

Impactites as a random medium—Using variations in physical properties to assess heterogeneity within the Bosumtwi meteorite impact crater

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(Received 03 August 2006; revision accepted 12 January 2007)

Abstract—The recent drilling of the Bosumtwi impact structure, Ghana, has provided a unique opportunity to study the petrophysical properties of a young, well-preserved impact crater. The damage induced by impact results in extensive fracturing and mixing of target materials. We discuss here a means of using sonic velocity and density logs from two boreholes through the Bosumtwi crater fill and basement to estimate the degree of heterogeneity and fracturing within the impacted target, in order to understand the discrepancy between the large impedances derived from the log data and the nonreflective zone of impactites observed in seismic sections. Based on an analysis of the stochastic fluctuations in the log data, the Bosumtwi impactites are characterized by vertical scale lengths of 2–3 m. From the resolution of the seismic data over the crater, horizontal scale lengths are estimated at <12 m. The impactites therefore fall within the quasi-homogeneous scattering regime, i.e., seismic energy will propagate through the medium with little disruption. Scale lengths as small as these are observed in the fractured basement rocks of impact structures, whereas non-impact related crystalline environments are characterized by scale lengths an order of magnitude larger. Assuming that the high-frequency fluctuations observed in the log data are more sensitive to fracture distribution than petrology, this suggests that the small scale lengths observed within impact structures are characteristic of impact-induced damage, and could be used to estimate the extent of fracturing undergone by the rocks at any depth below an impact structure.

INTRODUCTION

Petrophysical logs provide essential ground-truthing for the verification and interpretation of geophysical data. For the study of meteorite impact structures, these data provide a way of comparing the physical characteristics of structures in different parts of the world, characterized by different morphologies and target rock types. In this paper we present the results of an analysis of the newly acquired petrophysical log data from the Bosumtwi impact structure in Ghana, drilled in 2004 by the International Continental Scientific Drilling Program (ICDP). The Bosumtwi structure (10.5 km in diameter) is one of the youngest impact structures in the world, with an age of 1.07 Myr (e.g., Koeberl et al. 1997; Koeberl and Reimold 2005; Koeberl et al. 2007). Given that the crater is almost entirely filled by Lake Bosumtwi (8 km in diameter), it is also one of the best-preserved impact structures of its type due to the thick layer of overlying lacustrine sediments. Its relatively small size and emplacement in crystalline target rocks make it of particular interest for the study of fracturing and impact-induced porosity.

The target of the Bosumtwi impact was the Proterozoic metasedimentary and metavolcanic rocks of the Birimian Supergroup (Jones et al. 1981) that are locally intruded by granitoid bodies (Koeberl and Reimold 2005). Samples of various target rocks have an average density of 2680 kg/m³ (Plado et al. 2000), and wide-angle seismic data indicate velocities of >5000 m/s (Scholz et al. 2002). Until recently, only two samples of impactite (suevite ejecta) collected from outside the structure (Plado et al. 2000) had been measured to give an average dry density of 2370 kg/m³ and porosity of 26%.

In 1999, 2000, and 2004, seismic refraction and reflection data were collected over the Bosumtwi crater to delineate its subsurface structure (Karp et al. 2002; Scholz et al. 2002; Scholz et al. 2007). The interpretation of the Bosumtwi seismic data (Fig. 1) (Scholz et al. 2002) and velocity model (Karp et al. 2002) shows a thick package of post-impact lacustrine sediment as well as the crater structure below, including a well-defined central uplift, and a breccia/melt layer underlain by uplifted basement at a depth of approximately 450 m. The lack of reflectivity in the

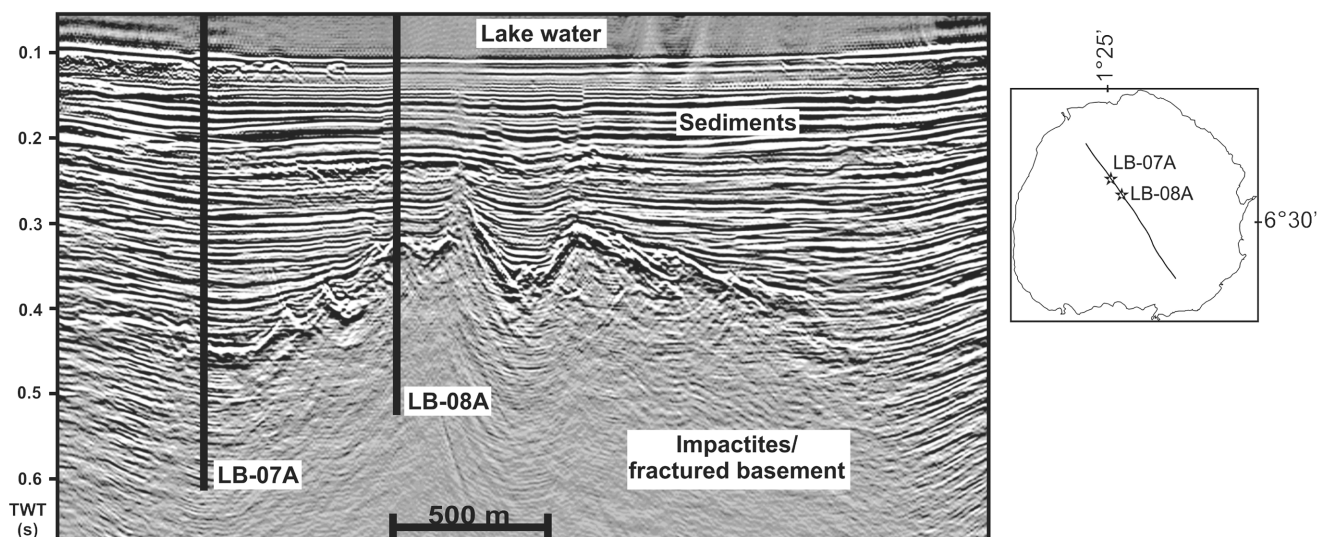


Fig. 1. Depth-migrated seismic section through the Bosumtwi impact structure (Karp et al. 2002). The data have a dominant frequency of 100 Hz and bandwidth of 50–150 Hz. The total depth of the section is approximately 450 m. Hard-rock drill holes LB-07A and LB-08A are indicated by black lines. Locations of the boreholes and the seismic line within the crater are indicated in the inset map. The outside edges of the profile are obscured by strong reflections from the lake bottom and sediments, as well as multiple reflections (for a complete description of the seismic data and interpretation, see Scholz et al. 2007).

breccias is evident, however, data from a wide-angle refraction experiment (Karp et al. 2002) show that this is not due to a wave propagation problem. The data exhibit a characteristic feature observed over many impact structures around the world: seismically nonreflective, or transparent, impactites. This effect is often observable, for example, through the disruption of pre-impact features such as over the Ries crater in Germany (Angenheister and Pohl 1969), bounded by impact-related reflectors such as the thrust boundary features in the Chicxulub impact structure (Morgan et al. 2000), or through the differences in reflective character between post-impact sediments and fractured basement rocks such as those at Bosumtwi. The cause of this feature lies in the heterogeneous nature of the medium, something that can be quantified through dimensional parameters that describe the dominant scale of the variations in physical properties.

To completely describe and quantify the degree of heterogeneity in a random medium such as the Bosumtwi impactites and fractured basement rocks, we need to assess the statistical distribution of its physical properties, namely densities (ρ) and seismic velocities (V_p). This can be done with borehole petrophysical logs and seismic data, which provide a measure of this heterogeneity both in the vertical and lateral directions. We describe here the recently acquired V_p and density logs from two boreholes in the Bosumtwi structure, and use these data to characterize the impactite/fractured basement interval and relate its physical properties to those predicted by seismic data. This will, in addition, allow us to constrain the level of damage induced in target rocks due to the impact event.

PETROPHYSICAL DATA

To better understand the effect of impact on crystalline target rocks, two hard-rock boreholes were drilled into the flank of the central uplift (LB-08A) and in the surrounding trough (LB-07A) of the Bosumtwi impact structure by the ICDP (Fig. 1). Core samples were recovered from both boreholes, including polymict lithic impact breccias and suevites (Koeberl et al. 2007). For simplicity, we refer to these lithologies, including fractured basement rocks, as the “impact unit” of the Bosumtwi structure. P-wave velocities sampled at 0.1 m were picked from first arrivals of the sonic borehole measurements (minimum source-receiver spacing of 1 m) from 309–544 m in borehole LB-07A, and from 228–452 m in LB-08A (Fig. 2). Density values were extracted from gamma-gamma measurements on core samples at an irregular sampling rate (Morris et al. 2007).

The two boreholes provided a total of 433 m of core from the Bosumtwi impact unit, and 460 m of petrophysical log data. Core samples are highly fractured and weakly compacted, and show variable porosities between 1 and 40% (Brown et al. 2006; Schleifer et al. 2006). The logs of borehole LB-08A show high spatial frequency fluctuations in the data below ~380 m, where large sections of graywacke dominate (Fig. 2). The impact unit from both boreholes has much lower seismic velocities and densities than the pre-impact target rocks; however, in general, average velocities and densities are higher in LB-08A than in LB-07A (3044 m/s and 2564 kg/m³ in LB-08A versus 2313 m/s and 2333 kg/m³ in LB-07A). The lower physical property values in LB-07A are likely a result of the greater abundance of high

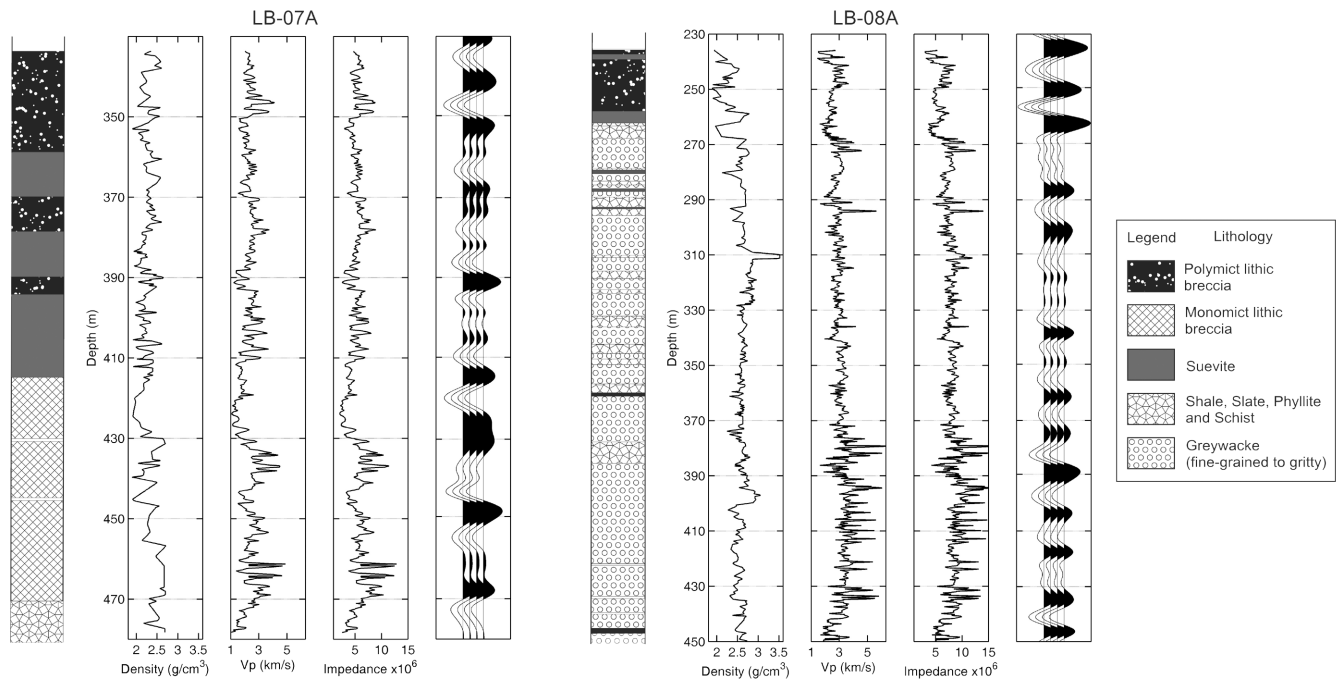


Fig. 2. Lithology, density, velocity, impedance, and synthetic seismograms for boreholes LB-07A (left) and LB-08A (right) in Bosumtwi. Lithological plots adapted from Coney et al. (2007) and Ferrière et al. (2007).

porosity breccias and suevite in the impactite material within the trough. Given that central uplifts are thought to be created through movement of intact blocks of fractured target rocks (see, for example, Melosh 1989) during the formation of the crater, we also expect higher velocities and densities in the parautochthonous rocks of the central uplift than in the allochthonous impactite material from the trough.

Estimating Damage Depth

During impact, target rocks are subjected to high pressures (see, for example, Artemieva et al. 2004 or Ugalde et al. 2005) resulting in fracturing, stress-induced shearing, and mixing of target materials. Polanskey and Ahrens (1990) conducted laboratory experiments to map the distribution of impact-related damage in samples of gabbroic rocks in the less than 10 GPa pressure range. The experiments revealed two main zones of fractures beneath a simple crater: 1) a hemispherical zone beneath the crater consisting of shear, radial, and concentric fractures, where rocks immediately below the crater are most heavily crushed; and 2) a set of thin elongated fractures originating from the crater wall and extending down below the crater and out beyond the zone of high fracture density (zone 1). This latter zone defines the upper limit of damage for an impact crater and is approximated by a hyperbolic curve originating from the surface point of impact and increasing in depth as radial distance increases. The two Bosumtwi boreholes, near the center of the crater structure, would be located within zone 1.

Xia and Ahrens (2001) defined the lowermost extent of the damage zone in terms of the attenuation of a propagating shock wave and the critical pressure required to fracture target rocks. For a critical pressure (P_c) of 0.1 GPa, peak shock pressure (P_0) of 30–40 GPa, and impactor radius (r) of 375–500 m (Artemieva et al. 2004), we can extrapolate the results of Xia and Ahrens (2001) to estimate the hemispherical limit of impact damage below the Bosumtwi crater as $L_D = r(P_0/P_c)^{1/n}$, where n is the attenuation index of the material ($n = 2$ for large-scale impacts [Ahrens and O'Keefe 1987]). In the vicinity of the two boreholes we therefore estimate a total depth of fracturing of between 5 and 10 km below the point of impact.

Numerical models of the impact show an estimated limit of impact damage at up to 8 km depth and up to 5 km outside the 10 km diameter crater rim (Artemieva et al. 2004). Recent modeling of the gravity anomaly over the crater, constrained by the newly acquired density logs, suggests a maximum depth of the impact unit (including fractured basement rocks) at 500 m below surface, underlain by unfractured basement below 500 m (Ugalde et al. 2007). This is in apparent contradiction with estimates based on laboratory work and numerical modeling. However, as the gravity signature of the crater structure is dependent on density contrasts, the model may not have the necessary resolution to outline the absolute limit of fracturing.

Scaling the results of laboratory experiments to those expected for large meteorite impacts can only reveal rough estimates of impact-induced damage zones. Numerical

simulations, on the other hand, can provide a view of pressure and temperature distribution as well as crater morphology during impact; however, they cannot predict fracture patterns. Seismic images and petrophysical logs thus provide a means of filling the gap in our description of impact structures and their associated fracturing and porosity distributions. Although the limited depth extent of the logs and seismic sections from Bosumtwi cannot confirm the outer limit of the damage zone, they can nevertheless provide a first-order quantification of the amount of damage beneath the crater in terms of heterogeneity of the medium.

Autocovariance Analysis

The fluctuations observed in the Bosumtwi log data (Fig. 2) are indicative of a medium with a heterogeneous distribution of physical properties. An autocovariance analysis can be used to gain a more quantitative estimate of the degree of heterogeneity along the two Bosumtwi boreholes. The method was first described by Goff and Jordan (1988) and is applied here to fit the petrophysical log data and to estimate the dominant scale of heterogeneity in the Bosumtwi impact unit. This parameter will dictate how the unit scatters or reflects seismic energy, allowing us to better understand the seismic data over the crater structure, in addition to providing a means of comparison with observations at various other impact structures.

Petrophysical log data are considered the sum of a deterministic (p_0) and a stochastic (Δp) component: $P(z) = p_0(z) + \Delta p(z)$. The deterministic trend describes the large-scale variation in the properties and is typically approximated as a low-order polynomial best-fit through the data series (Bendat and Piersol 1986). This is subtracted from the series in order to isolate the small-scale fluctuations in the physical log data, which describe the inherent heterogeneity of the random medium. If the probability distribution of the remaining stochastic series is Gaussian, it can be fully characterized by its first and second statistical moments (mean and autocovariance) (Holliger et al. 1996). Estimating the scale of heterogeneity within the medium can therefore be accomplished by fitting the autocovariance C of the stochastic component of the log data to a von Karman function, governed by two main parameters: the Hurst number ν and scale length a_z :

$$C\left(\frac{z}{a_z}\right) = \frac{\sigma^2 \left(\frac{z}{a_z}\right)^\nu K_\nu\left(\frac{z}{a_z}\right)}{2^{\nu-1} \Gamma(\nu)} \quad (1)$$

where σ^2 is the variance of the property fluctuations, K_ν the modified Bessel function of the second kind of order ν , $\Gamma(\nu)$ a gamma function of order ν , and z indicates the vertical direction (positive downward). The scale parameter a_z defines the dominant scale of physical property variations in

the vertical direction, or the scale of heterogeneity within the area surrounding the boreholes.

RESULTS

The autocovariance, as a function of lag (z/a_z), of each of the Bosumtwi velocity and density logs was calculated, and the best-fit von Karman function was determined by nonlinear least-squares analysis. Figure 3 shows the results of the above analysis, and Table 1 summarizes the von Karman parameters for each borehole. Confidence intervals are 15–20% on scale parameter estimates, and 40–50% for Hurst numbers. Small changes in the Hurst number induce only a slight change in the overall autocovariance function, giving rise to the large range of estimated values.

The autocovariances of Fig. 3 represent the small-scale variations after a deterministic trend was removed from each of the logs. The choice of trend was decided by examining the distribution of the remaining stochastic fluctuations (probability plots inset in Fig. 3). For logs in crystalline environments, a linear trend typically suffices (see Holliger 1996, for example); however, it was necessary to remove a third order polynomial for the density log of LB-07A in order for the resulting stochastic series to have a Gaussian distribution (and hence for the autocovariance analysis to be valid). The effect of removing a larger-order trend, or that of a smooth series obtained by filtering the log, is to decrease the value of the estimated scale parameter (Holliger 1996). By leaving the highest order trends possible in the data, we are considering the larger-scale bulk variations (or lithological trends) as heterogeneity; hence we obtain a larger estimate for the scale length. A linear trend makes sense for the Bosumtwi logs if we assume that the brecciated impactites and fractured basement rocks represent one unit. This assumption does not appear to be valid however for the density variations of LB-07A (the nonlinear deterministic trend links large-scale variations in density to different lithologies, hence the physical properties represent more than one unit; see Fig. 2).

In complex impact structures, the allochthonous material of the trough is expected to be highly variable over short distances, as compared to the slightly more lithologically homogeneous rocks of the central uplift. As anticipated, LB-07A, where low velocity/density breccias dominate, has smaller vertical scale lengths compared to the material in LB-08A, suggesting a medium with a less (if only slightly) continuous distribution of physical properties. The 17 m scale length estimated for the density log of LB-08A is likely a reflection of the lower sampling rate of the data (an average 0.5 m as opposed to the 0.1 m of the sonic tool), making the density log less sensitive to small fluctuations in lithology. We would expect the same effect for LB-07A, however the estimate of a_z is influenced by the removal of the third order deterministic trend, resulting in a smaller scale estimate.

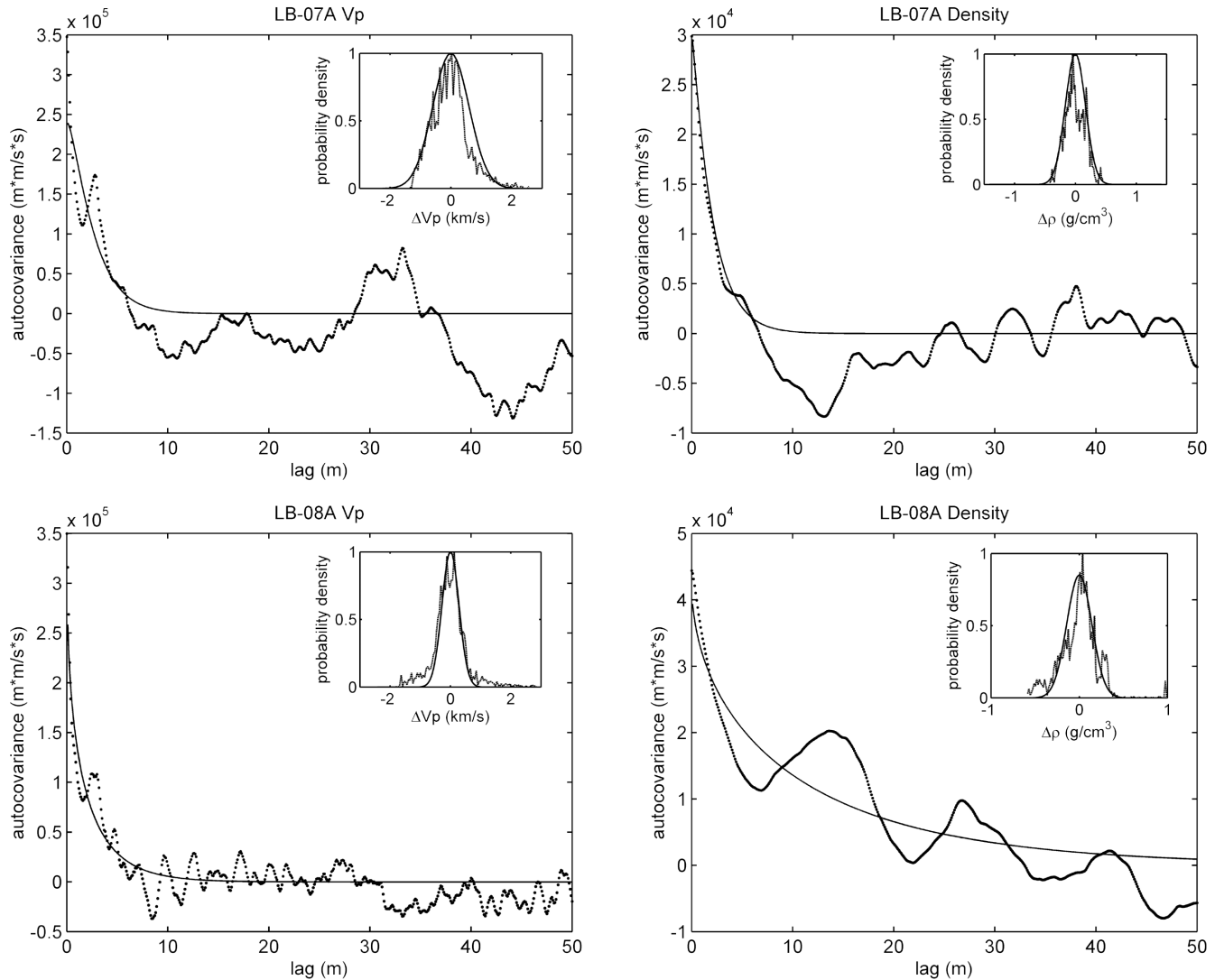


Fig. 3. Autocovariance (dots) and best-fitting von Karman functions (line) for: top row) LB-07A Vp, density; bottom row) LB-08A Vp and density. Inset figures represent the normalized distribution of the stochastic fluctuations for each log (dashed line), with best-fitting Gaussian distribution (solid line).

DISCUSSION

A reduction in both density and seismic velocity is expected within brecciated and fractured impact rocks. The velocity model of the Bosumtwi structure derived by Karp et al. (2002) shows clear evidence of this effect: the average P-wave velocity of Bosumtwi impactites is well defined at ~ 3200 m/s by semblance analysis of multichannel seismic reflection data (interval velocities) and ocean-bottom hydrophone records (Scholz et al. 2002), whereas the Proterozoic target rocks typically have >5000 m/s values. Both the velocity model and log data show a $\sim 40\%$ reduction in velocity between target and impact rocks (in agreement with recent VSP results from LB-08A [Schmitt et al. 2007]). However, the log data indicate a slower increase in velocity with depth compared to the model derived from the seismic data.

Gardner et al. (1974) and Castagna et al. (1993) described empirical power-law and polynomial relationships between Vp and density for specific rock types. The relationship between the two properties in the Bosumtwi logs is shown in Fig. 4a, with the data from LB-08A plotting at higher values than those of LB-07A, as expected. However, even while the assumption that the logs from the impact-related rocks represent one unit is generally valid, the wide spread of the Bosumtwi data suggests a complete mixing of material producing only a minimal Vp- ρ trend at best. The most evident trend appears when the two physical properties are sorted by depth (Fig. 4b): velocity and density increase as depth down the borehole (and pressure) increases, or as porosity decreases. While both density and velocity are highly dependent on porosity, velocities are also sensitive to crack geometry and grain boundary contacts (Mavko et al. 1998).

Table 1. Estimated von Karman parameters (Goff and Jordan 1988) for velocity and density logs in impact structures and crystalline environments.

Logs	Lithology	Velocity			Density			Reference
		σ (m/s)	a_z (m)	ν	σ (kg/m ³)	a_z (m)	ν	
Sudbury (Canada)								
Trill AC	Melt rock of the SIC	452	46	0.02	68	512	0.26	This study
Inco 60064 AC	Melt rock of the SIC	276	64	0.10	n.d.	n.d.	n.d.	This study
Moose AC	Melt rock of the SIC	360	2723	0.01	83	1471	0.22	This study
Trill BC	Gneissic basement	174	1	1.00	n.d.	n.d.	n.d.	This study
Moose BC	Gneissic basement	204	2	0.16	107	2	0.10	This study
WTR-001 BC	Gneissic basement	n.d.	n.d.	n.d.	74	1	1.00	This study
WTR-004 BC	Gneissic basement	n.d.	n.d.	n.d.	65	9	1.00	This study
Bosumtwi (Ghana)								
LB-07A	Impactite and basement rock	491	1.8	1.00	175	1.9	0.58	This study
LB-08A	Impactite and basement rock	611	3.5	0.16	208	17.2	0.23	This study
Siljan (Sweden)								
Stenberg-1	Granitic basement	301	100	0.10	n.d.	n.d.	n.d.	Holliger et al. 1996
Gravberg-1	Granitic basement	370	45	0.18	n.d.	n.d.	n.d.	Frenje and Juhlin 1998
Non-impact media								
Leuggern	Metasediments	317	60	0.14	n.d.	n.d.	n.d.	Holliger 1996
Bottstein	Metasediments	370	80	0.12	n.d.	n.d.	n.d.	Holliger 1996
KTB-1	Paragneisses + metabasites	315	160	0.10	n.d.	n.d.	n.d.	Holliger 1996
KTB-2	Paragneisses + metabasites	358	150	0.13	n.d.	n.d.	n.d.	Holliger 1996
Abitibi-1	Greenstone belt metavolcanics	266	110	0.18	n.d.	n.d.	n.d.	Holliger 1996
Abitibi-2	Greenstone belt metavolcanics	241	60	0.18	n.d.	n.d.	n.d.	Holliger 1996
Cajon Pass	Gneiss + granite	399	140	0.11	n.d.	n.d.	n.d.	Holliger 1996

Abbreviations: σ = standard deviation, a_z = vertical scale length; ν = Hurst number, AC = above melt/footwall contact, BC = below melt/footwall contact, SIC = Sudbury Igneous Complex.

Seismic Scattering

Given the observed poor Vp- ρ relationships, the impact unit in the Bosumtwi structure can be characterized as a random medium influenced by high porosity and fracturing of heterogeneous material. In this type of environment, incident seismic energy is scattered depending on specific parameters that were first described by Wu (1989). Three main scattering regimes are defined based on the wavelength of seismic waves ($\lambda = 1/k$) and the scale of heterogeneity (a) in the medium: the quasi-homogeneous regime ($ka \ll 1$), the large-angle regime ($ka \sim 1$), and the small-angle regime ($ka \gg 1$). When $ka \ll 1$, heterogeneities are too small to be “seen” by the seismic waves, and little to no energy is scattered back to the surface. When heterogeneities are of the same order of magnitude as the seismic wavelength, a large portion of the incident energy is scattered in the backward direction, toward the surface, causing random events in seismograms and low signal to noise ratios. Lastly, in the small-angle regime, a large part of the scattered energy is directed forward, producing travel-time and amplitude fluctuations in the incident wave front.

The small vertical scale lengths estimated from both Bosumtwi logs indicate that the impact-related rocks of the crater fall into the quasi-homogeneous scattering regime. In terms of seismic energy, this type of medium will transmit a propagating wave front with very little

distortion, and almost no energy will be scattered back to surface receivers. On the other hand, impedance contrasts within the Bosumtwi impactite and target rock sequence show fluctuations large enough to cause significant scattering or reflection of seismic energy ($>2.5 \times 10^6$ kg/m²s) (Fig. 2). This discrepancy is resolved in terms of horizontal scale parameters: for a given vertical scale, increasing horizontal scale lengths cause variations in physical properties over a larger distance, and seismic scatterers become seismic reflectors (Fig. 5).

The lack of correlation between impedance contrasts in LB-07A and LB-08A (Fig. 2) allows us to assume that horizontal scale lengths are less than the distance between boreholes, i.e., $a_x < 611$ m. In addition, the lack of bright reflectors in the Bosumtwi seismic data allows us to make further assumptions about the horizontal extent of heterogeneity. With a dominant frequency of 100 Hz, the first Fresnel zone at the base of LB-08A has a width of ~ 200 m in unmigrated data, or a resolution of approximately the dominant wavelength (30 m) in migrated data. Therefore, we can assume $a_x < 30$ m. Finally, given that in the quasi-homogeneous regime $a_x \ll \lambda/2\pi$, the horizontal scale parameter must be less than ~ 5 m around LB-08A and less than 4 m around LB-07A. Given the resolution of the seismic data however, we can only resolve an upper limit for a_x of twice the common midpoint (CMP) spacing, or $a_x < 12$ m.

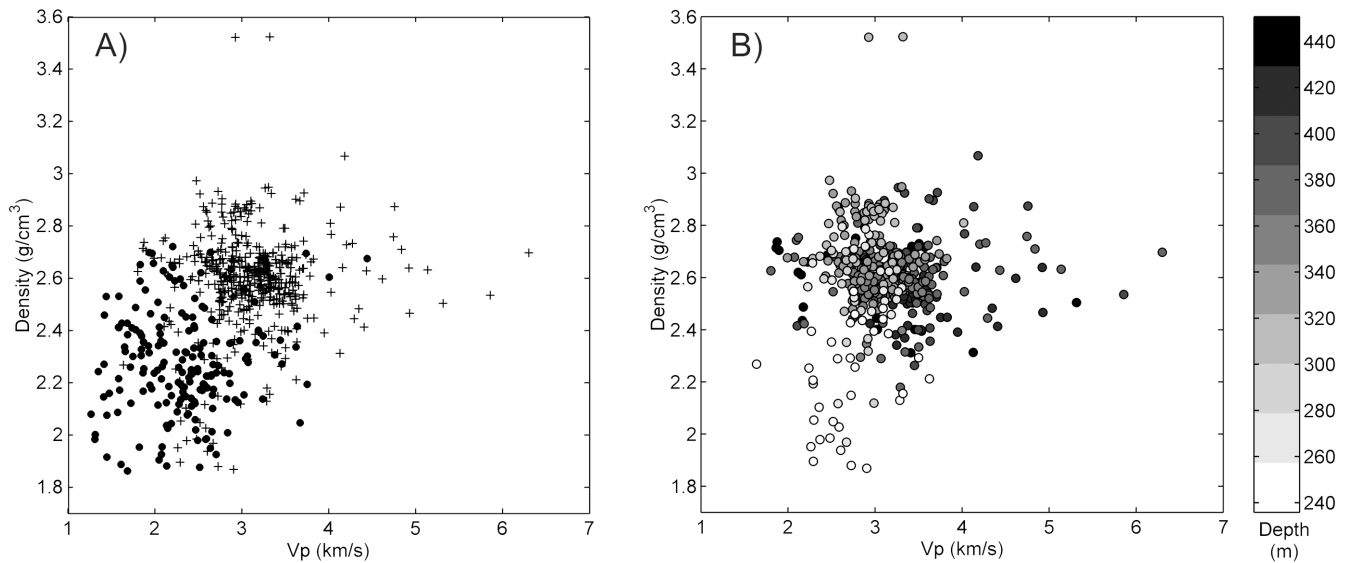


Fig. 4. Density versus Vp plots for Bosumtwi boreholes. a) Circles represent data from LB-07A, + signs represent data from LB-08A. b) Data from LB-08A are shaded to show the dominant trend with depth.

Comparison to Other Scale Estimates

To relate the scale properties of Bosumtwi to other impact structures around the world, a comparison was made to log data from the Sudbury (Canada) and the Siljan (Sweden) impact structures, as well as to data from various non-impact crystalline environments (Table 1). The 1850 Myr Sudbury structure had an estimated initial diameter of ~200 km and was emplaced in the crystalline rocks of the Canadian Shield (see Boerner et al. 2000 and references therein). The log data penetrate both the impact-melt sheet (Sudbury Igneous Complex) and the fractured basement. The 377 Myr Siljan structure is possibly as large as 85 km in diameter (Reimold et al. 2005); the Stenberg-1 borehole penetrates the Precambrian granitic basement of the structure (Holliger 1996), and the Gravberg-1 well was drilled 14 km north of the crater center into fractured Proterozoic granites (Frenje and Juhlin 1998).

Although they differ in terms of target, size, breccia fill, etc., the three impact structures can be compared through the stochastic variations in their physical properties, which describe the inherent heterogeneity of each medium despite the sometimes large differences in average property values (compare ~6 km/s in the Sudbury impactites to the ~3 km/s velocities in Bosumtwi). On the whole, the rocks from the impact-melt layer in Sudbury show large scale lengths, similar to the average 100 m scales from other igneous environments (Table 1). The fractured basement of the Sudbury footwall structure however shows much smaller scale lengths, comparable to those from the Bosumtwi impact unit.

The uniformity of results from analyses of logs from crystalline environments has led to the speculation that log

fluctuations are more sensitive to mechanical rock properties such as the distribution of cracks rather than petrological composition (Holliger 1996). It can be inferred from the results of this study (Table 1) that the small vertical and horizontal scale lengths encountered in the impact units of Bosumtwi and Sudbury are seemingly characteristic for impact structures and reflect the nature of fracturing in basement rocks. As discussed earlier, the degree of damage is dependent on depth and position beneath and within a complex impact structure, hence the magnitude of scale lengths estimated below these structures may be indicative of the location and depth of penetration of a borehole with respect to crater floor. In the cases of both Bosumtwi and Sudbury, log data are from the impactites and immediate crater floor (below the melt sheet, just within the impacted footwall rocks, in the case of Sudbury), where the highest degree of damage (zone 1) must be expected. The Stenberg-1 borehole is located at the center of the Siljan structure, and, like the Gravberg-1 well, is intersected by several dolerite units and wide zones of fracturing layered with zones of minor fracturing (Papasikas and Juhlin 1997). It is possible that these layered zones within parautochthonous rocks obscure the smaller-scale fluctuations in physical properties, giving rise to the larger scale length estimated for Stenberg-1.

CONCLUSION

The Bosumtwi drilling project has provided a unique opportunity for assessing the physical properties of a young and well-preserved meteorite impact structure. From pre-drilling geophysical surveys to studies of recovered core samples, we have gained insight into the physical structure of the Bosumtwi impactites and basement rocks at various

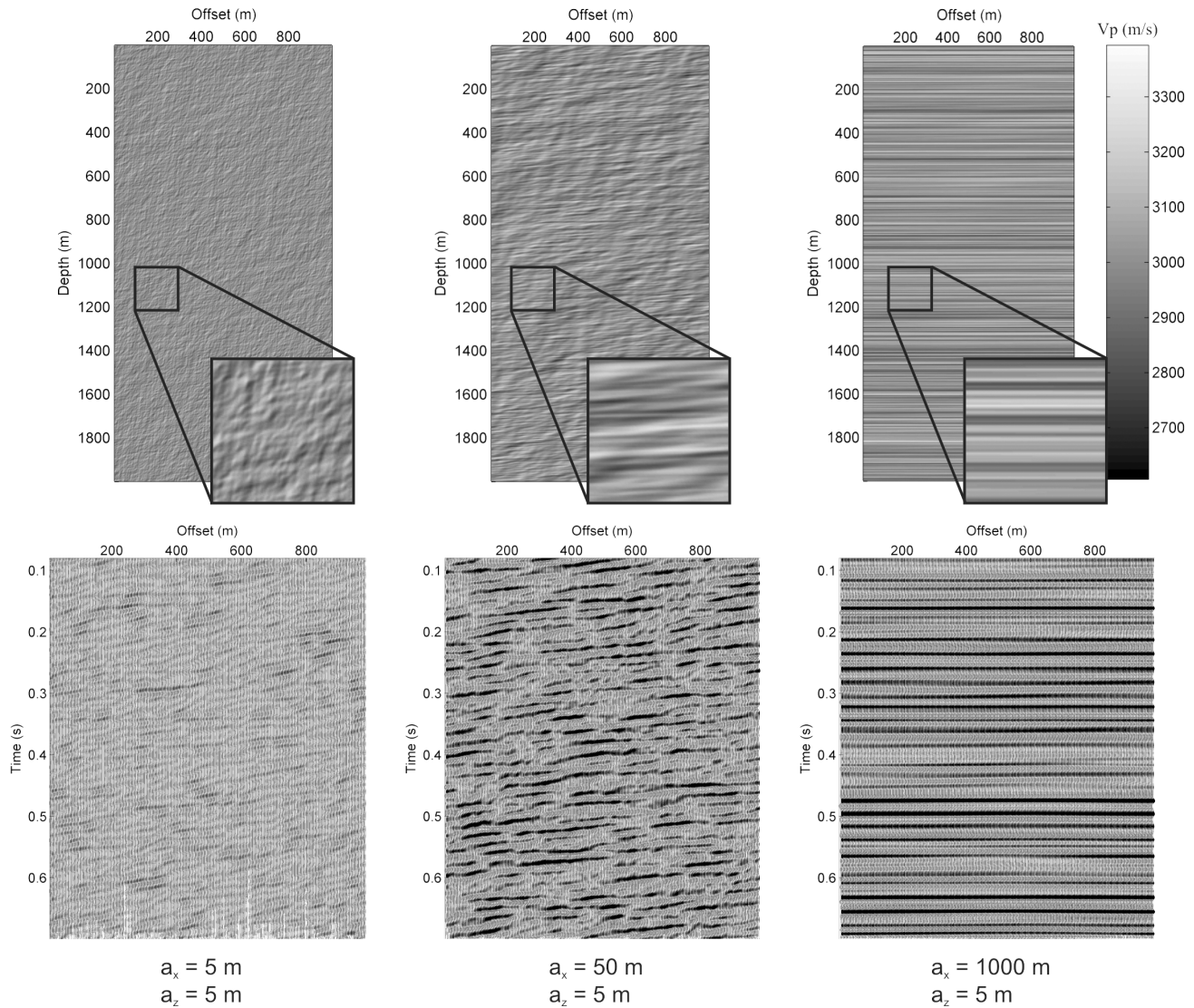


Fig. 5. Top: synthetic models of Vp distributions: (left) $a_x = a_z = 5$ m; (middle) $a_x = 50$ m, $a_z = 5$ m; (right) $a_x = 1000$ m, $a_z = 5$ m. As a_x increases, seismic energy is increasingly reflected from layered impedance contrasts. Bottom: synthetic seismograms generated with a finite-difference viscoelastic model (Bohlen 2002), plane wave source frequency ~ 50 Hz, receiver spacing 4 m.

scales: the velocity model derived from seismic reflection data, VSP results, logging, and laboratory sampling results all indicate a reduction in velocity of $\sim 40\%$ between the target and impact rocks of the crater. The velocity and density logs from the boreholes, in addition, show only slight differences between the central uplift and trough materials; however, they can be used to characterize the impactite and target rock sequence as a whole in terms of their seismic parameters. The slight differences in the logs indicate that the central uplift has higher average velocities and densities, as well as lower porosity, and is slightly less homogeneous in terms of its seismic scattering response compared to the material in its environs. The correlation between density and velocity is poor within both boreholes and only a slight trend with increasing depth is observable.

Although the depth extent of the log data is not large enough to estimate the total depth of damage beneath the Bosumtwi impact crater, an autocovariance analysis of the logs reveals the extent of mixing/fracturing that the impactites and the rocks immediately below the crater floor have endured. Velocity and density logs show horizontal scale lengths < 12 m, and vertical scale lengths of 2–3 m, similar to those of the Sudbury structure footwall rocks. In contrast, logs from various crystalline environments show scale lengths on the order of 100 m. If scale length estimates are indeed dependent on cracks and fracture distributions, the small length scales from impact structures are indicative of media with a high degree of fracturing (and/or porosity). This is characteristic of impactite zones as well as the shallow zones of high brecciation beneath impact structures,

independent of the size or age of the impact event. Based on these estimates, we conclude that the brecciated and fractured lithological units of impact structures will typically fall into the quasi-homogeneous scattering regime, and appear as transparent zones in seismic data collected at typical exploration frequencies of 40–70 Hz. One of the advantages of this type of environment is that post-impact intrusions, including the mineralized zones of Sudbury, will appear as bright reflections within a nonreflective background. This may also allow us to better map out fracture patterns in impact structures through seismic methods.

Acknowledgments—Drilling at Bosumtwi was funded by the International Continental Scientific Drilling Program (ICDP), the U.S. NSF-Earth System History Program under grant no. ATM-0402010, the Austrian FWF (project P17194-N10), the Canadian NSERC, and the Austrian Academy of Sciences. Drilling operations were performed by DOSECC; logging by the GFZ wireline crew led by J. Kuck. Local help by the Geological Survey Department (Accra) and KNUST (Kumasi), Ghana, was invaluable. The authors would also like to thank H. Ugalde for the density logs, T. Karp for the velocity model, C. Scholz for the Bosumtwi seismic data, and Wallbridge, Inco (CVRD) and Falconbridge (XStrata) for the Sudbury log data. E. L'Heureux is funded by NSERC, with support from the Ontario Government and the CSEG. Comments and suggestions by reviewers J. Morgan and M. Muller were greatly appreciated.

Editorial Handling—Dr. Wolf Uwe Reimold

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