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**Abstract:**

The development of microfractures in the deformation of rocks was studied with microscopic method and the observation of microfracturing shocks. A coarse sandstone was deformed under various confining pressures at strain rates  $2.7 \times 10^{-6}$ /sec and  $3.5 \times 10^{-5}$ /sec. The locality of the sandstone is Oshima in Sakito-Matsushima coal field, northwestern Kyushu, Japan. The age is oligocene. Most of phenocrysts are quartz and the matrix contains a lot of calcareous materials. The specimens, which were deformed under the confining pressures 500 kg/cm<sup>2</sup> and 1500 kg/cm<sup>2</sup> at a strain rate  $2.7 \times 10^{-6}$ /sec, were examined microscopically. The mode of deformation is brittle under 500 kg/cm<sup>2</sup> and transitional under 1500 kg/cm<sup>2</sup>. The experimentation was stopped at several stages of deformation. The deformed specimens were cut into thin sections parallel to the axis of cylinder and perpendicular to the fractures. When the microfractures have opening, they are dark under crossed nicols and clear under uncrossed nicols. Microfractures appear at very early stage of deformation. They originate from grain boundaries or traces of old fractures. Most of microfractures have zigzag patterns. Average length of the straight parts of this zigzag lines ranges from 0.01 to 0.03 mm. The density of microfractures increases approximately in proportion to strain. Its opening begins to spread at about the yield point. The preferred orientation of microfractures are visible in early stage. They concentrate to the direction parallel to the maximum compression and two conjugate directions which have an angle of 30 – 40 degrees with it. Under the confining pressure of 500 kg/cm<sup>2</sup>, they concentrate relatively more to the direction parallel to the maximum compression than under 1500 kg/cm<sup>2</sup>. Microfractures concentrate in some particular bands at early stage. The band is called “deformation band” in this paper. The direction of deformation band has an angle of 45 degrees or a little less degrees with maximum compression. The deformation bands grow at stages. Macrofractures occur along the deformation bands. It seems with increase of the confining pressure that the angles of macrofractures and deformation bands to the direction of maximum compression becomes larger, that the numbers of microfractures and deformation bands increase and that their sizes are reduced. The directions of microfractures in a deformation band are not necessarily parallel to the direction of the deformation band. Microfracturing shocks arise at very early stage of deformation (the 1st stage). It accords with the microscopic observation. Then the specimen is further deformed, the occurrence of microfracturing shocks becomes few (the 2nd stage). When the velocity of plastic deformation becomes larger the microfracturing shocks occur frequently again (the 3rd stage). The relation among stress-strain curve, development of microfractures and occurrence of microfracturing shocks is tentatively summarized in table 1.

**Table 1. Process of Fracturing in Rocks**

	Stress strain relation	Fracturing	Microfracturing shocks	Stage of yield
<b>I</b>	Initial stage			
<b>II</b>	Linear stage	initiation of microfracturing increasing of microfractures	generation (1) ↓ few * (2)	micro yielding
<b>III</b>	Flattening stage	formation of deformation bands extension and opening of microfractures	↑ generation (3)	macro yielding
<b>IV</b>	Ultimate stage	macrofracturing along deformation bands	↓	

\* depends on the condition of experiment, loading rate, confining pressure, rock material and so on.







次のように考えられる。圧縮応力下では、微小割れ目相互の干渉によって、応力集中の高い場が生じ、新しい割れ目が作られ、それらは連結し合って“変形帯”を形成して行く。変形帯の生長する方向は割れ目相互の干渉による応力集中の生じやすい方向であって、はじめに述べた剪断面の角度( $\theta_s$ )

を形成するものである。すなわち巨視的割れ目は変形帯にほぼそって生じる。巨視的割れ目は変形帯の cataclastic sliding によって生じると考えられ、その方向は個々の微小割れ目の方向に直接の関係はなく、変形帯の方向に支配されている。

Ramez<sup>(13)</sup> は破断後の岩石試料中の微小割れ目を観察し、巨視的割れ目の近くで微小割れ目が多いとしている。

破壊音の発生の第1状態は非常に早い変形の stage ではじまる。これは顕微鏡による微小割れ目の観察の結果と一致する。Gilman<sup>(14)</sup>によれば、応力が増大すると dislocation velocity が大きくなり、塑性変形は dislocation velocity と density とによって規制される。

破壊音の第2状態では、stress-strain curve の上からはある程度の塑性変形がおきていると見られるにもかかわらず、破壊音はほとんど発生しない。これは塑性変形が dislocation の速い移動によってまかなわれるためと考えられ、所謂 flow の状態に相当すると思われる。破壊音が発生するか、しないかは、変形速度に依存すると考えられる。変形速度が大きくなると flow だけでは塑性変形をまかないきれず新しい割れ目の発生がおきる。これが破壊音発生の第3状態と考えられる。

微小割れ目の発生の過程とその岩石の変形・破壊の過程への結びつきについてはこのように、まだわずかな資料しかないが、微小割れ目の発達過程、破壊音の発生過程との関係を1つの試案として、第1表の如くまとめてみた。

stress-strain relation は、ほゞ Brace<sup>(11)</sup> の区分にしたがって4 stage に分けた。I の stage は stress-strain curve の立ちあがりの曲線部であって、岩質や実験条件の差によってかなり傾斜が異なる。破壊音はほとんど発生せず、微小割れ目もほとんど作られていないと考えられる。II は直線ないし直線に近い部分で通常弾性的と考えられている。しかし、この stage の初期の部分で多くの破壊音が発生し、また顕微鏡によって微小割れ目が観察されることは、塑性変形の存在を示している。このとき局部的な yielding がおきていると考え、micro-yielding とよぶことにした。

III, IV の stage は、塑性変形が大きく生じ巨視的な降伏、破壊に至るクラックの開口、拡大、また変形帯の形成が行なわれる領域に相当する。その区分は岩質、封圧によって、あらわれかたが異なる。まっ

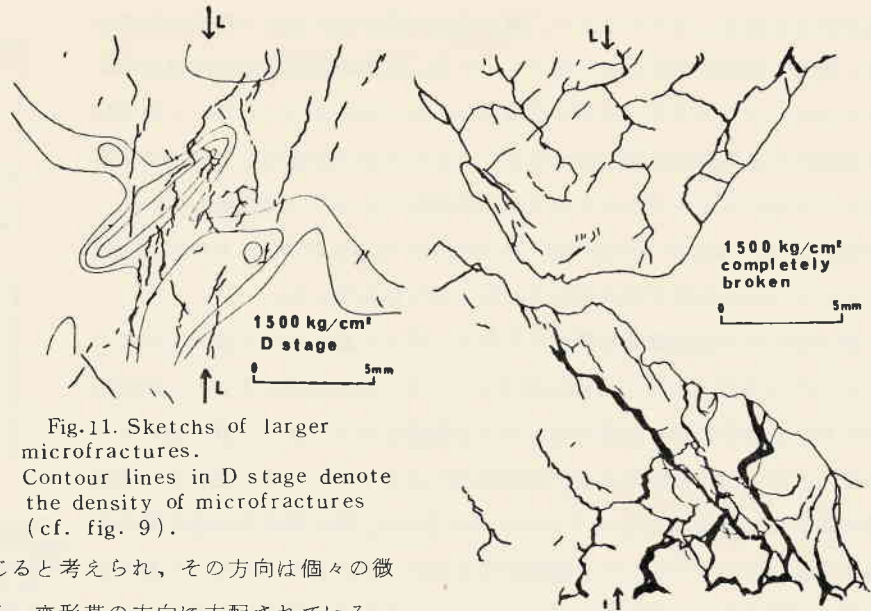


Fig.11. Sketches of larger microfractures. Contour lines in D stage denote the density of microfractures (cf. fig. 9).

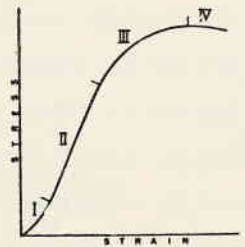


Fig.12 Stages of stress-strain curve.

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たく brittle な場合には、Ⅲ、Ⅳの stage がほとんどあられわずに直ちに破断する。ductile になるとⅢの stage が非常にながくなり、通常の実験ではⅣの stage に到達せず、いわゆる strain hardening の状態になる。

## 結 論

砂岩の三軸変形実験を行ない、微小割れ目を顕微鏡によって観察し、破壊音を測定した。

顕微鏡による観察によっても、破壊音の測定によっても、微小割れ目は変形の非常に早い stage から発生する。微小割れ目は粒界や古い割れ目の跡などから発生することが多い。

微小割れ目の頻度は歪の増加にほぼ比例して増加する。微小割れ目の方向は、最大圧縮方向およびそれと  $30^{\circ}\sim 40^{\circ}$  の角度をなす二方向に集中する。

微小割れ目の分布は一様ではなく、最大圧縮方向に  $45^{\circ}$  ないしそれよりやや小さい角度をもつ方向に伸びた帯状に集中する。これを変形帯とよぶ。変形帯内の微小割れ目の方向は必ずしも変形帯の方向と一致せず、雁行状に配列している。

巨視的割れ目は変形帯にそって発生する。

封圧が大きくなると、巨視的割れ目と変形帯が最大圧縮方向となす角度は大きくなり、微小割れ目も角度の大きいものの数が増す。

破壊音の発生は3状態にわけられる。破壊音が多数発生する状態は変形の非常に早い stage と塑性変形がかなり大きくなった部分とにあり、中間に散発的にしか発生しない状態がある。破壊音の発生頻度は塑性変形速度に影響される。

現在までの実験の結果から、岩石破壊の進行の過程をしめす表を作った。この表は今後の実験によってさらに改善していく必要がある。

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## 参考文献

- (1) K.Mogi: Study of elastic shocks caused by the fracture of heterogeneous materials and its relations to the earthquake phenomena, Bull. of the Earthquake Research Inst., 40 (1962) 125-173
- (2) 佐々木和郎, 高多明, 戸辺雅行: 岩石の破壊音の測定, 岩の力学国内シンポジウム 1964
- (3) N.G.W.Cook: The failure of rock, Int. J. Rock Mech. Min. Sci., 2 (1965) 389-403
- (4) 星野一男: 岩石変形の基礎理論と地質構造要素, 地質学雑誌, 72 (1966) 105-116
- (5) J.Handin: Strength and ductility, G.S.A. Memoir 97
- (6) 星野一男: 日本産堆積岩の高圧物性について (第1報), 応用地質 8 (1967) 151-164
- (7) 星野一男, 南雲昭三郎: 松代産岩石の高圧変形実験 (第1報), 防災科学技術総合報告第5号 (1967) 41-47
- (8) 小出仁, 星野一男: 三軸変形下の岩石中の微小割れ目の発達について (序報), 地震 20 (1967) 83-97
- (9) 南雲昭三郎, 星野一男: 印刷中
- (10) W.G.Johnston, J.J.Gilman: Dislocation velocities, dislocation densities and plastic flow in lithium fluoride crystals, Jour. of Applied Physics 30 (1959), 129-144
- (11) W.F.Brace: Brittle fracture of rocks, in State of Stress in the Earth's Crust, 1963

- (12) E. Smith : Fracture at stress concentration, First Int. Conf. on Fracture, Sendai, 1965
- (13) M.R.H. Ramez : Fractures and the strength of a sandstone under triaxial compression, Int. J. Rock Mech. Min. Sci., 4 (1967)
- (14) J.J. Gilman : The dynamics of fracture initiation, First Int. Conf. on Fracture, Sendai, 1965

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