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Laboratory testing of Kivetty porphyritic granodiorite in borehole KI-KR10

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The conclusions and viewpoints presented in the report are those of author(s) and do not necessarily coincide with those of Posiva.
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LABORATORY TESTING OF KIVETTY PORPHYRITIC GRANODIORITE IN BOREHOLE KI-KR10

ABSTRACT

The complete stress-strain behaviour of porphyritic granodiorite from Posiva Oy's investigation site at Kivetty was studied with a total of 40 loading tests. In this report the established name of porphyritic granodiorite is used for the tested rock type, although the true modal name should be porphyritic granite. The porphyritic granodiorite is the other main rock type between 300 m ... 800 m levels at the Kivetty site. The difference between these two rock types can only be seen in thin section mineral counts. The 62 mm diameter specimens were taken from the deep borehole KI-KR10 representing the depth region 200 ... 250 m, because the borehole KI-KR10 does not intersect the porphyritic granodiorite at greater depth. The test program included indirect tensile tests with uniaxial and triaxial monotonic loading tests. The influence of moisture was studied with the indirect Brazil tensile test using adjacent specimens. The petrography and mineral compositions were observed from 12 thin sections taken from the two weakest, two middle strength and two strongest specimens.

Based on the test results porphyritic granodiorite is brittle rock. In uniaxial loading the majority of bearing capacity was lost right after achieving peak strength. The post peak behaviour of the tested porphyritic granodiorite specimens was clearly Class I type and this behaviour was clearly emphasized with confinement. In uniaxial loading the destruction of the porphyritic granodiorite specimen usually started by coalescence of axial fractures or the peeling off of little pieces from the sides leading to failure through buckling. In triaxial tests a large shear fracture through the whole specimen was seen in a majority of the tests.

In borehole scale the structure of the porphyritic granodiorite is homogenous, but in test specimen scale the large grain size makes it non-homogenous. However, the defined elastic parameters and critical pre-peak stress states in uniaxial and triaxial compression tests had small deviation between ±6% to ±18%. The defined values showed a good agreement with normal distribution. Considering the crack damage stress $\sigma_{cd}$ as the true undisturbed strength of the porphyritic granodiorite, then the lower 95% confidence limit for the strength is defined by the envelope of 86 MPa uniaxial compressive strength and 182 MPa compressive strength with 15 MPa confinement. The corresponding upper 95% confidence envelope is $\sigma_{cd,0} = 124$ MPa and $\sigma_{cd,15} = 242$ MPa. The 95% confidence envelopes for crack initiation stress $\sigma_{ci}$ are defined by the stress pairs $\sigma_{ci,0} = 64/72$ MPa and $\sigma_{ci,15} = 114/162$ MPa.

Tests with dry specimens gave practically the same indirect tensile strength than tests with saturated specimens.

Keywords: porphyritic granodiorite, laboratory testing, brittle rock, nuclear waste management
KIVETYN KAIRAREIÄN KI-KR10 PORFYRYRisen GRANODIORIITIIN LABORATORIOTESTAUS

TIIVISTELMÄ


Kairareikämittakaavassa porfyryrinen granodioriitti on homogeениstä isokiteisistä kiveä, mutta suuret kiihtyvät tekevät siitä epähomogeneisen testausnäytteen mittakaavassa. Tästä huolimatta määritettyjen kimmoisten ominaisuuksien ja kriittisten jännitysluojien hajonta on suhteellisen pieni (±6% ... ±18%). Tulokset noudattivat hyvin normaalijakaumaa. Määritättyneen häiriytymättömän kiven todellinen lujus jännitystasoksi, jolla hallitsemanet mikrorakoiulut alkaa (σcd), voidaan lujuuden alempi 95% luottamusvälimpintä esittää pistein 86 MPa yksiaksiaalinen puristuslujuus ja 182 MPa puristuslujuus 15 MPa sivupaineella. Vastaava ylempi 95% luottamusvälimpintä on σcd,0 = 124 MPa ja σcd,15 = 242 MPa. Mikrorakoiulun alun σci vastaavat luottamusvälit saadaan jännityspareista σci,0 = 64/72 MPa ja σci,15 = 114/162 MPa.

Kosteudella ei ollut vaikutusta Kiveten porfyryrisen granodioriitin epäsuoraan vetolujuuteen.

Avainsanoja: porfyryrinen, granodioriitti, graniitti, laboratoriotestaus, hauras kivi, ydinjätteiden loppusijoitus
PREFACE

This study, carried out by Posiva Oy, is related to a technical development for the disposal of spent nuclear fuel. The aim of Posiva’s work is to develop the rock engineering design and construction methods related to final disposal of spent fuel in the Finnish bedrock. Currently Posiva Oy is performing site specific investigations to gather rock mechanical data from four investigation sites.

The work has been commissioned by Posiva Oy and carried out by the Laboratory of Rock Engineering at Helsinki University of Technology. The preparation and analyses of thin sections were done by Geological Survey of Finland (GTK).

The following organizations and persons have participated in the project:

- Posiva Oy
- Helsinki University of Technology, Laboratory of Rock Engineering
- Saanio & Riekkola Oy
- Gridpoint Finland Oy

- Jukka-Pekka Salo
- Pekka Särkkä
- Pekka Eloranta
- Harri Kuula
- Reijo Riekkola
- Erik Johansson
- Jorma Autio
- Matti Hakala
LABORATORY TESTING OF KIVETTY BOREHOLE KI-KR10 PORPHYRITIC GRANODIORITE

1 INTRODUCTION 9

2 TEST PROGRAM 10

3 TEST SPECIMENS 11
3.1 SELECTION OF SAMPLES 11
3.2 SPECIMEN HANDLING PROCEDURE 13
3.3 CLASSIFICATION 14
3.4 PHYSICAL PROPERTIES 16
3.5 PETROGRAPHY 19

4 TEST CONFIGURATIONS AND PROCEDURES 21
4.1 TESTING SYSTEM 21
4.2 MONOTONIC COMPRESSION TESTS 22
4.3 TENSILE TESTS 26
4.4 QUALITY CONTROL 28

5 TEST RESULTS 31
5.1 INTERPRETATION METHODS 31
5.2 CHARACTERISTICS OF STRESS-STRAIN BEHAVIOUR 36
5.3 ELASTIC PARAMETERS 38
5.4 STRENGTH PARAMETERS 41

6 CONCLUSIONS 45

7 RECOMMENDATIONS 54

REFERENCES 56

LIST OF APPENDICES 58
1 Photographs of Kivetty borehole KI-KR10 core samples 59
2 Test information form 66
3 List of test specimens and physical properties 68
4 Results from thin section observations 69
5 Results from loading tests 79
6 Elastic parameters, critical stress states and corresponding strains 99
7 Photographs of tested specimens 100
8 Deviation of elastic parameters 110
9 Deviation of critical stress states 112
LIST OF SYMBOLS

Roman Letters

$E$  
Young’s modulus ( Pa )

$n$  
number of samples ( pcs )

$s$  
standard deviation

$x$  
value

$\hat{x}_L$  
lower estimate for value $x$

$\hat{x}_U$  
upper estimate for value $x$

Greek Letters

$\chi^2$  
the inverse of one-tailed probability of the chi-squared distribution

$\varepsilon_{1,2,3}$  
strains corresponding to major, intermediate and minor principal stresses ( m/m )

$\varepsilon_a$  
axial strain ( m/m )

$\varepsilon_r$  
radial strain ( m/m )

$\varepsilon_v$  
volumetric strain ( m$^3$/m$^3$ )

$\varepsilon_{v,e}$  
elastic volumetric strain ( m$^3$/m$^3$ )

$\varepsilon_{v,r}$  
-crack volumetric strain ( m$^3$/m$^3$ )

$\phi$  
friction angle ( degrees )

$\sigma_{1,2,3}$  
-major, intermediate and minor principal stress ( Pa )

$\sigma_a$  
axial stress ( Pa )

$\sigma_{u cs}$  
uniaxial compressive strength ( Pa )

$\sigma_{cp}$  
-confining stress ( Pa )

$\sigma_{ci}$  
-crack initiation stress ( Pa )

$\sigma_{ci,t}$  
-crack initiation stress in tension ( Pa )

$\sigma_{ci,0}$  
- uniaxial crack initiation stress ( Pa )

$\sigma_{ci,15}$  
-crack initiation stress with 15 MPa confinement ( Pa )

$\sigma_d$  
-crack damage stress ( Pa )

$\sigma_{dt}$  
-crack damage stress in tension ( Pa )

$\sigma_{d,0}$  
- uniaxial crack damage stress ( Pa )

$\sigma_{d,15}$  
-crack damage stress with 15 MPa confinement ( Pa )

$\sigma_p$  
peak stress ( Pa )

$\sigma_t$  
tensile strength ( Pa )

$\nu$  
Poisson’s ratio ( )
## NOTATIONS

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Uniaxial compression test with 0.75 MPa/s loading rate</td>
</tr>
<tr>
<td>3A-15</td>
<td>Triaxial compression test with 15 MPa confinement</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic emission</td>
</tr>
<tr>
<td>BT</td>
<td>Indirect Brazil tensile test</td>
</tr>
<tr>
<td>EPDM</td>
<td>Ethene-propylene rubber</td>
</tr>
<tr>
<td>HUT</td>
<td>Helsinki University of Technology</td>
</tr>
<tr>
<td>ISRM</td>
<td>International Society for Rock Mechanics</td>
</tr>
<tr>
<td>KI</td>
<td>Kivetty</td>
</tr>
<tr>
<td>LRE</td>
<td>Laboratory of Rock Engineering</td>
</tr>
<tr>
<td>RO</td>
<td>Romuvaara</td>
</tr>
<tr>
<td>OL</td>
<td>Olkiluoto</td>
</tr>
<tr>
<td>URL</td>
<td>Underground Research Laboratory / Atomic Energy of Canada Limited</td>
</tr>
<tr>
<td>OL-KR10</td>
<td>Borehole OL-KR10 at Olkiluoto investigation site</td>
</tr>
<tr>
<td>RO-KR10</td>
<td>Borehole RO-KR10 at Romuvaara investigation site</td>
</tr>
<tr>
<td>KI-KR10</td>
<td>Borehole KI-KR10 at Kivetty investigation site</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

Rock strength information, together with a complete knowledge of stress-strain behaviour of the rock, *insitu* stress, structural geology and groundwater conditions is essential for selecting the depth for the high level nuclear waste repository. These same factors also affect the shape and orientation of deposition tunnels and holes. Safety during the construction period is moreover related to the strength of the rock and the *insitu* stress state. At present, Posiva is performing detailed site investigations to gather rock mechanical data from the Olkiluoto, Romuvaara, Kivetty, and Hästholmen investigation sites. The potential repository depth level is between 300 m to 700 m.

Before this study, preliminary data of stress-strain behaviour and strength of the investigation site main rock types existed. This knowledge was based on a few uniaxial (9 to 13), damage controlled (5) and indirect tensile tests (5) of each main rock type (Matikainen and Simonen 1992, Kuula 1994, Kuula 1995, Johansson and Autio 1995). All previous test results are from 42 mm diameter core samples.

This work is based on the investigation of literature study of the stress-strain behaviour of crystalline rock, development of a test program (Hakala 1996) and the laboratory testing of Olkiluoto mica gneiss (Hakala & Heikkilä, 1997), Romuvaara tonalite gneiss (Heikkilä & Hakala 1998) and Kivetty granite (Heikkilä & Hakala 1998).

In this work, the stress-strain behaviour and the strength of Kivetty borehole KI-KR10 porphyritic granodiorite are studied based on the suggested test methods. The porphyritic granodiorite is the second rock type at the Kivetty investigation site. All specimens were 62 mm in diameter. The work includes characterization of test specimens, description of the testing system and test configurations used as well as procedures and the interpretation of test results. Recommendations for future testing are also given.

The results of this study can be used to define material parameter values for rock mechanical analyses and numerical models. The experiences from the Kivetty site can also be used to improve testing of the Hästholmen main rock types.
2 TEST PROGRAM

The test program was prepared in order to determine the characteristic stress-strain behaviour of Kivetty borehole KI-KR10 porphyritic granodiorite. This includes the elastic behaviour, short and long term strength of the rock specimen. The test program used is based mainly on test experiences from the Lac du Bonnet gray granite at the Underground Research Laboratory (URL) (Martin 1994), development and qualification of laboratory tests (Hakala 1996) and laboratory testing of Olkiluoto mica gneiss in borehole OL-KR10 (Hakala & Heikkilä, 1997).

With uniaxial and triaxial monotonic compression tests, the elastic stress-strain behaviour, critical stress states and the post-failure phase are studied. The tensile strength was studied using the indirect Brazil tensile tests.

All tests were conducted according to suggestions of the International Society for Rock Mechanics, except that the strain rate control, instead of the suggested loading rate control, was used (ISRM 1981). In the compression test, the radial strain rate was used to control the specimen loading and in both tensile tests axial strain was used. The strain rates are selected to correspond to the suggested loading rates in the elastic region. The radial strain rate control enables controlled testing of the post-failure phase with most Class II rock types (Wawersik 1968).

The test program included 40 rock mechanical tests with porphyritic granodiorite. In addition 12 thin sections were studied to determine petrography (Table 2.1).

<table>
<thead>
<tr>
<th>Test configuration</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compression test</td>
<td></td>
</tr>
<tr>
<td>0.75 MPa/s</td>
<td>10</td>
</tr>
<tr>
<td>Triaxial compression test</td>
<td></td>
</tr>
<tr>
<td>15 MPa confined</td>
<td>10</td>
</tr>
<tr>
<td>Tensile tests</td>
<td></td>
</tr>
<tr>
<td>indirect Brazil test, wet specimens</td>
<td>10</td>
</tr>
<tr>
<td>indirect Brazil test, dry specimens</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total porphyritic granodiorite specimens</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

*Table 2.1 Final test program of Kivetty borehole KI-KR10 porphyritic granodiorite specimens.*
3 TEST SPECIMENS

The following describes the whole specimen handling procedure from the core drilling to the loading. The results of pre-test classification, physical properties and petrography are given.

3.1 SELECTION OF SAMPLES

The studied specimens were from the borehole KI-KR10 at Posiva's Kivetty investigation site (Figure 3.1.1 and 3.1.2). The approximately 600 m long borehole with a diameter of 76 mm was drilled in summer 1995 (Jokinen 1995, p.6). One of the objectives of the borehole was to facilitate overcoring rock stress measurements at depth levels of 300 m, 450 m and 600 m. Also hydrofracturing tests were carried out in KI-KR10 (Ljunggren and Klasson 1996).

Figure 3.1.1 Location of Kivetty investigation site.
The granitoids of the drill core can be divided into three classes according to their petrographical features and whole rock compositions: a granodiorite unit, red potassium granites and mylonitic granites. The red potassium granites are medium to coarse-grained and even-grained in texture. They typically contain from 5 to 10% mafic minerals, and plagioclase is oligoclase (Gehör et al. 1996).

During the drilling and in situ stress measurements the core samples were stored at the drilling site. At the end of the field work the core samples were transferred to the storage of the Geological Survey of Finland at Loppi. After detailed geological inspections the core samples for this study were selected on 5.2.1998 and transferred to the Laboratory of Rock Engineering (LRE) at Helsinki University of Technology (HUT). Before specimen preparation the core samples were stored in warm storage room conditions with an average 22°C temperature and 30%-40% air humidity.

The study concentrated on porphyritic granodiorite, one of the two dominant rock types at the depths investigated. The samples for the testing were selected from the depth level of 206-246 m, because the borehole KI-KR10 does not intersect with porphyritic granodiorite at greater depth. The reported porphyritic granodiorite section at the depth level of 500-520 m proved not to be the rock type wanted (Appendix 1).
Before selection of the core samples for specimen preparation, the cores were carefully inspected visually to avoid pre-existing joints. Special attention was paid to the selection of representative rock samples. The photographs of cores between levels 206 m to 246 m are presented in Appendix 1. The total lengths of the selected core samples are listed in Table 3.1.1 and the list of selected cores is found in Appendix 3.

Table 3.1.1  Total length of test core samples in Kivetty borehole KR10

<table>
<thead>
<tr>
<th>Depth level</th>
<th>Rock type</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>206 - 240</td>
<td>porphyritic granodiorite</td>
<td>7.11</td>
</tr>
</tbody>
</table>

Total length 7.11

3.2 SPECIMEN HANDLING PROCEDURE

During the development and qualification of laboratory tests, a procedure for specimen handling was introduced (Hakala 1996). This procedure was improved based on experiences of testing of Olkiluoto mica gneiss and Romuvaara tonalite gneiss (Hakala & Heikkilä 1997 and Heikkilä & Hakala 1998). In the following a description of the different handling stages is given. The combined control and the data collection form is in Appendix 2. At each handling stage, special care was taken to report all observations differing from the normal procedure.

In the core sample selection phase at Loppi, the bottom and top end of each core sample was marked.

Before specimen preparation the core samples were stored in sample boxes. The specimen preparation begins with measuring the length of each continuous core sample part. At the same time the cores were classified. The idea of pre-classification was to divide geologically different samples equally for different tests.

After the previous phase, the specimen names, the cut lines of each test specimen, the schistosity angle and an arrow pointing downwards were marked on the cores. The naming system consists of the borehole name ‘KIKR10-’ and the upper depth of the specimen within one centimeter accuracy. i.e. ‘543.21’. The cut levels and the downward arrows were also marked on the remaining parts of the cores. A file form was opened for each specimen (Appendix 2).
The test type defines the specimen preparation order. The specimens were cut from core samples with a 35 cm diameter diamond saw. During the sawing the core is held by hand and the blade pressure is controlled manually. After sawing the specimen the ends were flattened with a grinding machine to fulfil the ISRM (1981) suggestions. The prepared specimens were photographed and stored in a sample box in warm storage room conditions with an average 22°C temperature and 30% - 40% air humidity until cutting.

Before testing, the specimens were immersed in a vacuum for one hour and stored in -100% humidity for a week to obtain an even saturation level before testing. The porosity of porphyritic granodiorite was evaluated with six separate specimens.

Just before testing, the length, diameter, mass, perpendicularity of specimen ends and the straightness of sample sides were measured. All length dimensions were measured to within 0.05 mm accuracy and the mass to within 0.1 gram accuracy. The perpendicularity of specimen ends and the straightness of sample sides were taken at maximum difference. An illustration of the specimen side wall flatness was drafted, because no generally accepted defining method existed.

Prior to loading, information of the test type, test control file, resulting data file, test control method and loading rate were recorded. Also, the gap between the circumferential extensometer jaws was recorded as an essential value in calculating the radial strain from the measured circumferential displacement. The test instrumentation was reported in the MTS testing system diary. The conduction of the tests was done according to suggested test procedures introduced later on in chapters 4.2 to 4.4. All the test results were stored in digital form, and only the maximum axial load and confining pressure were recorded in the specimen file form.

After each test the observed failure surfaces were marked on the specimen and photographed. Until further notice, the tested specimens are stored in sample boxes at LRE/HUT.

3.3 CLASSIFICATION

In order to divide geologically different samples equally for the planned tests all core samples were classified. In this way the possible deviation caused by the geological nature of the rock is represented in each test type and the results can be interpreted together. The classification criteria used were a) the rock type, b)
particle arrangement, c) degree of arrangement, d) the schistosity angle e) the depth level and f) mica concentration in the planes

The particle arrangement has three classes; massive (M), schistous (L) and mixed (S). The degree of arrangement is expressed on a scale from none (0) to strong (3). The angle of schistosity is defined as the angle from plane perpendicular to core axis and it is given in degrees. Using this definition the angle of schistosity becomes the same as the dip of schistosity plane in the case of a vertical borehole.

On the basis of experiences in testing Olkiluoto mica gneiss, specimens were also classified by the concentration of mica in the planes (Hakala & Heikkilä, 1997 p.76). The concentration has three classes; mixed (S), schistous (K) and single layer (Y).

All the specimens are classified as massive porphyritic granodiorite. The degree of arrangement is weak (1) (Appendix 3). No schistosity can be found. None of the specimens had clear mica planes. Maximum and average grain size varies slightly between specimens (Figure 3.3.1).

![Figure 3.3.1](image)

*Figure 3.3.1 Classification of Kivetty KR10 porphyritic granodiorite specimens based on maximum grain size.*
3.4 PHYSICAL PROPERTIES

Determination methods

For determine the wet mass of the tested specimen it was saturated by water immersion at a pressure of 732±5 Hg mm below atmospheric for a period of at least one hour. The ISRM (1981) suggestion for a vacuum is at least 700 Hg mm below atmospheric. The absolute pressure was not determined. After immersion, samples were stored in approximately 100% humidity for a week. Before testing, the specimen surface was dried to remove surface water and the mass was determined. The measuring accuracy was 0.1 grams.

The specimen volume was determined by measuring the diameter and height (ISRM 1981). For diameter the average value of six measurements is used and for height three measurements were taken. The reading accuracy used was 0.01 mm.

The porosity of Kivetty porphyritic granodiorite was determined with six specimens. First they were immersed for one hour and the first saturated mass of the specimen was measured. The second saturated mass was measured after a week in storage at approximately 100% humidity. The higher mass of these two was taken as the saturated mass. The volume of the specimens was measured with the buoyancy method. After that they were dried at 105°C for approximately three weeks, until the masses were constant (Figure 3.4.3).

Results

It was planned that all compression test specimens prepared would have a 2.5 height-width ratio, but the accuracy of sawing and the amount of grinding needed produced deviation. The average height-width ratio was 2.53 with a deviation of 0.006 (Figure 3.4.1).

The average dry density of Kivetty porphyritic granodiorite based on 20 specimens was 2731 kg/m³ with a deviation of 8.5 kg/m³ (Figure 3.4.2).

The average porosity of six porphyritic granodiorite specimens was 0.47% and the standard deviation was 0.07% (Figure 3.4.4). The porosity values are quite similar. The average of the saturation of these specimens before immersion was 71.0% and the standard deviation was 8.8%. This is the saturation of the specimens in warm storage room conditions.

The list of all specimens and their physical properties is in Appendix 3.
Figure 3.4.1  Heighth-width ratio variation of KI-KR10 specimens.

Figure 3.4.2  Dry density variation of KI-KR10 porphyritic granodiorite specimens.
Figure 3.4.3 Development of saturation level of KI-KR10 porphyritic granodiorite specimens at 105°C temperature.

Figure 3.4.4 Porosity of six Kivetty KI-KR10 porphyritic granodiorite specimens.
3.5 PETROGRAPHY

The mineral compositions of 12 specimens were determined with the standard geological point counter technique. From each thin section 500 points were counted under polarising microscopy.

Based on the thin sections studied, feldspar, quartz, mica and hornblende were the main minerals, being at least 99% of all minerals (Figures 3.5.1). The average values and 95% confidence limits for standard deviation of the four main minerals are:

<table>
<thead>
<tr>
<th>mineral</th>
<th>average</th>
<th>upper 95% confidence limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>feldspar</td>
<td>59%</td>
<td>±22%</td>
</tr>
<tr>
<td>quartz</td>
<td>19%</td>
<td>±14%</td>
</tr>
<tr>
<td>mica</td>
<td>12%</td>
<td>±7%</td>
</tr>
<tr>
<td>hornblende</td>
<td>9%</td>
<td>±6%</td>
</tr>
</tbody>
</table>

The texture is non-oriented, the grain size varies between 10 mm and 30 mm and no weathering exists (Table 3.5.1).

Figure 3.5.1 Composition of major minerals of each Kivetty KR10 porphyritic granodiorite thin section.
Table 3.5.1  Results from the Kivetty KR10 porphyritic granodiorite thin section study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Texture</th>
<th>Grain size</th>
<th>Dominating grain size (mm)</th>
<th>Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>207.93A</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>207.93B</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>215.68A</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
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</tr>
<tr>
<td>215.68B</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
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<td>10-30</td>
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<tr>
<td>216.00B</td>
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<td>no</td>
<td></td>
</tr>
<tr>
<td>220.99B</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
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<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>240.21B</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>243.73A</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>243.73B</td>
<td>no varying, porphyritic</td>
<td>10-30</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
4 TEST CONFIGURATIONS AND PROCEDURES

4.1 TESTING SYSTEM

In all compression and tensile tests the MTS 815 Rock Mechanics Testing System, a computer controlled servo hydraulic compression machine, was used. The system consists of load cell, load frame, hydraulic power supply, test controller, test processor and PC micro computer (Figure 4.1.1).

Figure 4.1.1 MTS 815 Rock Mechanics Testing System.
4.2 MONOTONIC COMPRESSION TESTS

Both uniaxial and triaxial monotonic compression tests were used to study the stress-strain behaviour of Kivetty porphyritic granodiorite. In both tests 62 mm diameter and 155 mm high specimens were used.

Uniaxial compression tests

In the uniaxial test, three averaging direct contact axial extensometers are used to measure axial strain (Figure 4.2.1). The deformation is measured from a 50 mm gage length. The radial strain is measured with one circumferential extensometer connected to the roller chain assembly wrapped around the specimen. All extensometers are held around the specimen by a contact force produced by mount springs. The actuator movement is also measured. At the specimen ends non-lubricated steel end caps were used. In order to assure uniform load distribution the axial load was applied through one spherical seat.

![Uniaxial test configuration](image)

Figure 4.2.1 Uniaxial test configuration.

The monotonic uniaxial compression tests were done under radial strain rate control, corresponding to an elastic axial loading rate of 0.75 MPa/s. The ISRM suggestion for the uniaxial loading rate is 0.5 - 1.0 MPa/s. The uniaxial compression tests with a 0.75 MPa/s loading rate were conducted according to
Table 4.2.1. The specimen is driven to contact under programmed control to get exact zero stress extensometer readings. One loading ramp in the elastic region was done to ensure a well-settled sample before loading it to failure. In both of these loading steps, axial load control was used first to overcome the radial extensometer hysteresis and after that the control is changed to radial strain to ensure a controlled test condition in the post-failure phase.

<table>
<thead>
<tr>
<th>No.</th>
<th>Step Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drive specimen manually near to contact</td>
</tr>
<tr>
<td></td>
<td>- no axial force is allowed.</td>
</tr>
<tr>
<td>2</td>
<td>Reset readings</td>
</tr>
<tr>
<td></td>
<td>- reset readings of axial and radial extensometer, actuator displacement and axial force.</td>
</tr>
<tr>
<td>3</td>
<td>Start programmed test control</td>
</tr>
<tr>
<td>4</td>
<td>Drive specimen to force contact</td>
</tr>
<tr>
<td></td>
<td>- move actuator up 0.2 mm/min until axial force is 1.0 kN, the maximum actuator movement allowed is 3 mm.</td>
</tr>
<tr>
<td>5</td>
<td>Axial loading ramp to settle specimen</td>
</tr>
<tr>
<td>5a</td>
<td>Increase axial load so that loading rate is 0.75 MPa/s until radial strain is -0.01% or axial stress is 35 MPa.</td>
</tr>
<tr>
<td>5b</td>
<td>Decrease axial load so that loading rate is 0.75 MPa/s until axial force is 1.0 kN.</td>
</tr>
<tr>
<td>6</td>
<td>Loading to rupture</td>
</tr>
<tr>
<td>6a</td>
<td>Increase axial load so that loading rate is 0.75 MPa/s until radial strain is -0.01% or axial stress is 35 MPa.</td>
</tr>
<tr>
<td>6b</td>
<td>Change to radial strain rate control.</td>
</tr>
<tr>
<td>6c</td>
<td>Increase radial strain corresponding to the elastic loading rate of 0.75 MPa/s until the end of the radial extensometer range is reached.</td>
</tr>
<tr>
<td>7</td>
<td>Unloading</td>
</tr>
<tr>
<td></td>
<td>- Decrease axial load to zero with 50 kN/min loading rate.</td>
</tr>
</tbody>
</table>

**Triaxial compression tests**

In triaxial tests the specimen and the deformation measuring instruments are inside the pressure vessel (Figure 4.2.2). The confining pressure was produced by the confining oil. To prevent the confining oil from penetrating into the specimen, it was sealed with an EPDM rubber jacket. The deformations were measured on the jacket. The axial strain was measured with two separately read direct contact axial extensometers. The gage length of the axial extensometers
was 50 mm. The radial strain was measured with one circumferential extensometer connected to a roller chain assembly wrapped around the jacketed specimen. All extensometers were held around the jacketed specimen by springs. Non-lubricated steel end caps were used at the specimen ends. In order to assure uniform load distribution the axial load was applied through one spherical seat.

![Triaxial test configuration](image)

*Figure 4.2.2 Triaxial test configuration.*

All monotonic triaxial compression tests were done under a radial strain rate control corresponding to a 0.75 MPa/s elastic axial loading rate. The concept of the triaxial compression test procedure is based on the uniaxial test but having additional steps to handle confining pressure (Table 4.2.2). As the pressure vessel can not be filled by computer control, the programmed test control was set to the hold mode for this period. To settle the jacket and the extensometers on the jacket a confining ramp was done the same way as in the axial direction. After the confining ramp, the pressure was set to test value. With Kivetty porphyritic granodiorite a confining pressure of 15 MPa was used.
Table 4.2.2  Triaxial compression test procedure with a 0.75 MPa/s loading rate.

1 Drive specimen manually near to contact
   - no axial force is allowed.

2 Reset readings
   - reset readings of axial and radial extensometer, actuator displacement, axial force and confining pressure.

3 Start programmed test control

4 Drive specimen to force contact
   - move actuator up 0.2 mm/min until axial force is 1.0 kN, the maximum allowed actuator movement is 3 mm.

5 Hold axial load while filling the pressure vessel with confining oil
   5a Hold axial load for 60 seconds; during this period the test control is set manually to the hold state. During the manual hold the axial load remains.
   5b Fill pressure vessel, while manually controlled, with confining oil.
   5c Release the manual hold to continue with programmed control.

6 Confining ramp to settle jacket and extensometers on jacket
   6a Increase confining pressure 0.05 MPa/s to 15 MPa.
   6b Decrease confining pressure 0.05 MPa/s to 0.5 MPa.

7 Set confining pressure to test value
   - Increase confining pressure 0.05 MPa/s to test value.

8 Axial loading ramp to settle specimen
   8a Increase axial load so that loading rate is 0.75 MPa/s until radial strain is -0.01% or axial stress is 35 MPa.
   8b Decrease axial load so that loading rate is 0.75 MPa/s until axial force is 1.0 kN.

9 Loading to rupture
   9a Increase axial load so that loading rate is 0.75 MPa/s until radial strain is -0.01% or axial stress is 35 MPa.
   9b Change to radial strain rate control.
   9c Increase radial strain corresponding to the elastic loading rate of 0.75 MPa/s until the end of the radial extensometer range is reached.

10 Unloading
   10a Decrease axial load to zero with 50 kN/min loading rate.
   10b Decrease confining pressure 0.05 MPa/s to 0.5 MPa.
4.3 TENSILE TEST

Indirect tensile tests were used to define tensile strength of the Kivetty porphyritic granodiorite. In the indirect Brazil tensile test the height of the specimen is 31 mm. The tension is produced indirectly by compression.

As the tensile failure is extremely brittle and the needed loads are relatively small compared to the system control accuracy, no settling ramps were done in indirect tensile tests. Test is conducted under actuator movement control.

Indirect Brazil tensile test

In the indirect Brazil tensile test only the applied load and actuator movement are measured. The compressive load is applied in a normal direction to the specimen surface inducing a horizontal tension to the specimen (Figure 4.3.1). The load is applied through two 3.5 mm wide flat steel jaws. To extend the contact area from the theoretical line contact a 0.15 mm thick paper tape is used around the specimen. The indirect test configuration used is not according to ISRM (1981) suggestions, in which the specimen is loaded between two concave steel plates having a surface radius 1.5 times the specimen radius.

In the test procedure used the specimen is first driven slowly to contact (Table 4.3.1). After that the tensile test is conducted with constant compressive actuator movement.

Figure 4.3.1 Indirect Brazil tensile test configuration.
Table 4.3.1  
*Procedure for indirect Brazil tensile test*

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drive specimen manually near to contact</td>
</tr>
<tr>
<td></td>
<td>- no axial force is allowed.</td>
</tr>
<tr>
<td>2</td>
<td>Reset readings</td>
</tr>
<tr>
<td></td>
<td>- reset readings of actuator displacement and axial force.</td>
</tr>
<tr>
<td>3</td>
<td>Start programmed test control</td>
</tr>
<tr>
<td>4</td>
<td>Drive specimen to force contact</td>
</tr>
<tr>
<td></td>
<td>- move actuator up 0.2 mm/min until axial force is 1.0 kN,</td>
</tr>
<tr>
<td></td>
<td>maximum actuator movement allowed is 3 mm.</td>
</tr>
<tr>
<td>5</td>
<td>Loading to tensile failure</td>
</tr>
<tr>
<td></td>
<td>- Move actuator up with a speed corresponding to 200 Pa/s elastic loading rate, maximum actuator movement is restricted to 4 mm.</td>
</tr>
</tbody>
</table>
4.4 QUALITY CONTROL

To assure that all test phases are done to each specimen in the planned order, and to make it possible to re-analyse possible errors and deviations in the results, all preparation and test phases of each specimen were reported on a test information form (Appendix 2). The test information forms are not included in this report, instead they are stored in the LRE/HUT and in Posiva Oy.

Before the laboratory testing of OL-KR10 the extensometers of the MTS test system were calibrated (Hakala & Heikkilä, 1997 p.39). During the tests of OL-KR10 and RO-KR10 the extensometer readings were checked with a 56 mm aluminium specimen. The reference values for the aluminium specimen were measured right after the extensometer calibration. The checking was done at the beginning of each new test series. Young’s modulus and Poisson’s ratio were used as monitoring values. Both values were determined as a secant from the range of 0.01% radial strain to 150 MPa axial stress. The checking was done with uniaxial and triaxial configurations. In the triaxial case the confining pressure was 20 MPa and no jacket was used.

When testing of RO-KR10 was completed, the uniaxial radial extensometer was changed to a similar one. This was done because the former extensometer had some damage in the body. This did not in any case affect the accuracy of measuring the radial strain. This could be seen from the quality control tests. The new extensometer was calibrated before testing the Kivetty specimens.

The average of Poisson’s ratio in the quality control tests with the new radial extensometer was 0.31 and with the former extensometer 0.36. The reason for the difference is unclear. The calibration of both extensometers was done very carefully with proper instruments, and no error was found in either radial extensometer. Evidently, the reason for different readings is the accuracy of the extensometer compared to the sensitivity of determining Poisson’s ratio. MTS reports unlinearity of 0.15% for extensometers. That is 0.006 mm of 4 mm, which is the middle range of the radial extensometer (max 8 mm). The value of 0.006 mm is as much as 5% of the total movement of the radial extensometer in the quality control test.

In the monitored check values no trend can be seen, but deviation is clear, especially in the case of triaxial configuration (Figure 4.4.1). The uniaxial configuration gives stable values with minor deviation. With 95% confidence the deviation of uniaxial Young’s modulus is less than ±3.5% and triaxial Young’s modulus is less than ±2% (Figure 4.4.2). The 95% confidence limits for Poisson’s ratio are 5% for uniaxial and 7% for triaxial extensometers. The
total number of uniaxial check tests was 12 and the number of triaxial check tests was 17.

**Figure 4.4.1** Development of uniaxial and triaxial extensometer monitoring values in the case of the same 56 mm aluminium specimen.

**Figure 4.4.2** 95% confidence limits and average value of extensometer monitoring values, in the case of the 56 mm aluminium specimen.
The difference of average values between uniaxial and triaxial configuration is also clear (Figure 4.4.2). With triaxial configuration the average Young's modulus is 4% higher and the average Poisson's ratio is 6% higher. Although the difference in Young's modulus is minor, it can be taken into account because the deviation ranges overlap only slightly. The previous measurements with strain gauges and the values found from literature give an average modulus of 70.6 GPa for aluminium (Hakala and Heikkilä 1997, p 100, Leppävuori et. al. 1981, p 100 and MAOL, 1978 p 50). Therefore it is suggested that the triaxial Young's modulus be reduced by 3.8% to make it comparable with the uniaxial value. The difference in Poisson's ratio is clearly related to the radial strain measurement. The Poisson's ratio obtained from triaxial tests (average 0.33) seems to be more real than the one obtained from uniaxial tests (average 0.31). According to Leppävuori (1981, p.100) the Poisson's ratio of aluminium is 0.33. Hakala (1996, p.49) obtained the value 0.321 in his measurements with a 62 mm specimen and strain gauges. The 62 mm specimen was made from the same aluminium as the 56 mm specimen used in quality control.
5 TEST RESULTS

5.1 INTERPRETATION METHODS

In the following the interpretation methods used to determine elastic parameters, critical stress states and damage from stress-strain data are described. Finally, the method to calculate confidence limits is presented.

Before interpretation, the axial and the radial stress strain curves are replaced with Fourier transformations to filter the noise and in this way to reduce the effect of subjective selection.

**Elastic parameters**

For all compression and direct tensile test specimens the elastic parameters, Young’s modulus ($E$) and Poisson’s ratio ($v$), are determined. The determination is basically done as secant value from the range of $-0.01\%$ radial strain ($\varepsilon_r$) to half of peak strength ($\sigma_p$) (Figure 5.1.1). The range is changed only if axial or radial stress-strain behaviour is clearly non-linear within this range. The definition of the determination limits is presented in Hakala (1996).

![Figure 5.1.1 Determination of elastic parameters.](image)

$$E = \frac{\Delta\sigma_a}{\Delta\varepsilon_a}$$

$$v = -\frac{\Delta\varepsilon_r}{\Delta\varepsilon_a}$$

**Lower limit**

$\varepsilon_r = -0.01\%$

$\Delta\varepsilon_r$

$\Delta\sigma_a$

$\sigma_p$  

*Upper limit*  

$\sigma_p/2$

$\sigma_{cd}$

$\sigma_{cs}$

$\Delta\varepsilon_a$

$\Delta\varepsilon_a$
Critical Stress States

The critical stress states here refer to tensile strength ($\sigma_t$), crack initiation stress ($\sigma_{ci}$), crack damage stress ($\sigma_{cd}$) and peak strength ($\sigma_p$) (Figure 5.1.2). In addition to these stress values the corresponding axial and radial strains are also recorded.

![Critical Stress States Diagram](image)

Figure 5.1.2 Determination of critical stress states $\sigma_t$, $\sigma_{ci}$, $\sigma_{cd}$ and $\sigma_p$. 
The tensile strength ($\sigma_t$) is defined as the ultimate tensile capacity of the direct tensile test or from the compression load of the indirect Brazil test (Equation 5.1.1) (ISRM 1981). The corresponding axial and radial strains can not be defined from the results of the indirect tensile test.

$$\sigma_t = \frac{2F}{DL\pi} \quad (5.1.1)$$

where $F$ is maximum axial load (N), $D$ specimen diameter (m), and $L$ specimen length (m).

The crack damage stress ($\sigma_{cd}$) is defined as the reversal of the volumetric strain ($\varepsilon_v$) curve (Figure 5.1.2). At this point the total volume of the specimen turns from compaction to dilation. The total volumetric strain ($\varepsilon_v$) is approximated from axial ($\varepsilon_a$) and radial strains ($\varepsilon_r$) (Equation 5.1.2).

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_r \quad (5.1.2)$$

The crack initiation stress is defined as a stress level where the crack volumetric strain ($\varepsilon_{v,cr}$) deviates from zero (Figure 5.1.2). The crack volumetric strain ($\varepsilon_{v,cr}$) is calculated by subtracting the elastic deformations ($\varepsilon_{v,e}$) of the rock matrix from the total volumetric strain ($\varepsilon_v$). The elastic volumetric strain ($\varepsilon_{v,e}$) is defined by Young’s modulus ($E$) and Poisson’s ratio ($\nu$) and current major ($\sigma_1$) and minor principal stresses ($\sigma_3$) (Equation 5.1.3).

$$\varepsilon_{v,e} = \frac{1-2\nu}{E} (\sigma_1 - \sigma_3) \quad (5.1.3)$$

After subtracting the elastic volumetric strain ($\varepsilon_{v,e}$) from the total volumetric strain ($\varepsilon_v$), the crack volumetric strain curve is shifted so that the maximum value is zero (Figure 5.1.2).

The determination of the crack initiation stress ($\sigma_{ci}$) state is not always clear, therefore the first guess for $\sigma_{ci}$ is determined as the last point having a crack volumetric strain ($\varepsilon_{v,cr}$) equal to 0.5% of total compaction (Figure 5.1.3a). This value, checked visually, is to be at the intersection of the horizontal line and the extension of the increasing crack volume (Figure 5.1.3b).
The peak strength ($\sigma_p$) is defined as the highest observed axial stress (Figure 5.1.2).

**Figure 5.1.3** Determination of the crack initiation stress ($\sigma_{ci}$) as a first non-zero point of fitted crack volumetric curve (a) or as an intersection point of visual trend lines (b).
Statistics

Besides the commonly presented sample variation, average value and standard deviation, the upper and lower 95% confidence limits for standard deviation are also given. The calculation of confidence limits assumes that the results are normally distributed. Therefore the normality of test results are shown in Appendices 8 and 9. The upper and lower estimator for standard deviation ($s$) with $100(1-\alpha)$% confidence is calculated from equation (Laininen 1980, p 181):

$$\frac{(n-1)s^2}{\chi^2_{1-\alpha}(n-1)} \leq s \leq \frac{(n-1)s^2}{\chi^2_{\alpha}(n-1)} \quad (5.1.4)$$

where $n$ is number of samples
$\chi^2$ the inverse of the one-tailed probability of the chi-squared distribution

In confidence results the upper estimator for standard deviation is used, i.e. the upper and lower estimate for estimated value ($\bar{x}$) are:

$$\hat{x}_L = \bar{x} - \frac{s}{\sqrt{u}} \quad (5.1.5a)$$

$$\hat{x}_U = \bar{x} + \frac{s}{\sqrt{u}} \quad (5.1.5b)$$

The normality of the test results, and the estimators are presented as cumulative probability figures (Appendix 8 and 9). The figure shows all the test results sorted from minimum to maximum. Also the corresponding normal distribution calculated from the average value and the standard deviation is presented as a continuous line. The normal distribution line is in a different y-scale if the number of points for normal distribution is different from the total number of tested specimens. These number are shown in figures. Also, the values corresponding to the interpreted 95% confidence limits for standard deviation and the average of test results are shown.
5.2 CHARACTERISTICS OF STRESS-STRAIN BEHAVIOUR

On the borehole scale Kivetty porphyritic granodiorite is a homogenous, non orientated massive rock, but in the specimen scale the large grain size from 10 mm to 30 mm makes it visually non-homogenous. Despite the large grain size relatively small deviation of stress-strain and strength behaviour was measured (Figures 5.2.1 and 5.2.2).

Based on the test results the porphyritic granodiorite is brittle rock. In uniaxial loading the majority of bearing capacity was lost right after achieving peak strength. The post peak behaviour of the tested porphyritic granodiorite specimens was clearly Class I type and this behaviour was clearly emphasized with confinement. In uniaxial loading the destruction of the porphyritic granodiorite specimen usually started by coalescence of axial fractures or the peeling off of little pieces from the sides leading to failure through buckling. In triaxial tests a large shear fracture through the whole specimen was seen in a majority of the tests. When a fracture appeared under the chain of the radial strain extensometer, the measuring of the radial strain becomes unclear and the calculation of volumetric strain is also unclear. The axial deformation can still be defined quite reliably from the actuator displacement.

A confinement of 15 MPa increases the achieved peak strength clearly over the corresponding uniaxial values. Besides the different destruction types, the deviation of results was larger than in uniaxial tests. The average axial and radial strains for uniaxial peak strengths are 0.22% and -0.11%. The corresponding values for triaxial tests with 15 MPa confinement are 0.44 % and -0.29%. None of the specimens bear axial strain over 1% with notable post peak bearing capacity.
Figure 5.2.1 Variation of uniaxial stress-strain behaviour of Kivetty porphyritic granodiorite with a typical stress-strain curve.

Figure 5.2.2 Variation of triaxial stress-strain behaviour of Kivetty porphyritic granodiorite with a typical stress-strain curve.
5.3 ELASTIC PARAMETERS

**Young’s modulus**

With 95% confidence the uniaxial Young’s modulus of the Kivetty porphyritic granodiorite studied was between 61 GPa to 77 GPa. The upper confidence limit was ±12% (Appendix 8). Based on quality control measurement the triaxial values were corrected by -3.6% (Figure 4.6.2).

![Graph showing Young's modulus](image)

*Figure 5.3.1* The 95% confidence limit for standard deviation of Young’s modulus.
**Poisson's ratio**

With 95% confidence Poisson's ratio of the porphyritic granodiorite studied is between 0.15 and 0.32 (Figure 5.3.2) (Appendix 8). The given values are based on corrected results. A high difference of 40% exists between the uniaxial and triaxial Poisson's ratio values. The deviation of triaxial values is 25% and in the case of uniaxial values 14%.

![Diagram of Poisson's ratio](image)

**Figure 5.3.2** The corrected 95% confidence limit for standard deviation of Poisson's ratio.

In the qualification of the test program it was found that the 0.5 mm thick rubber jacket could produce a -8% systematic error if the volume of rubber is assumed to be constant (Hakala 1996). Hakala and Heikkilä (1997, p.53) also found that in the case of Olkiluoto mica gneiss the confinement level does not have an effect on Poisson's ratio. Therefore, a correction of +8% was made on the defined triaxial values. The quality control measurement systematically gave about 0.016 lower Poisson's ratio values with uniaxial extensometers than with triaxial extensometers (Figure 4.6.2). Therefore a correction of +0.016 was applied to uniaxial Poisson's ratio. The measured uncorrected values are in Figure 5.3.3.
Figure 5.3.3 The uncorrected 95% confidence limit for standard deviation of Poisson's ratio.
5.4 STRENGTH PARAMETERS

Tensile Strength

The tensile strength of Kivetty porphyritic granodiorite was defined with the indirect Brazil tensile test. The influence of moisture on tensile strength was tested using ten pairs of adjacent specimens. Half of the specimens were tested at room humidity, and the other half was saturated in a like manner as the compression test specimens.

No effect of pore water on defined tensile strength was found, and both the test series gave practically the same results with the same deviation. Therefore it can be concluded that the indirect tensile strength of the porphyritic granodiorite studied was, with 95% confidence, between -4.9 MPa and -10.9 MPa, while the average was -7.9 MPa.

![Diagram showing tensile strength results](image)

Figure 5.4.1 The 95% confidence limit for standard deviation of tensile strengths.
Crack Initiation

With 95% confidence, the limits for uniaxial crack initiation are 64 MPa and 72 MPa. With 15 MPa confinement the limits are 114 MPa and 162 MPa. The effect of confinement on the average crack initiation stress is clear. In uniaxial tests the maximum deviation was extremely small being 6% of the average and in the triaxial test the maximum deviation was 17%. The defined uniaxial crack initiation values varied from 64 MPa to 73 MPa and corresponding triaxial values varied from 126 MPa to 168 MPa (Appendix 9).

Figure 5.4.2 The 95% confidence limit for standard deviation of crack initiation stress.
Crack Damage

With 95% confidence, the limits for uniaxial crack damage stress are 86 MPa and 124 MPa. With 15 MPa confinement the limits are 182 MPa and 242 MPa. The effect of confinement on the average crack stress is clear. In uniaxial tests the maximum deviation was 18% of the average and in the triaxial test the maximum deviation was 14%. The defined uniaxial crack damage values varied from 93 MPa to 124 MPa and corresponding triaxial values varied from 188 MPa to 246 MPa (Appendix 9).

Figure 5.4.3 The 95% confidence limit for standard deviation of crack damage stress.
**Peak Strength**

With 95% confidence, the limits for uniaxial peak stress are 115 MPa and 152 MPa. With 15 MPa confinement the limits are 244 MPa and 304 MPa. The effect of confinement on the average crack stress is clear. In uniaxial tests the maximum deviation was 14% of the average and in the triaxial test the maximum deviation was 11%. The measured uniaxial peak strength values varied from 121 MPa to 151 MPa and corresponding triaxial values varied from 257 MPa to 312 MPa (Appendix 9).

![Graph showing peak strength values](image)

**Figure 5.4.4** The 95% confidence limit for standard deviation of peak strength.
CONCLUSIONS

In this study the stress-strain behaviour of porphyritic granodiorite from the Kivetty investigation site was studied with 40 specimens. In this report the established name of porphyritic granodiorite is used for the tested rock type, although the true modal name would be porphyritic granite. The porphyritic granodiorite is the other main rock type between 300 m ... 800 m levels at the Kivetty site. The 62 mm diameter specimens were taken from the borehole KI-KR10 representing the depth region 200 – 250 m, because borehole KI-KR10 does not intersect with the porphyritic granodiorite at greater depth.

Characteristics

In the bore hole scale of studied specimens the Kivetty porphyritic granodiorite is a massive, homogenous plutonic rock, although the characteristic large grain size visually dominates in the test specimens’ scale. The general stress-strain behaviour and strength is defined by the geological mode of origin and the average mineral content: 59% feldspar, 19% quartz, 12% mica and 9% hornblende. The measured mica content varied between 5% to 18%. Although the mica content and the deviation of mineral content can be considered moderate the deviation in defined elastic parameters and critical pre-peak stress states was small. All the measured values also showed good agreement with normal distribution, therefore all the results are presented in a form of upper and lower 95% confidence limits for standard deviation (Appendices 8 and 9).

Stress-Strain Behaviour

Based on the test results the porphyritic granodiorite is brittle rock. In uniaxial loading the majority of bearing capacity was lost right after achieving peak strength. The post peak behaviour of the tested porphyritic granodiorite specimens was clearly Class I type and this behaviour was clearly emphasized with confinement. In uniaxial loading the destruction of the porphyritic granodiorite specimen usually started by coalescence of axial fractures or by peeling off of little pieces from the sides leading to failure through buckling. In triaxial tests a large shear fracture through the whole specimen was seen in a majority of the tests. In many cases the first macroscopic fracture took place under the circumferential extensometer, thereby making the radial strain measurement unreliable for the rest of the post failure phase.
Based on the test results and the assumption that the crack damage stress is the true peak strength for undisturbed rock, the lower 95% confidence limit for the strength is defined by the envelope of 86 MPa uniaxial compressive strength and 182 MPa compressive strength with 15 MPa confinement. The corresponding upper 95% confidence envelope is $\sigma_{cd,0} = 124$ MPa and $\sigma_{cd,15} = 242$ MPa (Figures 6.1 and 6.2). The 95% confidence envelopes for crack initiation $\sigma_{ci}$ are defined by the stress pairs $\sigma_{ci,0} = 64/72$ MPa and $\sigma_{ci,15} = 114/162$ MPa.

![Graph showing 95% confidence limits for the crack initiation and crack damage stress envelopes.](image)

**Figure 6.1** 95% confidence limits for the crack initiation and crack damage stress envelopes.
Factors Affecting Observed Behaviour

In concluding the results, the possible factors affecting the measured stress-strain behaviour and the critical stress states were checked. The Kivetty porphyritic granodiorite is homogenous, without many connected structural factors, which make this study more reliable.

Because of the test program and the specimen handling procedures used, the possible effects of porosity and loading rate were not studied. In the study of Olkiluoto mica gneiss the loading rates 0.75 MPa/s and 0.0075 MPa/s were found to have only a minor affect on the observed critical stress values.

The studied depth range was quite short and the depth location of specimens did not show any major correlation with measured strength (Figure 6.3). The relative strength is below the average in depth range 208 m to 216 m and below the 234 m level the relative strength is above average except in three specimens.
The possible effect of mineral content on achieved strength was studied by inspecting thin sections from the two weakest, two middle strength and two strongest specimens. Two thin sections from each specimen were prepared (Figure 6.4). Neither the mica content nor any other mineral content showed clear correlation with the peak strength.

The degree of arrangement and the angle of schistosity can not affect measured behaviour because all the specimens were classified as massive without any orientation (M0).

The porphyritic granodiorite is featured by large grains. The average grain size, 10 mm to 15 mm, was practically the same for all specimens but all specimens also included bigger grains of 20 mm to 30 mm. However, the grain size does not correlate with the observed strength (Figure 6.5).
Figure 6.4 Mineral content and peak strength of the two weakest, two middle strength and two strongest Kivetty porphyritic granodiorite specimens.

The specimens were also reinspected visually after testing, but no features to explain the different strengths were seen (Figure 6.6).

Because there seems be no clear reasons for the deviation, the possible effect of side wall straightness and the straightness of the ground specimen ends also were checked. The straightness of specimen end did not show any correlation with peak strength, but the side wall straightness indicates at least minor correlation with achieved peak strength (Figure 6.7). Certain caution regarding this result should be taken because the side wall unstraightness values were relatively small.

The attempt to find factors affecting the measured critical stress states did not give any clear answers. Therefore the measured deviation should be considered as a natural deviation of the tested porphyritic granodiorite. The natural deviation includes all structural factors which can not be seen or measured without breaking the specimen. In the case of Kivetty porphyritic granodiorite compression tests this deviation was ±6% to ±18% and in tension it was ±37%.
Figure 6.5 Maximum and average grain size versus peak strength. Kivetty KI-KR10 porphyritic granodiorite.

As a controlled factor, the effect of saturation was tested with the indirect Brazil tensile test. The ten specimen pairs tested were adjacent and therefore as similar as possible. Being of 0.47% average porosity, the saturation has no effect on the achieved tensile strength (Figure 6.8).

Measuring techniques

The measuring of radial strain and thereby the definition of volumetric strain in the post failure phase was found to be problematic, but better measuring techniques probably do not exist.
Figure 6.6  Uniaxial test specimens before loading and the measured peak strength. Kivetty KI-KR10 porphyritic granodiorite.
Figure 6.7 Uniaxial test specimens before loading and the measured peak strength. Kivetty KI-KR10 porphyritic granodiorite.
Figure 6.7  The straightness of specimen side walls and specimen ends versus peak strength. Kivetty KI-KR10 porphyritic granodiorite.

Figure 6.8  The effect of saturation on the indirect Brazil tensile strength of Kivetty KI-KR10 porphyritic granodiorite.
Comparison of Strength deviation with Lac du Bonnet Granite, Olkiluoto Mica Gneiss, Romuvaara Tonalite Gneiss and Kivetty Granite Results

The unconfined compressive strengths of Kivetty porphyritic granodiorite were compared with corresponding values of Lac du Bonnet granite, Olkiluoto mica gneiss, Romuvaara tonalite gneiss and Kivetty granite (Martin 1994, Hakala and Heikkilä 1997, Heikkilä and Hakala 1998a, Heikkilä and Hakala 1998b) (Figure 6.9). The results show that the Kivetty porphyritic granodiorite results have a clear distribution, contrary to Olkiluoto mica gneiss and Romuvaara tonalite gneiss. For Kivetty porphyritic granodiorite the standard deviation is ±8% of the average uniaxial peak strength. The corresponding standard deviations are; ±11% for the Kivetty granite, ±28% for the Romuvaara tonalite gneiss, ±29% for the Olkiluoto mica gneiss and ±9% for the Lac du Bonnet granite. This comparison confirms the concept, that the statistical approach to measured values gives essentially better information of the studied rock types than the average values.

Figure 6.9  Deviation of unconfined compressive strengths of Kivetty porphyritic granodiorite, Kivetty granite, Romuvaara tonalite gneiss, Olkiluoto mica gneiss and Lac du Bonnet granite / URL.
RECOMMENDATIONS

Although the test program and interpretation methods used were found suitable to study the stress-strain behaviour of brittle rock, the following recommendations for future testing are given.

**Test Types and Number of Specimens Per Test**

According to Hakala & Heikkilä (1997, p. 74) for highly heterogeneous and anisotropic rock like mica gneiss, at least 15 specimens per test are recommended, while 20 is preferred. In this study of Kivetty porphyritic granodiorite uniaxial and triaxial tests both contained 10 specimens. Based on the 10 values for crack initiation stress, the uniaxial average value and the confidence limits stabilized after three tests but in the triaxial test at least five specimens were needed for acceptable confidence (Figure 7.1). Therefore five specimens for each test would have been an optimum with a homogeneous rock like Kivetty porphyritic granodiorite.

![Figure 7.1](image)

*Figure 7.1 Development of average value and 95% confidence limits for standard deviation in uniaxial test of Kivetty porphyritic granodiorite.*
AE-measurements

The acoustic emission measurements with all direct tensile tests would be useful to obtain values for crack initiation and crack damage in tension. The currently used extensometers are not suitable for this purpose because of the extensometer hysteresis. With AE, comparable information of the critical stress states in compression would also have been achieved.
REFERENCES


# APPENDICES

<table>
<thead>
<tr>
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<th>Description</th>
<th>Pages</th>
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<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>Test information form.</td>
<td>66 - 67</td>
</tr>
<tr>
<td>3</td>
<td>List of test specimens and physical properties.</td>
<td>68</td>
</tr>
<tr>
<td>4</td>
<td>Results from thin section observations.</td>
<td>69 - 78</td>
</tr>
<tr>
<td>5</td>
<td>Results from loading tests.</td>
<td>79 - 98</td>
</tr>
<tr>
<td>6</td>
<td>Elastic parameters, critical stress states and corresponding strains.</td>
<td>99</td>
</tr>
<tr>
<td>7</td>
<td>Photographs of tested specimens.</td>
<td>100 - 109</td>
</tr>
<tr>
<td>8</td>
<td>Deviation of elastic parameters.</td>
<td>110 - 111</td>
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<tr>
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<td>Deviation of critical stress states.</td>
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Kivetty Bore Hole K3-KR10 Porphyritic Granodiorite
Physical properties of specimens and test type

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**Note:** The table includes various physical properties and test types for the specimens, including rock type, particle arrangement, angle of schistosity, dimensions, parallelism, height/width ratio, density, average grain size, and text type. The control and loading rate (MPa) are also specified for each specimen.
SAMPLE KIKR10 - 207.93A

PETROLOGY

Rock type:
Granite
(Coarse-porphyritic granite)

x Magmatic
Metamorphous
Sedimentary
Ore

a. Oxide
b. Sulphide

MINERAL COMPOSITION

Essential minerals:             vol. %             Accessory minerals ( < 5 vol. %):
1. Quartz (10.6)                 1. Opaque (2.4)
2. Potassium feldspar (43.0)     2. Sphene (+)
4. Biotite (7.0)                 4. Apatite (+)
5. Hornblende (5.6)              5. Zircon (+)
6.                                 6.

TEXTURE

Orientation:

x No
Weak
Moderate
High

Grain size distribution

Even grained
Varying
Porphyritic

Appearance of minerals:

- Hypidiomorphic granular feldspars showing some porphyric features being allmost euhedral
- Abundant myrmeck+J9ite
- Quartz undulatory (not so strong)
- Some mortar texture

DOMINATING GRAIN SIZE

< 1 mm
1-3 mm
3-10 mm
x 10-30 mm
> 30 mm

DEGREE OF WEATHERING

x No weathering
Weak
Moderate
High

Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains before serisitization and myrmekitic growth.

Examiner of geological data: M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE  KIKR10 - 207.93B

PETROLOGY

Rock type:
Granite
(Coarse-porphyritic granite)

x  Magmatic
Metamorphous
Sedimentary
Ore
a. Oxide
b. Sulphide

MINERAL COMPOSITION

Essential minerals:  vol. %  Accessory minerals ( < 5 vol. % ):
1  Quartz  ( 34.6 )  1  Opaque  ( 1.4 )
2  Potassium feldspar  ( 16.3 )  2  Sphene  ( + )
3  Plagioclase  ( 24.0 )  3  Serisite-Sauss.  ( 0.4 )
4  Biotite  ( 13.0 )  4  Apatite  ( + )
5  Hornblende  ( 9.8 )  5  Zircon  ( + )
6  ( )  6  Carbonate  ( 0.2 )

TEXTURE

Orientation:  Grain size distribution  Appearance of minerals:
X  No  Even grained  - Hypidiomorphic
Weak  Varying  granularic feldspars
Moderate  showing some porphyric
High  Porphyritic  features being allmost euhedral

DOMINATING GRAIN SIZE  DEGREE OF WEATHERING

< 1 mm  X  No weathering
1-3 mm  Weak
3-10 mm  Moderate
X  10-30 mm  High
> 30 mm  Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains with serisitic infill.

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
**SAMPLE**  KIKR10 - 215.68A

**PETROLOGY**

*Rock type:*

<table>
<thead>
<tr>
<th>Granite (Coarse-porphyritic granite)</th>
<th>x Magmatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphous</td>
<td>Sedimentary</td>
</tr>
<tr>
<td>Ore</td>
<td>a. Oxide</td>
</tr>
<tr>
<td></td>
<td>b. Sulphide</td>
</tr>
</tbody>
</table>

**MINERAL COMPOSITION**

<table>
<thead>
<tr>
<th>Essential minerals:</th>
<th>vol. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quartz</td>
<td>11.8</td>
</tr>
<tr>
<td>2 Potassium feldspar</td>
<td>32.8</td>
</tr>
<tr>
<td>3 Plagioclase</td>
<td>38.2</td>
</tr>
<tr>
<td>4 Biotite</td>
<td>10.2</td>
</tr>
<tr>
<td>5 Hornblende</td>
<td>5.8</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accessory minerals (&lt; 5 vol. %):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Opaque</td>
</tr>
<tr>
<td>2 Epidote</td>
</tr>
<tr>
<td>3 Serisite-Sauss.</td>
</tr>
<tr>
<td>4 Apatite</td>
</tr>
<tr>
<td>5 Zircon</td>
</tr>
<tr>
<td>6 Carbonate</td>
</tr>
</tbody>
</table>

**TEXTURE**

<table>
<thead>
<tr>
<th>Orientation:</th>
<th>Grain size distribution</th>
<th>Appearance of minerals:</th>
</tr>
</thead>
<tbody>
<tr>
<td>x No Weak</td>
<td>Even grained</td>
<td>- Hypidiomorphic</td>
</tr>
<tr>
<td>Moderate</td>
<td>x Varying Porphyritic</td>
<td>granularic feldspars</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td>showing some porphyric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>features being almost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>euhedral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Abundant myrmekite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Quartz undulatory (not</td>
</tr>
<tr>
<td></td>
<td></td>
<td>so strong )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Well developed mortar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>texture</td>
</tr>
</tbody>
</table>

**DOMINATING GRAIN SIZE**

<table>
<thead>
<tr>
<th>&lt; 1 mm</th>
<th>1-3 mm</th>
<th>3-10 mm</th>
<th>x 10-30 mm</th>
<th>&gt; 30 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>x No weathering</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weak</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Perfectly weathered</td>
<td></td>
</tr>
</tbody>
</table>

**DEGREE OF WEATHERING**

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x No weathering</td>
</tr>
<tr>
<td>Weak</td>
</tr>
<tr>
<td>Moderate</td>
</tr>
<tr>
<td>High</td>
</tr>
<tr>
<td>Perfectly weathered</td>
</tr>
</tbody>
</table>

**COMMENTS:**

Some micro jointing in large feldspar grains with serisitic infill. Biotite twisted.

**Examiner of geological data:**

M. Vaarma
Geologian Tutkimuskeskus
1998-04-14
SAMPLE KIKR10 - 215.68B

PETROLOGY

Rock type:
Granite (Coarse-porphyritic granite)  x Magmatic
Metamorphous
Sedimentary
Ore  a. Oxide  b. Sulphide

MINERAL COMPOSITION

Essential minerals:  vol. %
1 Quartz  (18.8 )
2 Potassium feldspar  (20.2 )
3 Plagioclase  (34.6 )
4 Biotite  (14.0 )
5 Hornblende  (11.6 )
6 ( )

Accessory minerals (< 5 vol. %):
1 Opaque  ( 0.4 )
2 Sphene  ( + )
3 Serisite-Sauss.  ( + )
4 Apatite  ( 0.4 )
5 Zircon  ( + )
6 Carbonate  ( + )

TEXTURE

Orientation:
X No
Weak
Moderate
High

Grain size distribution
Even grained
X Varying
Porphyritic

Appearance of minerals:
- Hypidiomorphic granularic feldspars
  showing some porphyric features being almost euhedral
- Abundant myrmekite
- Quartz undulatory (in places strong)
- Well developed mortar texture

DOMINATING GRAIN SIZE

< 1 mm
1-3 mm
3-10 mm
X 10-30 mm
> 30 mm

DEGREE OF WEATHERING

X No weathering
Weak
Moderate
High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic infill, some are annealed by quartz. Biotite twisted.

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE  KIKR10 - 216.00A

PETROLOGY

Rock type:  
Granite  (Coarse-porphyritic granite)  x  Magmatic  
Metamorphous  Sedimentary  
Ore  
a. Oxide  
b. Sulphide

MINERAL COMPOSITION

Essential minerals:  
1  Quartz  (16.6 )  
2  Potassium feldspar  (22.8 )  
3  Plagioclase  (32.6 )  
4  Biotite  (18.0 )  
5  Hornblende  (9.4 )  
6  
Accessory minerals ( < 5 vol. % ):  
1  Opaque  (0.4 )  
2  Epidote  (+ )  
3  Serisite-Sauss.  (+ )  
4  Apatite  (+ )  
5  Zircon  (+ )  
6  Carbonate  (0.2 )

TEXTURE

Orientation:  
X No  
Weak  
Moderate  
High  

Grain size distribution:  
Even grained  x  Varying  
Porphyritic  

Appearance of minerals:  
- Hypidiomorphic granularic feldspars showing some porphyric features being almost euhedral  
- Some myrmekite  
- Quartz undulatory (in places moderate)  
- Narrow mortar texture zones

DOMINATING GRAIN SIZE  DEGREE OF WEATHERING

< 1 mm  x No weathering  
1-3 mm  Weak  
3-10 mm  Moderate  
10-30 mm  High  
> 30 mm  Perfectly weathered

COMMENTS:  
Some micro jointing in large feldspar grains, some with serisitic infill, some are annealed by albitic plagioclase.

Examiner of geological data:  
M. Vaarma  
Geologian Tutkimuskeskus  
1998-04-14
SAMPLE  KIKR10 - 216.00B

PETROLOGY

Rock type:
Granite (Coarse-porphyritic granite)  x  Magmatic
Metamorphous
Sedimentary
Ore

MINERAL COMPOSITION

Essential minerals:  vol. %
1  quartz  ( 13.6 )
2  potassium feldspar  ( 29.8 )
3  plagioclase  ( 40.6 )
4  biotite  ( 5.4 )
5  hornblende  ( 8.6 )
6  ( )

Accessory minerals ( < 5 vol. %):
1  opaque  ( 1.2 )
2  sphene  ( 0.2 )
3  serisite-sauss.  ( 0.2 )
4  apatite  ( 0.2 )
5  epidote  ( + )
6  carbonate  ( 0.2 )

TEXTURE

Orientation:
x  No
Weak
Moderate
High

Grain size distribution
Even grained
x  Varying
Porphyritic

Appearance of minerals:
-  hypidiomorphic
  granularic feldspars
  showing some porphyric
  features being almost euhedral
-  some myrmecite
-  quartz undulatory (in places moderate)
-  narrow mortar texture zones

DOMINATING GRAIN SIZE
< 1 mm
1-3 mm
3-10 mm
10-30 mm
> 30 mm

DEGREE OF WEATHERING
x  No weathering
Weak
Moderate
High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic infill.
K-feldspar shows in places wiborgitic features.

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE  KIKR10 - 220.99A

PETROLOGY

Rock type:
Granite
(Coarse-porphyritic granite)  x  Magmatic
Metamorphous
Sedimentary
Ore  a. Oxide
     b. Sulphide

MINERAL COMPOSITION

<table>
<thead>
<tr>
<th>Essential minerals:</th>
<th>vol. %</th>
<th>Accessory minerals (&lt; 5 vol. %):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quartz</td>
<td>(20.8)</td>
<td>1 Opaque</td>
</tr>
<tr>
<td>2 Potassium feldspar</td>
<td>(18.4)</td>
<td>2 Carbonate</td>
</tr>
<tr>
<td>3 Plagioclase</td>
<td>(25.4)</td>
<td>3 Sericite-Sauss.</td>
</tr>
<tr>
<td>4 Biotite</td>
<td>(17.6)</td>
<td>4 Apatite</td>
</tr>
<tr>
<td>5 Hornblende</td>
<td>(16.6)</td>
<td>5 Zircon</td>
</tr>
<tr>
<td>6 Actinolite</td>
<td>(+)</td>
<td>6</td>
</tr>
</tbody>
</table>

TEXTURE

Orientation:  x No
Weak
Moderate
High
Grain size distribution  x Varying
Even grained
Porphyritic
Appearance of minerals:
- Hypidiomorphic granularic feldspars showing some porphyric features being almost euhedral
- Some myrmekite
- Quartz undulatory (in places moderately)
- Narrow mortar texture zones

DOMINATING GRAIN SIZE

< 1 mm
1-3 mm
3-10 mm
x 10-30 mm
> 30 mm

DEGREE OF WEATHERING

x No weathering
Weak
Moderate
High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic infill, some partly annealed by quartz and albite.

Examiner of geological data:

M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE  KIKR10 - 220.99B

PETROLOGY

Rock type:
Granite
(Coarse-porphyritic granite)  x  Magmatic

Metamorphous
Sedimentary
Ore
a. Oxide
b. Sulphide

MINERAL COMPOSITION

<table>
<thead>
<tr>
<th>Essential minerals:</th>
<th>vol. %</th>
<th>Accessory minerals (&lt; 5 vol. %):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quartz</td>
<td>17.6</td>
<td>1 Opaque</td>
</tr>
<tr>
<td>2 Potassium feldspar</td>
<td>25.8</td>
<td>2 Carbonate</td>
</tr>
<tr>
<td>3 Plagioclase</td>
<td>29.8</td>
<td>3 Serisite-Sauss.</td>
</tr>
<tr>
<td>4 Biotite</td>
<td>13.4</td>
<td>4 Apatite</td>
</tr>
<tr>
<td>5 Hornblende</td>
<td>11.4</td>
<td>5 Epidote</td>
</tr>
<tr>
<td>6 Actinolite</td>
<td>+</td>
<td>6 (</td>
</tr>
</tbody>
</table>

TEXTURE

Orientation:
X No
Weak
Moderate
High

Grain size distribution
Even grained
X Varying
Porphyritic

Appearance of minerals:
- Hypidiomorphic granularic feldspars showing some porphyric features being allmost euhedral
- Abundant myrmekite
- Quartz undulatory (in places moderately)
- Narrow mortar texture zones

DOMINATING GRAIN SIZE

< 1 mm
1-3 mm
3-10 mm
X 10-30 mm
> 30 mm

DEGREE OF WEATHERING

X No weathering
Weak
Moderate
High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic infill, some partly annealed by quartz and albite. Some empty micro joints.

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus
1998-04-14
SAMPLE KIKR10 - 240.21A

PETROLOGY

Rock type: Granite (Coarse-porphyritic granite) x Magmatic
Metamorphous
Sedimentary
Ore

MINERAL COMPOSITION

Essential minerals: vol. %
1 Quartz ( 26.6 )
2 Potassium feldspar ( 4.4 )
3 Plagioclase ( 42.2 )
4 Biotite ( 16.6 )
5 Hornblende ( 8.8 )
6 ( )

Accessory minerals (< 5 vol. %):
1 Opaque ( 0.2 )
2 Sphene ( 0.8 )
3 Serisite-Sauss. ( 0.4 )
4 Apatite ( + )
5 Epidote ( + )
6 Carbonate ( + )

TEXTURE

Orientation: Grain size distribution Appearance of minerals:
X No Even grained - Hypidiomorphic
Weak granularic feldspars
Moderate Porphyritic showing some porphyric
High features being almost euhedral

DOMINATING GRAIN SIZE DEGREE OF WEATHERING

< 1 mm X No weathering
1-3 mm Weak
3-10 mm Moderate
X 10-30 mm High
> 30 mm Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic and carbonatic infill.
Note! The whole rock contains abundant potassium feldspar!

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE KIKR10 - 240.21B

PETROLOGY

Rock type: Granite (Coarse-porphyritic granite) x Magmatic
Metamorphous Sedimentary Ore

a. Oxide
b. Sulphide

MINERAL COMPOSITION

<table>
<thead>
<tr>
<th>Essential minerals:</th>
<th>vol. %</th>
<th>Accessory minerals (&lt; 5 vol. %):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quartz</td>
<td>(32.8)</td>
<td>1 Opaque (0.4)</td>
</tr>
<tr>
<td>2 Potassium feldspar</td>
<td>(27.2)</td>
<td>2 Sphene (0.8)</td>
</tr>
<tr>
<td>3 Plagioclase</td>
<td>(22.0)</td>
<td>3 Serisite-Sauss. (+)</td>
</tr>
<tr>
<td>4 Biotite</td>
<td>(11.2)</td>
<td>4 Apatite (+)</td>
</tr>
<tr>
<td>5 Hornblende</td>
<td>(5.0)</td>
<td>5 Epidote (+)</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6 Carbonate (0.6)</td>
</tr>
</tbody>
</table>

TEXTURE

Orientation: x No Weak Moderate High
Grain size distribution: Even grained x Varying Porphyritic
Appearance of minerals:
- Hypidiomorphic granularic feldspars showing some porphyric features being almost euhedral
- Abundant myrmekite in places
- Quartz undulatory (in places moderately)
- Mortar texture zones around the feldspar

DOMINATING GRAIN SIZE

< 1 mm 1-3 mm 3-10 mm x 10-30 mm > 30 mm

DEGREE OF WEATHERING

x No weathering Weak Moderate High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic and carbonatic infill.

Examiner of geological data: M. Vaarma
Geologian Tutkimuskeskus 1998-04-14
SAMPLE  KIKR10 - 243.73A

PETROLOGY

Rock type:
Granite  (Coarse-porphyritic granite)  x  Magmatic
Metamorphous
Sedimentary
Ore  a. Oxide  b. Sulphide

MINERAL COMPOSITION

Essential minerals:  vol. %
1  Quartz  (13.4)
2  Potassium feldspar  (39.0)
3  Plagioclase  (34.4)
4  Biotite  (8.4)
5  Hornblende  (4.2)
6
Accessory minerals (< 5 vol. %):
1  Opaque  (0.4)
2  Serisite-Sauss.  (0.2)
3  Apatite  (+)
4  Epidote  (+)
5  Carbonate  (+)
6

TEXTURE

Orientation:  Grain size distribution  Appearance of minerals:
X  No  EVEN GRAINED  - Hypidiomorphic granular feldspars
     Weak  VARYING  - showing some porphyric features being almost euhedral
     Moderate  Porphyritic  - Abundant myrmecite in places
     High

DOMINATING GRAIN SIZE  DEGREE OF WEATHERING

< 1 mm  X  No weathering
1-3 mm  Weak
3-10 mm  Moderate
X  10-30 mm  High
> 30 mm  Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic and carbonatic infill, some annealed by quartz and albite.

Examiner of geological data:
M. Vaarma
Geologian Tutkimuskeskus  1998-04-14

Geological Laboratory of Rock Engineering
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Laboratory of Rock Engineering
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Finland
Tel. +358-9-451 2803
Fax. +358-9-451 2812
Email rocklab@hut.fi
SAMPLE  KIKR10 - 243.73B

PETROLOGY

Rock type:
Granite
( Coarse-porphyritic granite)

x Magmatic
Metamorphous
Sedimentary
Ore

a. Oxide
b. Sulphide

MINERAL COMPOSITION

Essential minerals: 
1 Quartz ( 12.0 )
2 Potassium feldspar ( 39.8 )
3 Plagioclase ( 34.0 )
4 Biotite ( 7.2 )
5 Hornblende ( 5.8 )
6 ( )

Accessory minerals ( < 5 vol. % ):
1 Opaque ( + )
2 Sphene ( 0.2 )
3 Serisite-Sauss. ( 0.4 )
4 Apatite ( + )
5 Zircon ( + )
6 Carbonate ( 0.6 )

TEXTURE

Orientation:
X No
Weak
Moderate
High

Grain size distribution
Even grained
X Varying
Porphyritic

Appearance of minerals:
- Hypidiomorphic
  granularic feldspars
  showing some porphyric
  features being almost euhedral
- Abundant myrmekite in places
- Quartz undulatory (in places moderately)
- Mortar texture zones around the feldspar

DOMINATING GRAIN SIZE

<1 mm
1-3 mm
3-10 mm
X 10-30 mm
>30 mm

DEGREE OF WEATHERING

X No weathering
Weak
Moderate
High
Perfectly weathered

COMMENTS:
Some micro jointing in large feldspar grains, some with serisitic and carbonatic infill, some annealed by quartz and albite.

Examiner of geological data:

M. Vaarma
Geologian Tutkimuskeskus

1998-04-14
Uniaxial Test of KI-KR10 - 207.93
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

---

**Axial Stress (MPa)**

- 200
- 160
- 120
- 80
- 40
- 0

---

**Radial Strain (mm/mm)**

**Axial Strain (mm/mm)**

---

**Failure Pattern**

---

**Volumetric Strain (mm³/mm³)**

- 0.20%
- 0.15%
- 0.10%
- 0.05%
- 0.00%
- -0.05%
- -0.10%
- -0.15%
- -0.20%

---

**Test Data**

- **Client:** Posiva Oy
- **Order Number:** 9537/98/JPS
- **Test:** Uniaxial
- **Equipment:** MTS 815

---

**Specimen Data**

- **Site:** Kivetty
- **Rock Type:** Porphyritic granodiorite
- **Hole:** KI-KR10
- **Depth:** 207.93

---

**Test Results**

- **Young's Modulus:** 74.9 GPa
- **Poisson's Ratio:** 0.28

---

**Test Saturation:**

---

**Peak Strength:** 127.3 MPa
**Crack Damage Stress:** 104.4 MPa
**Crack Initiation Stress:** 67.1 MPa

---

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FINLAND

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---
Uniaxial Test of KI-KR10 - 213.06
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Failure Pattern
Volumetric Strain (mm³/mm³)

Test Data

Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 213.06

Test Results
Young's Modulus: 69.3 GPa
Poisson's Ratio: 0.23

Test Date: 1998-03-03
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa
Diameter: 61.28 mm
Density: 2725 kg/m³
Porosity:
Test Saturation:
Peak Strength: 124.5 MPa
Crack Damage Stress: 98.7 MPa
Crack Initiation Stress: 66.6 MPa

LABORATORY OF ROCK ENGINEERING
Helsinki University of Technology

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FINLAND
Uniaxial Test of KI-KR10 - 215.68
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Radial Strain (mm/mm) Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm$^3$/mm$^3$)

Contraction

Dilation

Test Data

Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Test Date: 1998-03-04
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa

Specimen Data

Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 215.68

Diameter: 61.45 mm
Length/Diameter: 2.52
Density: 2737 kg/m$^3$
Porosity:
Test Saturation:

Test Results

Young’s Modulus: 63.0 GPa
Poisson’s Ratio: 0.27

Peak Strength: 121.5 MPa
Crack Damage Stress: 92.8 MPa
Crack Initiation Stress: 65.8 MPa

LABORATORY OF ROCK ENGINEERING
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FINLAND
Uniaxial Test of KI-KR1 0 - 216.00
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Axial Strain (mm/mm)

0.20%
0.15%
0.10%
0.05%
0.00%
-0.05%
-0.10%
-0.15%
-0.20%
0 40 80 120 160 200

Axial Stress (MPa)

Test Data
Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Test Results
Young's Modulus: 65.4 GPa
Poisson's Ratio: 0.28

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 216.00

Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa
Diameter: 61.48 mm
Length/Diameter: 2.52
Density: 2729 kg/m³
Porosity:
Test Saturation:

Peak Strength: 124.4 MPa
Crack Damage Stress: 93.8 MPa
Crack Initiation Stress: 64.3 MPa
Uniaxial Test of KI-KR1 0 - 218.26
Kivetty Bore Hole KI-KR1 0 Porphyritic Granodiorite

Test Data
- Client: Posiva Oy
- Order Number: 9537/98/JPS
- Test: Uniaxial
- Equipment: MTS 815

Specimen Data
- Site: Kivetty
- Rock Type: Porphyritic granodiorite
- Hole: KI-KR10
- Depth: 218.26

Test Results
- Young's Modulus: 63.9 GPa
- Poisson's Ratio: 0.26
- Peak Strength: 129.5 MPa
- Crack Damage Stress: 98.8 MPa
- Crack Initiation Stress: 67.2 MPa

Test Date: 1998-03-04
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa

Diameter: 61.53 mm
Length/Diameter: 2.53
Density: 2732 kg/m³
Porosity: 
Test Saturation: 

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Uniaxial Test of KI-KR10 - 220.99
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Radial Strain (mm/mm) Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Test Data

Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Test Date: 1998-03-05
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa

Specimen Data

Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 220.99

Diameter: 61.41 mm
Length/Diameter: 2.53
Density: 2739 kg/m³
Porosity:

Test Results

Young's Modulus: 67.7 GPa
Poisson's Ratio: 0.26

Peak Strength: 129.2 MPa
Crack Damage Stress: 98.3 MPa
Crack Initiation Stress: 68.7 MPa

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Uniaxial Test of KI-KR10 - 236.94
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Radial Strain (mm/mm)

Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Test Data
Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 236.94

Test Results
Young's Modulus: 66.8 GPa
Poisson's Ratio: 0.27

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Uniaxial Test of KI-KR10 - 240.21
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) — Axial Strain from Actuator Displacement

Radial Strain (mm/mm) Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

\[ \sigma_f \]

\[ \sigma_m \]

\[ \sigma_n \]

0 40 80 120 160

Axial Stress (MPa)

Test Data
Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Test Date: 1998-03-05
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 240.21

Diameter: 61.47 mm
Length/Diameter: 2.53
Density: 2742 kg/m³
Porosity:
Test Saturation:

Test Results
Young's Modulus: 71.1 GPa
Poisson's Ratio: 0.23

Peak Strength: 144.2 MPa
Crack Damage Stress: 124.0 MPa
Crack Initiation Stress: 69.6 MPa
Uniaxial Test of KI-KR10 - 243.41
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Test Data
Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Uniaxial
Equipment: MTS 815

Test Date: 1998-03-05
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 0 MPa

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 243.41

Diameter: 61.51 mm
Length/Diameter: 2.52
Density: 2744 kg/m³
Porosity:
Test Saturation:

Test Results
Young's Modulus: 68.1 GPa
Poisson's Ratio: 0.27

Peak Strength: 136.2 MPa
Crack Damage Stress: 104.8 MPa
Crack Initiation Stress: 68.3 MPa

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**Test Data**

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**Specimen Data**

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**Test Results**

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Triaxial Test of KI-KR10 - 208.09
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Test Data
- Client: Posiva Oy
- Order Number: 9537/98/JPS
- Test: Triaxial
- Equipment: MTS 815

Test Date: 1998-03-17
- Loading Control: Radial Strain Rate
- Equivalent Loading Rate: 0.75 MPa/s
- Confining Stress: 15 MPa

Specimen Data
- Site: Kivetty
- Rock Type: Porphyritic granodiorite
- Hole: KI-KR10
- Depth: 208.09

Diameter: 61.23 mm
- Length/Diameter: 2.54
- Density: 2724 kg/m³
- Porosity:
- Test Saturation:

Test Results
- Young’s Modulus: 73.1 GPa
- Poisson’s Ratio: 0.18
- Peak Strength: 266.0 MPa
- Crack Damage Stress: 206.2 MPa
- Crack Initiation Stress: 140.3 MPa
Triaxial Test of KI-KR10 - 213.22
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Radial Strain (mm/mm) Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)


c_{11}
c_{33}

Contraction

Dilation

Test Data
Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Triaxial
Equipment: MTS 815

Test Results
Young's Modulus: 71.2 GPa
Poisson's Ratio: 0.20

Specimen Data
Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 213.22

Test Date: 1998-03-16
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 15 MPa
Diameter: 61.28 mm
Length/Diameter: 2.53
Density: 2735 kg/m³
Porosity:
Test Saturation:

Peak Strength: 256.9 MPa
Crack Damage Stress: 188.0 MPa
Crack Initiation Stress: 125.6 MPa

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Triaxial Test of KI-KR10 - 215.84
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Axial Strain from Actuator Displacement

Radial Strain (mm/mm) Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Contraction

Dilation

Test Data

Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Triaxial
Equipment: MTS 815

Test Date: 1998-03-18
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 15 MPa

Specimen Data

Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 215.84

Diameter: 61.49 mm
Length/Diameter: 2.53
Density: 2727 kg/m³
Porosity: 
Test Saturation:

Test Results

Young’s Modulus: 71.8 GPa
Poisson’s Ratio: 0.21

Peak Strength: 265.6 MPa
Crack Damage Stress: 203.7 MPa
Crack Initiation Stress: 126.5 MPa

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Triaxial Test of KI-KR10 - 217.24
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

**Test Data**
- **Client:** Posiva Oy
- **Order Number:** 9537/98/JPS
- **Test:** Triaxial
- **Equipment:** MTS 815
- **Test Date:** 1998-03-18
- **Loading Control:** Radial Strain Rate
- **Equivalent Loading Rate:** 0.75 MPa/s
- **Confining Stress:** 15 MPa

**Specimen Data**
- **Site:** Kivetty
- **Rock Type:** Porphyritic granodiorite
- **Hole:** KI-KR10
- **Depth:** 217.24
- **Diameter:** 61.53 mm
- **Length/Diameter:** 2.52
- **Density:** 2734 kg/m³
- **Porosity:**
- **Test Saturation:**

**Test Results**
- **Young's Modulus:** 68.1 GPa
- **Poisson's Ratio:** 0.20
- **Peak Strength:** 262.3 MPa
- **Crack Damage Stress:** 198.3 MPa
- **Crack Initiation Stress:** 126.2 MPa

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Triaxial Test of KI-KR10 - 218.54
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Axial Strain from Actuator Displacement

Radial Strain (mm/mm)  Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm/mm³)

Test Data

Client: Posiva Oy  Test Date: 1998-03-19
Order Number: 9537/98/JPS  Loading Control: Radial Strain Rate
Test: Triaxial  Equivalent Loading Rate: 0.75 MPa/s
Equipment: MTS 815  Confining Stress: 15 MPa

Specimen Data

Site: Kivetty  Diameter: 61.55 mm
Rock Type: Porphyritic granodiorite  Length/Diameter: 2.52
Hole: KI-KR10  Density: 2724 kg/m³
Depth: 218.54  Porosity:

Test Results

Young's Modulus: 66.3 GPa  Peak Strength: 269.9 MPa
Poisson's Ratio: 0.18  Crack Damage Stress: 205.5 MPa

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Triaxial Test of KI-KR10 - 221.15
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) — Axial Strain from Actuator Displacement

Radial Strain (mm/mm)     Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Contraction

0  40  80  120  160  200  240  280  320
Axial Stress (MPa)

Test Data

Client: Poiva Oy
Order Number: 953798/JPS
Test: Triaxial
Equipment: MTS 815

Test Results

Young's Modulus: 74.5 GPa
Poisson's Ratio: 0.17

Specimen Data

Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 221.15

Test Date: 1998-03-19
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 15 MPa
Diameter: 61.41 mm
Length/Diameter: 2.53
Density: 2730 kg/m³
Porosity:

Test Saturation:

Peak Strength: 271.4 MPa
Crack Damage Stress: 207.9 MPa
Crack Initiation Stress: 137.4 MPa

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Triaxial Test of KI-KR10 - 237.17
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm/m)^3

Test Data
- Client: Posiva Oy
- Order Number: 9537/98/JPS
- Test: Triaxial
- Equipment: MTS 815

Specimen Data
- Site: Kivetty
- Rock Type: Porphyritic granodiorite
- Hole: KI-KR10
- Depth: 237.17

Test Results
- Young's Modulus: 75.7 GPA
- Poisson's Ratio: 0.18
- Peak Strength: 286.2 MPa
- Crack Damage Stress: 228.7 MPa
- Crack Initiation Stress: 149.0 MPa

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Appendix 5
Triaxial Test of KI-KR1 0 - 240.43
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa)

Radial Strain (mm/mm)  Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm$^3$/mm$^3$)

Test Data

Client: Posiva Oy
Order Number: 9537/98/JPS
Test: Triaxial
Equipment: MTS 815

Test Results

Young's Modulus: 77.0 GPa
Poisson's Ratio: 0.18

Specimen Data

Site: Kivetty
Rock Type: Porphyritic granodiorite
Hole: KI-KR10
Depth: 240.43

Test Date: 1998-03-20
Loading Control: Radial Strain Rate
Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 15 MPa
Diameter: 61.48 mm
Length/Diameter: 2.53
Density: 2742 kg/m$^3$
Porosity:
Test Saturation:

Peak Strength: 271.9 MPa
Crack Damage Stress: 220.9 MPa
Crack Initiation Stress: 139.5 MPa

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Triaxial Test of KI-KR10 - 243.57
Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite

Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

Failure Pattern

Volumetric Strain (mm³/mm³)

Test Data
- Client: Posiva Oy
- Order Number: 9537/98/JPS
- Test: Triaxial
- Equipment: MTS 815

Test Results
- Young's Modulus: 74.9 GPa
- Poisson's Ratio: 0.19

Specimen Data
- Site: Kivetty
- Rock Type: Porphyritic granodiorite
- Hole: KI-KR10
- Depth: 243.57

Equivalent Loading Rate: 0.75 MPa/s
Confining Stress: 15 MPa

Diameter: 61.53 mm
Length/Diameter: 2.52
Density: 2747 kg/m³
Porosity:
Test Saturation:

Peak Strength: 276.9 MPa
Crack Damage Stress: 212.4 MPa
Crack Initiation Stress: 140.5 MPa

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**Triaxial Test of KI-KR10 - 244.90**

**Kivetty Bore Hole KI-KR10 Porphyritic Granodiorite**

### Axial Stress (MPa) vs. Axial Strain from Actuator Displacement

### Radial Strain (mm/mm) vs. Axial Strain (mm/mm)

### Failure Pattern

### Volumetric Strain (mm³/mm³)

**Test Data**
- **Client:** Posiva Oy
- **Order Number:** 9537/98/JPS
- **Test:** Triaxial
- **Equipment:** MTS 815

**Specimen Data**
- **Site:** Kivetty
- **Rock Type:** Porphyritic granodiorite
- **Hole:** KI-KR10
- **Depth:** 244.90

**Test Results**
- **Young's Modulus:** 77.2 GPa
- **Poisson's Ratio:** 0.17

**Test Saturation:**

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- **FIN-02015 HUT FINLAND**
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Additional data for Critical stress states, Critical axial strains, Critical radial strains, and Volumetric strain are provided in the table.
KIKR10-243.41
Uniaxial, 0.75 MPa/s

KIKR10-243.73
Uniaxial, 0.75 MPa/s

KIKR10-208.09
Triaxial, $\sigma_c$=15 MPa, 0.75 MPa/s

KIKR10-213.22
Triaxial, $\sigma_c$=15 MPa, 0.75 MPa/s
KIKR10-208.25
Indirect Tension

KIKR10-213.38
Indirect Tension

KIKR10-216.16
Indirect Tension

KIKR10-218.42
Indirect Tension
Indirect Tension

KIKR10-216.20

Indirect Tension

KIKR10-218.46

Indirect Tension

KIKR10-218.74

Indirect Tension

KIKR10-234.66

Indirect Tension
Appendix 7
Deviation of Young's modulus in uniaxial compression test, 0.75 MPa/s

Deviation of Young's modulus in triaxial compression test, $\sigma_c = 15$ MPa
Deviation of Poisson's ratio in uniaxial compression test, $0.75 \text{ MPa/s}$

Deviation of Poisson's ratio in triaxial compression test, $\sigma_c=15 \text{ MPa}$
Deviation of tensile strength in Brazil test with dry specimens

- Cumulative Probability

Deviation of tensile strength in Brazil test with wet specimens

- Cumulative Probability
Deviation of crack initiation stress in uniaxial compression test, 0.75 MPa/s

Deviation of crack initiation stress in triaxial compression test, 0.75 MPa/s
Deviation of crack damage stress in uniaxial compression test, 0.75 MPa/s

Deviation of crack damage stress in triaxial compression test, 0.75 MPa/s
Deviation of crack peak strength in uniaxial compression test, 0.75 MPa/s

Deviation of crack peak strength in triaxial compression test, 0.75 MPa/s