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THERMOMECHANICAL STUDIES IN GRANITE AT STRIPA, SWEDEN

N. G. W. Cook[1] and L. R. Myer[2]

Introduction

Geological disposal of nuclear wastes within excavations made at depth in suitable media has long been [1] and continues to be [2] favored as the currently most practicable means of isolating them from the biosphere over the long term. Although a significant body of experience exists concerning underground excavation, it does not include the effects of heat generation on the excavations and the geologic media. Experiments to assess some of these effects have been done for salt in Project Salt Vault [3] but it is now agreed that other media be examined [2]. Access to tunnels driven into the granite country rock 340 meters below surface adjacent to a defunct iron ore mine at Stripa, Sweden, provided a unique opportunity for doing experiments in grante without delay and at minimal cost, at a depth where conditions of stress, jointing, groundwater and other factors associated with depth similar to those likely to be encounted at the site of an actual waste repository exist.

In Situ Experiments

The disposal of high level nuclear waste deep underground will result in the geologic media in the vicinity of such a repository undergoing a thermal pulse. This pulse will induce thermomechanical displacements and stresses in the rock. In general, these displacements will be directed away from the source of the heat while the temperature is increasing then tending to return as the temperature decreases. Likewise, the thermomechanical stresses will result in the

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addition to the virgin state of stress in the rock of compressive stresses within the heated zone and the addition of shear and tensile stresses outside of it, outside of it.

Transport by groundwater is the most probable mechanism by which components of the wastes may find their way back to the surface. The intrinsic permeability of many granites is so low that the only hydraulic conduits of concern arise from joints and fractures in masses of such rock. Clearly, the thermomechanical perturbations may have significant effects on the hydraulic transmissivity of such features. Accordingly, it is necessary that the effects of these perturbations be understood if the utility of a geologic formation as a site for a potential waste repository is to be evaluated properly. Furthermore, the design of a repository and predictions concerning its performance in the long term cannot be done without such an understanding [4].

The value of field experiments depends upon the extent to which they provide sufficient understanding of the phenomena involved to enable transferral of results to other sites where repositories may be built. The Stripa program involves the collection of sufficient field and laboratory data to ensure that their analyses will provide either a high degree of understanding of the behavior of the rock mass or an identification and definition of those crucial issues requiring further research.

Three different thermomechanical experiments were carried out at Stripa [5]. The first was designed to study the short-term, near-field effects around an electrical heater simulating a full-size canister of reprocessed high level waste. The second was a similar experiment designed to study the long-term, near-field effects. The third was a time-scaled experiment designed to simulate the interaction of canisters placed either 9.6m or 22.4m apart over a period equivalent to about two decades, using the quadratic relationship between time and distance in linear thermoelasticity [6].

The power levels of the two full scale heaters were 3.6 kW and 5 kW corresponding to those projected for reprocessed fuel 5 years and 3.5 years after discharge from the reactor [7]. These power levels, together with the peripheral heaters used in the second stage of the 5 kW heater experiment to simulate the effects of increasing the temperature of the rock containing a waste canister, produced thermal stresses on the walls of the boreholes containing these heaters below, at and above those sufficient to cause decrepitation of these holes [8]. This enabled the conditions causing decrepitation to be defined, Figure 1.

Starting in June 1979, power to the heaters was turned off. Continuous measurements were made during the cool down period, as they were during the heat up period. It is expected that a substantial amount of additional information, especially concerning nonlinear phenomena, will be obtained by analysis of hysteresis over the full thermal cycle.

Thermal and Thermomechanical Analysis

Based on the theory of linear thermoelasticity and properties of the granite measured in conventional small scale laboratory tests, the results of all three experiments, namely the expected temperature, displacement and stress fields as functions of time, were predicted in advance of the collection of field data. The field data was collected in such a way as to allow comparisons between theoretical predictions and underground measurements made continuously during the experiment. To date the comparisons have shown that the use of simple linear heat conduction provides an adequate prediction of the temperature fields around the experments, Figures 2 and 3. According to the theory of linear thermoelasticity, displacements should be related to temperature fields by a simple factor, $\alpha_\ell[(1+\nu)/(1-\nu)]$, where α_ℓ= the linear coefficient of thermal expansion of the rock, and ν = Poisson's ratio for the rock. All the measured displacements differ significantly from predicted values in two different ways, Figure 4. First, initial displacements, of the order 100 m per meter; are highly nonlinear, reflecting possibly the effects of joints in the rock. Second, greater displacements than these appear to be linear but to have a magnitude only about half that expected from values derived from simple laboratory measurements. Likewise the stresses appear to have values different from that given by the temperature field and a factor $\alpha E/(1-\nu)$, where E = the Youngs' modulus of the rock and the other symbols are as defined above, Figure 5 [9, 10].

Another possible contributing factor to the discrepancies between predicted and measured values was that the temperature dependence of the thermomechanical properties was not included in the predictive model. Subsequent work has been directed at studying the effect of temperature and stress dependent properties on predicted stresses and displacement. An indication of the improvement in displacement predictions is shown in Figure 6 [11]. These results indicated the importance of considering temperature dependent properties but they are preliminary in that the data base for the properties was incomplete and insufficient in number of tests.

Though an expanded data base is needed, discrepancies between measured and predicted values may continue. It is important to note that the disparities between measurement and predictions using simple theory and laboratory data should not be regarded as evidence of a lack of predictive capability but, rather, as a means for identifying and understanding the important difference in behavior between a rock mass and laboratory specimens of rock.

Thermomechanical Properties Investigation

A laboratory program to more thoroughly investigate the thermoelastic properties of the Stripa rock mass is presently underway. Core from every instrumentation hole at Stripa was kept. Thus properties will be obtained from specimens of core taken from the same holes in which measurements of displacements and stresses were previously made. Tests are performed over a range of temperature and hydrostatic and deviatoric (unequal axial and radial) stresses in order to bracket stresses and temperatures experienced by the rock in the field. Planned tests include dry, wet, intact and fractured samples, though to date only intact dry specimens have been tested. Results of the test program will be used to refine the predictive models, incorporating such non-linear properties as may be revealed by the tests.

The laboratory program began with the development of a test facility emphasizing thermomechanical property measurement capabilities. Figure 7 is a photo of the test frame and power pack. The test machine is a stiff triaxial test machine capable of providing a maximum confining pressure of 70 MPa and a maximum axial load of 1.4 MN. Independent systems for heating and cooling the cell are provided with a maximum sustained test cell temperature of 200°C. Either 52 mm diameter or 62 mm diameter core with a length to diameter ratio of 3 to 1 can be accommodated by the test cell. Confining pressure and deviator stress loading paths are controlled by an electroservo control system using a PDP 11/44 computer to close the feedback control loop (schematically illustrated by Figure 8). Such a system was necessary to maintain test control for extended periods of time required for completion of the testing of each sample. Automatic data acquisition was also integrated into the computer control system.

To bracket the in-situ temperature and stress conditions by a test matrix in which one sample was tested at each selected pressure-temperature (P-T) state would require an exceedingly large number of samples for statistically meaningful data. Each sample is therefore subjected to a matrix of P-T states with the test sequence designed to minimize sample damage (Figure 9). Property measurements are begun at the highest pressure and lowest temperature and sample temperature is increased by not more than 2°C per minute. In addition, the maximum axial load applied for stress-strain measurements is 40 percent of the average strength at the given confining pressure and temperature as deterimined by Swan [12].

Laboratory testing is not complete but preliminary results indicate general trends in the data. Elastic modulii were found to be somewhat dependent upon stress state and temperature, as, for example, seen in Figure 10 and Figure 11. At confining pressures less than 30 MPa, increasing temperature resulted in lower moduli. Peculiarly, at high confining pressure, E increased somewhat at higher temperatures, whereas continued to exhibit a decreasing trend. If data at one temperature is compared, it is seen that the rock stiffness increased at the higher confining pressures. This effect was more pronounced at the highest test temperatures. Figures 10 and 11 also present data by Swan [12] for Stripa granite which exhibit some discrepancies as yet unexplained.

Thermal expansion measurements were made every 25°C during heat-up and cool-down to determine the dependence of the thermal expansion coefficients on confining pressure and temperature. This dependence is illustrated by Figure 12 for the volumetric coefficient of expansion, α_v, obtained during heat-up for one sample. For a given confining pressure there is a significant increase in the thermal expansion coefficient with increasing temperature. The effect was less, however, at the higher confining pressures. For a given temperature, an increase in confining pressure resulted in a decrease in α_v for the data in Figure 12 but it is not clear that this represents a general trend. Discrete data points in Figure 12 represent values of α_v determined by assuming a straight line relationship between adjacent data points whereas the smooth curves represent values of α_v derived from a polynomial regression analysis of the thermal expansion data. The shape of the curve is related to the degree of polynomial selected as the "best fit" of the data and does not have any particular physical significance. Curve fitting, though useful in smoothing and sometimes in defining trends, should not be considered a replacement for sound theoretical work in defining functional relationships between variables. Use of regression analysis of the thermal expansion data in fact reflects the need for further theoretical work in the area of thermomechanical constitutine relations for rock to better define the functional relationship between thermal expansion and temperature.

For purposes of comparison with results of other work on Stripa granite, Figure 13 compares values of α_ℓ for one test at a confining pressure of 30 MPa with those from Heard [13] and Board [14]. The values of α_ℓ were significantly higher at low temperature than those of the other authors, while the rate of increase with temperature was less. Further testing now in progress will aid in understanding these discrepancies as well as lead to increased confidence in trends observed thus far.

Acknowledgement

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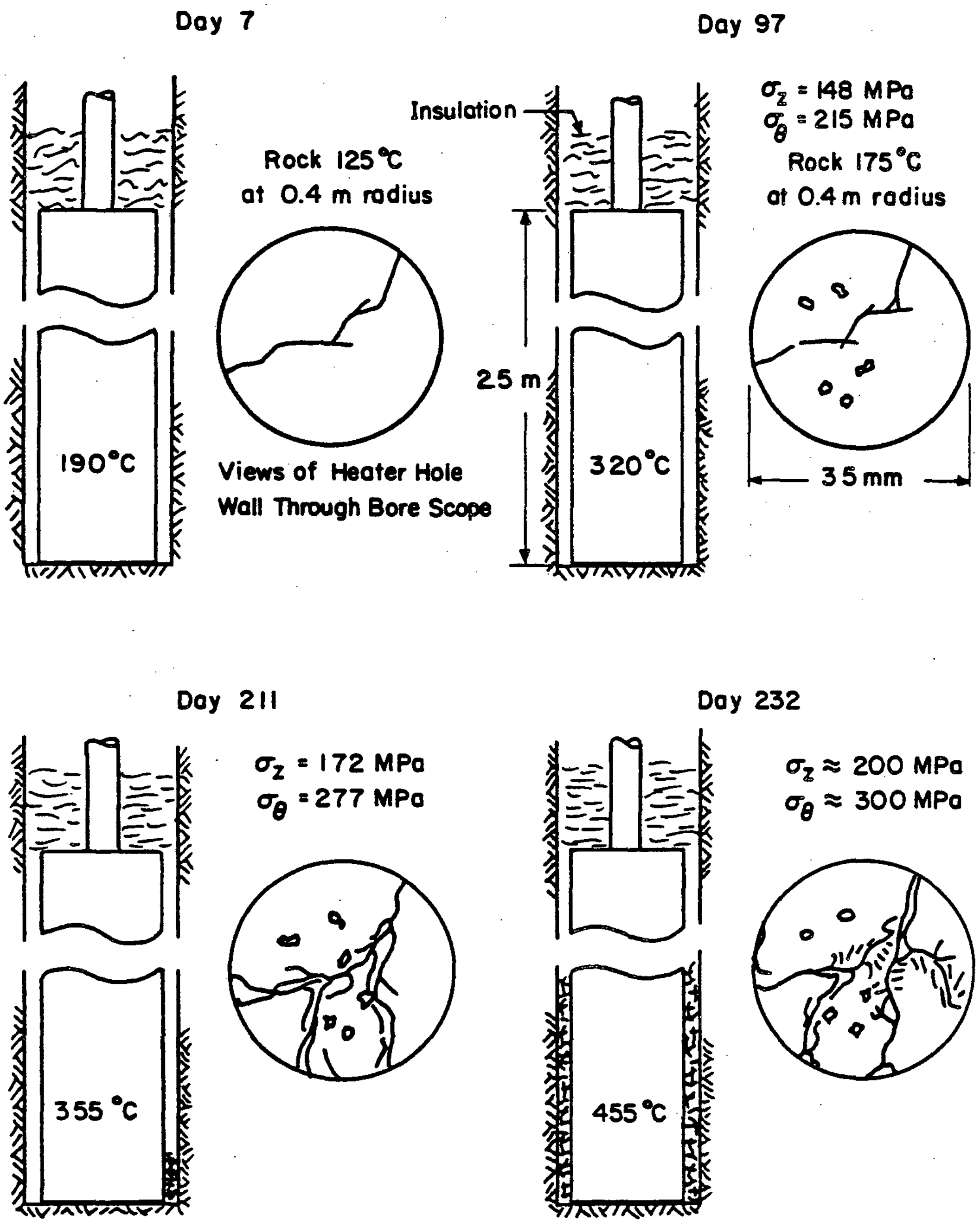

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Figure 1. Axial section through the 5 kW full-scale heater with sketches of borescope views of portions of the hole containing this heater at 7, 97, 211 and 232 days after the start of heating, illustrating the decrepitation of the borehole wall caused by thermally induced stresses, the magnitudes of which are given. Note that the gross decrepitation caused by the additional stress induced by turning on the 8 peripheral heaters on day 204 impeded the radiant heat transfer from the heater to the rock causing the temperature of the heater to increase by about 100°C.

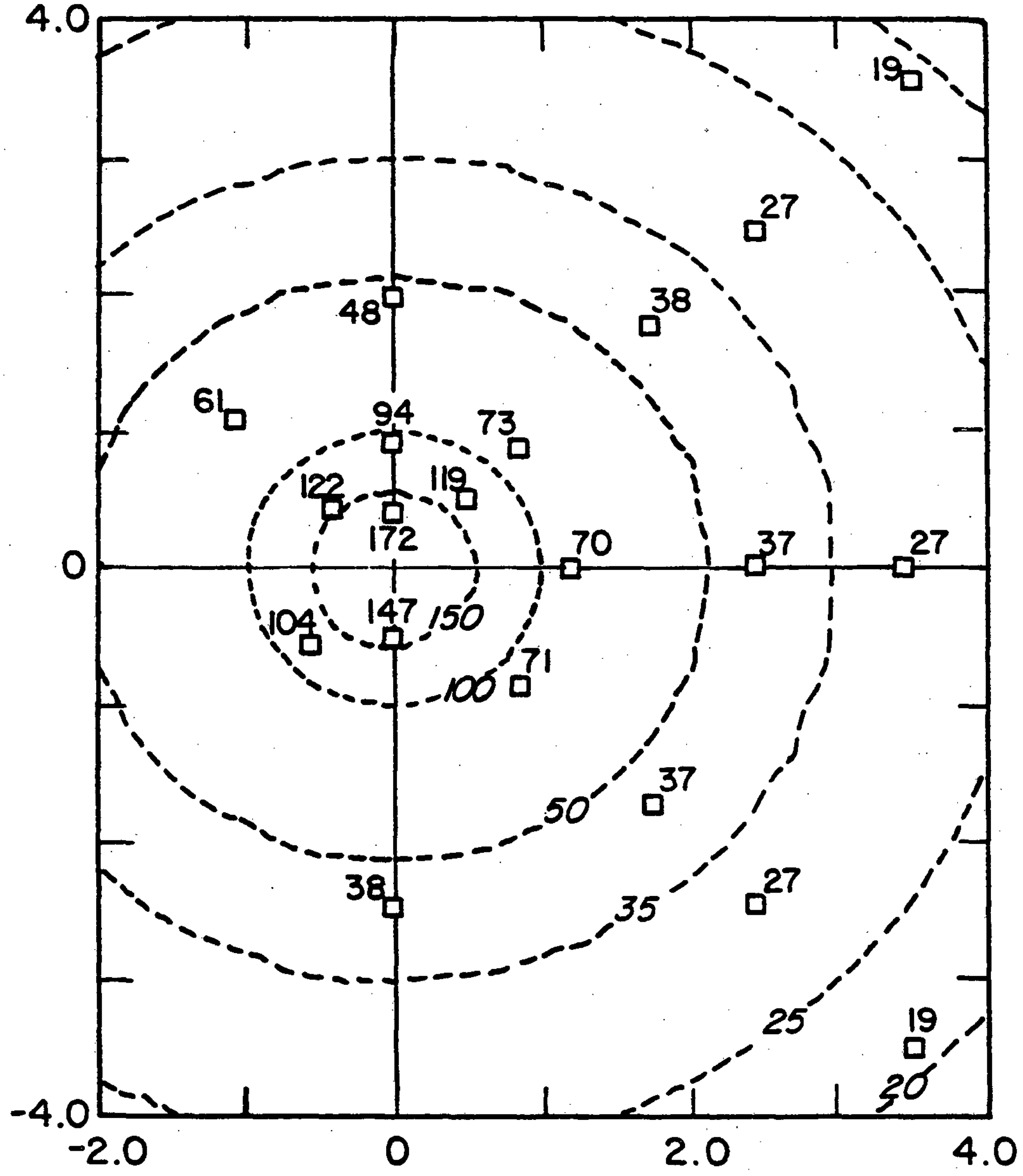

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Figure 2. A plan of the horizontal plane through the middle of the 5 kW full-scale heater showing the predicted isotherms (dashed lines) and actual temperatures (squares with numbers) measured along different directions at 190 days after the start of heating. Note the relatively good correlation between measurement and prediction and the high degree of axial symmetry (Scales for the X- and Y-axes are shown in meters.)

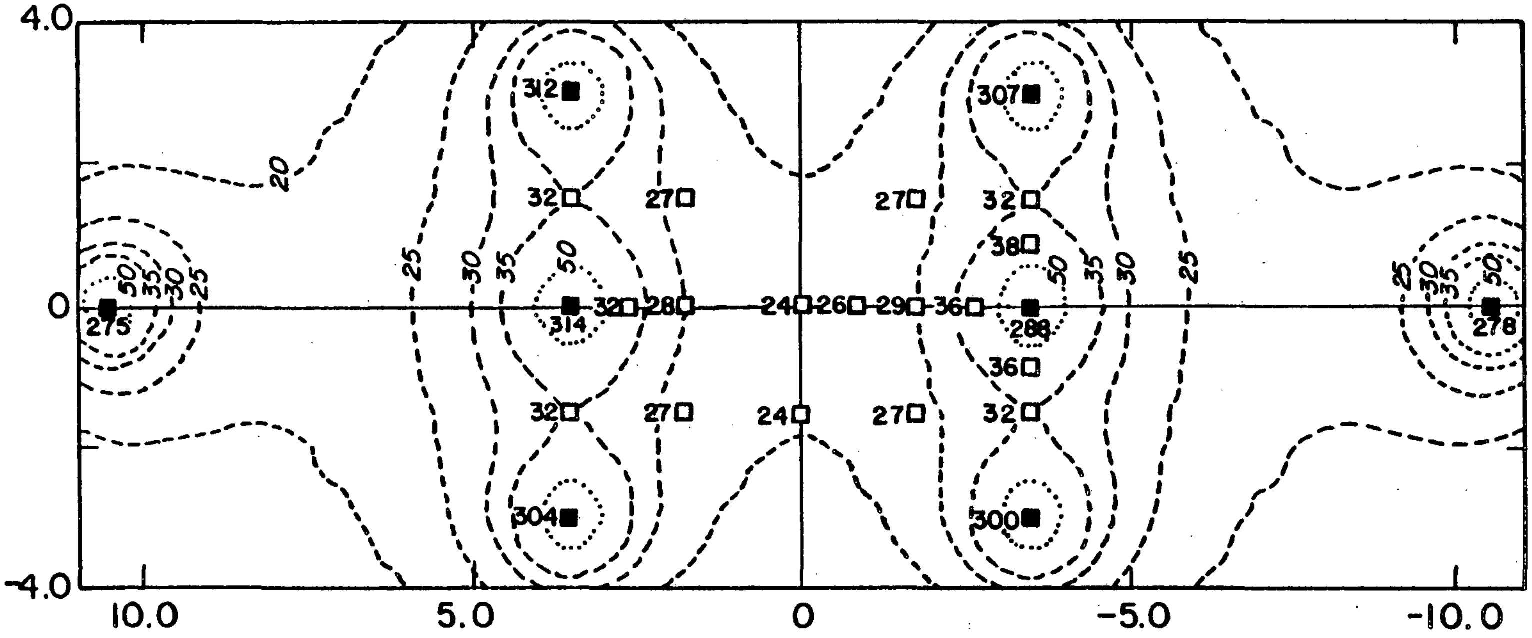

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Figure 3. A plan of the horizontal plane through the middle of the array of 8 time-scaled heaters showing the predicted isotherms (dashed lines) and measured temperatures (squares with numbers) at 190 days after the start of the experiment. Actual distances between the heaters (black squares) are given in meters along the X- and Y-axes. The spacing between these heaters corresponds to 7 meters and 22 meters for full-scale heaters and the temperatures to those at 1,938 days (5.3 years) because of the time scaling.

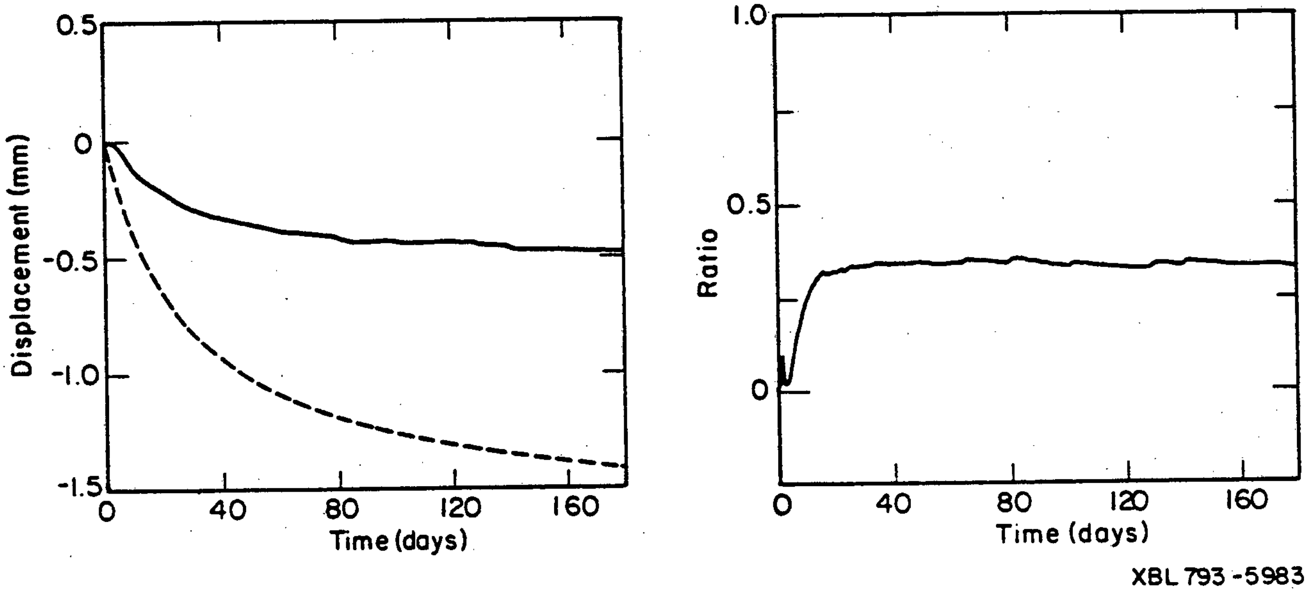

Figure 4. An example showing the predicted (dashed lines) and measured (solid lines) displacements between anchor points situated 3 meters above and below the mid-plane of the 5 kW heater and at a radial distance of 2 meters as a function of time (left), together with a plot of the ratio between the measured and predicted values as a function of time (right). Note the initial non-linearity of the displacements and their subsequent linear, but lower than predicted, behavior revealed by the right hand plot.

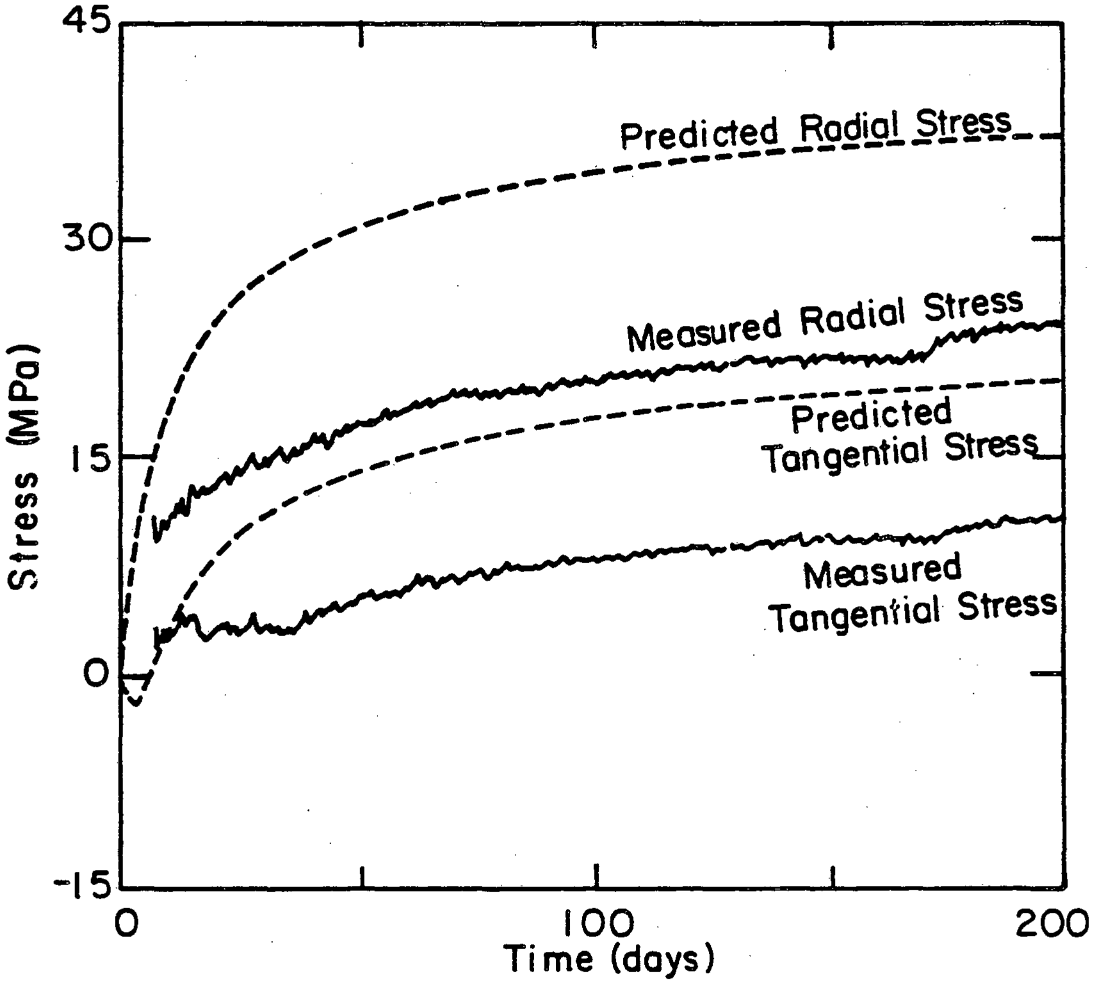

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Figure 5. An example of the predicted changes (dashed lines) and measured changes (solid lines) in stress as a function of time, inferred from a vibrating wire borehole strain gauge located 0.85 meters above the mid-plane and 1.5 meters radially from the 5 kW full-scale heater.

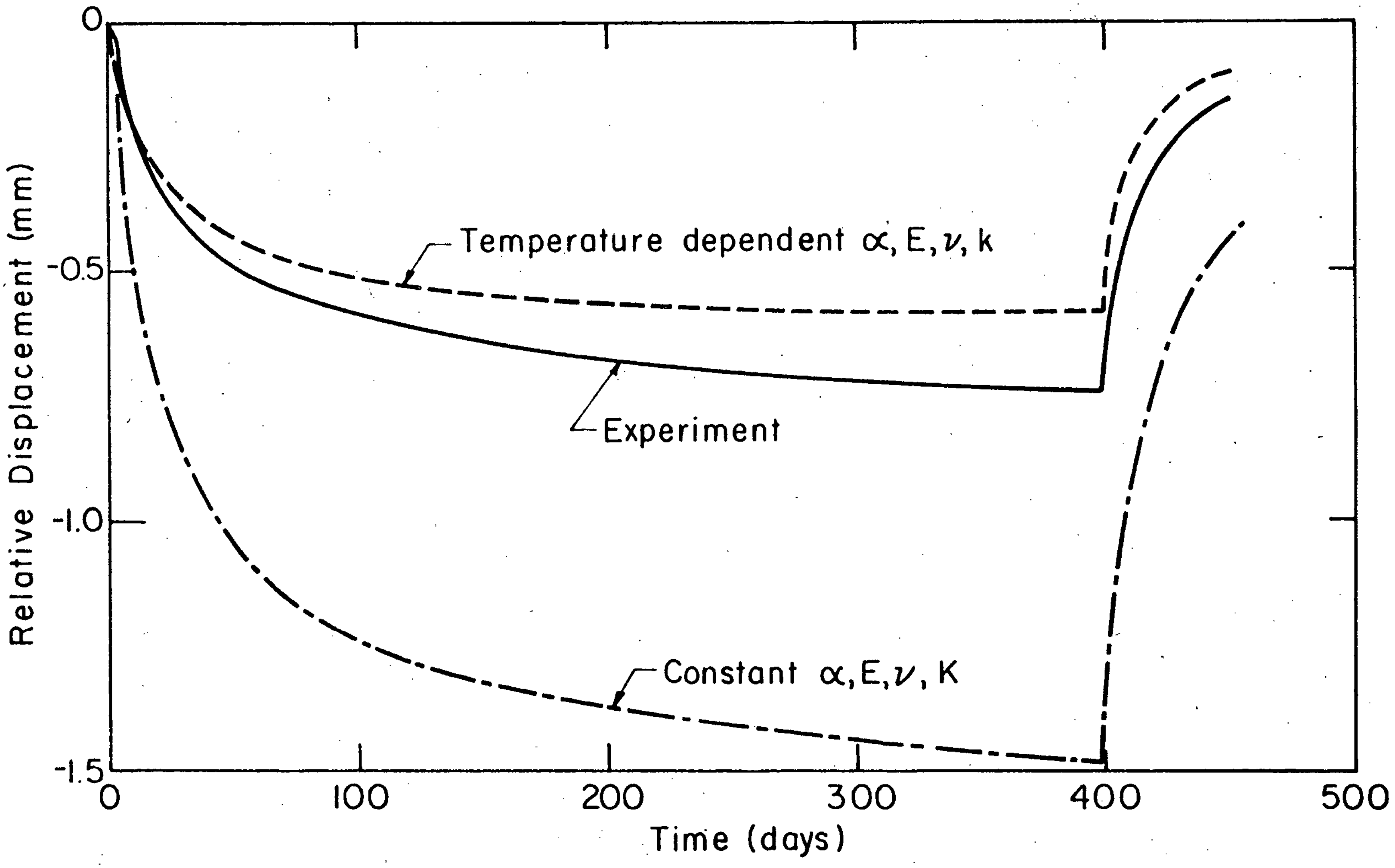

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Figure 6. A plot comparing measured and predicted rock displacements in the vertical plane between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1 m from the 3.6 kW heater. This graph shows the predicted displacements for both temperature dependent and temperature independent material properties. Also illustrated in this Figure are the displacements, both measured and predicted during the cool down after the heater was turned off.

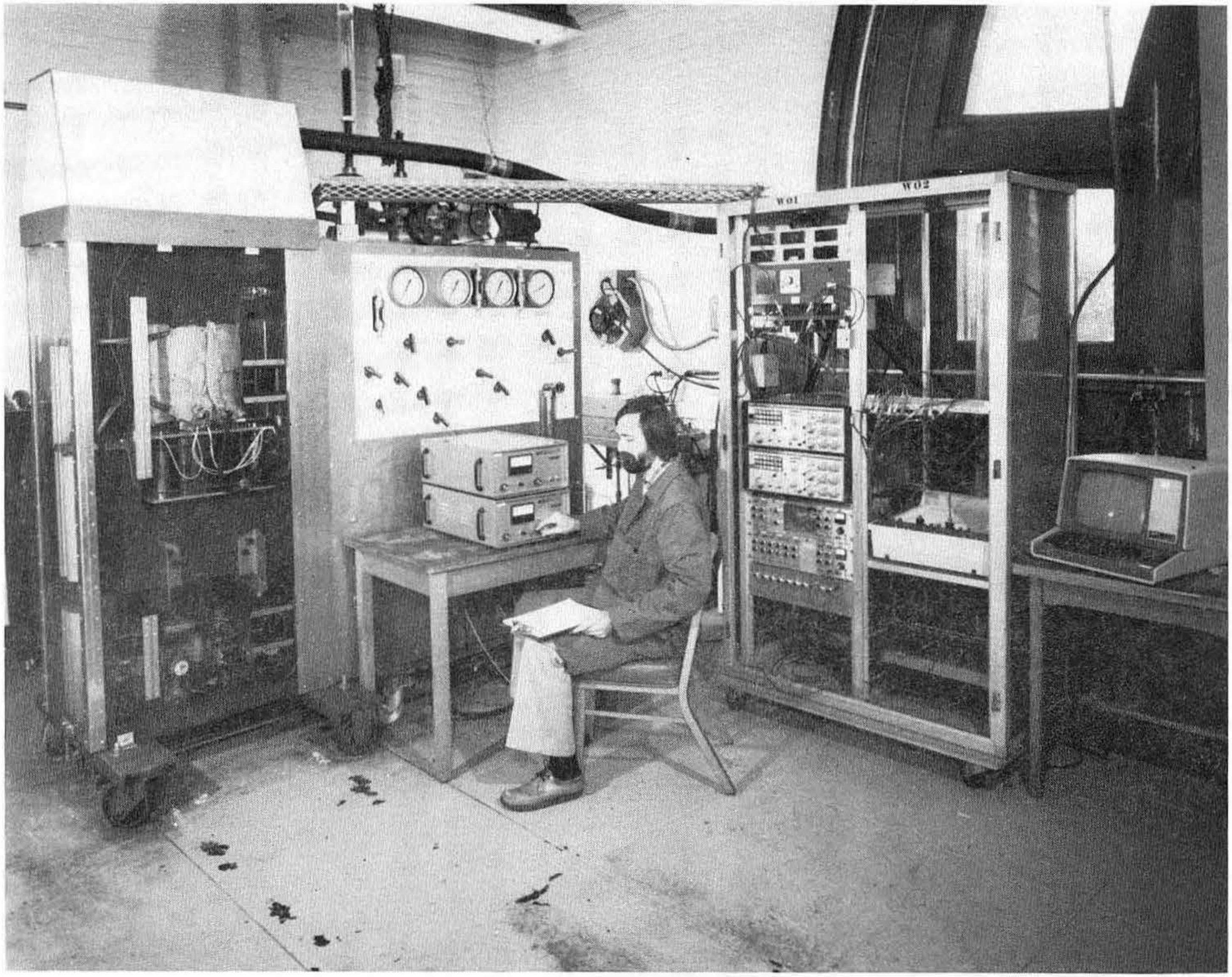

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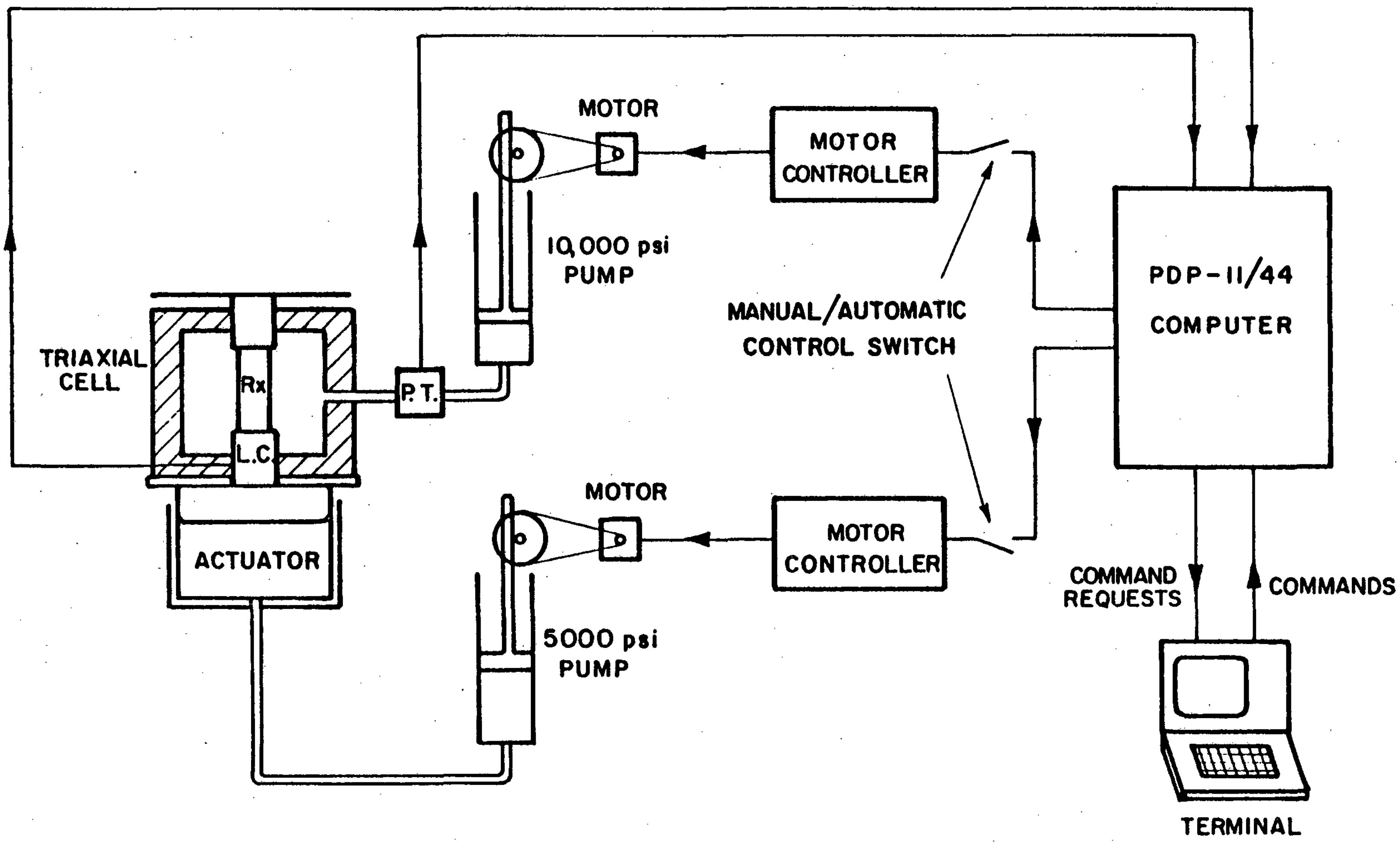
Figure 7. Photo of test equipment. The various components, from left to right are: stiff testing frame with test cell in place; power pack with electric motor driven pumps; and instrumentation rack.



L.C. - LOAD CELL

P.T. - FLUID PRESSURE TRANSDUCER

XBL 814-9381

Figure 8. Schematic representation of test control system illustrating mechanism for independent control of axial load and confining pressure by computer. Computer adjusts electric motor driven pumps according to signals received from transducers in test system. Pumps can also be controlled manually from the motor control console.

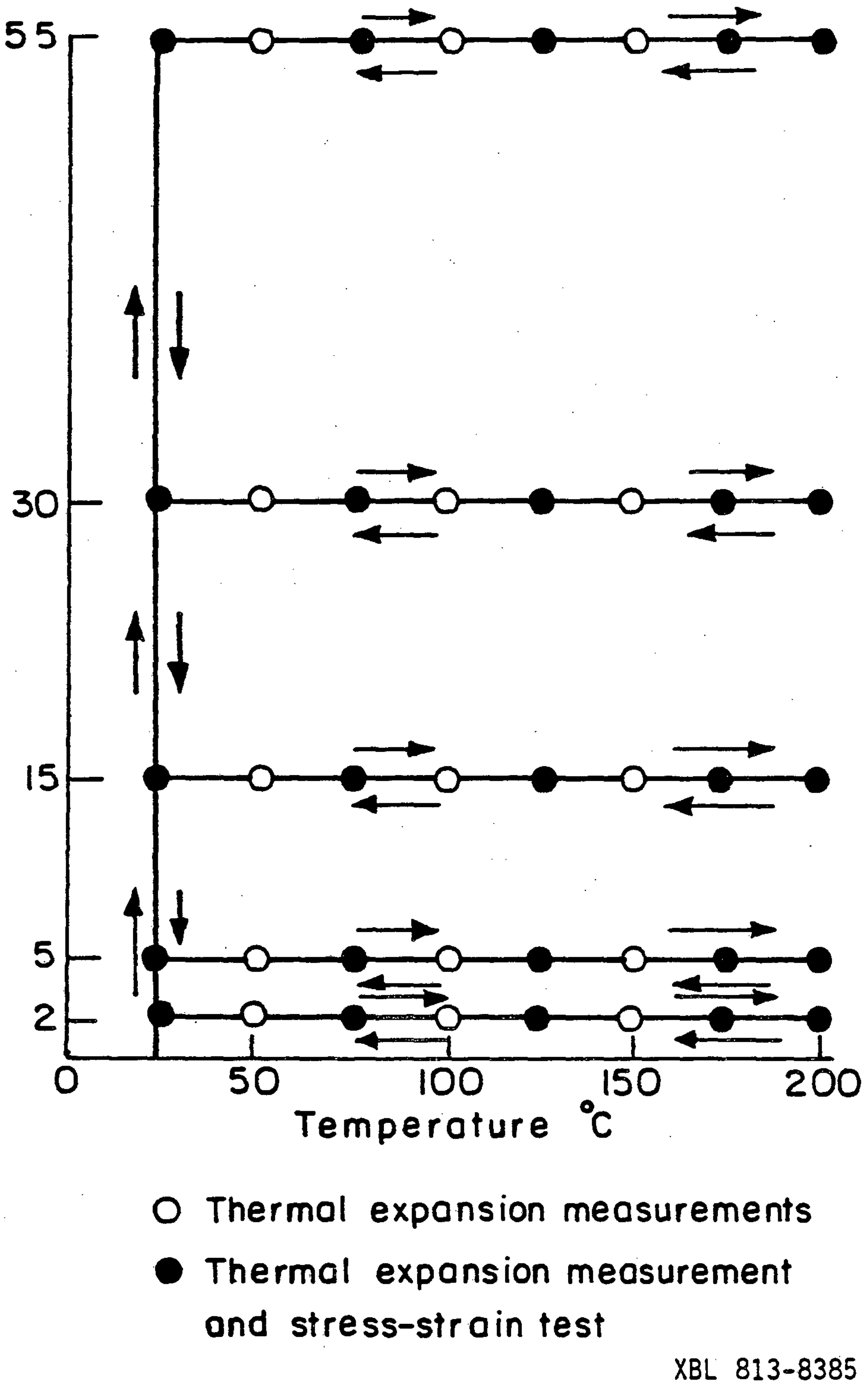


Figure 9. Test sequence for property measurement. Arrows indicate the manner in which the testing proceeded from one pressure-temperature (P-T) state to the next. Symbols represent the (P-T) state at which either elastic modulii or thermal expansion measurements were made.

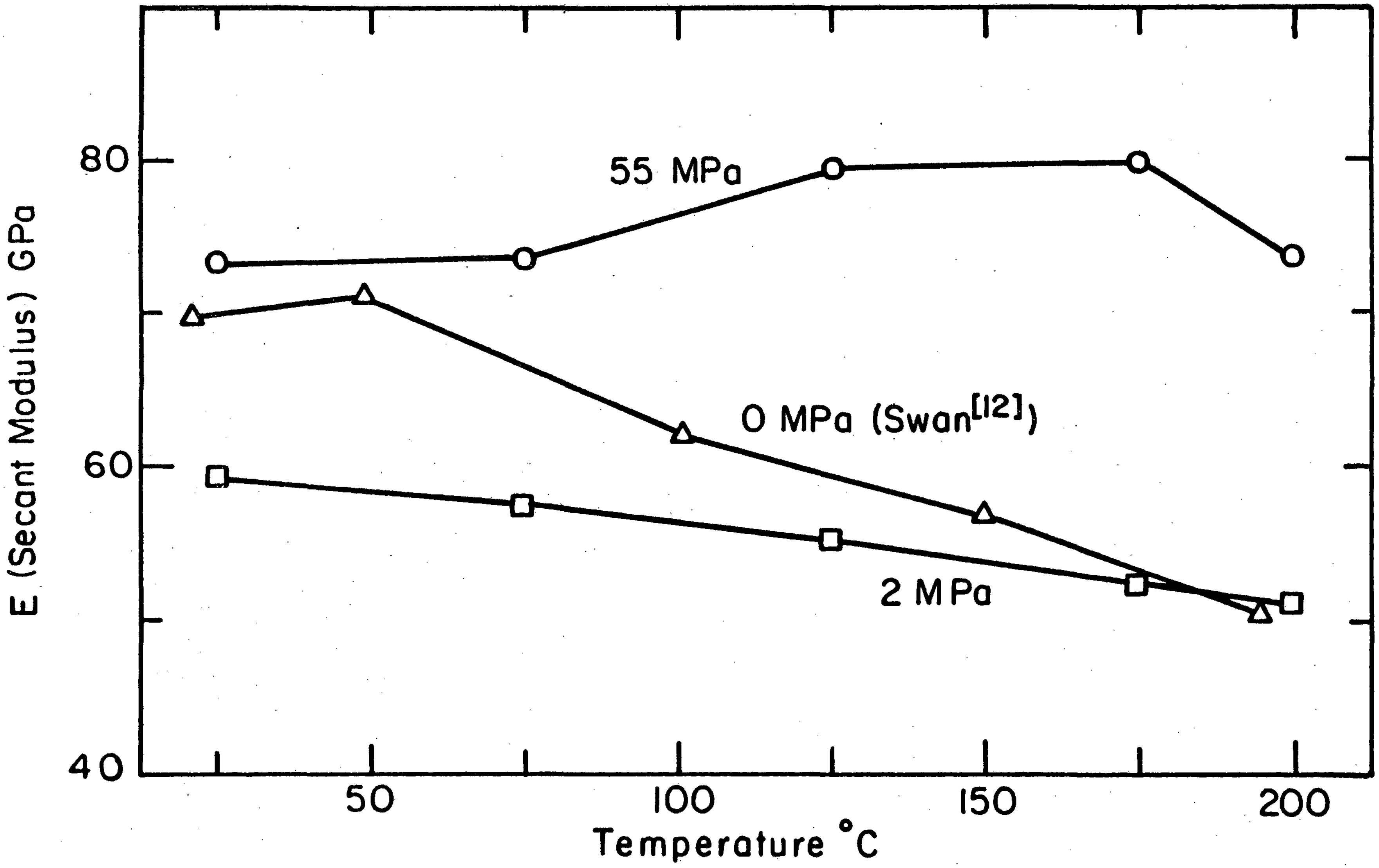


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Figure 10. Example of measurements of Young's modulus (secant modulus) at 55 MPa and 2 MPa confining pressure and test temperatures from room to 200°C. Data are for one sample, no. E024.38-4.57. For comparison, data obtained by Swan [12] for Stripa granite under unconfined conditions is also shown.

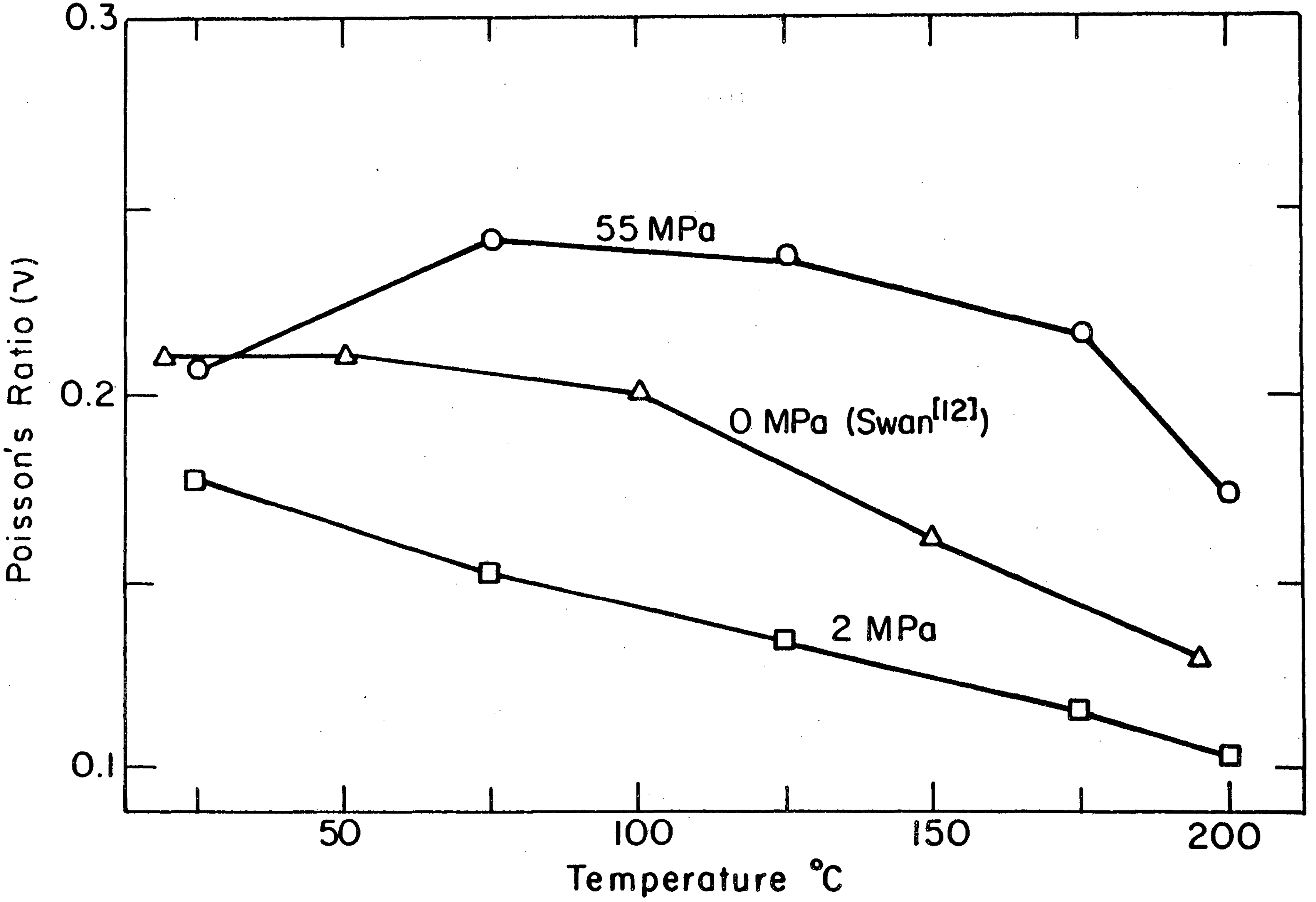

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Figure 11. Example of measurements of Poisson's Ratio at 55 MPa and 2 MPa confining pressure and test temperatures from room to 200°C. Data are for sample no. E024.38-4.57. For comparison data obtained by Swan [12] under unconfined conditions is also shown.

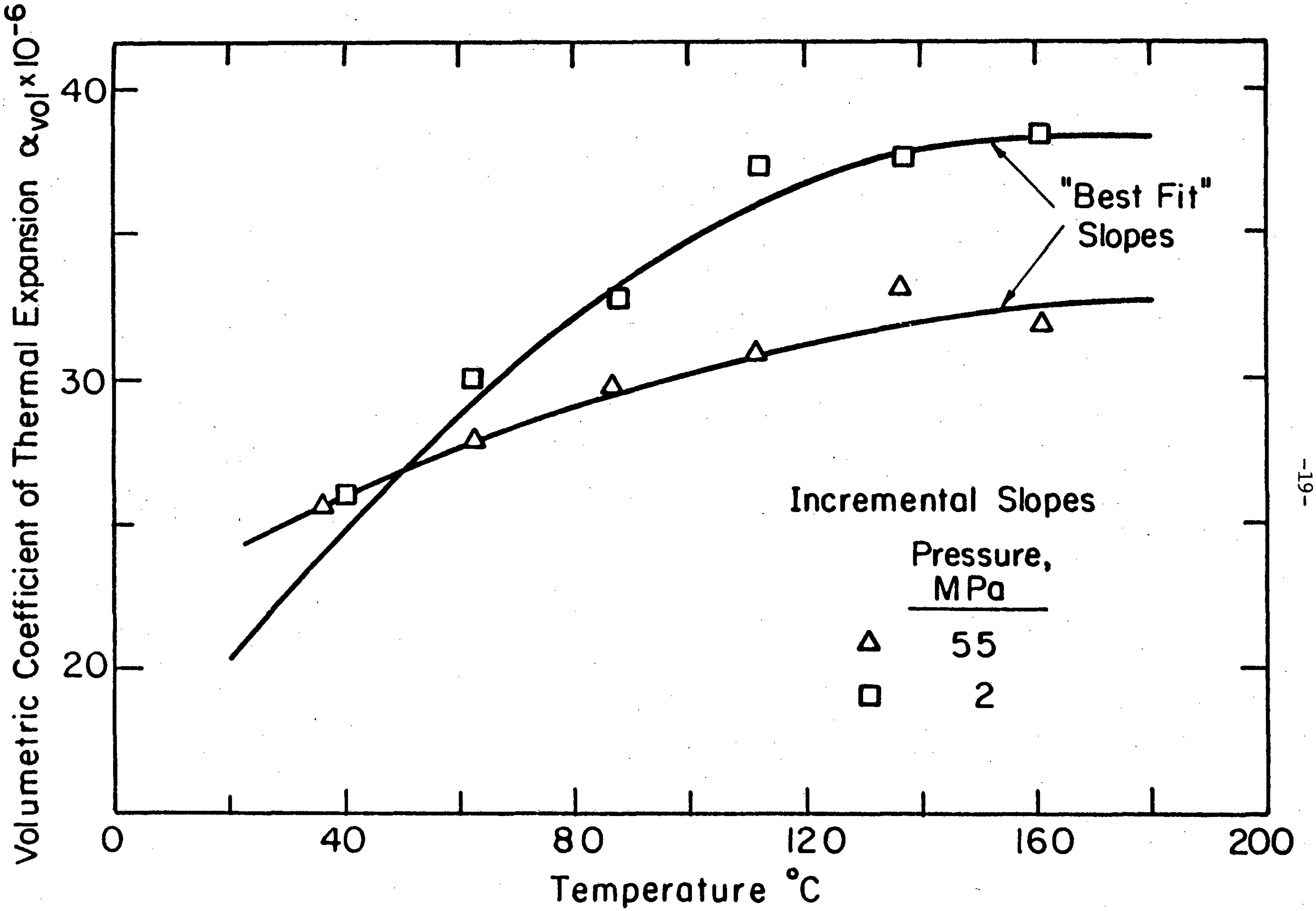

Figure 12. Volumetric coefficient of thermal expansion determined at 55 MPa confining pressure over temperature range of room to 175°C. Data are from sample E020.32-0.51. Discrete points represent values of α_v calculated by assuming a linear relationship between strain and temperature for an incremental increase in temperature. Solid curves represent values of α_v derived from a from a polynomial regression analysis of the data.

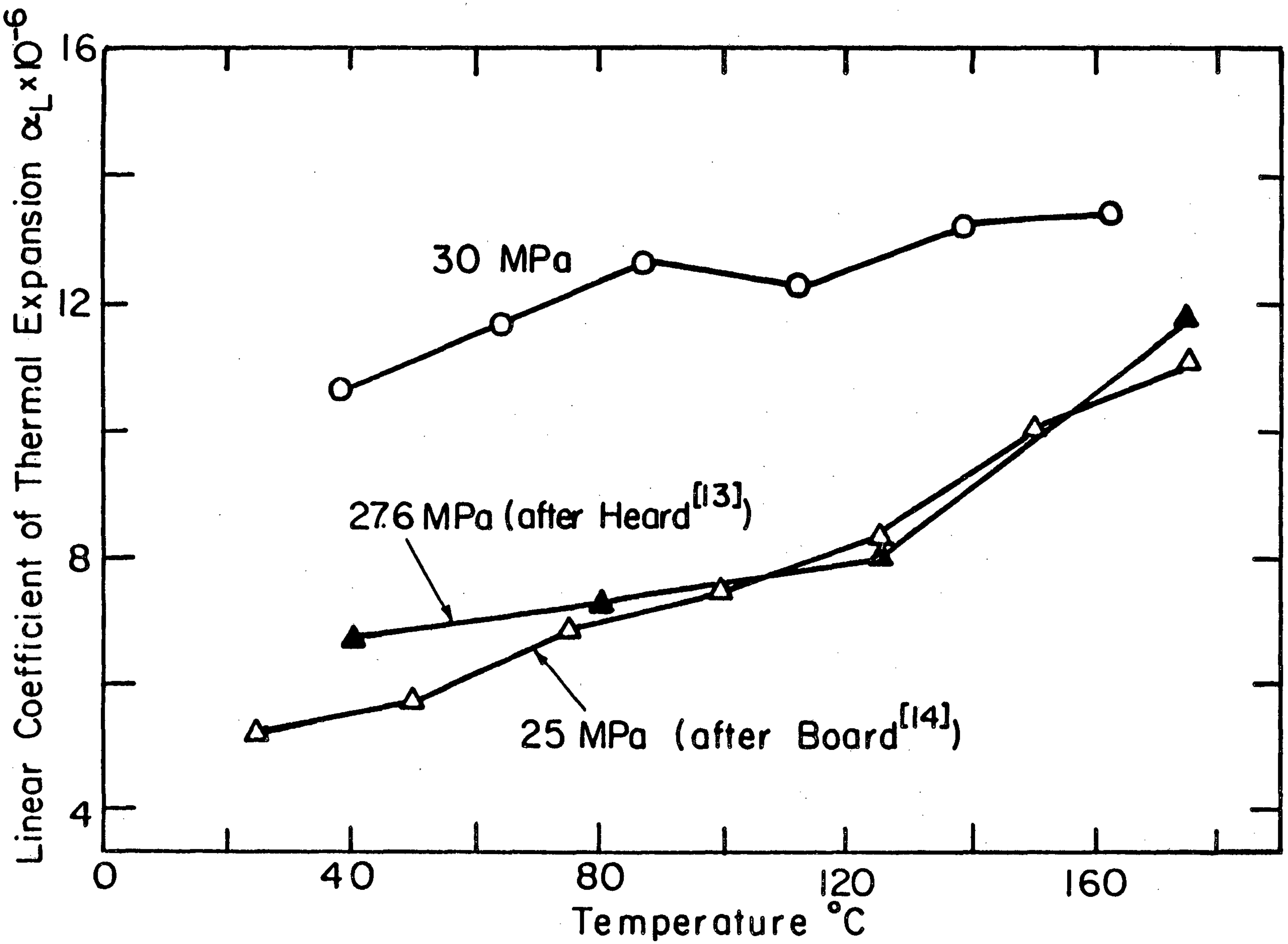

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Figure 13. Comparison of the one dimensional coefficient of thermal expansion α_ℓ at 30 Mpa confining pressure for sample E020.32-0.51 with other data obtained for Stripa granite. Values of α_ℓ calculated assuming a linear relationship between strain and temperature for an incremental temperature increase.

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