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International Journal of Rock Mechanics & Mining Sciences 42 (2005) 900–910

International Journal of
**Rock Mechanics
and Mining Sciences**

www.elsevier.com/locate/ijrmms

Relating seismic velocities, thermal cracking and permeability in Mt. Etna and Iceland basalts

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Accepted 3 May 2005

Available online 11 August 2005

Abstract

We report simultaneous laboratory measurements of seismic velocities and fluid permeability on lava flow basalt from Etna (Italy) and columnar basalt from Seljadur (Iceland). Measurements were made in a servo-controlled steady-state-flow permeameter at effective pressures from 5–80 MPa, during both increasing and decreasing pressure cycles. Selected samples were thermally stressed at temperatures up to 900 °C to induce thermal crack damage. Acoustic emission output was recorded throughout each thermal stressing experiment.

At low pressure (0–10 MPa), the P-wave velocity of the columnar Seljadur basalt was 5.4 km/s, while for the Etnean lava flow basalt it was only 3.0–3.5 km/s. On increasing the pressure to 80 MPa, the velocity of Etnean basalt increased by 45%–60%, whereas that of Seljadur basalt increased by less than 2%. Furthermore, the velocity of Seljadur basalt thermally stressed to 900 °C fell by about 2.0 km/s, whereas the decrease for Etnean basalt was negligible. A similar pattern was observed in the permeability data. Permeability of Etnean basalt fell from about $7.5 \times 10^{-16} \text{ m}^2$ to about $1.5 \times 10^{-16} \text{ m}^2$ over the pressure range 5–80 MPa, while that for Seljadur basalt varied little from its initial low value of $9 \times 10^{-21} \text{ m}^2$. Again, thermal stressing significantly increased the permeability of Seljadur basalt, whilst having a negligible effect on the Etnean basalt. These results clearly indicate that the Etnean basalt contains a much higher level of crack damage than the Seljadur basalt, and hence can explain the low velocities (3–4 km/s) generally inferred from seismic tomography for the Mt. Etna volcanic edifice.

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Keywords: Physical properties; Lava flows; Columnar basalts; Thermal cracking

1. Introduction

The complex stress field acting in active volcanic areas is generated by the combined effects of regional tectonics and transient local stresses caused by magma rise into feeder dykes. Hence, the most evident precursors to volcanic activity are, increases in seismicity and ground deformation, caused by magma distorting the crust as it pushes its way to the surface [1]. Improvements in volcano monitoring techniques

have resulted in interpretative models of the physical changes of the edifice associated with the renewal of activity of volcanic systems. However, accurate and meaningful interpretation of the relationship between the build-up of tectonic and magmatic stresses and precursory deformation requires a-priori knowledge of the changing physical and mechanical properties of the associated rocks. The high level of mechanical and thermal stresses acting in volcanic areas, along with circulation of fluids at high temperatures, are believed to enhance mechanical damage of the host rocks to cyclic magmatic pressurisations, leading to the failure of rocks over extended periods of time at stresses far below their short-term failure stress, through mechanisms such as stress corrosion crack growth [2]. The physical state of

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the host rock has been recognised as crucial in determining preferential penetration of magma or steam in local fractures [3], hydrofracturing by magma injection, development of shear zones during indentation [4], and the response to the pressurization of fluids within the rock matrix [5,6]. Magmatic pressure distributions and edifice failure episodes will then depend on a high number of variables, given by the size, orientation, degree of alignment, aspect ratio and, importantly, fluid content; and from the micro to the macro scale. Thus, understanding the dynamics of volcanic systems requires the determination of physical properties of volcanic rocks as a function of the extrinsic conditions of stress state, pressure and temperature.

Simultaneous inversion of P and S wave arrivals is a standard technique [7,8] to carry out seismic tomography in volcanic areas. Changes in P- and S-wave velocity have been interpreted as being due to cooling intrusive bodies or molten rocks (e.g. [9,10]). However, despite the improvement in local seismic tomography techniques, no corresponding direct measurements are available, and there is a paucity of quantitative experimental data.

Reliable laboratory measurements of physical properties, such as seismic velocity and permeability under simulated in situ conditions, are therefore essential for meaningful interpretation of seismic data at the field scale, and the validation of theoretical models; a point that has been stressed by many authors (e.g. [11–15]). Vanorio et al. [16] have previously reported P- and S-wave velocity data for volcanic rocks, including some from Etna. However they report only dry measurements relative to exhumed old intrusive bodies.

In this study, we are concerned with investigating the physical properties of typical basalts forming the edifice of active volcanoes, built up by a pile of lava flows, and comparison with intrusive magma bodies. We therefore used material obtained from extruded lava flows from Mt. Etna volcano, Italy. Mt. Etna is a basaltic shield volcano, and is the largest continental volcano in Europe. It is continuously active, and has a basal diameter of 40 km and a height of a little over 3000 m above sea level. It is formed from a lava flow pile, and exposures through ancient volcanic sequences show that the volume of pyroclastic material in the sequence is essentially insignificant [17]. As a basis for comparison, we have also investigated the physical properties of samples of fresh, columnar basalt, formed in an intrusive environment, from Seljadur in the south of Iceland. For brevity, we will use the acronym EB for Etnan basalt and SB for Seljadur basalt throughout the remainder of this paper.

We report simultaneous laboratory measurements of seismic velocities and fluid permeability at confining pressures from 5–80 MPa; approximately equivalent to depths from 0.3–3.5 km. Measurements were made in a servo-controlled steady-state-flow permeameter, during

both increasing and decreasing pressure cycles. In order to investigate the effect of thermal stress on the physical properties of basalt, selected samples were thermally stressed to temperatures up to 900 °C to induce thermal crack damage. Acoustic emission output was recorded throughout each thermal stressing experiment.

2. Methodology

The material from Etna (EB) is a porphyritic alkali basalt [18] with an initial density of $2860 \pm 10 \text{ kg/m}^3$ and a porosity of 2.1% (Fig. 1a). The material from Iceland

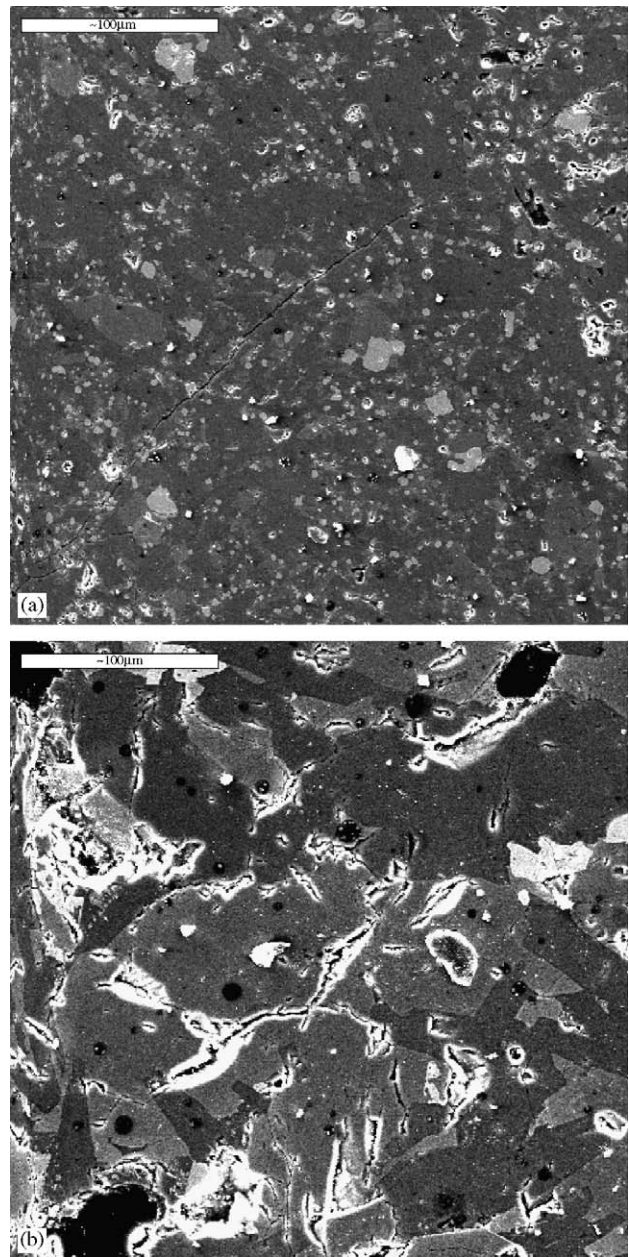


Fig. 1. Optical images (SEM) of EB (a) and SB (b), after a pressurization–depressurisation cycle.

(SB) is a tholeiitic basalt with an initial density of $2900 \pm 10 \text{ kg/m}^3$ and a porosity of around 1% (Fig. 1b).

Preliminary ultrasonic wave velocity measurements were made on cylindrical samples 38 mm in diameter by 40 mm long to characterize the test materials under

ambient conditions. A 900 V pulser was used to excite a 1 MHz resonant frequency piezo-electric transmitting transducer. Waveforms captured from an identical receiver were first pre-amplified and then recorded and displayed on a digital storage oscilloscope. Radial

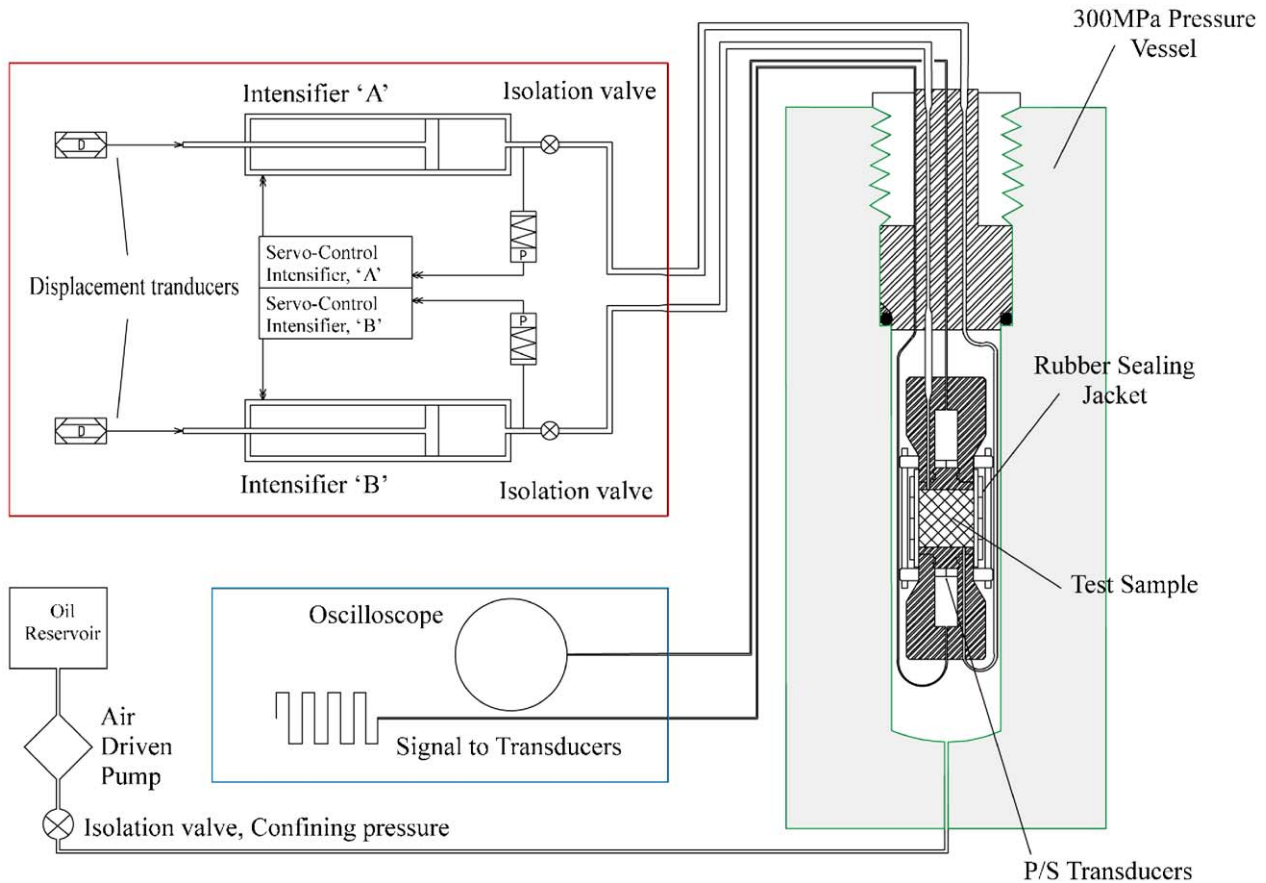


Fig. 2. Schematic sketch of the servo controlled permeameter equipped for V_p , V_s and permeability measurements.

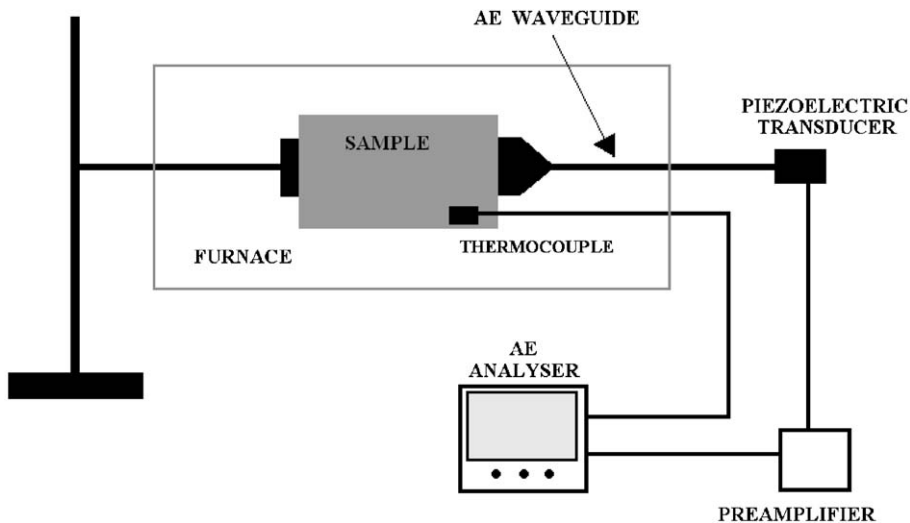


Fig. 3. Sketch of the experimental apparatus for thermal treatment.

measurements were made in 10° increments around the circumference of each sample.

P- and S-wave velocity measurements were subsequently performed inside an hydrostatic pressure vessel, using silicone oil, equipped for measuring P- and S-wave velocity with two 1 MHz piezo-electric resonance frequency transducer crystals, one each for compressional and shear mode. Accuracy of first arrival gives errors of 1–4%.

Two 70 MPa servo-controlled fluid pressure intensifiers (volumeters) were used to provide pore pressure independently to each end of the sample. Since the inner piston position inside the volumeter is monitored by a linear variable differential transformer (LVDT), pore volume change was measured from the water volume expelled during increasing of confining pressure (P_c), because of closing of voids. Pore pressure (P_p) and minimum effective pressure ($P_e = P_c - P_p$) has been set at 5 MPa. The effective stress increased by steps of 5 MPa up to 40 MPa, and by steps of 10 MPa up to 80 MPa. A pore fluid pressure gradient between the two volumeters has been set at 0.2–0.5 MPa for measuring permeability, according to the Darcy's law (Fig. 2). See Benson et al. [19] for further details.

3. Thermal treatment

Since volcanic areas are characterized by high temperatures at shallow depths, we also investigated how thermal stressing can induce additional crack damage into the microstructure of our rocks, and the influence this has on their physical and transport properties. Selected samples were therefore heated to temperatures of 300, 600 and 900 °C at a rate of 1 °C/min inside a tube furnace, and then allowed to cool to room temperature at the same rate. Acoustic emission (AE) output was recorded throughout each thermal stressing experiment in order to monitor the evolution of thermally induced cracking. A schematic diagram of the experimental arrangement is given as Fig. 3. A detection threshold of 35 dB was set to eliminate background laboratory noise, and the measurement transducer was located outside the furnace at the end of a stainless steel waveguide.

AE recorded during heating indicates a marked difference in behaviour between the two rocks (SB and EB) as shown in Fig. 4. For SB the cumulative number of events increases continuously, with a higher event rate from about 400–700 °C, where the bulk of the AE energy is released. A lower number of events are recorded for EB, and they are generated in episodic bursts of activity at low temperature (20–150 °C), and around 400 °C. This indicates that EB may contain a high level of pre-existing crack damage; probably due to the fast rate of cooling in lava flows. By contrast, SB is a

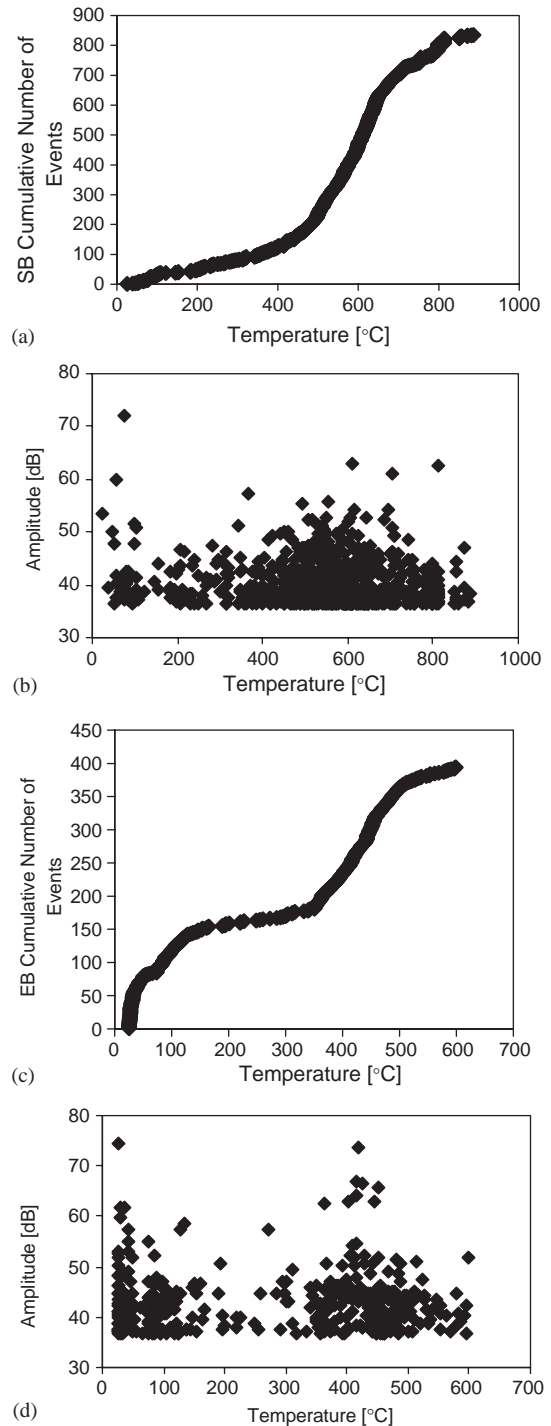


Fig. 4. Amplitude vs. temperature and cumulative number of events vs. time for EB (a,b) and SB (c,d).

more homogeneous material formed at a much slower rate of cooling in an intrusive environment.

4. Results and discussion

Radial P-wave velocity measurements made as a function of azimuth under ambient pressure are

Table 1
EB and SB ambient pressure measurements as a function of azimuth

Degree	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	
V_p (km/s)																			
EB_01 nott	3.24	3.20	3.20	3.15	3.20	3.38	3.38	3.27	3.22	3.22	3.27	3.15	3.20	3.20	3.35	3.35	3.35	3.30	
EB_01 tt900°	3.32	3.35	3.32	3.32	3.32	3.40	3.32	3.32	3.32	3.32	3.32	3.40	3.35	3.32	3.40	3.40	3.38	3.35	
EB_04 nott	3.20	3.08	3.15	3.05	3.15	3.05	3.08	3.20	3.17	3.20	3.17	3.10	3.12	3.12	3.10	3.22	3.22	3.22	
EB_04 tt900°	3.22	3.32	3.32	3.24	3.22	3.27	3.32	3.27	3.32	3.22	3.30	3.22	3.22	3.22	3.22	3.15	3.22	3.32	
EB_05 nott	3.43	3.32	3.32	3.32	3.32	3.32	3.35	3.40	3.38	3.40	3.40	3.32	3.38	3.22	3.32	3.40	3.43	3.38	
EB_05 tt900°	3.32	3.24	3.32	3.32	3.35	3.40	3.32	3.40	3.40	3.32	3.32	3.32	3.35	3.32	3.38	3.40	3.43	3.40	
EB_07 nott	3.15	3.27	3.23	3.17	3.11	3.10	3.12	3.05	3.20	3.22	3.30	3.27	3.17	3.20	3.10	3.15	3.15	3.22	
EB_07 tt900°	3.22	3.20	3.22	3.14	3.08	3.14	3.08	3.14	3.22	3.17	3.22	3.22	3.14	3.20	3.14	3.14	3.22	3.24	
SB_01 nott	5.31	5.36	5.36	5.42	5.42	5.39	5.31	5.31	5.42	5.31	5.31	5.36	5.42	5.42	5.42	5.31	5.28	5.31	
SB_01 tt900°	3.17	3.15	3.15	3.14	3.17	3.17	3.16	3.16	3.17	3.15	3.13	3.15	3.17	3.16	3.18	3.16	3.14	3.16	

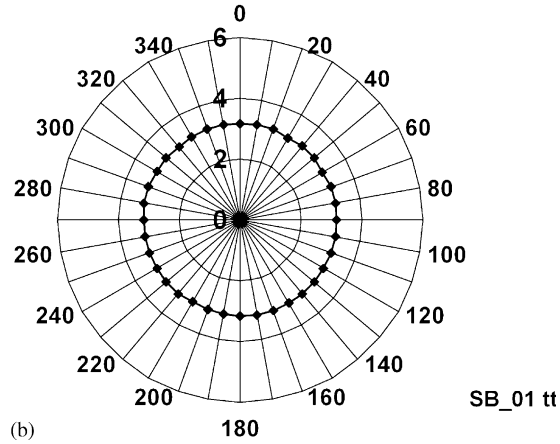
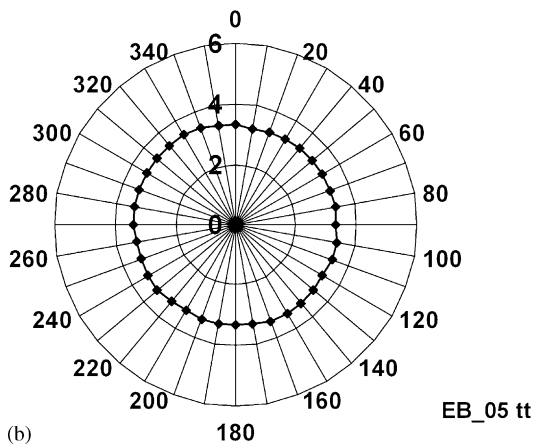
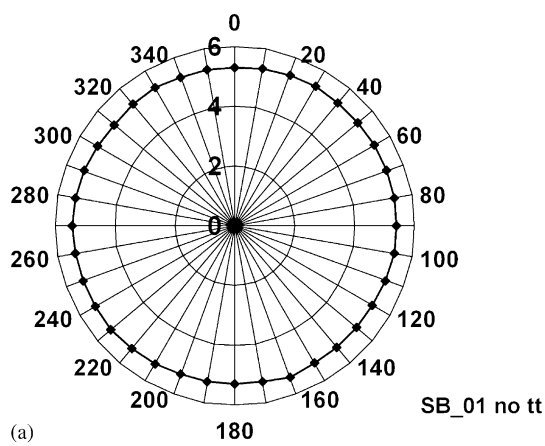
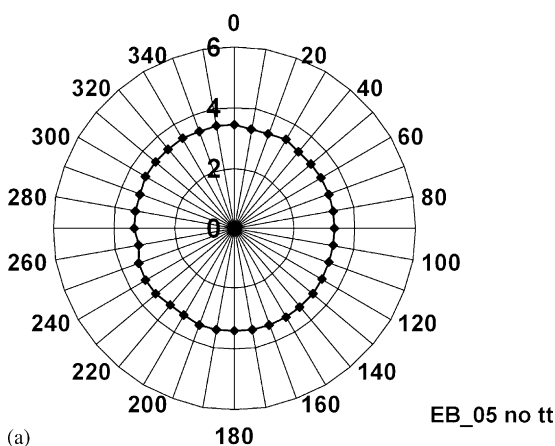


Fig. 5. Radial P-wave velocity for (a) untreated and (b) 900 °C thermally treated EB.

Fig. 6. Radial P-wave velocity for (a) untreated and (b) 900 °C thermally treated SB.

reported in Table 1. Values for non-heat-treated EB range from 3.05–3.43 km/s. These values are very low for a basalt. Since the porosity is also rather low [16], this suggests that EB contains a high density of pre-existing microcracks. However, within individual samples, the velocity anisotropy ranges from only 4% to 7%, indicating that both the matrix and the crack

population are relatively isotropic. The supporting evidence comes from the measurements on the thermally stressed samples. Even after thermal stressing to 900 °C, radial P-wave velocities for EB do not show any significant change (Figs. 5a and b). This suggests that relatively few new cracks have been introduced by the thermal treatment.

Results of comparable measurements on samples of SB are in marked contrast. Azimuthal P-wave velocities for untreated SB (Table 1) range from 5.28–5.42 km/s, with an anisotropy of less than 3%. These velocities are more typical of a fresh, relatively unfractured basalt. Consequently, after thermal stressing to 900 °C, velocities decrease significantly by more than 40% to lie in the range 3.13–3.18 km/s (Table 1 and Fig. 6). This suggests that many new, thermally induced cracks were generated during the thermal treatment process.

The AE generated during thermal stressing supports these observations, and suggests that EB contains many pre-existing cracks that re-open during heating and close again during cooling. By contrast, considerable crack damage is generated during heating of SB, and this reduces the P-wave velocity significantly.

Subsequently, simultaneous measurements of P- and S-wave velocities were made on both dry and water fully saturated samples (hereafter named as “wet” samples) at effective pressure from 5–80 MPa. Measurements were

made during both the pressurisation and depressurisation cycles on non-thermally treated EB samples, and on samples previously heated to 300, 600 and 900 °C. Again, for purposes of comparison, measurements were made on samples of SB in the non-thermally treated state and samples heated to 900 °C. Measurements of the change in porosity and permeability were also made at the same time on the wet samples.

At low confining pressure (5 MPa), P-wave velocities for dry samples of EB were in the range 2.94–3.21 km/s, while S-wave velocities ranged from 2.47–2.81 km/s. As effective pressure was increased to 80 MPa, these values increased from 4.71–4.96 km/s and 3.50–3.79 km/s, respectively (Table 2); an average increase of 55% for P-waves and 35% for S-waves. Significantly, no discernible change in either P- or S wave velocity was observed between non-thermally treated and thermally treated samples, and no significant velocity hysteresis was detected (Fig. 7). For dry samples of SB, the P-wave velocity for the non-thermally treated sample increases

Table 2
EB dry measurements vs. confining pressure

P_c (Mpa)	5	10	15	20	25	30	35	40	50	60	70	80
V_p (km/s)												
EB_01	2.94	3.33	3.57	3.74	3.87	4.01	4.08	4.40	4.40	4.44	4.62	4.72
EB_02	3.29	3.49	3.61	3.76	3.88	3.95	4.22	4.22	4.33	4.52	4.61	4.71
EB_04	3.49	3.67	3.90	4.00	4.11	4.30	4.39	4.39	4.56	4.75	4.85	4.96
EB_10	3.21	3.51	3.62	3.77	3.90	3.97	4.04	4.11	4.31	4.52	4.61	4.77
V_s (km/s)												
EB_01	–	1.87	1.95	2.00	2.05	2.11	2.16	2.20	2.27	2.44	2.49	2.55
EB_02	2.81	2.98	3.09	3.15	3.20	3.27	3.34	3.40	3.48	3.58	3.66	3.76
EB_04	2.47	2.60	2.71	2.81	2.88	2.98	3.06	3.12	3.23	3.32	3.42	3.50
EB_10	2.66	2.79	2.88	2.97	3.06	3.15	3.23	3.30	3.43	3.56	3.68	3.79

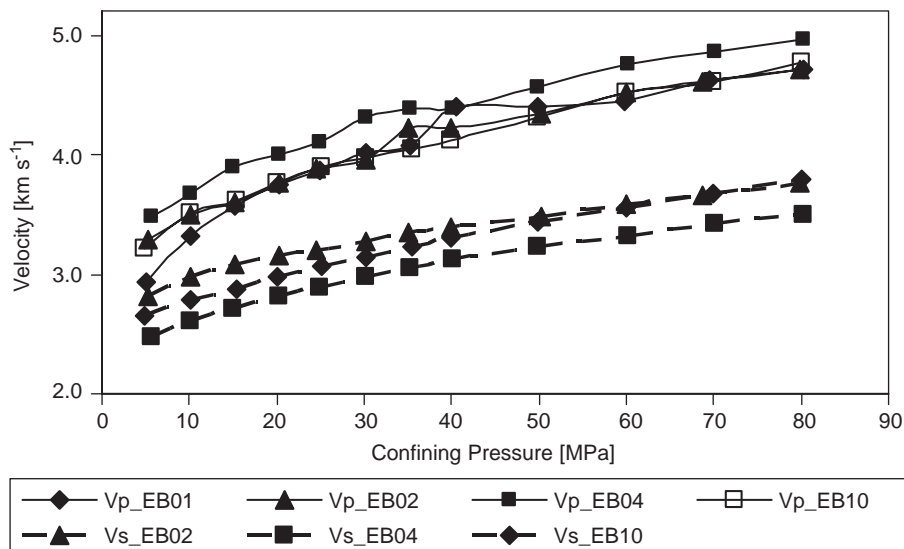


Fig. 7. P and S-wave velocities vs. confining pressure for EB dry samples.

from 5.43–5.85 km/s as effective pressure is increased from 5–80 MPa; an increase of 8%. The commensurate increase in the S-wave velocity is 4%; from 3.03–3.14 km/s (Table 3). In this case, however, dramatic decreases in both P- and S-wave velocities are observed in the thermally treated material. Initial P-wave velocity is 3.19 km/s, and this increases by 47% to 4.69 km/s at 80 MPa. For S-waves the initial value is 2.05 km/s, and this increases by 30% to 2.64 km/s at 80 MPa. Again no velocity hysteresis is observed. Fig. 8 shows that the initial velocities are some 70% and 30% lower in the thermally treated SP, for P and S waves, respectively. However, the increase in velocity with increasing effective stress is about an order of magnitude higher for the thermally treated material.

Taken together, these observations provide strong evidence for a very high crack density in EB in its as-received state. Increasing the effective pressure closes many of these cracks, resulting in a significant increase in both P-wave and S-wave velocities. The absence of hysteresis suggests that during depressurisation the cracks re-open and, hence, the velocity values are recovered. Conversely, SB exhibits considerably higher

P- and S-wave velocities in its as-received state; by about 2.3 and 1.0 km/s, respectively. It is virtually insensitive to changes in effective pressure (Fig. 9a). This is indicative of an almost crack free material. However, when it is thermally stressed, many new cracks are generated, the wave velocities decrease to values very close to those for EB, and the effect of pressure becomes significant (Fig. 9b).

As expected, P-wave velocities were significantly higher in wet samples of EB. More surprisingly, S-wave velocities were also higher for the wet samples. P-wave velocities ranged from 5.35 ± 0.13 km/s at 5 MPa to 5.88 ± 0.12 km/s at 80 MPa; while S-wave velocities ranged from 3.30 ± 0.04 km/s to 3.60 ± 0.04 km/s over the same pressure interval (Table 4). These velocity increases of about 10% are associated with a 25% decrease in porosity, i.e. from about 2% to about 1.5% (Fig. 10). Fig. 11 shows that, again, there is no discernible change in either velocity as a function of thermal stressing temperature, and no hysteresis. Similar results are seen for the wet sample of SB that had been thermally stressed to 900 °C (Table 5). P-wave velocity increased from 5.16 km/s at 5 MPa to 5.80 km/s at

Table 3
SB dry measurements vs. confining pressure

P_c (Mpa)	0	5	10	15	20	25	30	35	40	50	60	70	80
V_p (km/s)													
SB_02	3.19	3.22	3.32	3.43	3.55	3.62	3.73	3.83	3.95	4.10	4.29	4.45	4.69
SB_03	5.43	5.51	5.66	5.72	5.72	5.72	5.75	-	5.75	5.78	5.82	5.85	5.85
V_s (km/s)													
SB_02	2.05	2.10	2.14	2.17	2.22	2.26	2.30	2.35	2.39	2.46	2.52	2.58	2.64
SB_03	3.03	3.06	3.07	3.08	3.08	3.08	3.09	-	3.09	3.10	3.12	3.13	3.14

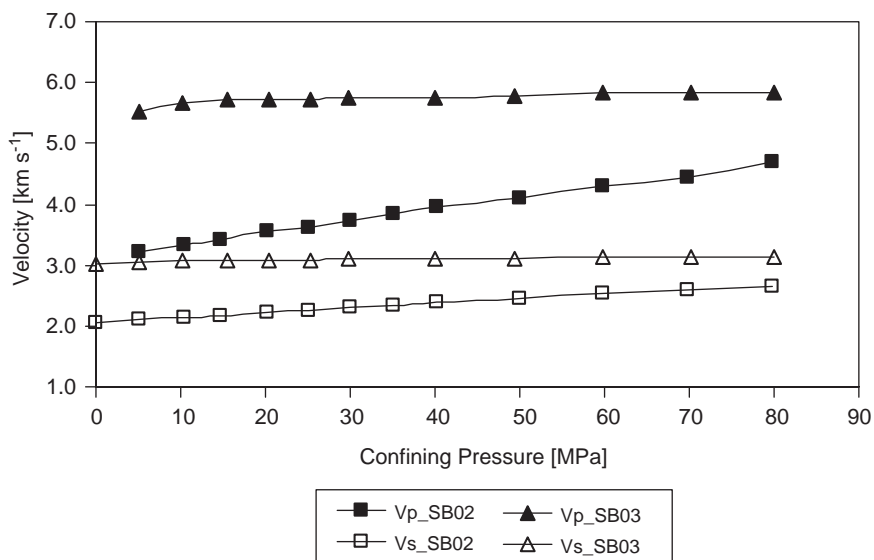


Fig. 8. P and S-wave velocities vs. confining pressure for SB dry samples.

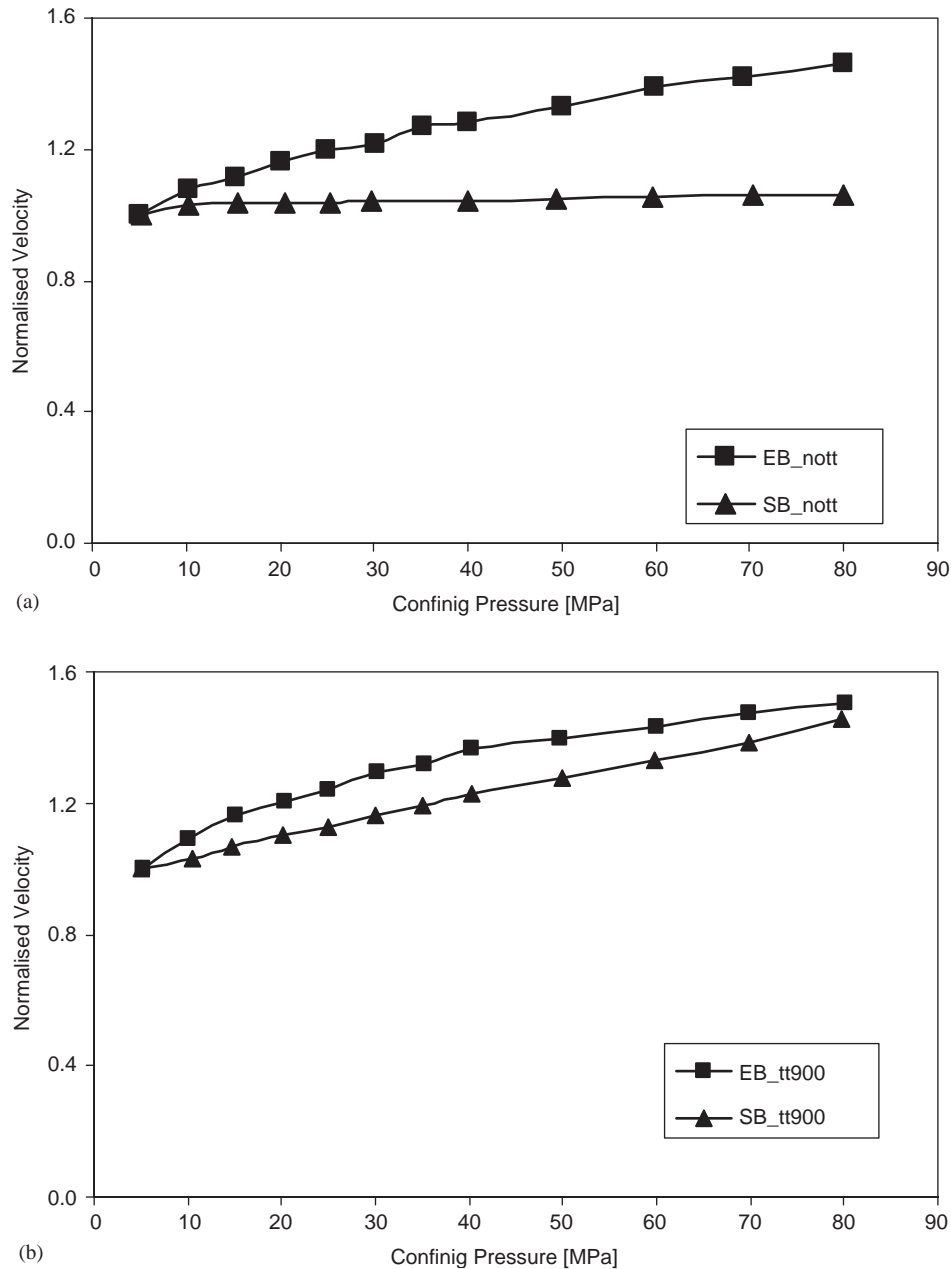


Fig. 9. Normalised P-wave velocity values for (a) untreated EB and SB samples and (b) 900 °C thermally treated samples.

80 MPa; and S-wave velocity increased from 3.22–3.62 km/s. No data are available for non-thermally stressed SB since it was impractical to fully saturate this material over the time-scale of the experiment due to its ultra-low permeability [22].

Fluid-filled cavities enhance the propagation of seismic waves and, when combined with crack closure due to the increase in effective pressure, explains both the higher velocities observed and their lower rate of increase with effective pressure. Once again, the similarity between velocity values for both thermally and non-thermally treated EB, and thermally treated SB

is strongly supports presence of a significant level of crack damage.

Finally, Fig. 12 shows how the permeability of EB decreased almost five-fold from about $7 \times 10^{-16} \text{ m}^2$ at an effective pressure of 5 MPa to about $1 \times 10^{-16} \text{ m}^2$ at 80 MPa. Most of the decrease (60–70%) occurs by 30 MPa, somewhat similar to the porosity decrease (Fig. 10) and corresponding to the highest increase of seismic velocities. By contrast, the permeability of untreated SB has previously been found to vary little with pressure from its initial low value of $9 \times 10^{-21} \text{ m}^2$ [22]. However, Fig. 12 shows that thermal stressing has

Table 4
EB wet measurements vs. effective pressure

P_{eff} (Mpa)	5	10	15	20	25	30	35	40	50	60	70	80
V_p (km/s)												
EB_01	5.22	5.25	5.31	5.37	5.40	5.46	5.49	5.52	5.56	5.64	5.72	5.76
EB_02	5.32	5.32	5.40	5.44	5.52	5.52	5.60	5.60	5.68	5.76	5.76	5.84
EB_03	5.40	5.48	5.52	5.60	5.64	5.68	5.72	5.72	5.80	5.84	5.88	5.92
EB_06	5.31	5.40	5.44	5.52	5.60	5.60	5.64	5.68	5.80	5.84	5.88	5.92
EB_07	5.25	5.31	5.34	5.40	5.48	5.48	5.56	5.60	5.64	5.68	5.76	5.80
EB_08	5.48	5.52	5.60	5.64	5.68	5.68	5.72	5.76	5.84	5.88	5.96	5.96
EB_09	5.48	5.56	5.60	5.60	5.68	5.68	5.76	5.76	5.84	5.88	5.96	6.00
V_s (km/s)												
EB_01	3.28	3.34	3.38	3.40	3.44	3.46	3.48	3.52	3.54	3.58	3.62	3.64
EB_02	3.26	3.28	3.34	3.36	3.38	3.40	3.44	3.48	3.50	3.52	3.54	3.56
EB_03	3.34	3.38	3.44	3.46	3.46	3.48	3.48	3.48	3.50	3.54	3.56	3.58
EB_06	3.28	3.32	3.36	3.38	3.40	3.42	3.44	3.46	3.52	3.54	3.58	3.60
EB_07	3.30	3.34	3.36	3.40	3.42	3.44	3.46	3.48	3.50	3.54	3.56	3.60
EB_08	3.30	3.32	3.36	3.38	3.40	3.42	3.42	3.44	3.48	3.50	3.54	3.56
EB_09	3.32	3.36	3.38	3.40	3.42	3.44	3.48	3.48	3.52	3.56	3.58	3.60

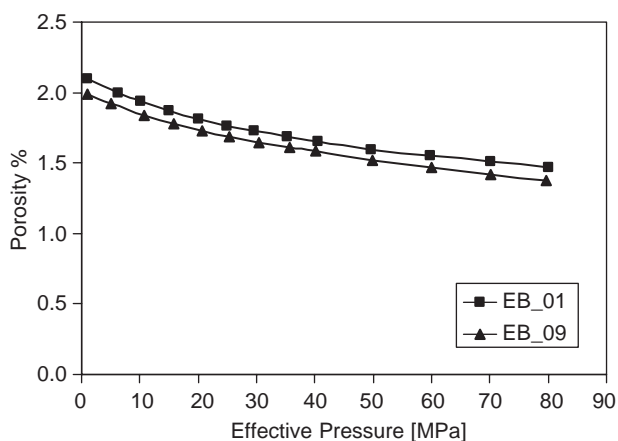


Fig. 10. Porosity vs. effective pressure for EB samples

significantly increased the permeability of SB to 200 mD at 5 MPa having a negligible effect on EB.

These results clearly demonstrate that lava-flow basalt from Etna contains a much higher level of crack damage than the columnar basalt from Iceland that is formed in an intrusive environment. Our results can explain the low seismic velocities (approximately 3–4 km/s) inferred for basaltic volcanic edifices, which are essentially formed from piles of lava flows, and the higher values (approximately 5–6 km/s) observed for intrusive cooled magma bodies, such as dykes emplaced in the volcanic edifice [9,10,20,21].

5. Conclusions

We have reported measurements of seismic velocities and fluid permeability on lava flow basalts from Etna

(Italy) and columnar basalts from Iceland at effective pressures from 5–80 MPa. Selected samples were thermally stressed at temperatures up to 900 °C to induce thermal crack damage.

The results demonstrate that the microstructure of erupted lava flows exhibit significantly different physical properties in comparison with columnar basalts formed in an intrusive environment. In detail the main implications are that:

(a) At low effective pressure, P-wave velocity for the columnar Icelandic basalt was 5.4 km/s, while for the Etnean lava flow basalt it was only 3–3.5 km/s. On increasing the pressure to 80 MPa, velocities of Etnean basalt increased by 45–60%, whereas those of Icelandic basalt changed by only 4–5%.

(b) The velocity of samples of SB thermally stressed to 900 °C fell by about 2.0 km/s, whereas the decrease for thermally stressed samples of EB was negligible:

(c) Permeability of EB fell from about $7 \times 10^{-16} \text{ m}^2$ to about $1 \times 10^{-16} \text{ m}^2$ over the pressure range considered, while that for SB varied little from its initial low value of $9 \times 10^{-21} \text{ m}^2$. Again, thermal stressing significantly increased the permeability of SB ($2 \times 10^{-16} \text{ m}^2$), whilst having a negligible effect on the EB.

(d) The main implication is that Etna basalts contain much higher levels of pre-existing crack damage than the Icelandic material. This results in EB having much lower seismic velocities than is generally assumed. This is consistent with the low seismic velocities (3–4 km/s) measured for basaltic volcanic edifices.

These results clearly demonstrate the importance of understanding the details of specific rock physical properties, and how they change in response to pressure and temperature, in interpreting models derived from the results of field-scale monitoring of active volcanoes.

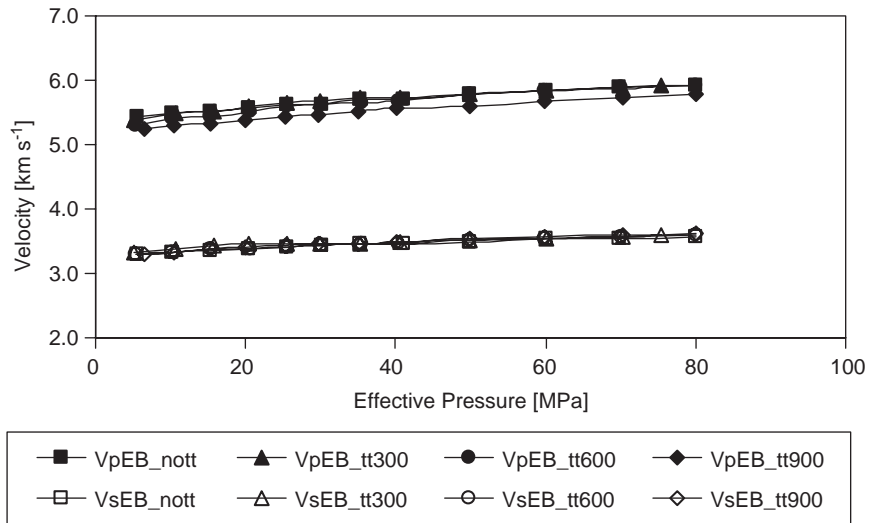


Fig. 11. Averaged P- and S wave velocities vs. effective pressure for EB wet samples.

Table 5
SB wet measurements vs. effective pressure

P_{eff} [Mpa]	5	10	15	20	25	30	35	40	50	60	70	80
SB_01												
V_p (km/s)	5.16	5.22	5.28	5.36	5.40	5.44	5.48	5.56	5.64	5.72	5.76	5.80
V_s (km/s)	3.22	3.26	3.30	3.36	3.38	3.42	3.44	3.46	3.52	3.54	3.60	3.62

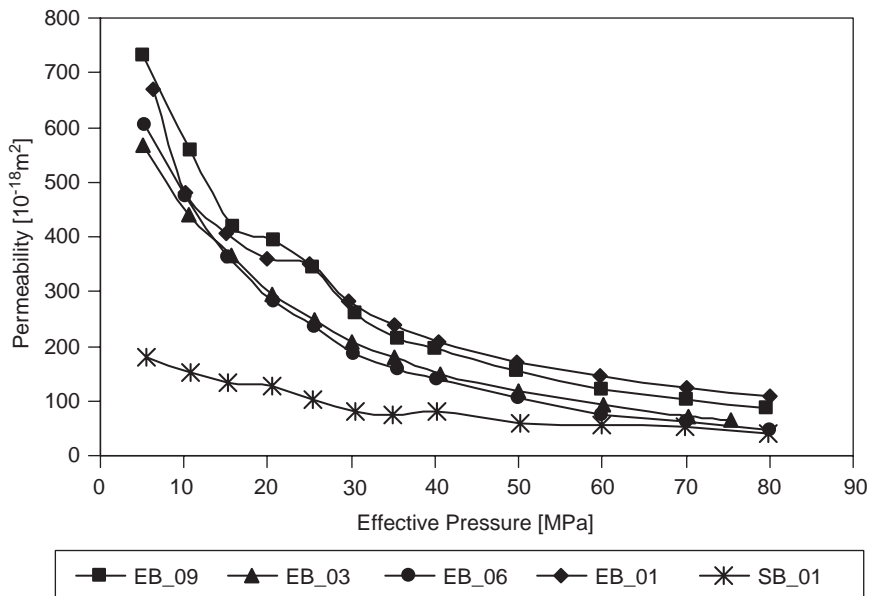


Fig. 12. Permeability vs. effective pressure for EB and SB thermally treated samples.

Acknowledgements

This work has been supported by EU contract EVG1-CT-2001-00047 and by The British Council exchange, which allowed S.V. and C.T. to work in the Department of Earth Sciences, University College London, under its Anglo-Italian scientific exchange programme.

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