ROLE OF FAULT GOUGE IN THE MECHANICS OF FAULTING

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I. Investigations

The proposed work aims at a clarification of the mineral composition of actual fault zone materials, and an assessment of the mechanical properties of such materials under crustal conditions. It includes the following elements:

A) The determination of the mineralogy of fault gouge in deep mining tunnels.

B) The determination of the mineralogy of old fault zones on the earth's surface and the relation of the composition of the gouge to that of the wall rocks.

C) The determination of the mechanical properties of the constituent clays under high pressuresμ the range of strengths that clays can have and the factors that governs the strengths of the clays.

II. Results.

In the previous reporting period, gouge samples were collected and analyzed. It was found that common clays can be abundant enough to control the mechanical properties of the faults. And from available clay data in the literature, there are ample reasons to believe that although clay mineral assemblages cannot be used to determine the pressure-temperature range at which those assemblages were formed, they can exist at depths of importance to earthquake generation.

In a detailed analysis of three fault zones in the Adirondacks, New York, Kasza (1981) has determined the mineralogy of fault zone rocks that were once at depths of 5 to 10 km. She found that not only minerals were altered in the fault zone, the bulk chemistry also underwent remarkable changes. The conclusion that is pertinent to the problem of faulting is that significant fluid percolation must have taken place through the fault zone at the time the fault zone rocks were formed at perhaps a depth of 10 km or deeper, so that water and MgO could be added to the crushed rocks to form chlorite.

In this reporting period some of the above-mentioned works were brought to a conclusion. The main effort was on the design of experimental setup and the triaxial testing of samples. As reported in Wang, Mao and Wu(1979), montmorillonite (Wyoming Bentonite) has a strength of the order of 250-350 bars up to a confining pressure of 4 kb and that the peak-strength is reached at 5% strain with the failure occurring at more than 20% strain. These results are notably different from those of intact rocks and rock samples with sawcut faults. Subsequent works on other clays proved that at a strain-rate of 10(-5), the ordinary clays all have strengths less than 1 kb and can all undergo strain of more than 20 % before failure (Wang, Mao

and Wu, 1980).

We have at SUNY Binghamton redesigned the experimental setup
from those we used at UC Berkeley. The objective was to speed up the
sample-making process so that more experements can be conducted in a
relatively short time. With the assistance of Dr. Randy Martin at
Penn State we were successful in using core drill for making
cylindrical samples and a novel jacket was used in the process. The
results are shown later.

For the present work, five main types of clays were used. These
are purchased from the Clay Mineral Society (University of Missouri)
and they have been studied extensively in terms of their chemical
composition and crystalline structures (Van Olphen and Fripiat,
1979).

Sample KGa-1 is a very pure kaolinite (90%). Very little ion
substitution occurs within the lattice. The cation-exchange capacity
is measured to be 2.0 meq/100g, a very low figure.

Sample KGa-2 is poorly crystalline. It has more iron and
titanium than KGa-1. The X-ray diffraction shows larger
width-to-peak ratio than that of the KGa-1 sample, indicating poor
crystallinity. The cation-exchange capacity is slightly higher,
indicating less resistance to cation exchange.

Sample Swy-1 is a sodium montmorillonite, essentially same as
that used in Wang, Mao and Wu (1979). In this clay, about 2/3 of the
possible octahedral positions are filled. The monovalent sodium is
the dominant exchangeable cation in the interlayer position. The
cation is hydrated, with one water layer between the stacked sheets.
Mixed layer clays are present in small quantities. The cation
exchange capacity is 76.4 meq/100g, low among the dioctahedral
smectites.

Sample Saz-1 is calcium-bearing montmorillonite. It is also a
dioctahedral smectite. The bivalent calcium are the dominant
exchangeable cations. It has two layers of water between the stacked
sheets. The cation exchange capacity is high at 120 meq/100g. Thus
it is least resistant to cation exchange.

SHCa-1 is hectorite, a trioctahedral smectite. It is present in
among ultrabasic rocks. All possible positions within the octahedral
later are filled. The cation exchange capacity is 43.9 meq/100g.
This clay can exist at temperatures and pressures significantly
higher than the dioctahedral smectities. Thus, it can possibly be
present at greater depths in the fault zone with appropriate wall
rocks, e.g., in fault zones related to ancient collision zones.

The chemical compositions of the clays are shown in Table 1.

At each confining pressure the order of strength for different clays is invariably: Hectorite, well-crystalline kaolinite, poor-crystalline kaolinite, sodium montmorillonite and calcium montmorillonite. This ordering for dioctahedral clays can be explained nicely by the exchangebility of cations (figure 9). The less resistance to cation exchange means less strength.

III. Discussion.

From our results it can be concluded that clays are in general weaker than intact rocks or rocks with sawcut faults. The montmorillonte-rich, especially Ca-montmorillonite-rich gouge may have a strength of the order of 200 bars, while under mid-crustal pressure and undrained conditions hectorites may be as strong as 2 kb. It is too early yet to conclude, because the strengths and deformation characteristics may be quite different when temperature is high and when water is available. Because montmorillonite-rich gouge is common in fault zones, our results may be important in the consideration of faulting in those zones.

References

Kasza, S., Cataclastic metamorphism in the Southeastern Adirondack Mountains, New York State, M. A. Thesis, SUNY Binghamton, New York, 1980.

Van Olphen, H. and J. J. Fripiat, Data Hankbook for Clay Materials and Other Non-metallic Minerals. Pergamon Press, New York, 346 pp., 1979.

Wang, C. Y., N. H. Mao and F. T. Wu, The mechanical property of montmorillonite clay at high pressure and implications on fault behavior. Geophys. Res. Lett., v. 6, p. 476, 1979.

Wang, C. Y., N. H. Mao and F. T. Wu, Mechanical property of clays at high pressure. Jour. Geophys. Res., v. 85, pp. 1462-1468, 1980.

The water content of the clays are shown in Table 2.

As was done previously at UC Berkeley (see Wang et al, 1980), the powder clays were first sieved and then put in a synthetic membrane pouch. Air among the particles was drawn out under a partial vacuum. The pouch is sealed and put under various confining pressures (2,3,4 kilobars) for a period of 24 to 72 hours.

The compressed clays are hard enough to be core-drilled with a .5 inch diameter hardened steel drill bit. The cores of 1.00 - 1.25 inch length are surface ground at both ends to within 1/1000 inch. The clay cylinders thus obtained were jacketed with heat-shrinkage tubing and capped with steel caps of .5 inches. The jacketed samples were coated with several layers of rubber and dried before subjected to triaxial tests.

The tests were all performed at Professor Randy Martin's laboratory at Penn State University.

The present series of experiments was performed with a strain rate of approximately 3x10(-4).

Figure 1-3 show the stress-strain curves for several clays at different confining pressures. Figure 4-7 show that the strengths of different clays under confining pressures of 2 to 4 kb.

Calcium montmorillonite is the weakest among the clays tested. It can be seen from figure 1, the maximum shear strength varies from 180 bars at 2 kb to 250 bars at 4 kb. The sodium montmorillonite is stronger than the cacium one, the strength varies from 420 bars at 2 kb to 550 bars at 4 kb (figure 2). Combining these data with those in Wang et al. (1979), we can infer that the strength decreases with decreasing strain rate (figure 8).

Kaolinite is quite a bit stronger than the montmorillonites (figure 3). At 2 kb confining pressure a concave upward portion of the stress- strain curves can be seen for both the well-crystalline and the poor-crystalline samples. But at higher confining pressures such behavior disappears. We do not yet have an explanation for this.

Hectorite is the strongest among the tested clays (figure 4). Although its cation exchange capacity is higher than that of the kaolinites. Most probably, such difference is due to the clay structural differences. The hectorite is trioctahedral and the kaolinites and the other clays are dioctahedral. It would be interesting to conduct another series of experiments with trioctahedral clays.
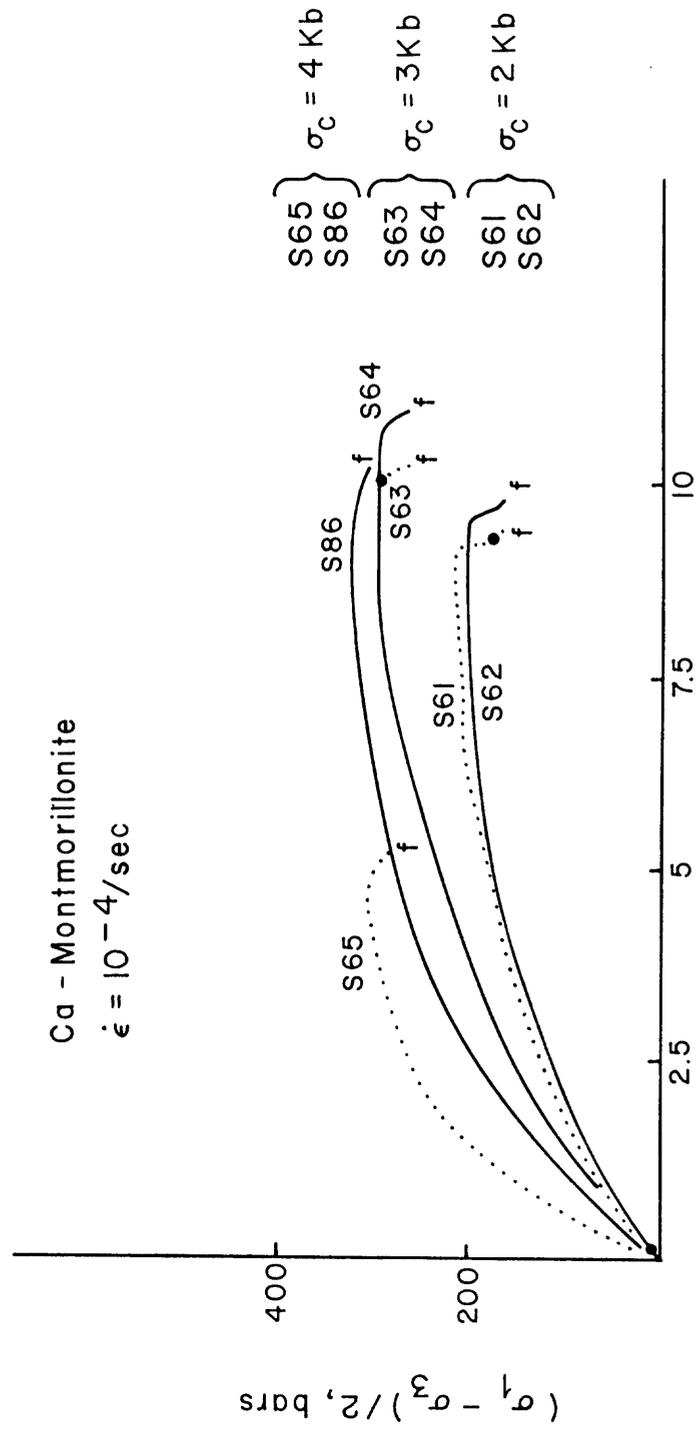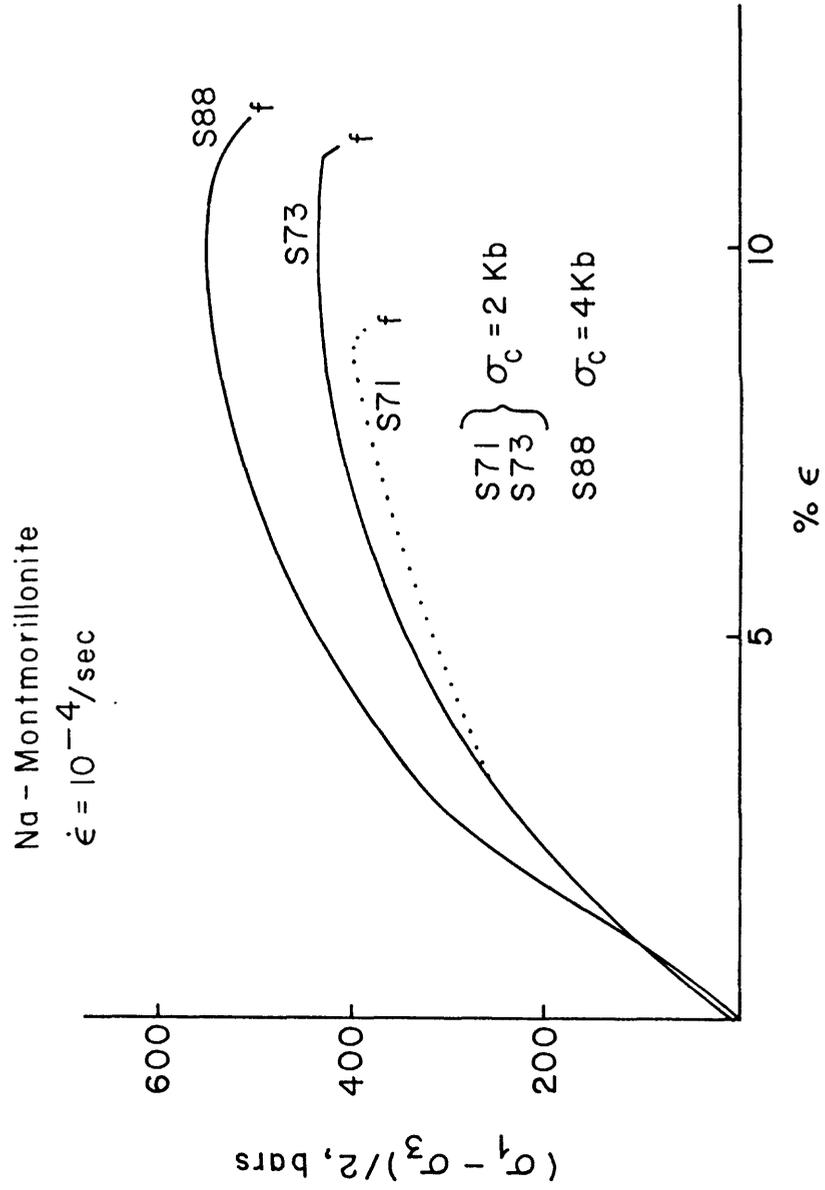
Figure 1

Ca – Montmorillonite
$\dot{\epsilon} = 10^{-4}/\text{sec}$

S86

S65

f

S64

f

S63

f

f

S61

S62

f

f

$(\sigma_1 - \sigma_3)/2$, bars

400

200

2.5   5   7.5   10

$\left.\begin{array}{c} \text{S65} \\ \text{S86} \end{array}\right\}$ $\sigma_c = 4\,\text{Kb}$

$\left.\begin{array}{c} \text{S63} \\ \text{S64} \end{array}\right\}$ $\sigma_c = 3\,\text{Kb}$

$\left.\begin{array}{c} \text{S61} \\ \text{S62} \end{array}\right\}$ $\sigma_c = 2\,\text{Kb}$

Figure 2

Figure 3

fig 4

SHCa-1
Hectorite

$\sigma_3 = 4\,Kb$

$\sigma_3 = 3\,Kb$

To $\epsilon_a = 20\%$ at 2.22 Kb

$\epsilon_a = 30\%$

$(\sigma_1 - \sigma_3)Kb/2$

ϵ %

fig 5

$\sigma_3 = 2 \, kb$

KGa-2

Swy-1

Saz-1

$\epsilon \, \%$

$(\sigma_1 - \sigma_3) Kb/2$

fig 6

$\sigma_3 = 3kb$

SHCa-1

KGa-1

Swy-1

Saz-1

$(\sigma_1 - \sigma_3)Kb/2$

$\epsilon \%$

fig 7.

$\sigma_3 = 4 \, kb$

SHCa-1

KGa-1

KGa-2

Suy-1

Sa$_3$-1

$(\sigma_1 - \sigma_3) Kb / 2$

$\epsilon \, \%$
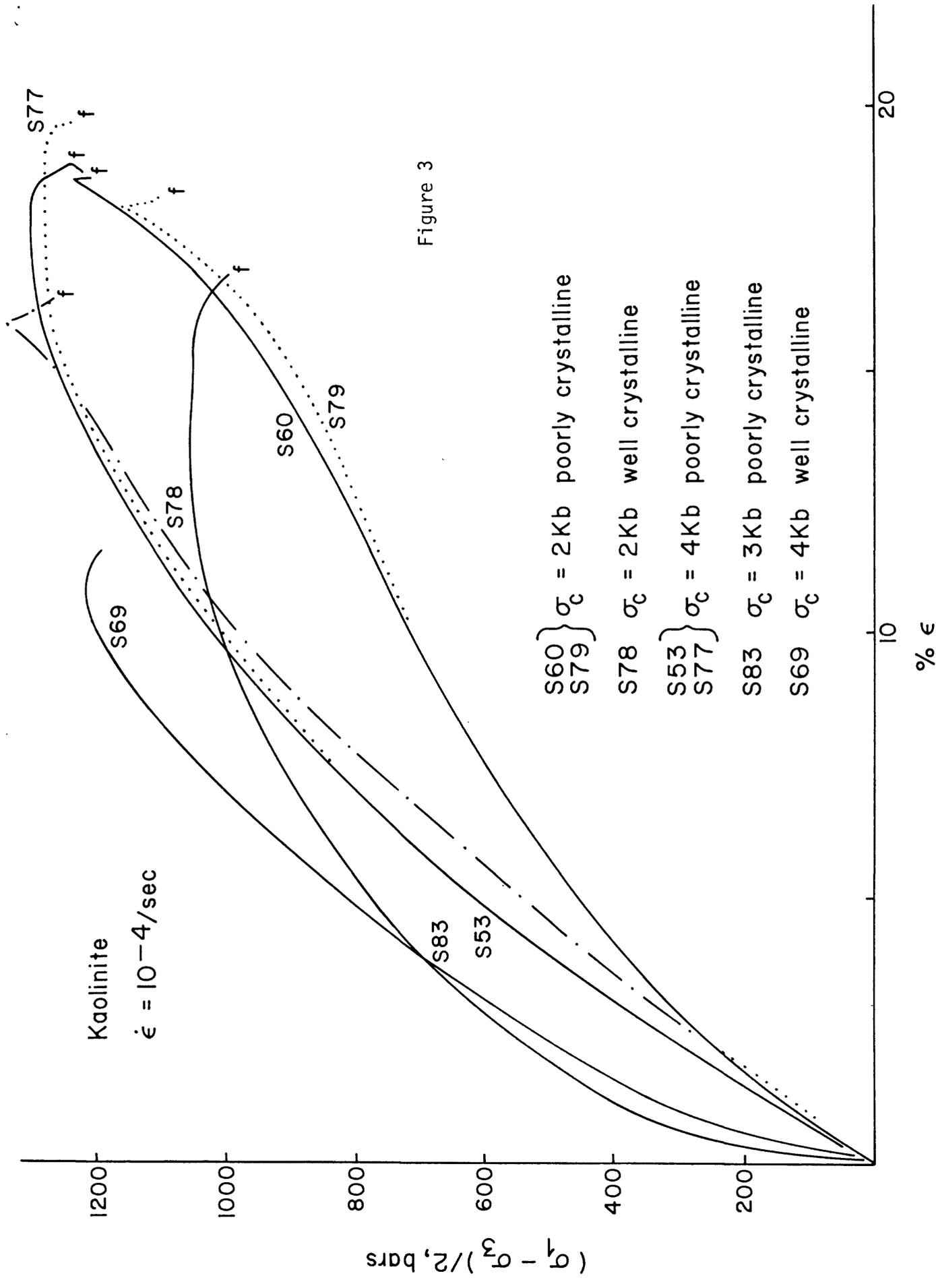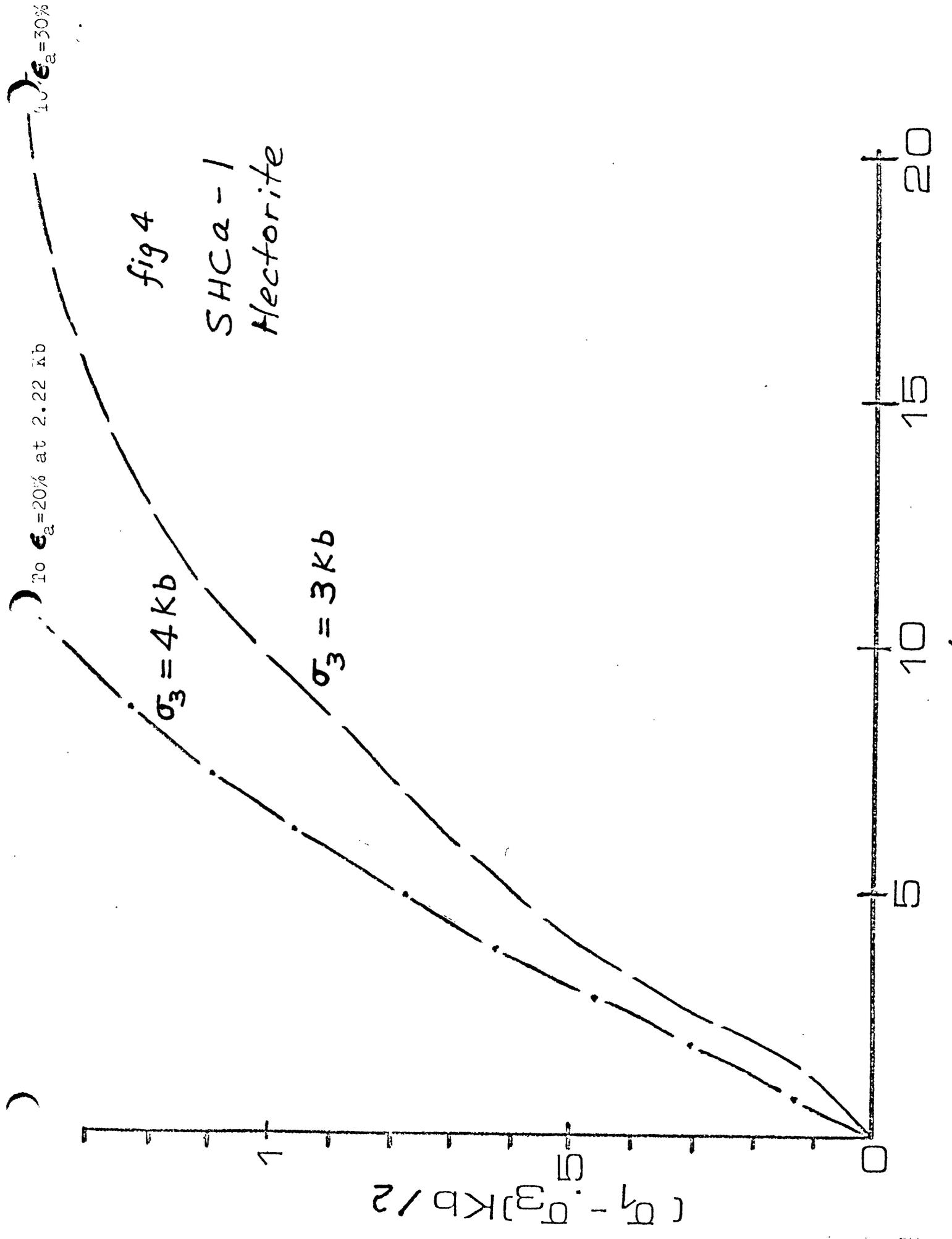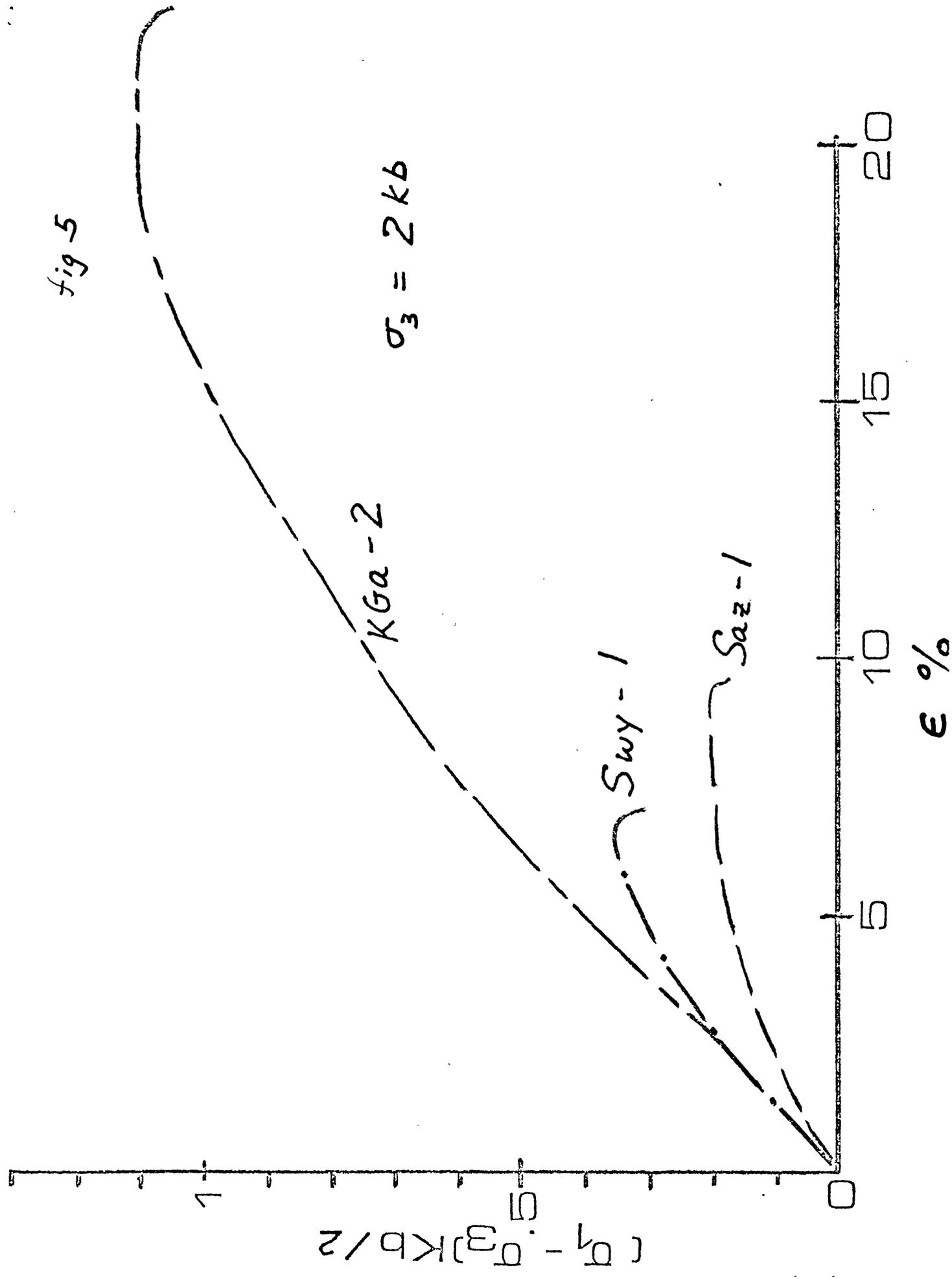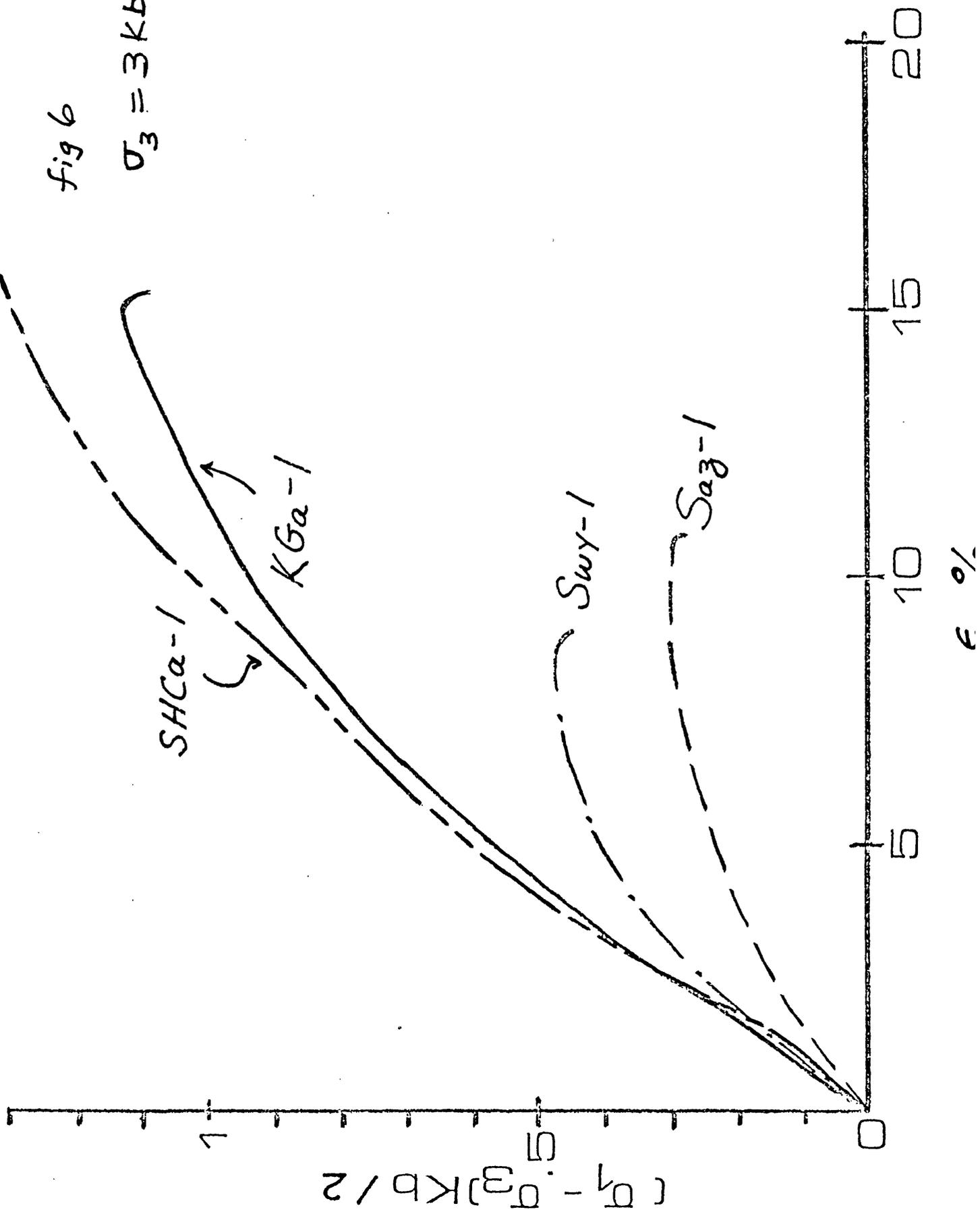
fig 8
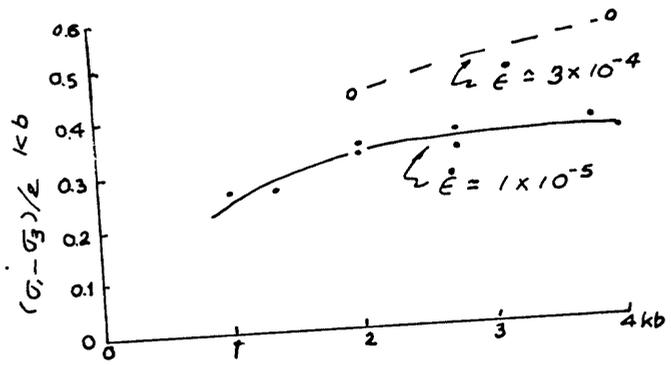
Figure 9
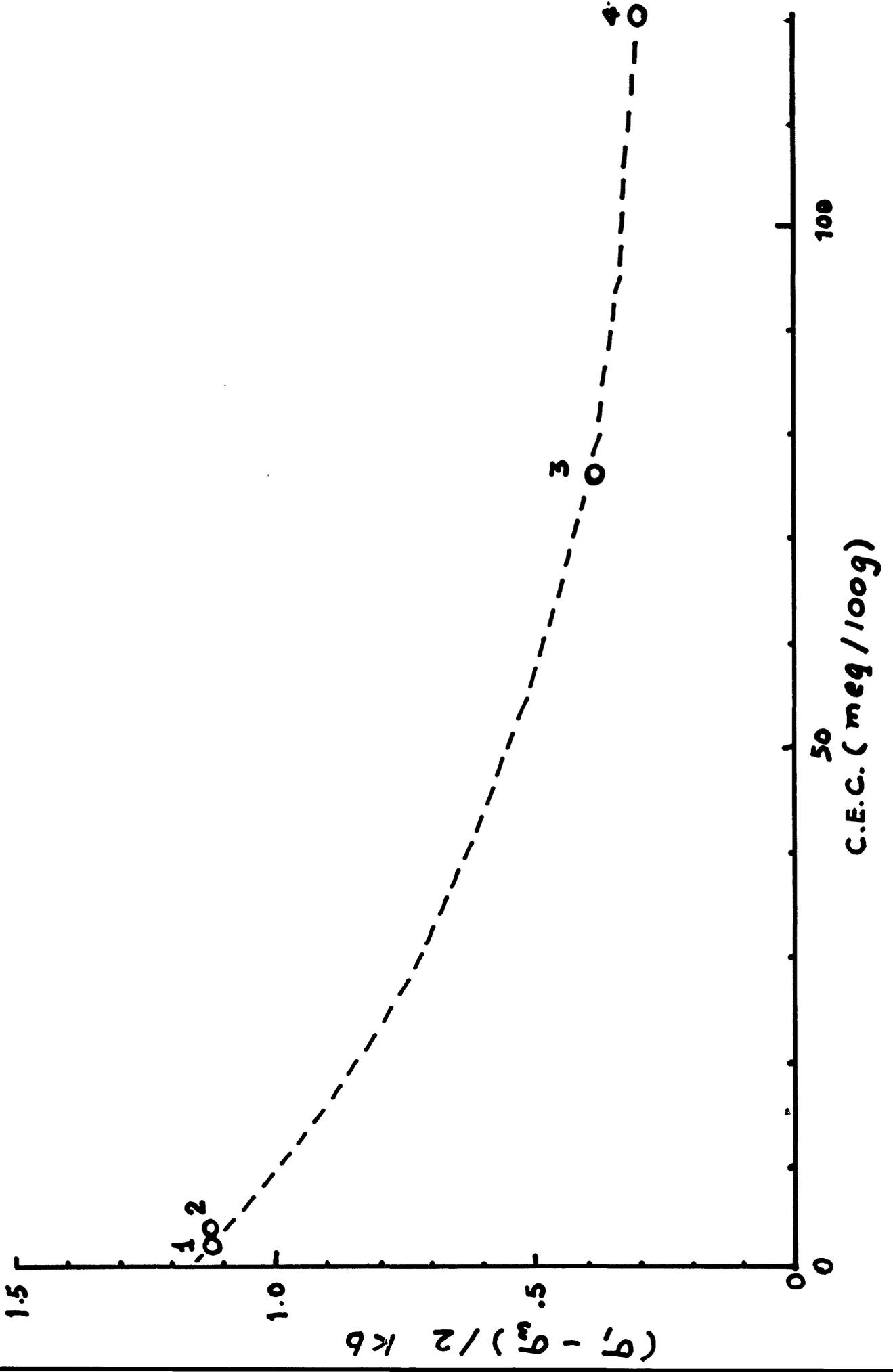
	KGa-1		KGa-2		SWy-1		SAz-1	HCa-1
	CL	MH	CL	MH	CL	MH	MH	MH
SiO_2	45.0	44.2	44.2	43.9	62.9	62.9	60.4	34.7
Al_2O_3	38.0	39.7	37.2	38.5	19.3	19.6	17.6	0.69
TiO_2	1.58	1.39	2.17	2.08	0.16	0.090	0.24	0.038
Fe_2O_3	0.26	0.13	1.14	0.98	3.85	3.35	1.42	0.02
FeO	0.02	0.08	0.05	0.15	0.12	0.32	0.08	0.25
MnO	0.00	0.002	0.00	--	0.01	0.006	0.099	0.008
MgO	0.02	0.03	0.04	0.03	2.80	3.05	6.46	15.3
CaO	0.02	--	0.04	--	1.80	1.68	2.82	23.4
Na_2O	0.01	0.013	0.02	<0.005	1.54	1.53	0.063	1.26
K_2O	0.04	0.050	0.02	0.065	0.56	0.53	0.19	0.13
Li_2O								2.18
P_2O_5	0.05	0.034	0.06	0.045	0.06	0.049	0.020	0.014
S	--	--	--	0.02	--	0.05	--	0.01
F (§)	(0.013)		(0.020)		(0.111)		(0.287)	(2.75)
(°)								(2.60)
ign.loss	14.31		14.24		5.10			
-550		12.6		12.6		1.59	7.54	1.20
550-1000		1.18		1.17		4.47	2.37	20.6
CO2					1.33			
total	99.38	99.40	99.18	99.54	99.54	99.22	99.30	99.80

Table 1: Chemical analyses of clay minerals
(from van Olphen and Fripiat, 1979)

		sample weight mg	ads. water %	struct. water %
KGa-1	Kaolinite, well crystallized	424.6	0.26	13.11
KGa-2	Kaolinite, poorly crystallized	363.2	0.74	13.14
SWy-1	Montmorillonite Wyoming	414.8	4.99	5.53
STx-1	Montmorillonite Texas	358.9	12.45	3.88
SAz-1	Montmorillonite Arizona	403.5	12.76	4.69
SHCa-1	Hectorite California	469.3	3.34	20.28°°
Syn-1	Synthetic mica-montmorillonite	230.4	3.56	10.35
PFl-1	Attapulgite Florida	239.2	12.96	5.52

Table 2: Water content of clay minerals
          (from: van Olphen and Fripiat, 1979)