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ACOUSTIC EMISSION IN CARBONIFEROUS SANDSTONE AND MUDSTONE SAMPLES SUBJECTED TO CYCLIC HEATING

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Abstract: The thermal stresses in rock samples have been studied by means of the acoustic emission monitoring. The possible application of the obtained results to the underground fire observations and coal gasification studies was the main reason for undertaking this research. Results obtained in tested rocks indicate that the acoustic emission is occurring during heating and cooling. In the course of AE the effect of the maximum temperature memory exists, we can estimate the maximum temperature reached by the sample in the preeceding cycle.

1. INTRODUCTION

Thermal stresses can generate acoustic emission in rock (Warren and Latham, 1970); (Stesky, 1975). Thermally induced acoustic emission in igneous rocks in recent years has been a subject of extensive research in a few rock mechanics and geophysical laboratories around the world (Chen and Wang, 1980); (Atkinson et al. 1984); (Majer et al. 1984);(Montoto et all.1989); (Carlson et al. 1990); (Montoto and Hardy, 1991) but the studies of this effect in sedimentary rocks have been very limited (Zuberek and Żogała, 1988); (Żogała, 1991); (Żogała et al. 1992).

The emission and location of AE signals from the rock mass subjected to thermal stresses create the unique possibility to use this effect for remote control and observation of underground openings destined for storage of radioactive wastes, both solid and liquid. Such storage installation must be remotely controlled because of the possibility of severe environmental contamination in case of the rock mass cracking. Radioactive waste storage is connected with the emission of a large amount of heat which causes thermal stresses in rocks. As a consequence, rocks crack and AE sources appear.

The phenomenon of AE has also been used to observe displacements of the thermal stress front in the process of underground fire flooding of heavy crude oil (to decrease the viscosity and to increase the recovery of crude oil from the deposit) (Dusseault and Nyland, 1982,1984). By observing the fire flooding and movement of it's flame front with AE it is possible to control the fire flooding process by the regulation of oxygen or air inflow. Similar techniques may be used to control the process of underground coal gassification, (Hardy, 1982) or underground fires. Location of AE sources occurring in the rock mass can be used for the observations and sometimes to control the underground gassification or the combustion process.

It has been observed in some igneous and metamorphic rocks that in the course of AE there exists a discrete memory effect of the maximum memory and temperature (Chen and Wang, 1980); (Atkinson et al. 1984); (Montoto and Hardy, 1991). It seems that this effect can also be used for several geotechnical and mining purposes.

Generally, these were the main reasons to undertake the fundamental research explaining the main features of acoustic emission during cyclic temperature changes on some selected sedimentary rock samples from the Upper Silesia area. Described in this paper are results obtained for Carboniferous sandstones and mudstones.

The research were designed to answer the following questions:

- is AE occurring in sedimentary rocks during heating and cooling in some regular way,
- does the memory effect of the maximum temperature exist and how it is changing with the seasoning time,
- is the heating rate affecting the course of AE in the rocks.

2. EXPERIMENTAL PROCEDURE

The Upper Silesian Carboniferous sandstone samples were obtained from the depth 360 - 370m, and mudstone samples from the depth 215 - 220 m from borehole cores (short rock description are given in appendix 1). These samples were heated in a standard laboratory dryer with constant heating rate (approx 2°C per minute) in five cycles (Zuberek and Zogała, 1988); (Żogała and Zuberek, in press).

Each heating cycle was started at room temperature and continued up to the maximum temperature. During the first heating cycle a maximum temperature of 150°C was achieved and in each following heating cycle, the maximum temperature was increased by 10°C. After each heating cyclethe samples were naturally cooled at an approx. rate of 1,5°C/min - 1,8°C/min and next they were seasoned at room conditions. The seasoning times between subsequent cycles were 2;24;168 and 720 hours.

During heating and first cooling the AE count rate in the low frequency range (below 8000 cps) and rock temperature, with accuracy 0,1°C, was measured and recorded. Before AE measurements the complete AE channel was calibrated by breaking a graphite pencil bar (0,5mm dia) at a standard distance (Anon, 1981); (Zuberek and Żogała 1988).

The majority of tested samples were thermally loaded in such a way that immediately after they reached maximum temperature in a given cycle, the cooling was been started. Additionally, six sandstone samples were thermally loaded to maximum temperature and then we have held this temperature approximately constant for 45 minutes, next cooled and then heated them again in the second cycle. For a few samples, we increased the heating rate to 4,0°C/min, realizing the same thermal loading program.

3. EXPERIMENTAL RESULTS

The AE occurred during heating as well as during cooling of the samples, and the obtained results were quite well repeatable between different samples. One could distinguish three distinct stages of AE during heating as well as during cooling (Fig. 3,4). The first one - no or very low AE rate, the second - low, approximately constant AE rate level and the third an instant areous increase and high level of AE rate.

Denoting the temperatures at which the second stage and the third stage are occurring in the first heating cycle (Żogała, 1992) as T_{PAEI} and T_{LAEI}, respectively we have found the following values for mudstones and sandstones (see Table I) (Żogała, 1992).

Similar stages of AE can be distinguished during cooling (see Fig.3, 4). Denoting the temperatures at which the third stage and the second stage are diminishing during cooling as T_{ZAEIII} and T_{ZAEII} respectively we have obtained the following values for tested samples (see Table II).

Table I. The temperatures at which the second stage T_{PAEI} and third stage T_{LAEI} of AE occurs during the first heating cycle in tested samples.

rock type	T_{PAEI} (°C)				T_{LAEI} (°C)			
	min	max	average	σ_{n-1}	min	max	average	σ_{n-1}
mudstones	41.7	62.1	53.9	7.3	60.0	103.7	85.9	17.5
sandstones	37.0	61.7	48.4	10.9	64.8	75.8	70.6	4.1

Table II. The temperatures at which AE disappears for high T_{ZAEIII} and low level T_{ZAEII} of emission rate during cooling, with corresponding standard deviations σ_{n-1}.

rock type	$\bar{T}_{ZAEII}$ (°C)	σ_{n-1}	$\bar{T}_{ZAEIII}$ (°C)	σ_{n-1}
mudstones	52.72	4.40	76.55	10.67
sandstones	49.40	6.58	70.90	13.64

The recorded levels of AE rate during heating and cooling are similar and the temperatures of their appearance and disappearance are close, although in the case of mudstones, the average temperature at which the level of high AE rate is diminishing is about 10°C lower than in the case of heating.

In the Fig.5 and Fig.6 cumulative AE count number, N_z, versus temperature T for sequential heating cycles on both types of tested rocks are presented. It can be seen that the cures of cumulative AE count number change slope around the previous maximum temperature value. Introducing the so called felicity ratio, defined as

$$B = \frac{T_{LAE\ i+1}}{T_{max\ i}}$$

where:

$T_{LAE\ i+1}$ – temperature at which the third stage of sudden increase and high level of AE rate is occurring in the i+1 heating cycle

$T_{max\ i}$ – maximum temperature in the preceeding in heating cycle,

one can quantitatively estimate the effect of maximum temperature memory in tested rock samples. Values of felicity ratio, B, close to 1.0 indicate exact memory. The decrease of the B values can be related to gradual memory loss. In the Fig.7 the average B values with their standard deviations for tested rocks versus seasoning time is shown. For short seasoning times the values of coefficient B are high, very close to the value 1.0 and, base on the AE count rate, one can estimate the previous maximum temperature with an accurracy of approx. 5%. It is evident that with the seasoning time increase the B value is decreasing. This effect can be seen in both types of rocks just after one week between sequential heating cycles. It is interesting to note that, the maximum temperature memory effect is closely connected with the total cumulative AE count number in the same way that the highest B values are connected with lower cumulative AE count numbers (Fig. 7,8).

The gradual decay of the maximum temperature memory effect with seasoning time is connected with appropriate increase of cumulative AE count number (Fig. 8) and one may suppose that with increased seasoning time the rocks are recovering their former properties.

The obtained results indicate also that the AE count rate depends on the temperature level and on the heating rate. In sandstones increasing the heating rate the corresponding increase of AE rate can be observed (Fig. 9) but above some temperature level for very low heating rates the AE rate is still high and even is increasing (Fig. 10). It can be noticed also that holding the tested samples at the maximum temperature through longer time interval (approx. 45 minutes) in comparison with usually heated and cooled samples the decrease of the AE count rate below this temperature in following heating cycle is observed. Due to this the maximum temperature memory effect is more clearly visible in AE rate courses.

4. DISCUSSION

It looks reasonable to assume that different factors affect thermally induced AE in rocks. It could be supported by the presence of the three distinct stages in AE course. The first stage could be considered as a random occurrence of AE signals connected with sliding on existing discontinuities (microcracks, intergranular borders, etc.) homogeneously distributed throught the entire volume of the rock sample. From our point of view these signals can be considered as stationary random noise. The second stage, with constant low level of AE, can be related to stable crack growth due to increased temperature. The third stage is probably related to rapid microcrack growth and coalescence. This process starts above the maximum temperature achieved in the previous heating cycle.

Assuming the above features of the AE course, an attempt to formulate an empirical model describing the cumulative count number has been made (Żogała et al. 1991).

Let us suppose that the AE signals during heating of rock are generated mainly due to sliding on closed microcrack surfaces, their increase and development similarly (Yamamoto et al. 1990).

The part of the inelastic strain connected with crack opening will be reversible, it means that after opening of microcracks the rocks are changing their properties and the AE recorded in the following heating cycle below the the maximum temperature is low. With the increase of seasoning time, due to inelastic strain relaxation in individual mineral grains, previously opened microcracks are gradually closing and this process can be considered as responsible for the effect of partial recovery by heated rocks of their former properties after cooling and appropriate seasoning.

5. CONCLUSIONS

1. The AE is regularly occurring during heating and cooling of tested Carboniferous sandstones and mudstones. In the course of AE rate one can distinguish three distinct and different stages.
2. The occurrence of AE in tested rocks is connected with temperature level and heating rate.
3. In the course of AE count rate the effect of the maximum temperature memory from the preceeding heating cycle exists. This effect diminishes with time as can be observed in both tested rock types begining from one week seasoning time.

REFERENCES

Anon, (1981). In situ sensitivity calibration of acoustic emission systems, Technical Review, A.Brüel & Kjaer Publ., Nr 2, 38-42.

Atkinson, B.K., D. Mc Donald and P.G.Meredith (1984). Acoustic response and fracture mechanics of granite subjected to thermal and stress cyclic experiments, [in:] Proc. of the 3rd Conf. Acoustic Emission /Microseismic Activity in Geologic Structures and Materials (ed. H.R. Hardy Jr., F.W. Leighton). Trans Tech Publ., Clausthal - Zellerfeld, 5-18.

Carlson, S.R.,M. Wu and H.F. Wang (1990). Micromechanical modeling of thermal cracking in granite, Geophysical Monograph 56, American Geophysical Union, 37-48.

Chen, Y. and C.Wang (1980). Thermally induced acoustic emission in Westerly granite, Geoph. Res. Letters, 7, 12, 1089-1092.

Dusseault, M.B. and E. Nyland (1982). Fireflood microseismic monitoring, Rock Mechanics Implications, [in:]Proc.23 US Symp. on Rock Mechanics, SME and AJMM and Patr. Eng., New York, 1065-1076

Dusseault, M.B., and E. Nyland (1984). Passive seismic monitoring of in situ processes for energy recovery, [in:] Proc. Int. Symp. on Field Measurements in Geomechanics, Zurich - Balkema - Rotterdam, 81-92.

Hardy Jr, H.R. (1982). Applications of acoustic emission techniques to rock and structures, A State-of-the-Art Review Acoustic Emission in Geotechnical Engineering Practice. ASTM STP750, Philadelphia, 4-92.

Majer, E.L., M.S. King and T.V. McEvilly (1984). The application of modern seismological methods to acoustic emission studies in a rock mass subjected to heat [in:], Acoustic Emission / Microseismic Activity in Geologic Structures and Materials., Proc. Third Conf., Trans Tech Publ., Clausthal - Zellerfeld, 499-516.

Montoto, M., V.G. Ruiz de Argandona, L.Calleja and L.M. Suarez del Rio (1989). Kaiser effect in thermo cycled [in:] Proc. of the 4th Conf. Acoustic Emission/Microseismic Activity in Geologic Structures and Materials (ed. H.R. Hardy Jr.), Trans Tech. Publ. Clausthal - Zellerfeld, 97-116.

Montoto, M. and H.R. Hardy (1991). Kaiser effect in intact rock: Current status as a feasible means of evaluation thermal and mechanical loading.[in:] - Proc. Internacional Congres of Rock Mechanics (ed. Wittke) Balkema, Rotterdam, 569-572.

Stesky, R.M. (1975). Acoustic emission during high temperature frictional sliding, Pageoph, Special Issue, 113, 1/2, 31-43.

Warren, N.W. and G.V Latham (1970). An experimental study of thermally induced microfracturing and its relation to volcanic seismicity, J. Geophys. Res., 75, 23, 4455-4464.

Yamamoto, K, Y. Kuwahara, N. Kato and T. Hirasawa (1990). Deformation Rate Analysis: A new method for in situ stress estimation from inelastic deformation of rock samples under uni-axial compression, Tohoku Geophys. Journ. (Sci. Rep. Tohoku Univ., Ser.5), Vol.33, No.2, 127-147.,

Zuberek, W.M. and B. Żogała (1988). Badanie emisji sejsmoakustycznej w skałach zwięzłych w trakcie cyklicznych zmian temperatury,(in Polish) Zeszyty Naukowe AGH, Geofizyka Stosowana nr 1, 393-407.

Żogała, B. (1991). Efekt pamięci maksymalnej temperatury w skałach,(in Polish) [in:] Materiały III Krajowej Konferencji Naukowo - Technicznej nt. Zastosowanie metod geofizycznych w górnictwie kopalin stałych, Jaworze Listopad 1991, t. 1, 367-377.

Żogała, B. A. Idziak and W.M. Zuberek (1992). Acoustic emission in sedimentary rock samples during cycling heating up to 190°C, European Working Group on AE, Symposium, Leuven.

Żogała, B. (1992). Wykorzystanie emisji sejsmoakustycznej do obserwacji pękania próbek skał osadowych poddanych zmianom temperatury, [in Polish] PhD Thesis Faculty of Earth Sci., Silesian Univ., Sosnowiec.

Appendix 1

Rock sample description:

<u>Mudstone</u> samples have been taken from borehole core from the "Centrum" coal mine. The diameter of the samples is 100mm and the length is 100mm.

The samples are quartz mudstone with carbonate cement. The samples have aleuric structure with the sharp-edged granules of quartz. They have compact, disorderly texture. Inregular macropores, microcracks filled with calcite and calcites druses 10mm diameter have occured in the samples.

Petrographically, the mudstone consists of: silica, feldspar, argillaceous minerals admixture, ferriferous oxide. Ferriferous oxides are responsible for the colour. Colour of the samples varies from cherry-grey to yellow.

<u>Sandstone</u> samples belong to Carboniferous productive formation, mudstone series, Orzesze beds.

They have been taken from the "Silesia" borehole .

They have a psammitic structure with vari-size granules. Sandstone has a compact texture with parallel lamination often visible with carbonaceous substances. The quartz granules are placed disorderly and are relatively well rounded. The samples have grey colour.

Petrographically they consist of: silica, mica, feldspar and small rock pieces. The binding agent composes about 35% of the matrix.

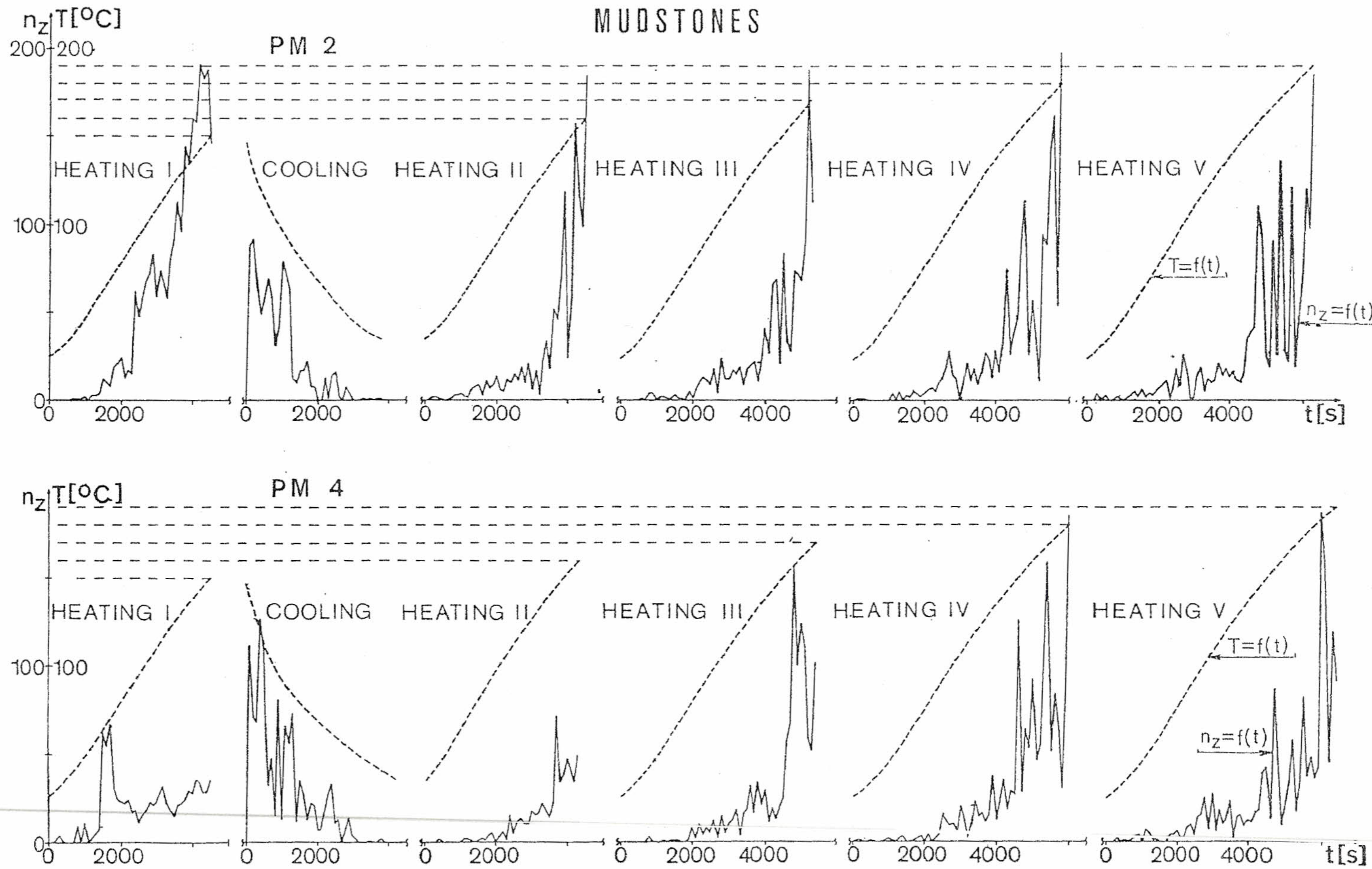

Fig. 1. AE rate n_z and temperature T versus time t for two mudstone samples.

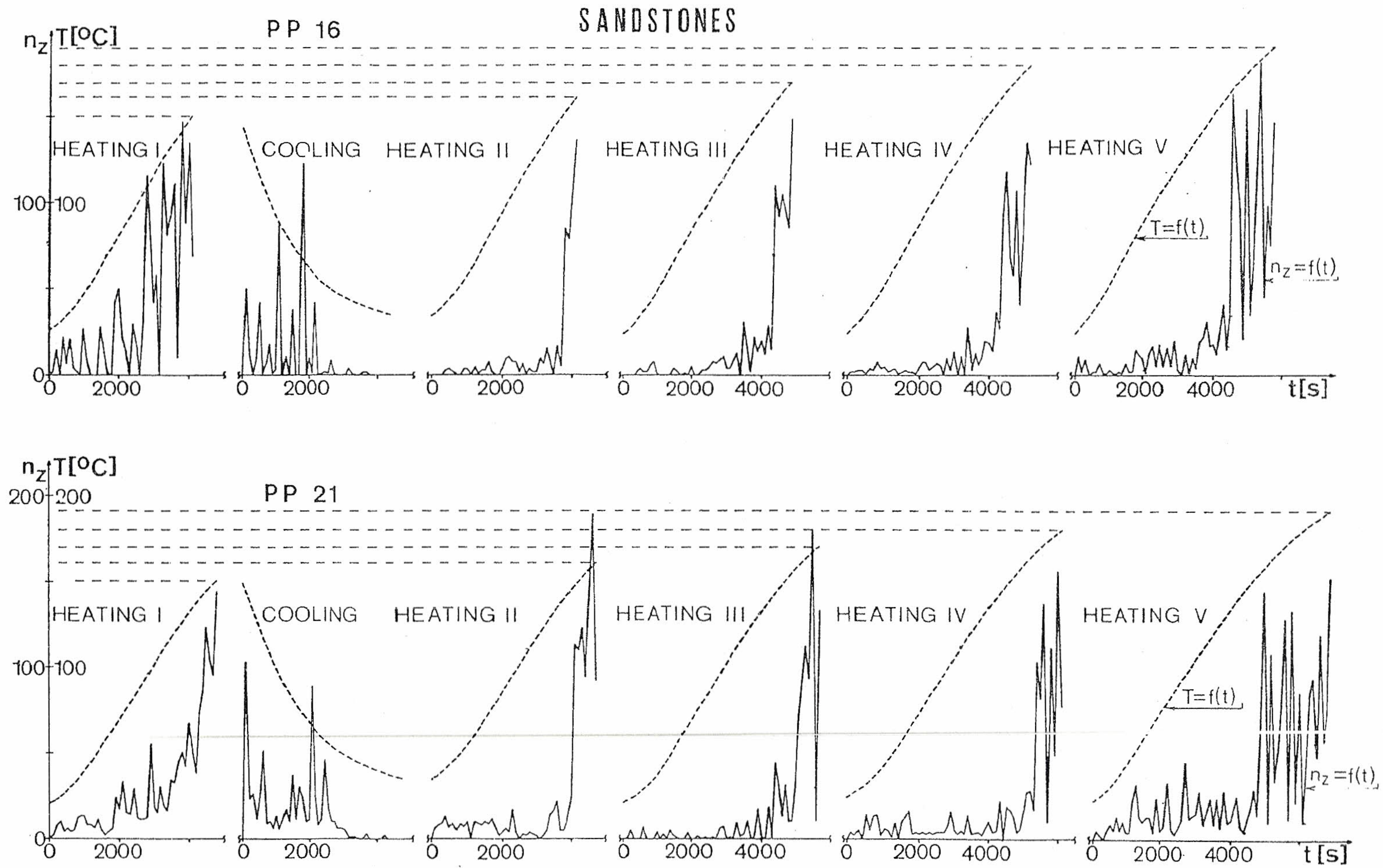

Fig. 2. AE rate n_z and temperature T versus time t for two sandstone samples.

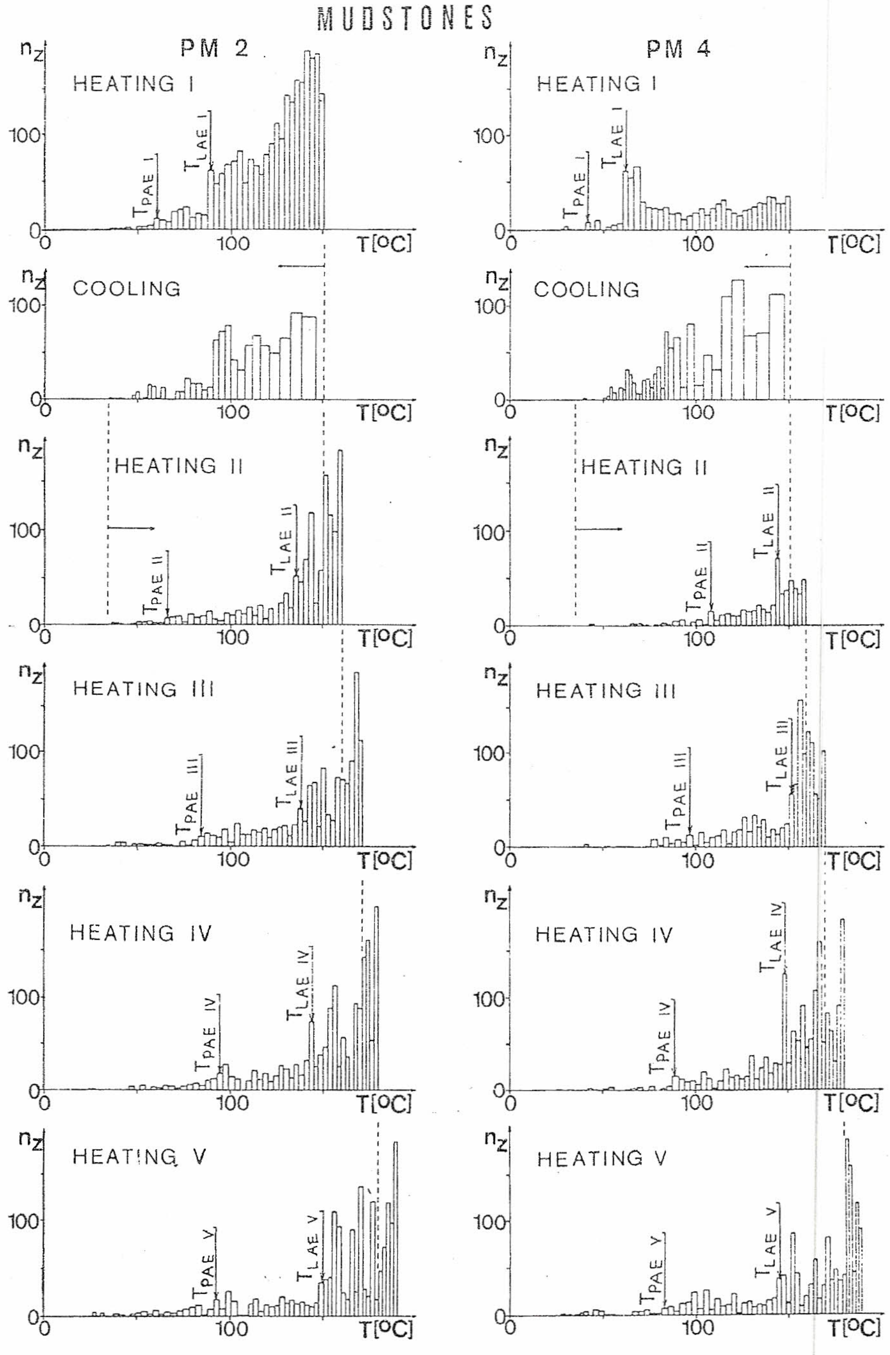

Fig. 3. AE rate n_z during heating cycles and cooling versus temperature T for two mudstone samples. Dashed lines show maximum temperature achieved in previous cycle. See Note on page 20.

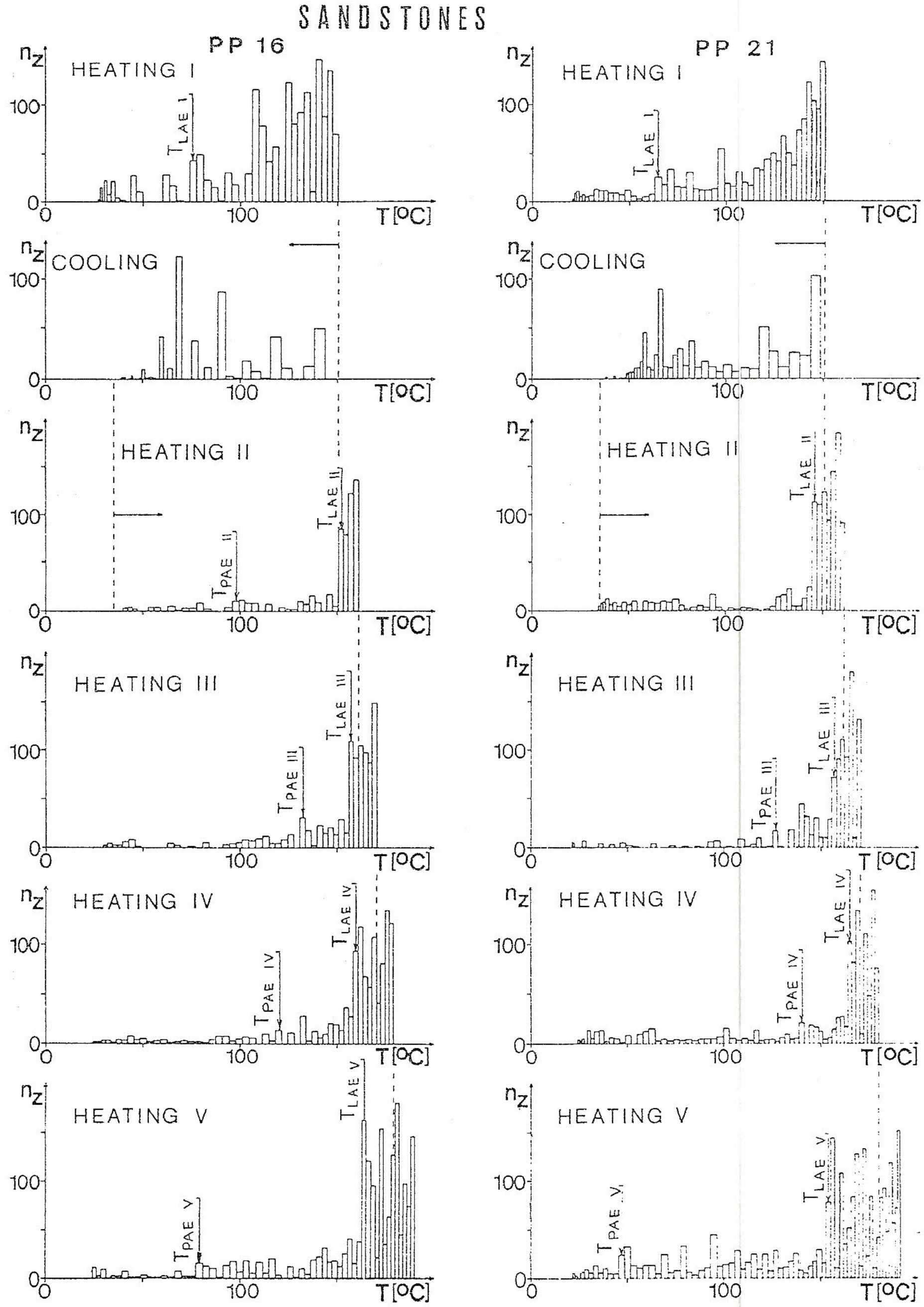

Fig. 4. AE rate during heating cycles and cooling versus temperature for two sandstone samples. Dashed lines show maximum temperature achieved in previous cycle.

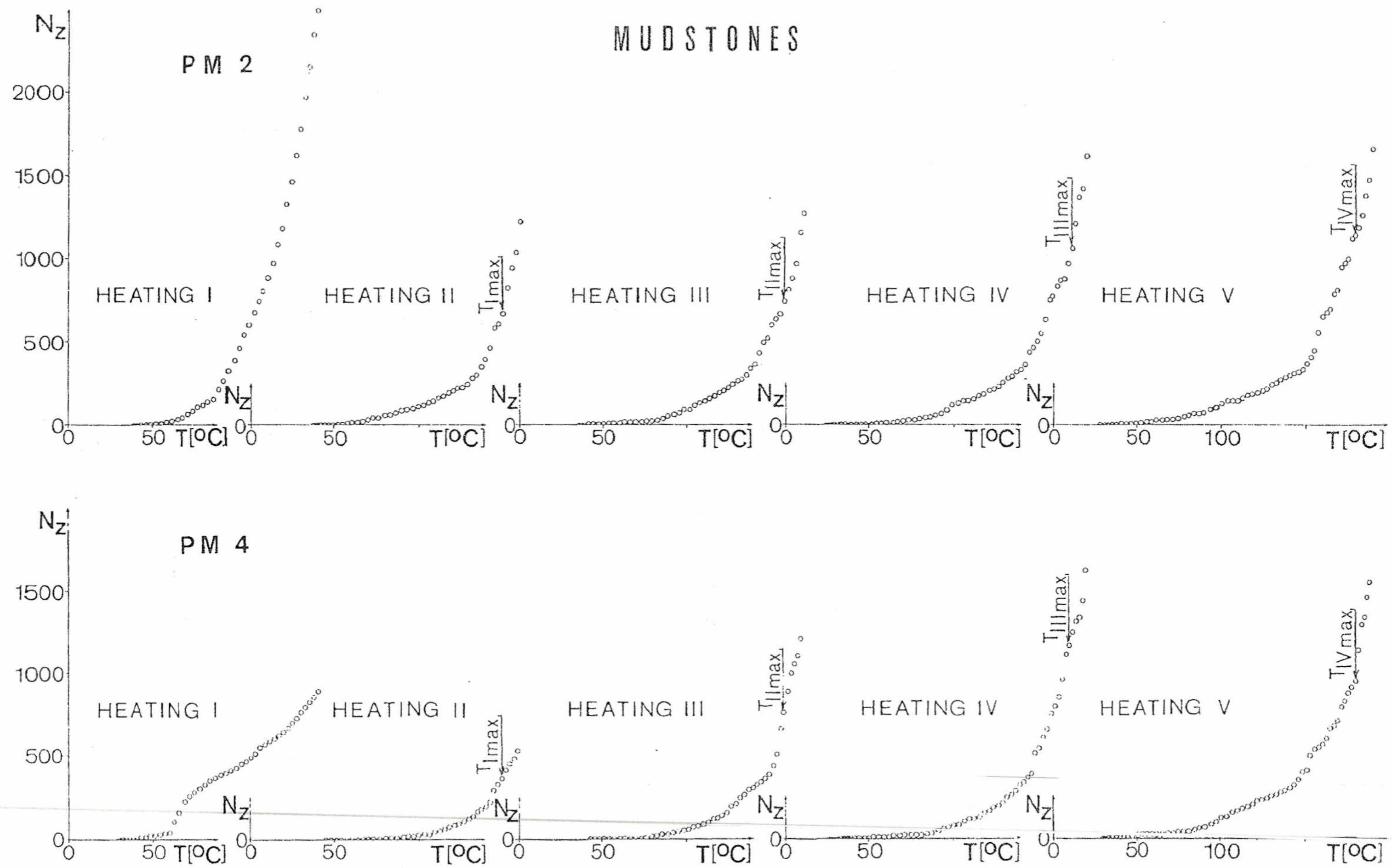

Fig. 5. Cumulative AE count number N_z versus temperature T for two mudstone samples (maximum temperature from previous heating denoted).

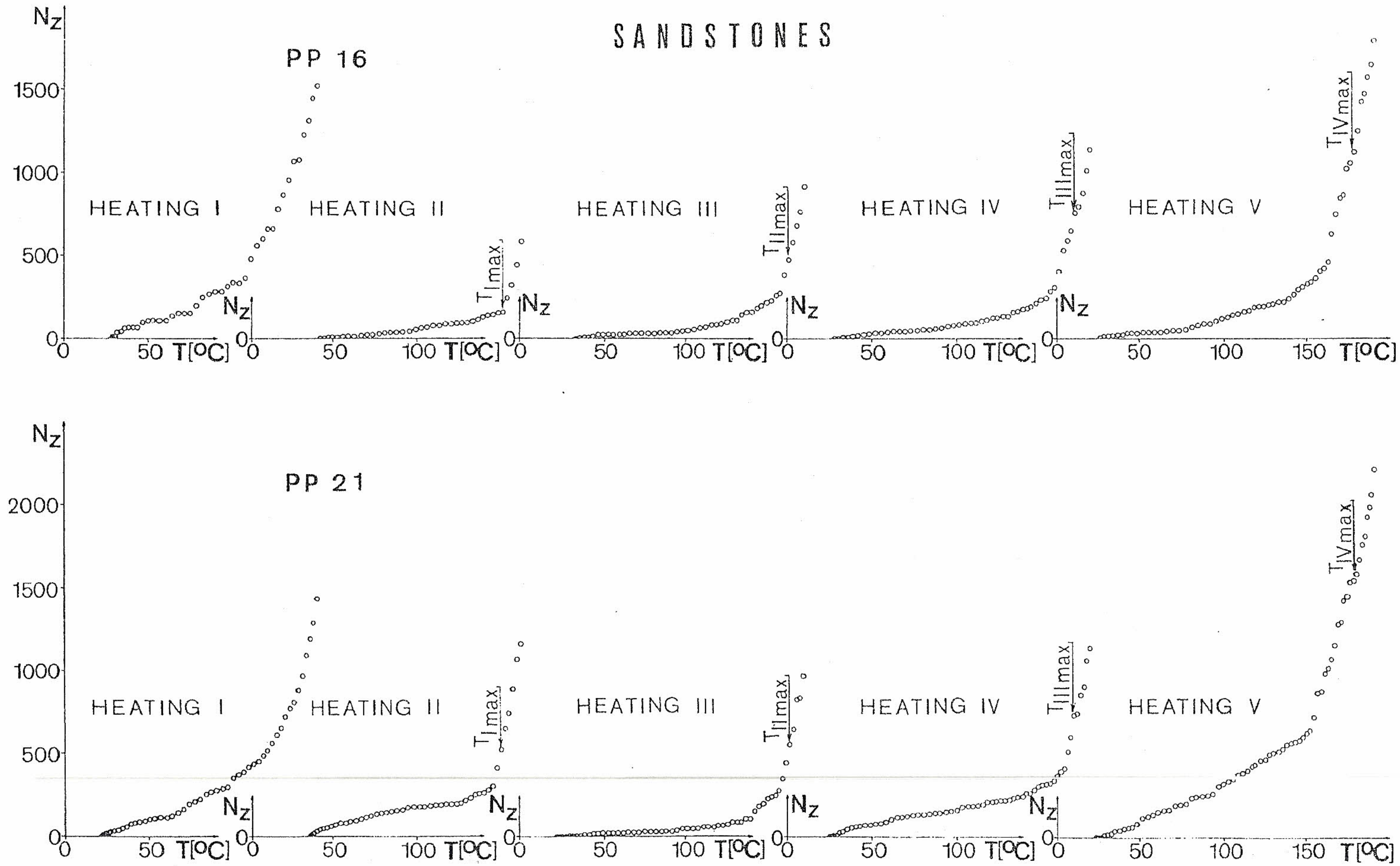

Fig. 6. Cumulative AE count number N_z versus temperature T for two sandstone samples (maximum temperature from previous heating denoted)

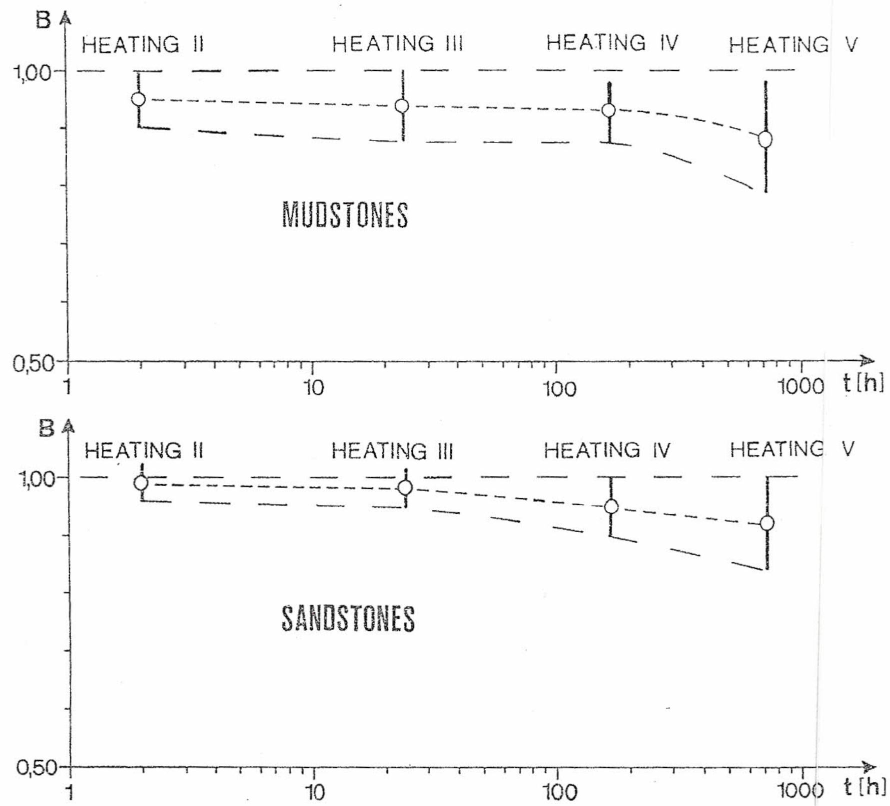

Fig. 7. Felicity ratio mean values B with their standard deviations versus seasoning time t

Note to Fig. 3 (see p.16)

T_{PAEII} - temperature at which a second, low AE rate level, stage starts during heating

T_{LAEIII} - temperature at which a third, high AE rate level, stage begins during heating

T_{ZAEIII} - temperature at which third AE stage decays during cooling

T_{ZAEII} - temperature at which a second AE stage decays during heating

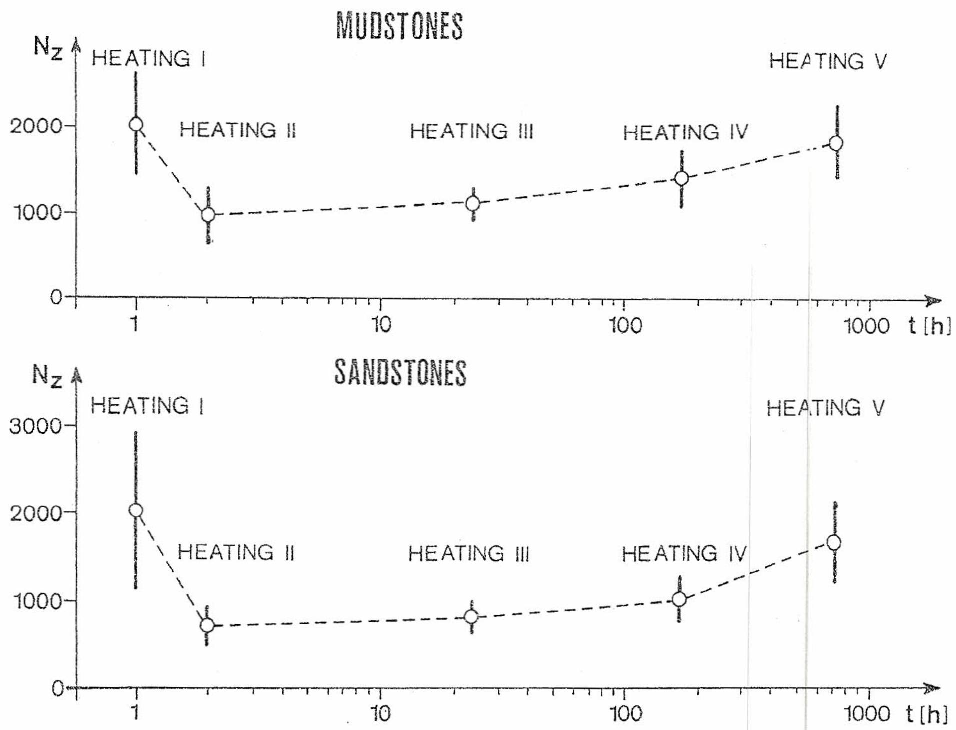

Fig. 8. Mean cumulative AE count numbers N_z (with their standard deviations) recorded during heating cycles versus seasonig time t.

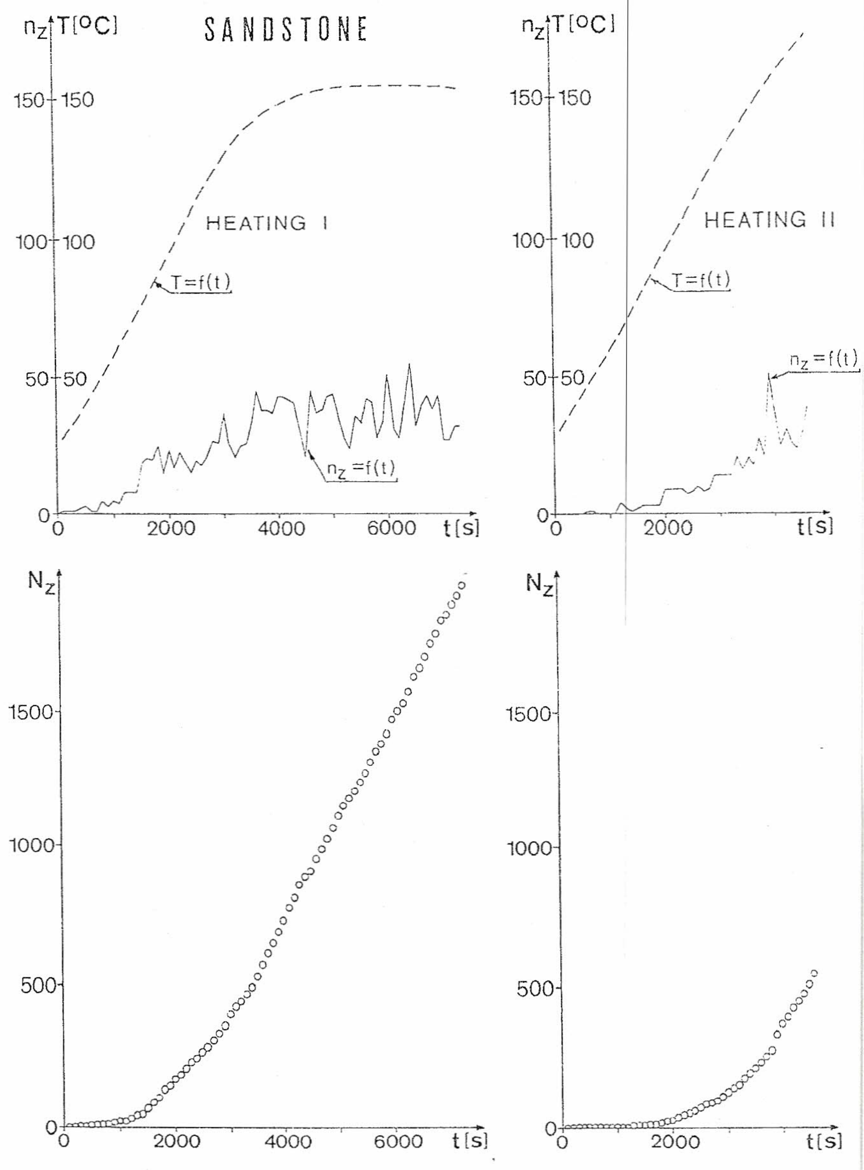

Fig. 9. AE rate n_z and temperature T during heating versus time t for sandstone samples with variable heating rate. Below the cumulative AE count numbers N_z versus time t are also presented.

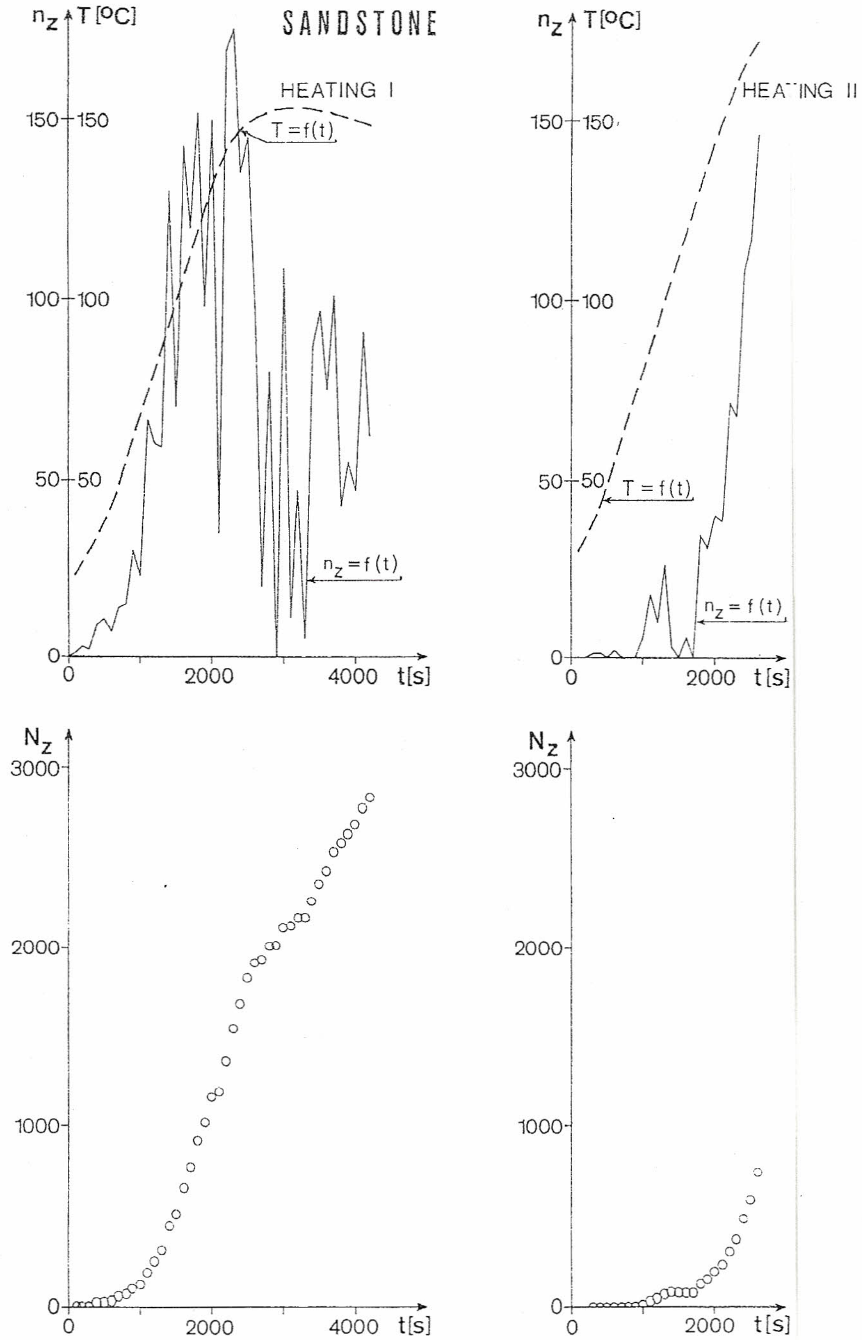

Fig.10. AE rate n_z and temperature T during heating versus time t for sandstone samples with variable heating rate. Below the cumulative AE count numbers N_z versus time t are also presented.