ORIGINAL PAPER

Comparison of stresses obtained from Acoustic Emission and Compact Conical-Ended Borehole Overcoring techniques and an evaluation of the Kaiser Effect level

Ergün Tuncay · Yuzo Obara

Abstract The purpose of the study was to compare stress values obtained from Acoustic Emission and Compact Conical-Ended Borehole Overcoring stress measurement techniques applied at an underground limestone mine in Japan, and to investigate the effect of rock anisotropy and confining pressure on the Kaiser Effect level which has been used to determine in situ stresses by the Acoustic Emission technique. Initially, Acoustic Emission tests were carried out on limestone cores extracted from horizontal boreholes in a pillar and hanging wall in the underground mine. The stress values obtained were two or three times greater than those obtained by the Compact Conical-Ended Borehole Overcoring method. In the second stage, the anisotropy of a granite block was determined by P-wave measurements. Core specimens extracted from two different directions were pre-loaded under axisymetric triaxial conditions by applying a series of differential stresses. The cores were then re-loaded under uniaxial conditions and the Kaiser Effect levels were determined. It was concluded that both the anisotropy and confining pressure have an important influence on the Kaiser Effect level.

Keywords Acoustic Emission (AE) · Compact Conical-ended Borehole Overcoring (CCBO) · Kaiser Effect (KE) · Rock anisotropy · Rock stress

Résumé Le but de l'étude était de comparer les valeurs de contraintes obtenues à partir de la technique de mesure par Emission acoustique (AE) et une technique de Sur-carottage (CCBO), mises en œuvre dans une mine souterraine de calcaire au Japon. De plus, les effets de l'anisotropie de la roche et de la pression de confinement sur l'effet Kaiser défini dans les techniques d'émission acoustique ont été étudiés. Initialement les essais d'émission acoustique ont été réalisés sur des carottes de calcaire issues de forages horizontaux réalisés dans un pilier et une couche de toit de la mine souterraine. Les valeurs de contraintes obtenues étaient deux ou trois fois plus grandes que celles obtenues par la méthode de sur-carottage. Dans une deuxième étape, l'anisotropie d'un bloc de granite a été déterminée par des mesures de vitesses d'ondes P. Des échantillons carottés suivant deux directions différentes furent pré-chargés sous conditions triaxiales symétriques en appliquant différents niveaux de contraintes. Les échantillons furent re-chargés sous conditions uni-axiales et les valeurs d'effet Kaiser déterminées. On a conclu que l'anisotropie et la pression de confinement avaient tous deux une influence importante sur les valeurs d'effet Kaiser.

Mots clés Emission acoustique (AE) · Sur-carottage (CCBO) · Effet Kaiser · Anisotropie des roches · Etat de contraintes

E. Tuncay (✉)
Department of Geological Engineering,
Hacettepe University, Beytepe, 06800 Ankara, Turkey
e-mail: etuncay@hacettepe.edu.tr

Y. Obara
Department of Civil and Environmental Engineering,
Kumamoto University, Kumamoto, Japan

Introduction

One of the core-based methods used to determine in situ stresses is the Acoustic Emission (AE) technique suggested by Kanagawa et al. (1976). In this technique, the Kaiser Effect (KE) level (Kaiser 1953), commonly known as the

memory effect, is determined from the "Cumulative AE count-stress" response during uniaxial re-loading of an oriented rock core (Fig. 1a). It is assumed that the KE level is equal to the normal stress component to which the specimen was subjected in the earth's crust. In addition, if AE tests under uniaxial compressive loading are performed on at least six cores extracted from different orientations (Fig. 1b) and the KE levels in each test are determined, the complete stress tensor can be inferred for the location where the rock was taken. Following Kanagawa et al. (1976), particularly in the last two decades, numerous studies have been undertaken to clarify the applicability of the AE method to determine in situ stresses. These studies are reviewed under two main groups below.
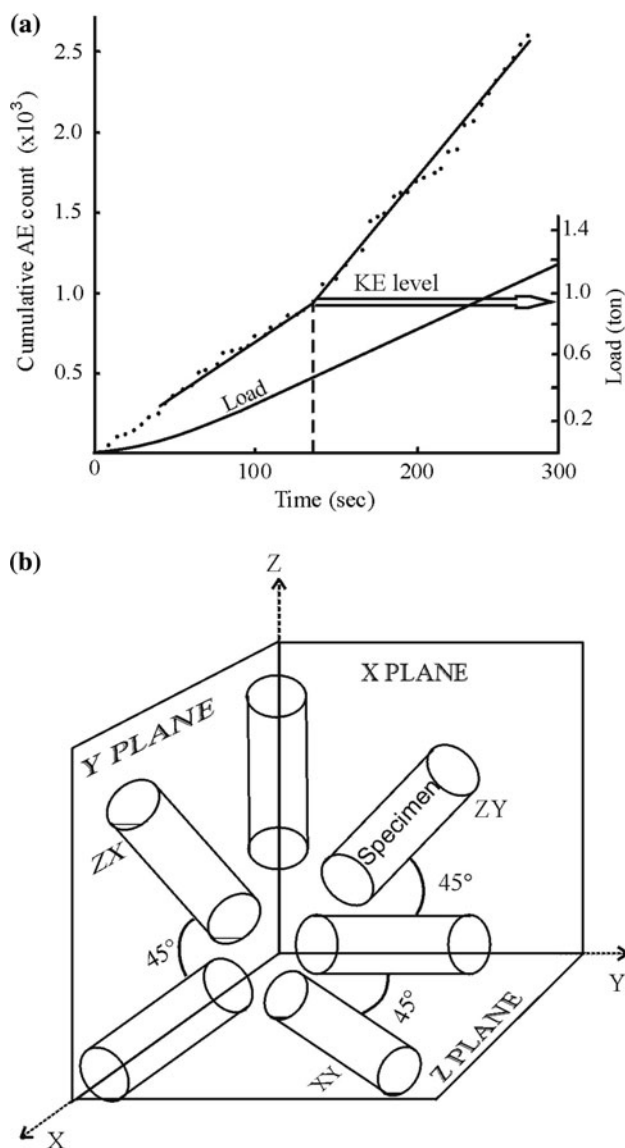

Fig. 1 **a** Estimation of Kaiser Effect (KE) from "total AE count-time" graph (Hayashi et al. 1979) and **b** oriented specimens subjected to uniaxial re-loading with AE measurement

In situ stress measurement studies by the AE technique:

Some investigators (i.e. Hayashi et al. 1979; Jupe et al. 1992; Seto et al. 1992; Momayez and Hassani 1992; Jingen et al. 1995; Barr et al. 1999; Ishiguro et al. 1999; Seto et al. 1999; Watanabe et al. 1999; Wang et al. 2000; Villaescusa et al. 2002; Ulusay et al. 2003; Windsor et al. 2006; Villaescusa et al. 2006) assumed that the KE value determined for an oriented core was equal to the in situ normal stress as suggested by Kanagawa et al. (1976). In some of these studies, the results obtained from the AE method were compared with those obtained by overcoring and hydraulic fracturing methods for the same sampling locations. They generally concluded that the in situ stress values inferred from the AE technique and the other well-known stress measurement methods were similar. These results suggest the AE technique may be a cheap and practical method of measuring in situ stresses.

Laboratory based studies:

The KE level was first discovered by Kaiser (1953) who carried out AE studies in the laboratory on sandstone and some other materials such as steel, copper and wood. The main conclusion of his study was that the materials pre-loaded uniaxially to a certain stress could remember this stress when they were re-loaded under the same loading conditions. During re-loading, little or no AE activity was observed until the maximum stress of the pre-loading, and then an evident activity was observed. This phenomenon (KE) was confirmed by several researchers on different types of rock (i.e. Hardy et al. 1989; Seto et al. 1999; Park et al. 2001; Tuncay and Ulusay 2008). On the other hand, based on the suggestion by Kanagawa et al. (1976), in situ normal stress is inferred from the AE activity during uniaxial re-loading even if the test specimen has been subjected to multi-axial in situ stresses in nature. As Holcomb (1993) emphasized, the most important question was "How valid is it to extrapolate from uniaxial re-loading to multi-axial stress states?"

For this reason, some researchers (i.e., Hughson and Crawhord 1987; Watanabe et al. 1994; Hardy et al. 1989; Shen 1995; Stuart et al. 1995; Seto et al. 1999; Filiminov et al. 2001; Tuncay and Ulusay 2008) focused on the effect of confining pressure. In these previous studies, rock cores were pre-stressed under triaxial loading conditions and re-loaded uniaxially in the laboratory. During uniaxial re-loading of these cores, the AE activity against stress increment was recorded, and the KE levels were determined. Some of these researchers (i.e., Watanabe et al. 1994; Seto et al. 1999) concluded that the KE level was equal to the stress component of triaxial pre-loading carried out in the same direction as uniaxial re-loading. This

conclusion suggests that the AE method can be used to determine in situ stresses using the sampling method recommended by Kanagawa et al. (1976). However, other investigators (i.e., Hardy et al. 1989; Shen 1995) concluded that even if samples are uniaxially re-loaded in the direction of axial pre-stress, the KE level is equal to the confining pressure (σ_{3p}) of pre-loading.

In addition, the results of the studies indicating that the KE level is equal to differential pre-stress ($\sigma_{1p}-\sigma_{3p}$) have also been published (Hughson and Crawford 1987). On the basis of the AE tests performed on rock salt, Filiminov et al. (2001) suggested that the KE level (σ_{KE}) obtained from AE tests during uniaxial compressive loading was a linear combination of the axial and confining pre-stresses. In this approach, a damage surface with a slope of rock dependent "k" coefficient is generated after axisymmetric triaxial pre-stresses (Fig. 2). They suggested a "k" constant of 0.6 for the rock salt they tested. Tuncay (2006) and Tuncay and Ulusay (2008) performed a number of AE tests on different types of rocks. They applied axisymmetric triaxial pre-loadings to rock specimens and then re-loaded the same specimens under uniaxial condition. Based on the assessments of the KE levels obtained during the uniaxial re-loadings, these researchers found that the KE level was not equal to one of the pre-stresses or their differences. In addition, "k" constants (Fig. 2) determined for each rock type exhibited an irregular distribution over a wide range.

Another approach based on the Griffith theory was made by Tuncay and Ulusay (2008) in order to relate the KE level determined during uniaxial re-loading to the stresses of axisymmetric triaxial pre-loading. However, half of the KE data from the experiments of these investigators did not show a good agreement with those obtained using the
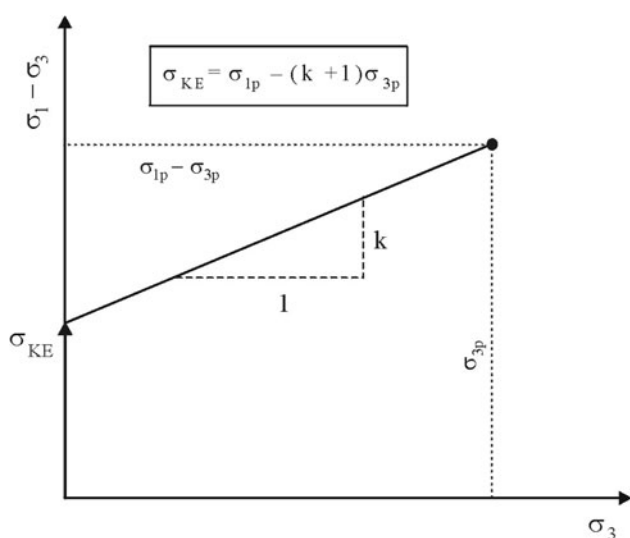
theoretical approach. Finally, they concluded that the KE level may be related to the combined effect of axial and confining pre-stresses and some rock-dependent characteristics such as grain boundary, microcrack population and orientation, etc.

In view of the above-mentioned work, this study was undertaken to compare the stress values inferred from the AE and Compact Conical-Ended Borehole Overcoring (CCBO) techniques. In addition, laboratory studies were performed on a granite sample to assess the effect of rock anisotropy on the KE level. In the first stage of the study, oriented cores (from the horizontal) extracted from the pillar and hanging wall in an underground mine in Japan were prepared for AE tests. The AE tests were carried out under uniaxial loading conditions and the KE levels were determined. Comparisons were made between the stress values obtained based on the KE levels and the in situ stress values obtained using the CCBO stress measurement method which was performed by a company at the same locations. In the second stage, the anisotropy of a granite rock was determined with the aid of ultrasonic wave tests. Numerous core specimens were extracted from two different directions. These specimens were subjected to confining and axial stresses of several magnitudes during axisymmetric triaxial pre-loadings. Then the AE tests were conducted on the same specimens by re-loading them under uniaxial conditions. The paper discusses the KE levels determined.

Stress measurements

In order to compare the stresses obtained using the AE technique and a well-known stress measurement method, AE tests were conducted on core specimens taken from boreholes drilled for CCBO measurement at an underground limestone mine in the western part of Honshu Island, Japan. In the region of this mine, part of the limestone deposit is crystallized. Figure 3 shows the distribution of the mine workings from which the material is extracted using the room and pillar method. The pillars in the mine are 10×20 m and 5 m in height. There are 9 excavation levels in the mine (9–17, see Fig. 3a) separated by a thickness of 8 m. The overburden of the deepest level (17) is about 200 m.

Rock stress measurements using the CCBO technique were carried out to estimate the stability of a pillar, following the ISRM suggested method proposed by Sugawara and Obara (1999). The measurements were undertaken in horizontal boreholes drilled in a pillar and a hanging wall at excavation level 6, at an average depth of about 150 m (Fig. 3). The stress state was measured in three dimensions. The stress in the direction of the borehole axis was

Fig. 2 Damage surface projection onto the left from the point corresponding to the axisymmetric triaxial pre-stresses (Lavrov 2003)

In the figure: $\sigma_{KE} = \sigma_{1p} - (k+1)\sigma_{3p}$

Fig. 3 a Section showing the
floors and **b** plan view showing
the locations of CCBO
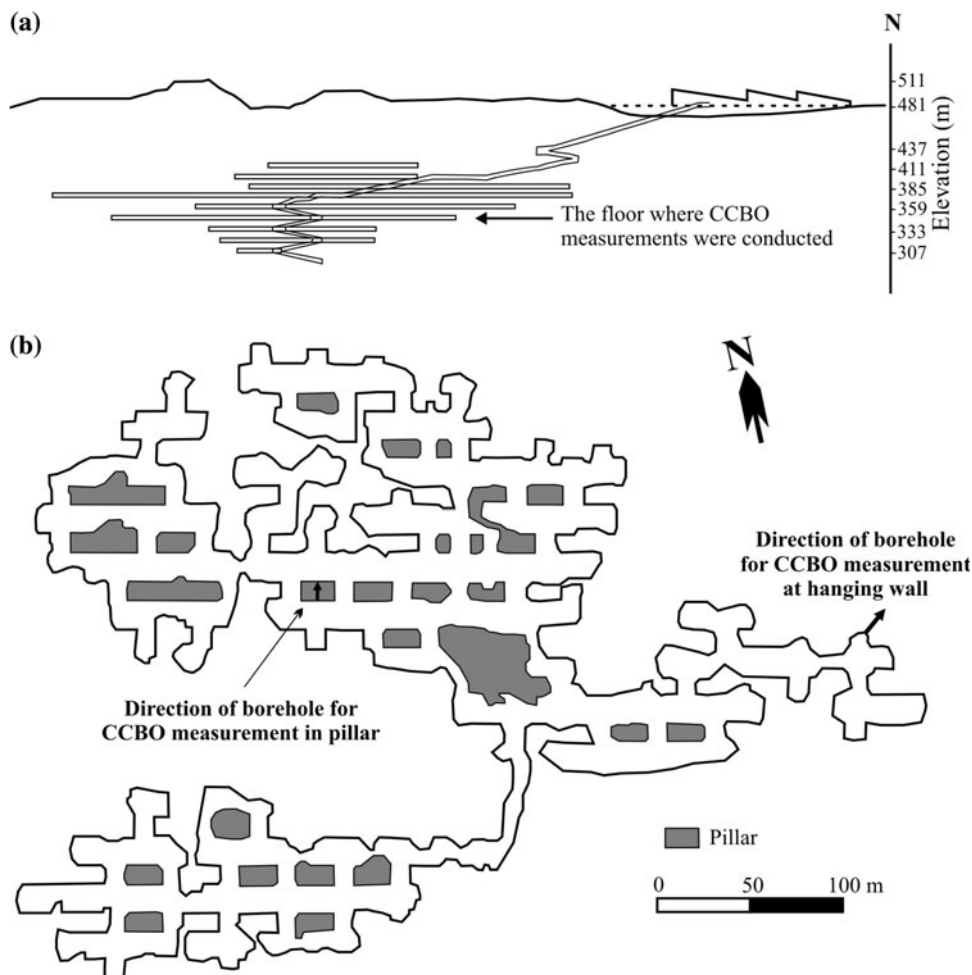measurements at the sixth floor
of the underground mine

Table 1 Stress in the direction
of horizontal borehole axis
determined by CCBO method at
each measurement location

| Location	Horizontal stresses at some distances from free surface (MPa)					
Hanging wall	10.16 m	12 m				
	4.3	7.4				
Pillar	0.35 m	1.43 m	2.83 m	4.43 m	5.60 m	7 m
	2.6	6.7	3.7	3.2	6.0	2.3

determined at each measurement point; see summary in
Table 1. There are two measurement points within the
hanging wall. As the points are located at 10 and 12 m
from the lateral wall of excavation, the stress state was
assumed to be the initial stress state while the pillar is
under uniaxal compression, hence the horizontal stress is
relatively smaller than that of the hanging wall.

Rock cores obtained from the same boreholes during
CCBO were also prepared for AE testing. The specimens
were directly reloaded under uniaxial compression and AE
signals, ring down counts and AE energy were detected
using the MISTRAS 2001 system. In order to reduce the
friction between the core and loading plate, two Teflon
sheets were placed at the bottom and top of the core and oil

was applied between these sheets. A piezoelectric trans-
ducer with a resonant frequency of 270 kHz, which is also
sensitive to 10–1,000 kHz frequencies, was used. The pre-
amplifier and post-amplifier were set to gains of 40 and
40 dB, while high and low pass filters were set to 100 and
400 kHz, respectively. The threshold level was fixed at
45 dB. Load applied to the limestone cores was recorded
by a load cell and the data were transferred to the computer
via a data acquisition system. A detailed illustration of the
test system is given in Fig. 4.

In the literature, "AE signal activity" or "ring down
counts" are commonly used to determine the KE levels. In
this study, energy was also evaluated. KE levels were
determined from the plots of "time–stress" and "time–AE

Fig. 4 View from AE test during uniaxial re-loading and schematic illustration of the test system used in this study
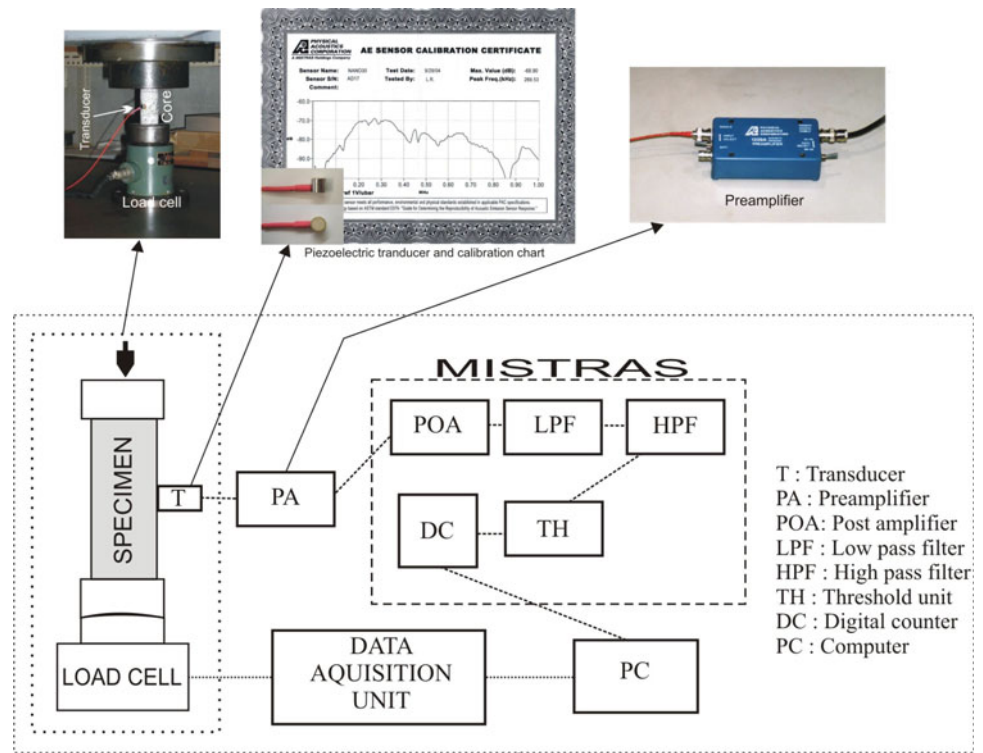
parameters" by determining the stresses at which AE parameters show a clear increase for the first time (Fig. 5). Based on the meaning of the KE level as proposed by Kaiser (1953), the secondary increases in AE activity at advance stress levels would be considered to be the result of other effects, such as crack propagation. The first increase points were very clear from AE energy and ring down counts; an additional process was necessary in order to fix this level for AE signal activity as shown in Fig. 5.

The KE levels determined from AE signal activity were different from those determined from the ring down counts and energy activity for some cores, although close. By considering the suggestion of Kanagawa et al. (1976), KE levels were assumed to be equal to the in situ normal stresses, parallel to the borehole axis (horizontal), acting on the points where the cores were taken (Table 2). The stress values obtained from the AE and CCBO techniques are shown in Fig. 6.
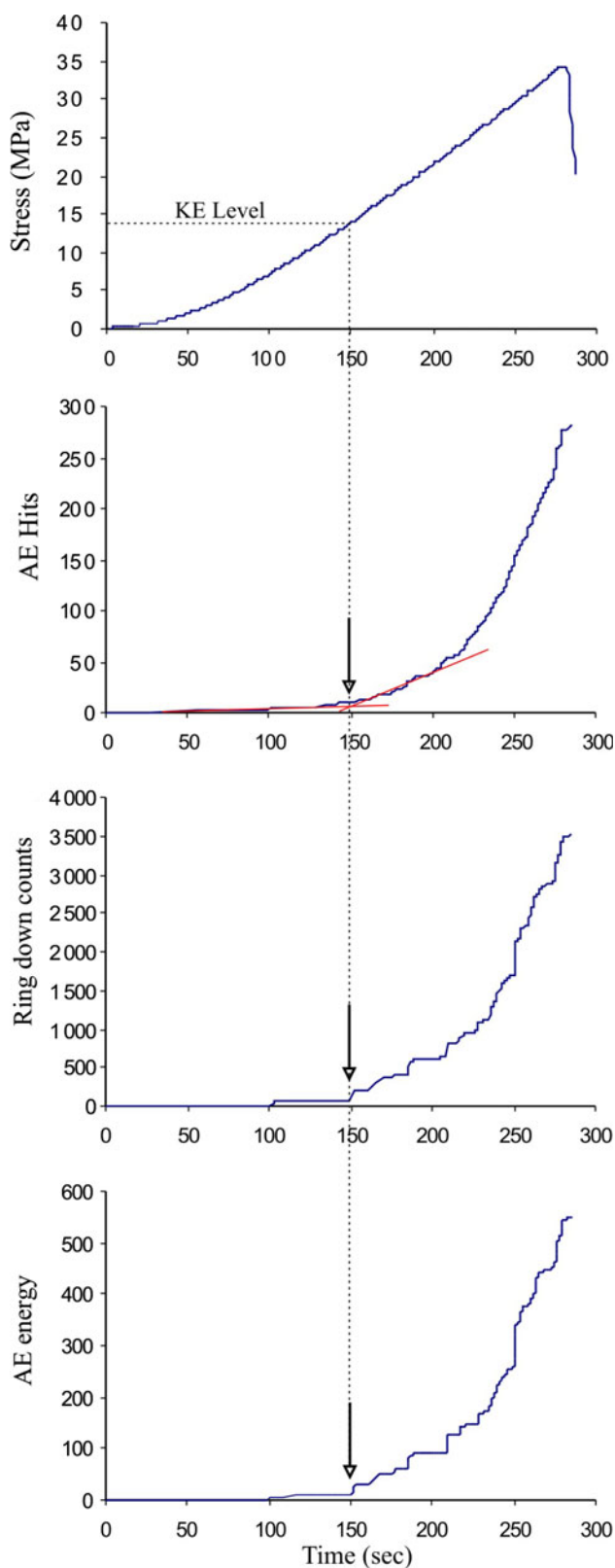
Fig. 5 Typical graphs of "time–stress" and "time–AE activity" obtained from uniaxial re-loading of a limestone core taken from boreholes of CCBO tests, and the stress level corresponding to the KE level

Table 2 Stress in the direction of horizontal borehole axis determined by AE technique with uniaxial re-loading of the cores taken from the boreholes of CCBO tests

Location	Horizontal stresses (KE levels) at some distances from free surface (MPa)		
Hanging wall	10.5 m		
	13.5		
Pillar	1.84 m	1.9 m	2.3 m
	10.9–13.6	10.8–11	12.1–13.6

Effect of anisotropy on KE level

As noted above, Tuncay and Ulusay (2008) concluded that in addition to the combined effect of axial and confined pre-stresses some rock-dependent characteristics such as grain boundary, microcrack shape (open or close), distribution of microcrack orientation and their population, may have an important influence on the KE level. For this reason, in this study, in addition to the triaxial pre-stresses on KE level, the effect of anisotropy was also considered. Granitic rocks, in general, have two sets of preferred orientation of microcracks, and most of the microcracks exist within the "rift plane" and are approximately parallel to each other (Sano et al. 1992). In quarryman's terms, the secondary orientation of cracks is almost perpendicular to the rift plane and known as the "grain plane" while the "hardway plane" is defined by the plane perpendicular to both the rift and grain planes (Sano et al. 1992). Principal P wave velocities generally coincide with the pre-existing microcrack orientations within the granite (Sano et al. 1992). According to the results of the crack density calculations, fracture toughness tests and ultrasonic sound velocity measurements carried out by Sano et al. (1992), Obara et al. (1992) and Nara and Kaneko (2006), the direction of the maximum P wave velocity is approximately parallel to the preferred microcrack orientation in the "rift plane" in granite. The lowest P wave was propagated in the direction perpendicular to this plane.

Considering these inferences, a granite block was obtained from the vicinity of Kumamoto city (Japan). This light coloured rock has a massive structure and is mainly composed of quartz and fresh feldspar grains of about 5–7 mm diameter. Biotite and hornblende are rare and found as mafic minerals. Some basic geomechanical properties of the granite (Table 3) were determined following ISRM (2007). A series of ultrasonic transmission tests were carried out on the $30 \times 30 \times 30$ cm granite cube, which was prepared taking into account the pre-existing crack orientations. The P-wave velocities (V_p) in the main anisotropy directions were determined; the maximum was measured in the direction of the X axis and the
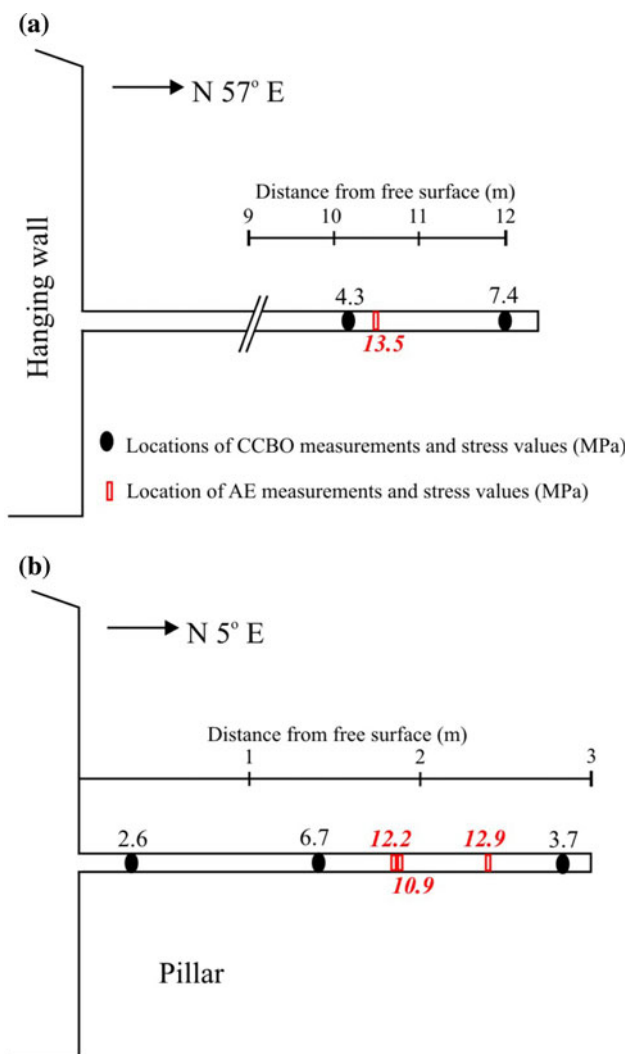
Fig. 6 Illustration of the locations in boreholes where in situ stresses were determined and the stress values measured by CCBO tests and the AE technique **a** at hanging wall and **b** in the pillar

Fig. 7 P-wave velocities (V_p) with respect to the orthogonal axes in a cubic granite sample

minimum in the direction of the Z axis (Fig. 7). These results and those indicated by previous studies imply the majority of the microcracks are in the Y plane (rift plane) with a main orientation parallel to the X axis.

In order to carry out the AE tests on cores including microcracks oriented in different directions, two sets of rock cores were extracted from the granite block. 18 cores were drilled at an angle of 60° from the X axis in the Y plane and a second set of 17 cores were drilled at an angle of 30° (Fig. 8). All of the cores were pre-loaded under axisymmetric triaxial conditions until differential
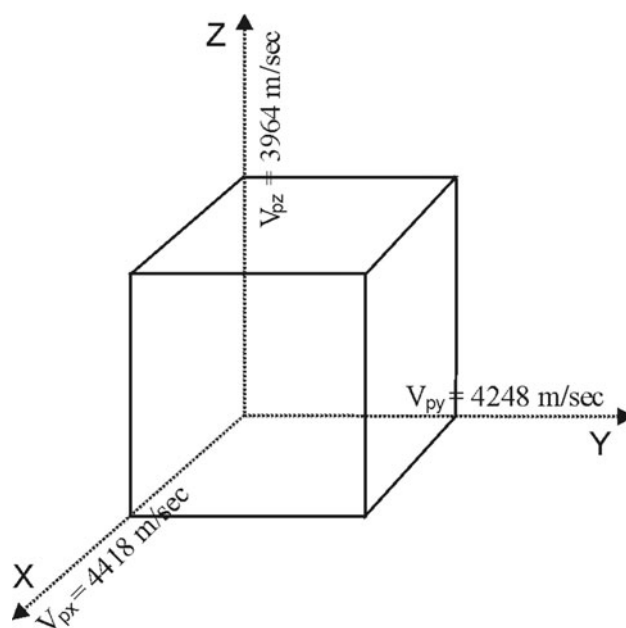
stress levels were achieved (Fig. 9). These differential stresses were greater than the initiation threshold of crack propagation stage determined following Eberhardt et al. (1998). After triaxial pre-loading, the core specimens were re-loaded under uniaxial conditions and the AE activity was recorded relative to the stress increment. The KE levels were determined from the plots of "time–stress" and "time–AE parameters" by determining the stresses at which AE parameters show a clear increase above previous activity.

The pre-stresses applied to the specimens, KE levels, and "k" values calculated following Filiminov et al. (2001) are given in Table 4. It is clear from the results from both sets of cores that the KE levels are not equal to one of the pre-stresses (σ_{1p} or σ_{3p}) or their differences (σ_{1p}–σ_{3p}), and a combined effect of the pre-stresses has an influence on the KE level. In addition, "k" values are not constant for the granite tested but vary with different pre-stresses. Figure 10 illustrates the effect of the anisotropy on the KE level. As shown in Fig. 10, the KE levels obtained from the cores of set no: 1 are smaller than those from set no: 2. This suggests that a greater KE level is obtained when most microcracks have a direction closer to the maximum pre-stress direction. This confirms

Table 3 Some geomechanical properties of the granite

Number of specimens	Unit weight (kN/m^3)	UCS (MPa)	E (GPa)	N
8	25.6	160 (140.8–172.5)	54.6 (51.5–57.9)	0.23 (0.20–0.26)

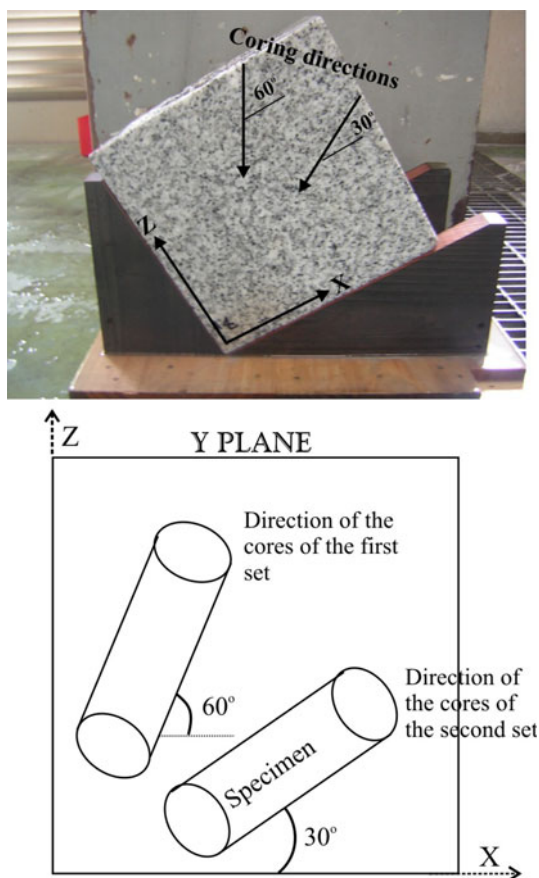*UCS* Uniaxial compressive strength, *E* modulus of elasticity, *n* Poisson's ratio

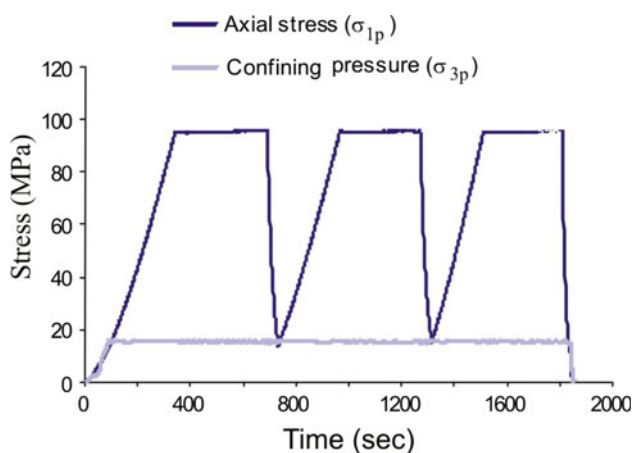**Fig. 8** Directions of the cores belonging to the first and second set

Fig. 9 Axisymetric triaxial pre-loading and unloading forms

Table 4 Axial and confining pre-stresses (σ_{1p} and σ_{1p}) applied in axisymetric triaxial pre-loadings and KE levels determined during uniaxial re-loading, and "k" coefficients calculated from the damage surface equation proposed by Filiminov et al. (2001)

Set no	Specimen no	Triaxial pre-loading		Uniaxial re-loading	k
		σ_{1p} (MPa)	σ_{3p} (MPa)	KE level (MPa)	
1	a	95.1	15.0	23	3.8
	b	96.4	15.0	33.3	3.2
	c	94.2	8.0	37.2	6.1
	d	94.4	8.0	32	6.8
	e	95.8	1.0	57	37
	f	96.6	1.0	55.7	39.2
	g	80.6	15.0	25	2.7
	h	80.8	15.0	24	2.8
	i	80.8	8.0	29.2	5.4
	j	79.6	8.0	28	5.4
	k	80.5	1.0	45.6	33.6
	l	80.5	1.0	58	21.2
	m	50.4	15.0	23	0.8
	n	50.3	8.0	31.5	1.4
	o	50.3	1.0	36	13.1
	p	50.2	8.0	26.6	1.9
	r	50.4	1.0	33	16
	s	50.3	14.9	21	1
2	a	95.6	15.0	37	2.9
	b	94.1	8.0	42	5.5
	c	94.8	8.0	40	5.8
	d	95.1	1.0	56	37.6
	e	95.0	1.0	59.6	34.1
	f	95.0	15.0	34	3.1
	g	80.4	15.0	31	2.3
	h	80.2	15.0	32.4	2.2
	i	80.2	8.0	34.6	4.7
	j	80.4	8.0	37.5	4.4
	k	80.6	1.0	51.9	26.9
	l	50.5	15.0	26	0.6
	m	50.2	15.0	26.7	0.6
	n	50.1	8.0	30	1.5
	o	51.3	8.0	28	1.9
	p	54.5	1.0	46.4	7.0
	r	54.3	1.0	38	15.1

that not only the combined effect of the pre-stresses but also anisotropy based on the microcrack pattern have an important role in the KE level. The change in "k" value with confining pre-stress (σ_{3p}) is shown in Fig. 11. For both sets of cores, the "k" value decreases with increasing confining pre-stress for the same maximum pre-stress (σ_{1p}), indicating the KE mechanism after this type of

pre-loading and re-loading cannot be explained by a linear damage surface for the granite tested.

The results from the second stage of this study and those of some previous studies show that the KE level in uniaxial re-loading is not equal to the axial stress of triaxial pre-loading. Accordingly, the KE level obtained using the AE technique with simply uniaxial re-loading should not be
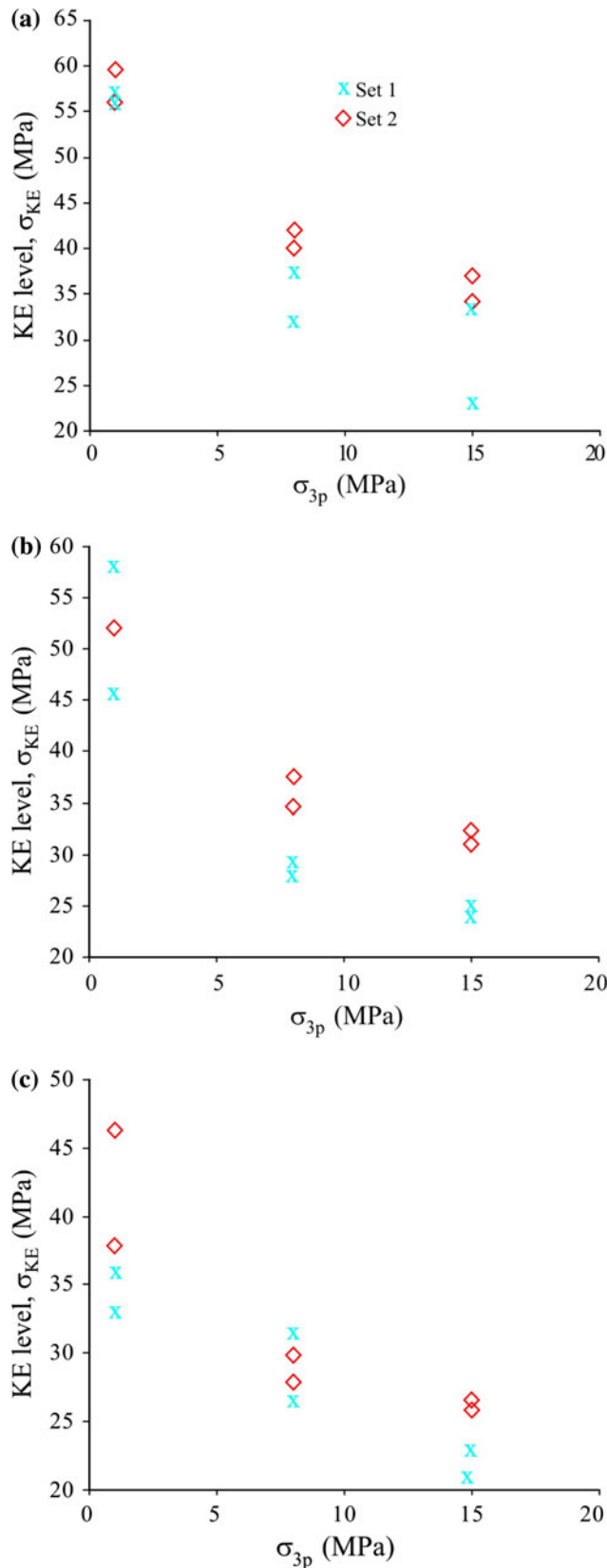
Fig. 10 Change in KE level with respect to the confining pre-stress applied with **a** 95, **b** 80 and **c** 50 MPa axial pre-stresses
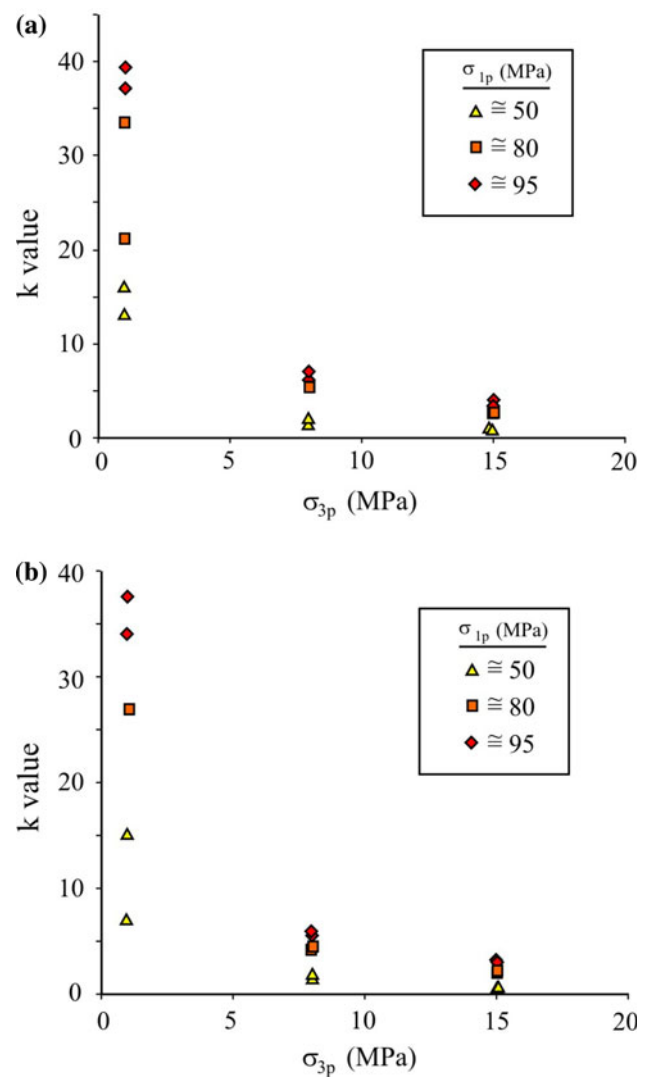

Fig. 11 Change in the "k" coefficient with respect to the pre-stresses

equal to the normal stress component of the complete stress tensor acting on the specimen in the earth's crust. Filiminov et al. (2001) suggested a "k" coefficient for rock salt which characterizes the slope of the damage surface projected onto the plane stress difference ($\sigma_1 - \sigma_3$) versus σ_3 (Lavrov 2003); see Fig. 2. According to Lavrov (2003), at best such a method allows an estimation of the linear combination of in situ stresses, when testing the specimen oriented precisely in the direction of the in situ major principle stress (σ_1). However, in this study, the "k" coefficient determined for the granite is not constant but varies non-linearly depending on the magnitude of the pre-stress. In addition, the study confirmed the effect of anisotropy on the KE level determined during uniaxial re-loading after triaxial pre-loading in the laboratory.

The relationship between AE activity and microcrack propagation is well-known (e.g., Eberdhart et al. 1998;

Diederichs et al. 2004). When a rock specimen taken in the field is re-loaded uniaxially, the AE activity should increase at the stress level at which the microcracks oriented most critically with respect to the uniaxial re-loading direction propogate. The KE level, which is assumed to be equal to in situ normal stress in the AE technique (Kanagawa et al. 1976) may be related to this increase in AE activity. However, rocks are subjected to multi-axial stress states in the earth crust and microcracks are also formed or propagated by the effect of multi-axial stress states. In addition, the damage caused during extraction of the rock, preparation of the test specimen etc. (e.g., microcrack formation, propagation, opening) results in a change in the microcrack pattern from its original in situ form. Consequently, the AE activity, and therefore the KE level, is not directly related to the in situ case. For these reasons, the stress results obtained from the AE technique in the first stage of this study should not be equal to the lateral normal stresses at borehole locations. The sensitivity of the KE level to microcrack anisotropy as well as some other effects suggest that the AE technique conducted with a simple uniaxial re-loading of the rock specimen has serious limitations for the determination of in situ stresses.

Conclusions

The following main conclusions are drawn from the study.

1. Stresses obtained using the AE technique during uniaxial re-loading of core specimens extracted from CCBO test boreholes were two or three times greater than in situ stresses determined using the CCBO technique.
2. Laboratory-based studies on a granite showed that the KE level obtained during uniaxial re-loading of a rock specimen, which was pre-loaded triaxially, cannot be equal to only one of the pre-stresses or their differences. Its value is related to the damage created by the combined effects of pre-stresses. A non-linear damage surface projection onto plane stress difference versus confining stress was determined for the granite studied.
3. The anisotropy in the granite, mainly related to the microcracks, was seen to have an important influence on the KE level. Damage, such as microcrack opening and propagating, etc. which occurs during extraction and preparation of a test specimen, may result in the determination of another stress level rather than the KE level related to the in situ stress.
4. Based on these conclusions, it seems unrealistic to determine in situ stresses by applying the AE technique with a simple uniaxial re-loading of the oriented rock specimens.

References

Barr SP, Jupe A, Hunt DP (1999) The Kaiser Effect for samples pre-stressed at 820 m and 2.4 km with stress tensor results. In: Vouille G, Berest P (eds) Proceedings of the ISRM international congress on rock mechanics, Paris, vol 2, pp 1133–1136

Diederichs MS, Kaiser PK, Eberhardt E (2004) Damage initiation and propagation in hard rock during tunneling and the influence of near-face stress rotation. Int J Rock Mech Mining Sci 41(5):785–812

Eberhardt E, Stead D, Stimpson B, Read RS (1998) Identifying crack initiation and propagation thresholds in brittle rock. Can Geotech J 35:222–233

Filimonov YL, Lavrov AV, Shafarenko YM, Shkuratnik VL (2001) Memory effects in rock salt under triaxial stress state and their use for stress measurement in a rock mass. Rock Mech Rock Eng 34(4):275–291

Hardy HR Jr, Zhang D, Zelanko JC (1989) Recent studies of the Kaiser Effect in geologic materials. In: Proceedings of the 4th conference on acoustic emission/microseismic activity in geologic structures and materials. Trans. Tech. Publications, State College, pp 27–55

Hayashi M, Kanagawa T, Hibino S, Motozima M, Kitahara Y (1979) Detection of anisotropic geo-stresses trying by acoustic emission, and non-linear rock mechanics on large excavating caverns. In: Proceedings of the 4th ISRM international congress on rock mechanics. Montreux 2:211–218

Holcomb DJ (1993) General theory of the Kaiser Effect. Int J Rock Mech Mining Sci Geomech Abst 30(7):929–935

Hughson DR, Crawhord AM (1987) Kaiser Effect gauging: the influence of confining stress on its response. In: Proceedings of the 6th ISRM international congress on rock mechanics, Montreal, pp 981–985

Ishiguro Y, Nishino K, Murakami A, Sugawara K, Kawamoto T (1999) In situ initial rock stress measurement and design of deep underground powerhouse cavern. In: Proceedings of the 9th ISRM international congress on rock mechanics. pp 1155–1158

ISRM (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. In: Ulusay R, Hudson JA (eds) Suggested methods prepared by the commission on testing methods, ISRM, compilation arranged by the ISRM Turkish National Group, Kozan ofset, Ankara

Jingen D, Kangping W, Rongzun H (1995) In situ stress determination at great depth by using acoustic emission. In: Proceedings of the 35th U.S. symposium on rock mechanics. Reno, pp 245–250

Jupe AJ, Barr SP, Pine RJ (1992) In situ stress measurements obtained using overcoring and the Kaiser Effect of acoustic emissions within the Carnmenellis granite. In: Proceedings of the 11th international acoustic emission symposium, progress in acoustic emission VI. Fukuoka, The Japanese Society for Non-Destructive Inspection, pp 167– 174

Kaiser J (1953) Erkenntnisse und Folgerungen aus der Messung von Geräuschen bei Zugbeanspruchung von metallischen Werkstoffen. Archiv Eisenhüttenwesen 24(1/2):43–45

Kanagawa T, Hayashi M, Nakasa H (1976) Estimation of special geo-stress components in rock samples using the Kaiser Effect of acoustic emission. Technical report, C.R.I.E.P.I., E375004 (in Japanese)

Lavrov A (2003) The Kaiser Effect in rocks: principles and stress estimation techniques. Int J Rock Mech Mining Sci 40:151–171

Momayez M, Hassani FP (1992) Application of Kaiser Effect to measure in situ stresses in underground mines. In: Proceedings of the 33rd US Symposium, Rock Mechanics. A.A. Balkema, pp 979–988

Nara Y, Kaneko K (2006) Sub-critical crack growth in anisotropic rock. Int J Rock Mech Mining Sci 43:437–453

Obara Y, Sakaguchi, T. Nakayama T, Sugawara K (1992) Anisotropy effect on fracture toughness of rock. In: Proceedings of Eurock'92. Thomas Telford, pp 7–12

Park P, Park N, Hong C, Jeon S (2001) The influence of delay time and confining pressure on in situ stress measurement using AE and DRA. In: Proceedings of the 38th US symposium, rock mechanics in the national interest. Swets & Zeitlinger Lisse, pp 1281–1284

Sano O, Kudo Y, Mizuta Y (1992) Experimental determination of elastic constants of Oshima granite, Barre granite, and Chelmsford granite. J Geophys Res 97(B3):3367–3379

Seto M, Utagawa M, Katsuyama K (1992) The estimation of pre-stress from AE in cyclic loading of pre-stressed rock. In: Proceedings of the 11th international acoustic emission symposium, progress in acoustic emission VI. Fukuoka, The Japanese Society for Non-Destructive Inspection, pp 159–166

Seto M, Nag DK, Vutukuri VS (1999) In situ rock stress measurement from rock cores using the acoustic emission method and deformation rate analysis. Geotech Geol Eng 17:241–266

Shen W (1995) Objective Kaiser stress evaluation in rock. In: Proceedings of the 5th conference on acoustic emission/microseismic activity in geologic structures and materials. Trans Tech Publications, State College, pp 177–195

Stuart CE, Meredith PG, Murrell SAF (1995) Van Munster *H. Influence* of anisotropic crack damage development on the Kaiser Effect under true triaxial stress conditions. In: Proceedings of the 5th conference on acoustic emission/microseismic activity in geologic structures and materials. Trans Tech Publications, State College, pp 206–219

Sugawara K, Obara Y (1999) Draft ISRM suggested method for in situ stress measurement using the compact conical-ended borehole overcoring(CCBO) technique. Int J Rock Mech Min Sci Geomech Abstr 36:307–322

Tuncay E (2006) An investigation on the applicability of the acoustic emission technique to determine in situ stresses. PhD Thesis. Ankara. Hacettepe University, Dept. of Geological Engineering, pp 206 (in Turkish)

Tuncay E, Ulusay R (2008) Relation between Kaiser Effect levels and pre-stresses applied in the laboratory. Int J Rock Mech Mining Sci 45(4):524–537

Ulusay R, Tuncay E, Watanabe H, Tano H, Aydan O (2003) The measurement of the stress state of Turkey by Acoustic Emission (AE) method. In: Proceedings of the 3rd international symposium on rock stress, RS KUMAMOTO '03. Kumamoto, Japan, pp 255–260

Villaescusa E, Seto M, Baird G (2002) Stress measurements from oriented core. Int J Rock Mech Mining Sci 39(5):603–615

Villaescusa E, Li J, Windsor CR, Seto M (2006) A comparison of overcoring and AE stress profiles with depth in Western Australian mines. In: Proceedings of international conference on in-situ rock stress, Taylor & Francis Group, Trondheim, pp 223–228

Wang HT, Xian XF, Yin GZ, Xu J (2000) A new method of determining geostresses by the acoustic emission Kaiser Effect. Int J Rock Mech Mining Sci 37:543–547

Watanabe H, Tano H, Akatsu T (1994) Fundamental study on pre-stress measurement of triaxial compressed rock. J College Eng Nihon Univ 35(A):11–19 (in Japanese)

Watanabe H, Tano H, Ulusay R, Yüzer E, Erdogan M, Aydan O (1999) The initial stress state in Cappadocia. In: Proceedings of the '99 Japan–Korea joint symposium on rock engineering, pp 249–260

Windsor CR, Cavieres P, Villaescusa E, Pereira J (2006) Rock stress tensor measurements at El Teniente Mine, Chile. In: Proceeding of international confernce in situ rock stress, Taylor & Francis Group, Trondheim, pp 67–72