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12. *Pressure Dependence of Rock Strength and Transition from Brittle Fracture to Ductile Flow.*

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Abstract

Different types of relations between compressive strength and confining pressure in dry rocks at room temperature are discussed on the basis of many available strength data, reported by various authors. Pressure dependence of strength is very different for different types of fractures and continuously changes from a brittle stage to a ductile stage. Average strength-pressure curves of each rock type are estimated.

A simple rule for transition from brittle fracture to ductile flow is found. The transition rule is different between silicate rocks and carbonate rocks, this being attributed to different transition mechanisms in each case.

1. Introduction

In general, rocks become stronger with the application of confining pressure. The pressure dependence of rock strength has been experimentally studied by many investigators.[1)-8)]

1) F. D. ADAMS and J. T. NICOLSON, "An experimental investigation into the flow of marble," *Royal Soc. London Philos. Trans.*, Ser. A, **195** (1901), 597-637.

2) T. VON KÂRMAN, "Festigkeitsversuche unter allseitigem Druck," *Zeitschr. Ver. Deut. Ing.*, **55** (1911), 1749-1757.

3) D. T. GRIGGS, "Deformation of rocks under high confining pressure," *Jour. Geol.*, **44** (1936), 541-577.

4) E. C. ROBERTSON, "Experimental study of the strength of rocks," *Bull. Geol. Soc. America*, **66** (1955), 1275-1314.

5) J. HANDIN and R. V. HAGER JR., "Experimental deformation of rocks under confining pressure, tests at room temperature on dry samples," *Bull. Assoc. Petrol. Geologists*, **41** (1957), 1-50.

6) D. T. GRIGGS and J. HANDIN, "Rock deformation," *Geol. Soc. America*, Memoir **79** (1960), 1-382.

7) W. F. BRACE, "Brittle fracture of rocks," *State of Stress in the Earth's Crust* (American Elsevier Publishing Company, New York, 1964), pp. 111-178.

8) K. MOGI, "Deformation and fracture of rocks under confining pressure (2) Elasticity and plasticity of some rocks," *Bull. Earthq. Res. Inst.*, **43** (1965), 349-379.

According to these investigations, breaking strength of brittle rocks increases markedly with pressure. In many cases, a linear relation between breaking strength and pressure has been observed. Especially, Robertson[9] found an approximate linear relation between breaking strength and mean pressure for various stress systems and rock types. Recently Brace[10] has shown that a linear relation between compressive strength and confining pressure is well applicable to some brittle rocks and this relation is explained on the basis of the Griffith theory, modified by McClintock and Walsh[11] to account for crack closure. On the other hand, Robertson[12] has shown that yield stress in ductile cases is practically independent on pressure in some limestones and marbles. That is, the maximum shear stress criterion is applicable to these ductile cases.

Thus, the pressure effect on rock strength is quite different between brittle and ductile fracture, and the above-mentioned two linear relations seem to be the most fundamental ones in brittle and ductile cases respectively. However, certain other cases which clearly deviate from these linear relations have been reported. As examples, strength-pressure curves of some brittle rocks are sometimes remarkably concave downward[13][14] and yield stress in some ductile rocks still increases appreciably with pressure.[15] An object of the present paper is to obtain a general picture of pressure dependence of compressive strength. In preceding papers,[16][17] various types of strengh-pressure curve of dry rocks at room temperature were experimentally studied. Here, they are more systematically discussed and are based on available strength data tested by various investigators, besides the preceding experiments.

As mentioned above, whether fracture type is brittle or ductile is an essential factor on the pressure effect of rock strength. The mechanical conditions of brittle-ductile transition have been studied for a few

9) E. C. ROBERTSON, *loc. cit.*, 4).

10) W. F. BRACE, *loc. cit.*, 7).

11) F. A. MCCLINTOCK and J. WALSH, "Friction on Griffith cracks in rocks under pressure," *Proc. 4th Natl. Congr. Appl. Mech.* (1962), 1015-1021.

12) E. C. ROBERTSON, *loc. cit.*, 4).

13) S. MATSUSHIMA, "On the flow and fracture of igneous rocks," *Disaster Prevent. Res. Inst. Bull.*, No. 36 (1960), 1-9.

14) K. MOGI, "Some precise measurements of fracture strength of rocks under uniform compressive stress," *In. Jour. Rock Mech.* (1966). (in press).

15) J. HANDIN and R. V. HAGER JR., *loc. cit.*, 5).

16) K. MOGI, Deformation and fracture of rocks under confining pressure (1) Compression tests on dry rock sample," *Bull. Earthq. Res. Inst.*, **42** (1964), 491-514.

17) K. MOGI, *loc. cit.*, 8).

rock types,[18)19)] but have not been systematically discussed for different types of rocks. In this paper, this problem is also discussed from experimental data of various rock types.

2. Relation between compressive strength and pressure

Compressive strength of dry rocks is plotted in Figs. 2 and 3 as a

Table 1. A list of rocks

A. Silicate rocks

No.	Rock	Tested by	Grouping
1	Aoishi Tuff	Mogi (1965)	*S1* (High Porous Porosity > 10)
2	Sakuishi Welded Tuff	Mogi (1965)	
3	Shinkomatsu Andesite	Mogi (1965)	
4	Mizuho Trachyte (1)	Mogi (1964)	*S1* (Porous Porosity: 1~10)
5	Mizuho Trachyte (2)	Mogi (1965)	
6	Tatsuyama Tuff (1)	Mogi (1964)	
7	Tatsuyama Tuff (2)	Mogi (1965)	
8	Schirochoba Andesite (1)	Mogi (1964)	
9	Schirochoba Andesite (2)	Mogi (1965)	
10	Bartlesville Sandstone	Handin & Hager (1957)	
11	Barns Sandstone (I)	Handin & Hager (1957)	
12	Westerly Granite	Mogi (1966)	*S3** (Nonporous Porosity < 1)
13	Barre Granite	Robertson (1955)	
14	Kitashirakawa Granite	Matsushima (1960)	
15	Inada Granite	Mogi (1964)	
16	Mannari Granite	Mogi (1965)	
17	Nabeishi Peridotite	Mogi (1965)	
18	Ukigane Diorite	Mogi (1964)	
19	Orikabe Diorite	Mogi (1965)	
20	Cabramurra Serpentinite	Raleigh & Paterson (1965)	
21	Tumut Pond Serpentinite	Raleigh & Paterson (1965)	
22	Pala Gabbro	Serdengecti *et al* (1961)	
23	Frederic Diabase	Brace (1964)	
24	Cheshire Quartzite	Brace (1964)	

*) Rocks of No. 12~16 and No. 17~21 are conveniently marked by *S3G* and *S3P*, respectively.

(to be continued)

18) H. C. HEARD, "Transition from brittle to ductile flow in Solenhofen limestone as a function of temperature, confining pressure, and interstitial fluid pressure," *Geol. Soc. America*, Memoir **79** (1960), 193-226.

19) C. B. RALEIGH and M. S. PATERSON, "Experimental deformation of serpentinite and its tectonic implication," *Jour. Geophys. Res.*, **70** (1965), 3965-3985.

Table 1. (continued)

B. Carbonate rocks

No.	Rock	Tested by	Grouping
1	Wombeyan Marble	Paterson (1958)	*CM* (Marble)
2	Carrara Marble	Kârman (1911)	
3	Yamaguchi Marble (Fine)	Mogi (1964)	
4	Yamaguchi Marble (Coarse)	Mogi (1964)	
5	Mito Marble (1)	Mogi (1964)	
6	Mito Marble (2)	Mogi (1965)	
7	Danby Marble	Robertson (1955)	
8	Solenhofen Limestone (1)	Heard (1960)	*CL* (Limestone)
9	Solenhofen Limestone (2)	Robertson (1955)	
10	Wells Station Limestone	Paterson (1958)	
11	Becraft Limestone	Robertson (1955)	
12	Devonian Limestone	Handin & Hager (1957)	
13	Fusselman Limestone	Handin & Hager (1957)	
14	Wolfcamp Limestone	Handin & Hager (1957)	
15	Blair Dolomite (1)	Brace (1964)	*CD* (Dolomite)
16	Blair Dolomite (2)	Robertson (1955)	
17	Webatuck Dolomite	Brace (1964)	
18	Clear Fork Dolomite	Handin & Hager (1957)	
19	Fusselman Dolomite	Handin & Hager (1957)	
20	Hasmark Dolomite (T)	Handin & Hager (1957)	
21	Luning Dolomite	Handin & Hager (1957)	

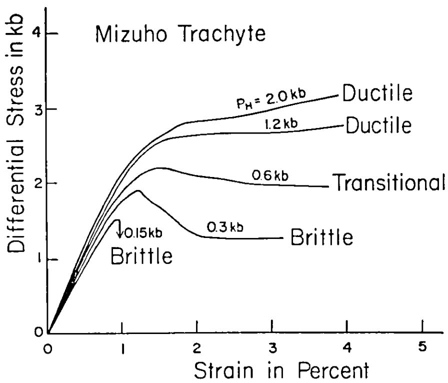

Fig. 1. Present definition of fracture behavior.

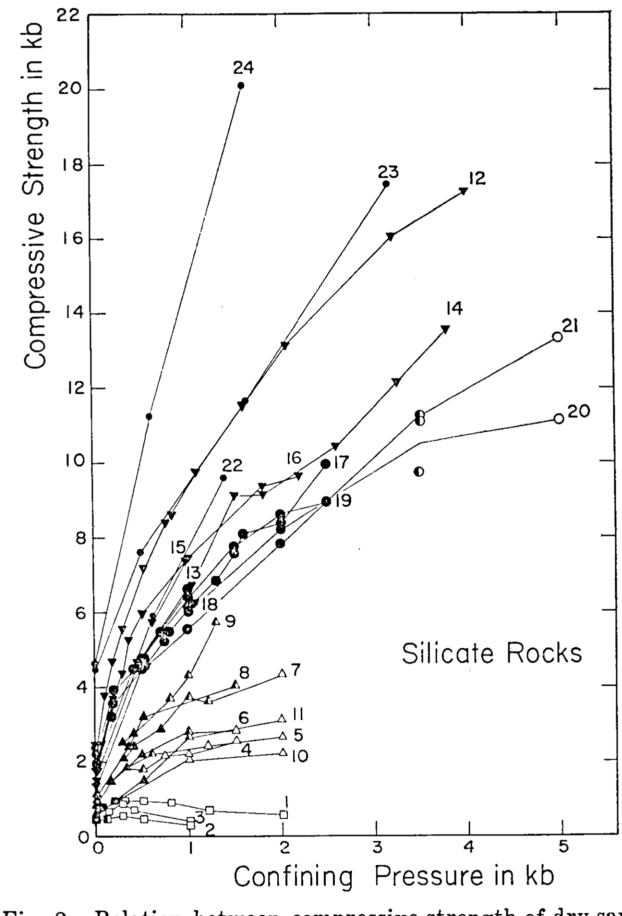

Fig. 2. Relation between compressive strength of dry samples at room temperature and confining pressure in silicate rocks. Numbers given for each curve correspond to those of rocks in Table 1. closed symbol: brittle, semi-closed symbol: transitional, open symbol: ductile.

function of pressure. Data were obtained from previous experiments by various authors (Table 1). When numerical values of strength were not given in original reports, approximate values were read from published stress-strain curves. Most of these strength values were obtained about a circular cylinder of a height-diameter ratio of 2, but some data were obtained by different methods to eliminate the end effect of the conventional tests.[20)21)] Difference among such is not considered in the

20) W. F. BRACE, *loc. cit.*, 7).
21) K. MOGI, *loc. cit.*, 14).

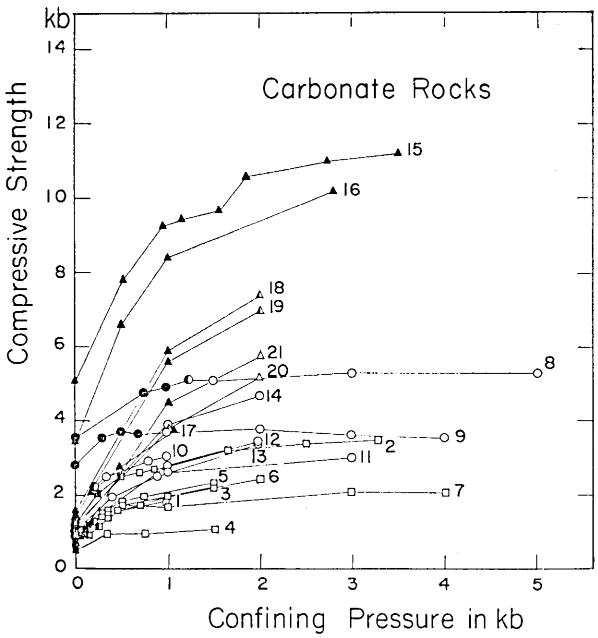

Fig. 3. Relation between compressive strength of dry samples at room temperature and confining pressure in carbonate rocks. Numbers given for each curve correspond to that of rocks in Table 1. closed symbol: brittle, semi-closed symbol: transitional, open symbol: ductile.

present discussion. However, the end effect in conventional tests should be considered in more detail in a future discussion, because the effect is considerable at low pressure.

In the figures, the closed, semi-closed and open symbols indicate brittle, transitional and ductile fracture types, respectively. The definition of these fracture types is as follows (Fig. 1). The brittle behavior is characterized by a sudden and appreciable drop of slope in the stress-strain curve after the yield point.[22] Ductile behavior is characterized by a stress-strain curve without any drop in slope after the yield point. The transitional behavior is an intermediate case between them. The appreciable stress drop by rupture is expected in the brittle fracture, but not in the ductile flow. Thus, the present definition of fracture behaviors is suitable for discussions related to earthquake mechanism. The breaking strength in the brittle state is the maximum differential stress achieved during an experiment. The strength in the ductile and

22) K. Mogi, *loc. cit.*, 8).

transitional states is the differential stress at the knee of stress-strain curves, namely yield stress. Sometimes, yield stress is indefinite because of the lack of a marked break in the curve. Extremely indefinite cases were not included in this discussion. These rocks are divided into the several groups shown in Table 1. This grouping is not systematic but for convenience in description.

Figure 2 shows strength-pressure curves for silicate rocks.* Nonporous silicate rocks (Group *S3* in Table 1) are very strong and become markedly stronger with the increase in pressure. These curves are almost straight, but an initial and later part of them frequently concaves downwards. Most of these rocks are brittle at the tested pressure, but the serpentines become ductile at about 4 kb. Strength of porous silicate rocks (*S2*) which is appreciably weaker than nonporous silicate rocks also increases remarkably with pressure, but the rate decreases gradually. These rocks become ductile at 1–2 kb. Very porous rocks (*S1*) are the weakest and become ductile at a few hundred bars or less. In this case, yield strength rather decreases with increase of confining pressure.

Strength-pressure curves in carbonate rocks are represented in Fig. 3.

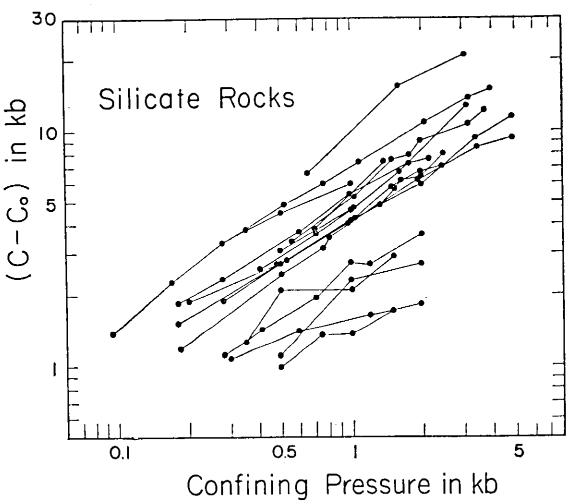

Fig. 4. Relation between (*C-Co*) and confining pressure in silicate rocks, except for very porous rocks (*S1*). *C*: compressive strength, *Co*: compressive strength at atmospheric pressure.

*) Mechanical behaviors of shales are exceptionally different from other silicate rocks, as observed by Handin and Hager (1957). Hence, shales are excluded in this discussion.

Dolomites are stronger, limestones are intermediate, and marbles are weaker. Strength markedly increases with pressure at an initial stage and gradually approaches to a constant value at higher pressure.

Thus, strength is very different for different types of rocks, but these strength-pressure curves seem to concave downward with a roughly similar shape. Figure 4 shows relations between $(C-C_0)$ and confining

Table 2. Average values of constants in the formula $C=C_0+\alpha P_H^n$

Rock Type	Number of Rocks	C_0	α	n
Porous Silicate Rock (*S2*)	5	1.0±0.1	1.9±0.4	0.4 ±0.1
Granite (*S3G*)	5	1.8±0.4	5.6±0.9	0.56±0.08
Peridotite & Others (*S3P*)	5	2.0±?	4.2±0.2	0.64±0.04
Quartzite	1	4.6	9.7	0.73
Marble (*CM*)	5	0.8±0.3	1.2±0.5	0.39±0.11
Limestone (*CL*)	5	1.4±1.0	1.9±0.5	0.38±0.08
Dolomite (*CD*)	6	2.6±1.4	3.5±0.9	0.48±0.12

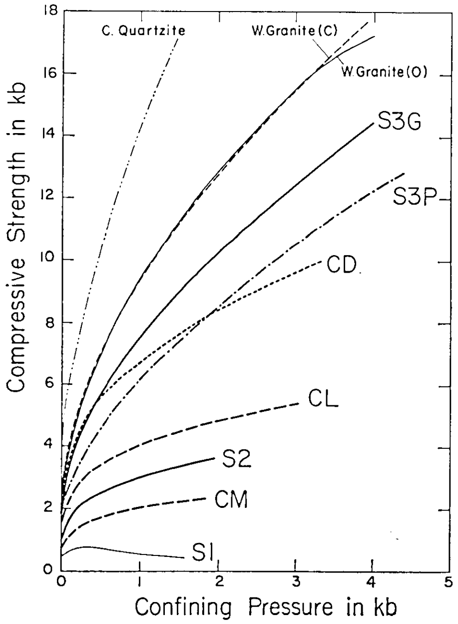

Fig. 5. Average strength-pressure curves of different rock types. *S1*: very porous silicate rocks, *S2*: porous silicate rocks, *S3*: nonporous silicate rocks (*G*: granites, *P*: peridotite and others), *CM*: marbles, *CL*: limestones, *CD*: dolomites.

pressure P_H in silicate rocks by logarithmic scales, where C and C_0 are compressive strength at the pressure P_H and at atmospheric pressure, respectively. Since these curves are almost straight, strengths are approximately expressed by*

$$C = C_0 + \alpha P_H^n \,, \tag{1}$$

where α and n are constants. If $n=1$, this equation becomes the Coulomb's formula and then α corresponds to the coefficient of internal friction. The average values of these constants for each rock group are shown in Table 2. The n value (nearly 0.5) is appreciably smaller than 1. As an example, good agreement between an observed curve and a curve calculated from Eq. (1) in Westerly granite is shown in Fig. 5. In general, this formula is applicable to the middle part of curves, but it deviates from observed values at an initial part and later ductile part of curves. Therefore, this formula may be useful only as a rough expression of strength-pressure curve. In Fig. 5, calculated average curves for different rock types are shown, except for *S1* which is not expressed by the formula. For *S1*, a rough average observed curve is represented in this figure.

3. Brittle-ductile transition boundary

As seen in Figs. 2 and 3, the fracture type changes from a brittle to a ductile one with the increase in pressure, the transition pressure being higher in stronger rocks. Figures 6 and 7 show the fracture behavior at various strength and pressure. In these figures, some other available data[23)24)] are added to that in Figs. 2 and 3. In silicate rocks, it is very noticeable that brittle state (closed circles) and ductile state (open circles) are clearly divided by a straight line passing through the origin (Fig. 6). This boundary line is expressed by

$$C = 3.4 P_H \tag{2}$$

or

$$\tau = 0.8 P_m \,, \tag{3}$$

where τ is the maximum shear stress and P_m is a mean pressure. That

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*) This is analogous to the formula which was obtained for a granite by S. Matsushima.

23) D. T. GRIGGS, F. J. TURNER and H. C. HEARD, "Deformation of rocks at 500° to 800°C," *Geol. Soc. America*, Memoir **79** (1960), 39-104.

24) C. B. RALEIGH and M. S. PATERSON, *loc. cit.*, 19).

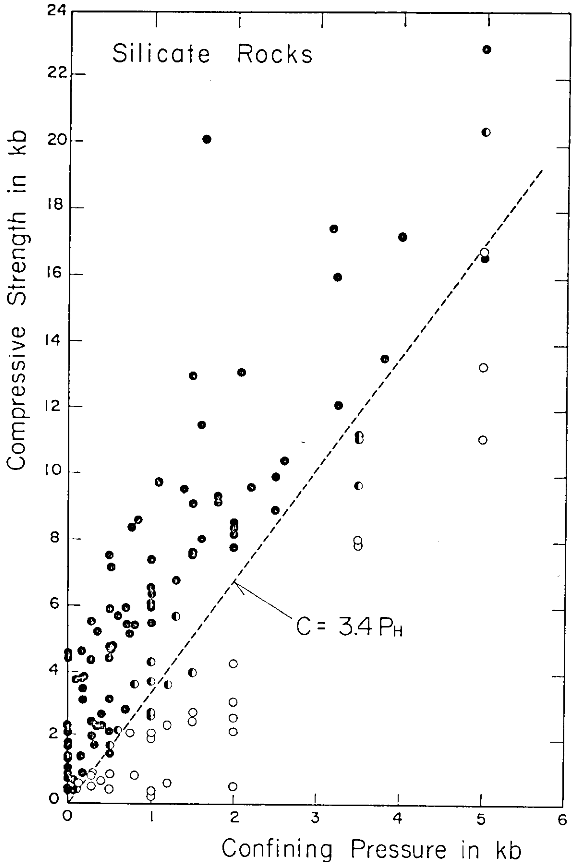

Fig. 6. Fracture behaviors of silicate rocks at various strength and pressure. dotted line: boundary between brittle region and ductile region, closed circle: brittle, semi-closed circle: transitional, open circle: ductile.

is, the fracture behavior, brittle or ductile, depends on whether or not compressive strength is larger than $3.4P_H$. On the other hand, the boundary in carbonate rocks is at the left side of the above-mentioned line (Fig. 7). Especially, the transition pressure of weaker marbles and limestones is appreciably lower than that of silicate rocks. This transition boundary is not linear, but slightly concave downward.

These results suggest a mechanism for the brittle-ductile transition. Recently, Orowan[25] pointed out that a drop of stress at fracture is

25) E. OROWAN, "Mechanism of seismic faulting, *Geol. Soc. America*, Memoir **79** (1960), 323-345.

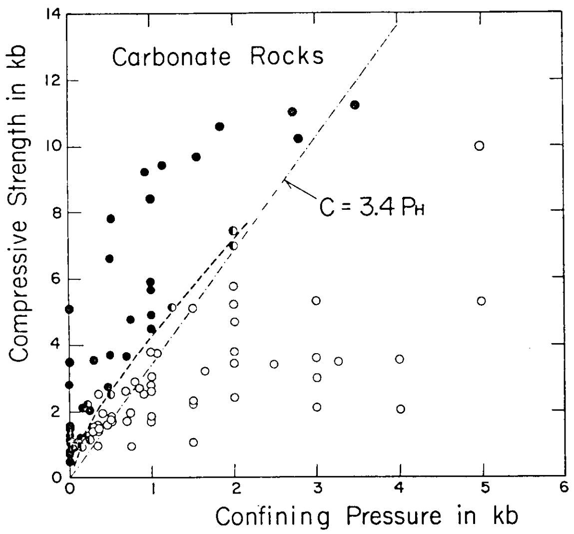

Fig. 7. Fracture behavior of carbonate rocks at various strength and pressure. dotted line: boundary between brittle region and ductile region, closed circle: brittle, semi-closed circle: transitional, open circle: ductile.

unlikely unless the shear strength is higher than the frictional resistance of the fracture surface produced. If this friction mechanism is applied, the fracture type is brittle for shear strength higher than the frictional resistance and ductile for shear strength equal to the frictional resistance. This mechanism seems to be fit for silicate rocks which flow cataclastically. The coefficient of friction on the fault plane at the transition pressure is calculated from the strength at the transition boundary.[26] From the above-mentioned linear boundary, it is deduced that various kinds of silicate rocks have an almost identical coefficient of friction (0.65) at the transition pressure.* This value seems reasonable.

On the other hand, it seems to be difficult to explain the brittle-ductile transition boundary in carbonate rocks by the friction mechanism, because the coefficient of friction calculated from the strength at the transition pressure is frequently over 1.0 and markedly larger than that of silicate rocks. In this case, since the gliding flow occurs at lower pressure than cataclastic flow, yielding takes place by gliding flow. Therefore, the transition from brittle fracture to ductile flow takes place

26) E. OROWAN, *loc. cit.*, 25).

*) The one exception to this is shales which were excluded from the present discussion.

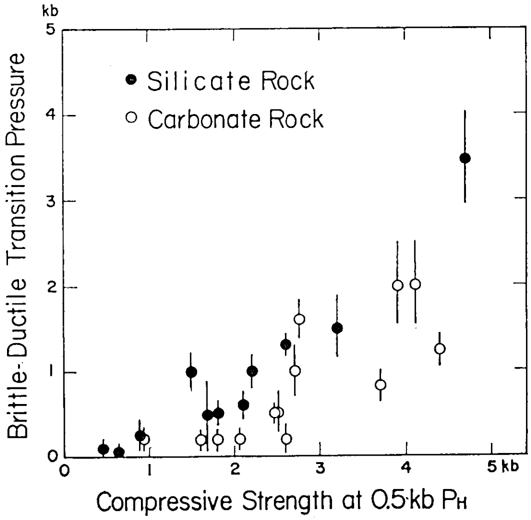

Fig. 8. Relation between the brittle-ductile transition pressure and the compressive strength at 0.5 kb confining pressure.

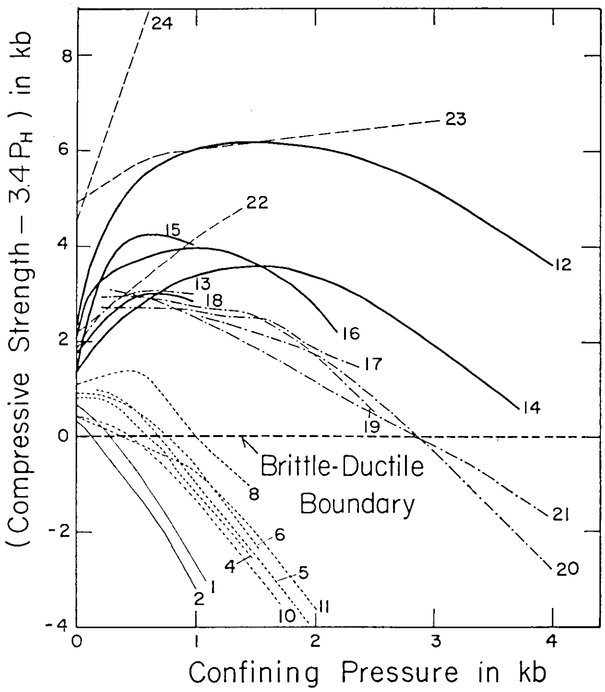

Fig. 9. Relation between $(C-3.4\,P_H)$ and confining pressure in silicate rocks. 1-2: very porous rocks, 4-11: porous rocks, 12-24: non-porous rocks.

when the stress for gliding flow becomes lower than breaking strength which increases remarkably with pressure. Thus, the transition pressure of carbonate rocks is lower than that of silicate rocks which do not yield until they flow cataclastically.

The transition pressure has a high correlation with the strength at a low pressure. Figure 8 shows its relation to the strength at 0.5 kb confining pressure. The correlation is higher in silicate rocks than in carbonate rocks.

If the right side of Eq. (2) gives a resistive stress after breaking in silicate rocks, a difference between C and $3.4\ P_H$ may give a possible stress drop at breaking. From this point of view, this value is shown as a function of pressure in Fig. 9. According to this result, the possible stress drop under lower pressure is much larger in nonporous silicate rocks than in porous silicate rocks.

4. Slope of strength-pressure curves

Figure 9 indicates the pronounced change of the pressure dependence of strength with pressure. Curves of some nonporous rocks are nearly

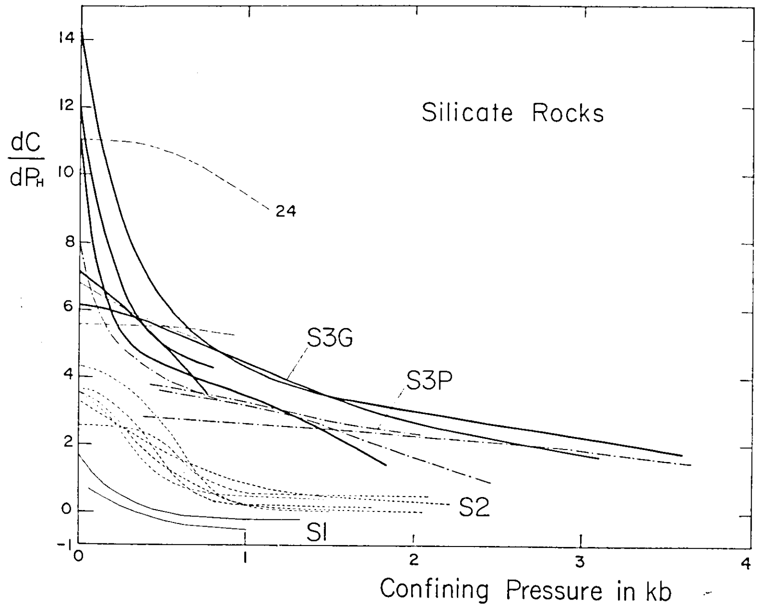

Fig. 10. Slopes of strength-pressure curves (dC/dP_H) vs. confining pressure in silicate rocks. *S1*: very porous rocks, *S2*: porous rocks, *S3*: nonporous rocks.

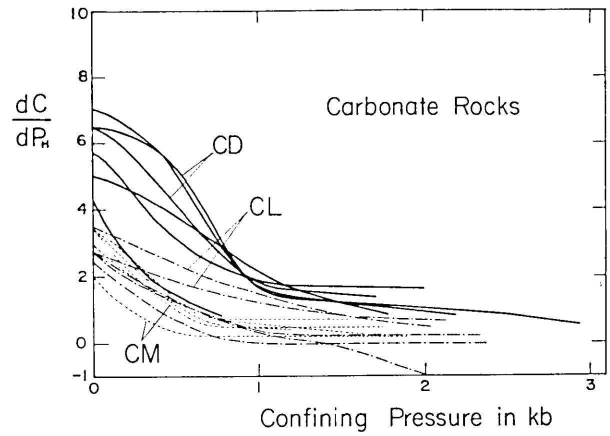

Fig. 11. Slopes of strength-pressure curves (dC/dP_H) vs. confining pressure in carbonate rocks. *CM*: marbles, *CL*: limestones, *CD*: dolomites.

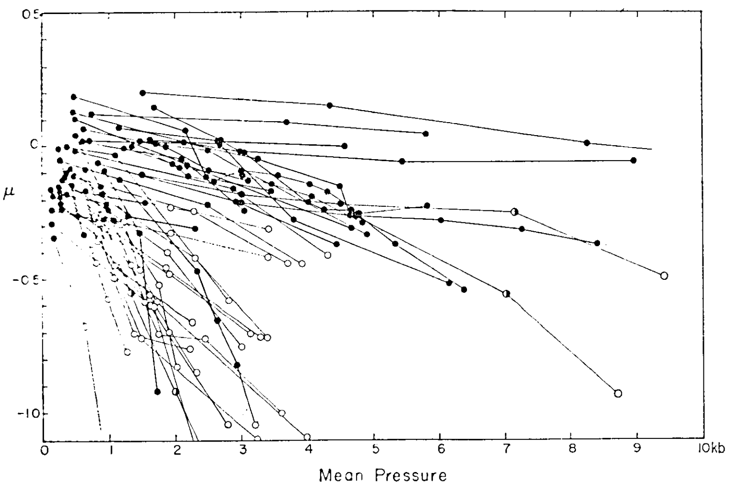

Fig. 12. Logarithm of the coefficient of Mohr's internal friction vs. mean pressure. closed circle: brittle, open circle: ductile.

linear under the tested pressure, but most are strongly concave downward. This change of pressure dependence of strength is more clearly expressed by relations between the slope of strength-pressure curve and pressure, shown in Figs. 10 and 11. According to these figures, the curve slope dC/dP_H is clearly larger in hard rocks than in soft ones. The slope dC/dP_H of granites (*S3G*) is abnormally large at an initial stage and rapidly decreases with the increase in pressure. In the group

S3P (peridotite and others), curve slopes decrease more gradually. In porous silicate rocks (*S1* and *S2*) and carbonate rocks this value is appreciably smaller than that of nonporous silicate rocks. It decreases gradually at an initial stage, but very markedly at 0.5~1.0 kb. In many cases, this value decreases continuously from a brittle stage to a ductile stage and approaches to zero at higher pressure.

Relations between shear strength and normal stress on shear plane, given by the Mohr envelope curve, are analogous to the above-mentioned strength-pressure relations. The slope of the Mohr envelope curve, namely, the coefficient of the Mohr's internal friction (μ), also decreases with the increase in pressure. Figure 12 shows relations between log μ and the mean pressure, except for very porous rocks (*S1*) for which yield strength decreases with pressure. The μ value ranges from zero to 1.5 and log μ seems to decrease almost linearly with pressure. Therefore, μ may be approximately expressed by

$$\mu = a10^{-bPm} , \qquad (4)$$

where a and b are constants in each rock. The μ value of hard silicate rocks, such as quartzite, keeps a near constant large value for the increase in pressure. On the other hand, the μ value of carbonate rocks strongly decreases with pressure. The fracture type changes from brittle fracture to ductile flow at a near constant μ value (~0.5). In many cases, the variation of μ value with pressure is continuous at the transition pressure.

5. Discussion

The pressure dependence of rock strength is schematically summarized in Fig. 13. The typical strength-pressure curve appears to be divided into different stages, shown in this figure. At first, the stage *Bi* is an initial stage in which the breaking strength increases steeply with pressure. The curve is nonlinear and concave downward. At the next stage *Bo*, the breaking strength increases proportionately with pressure. The curve is frequently linear. Then, the curve approaches to the brittle-ductile transition boundary decreasing its slope (*Bt*). The transition boundary from brittle fracture to ductile flow for all silicate rocks is given by the straight line $C = 3.4P_{H}$. In many cases, the curve passes through the transition boundary without any abrupt change of the curve slope. The type of fracture near the transition boundary is sometimes transitional. In the ductile region, the yield strength also continues to

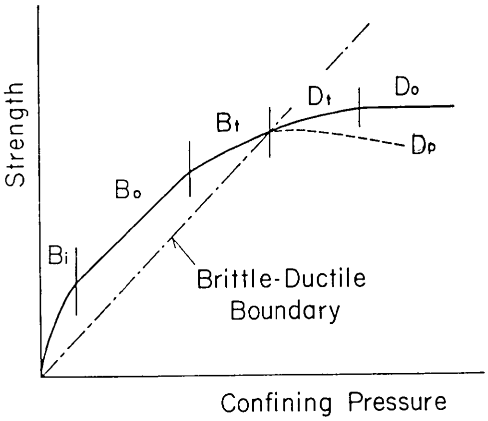

Fig. 13. A typical strength-pressure curve of dry rocks at room temperature.

increase with pressure. This transitional stage is shown by *Dt* in this figure. With further increase of pressure, the yield strength becomes near constant (stage *Do*). In very porous rocks, the yield strength decreases a little at high pressure (*Dp*).

The above-mentioned pressure-strength curve is a typical one. The curve of quartzite mainly consists of the stage *Bo* under the tested pressure and lacks the stage *Bi*. On the other hand, curves of granites continuously change from the stage *Bi* to the stage $Bt(P_H \leq 4\,\text{kb})$. In porous silicate rocks and carbonate rocks, curves change continuously from the stage *Bo* to the stage *Do* through the transitional stages *Bt* and *Dt* with the increase in pressure.

The stages *Bo* and *Do* may be the most fundamental ones in the brittle and the ductile regions, respectively. The Coulomb law and the maximum shear stress criterion are applicable to these stages, respectively.

The initial stage *Bi* seems to be conspicuous in rocks having loose crystalline structures, such as granites. The marked increase of strength in this stage may be due to the compaction of such loose structure, as the increase of the elastic wave velocity[27] or Young's modulus[28] at low pressure.

The transitional stages *Bt* and *Dt* are characterized by the gradual and continuous decrease of the curve slope. These stages are very

27) F. BIRCH, "The velocity of compressional waves in rocks at 10 kilobars, Part 1," *Jour. Geophys. Res.*, **65** (1960), 1083-1102.

28) W. F. BRACE, *loc. cit.*, 7).

conspicuous in heterogeneous or porous rocks, while they are not in homogeneous rocks, such as Solenhofen limestone.[29][30] This may be explained by the fact that these stages are caused by nonuniform structures of heterogeneous or porous rocks. That is, the stress distribution in such rocks is not uniform. Therefore, yielding, by gliding flow or cataclastic flow, does not occur simultaneously in the whole specimen at the transition pressure, but local yielding occurs gradually in the wide range of pressure extending over the stages *Bt* and *Dt*. Such a local ductile part increases gradually with pressure in these stages. This causes the gradual change of the pressure effect in the transitional stages. In this case, the macro-scopic fracture type may change from a brittle to a ductile one when the local ductile part exceeds the limit value.[31]

Yield stress, above, is taken as strength in the ductile state. On the other hand, the ultimate stress is also another kind of strength in ductile rocks. According to Handin and Hager,[32] the ultimate stress in ductile rocks continues to increase linearly with pressure. This is very different from the above-mentioned result for yield stress. The ultimate stress in ductile rock is frequently the strength after a large deformation (over several percent strain). Such a large deformation in rocks takes place mainly by cataclastic flow even in carbonate rocks. In a cataclastic stage, the strength mainly depends on the frictional resistance between fragments, and so it increases linearly with pressure. For example, stress-strain curves of Solenhofen limestone obtained by Heard[33] indicate the relation one might expect between the yield stress and the ultimate stress. The yield stress is nearly constant for various pressure, although the stress at large strain increases strongly with pressure. This pressure dependence of the strain hardening in rocks which flow cataclastically may be attributed to the frictional force between fragments, which increases linearly with pressure.

Thus, a general feature of the pressure dependence of compressive strength, including the brittle and the ductile regions, were obtained based on strength data of different rock types. For more detailed discussions, it seems to be necessary to get a lot of more precise strength

29) E. C. Robertson, *loc. cit.*, 4).
30) H. C. Heard, *loc. cit.*, 18).
31) K. Mogi, *loc. cit.*, 8).
32) J. Handin and R. V. Hager Jr., *loc. cit.*, 5).
33) H. C. Heard, *loc. cit.*, 18).

data, including that under higher pressure. Then, the simple rule for transition from brittle fracture to ductile flow was found in silicate rocks. This result should be established by further experiments.

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12. 岩石の破壊強度と圧力との関係，並びに脆性—延性遷移

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岩石の破壊強度と圧力の関係については，従来，脆性破壊に関する Coulomb law, 延性破壊に関する Maximum Shear Stress Criterion が適用されると考えられてきた．しかし，本論文で多くの岩石の強度—圧力関係は この様な単純な直線関係からは ほど遠いものであることを示した．強度—圧力曲線は著しく彎曲し， 脆性破壊領域から 延性破壊領域へ徐々にその傾斜を減じ乍らうつりかわつている．すなわち，岩石強度の圧力依存性は，脆性—延性遷移過程を考慮することによつてはじめて統一的に理解される．また，脆性から延性への遷移条件について 1 つの簡単な法則が見出され，これにもとづいて遷移の機構を考察した。