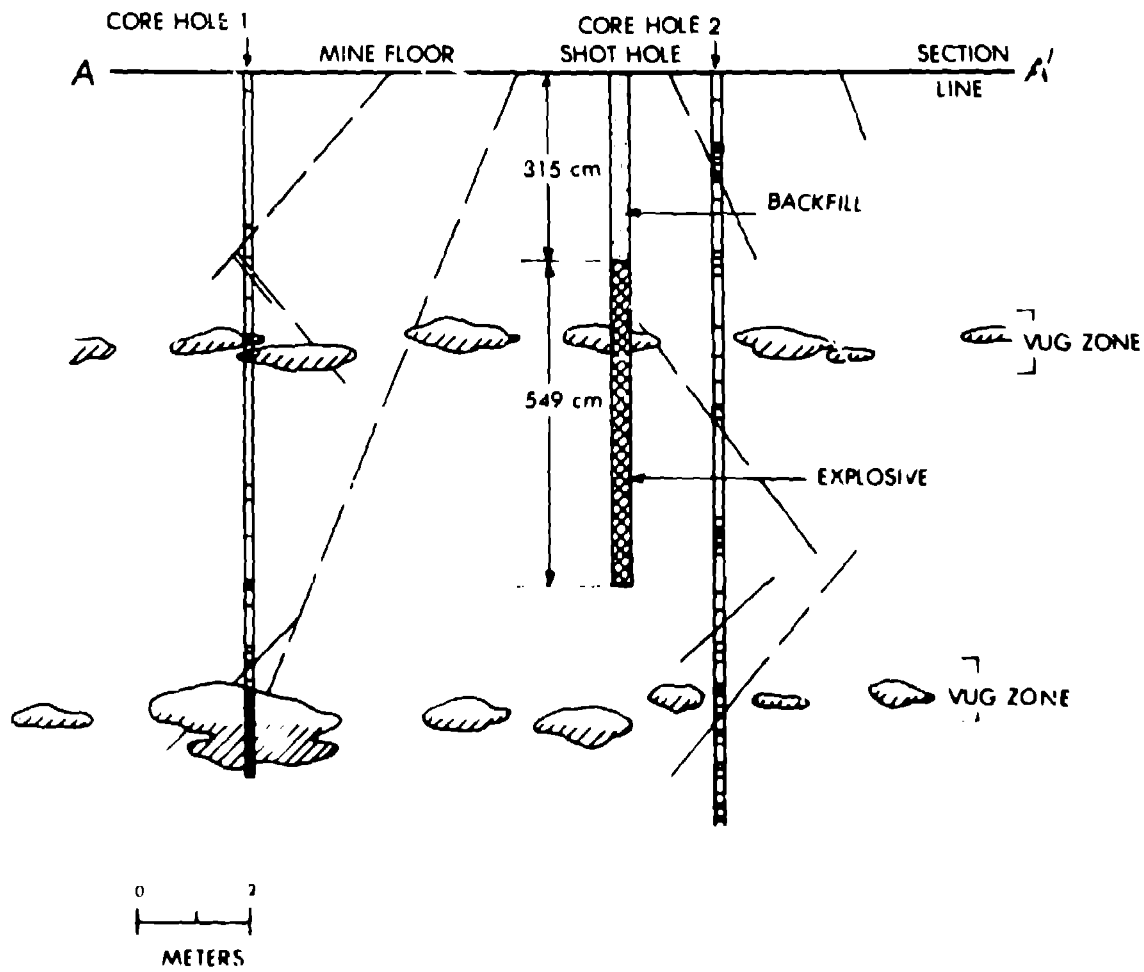

Fig. 23. Schematic cross section of experiment 79.02 illustrating the interpreted positions of two vug zones and several major joints.

joints. The plot documents the small percentage of fractures contributed by bedding planes represented by the small domain at the center of the diagram. This provides a significant window of information to computer modeling efforts by: (1) quantifying relative percentages of fracture orientation from a field verification experiment; and (2) dispelling the role incorrectly assigned to bedded cracks in the fragmentation process. The edge of the stereo net equates to verticality in the joints and the contours show the prominence of steeply dipping angles in the joint systems. Although the major joint set is considered to be the one striking NE, the polar plot gives evidence that the conjugate NW set survives the explosive much better. The NE joints tend to show greater continuity laterally but are fewer in number while the NW joints tend to be more numerous but discontinuous and subject to capture by the NE set. The specific influence of joints on crater symmetry is discussed in the section on explosive/rock interaction.

Fig. 24. Extensive permeability channels frequently associated with vugs were observed in the rib of room 5 at the Colony Mine.

Stability

Stability problems in MIS technology are formidable. There is an urgent need for preventing, or at least predicting, the onset of instability of single retorts and retort clusters during formation, processing, and abandonment. Thermomechanical effects include temperature and shrinkage, long-term creep, and fracture (Morris, 1982). Additional factors are retort geometry, amount of overburden, the presence of shale rubble in the cavity, stratigraphically sensitive physical properties, and retorting temperatures (Miller and Costin, 1981). Increases in the lengths of retorts and/or the rates of retorting will result in closer spacing of retorts and, therefore,

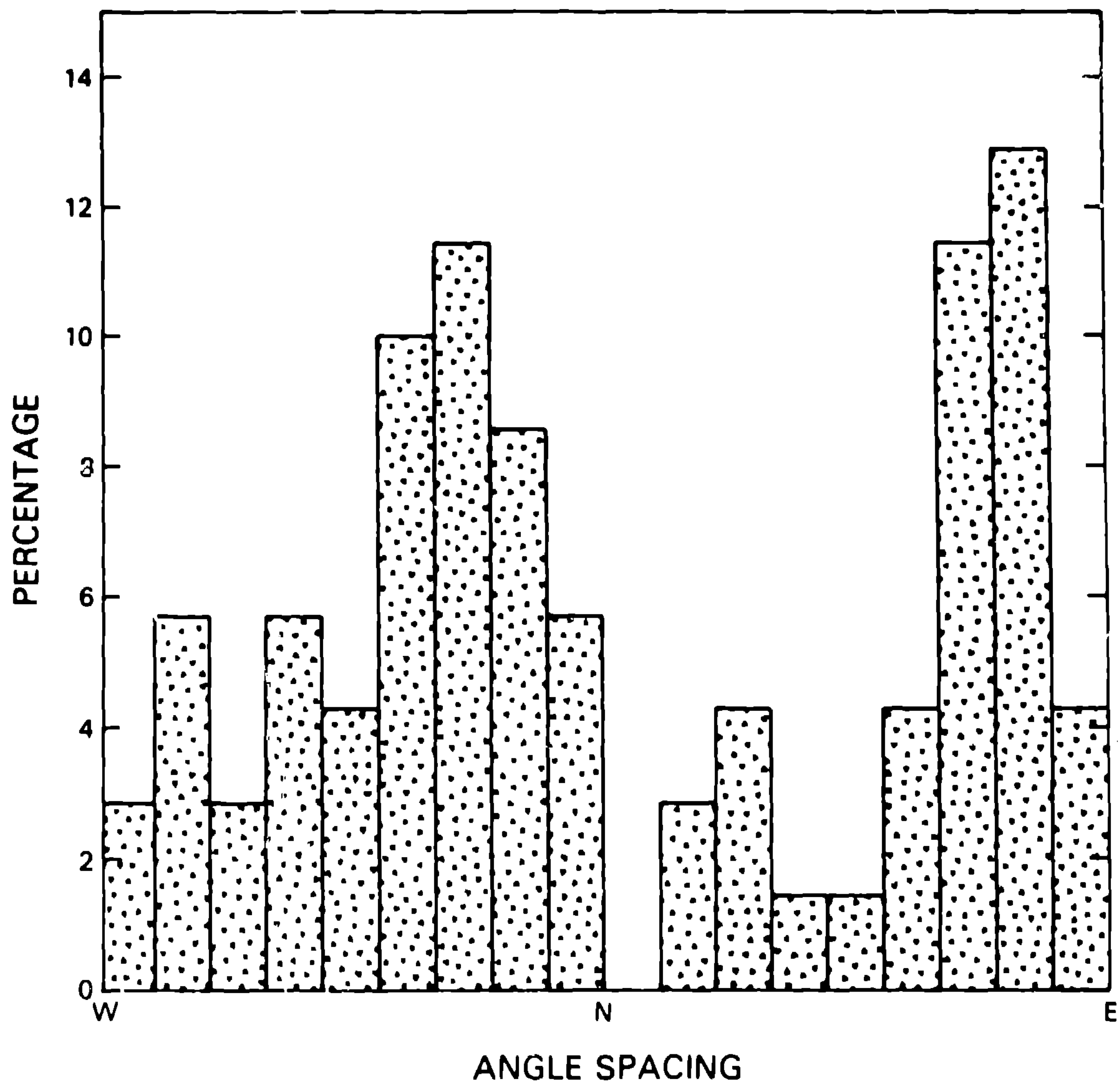

Fig. 25. Azimuth frequency distribution histogram for crater features mapped in the post-excavation crater from experiment 78.01.

have a commercially economic impact (Penner, 1981). Unfortunately, closer spacing of the retorts increases the probability of fracture propagation between chambers and resulting instability.

Process control is a key element of MIS technology that would suffer from retort communication through fractures. Combustion control is critical to the overall retorting process and would be adversely effected by retort communication. Combustion is normally controlled by simply shutting off the air inlets (Kilker, 1981). Primary factors to the containment of process gases were itemized by Ridley (1978). Five of those factors, listed here, have a close relationship to site geology and the design of blast patterns: (1)

head sill pillar at the Occidental retort #6 was a case example of >20% resource loss (McDermott, 1980) due to instability. The collapse resulted in a large redistribution of flow during processing (Campbell et al., 1981) and greatly inhibited the sweep efficiency.

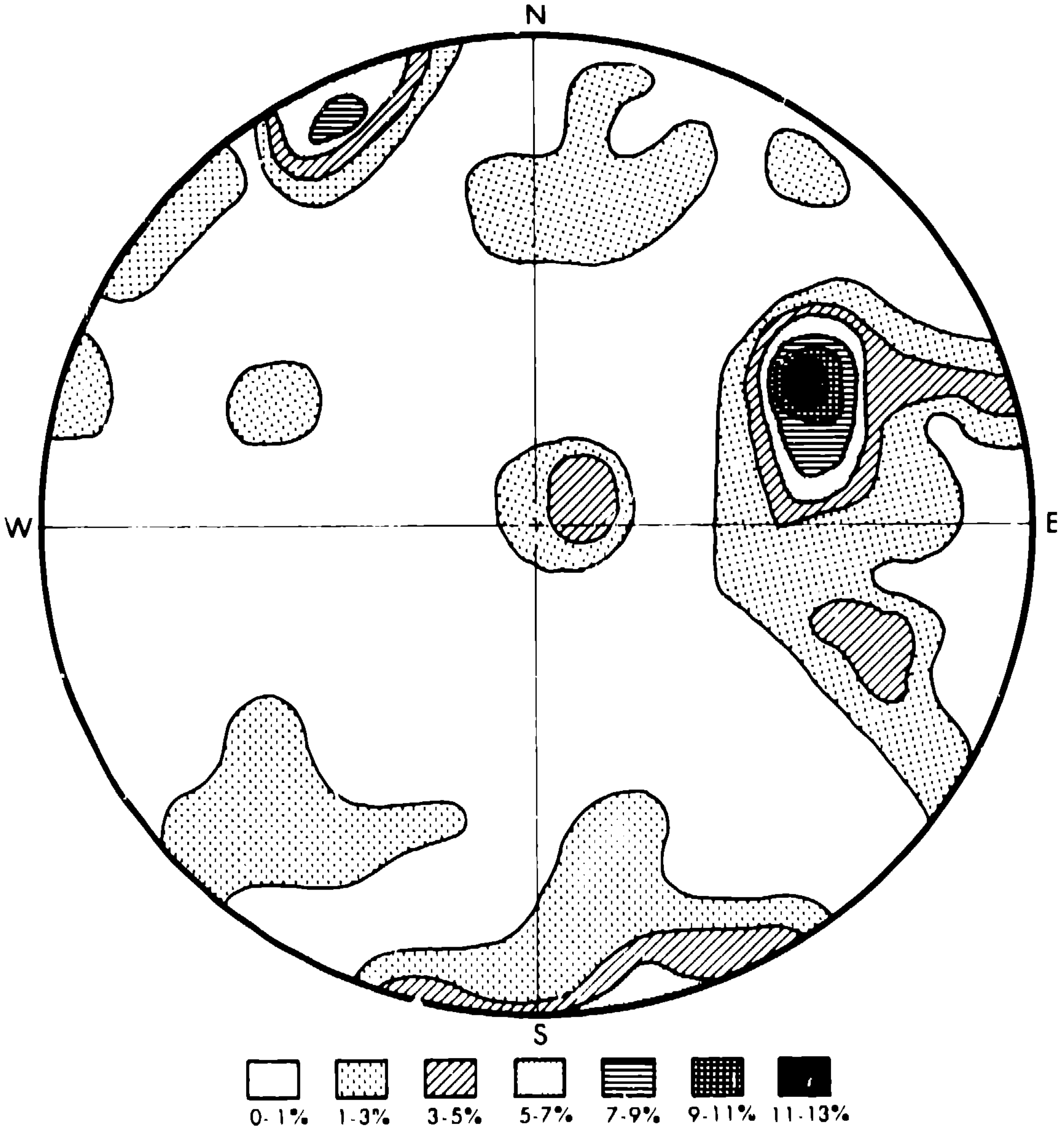

Fig. 26. Experiment 78.01 polar plot presenting point density contours of polar axes perpendicular to both the dip and the strike of the features mapped in the crater.

Special attention to blast parameters that produce minimal damage to the retort walls and ceiling are critical.

Safe operation will depend on the ability to maintain retort integrity and isolation for close retort spacing. The process gases contain large amounts of CO and H_2S, which could be lethal if significant flows occur into occupied mines. Strengthening abandoned retorts is desirable because of the potential long-term effects of acquifer communication with spent shale. The high concentrations of organic and inorganic materials that could occur in acquifers or surface streams may be toxic or carcinogenic (Persoff and Fox, 1979).

The Colony Mine experiments provided insight to certain aspects of rubble bed preparation that could ultimately jeopardize the stability of the retort chambers. A combination of low scaled depth of burial and proximate siting near a pillar for experiment 79.10, induced a partial pillar collapse near the experiment. Other experiments exhibited extensive fracture propagation beyond the crater periphery. Single shothole experiments drove fractures up to 3 depths of burial (DOB) laterally away from the charge. Multiple shothole experiments produced mappable fractures as far away as 6 DOB. The fractures usually were extensions of major joints and frequently penetrated adjacent ribs and pillars. Cooper and Blouin (1971) noted similar phenomenology where joint controlled failures of the _in situ_ rock mass occurred well beyond the cratering region in quartz diorite. So this type of extensive crack propagation beyond immediate crater damage is not unique to the Colony Mine and requires consideration in retort design and spacing. Agapito (1972) noted that specific roof falls and failures in the Colony Mine pointed to combinations of blasting shocks and adverse geology. Both of these problems may be approached within the scope of current technology.

Several measures may be prescribed to prevent, or at least improve, potential stability problems. The remedies are not exclusive, but include the following: (1) pre-split blasting to minimize pillar spall and slabbing; (2) kerfing, pre-split, or similar techniques to decouple confined volumes destined for rubblization; (3) judicious spacing of retort chambers to prevent partition collapse; (4) exhaustive site characterization efforts inclusive of geology, geophysics, and rock mechanics; and (5) orientation to minimize the effect of the major joint direction and to take advantage of the stress field.

Explosive/Rock Interaction

Agapito (1972) presented interpretations of overcoring data and concluded that the maximum principal stress was only 11.5° from the vertical. The intermediate stress was parallel to the major joint system and the minor stress was closely oriented to the conjugate joint system. He concluded that pillar orientation should be done on the basis of geology because the horizontal field stresses are small. The Colony Mine experiments consistently provided evidence of joint control on crater features. This evidence indirectly suggests the influence of *in situ* stresses on fracture propagation and crater growth. Two difficult problems are defined from the experimental results: (1) how to weigh the qualitative observations made during postshot site investigations; and (2) determining the magnitude of the influence that change of site-specific parameters may have. To resolve these problems, additional experiments are needed.

Certain crater features were noted to occur in consistent relationships with respect to the shothole. Some of these features were proximate to joints and, therefore, believed to be a product of the phenomenology associated with the joint systems. Postshot site characterization revealed that the three possible geometric orientations of joints, with respect to the shothole, resulted in three distinctly different dynamic responses to the detonation energy. These three orientations were: (1) joints that penetrated the shothole; (2) joints not penetrating the shothole and dipping away from the charge with depth; and (3) joints not penetrating the shothole and dipping toward the charge with depth. The joints penetrating the shothole generally showed little evidence of survival in the crater except at the edges, again underscoring the role of edge effects. The joints in this configuration were normally the ones showing extensive propagation, up to several depths of burial, beyond the crater periphery. Joints in the second configuration (dipping away with depth) were oriented approximately normal to the shock wave that propagates with conical symmetry from a bottom-detonated cylindrical charge (Johnson et al., 1977). This orientation resulted in truncation of the planar face of the joint and formation of terraces conformable with the bedding planes on the opposite side of the joint from the explosive charge. Joints in this configuration greatly inhibited the detonation energy and crater growth in that direction. Joints in the third configuration (dipping toward the charge with depth) provided natural slip faces for rubble release. Figure 27 shows the preferential throw of rubble from two rib experiments in room 1 of the Colony Mine. This phenomenon of directed flyrock was also observed on video monitors and postshot mapping of floor experiments. Figure 28 presents a plan view profile of experiment 79.03 and the major joints mapped and cored at that site relative to the shothole. These same joints were shown penetrating the ceiling (back)/rib interface in Fig. 7. The rubble dispersal ($\sim$118 m^3) and resulting crater was exemplary of joint control on crater features. But more importantly, these three configurations and the associated features were exhibited in the same relationship on both rib and floor experiments independent of the bedding orientation. The dynamic response of the joints in these three geometries should be considered carefully in shot design.

Radial fracturing near the charge was observed frequently on the experiments during crater excavation. The radials were noted to have limited continuity and were normally captured (terminated) by natural joints. They probably contributed little to the fragmentation process except toward fines immediately adjacent to the explosive

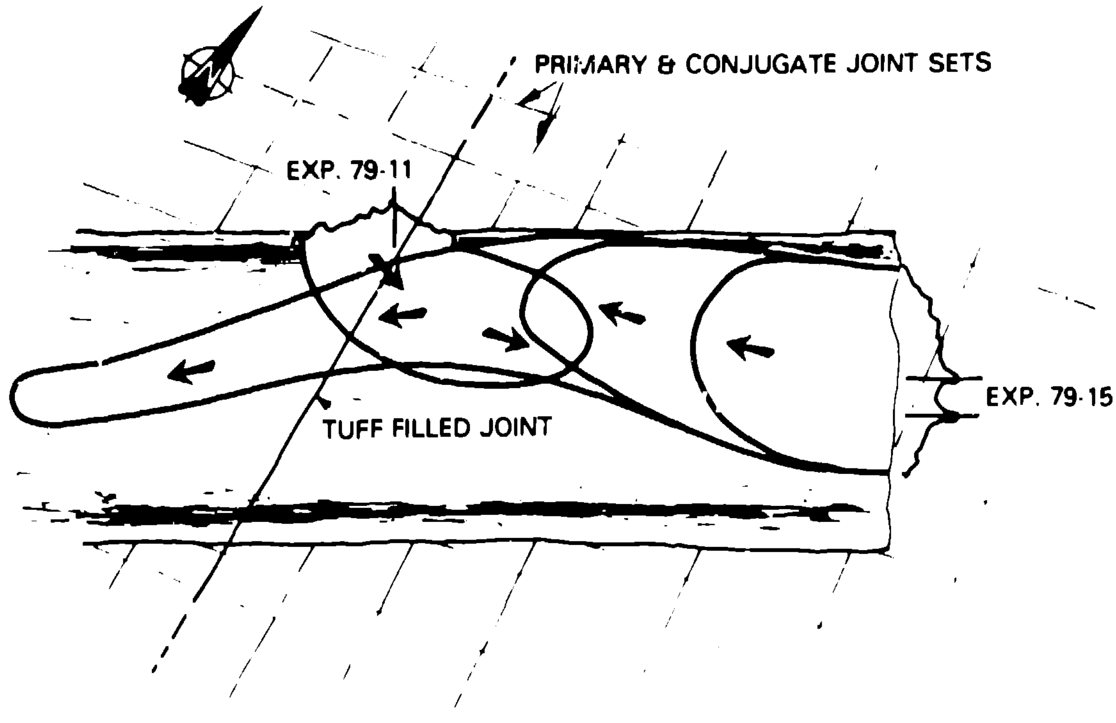

Fig. 27. Conceptual distribution and direction of rubble from two rib experiments in room 1 of the Colony Mine. Rubble was preferentially dispersed from the craters in a direction parallel to the major joint system.

charge. The radial fractures were categorized as a remnant feature of the rock/explosive interface.

Young and Smith (1979) cited tensile strength data for breakage on planes parallel to the bedding and concluded that natural parting planes and zones of low tensile strength could play a dominating role in rock breakage during *in situ* fracturing experiments. The compressive pulse of the shock wave interacts with the free surface and reflects in a downward-moving tensile relief wave (Adams, 1982). Significant fracture occurs during the initial propagation of the shock wave toward the free surface. The reflected tensile relief wave occurs in a favorable geometry to take advantage of the tensile weakness of the shale that was documented by Young and Smith. However, evidence for tensile fracture concordant with bedding orientations in the Colony Mine experiments occurred only near the free surface. The relative number of fractures mapped that were attributed to tensile rebound was small and categorized as surface spall.

The oblique nature of the shock wave propagation leads to flexure of the oil shale bed and development of shear stresses (Parrish et al., 1980 and Adams, 1982). Shear fractures were mapped in several

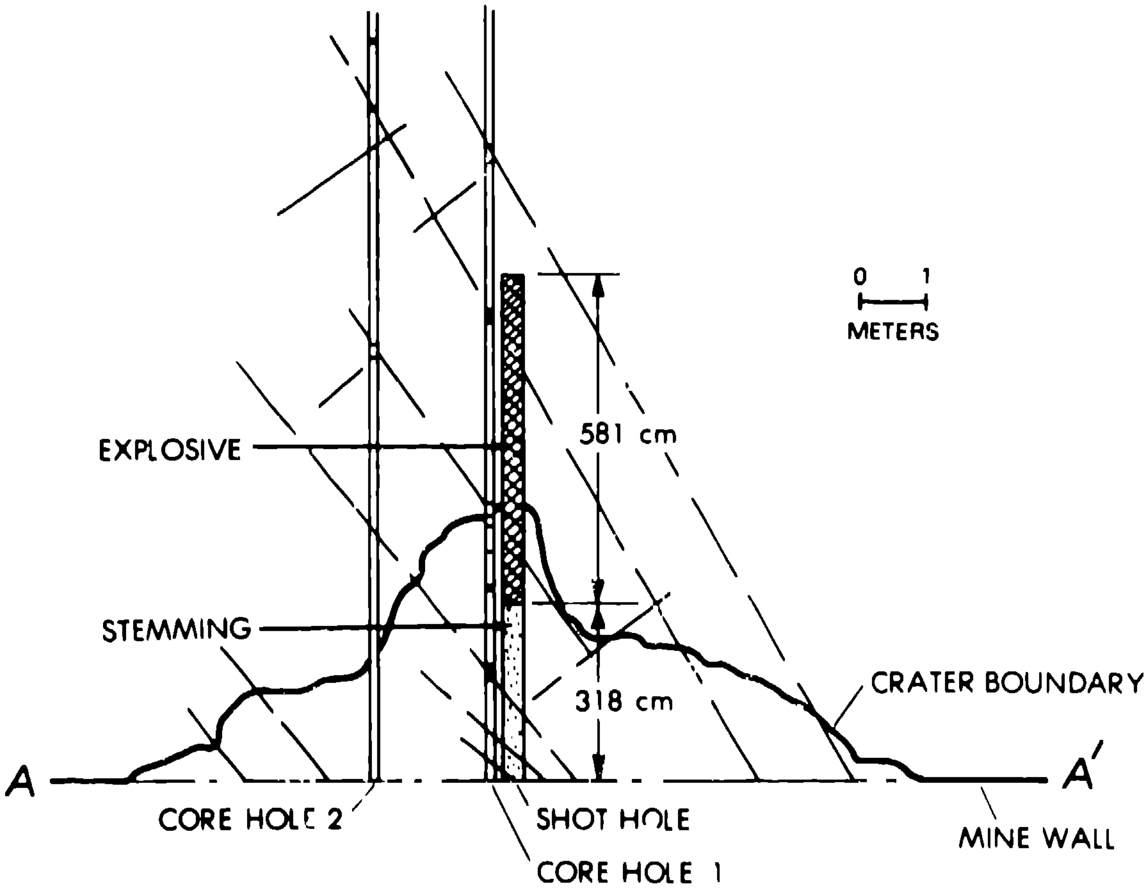

Fig. 28. Plan view cross section of experiment 79.03 crater profile showing the location of core holes and the relationship of pre-existing joints to crater experiments.

craters and generally dipped ($\sim 45^{o}$) conspicuously greater than horizontal bedding cracks but less than high-angle joints. The fractures interpreted as shear components were most often noted in a zone lying between the near-surface bedding spall and a horizon corresponding to the top of the charge. Although evidence for shear fracture was normally observed at the crater edges, it possibly contributed to rubble formation in the crater interior above the charge. Even if the shear fracture does occur in that region of the crater, the screening data from experiment 79.16 (Fig. 15) suggest that its contribution has an insignificant impact on fragment-size distribution. Based on evidence at the crater periphery, the number of shear fractures is substantially less than those correlative with natural joint orientations.

Crater symmetry provided a measureable result leading to a better understanding of the interaction of the explosive with the host rock. The resulting surface expression of the crater was subject to the joint orientation and was almost exclusively asymmetrical parallel to the major joint system. Experiment 79.08 exemplifies the crater

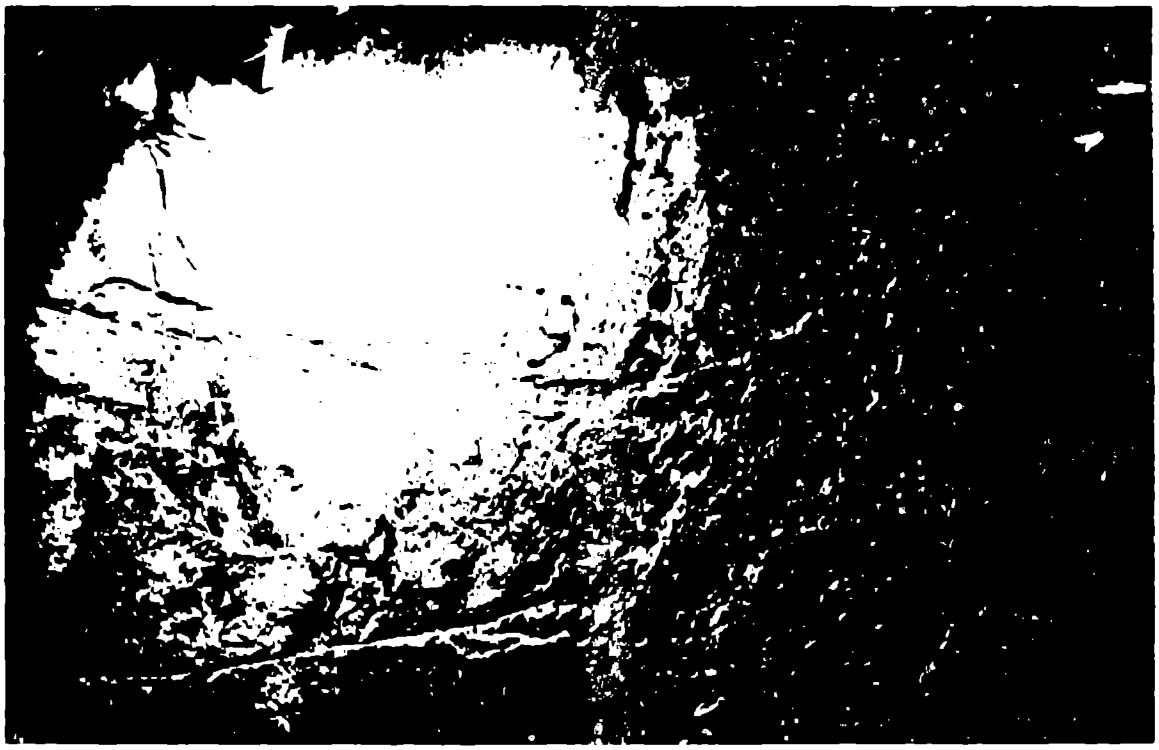

Fig. 29. Photograph of the preshot surface for experiment 79.08 showing several major joints trending east-northeast.

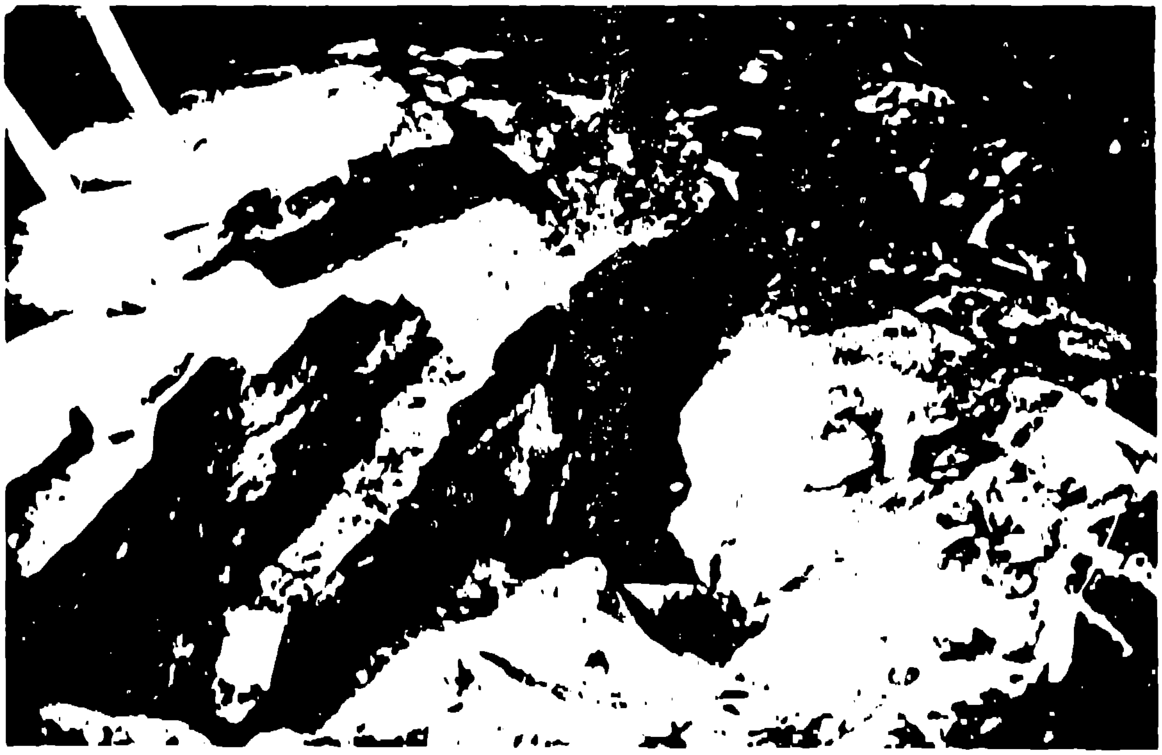

Fig. 30. Prominent surface expression of joints mapped in the experiment 79.08 crater.

elongation parallel to major joints. Figure 29 is a photograph of the preshot surface for 79.08 showing several major joints trending east-northeast. The postshot photograph in Fig. 30 underscores the dominant surface expression of those same joints adjacent to the shothole. Similar information is evident in the asymmetry of the postshot profiles in Fig. 31. The profiles show constrained crater dimensions on the N-S axis normal to the joints and enhanced crater

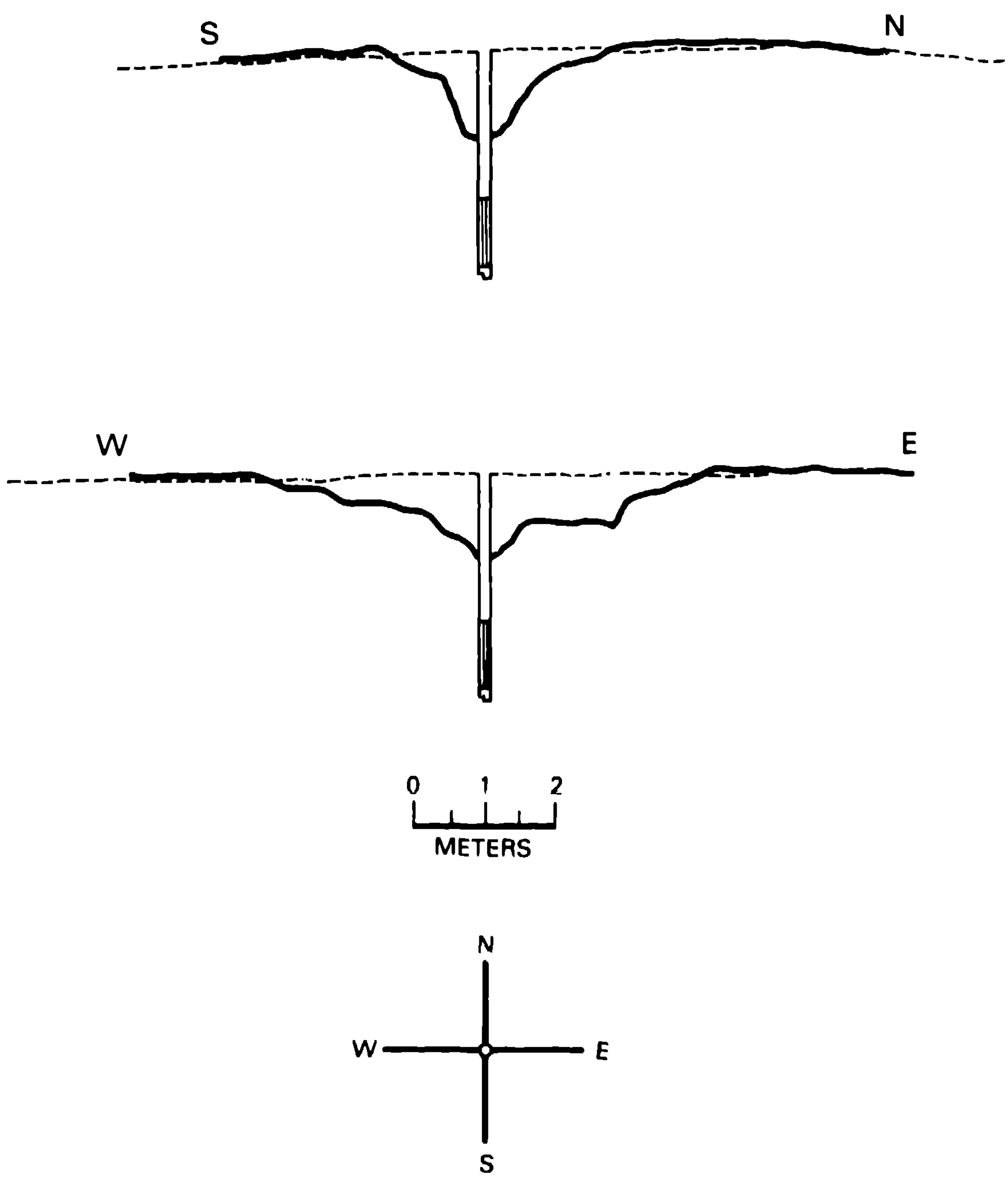

Fig. 31. Postshole crater profiles showing joint controlled crater geometry on experiment 79.08.

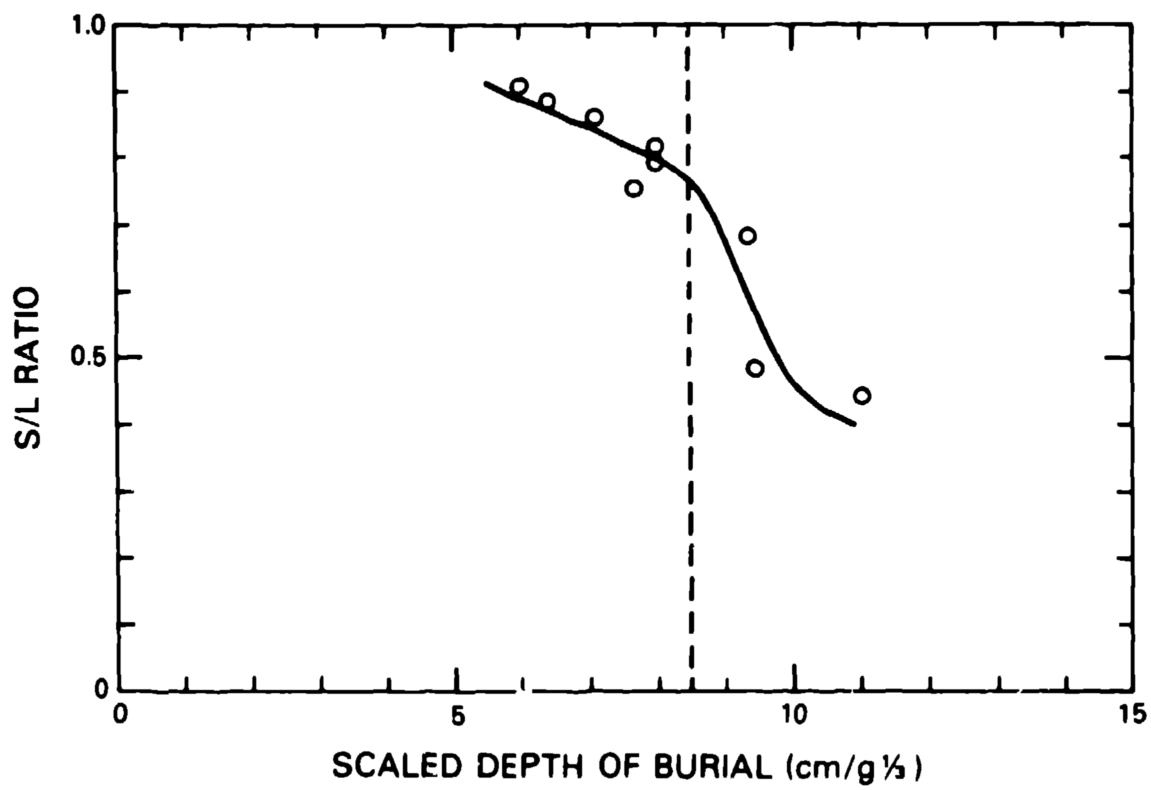

Fig. 32. Relative asymmetry of surface crater expression shows a dependence on the scaled depth of burial.

dimensions on the E-W axis parallel to the joints. The profile data for all the Colony Mine experiments with craters were reduced to a number for each experiment that represented a ratio of the short axis to the long axis (S/L ratio). Figure 32 presents the S/L ratio relationship to scaled depth of burial. The Colony Mine experiments with SDOB values less than the optimal depth of 8.5 $cm/g^{1/3}$ (represented by the dashed line) show a significantly greater tendency toward symmetrical craters (1.0 S/L ratio). The symmetry values decrease slightly as the SDOB approaches optimal depth and show a rapid departure from 1.0 symmetry below optimal depth. Figure 32 graphically states that the surface crater expression for shallow experiments (<8.5 SDOB) is not greatly influenced by natural joint patterns. The deeper experiments (>8.5 SDOB), in contrast, progressively trend toward surface crater asymmetry. The interpretation of joint influence from Fig. 32 should be restricted to surface crater expression and may not necessarily be true for other aspects of oil shale fragmentation.

Scaling

Several of the Colony Mine experiments were designed to investigate the application of existing scaling laws to oil shale. These laws allow the comparison of results from experiments with varying design parameters from a common perspective. The application of scaling laws requires full treatise of a separate report but is summarized here as an important objective of the Colony Mine experiments.

Investigations of the scaling laws considered data from both small-scale experiments using commercial blasting caps to intermediate-scale experiments using several kilograms of ANFO. Several parameters that were of interest in these investigations are as follows: (1) the depth of burial (DOB) of the explosive; (2) the depth of the resulting crater; (3) the average radius of the resulting crater; and (4) the volume of the crater. The value of the first three parameters from different experiments can be compared on a common scale by dividing the parameters by the cube root of the weight of the explosive (Edwards et al., 1981). The fourth parameter, the scaled variable for the crater volume, is obtained by dividing the volume by the weight of the explosive. These scaled parameters lend information toward a better understanding of critical depth and optimal depth relationships. Critical depth is the charge depth of burial below which no surface fracturing occurs. The optimal depth is the charge depth of burial that yields the greatest crater volume. Numerous small-scale experiments gave evidence of the influence of natural flaws on crater symmetry even on a very small scale. Figure 33 shows the resulting crater from a blasting cap

Fig. 33. Symmetrical crater resulting from detonation of a blasting cap in homogeneous oil shale.

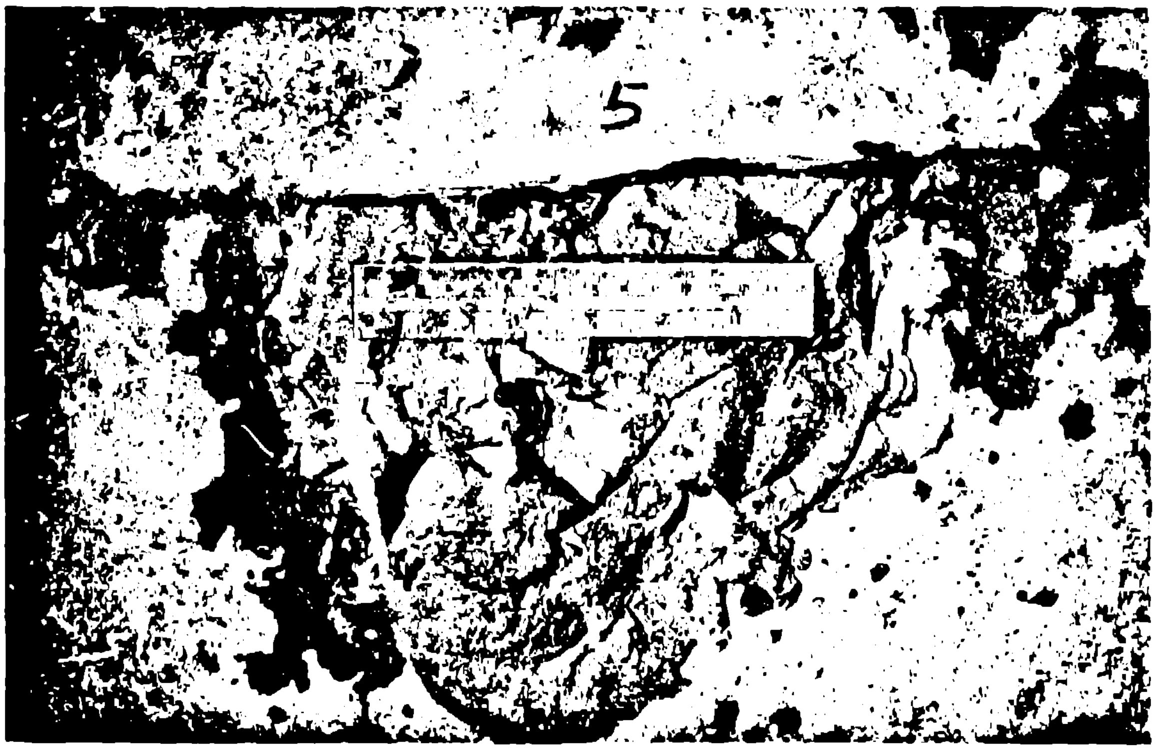

Fig. 34. Geologic features also expressed their influence on small-scale experiments, such as this blasting cap experiment sited next to a small joint.

placed in a homogeneous (relatively flaw free) oil shale environment. The shot resulted in good crater symmetry accompanied by traditional radial fractures. The crater in Fig. 34 resulted from the detonation of a blasting cap purposely sited next to a small joint.

The crater is sharply truncated by the flaw and accompanied by elongated symmetry parallel with the flaw. The asymmetry ratio of short crater axis to long crater axis is reasonably proportional to the intermediate-scale shots previously discussed.

The application of scaling laws to oil shale fragmentation is a technical subject important to understanding fragmentation processes and critical to eventually designing commercial size retorts.

CONCLUSIONS

The oil shale fragmentation experiments at the Colony Mine produced information and data with relevance to general interest in explosive/rock interaction and specific application to MIS retorting technology. The experimental results answered many questions and provided insight into other questions. Specific items of information that enhance the understanding of oil shale fragmentation and its implications to MIS retorting are categorized and summarized as follows:

Fragmentation

- o zones of rubblized rock are qualitatively characterized relative to their geometry around the explosive charge;
- o screen-size distributions are quantitatively determined for rubble from total crater volumes and from individual zones within some craters; and
- o a relationship for fragment sizes <5 cm and >45 cm vs scaled depth of burial (a critical shot design parameter) is identified and graphically defined.

Geological Influences

- o the susceptibility to fracture for oil shale of various grade values is quantitatively defined;
- o the role of several common geologic features in the fracture of oil shale is characterized; and
- o bedding features are documented to be relatively insignificant contributors toward the fragmentation process.

Stability

- o experiment results provide evidence of geologic phenomena (e.g. extensive fracture propagation beyond crater boundaries) with implications toward the compromise of retort stability;
- o information was obtained that has direct application to shot designs to optimize undesirable side effects; and
- o remedial measures are prescribed to prevent, or at least improve, potential stability problems.

Explosive/Rock Interaction

- o natural joint postures are identified, and their dynamic response to the explosive and resulting influence on the crater is qualitatively defined;
- c the relative importance to rubblization of different types of fractures identified in the experiments is prioritized; and
- o crater susceptibility to control from natural joint systems is quantitatively related to scaled depth of burial.

Scaling

- o parameters of interest to the application of scaling laws are identified and summarized; and
- o evidence of certain geologic influences are identified as elements in both the small-scale experiments and the intermediate-scale experiments and suggest probable roles in scaling considerations.

The Colony Mine experiments have also declared other problems to be resolved that would represent significant progress toward implementing MIS retorts. A partial list of work needed to address technical barriers follows:

(1) experiments, such as tracer flow studies, to determine void/permeability distributions and calibrate computer codes;
(2) experiments utilizing effective blasting mats to quantify zonal relationships of the rubble size to the explosive charge. This has direct application to three-dimensional spacing and design of explosive charge patterns;
(3) continued work to refine scaling relationships and the application of scaling laws;
(4) experiments to identify and prioritize the major contributors to fragmentation during early time (compression) and late time (tension) regimes are integral to timing delays in decked charges;
(5) analytical work devoted to specific effects of cavity gases; and
(6) experiments to ascertain the influence of _in situ_ maximum/minimum principal stresses and how they can be used to enhance predictable explosive/rock interaction and reduce degradation of retort stability.

Oil shale fracture is a multifaceted problem requiring a multidisciplinary approach. The specific needs of size uniformity and stability in large chambers reaches far beyond the conventional "drill, blast, and muck" technology. The Colony Mine experiments produced some informative results but also underscored the remaining questions about fracture of rock. Geology is only one of several data sets that need to be carefully integrated to determine their interdependence but experimental results dramatically designate it as a primary contributor to oil shale fragmentation.

ACKNOWLEDGMENTS

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