Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol. 3, No.7, 2013
www.iiste.org

Some Physical Properties of Suevites from the Bosumtwi Impact Crater, Ghana

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Abstract
Suevite is a polymict breccia of clastic material derived predominantly from the crystalline basement. It is an impact-derived rock usually found at meteorite impact crater sites. In Ghana, suevites have been found at two locations at the Bosumtwi meteorite impact crater. The suevites are located in the Northern and Southern parts outside the crater rim. Due to the presence of different rock clasts of various sizes, the suevite exhibits physical properties that are quite different from those of other rocks such as granites, gneisses, etc. Suevites found in the North and South locations have some characteristic differences. In this paper, we report on the anisotropic behaviour of the compressional wave velocity Vp with pressure and azimuth for suevite samples collected from the North and South locations. The effect of pressure on Vp for the sample from the South is more pronounced than that from the North because of the high porosity of the sample at the South location. Also, the seismic velocity anisotropy is more pronounced in the samples from the South probably due to the distribution of rock inclusions in the matrix. Vp-minimum directions determined for some samples indicate that the Vp-minimum axes seemed to point toward the center of the crater. This supports the reasoning that after the impact, the ejected material on the ground might have assumed a preferred orientation with respect to the center of the crater. It was also found that suevite samples require higher saturation pressures (650 MPa and above) than solid rocks such as amphibolite which reaches velocity saturation at 100 MPa.
Key words: suevites, impact crater, compressional wave velocity, anisotropy, velocity saturation

1. Introduction

1.1. Location of the Bosumtwi Crater

The Bosumtwi meteorite impact crater in Ghana is located about 32 km southeast of Kumasi, the capital town of the Ashanti Region (Fig. 1a). The crater, which is about 1.07 Ma old (Koeberl et al., 1997) has a rim-to-rim diameter of 10.5 km and was excavated in 2 Ga-old metamorphosed and crystalline rocks of the Birimian system (Junner, 1937, Leube et al., 1990, Koeberl et al., 1997). The Bosumtwi crater is associated with the Ivory Coast tektite strewn field (Koeberl et al., 1997) as shown on Fig. 1a.

1.2. The Bosumtwi Suevite

The impact formations at the Bosumtwi crater site are made up of breccias including suevites. The suevites (labelled **S** on Fig. 1b) are the most interesting deposits of the Bosumtwi crater in respect of the impact process. They are typical impact breccias, some of which have been thrown out from the crater during the explosion and deposited outside the crater rim. They are normally referred to as "fallout" suevites and are found mainly in the northern and southwesten parts of the crater (Fig. 1b). The suevites were first described as volcanic breccia because of their resemblance with pumiceous tuff (Junner, 1937, Jones et al., 1981). Consequently, some earlier researchers misinterpreted the origin of the crater to be due to volcanic action. Stoeffler and Grieve (1994) defined the suevite as polymict impact breccia including cogenetic impact melt particles, which are in a glassy or recrystallized state and occur in clastic matrix containing lithic and mineral clasts of various stages of shock metamorphism.

The Bosumtwi suevite (Fig. 2) is a glass-bearing breccia similar to the suevite found at the Ries crater in Germany (Jones et al., 1981). It contains melt inclusions and rock fragments (grewacke, phyllite, shale, granite) up to about 40 cm in size, with greywacke dominating. Most of the rock fragments are subangular in shape and less than 20 cm long and are arranged in a disordered fashion. The locations of these "fallout" suevites have come to be popularly known as the North and South locations. The suevites in the North are white grey whilst those in the South are dark grey.

This paper reports on seismic velocity measurements, which have been carried out for samples of suevite collected from both the Northern and Southern parts of the crater. A knowledge of the seismic velocity of suevites is important for the interpretation of the insitu seismic measurements. Compressional or P-wave velocities, Vp, have therefore been measured by ultrasonic methods as a funtion of azimuth and confining pressure in a special apparatus developed in the Institute for Meteorology and Geophysics of the University of Frankfurt am Main, Germany. This paper reports on experimental investigations carried out on the behaviour of the compressional wave velocity Vp of the Bosumtwi suevite samples under confining pressures and with azimuth to determine the velocity anisotropy. The orientation of the Vp-maximum and Vp-minimum directions in the suevite samples were determined to see if there is any reason to suspect that the suevites would have assumed some preferred orientation with respect to the center of the crater after the impact. Also, the behaviour of the compressional wave velocities of the suevites with pressure was studied to find out if these rocks reach a velocity saturation as found in other crystalline rocks which reach velocity saturation at about 100 MPa (Zang et al., 1996).

1.3. The Geology of the Bosumtwi Crater Area

The Bosumtwi impact event occurred about 1 million years ago in a target that consisted of Precambrian crystalline rocks, the 2.1-2.2 Ga metasedimentary rocks in greenschist facies of the Lower Birimian System of phyllites, graywackes, quarzites, sandstones, shale, micaschist, as well as granites as indicated in the geological map of Fig. 1b (Jones et al., 1981; Wright et al., 1985; Leube et al., 1990; Hirdes et al., 1996; Reimold et. al., 1998). Upper Birimian metamorphosed basalts and pyroclastic rocks (metavolcanics) occur in the Obuom Range, south-east of the crater. Precambrian Tarkwaian metasedimentary rocks occur to the east and south-east of the crater as well (Moon and Mason, 1967; Woodfield, 1966; Jones et al., 1981).

The regional geology is characterized by northeast-southwest trends with steep dips either to the northwest or southeast. However, variations in this trend, due to folding, have been observed (Reimold et al., 1998). Lithology at and around the Bosumtwi crater is dominated by metagraywackes and metasandstones, but some shale and mica schist are found, especially in the north-eastern and southern rim sectors (Reimold et al., 1997; Reimold et al., 1998). A variety of granitoid intrusions (mainly biotite or amphibole granites) have been mapped by Junner (1937) and Moon and Mason (1967). Small granite intrusions, probably connected with the Kumasi granite, crop out around the north-east, west, and south sides of the lake, the largest at Pepiakese on the north-east side of the crater (Jones et al., 1981). In addition, numerous, but generally less than 1-m-wide, dikes of biotite granitoid at many basement exposures in the crater rim have been observed. The overall granitoid component in the region is estimated at about 2 percent (Reimold et al., 1998).

Recent rock formations include the Bosumtwi lake beds, as well as soils and breccias associated with the formation of the crater (Junner, 1937; Kolbe et al., 1967; Woodfield, 1966; Moon and Mason, 1967; Jones et al., 1981; Koeberl et al., 1997, and Reimold et al., 1998).

2. Materials and Methods

2.1. Preparation of the Rock Samples

Several oriented rock samples were taken from the suevite outcrops from the North and South locations at the Bosumtwi crater (Fig. 1b). For the seismic velocity measurements, cylindrical cores of 30 mm diameter and 30 mm length were drilled out of the rock samples. The axes of the cylindrical samples were vertical and the north direction was marked on the cores. The cores were coated with three layers of oil resistant varnish to protect them from intrusion of pressure-oil. In some cases, the sealing failed due to irregularities of the rock and the softness of the cementation agent, and as a result, oil penetrated the sample. Those samples were however excluded from the measurements.

2.2. Experimental Procedure

The core was mounted in the measuring head. Two pairs of piezoelectric transducers were used as transmitter and receiver, respectively, for axial (vertical) and radial (horizontal) ultrasound transmission. The core can be rotated in the pressure vessel in steps of 10° (pressure steps) to measure the anisotropy. Pressures up to 400 MPa can be applied to measure the pressure dependence of the compressional wave velocity Vp. The travel times were measured automatically and plotted in different ways.

3. Results and Discussion

3.1. Results of Compressional Wave Velocity Vp of the Bosumtwi Suevite – Anisotropy and Pressure Dependence

The seismic velocity in radial direction of the core (horizontal-Vp) has been determined for the suevite samples from the two different locations. The results of the anisotropy and pressure dependence of the compressional wave velocity of the Bosumtwi suevite for sample 3a1 (from North location) and sample 12 (from South location) are shown in Fig. 3 and Fig. 4 respectively.

In Fig. 3a, Vp-horizontal (seismic velocity in radial direction in the core) has been plotted as a function of azimuth at different confining pressures of 5, 20, 80, 160 and 320 MPa. The increase of Vp with pressure is remarkable and is certainly due to the gradual closure of grain contacts and pores, and not to the intrinsic pressure sensitivity of the minerals of the rock. The suevite sample 3a1 from the North location can be described as exhibiting low anisotropy.

In general, Vp increases gradually with pressure for the samples from the North (Fig. 3b). This trend differs from that observed for samples from the South (Fig. 4b), where an initial fast increase of seismic velocity with pressure is observed for pressures below 40 MPa.

The behaviour of the compressional wave velocity Vp with confining pressure and azimuth for suevite sample 12 from the South location is shown in Fig. 4a.

From Fig. 4a, it can be seen that the compressional wave velocity Vp increases with increase in pressure. However, the suevite sample 12 is found to display significant anisotropic behaviour probably due to the distribution of rock inclusions in the matrix.

In general, the initial fast increase of Vp with pressure below 40 MPa (Fig. 4b) is due to the gradual closure of pores and grain contacts. This situation is more significant for the samples from the South location, which are more porous than those from the North, which do not display a similar phenomenon below 40 MPa (Fig. 3b). However, the gradual increase of the velocity with pressure above 40 MPa is explained as due to the dependence of the bulk modulus on pressure.

3.2. Significance of Vp-Minimum

The anisotropy measurements were made to find out whether there are any consistencies in the orientation of the maximum Vp or minimum Vp in such samples, which have considerable anisotropy. One could have suspected perhaps that after the impact, the ejected material on the ground might have assumed a preferred orientation with respect to the center of the crater. A compilation of results with the geographical position of the outcrops and the direction of Vp-min is ahown in Fig. 5.

Out of a total of 6 samples for which Vp-min directions were determined, it was found that 5 samples seemed to have some indications that the Vp–min axes pointed about toward the center of the crater. This is an interesting result. However, it is not considered as a conclusive proof yet because the number of samples which was used in the study was quite small. A confirmation of this result would need further investigation.

3.3. Dependence of Vp with Pressure for Suevite Samples from North and South

The compressional wave velocities Vp as a function of pressure for three suevite samples from the North (samples 3a1, 3a and 3b2) and South (samples 12, 6b2 and 10) have been measured and plotted as shown in Fig. 6. The effect of pressure on Vp for suevite is quite pronounced as can be seen on Fig. 6. It is possible to differenciate between suevite samples from the North (lower curve) and South (upper curve) on Fig. 6. Those from the North are usually more compact and lighter in colour than the sometimes very dark, porous and more weathered rocks from the South. The pressure dependence of Vp is stronger, the higher the porosity and the elastic compressibility of the structure of the matrix of the suevite. This is clearly exhibited by the three samples from the South location as indicated in Fig. 6.

In comparison with other solidified rocks, there is no occurrence of velocity saturation up to 300 MPa. For example, the behaviour of the compressional wave velocity with pressure for an amphibolite sample from the German deep drill hole shown in Fig. 7 indicates that saturation is reached at a pressure of about 100 MPa (Zang et al., 1996).

Very similar results have also been obtained from many rocks like crystalline gneiss (Zang et al. 1996). In the case of suevite, the saturation-pressure (or closing-pressure) p must be considerably higher. If one assumes that the relative closure of joints and pores (K) increases proportionally to the increase dp in pressure (Stiller et al. 1979), and the P–wave velocity V(p) at pressure p and that at atmospheric pressure V(0) are known, one can deduce p* and K(0) by the following consideration:

$dK/K \sim dp$

$K(p) = K(0) \exp(-p/p^*)$

if V_m = velocity of the compact solid matrix, then

$V(p) = V_m (1 - K(p)) = V_m (1 - K(0) \exp(-p/p^*))$

$V(0) = V_m (1 - K(0))$

Elimination of the unknown V_m leads to:

$$V(p) / V(0) = [1 – K(0) \exp(-p/p^*)] / [(1 - K(0)]$$

The two unknown parameters K(0) and p have to be determined simultaneously from the shape of the curves of the observations K(p) = f(p).

A good fit to the observed curves was obtained with the following results:

V(0) = 2500 m/s, K(0) = 0.5, p* = 650 MPa

for the samples from the South location and

V(0) = 2450 m/s, K(0) = 0.48, p* = 850 MPa

for the samples from the North location.

p = p* means that 63% of the pores and joints are closed. The high values of K(0) and of p* are quite unusual for solid rocks and apparently typical features of the Bosumtwi suevites.

4. Conclusion

Suevite outcrops from the North and South locations around the Bosumtwi impact crater have characteristic differences. Suevites in the North are more compact and light grey in colour whilst those in the South are more porous and darker in colour. Compressional wave velocities show more significant anisotropies in the suevites from the South than those from the North. Seismic velocities tend to increase faster with pressure initially for pressures below 40 MPa for the samples from the South whilst such a phenomenon is not observed for samples from the North. Vp-minimum directions determined for 6 samples indicate that the Vp-minimum axes seemed to point toward the center of the crater. This supports the reasoning that after the impact, the ejected material on the ground might have assumed a preferred orientation with respect to the center of the crater. The variation of P-wave velocity with pressure for the suevite samples does not show velocity saturation up to 300 MPa as observed for solid rocks such as amphibolite where velocity saturation is reached at a pressure of 100 MPa. It was found out that the suevites require much higher saturation pressures of 650 MPa for samples from the South and 850 MPa for samples from the North. This phenomenon is a typical feature of the Bosumtwi suevites.

Acknowledgement
The authors wish to thank the technicians of the geophysics laboratory of the Institute of Meteorology and Geophysics of the University of Frankfurt am Main, Germany for their support in the work. We also wish to express our sincere gratitude to the German Research Foundation (DFG) for the financial support they provided for the research work.

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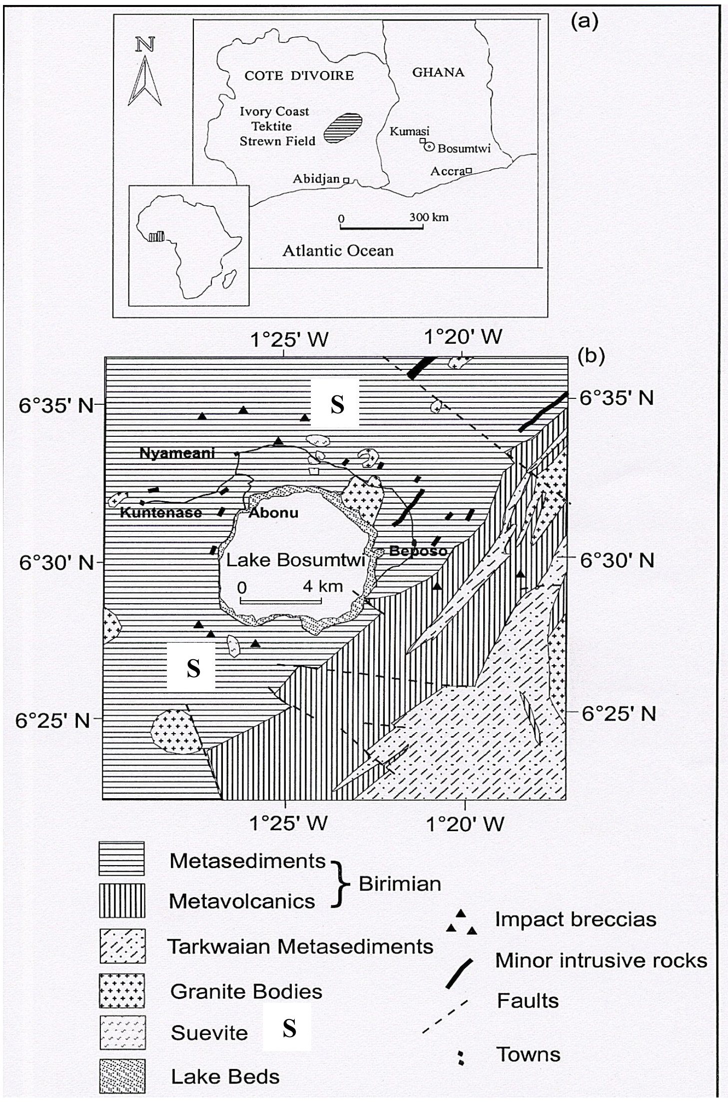

Fig. 1. a) The geographical location of the Bosumtwi crater, Ghana, in relation to the Ivory Coast tektite strewn field (after Koeberl et al., 1998). b) A geological map of the area around Lake Bosumtwi, showing the provenance of different target rocks (after Koeberl and Reimold, 2005). Suevite sites are labelled **S** on the map.

Fig. 2. Cross section of a typical suevite from the North of the Bosumtwi impact crater.

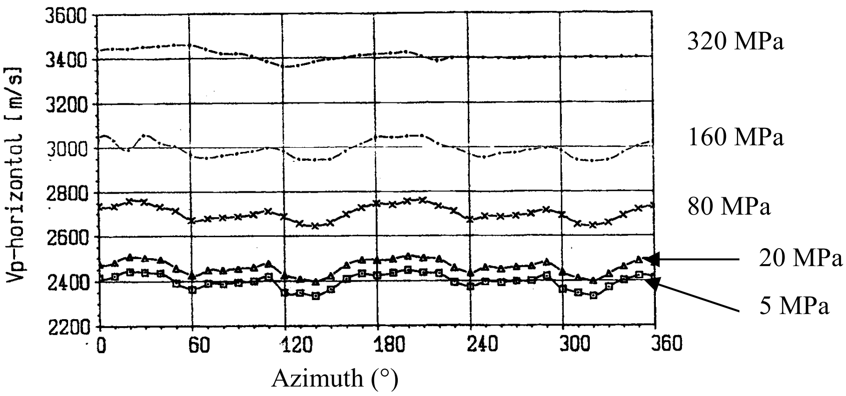

Fig. 3a. Variation of horizontal Vp with azimuth at constant confining pressures of 5, 20, 80, 160 and 320 MPa for sample 3a1 from North location; the different confining pressures are indicated on the left side of the figure.

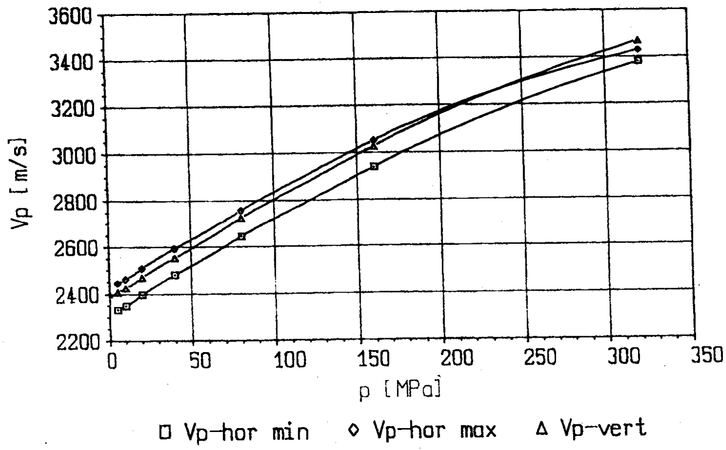

Fig. 3b. Variation of minimum and maximum horizontal Vp (Vp-hor min and Vp-hor max), and vertical Vp (Vp-vert) as a function of pressure for suevite sample 3a1 from North location.

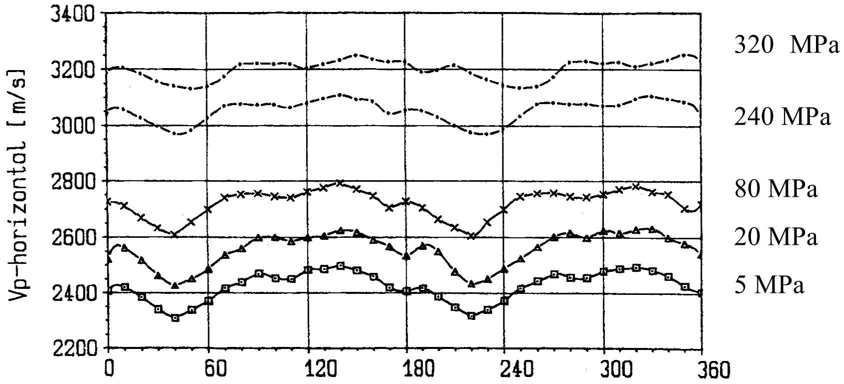

Fig. 4a. Variation of horizontal Vp with azimuth at constant confining pressures of 5, 20, 80, 240 and 320 MPa for suevite sample 12 from South location; the different confining pressures are indicated on the left side of the figure.

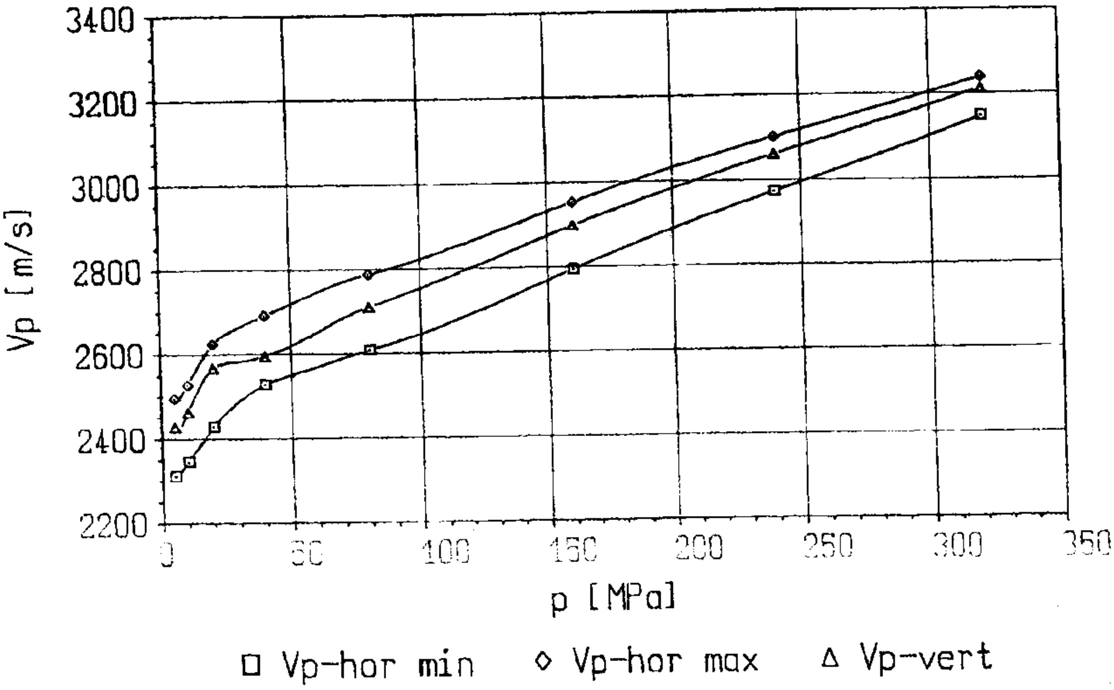

Fig. 4b. Variation of minimum and maximum horizontal Vp (Vp-hor min and Vp-hor max), and vertical Vp (Vp-vert) as a function of pressure for suevite sample 12 from South location.

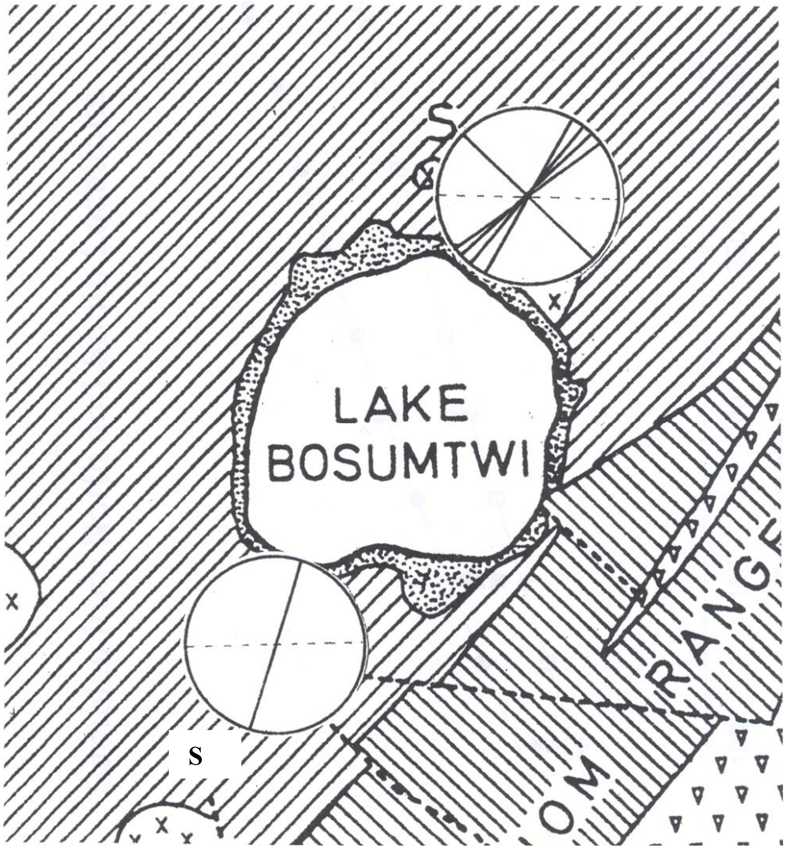

Fig. 5. Compilation of Vp-minimum directions for suevite samples from the North and South locations which show significant anisotropy. S is the location of the suevite deposit.

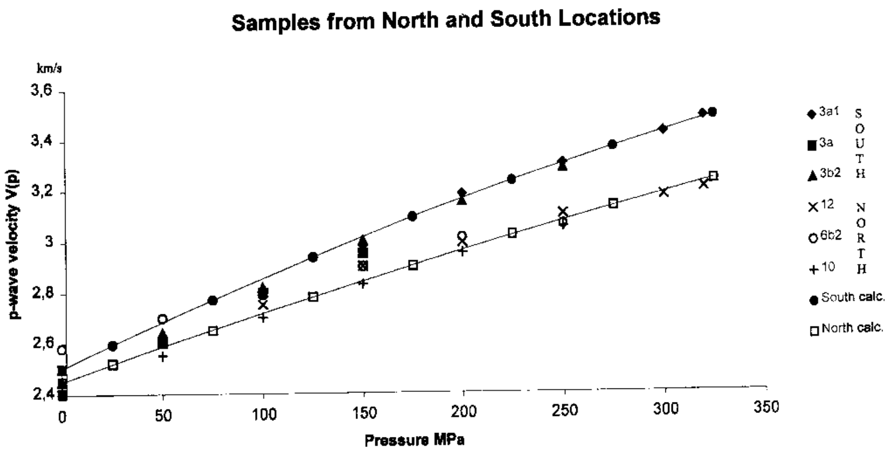

Fig. 6. Variation of P-wave velocity with pressure for samples from the North and South locations; upper curve refers to samples from the South and lower curve refers to those from the North.

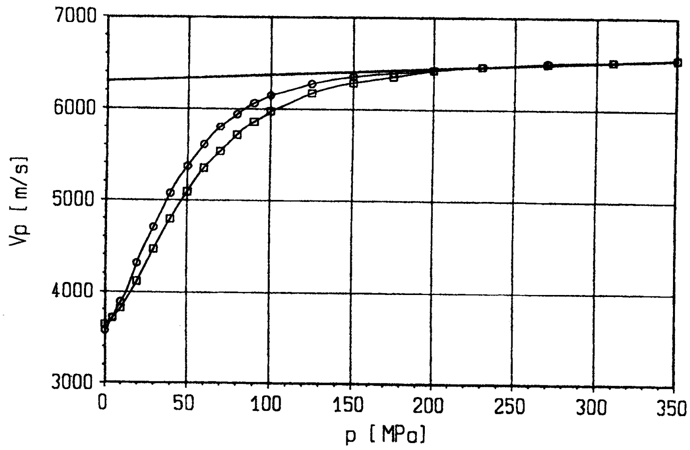

Fig. 7. Experimental results of Vp as a function of pressure for an amphibolite solid rock from the German deep drill hole (Zang et al., 1996); there is velocity saturation around 300 MPa.