PETROPHYSICAL STUDIES OF SANDSTONES UNDER TRUE-TRIAXIAL STRESS CONDITIONS

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ABSTRACT
Development of an innovative polyaxial (true-triaxial) stress loading system is described. The system was originally designed to determine ultrasonic velocities, fluid permeability and elastic properties on cubic rock specimens in which sets of orientated fractures and microcracks had been introduced. The original system was used also in conjunction with differential strain analysis (DSA) to compare DSA with ultrasonic shear-wave splitting (USWS) for predicting the *in situ* state of stress in rock masses.

The system was then modified to incorporate acoustic emission (AE) sensors, in addition to the ultrasonic velocity transducers, to investigate laboratory-induced fracturing of a sandstone and to analyse directly the mechanics driving the fracturing.

The loading system has subsequently been modified further to incorporate a pressure-sealing scheme, to enable high pore pressures to be achieved, and a dedicated loading frame with all principal stresses servo-controlled. In this latter form the system has been used to study directional permeability and electrical conductivity, pore volume change and capillary pressure characteristics at elevated external stresses and pore pressures, in addition to the measurements for which it was originally designed.

INTRODUCTION
A polyaxial (true-triaxial) stress loading system, based partly on a design described by Sayers *et al.* (1990), was developed originally for determining the ultrasonic velocities, fluid permeability and elastic properties on 51 mm-side cubic rock specimens. In this form, each of the three principal stresses could be varied independently in the range zero to 115 MPa in the horizontal principal directions and to over 750 MPa in the vertical principal direction. The pore pressure of the original system could be varied in the range zero to 3 MPa.

The system consists of a loading frame in the form of an aluminium-alloy ring within which two pairs of 30-tonne hydraulic rams (matched in load-actuating pressure characteristics) and ultrasonic transducer holders are mounted to provide orthogonal stresses on the cubic rock specimen in the horizontal plane. The horizontal principal stresses are manually controlled in the original system. The loading frame is shown

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diagrammatically in Fig. 1 and is illustrated in Fig. 2. A cubic sandstone specimen is shown mounted in the loading frame in Fig. 3.

The vertical principal stress on the cubic specimen is provided by a pair of transducer holders mounted in a 200-tonne closed-loop servo-controlled testing machine, as illustrated in Fig.4. Stress is transmitted to each of the six faces of the cubic rock specimen through 5 mm-thick plates, matching approximately the elastic properties (E/ν) of the rock specimen, in order to reduce frictional effects as the normal stress is changed. Magnesium has been found to be a suitable material for high-porosity sandstones. The edges of the cubic rock specimen, surrounded on six sides by the 5 mm-thick plates, chamfered at the edges, are sealed with RTV rubber. This degree of sealing has been found sufficient to permit pore pressures up to 3 MPa to be maintained within the rock specimen. Deformation of the rock is recorded by a pair of LVDTs mounted adjacent to the specimen in each of the three principal directions.

Each of the six transducer holders contains stacks of PZT piezo-electric transducers (CNS Farnell, Borehamwood, London) for producing or detecting pulses of compressional (P) and two shear (S) waves polarized at right angles propagating in each of the three principal directions. The transducer holders are similar to those described in Tao and King (1990), with bandwidths in the range 450-800 kHz for P-wave and 350-750 kHz for S-wave pulses. The system permits measurement of the deformation and elastic wave velocities and attenuation in each of the three principal directions as the rock specimen is subjected to a polyaxial state of stress.

Employing the time-of-flight technique (King, 1983) with digitized elapsed time and correcting for specimen deformation, nine components of velocity are calculated: three P and six S, as indicated in Fig. 5. Both P- and S-wave velocities may be measured with an accuracy of +/-1% and a precision of +/-0.5%. The redundancy in S-wave velocity measurements (three required from six measurements) provides the opportunity to confirm that the state of stress within the rock specimen is indeed homogeneous. Attenuation measurements are made using the spectral ratios technique with a 51 mm-side aluminium cube as a standard (Tao *et al.*, 1995), including corrections for the effects of diffraction. Arrangements are made for measuring fluid permeability in the major principal direction.

The system has also been used in conjunction with differential strain analysis (DSA) to compare this technique with that of ultrasonic shear-wave splitting (USWS) for predicting the *in situ* state of stress in rock masses (Widarsono *et al.*, 1998). Both techniques employ cubic specimens of rock of the same size.

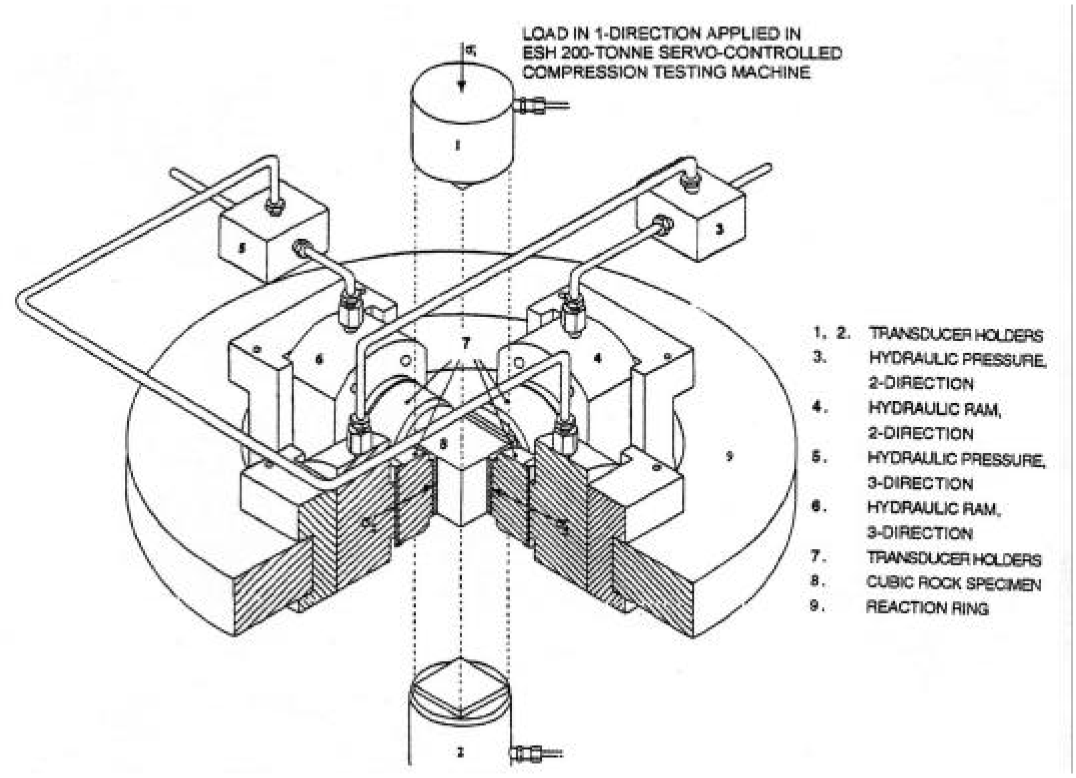

Fig. 1: Diagrammatic view of the true-triaxial loading frame

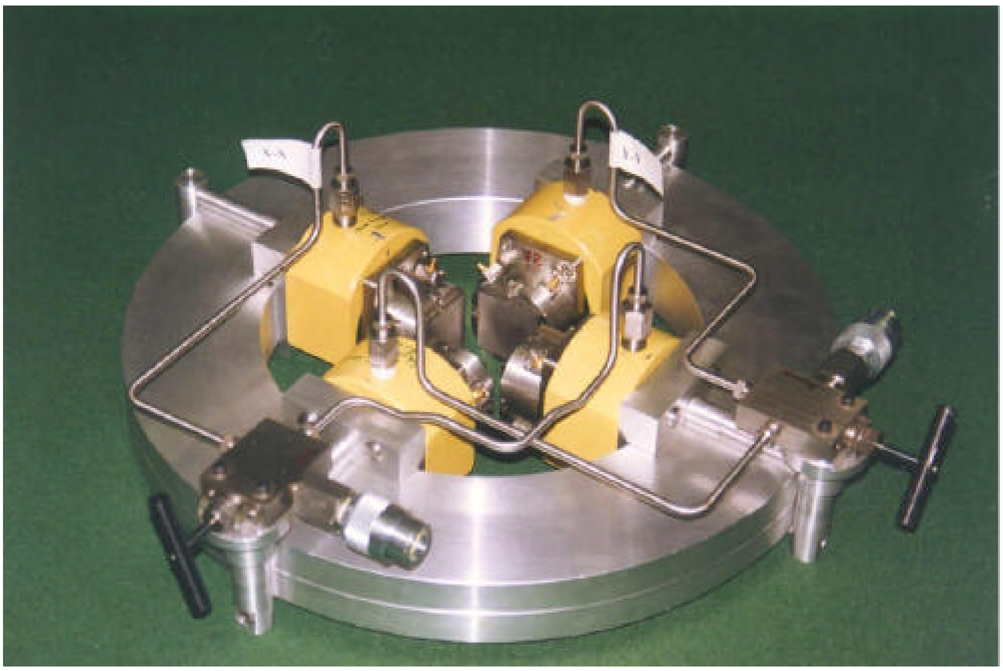

Fig. 2: Loading frame, showing rams and transducer holders for measurements in horizontal plane

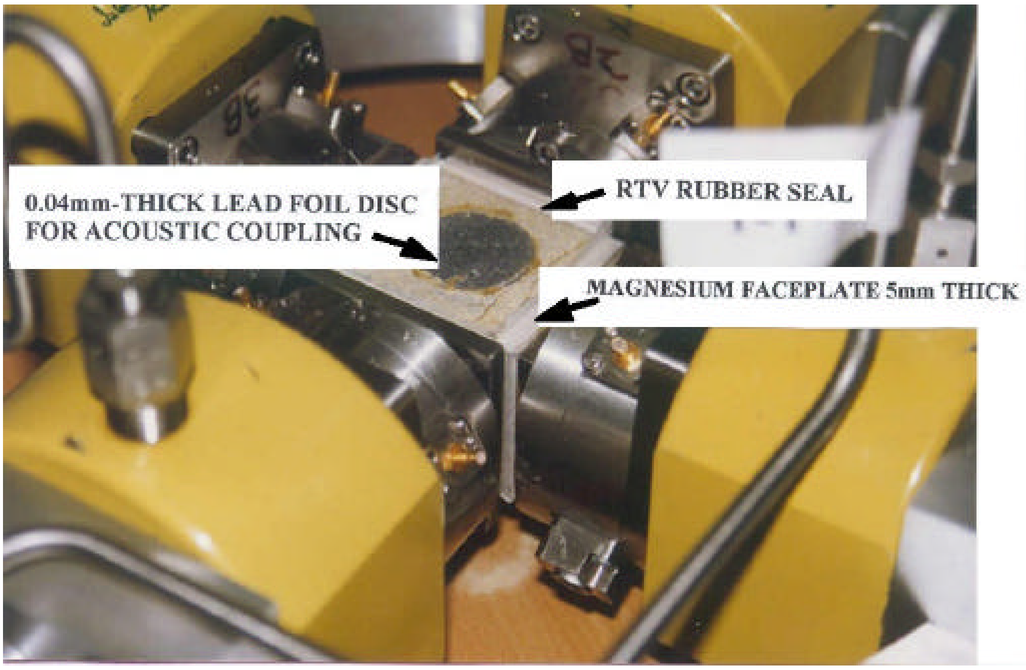

Fig. 3: Loading frame, showing 51-mm side cubis sandstone specimen with 5-mm thick magnesium plated between platens and specimen

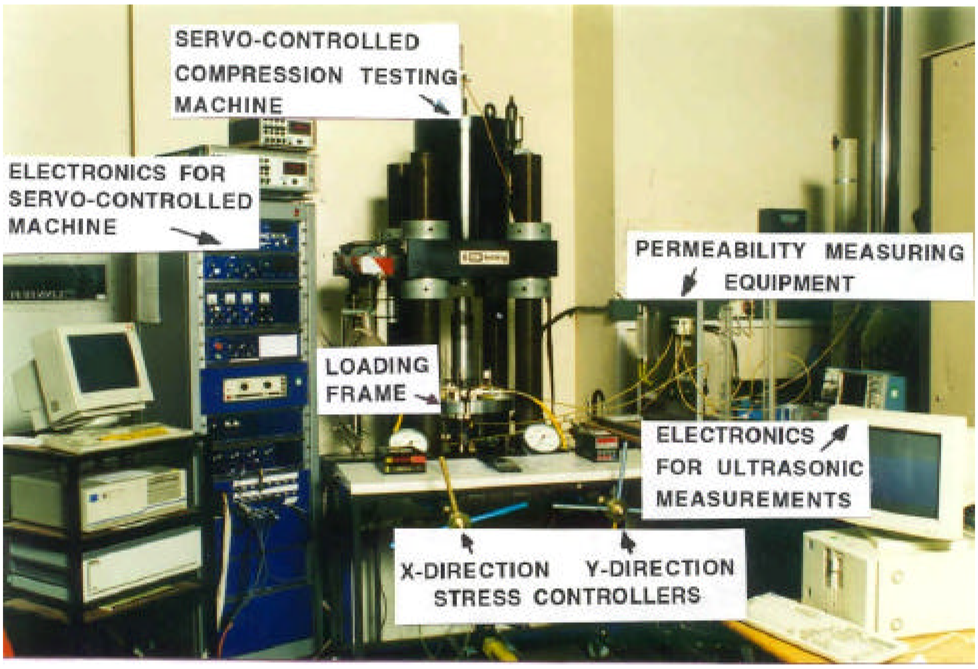

Fig. 4: Loading frame mounted in ESH 200-tonne servo controlled compression testing machine

Versatility of the system is demonstrated by a number of modifications that have been incorporated for different research purposes. First, Pettitt *et al.* (1998) replaced the upper and lower ultrasonic transducer holders with a different pair, each incorporating an array of six pin transducers, in order to study acoustic emission (AE) associated with the fracturing of a sandstone under controlled stress conditions. The system was calibrated using the ultrasonic transducers to provide controlled pulses of P- and S-wave energy. During loading and unloading tests it was demonstrated that there were very few AE events associated solely with the magnesium plate/rock specimen interfaces, indicating that use of the latter is indeed successful in reducing friction at the platen/rock interfaces.

Subsequently, the system was modified (Ergotech, Glan Conwy, Wales) to accommodate 40 mm-side cubic rock specimens (Al-Harthy *et al.*, 1998; 1999). To enable the use of elevated pore pressures, a pressure-sealing scheme (Fig. 6) and a dedicated loading frame have been incorporated. Each faceplate in contact with the specimen is made of a glass-fibre filled thermoplastic material (PEEK), which is non-porous and insulating, and which matches the elastic properties of sandstones. The system now is capable of achieving servo-controlled principal stresses independently to 200 MPa and pore pressures to 145 MPa. In addition to the original experimental uses outlined above, the system permits measurements of directional single-phase and relative permeability, directional electrical conductivity, pore-volume change and capillary pressure under these stress conditions.

RESULTS AND DISCUSSION

Geophysical Investigation

The experimental system has been successfully employed (King *et al.*, 1995) to introduce sets of fractures and microcracks orientated in a plane perpendicular to the minimum principal stress in a number of sandstone specimens. These are introduced by increasing two of the principal stresses in unison, while maintaining the third at a low level, until failure of the rock commences. The aligned discontinuities are distributed in a homogeneous manner throughout the rock specimen, as indicated by agreement between the redundant S-wave velocity measurements and as later observed when the rock specimen was removed from the apparatus. A high degree of correlation was found between fluid permeability measured in the direction of the aligned fractures and cracks, as these were closed under hydrostatic stress, and the velocities and attenuation of certain P and S waves. These include both P and S waves propagating normal to the discontinuities, and S waves propagating parallel, with polarization normal, to the discontinuities (King *et al.*, 1997). The results indicate that shear-wave splitting can provide a good measure of changes in permeability in a medium containing a system of orientated fractures and microcracks.

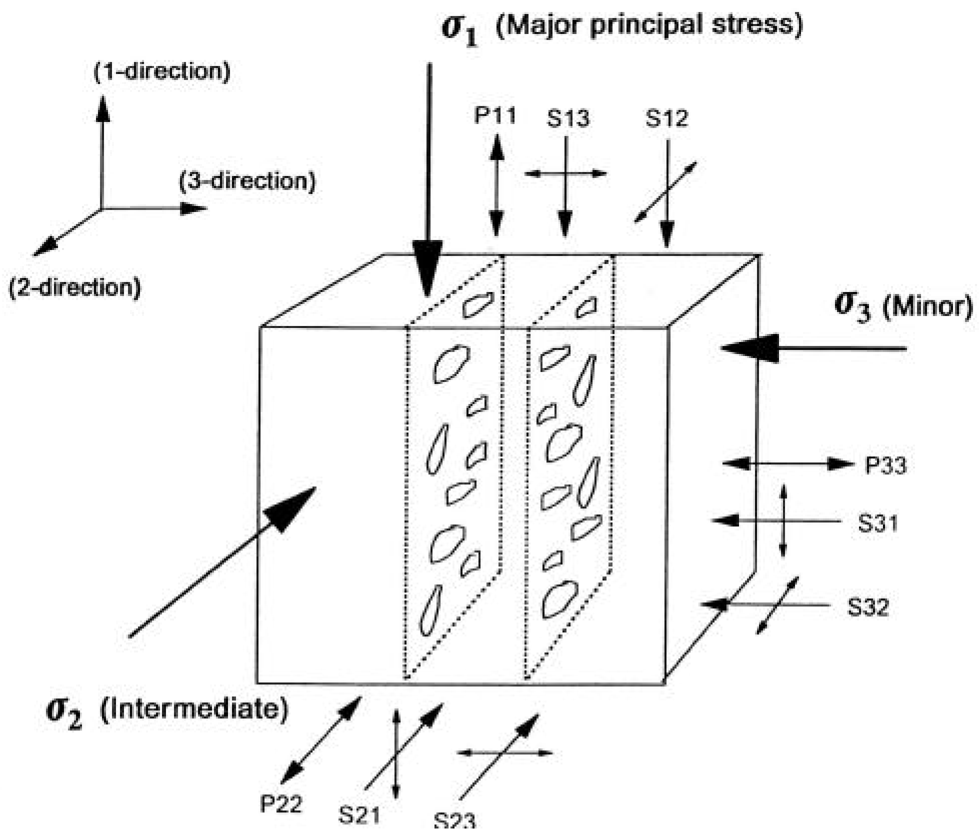

Fig. 5: Directions of propagation and polarization of the nine components of velocity with respect to the principal axes and planes of aligned fractures and microcracks

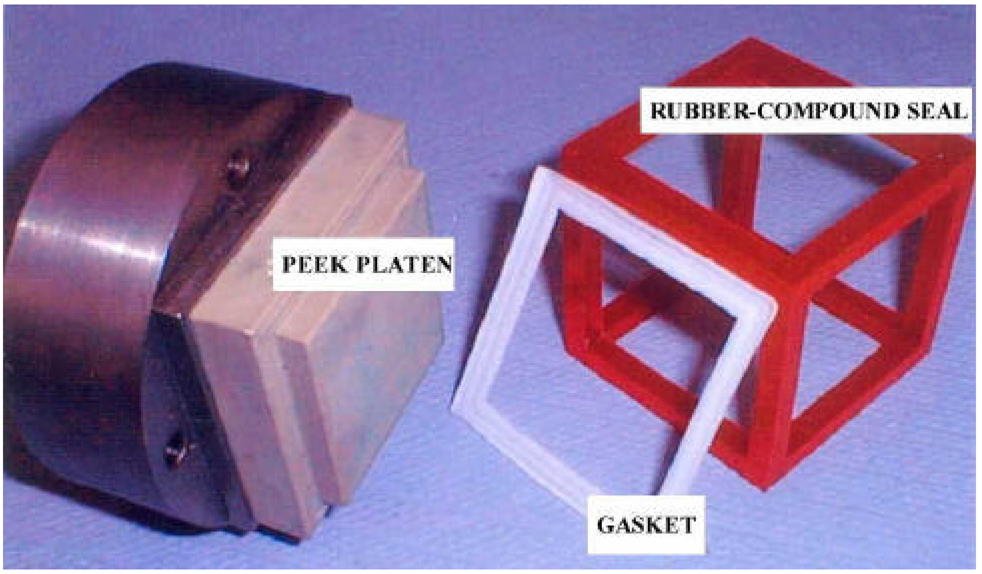

Fig. 6: Pressure sealing system for 40-mm side cuboc rock specimens

Shakeel and King (1998) demonstrate that the anisotropy in P-wave velocity in dry rocks is greater in magnitude and more sensitive to the presence of aligned fractures than that observed for S waves. In modelling studies, Shakeel and King (1998) indicate that the anisotropy in P-wave velocity is greatest when the saturating fluid is very compressible (gas) and when the fractures have small aspect ratios, whereas the magnitude of anisotropy in S-wave velocities is almost unaffected by the nature of the saturating fluid.

Widarsono *et al.* (1998) have made a study involving comparison between two laboratory techniques, based on the closure stress-relief microcracks on cubic rock specimens of the same size machined from core recovered from boreholes, for determining the *in situ* state of stress in a rock. Measurements on a number of sandstone samples made using the well-established technique of DSA, have been compared with the comparatively new technique of USWS using the true-triaxial loading system. Results of the research programme indicate that the USWS technique, with its ability to test a large number of samples quickly, provides a useful adjunct to DSA and borehole sleeve fracturing in determining trends for *in situ* stresses.

Employing the true-triaxial laboratory system, modified to undertake AE monitoring, Pettitt *et al.* (1998) simulated the stresses resulting from the excavation of large openings in rock underground. Pettitt *et al.* (1998) used triaxial stress measurements, three-dimensional ultrasonic surveys and AE studies to investigate laboratory induced fracturing of a sandstone. A moment tensor inversion procedure was developed to locate AE and to analyse directly the mechanics driving the fracturing. In both triaxial loading and triaxial unloading tests, the AE source mechanisms were shown to have a significant isotropic component. The mechanics of fracturing fit a combination of both Mode 1 tensile and shear sources, with orientations agreeing with fracturing parallel to the major principal stress direction.

Petrophysical Properties

Employing 40 mm-side cubic sandstone specimens with a special pressure-sealing scheme (Fig. 6) in the true-triaxial loading system, Al-Harthy *et al.* (1998) examined the effects of changes in pore pressure under hydrostatic, triaxial and polyaxial stress conditions. In particular, their study addressed the effects of hysteresis and stress-path on permeability under these stress conditions prior to incorporating the data into a reservoir simulator. Results of the study indicate the importance of petrophysical measurements under true-triaxial stress conditions and highlight some important implications with regard to the management of stress-sensitive reservoirs.

Using the same experimental system, Al-Harthy *et al.* (1999) report a study of directional permeability, directional electrical conductivity and pore volume change under conditions of hydrostatic and polyaxial stresses. Measurements of permeability and electrical conductivity were made in each of the three principal directions, with the objective of investigating their directional and stress dependence under polyaxial stress conditions. Table 1 shows the directional permeability and resistivity of a sandstone reservoir sample (from an oilfield n Oman) under an equivalent hydrostatic stress of 34.5 MPa. The results show that there is a strong permeability anisotropy, and a clear resistivity anisotropy in the three different directions (x:y:z). The observed permeability anisotropy is much more severe than the electrical anisotropy. This small scale anisotropy is attributed to packing and orientation of sand grains and laminations perpendicular to the z-direction. This has important implications for petrophysical evaluations and for reservoir engineering calculations. The results have demonstrated the importance of measuring directional transport properties and pore volume changes under realistic stress conditions.

Figure 7 shows the permeability of two adjacent outcrop samples in the z-direction vs. pore pressure simulating depletion for both hydrostatic and true triaxial stress paths. The permeability values are normalised to the initial values before depletion. The equivalent hydrostatic stress was set as the arithmetic mean of the three stresses in triaxial conditions. The results show a decrease in permeability of about 60% as pore pressure decreases, and up to 10% more reduction in permeability is observed under hydrostatic stress. The effect of stress path is likely to be more significant for more stress sensitive reservoirs such as fractured and very low permeability reservoirs. Figure 8 shows the results of oil/brine drainage capillary pressure curves under hydrostatic vs. true triaxial stresses. The results are consistent with the permeability results discussed above, i.e., equivalent hydrostatic loading causes more significant change in petrophysical than the true triaxial loading. The results can be explained by the nature of grain-gain contacts for non-spherical grains which are aligned according to the depositional environment. Similar results have been found for a range of reservoir and outcrop sandstones (Al-Harthy et al., 1999).

Table 1: Directional permeability and resistivity on a 40 mm cubic core sample (MM 220)

Directions	K(mD)	R(ohmm)	FF	m	$K_{x,,y}/K_z$	$R_{x,y}/R_Z$
X	366	3.27	22	1.9	24.4	0.63
Y	220	3.26	22	1.9	14.7	0.62
Z	15.0	5.22	36	2.2	-	-

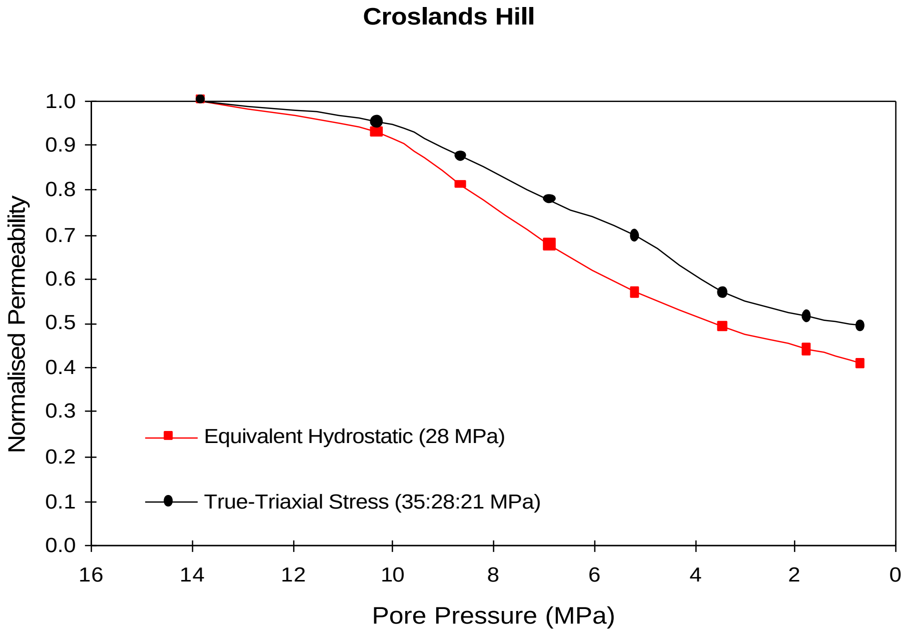

Fig. 7: Effect of pore pressure on permeability under different stress conditions

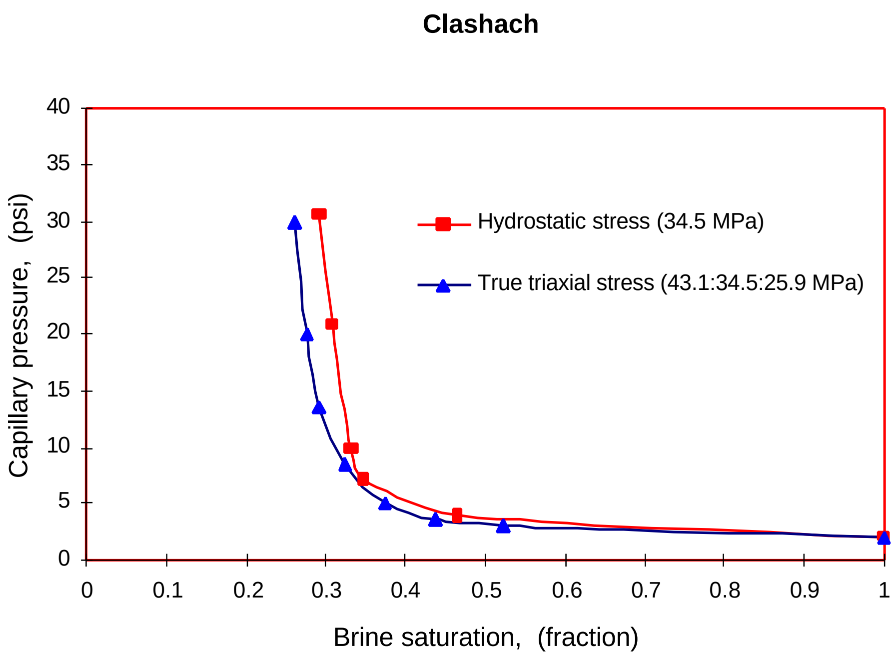

Fig. 8: Drainage capillary pressure curves under different stress conditions

CONCLUSIONS

1. The true-triaxial loading system has been used successfully to study relationships between directional fluid permeability and P- and S-wave velocities in sandstone specimens in which sets of orientated fractures and microcracks had first been introduced.

2. The system has been used to compare USWS with DSA to predict the *in situ* state of stress in rock masses.

3. In modified form, the system has been used successfully to study AE associated with the fracturing of a sandstone under controlled polyaxial stress conditions.

4. With further modifications, the system has been used successfully to study directional permeability, directional electrical conductivity and pore volume change in sandstones under polyaxial stress conditions. The modified system has also been used to study the effects of hysteresis and stress-path on permeability.

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NOMENCLATURE

AE	Acoustic emission
DSA	Differential strain analysis
E	Young's modulus
LVDT	Linear variable differential transducer
ν	Poisson's ratio
P-wave	Compressional-wave
PZT	Lead zirconate titanate
S-wave	Shear-wave
σ	Stress
USWS	Ultrasonic shear-wave splitting

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