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TRIAXIAL TESTING OF ICE:
A SURVEY OF PREVIOUS INVESTIGATIONS

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ABSTRACT

This paper is a compilation of previous experimental studies on the mechanical behaviour of ice under a triaxial state of stress. Fifty publications were extracted from the open literature and are summarised in a table.

INTRODUCTION

During the interaction of an ice feature with an engineered structure, the state of stress within the ice may involve significant levels of hydrostatic pressure. Triaxial testing of ice specimens provides a means to investigate this phenomenon. While consulting with earlier laboratory investigations, it was found that the amount of research done in this area is far more extensive than what the literature review in any given article would lead one to believe. The present paper is an attempt to guide the reader through this research.

SURVEY

This compilation only considers papers enclosing triaxial test data, and leaves out numerical and theoretical treatments. Testing under biaxial stress or plane strain conditions (*e.g.* Frederking 1977, Sinha 1984, Timco and Frederking 1986) was therefore not included. Investigations on the elastic properties of ice under confinement were not searched either. The reader is referred to Gagnon et al. (1988) for this topic. Moreover, all of the data encountered were obtained from the hexagonal polymorph of ice (Ih) with few exceptions (*e.g.* Kirby et al. 1985, Durham et al. 1996). These were also omitted. Finally, only the English literature was surveyed.

Table 1: List of abbreviations

C	Columnar-grained
CR	Constant rate
CS	Constant stress
D	Damage
F	Freshwater (non-saline)
G	Granular (isotropic)
I	Iceberg
L	Laboratory-made
M	Monocrystalline
N	Naturally-occurring
P	Polycrystalline
S	Saline
1Y	First year sea ice
<1Y	Multiyear sea ice

The results of our search is presented in Table 2 (the abbreviations used in this table are explained in Table 1).

Both artificial and naturally-occurring ice types were investigated. The control on the deviator was generally done in two ways. Constant strain rate tests are those for which either specimen deformation or the rate of relative displacement between the upper and lower platen was kept constant. Constant stress - or creep - tests were also used. The stress was usually nominal since few investigators (*e.g.* Jones 1978, Mizuno 1992, Melanson et al. 1999a) reported a correction to compensate for a change in specimen area (required especially when large strains are achieved). All confined testing was done with a compressive axial stress, with the exception of Rigsby (1958)(shear) and Haynes (1973) (tension). In a few cases, a damage mechanics approach, instead of conventional visco-elasticity, was applied to the behaviour of ice to acknowledge the effect of load history on further incremental deformation (*e.g.* Jordaan and collaborators). Maximum axial stress is indicated for constant load tests; the logarithm of strain rate is indicated for constant strain rate tests. The temperature range of the test series is also indicated, along with the salient results.

Specimen confinement was usually delivered by a hydraulic fluid. In some cases, a constant ratio between axial and confinement stresses was maintained throughout the deformation. True multiaxial testing with brush-type platens, whereby loading along all axes of three-dimensional space is controlled independently, was also conducted. For these cases, no maximum confinement is shown in the table. Discussions on the use of brush platens and multiaxial testing may be found in Haüsler (1981), Schulson et al. (1989), Haüsler et al. (1991) and Melton and Schulson (1998a).

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REFERENCES

Barrette P.D. and Jordaan I.J. 2001. Creep of ice and microstructural changes under confining pressure. In: S. Murakami and N. Ohno (Eds.). IUTAM Symposium on Creep in Structures. Kluwer Academic Publ., Boston, 479-488.

Beeman M., Durham W.B. and Kirby S.H. 1988. Friction of ice. J. Geophysical Research 93, B7, 7625-7633.

Blair S.C. 1988. Mechanical properties of first-year sea ice at intermediate strain rates. Proc. POAC Conf., Fairbanks, Alaska, Vol. 3, 1-9.

Cole D.M. 1996. Observations of pressure effects on the creep of ice single crystals. J. Glaciology 42, 169-175.

Cox G.F.N and Richter-Menge J.A. 1988. Confined compressive strength of multi-year pressure ridge sea ice samples. J. Offshore Mechanical and Arctic Engineering 110, 295-301.

Durham W.B., Heard H.C. and Kirby S.H. 1983. Experimental deformation of polycrystalline H_2O ice at high pressure and low temperature: Preliminary results. J. Geophysical Research 88, Supplement, B377-B392.

Durham W.B., Stern L.A and Kirby S.H.. 1996. Rheology of water ices V and VI. J. Geophysical Research 101, B2, 2989-3001

Frederking R.M.W. 1977. Plane strain compressive strength of columnar-grained and granular snow-ice. J. Glaciology 18, 505-516.

Gagnon R.E. and Gammon P.H. 1995. Triaxial experiments on iceberg and glacier ice. J. Glaciology 41, 528-540.

Gagnon R.E., Kiefte H., Clouter M.J., Whalley E. 1988. Pressure dependence of the elastic constants of ice Ih to 2.8 kbar by Brillouin Spectroscopy. J. Chemical Physics 89, 4522-4528.

Golubov A.I., Razbegin V.N. and Slepak M.E. 1990. Multiaxial creep of saline ice.
Proc. 1st European Offshore Mech. Symp., Trondheim, 556-561.

Goughnour R.R. and Andersland O.B. 1968. Mechanical properties of a sand-ice system. J. Soil Mechanics and Foundations Division, Proc. American Society of Civil Engineering SM-4, 923-950.

Gratz E.T. and Schulson E.M. 1997. Brittle failure of columnar saline ice under triaxial compression. J. Geophysical Research 102, B3, 5091-5107.

Haefeli R., Jaccard C. and De Quervain M. 1968. Deformation of polycrystalline ice under combined uniaxial and hydrostatic pressure. International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, General Assembly of Bern 1967, Publication # 79, 341-344.

Haüsler F.U. 1981. Multiaxial Compressive strength tests on saline ice with brush-type loading platens. Proc. 6th IAHR Conf., Québec, Vol. 2, 526-539.

Haüsler F.U., Matthies H.G. and Moore C.S. 1991. Sea ice under complex stress states: Constitutive modelling and testing. In: S.Jones, R.F. McKenna, J. Tillotson and I.Jordaan (Eds.) Ice-Structure Interactions. Proc. IUTAM-IAHR Symp., St.John's, Springer-Verlag, Berlin, 363-381.

Haynes F.D. 1973. Tensile strength of ice under triaxial stresses. CRREL report RR 312.

Jones S.J. 1978. Triaxial testing of polycrystalline of ice. Proc. 3rd Int. Conf. Permafrost, Edmonton, Vol. 1, 671-674.

Jones S.J. 1982. The confined compressive strength of polycrystalline ice. J. Glaciology 28, 171-177.

Jones S.J. and Chew A.M. 1983. Creep of ice as a function of hydrostatic pressure. J. Physical Chemistry 87, 4064-4066.

Kalifa P., Duval P. and Ricard M. 1989. Crack nucleation in polycrystalline ice under compressive stress states. Proc. 8th OMAE Conf., The Hague, Vol. 4, 13-21.

Kalifa P., Ouillon G., Duval P. 1992. Microcracking and the failure of polycrystalline ice under triaxial compression. J. Glaciology 38, 65-76.

Kirby S.H., Durham W.B. and Heard H.C. 1985. Rheologies of H_2O ices I_h, II and III at high pressures: A progress report. In: J. Klinger, D. Benest, A. Dollfus and R. Smoluchowski (Eds.), Ices in the Solar System, D. Reidel Publ. Comp., Hingham, MA, 89-107.

Mae S. and Azuma N. 1989. Ice sheet dynamics and rheology of ice under hydrostatic pressure. In: S. Karato and M. Toriumi (Eds.), Rheology of solids and of the Earth, Oxford University Press, N.Y., 209-222.

Meglis I.L., Melanson P.M. and Jordaan I.J. 1999. Microstructural change in ice: II. Creep behavior under triaxial stress conditions. J. Glaciology 45, 438-448.

Melanson P.M., Jordaan I.J. and Meglis I.L. 1999a. Modelling of damage in ice. In: H.T Shen (Ed.). Ice in surface waters. Proc. 14th Int. Symp. on Ice, A.A. Balkema, Brookfield, 979-988.

Melanson P.M., Meglis I.L., Jordaan I.J. and Stone B.M. 1999b. Microstructural change in ice :I. Constant-deformation-rate tests under triaxial stress conditions. J. Glaciology 45, 417-422.

Melton J.S. and Schulson E.M. 1995. Preliminary results on the ductile deformation of columnar saline ice under triaxial compressive loading. Proc. 14th OMAE Conf., Copenhagen, Vol. 4, 139-143.

Melton J.S. and Schulson E.M. 1997. The ductile deformation of columnar (S2) saline ice under triaxial compression. Proc. 7th ISOPE Conf., Honolulu, Vol. 2, 402-409.

Melton J.S. and Schulson E.M. 1998a. A comparison of the ductile compressive strength of columnar saline ice under proportional and conventional triaxial loading. Proc. 8th ISOPE Conf., Montréal, Vol. 2, 408-415.

Melton J.S. and Schulson E.M. 1998b. Ductile compressive failure of columnar saline ice under triaxial loading. J. Geophysical Research 103, C10, 21759-21766.

Mizuno Y. 1992. High temperature creep of polycrystalline ice under hydrostatic pressure. In: N. Maeno and T. Hondoh (Eds.), Physics and Chemistry of Ice, Hokkaido University Press, Sapporo, 434-439.

Mizuno Y. 1998. Effect of hydrostatic confining pressure on the failure mode and compressive strength of polycrystalline ice. J. Phys. Chem. B, 102, 376-381.

Murrell S.A.F., Sammonds P.R. and Rist M.A. 1991. Strength and failure modes of pure ice and multi-year sea ice under triaxial loading. In: S.Jones, R.F. McKenna, J. Tillotson and I.Jordaan (Eds.) Ice-Structure Interactions. Proc. IUTAM-IAHR Symp., St.John's, Springer-Verlag, Berlin, 339-361.

Nadreau J.P and Michel B. 1986a. Secondary creep in confined ice samples. Proc. 8th IAHR Conf., Iowa City, Vol. 1, 307-318.

Nadreau J.P and Michel B. 1986b. Yield envelope for confined ice. Proc. 1st Int. Conf. Ice Technology, 25-36.

Nadreau J.P., Nawwar A.M. and Wang Y.S. 1991. Triaxial testing of freshwater ice at low confining pressures. J. Offshore Mechanics and Arctic Engineering 113, 260-265.

Nawwar A.M., Nadreau J.P. and Wang Y.S. 1983. Triaxial compressive strength of saline ice. Proc. 7th POAC Conf., Helsinki, Vol. 3. 193-201.

Panov V.V. and Fokeev N.V. 1981. Compression strength of sea ice specimens under complex loading. In: A.F. Treschnikov (Ed.) Problems of the arctic and Antarctic, Division of Polar Programs, National Science Fondation, Washington, DC., Vol. 49, 97-104.

Richter-Menge J.A. 1991. Confined compressive strength of horizontal first-year sea ice samples. J. Offshore Mechanics and Arctic Engineering 113, 344-351.

Rigsby G.P. 1958. Effect of hydrostatic pressure on velocity of shear deformation of single ice crystals. J. Glaciology 3, 273-278.

Rist M.A. 1997. High-stress ice fracture and friction. J. Physical Chemistry B 101, 6263-6266.

Rist M.A, Jones S.J. and Slade T.D. 1994. Microcracking and shear fracture in ice. Annals of Glaciology 19, 131-137.

Rist M.A., Murrell S.A.F. and Sammonds P.R. 1988. Experimental results on the failure of polycrystalline ice under triaxial stress conditions. Proc. 9th IAHR Conf., Sapporo, 118-127.

Rist M.A. and Murrell S.A.F. 1994. Ice triaxial deformation and fracture. J. Glaciology 40, 305-318.

Sammonds P.R. and Murrell S.A.F. 1989. A laboratory investigation of the fracture of multi-year sea ice under triaxial stresses at -20C and -40C. Proc. 10th POAC Conf., Luleå, Vol. 1, 279-288.

Sammonds P.R., Murrell S.A.F. and Rist M.A 1989. Fracture of multi-year sea ice under triaxial stresses: Apparatus description and preliminary results. J. Offshore Mechanical Engineering 111, 258-263.

Sammonds P.R., Murrell S.A.F. and Rist M.A. 1998. Fracture of multiyear sea ice. J. Geophysical Research 103, C10, 21795-21815.

Schulson E.M., Gies M.C., Lasonde G.J. and Nixon W.A. 1989. The effect of the specimen-platen interface on internal cracking and brittle fracture of ice under compression: high-speed photography. J. Glaciology 35, 378-382.

Schulson E.M. and Gratz E.T. 1999. The brittle compressive failure of orthotropic ice under triaxial loading. Acta Materialia 47, 745-755.

Schulson E.M., Jones D.E., Kuehn G.A. 1991. The effect of confinement on the brittle compressive fracture of ice. Annals of Glaciology 15, 216-221.

Simonson E.R., Jones A.H. and Green S.J. 1975. High pressure mechanical properties of three frozen materials. Fourth International Conference on High Pressure, Kyoto, International Association for the Advancement of High Pressure Science and Technology, Physico-Chemical Society of Japan, Kyoto, 115-121.

Sinha N.K. 1984. Uniaxial compressive strength of first-year and multi-year sea ice. Canadian J. Civil Engineering 11, 82-91.

Stone B.M., Jordaan I.J., Jones S.J. and McKenna R.F. 1989. Damage of isotropic polycrystalline ice under moderate confining pressures. Proc. POAC Conf., Luleå, Vol. 1, 408-419.

Stone B.M., Jordaan I.J., Xiao J. and Jones S.J. 1997. Experiments on the damage process in ice under compressive states of stress. J. Glaciology 43, 11-25.

Timco G.W. and Frederking R.M.W. 1986. Confined Compression Tests : Outlining the Failure Envelope of Columnar Sea Ice. Cold Regions Science and Technology 12, 13-28.

Weiss J. and Schulson E.M. 1995. The failure of fresh-water granular ice under multiaxial compressive loading. Acta Metallurgica et Materialia 43, 2303-2315.

Table 2: Previous investigations on the triaxial testing of ice, arranged in chronological order by date of reference.

Investigator(s)	Ice type	Test	Max. P_c (MPa)	Max. Dev. (MPa)	Log_{10} strain rate (s^{-1})	Temp. (^oC)	Observations
Rigsby 1958	L,M,F	CS	31	0.26		-20 to -1	A higher temperature leads to higher shear strain rate. The latter is independent of hydrostatic pressure for a given difference between ice temperature and melting point.
Goughnour and Andersland 1968	L,P,F	CR	0.7		-3.9, -3.6	-12, -4	Strength increases with pressure at high strain rates, but varies little at the lower rate. Effect of load history investigated.
Haefeli et al. 1968	L,P,F	CS	30	0.08		-8.1 to -5.9	Higher confinement leads to higher creep rate of granular ice for a given ice temperature. This rate decreases again upon decrease in temperature equivalent to depression of pressure melting point.
Haynes 1973	L,G,F		0.2		-5	-7	Tensile strength tests. Axial stress delivered by confinement medium. Various confinement/axial stress ratios used. Yield stress decreases with increase in ratio.
Simonson et al. 1975	L,P	CR	200(ii)		-4 to 0	-10	Increase in strength with increasing strain rate. Decrease in strength with increase in hydrostatic pressure. Increase of pressure alone (no deviator) induces reduction in porosity, decrease in Young's modulus and melting of ice at 100 MPa.
Jones 1978, 1982	L,G,F	CR	85		-5.9 to -1.9	-12	Strength increases up to 25-30 MPa confinement but decreases slightly with further increase in confinement. This trend is more evident for higher strain rates. Stress exponent higher for unconfined than for confined. Confinement induces ductile (as opposed to brittle) deformation.
Panov and Fokeev 1981	L,P,S / N,S		12(i)	20		-23 to -1.9	Strength increases with confinement. Confinement is a ratio of axial loading.
Haüsler 1981	L,C,S	CR	(iii)		-3.7	-10	Strength vs stress ratios, and projection of a failure surface.
Jones and Chew 1983	L,G,F	CS	60	0.47		-10	Minimum creep rate is lowest at 15 MPa confinement then increases upon further increase in confinement. Activation volume discussed.
Durham et al. 1983	L,G,F	CR	350		-5.5 to -3.5	-196 to -15	Mapped brittle-ductile transition. Strength of granular ice increases with confinement at both end of temperature scales to confinements of 50 MPa. It then levels (for brittle behaviour) or drops (ductile behaviour) at higher confinements. Low temperature causes strength to increase. Enthalpy variation with temperature.
Nawwar et al. 1983	L,C,S	CR	2.8		-5.3 to -1.2	-2 to -20	Linear dependency of strength on confining pressure above 1MPa. At a confinement of 2.8 MPa the strength is about 2.3 times the uniaxial strength.

Kirby et al. 1985	L,G,F	CR	50		-6.5 to -2.5	-120 to -5	Identification of three flow regimes at different temperature intervals. Variation in activation energy discussed.
Nadreau and Michel 1986a,b	L,G,F / L,G,S / I	CR, CS	70	not provided	-6 to -4	-20,-10, -5, -3	Glen's exponent *n* decreases with increase in confinement. Increase of maximum shear stress up to 15-20 MPa confinement followed by decrease at higher confinement.
Blair 1988	1Y	CR	50		-2 to 3.3	-20 to -8	Axial strain as a function of hydrostatic pressure. Strength increases with mean stress up to 7.5 MPa and levels off at a higher confinement. Decrease in strength from $10^{-2}s^{-1}$ to 0.5 s^{-1} and levelling off at higher strain rate.
Rist et al. 1988	L,G,F	CR	30		-4, -3, -2	-20	Variation of failure mode with confinement. Strength increases with confinement for all strain rates.
Beeman et al. 1988	L,G,F	CR	250		-3.8, -2.7, -1.7	-196, -183, -158	Investigations of friction on 45 deg. saw cuts surfaces. μ = 0.55 and 0.20 below and above 10 MPa, respectively, of confining pressure. Independent of temperature and average sliding velocity.
Sammonds and Murrell 1989, Sammonds et al. 1989	>1Y	CR	30		-6 to -2	-40, -20, -10	Modes of failure described. Comparison of data with failure surfaces. Pressure dependence of fracture strength only for lowest temperature.
Cox and Richter-Menge 1988	>1Y	CR	20(i)		-5, -3	-20, -5	Constant ratio between radial and axial stress. Classification of stress-strain curves. Strength increases with increase in confinement and strain rate, and decreasing temperature.
Kalifa et al. 1989	L,G,F	CR	10		-4.6 to -3	-10	Confinement increases the deviatoric stress level and the strain when the first crack is observed. The cracks tend to form parallel to the largest stress deviator. Intra- vs intercrystalline cracks investigated.
Stone et al. 1989	L,G,F	CR,D	5		-4.3, -4, -3	-10	Damage, defined as change in apparent elastic moduli, is increased by confinement. Flow stress decreases and stabilises with repeated loading.
Mae and Azuma 1989	M,F / P,F		56(ii)		-7	-20 to -5	Stress relaxation tests on crystals. Activation volume. Effect of hydrostatic pressure on flow law of polycrystalline ice. Hydrostatic stress hardens crystals but softens polycrystals.
Golubov et al. 1990	L,P,S	CS	7(ii)	2.4		-5	Both strength (but not CR) and creep tests reported. Strength increases by a factor of 2.5 from lowest to highest hydrostatic pressure. Increase in creep rate with decrease in pressure. Volume strains discussed. Visco-elastic theory presented.
Richter-Menge 1991	1Y	CR	20(i)		-5, -3	-10	Constant ratio between radial and axial stress. Stress exponent not affected by confinement. Strength, strain at failure and initial tangent modulus increase with confinement for all orientation of columnar grained specimens. Classification of stress-strain curves.

Nadreau et al. 1991	L,C,F	CR	2.85		-5.5 to -1.4	-20, -10, -2	Specimens cut parallel, perpendicular and at an angle with the columnar structure. Strength increases with confinement and strain rate. Tear drop failure envelope discussed.
Schulson et al. 1991	L,G,F	CR	(iii)		-3	-40	Fracture stress increases with confinement ratio. Brittle mechanisms discussed and cracking mechanism presented.
Murrell et al. 1991	L,G,F / >1Y	CR	30		-5 to -2	-40, -20, -10	Brittle and ductile failure described, through specimen yield mode and acoustic emission. Increase in strength with confining pressure (up to 10-15 MPa) is more significant at higher strain rate.
Mizuno 1992	L,G,F	CS	35	3		-10 to -0.8	Accelerating creep, grain growth and preferred crystal orientation followed by strain rate reduction and grain refinement. Interpretation of minimum creep rate in terms of homologous temperature. Activation enthalpy is higher above -6^{o}C and for higher pressure.
Kalifa et al. 1992	L,G,F	CR,D	10		-5.2 to -2.3	-10	Crack density decreases and peak stress and corresponding strain increase with confinement. At higher strain rates, the strength of ice decreased with increase in grain size. Relative contribution of elastic strain to total strain is reduced at higher confinement assuming damage does not affect elastic modulus.
Rist and Murrell 1994	L,G,F	CR	46		-5 to -2	-40 to -5	Cracking activity mapped as a function of confinement and strain rate. At high strain rate, strength increases up to 10 MPa confinement, above which it becomes pressure-independent. At low strain rate, it is mostly pressure independent. Failure modes, activation energy and friction.
Rist et al. 1994	L,G,F	CR,D	30		-4, -2	-20	Shear fracture strength weakly dependant on confinement. Crack sliding not observed. No effect of damage on fracture strength. Pressure prevents cracking and reduce post-failure drop, despite 4^{o}C decrease in pressure-melting point.
Gagnon and Gammon 1995	I	CR	14		-4.3 to -1.3	-16 to -1	Variation of failure mode mapped with pressure-strain rate. Strength increases with decreasing temperature, increasing strain rate up to $5x10^{-3}$ s^{-1}, and increase in confinement at lower temperatures. Friction and activation energy discussed.
Weiss and Schulson 1995	L,G,F	CR	(iii)		-3	-40, -20, -10	Brittle to 'pseudo'-ductile failure of granular ice ice under various loading configurations. At low confinement, failure stress increases with confinement. Role of boundary conditions in ice failure at high confinement. Failure stress related to the boundary conditions.
Cole 1996	L,M,F	CS	19	0.33		-10	Small variations of steady-state strain rate with axial load and pressure.
Rist 1997	L, M / L,G	CR	20		-3, -2	-20, -10	Elastic-brittle failure mode of crystals with different orientations and polycrystals. Correspondence of shear and normal stresses. Frictional sliding along yield surfaces investigated.
Gratz and Schulson 1997	L,C,S	CR	(iii)		-2.2	-10	Brittle failure of columnar grained ice under various loading configurations. Three regimes of behaviour described. High sensitivity

							of strength to confining stress. Frictional cracking mechanisms.
Stone et al. 1997	L,G,F	CS, CR, D	20	7.65	-4	-10	Confinement suppresses cracking in favour of recrystallisation and void formation. Creep enhancement due to damage more important when damage done under triaxial conditions. Pressure reduction leads to increase in deformation.
Melton and Schulson 1995, 1997, 1998a,b	L,C,S	CR	(iii)		-4.4	-10	Ductile failure of columnar grained ice under various loading configurations. Strength independent of along-column confinement under small across column confinement but increases with along column stress at high across column confinement.
Mizuno 1998	L,G,C,F	CR	50		-3.5 to -1.3	-11	Peak in strength at mid-confinement for high strain rate. This peak increases with strain rate and grain size. Internal structure discussed.
Sammonds et al. 1998	>1Y	CR	30		-6.3 to -2	-40 to -3	Failure modes. Pressure dependency of failure modes across brittle-ductile transition. Frictional sliding investigated. Shear fracture weakly pressure dependant at -20^{o}C and above, stronger dependency at -40^{o}C up to 14 MPa confinement. Fracture toughness investigated.
Melanson et al. 1999a	L,G,F	CS, D	60	24		-10	High strains achieved to investigate tertiary creep behaviour. Deformation described by a damage parameter whose rate decreases at mid pressure range and increases again at higher pressure. Constitutive model presented.
Schulson and Gratz 1999	L,C,F	CR	(iii)		-2.2	-10	Brittle failure of columnar grained ice studied with various loading configurations. Similar mechanisms to those observed in saline ice at same conditions (Gratz and Schulson 1997).'Splay' cracking mechanism described.
Melanson et al. 1999b	L,G,F	CR	20		-4, -2	-10	Higher peak stress at high strain rate. Reduction of grain size observed between strain at failure and 3-5% strain, stabilises upon further deformation.
Meglis et al. 1999	L,G,F	CS,D	60	25		-10 to -8	Stress exponent independent of confinement and strain level. Viscosity decreases with strain up to 44%. Microcracking and dynamic recrystallization predominate at low and high confinement, respectively. Characterisation of microstructure with strain and confinement.
Barrette and Jordaan 2001	L,C,F	CS	70	30		-10	Viscoelastic compliance highest at low and high pressure ranges, with a minimum in between. The morphology of shear fractures at low and high confinement is compared.

(i) Estimated. (ii) Hydrostatic (mean) stress. (iii) Multiaxial, brush-type platens.