The shock gun: VSP experiments with a new seismic source

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Over the past few years tests have been performed on a portable seismic source, developed by BG plc from the principles of gas dynamics, which is sufficiently lightweight to be deployed on an all-terrain truck or Land Rover, yet has enough power to access hydrocarbon exploration depths.

The technique utilizes a near one-dimensional free shock wave, created by the instantaneous discharge of a gas with high sound velocity (such as helium) and at high pressure, into a gas with low sound velocity (such as air) at atmospheric pressure. To understand its formation, one should imagine the helium acting as a piston which accelerates from rest to a velocity greater than the speed of sound in the low-pressure gas. This acceleration can be segmented into velocity increments, with a compressional wave being generated at each increment which then propagates into the low-pressure gas. At each step the gas between the piston and the compressional wavefront assumes an axial flow velocity equal to the piston velocity. Further increments in piston velocity produce compressional waves into this flowing gas which, due to the ever-increasing flow velocity, travel at increasing speeds relative to the tube walls. Hence a series of waves is produced traveling at increasing velocities. After some distance they coalesce to form a planar shock front with large gradients of pressure and temperature. As an example, given an initial pressure ratio of 100, the shock velocity in the low pressure gas is approximately 1100 m/s and the temperature change across the shock front is nearly 1000 K.

In the present design, the shock-wave generation is implemented using a shuttle-valve system, which separates a chamber of 300 in^3 in volume from a long open tube (2-3 m in length and 5 cm in diameter). The shock wave develops ahead of the main compression wave within this tube, and is released at the open end in about 5 ms. The shock is followed out of the tube by a large gas volume at high pressure, leading to a secondary (undesirable) explosive element. The resultant pressure profile initially possesses strong radial and axial components. As a typical example, when measured at 1 m axially from the outlet in free water, the peak pressure is 1.7 bar-m and the peak-to-bubble ratio is 4.3. An important aspect of the shock wave is pressure rises very fast (on the order of 6 μs). When compared to a small (20 in^3) air gun (Figure 1), the shock gun is considerably more front-loaded.

As a secondary feature, the shock-gun signature appears to lack a strong ghost reflection. We believe this may be due to the shock wave disturbing the water's surface; this explanation is supported by tests made at greater source depths where the ghost is better formed. Further general characteristics are detailed in Table 1.

Observed performance. To be useful as a seismic source, the emitted waveform must be repeatable. Timing variation, in particular, has proved problematic for impulsive land sources. Of further concern is the variation that can occur due to changes in coupling, which for the shock gun would include compaction or degradation of the material around the shot hole. To evaluate these features, signatures from the shock gun were recorded under three separate conditions:

Gun fired and recorded in water. An illustration of the degree of timing-drift and near-field signature variation experienced during ideal operational use is given in Figure 2. For these tests the shock gun is deployed in a vertical position, with the tube submerged but the gun body clear of the water. The pressure signatures are recorded on omnidirectional ball hydrophones 5.48 m below the end of the tube. We find the timing variation to have a standard deviation of 0.70 ms and a peak amplitude deviation of 3.4%. This may be compared to the lower drift values of 0.075 ms for a 20 in^3 air gun when fired for comparison under similar conditions. We shall argue later that the shock-gun deviation is within acceptable limits for VSP surveying.

Shock gun fired in a water pit and recorded downhole. The most comprehensive tests were carried out on land at the Shell test site in Rijswijk, Holland, where a vertical test well is drilled into sandy clay. It is 176 m deep and instrumented by an array of cemented 3-C receivers. The properties of the cement are selected to minimize tube waves. Here we compared sleeve guns, air guns, and the shock gun in different acquisition configurations (Figure 3a). Figure 3b compares the shock gun, the Bolt 1900C 120 in^3 air gun, and the HGS 150 in^3 sleeve gun. There is a clear similarity between recorded source wavelets, with the main differences arising from variations in the interference of the bubble pulses and the shear waves. The timing deviations for the shock gun in Figure 3 result in a standard deviation of 0.18 ms, compared to 0.35 ms and 0.12 ms for the air and sleeve guns, respectively.

Table 1. **Technical description of shock gun**

Gun volume range	300 in^3
Gun pressure range	1000 - 2000 psi
Cycle time	10 seconds
Gun potential energy	67 kJ - 134 kJ
Weight	215 kg
Duration of wavelet (no ghost)	4 ms
Peak amplitude in water	1.7 bar-m
Peak-to-bubble ratio	4.3
Bubble period	110 ms
Rise time of the shock wave	6 μs
Estimated manufacturing cost	less than f 10k
Cost per shot activation	less than f3.00

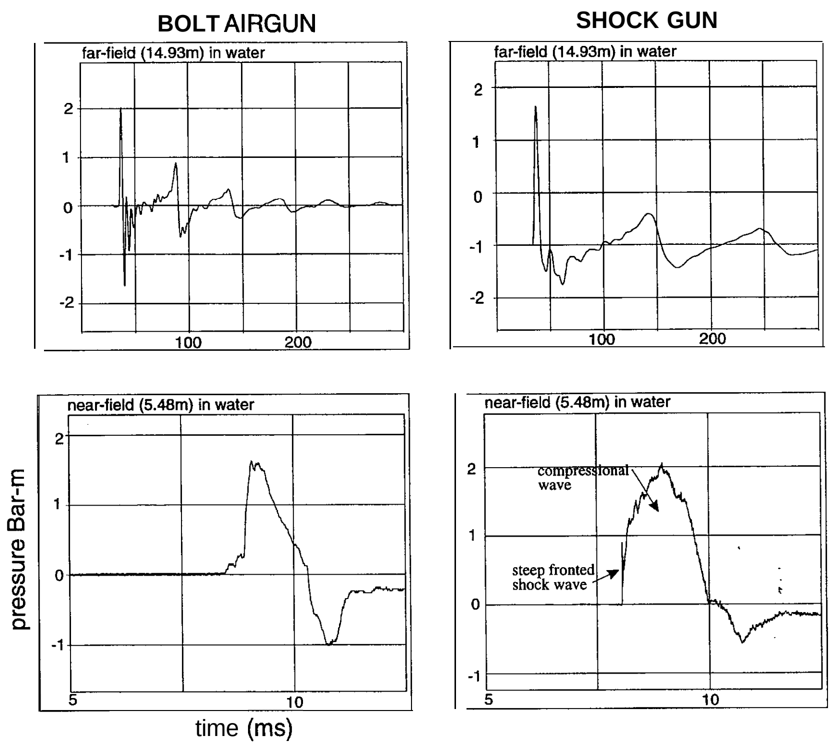


Figure 1. Tests at Wraysbury reservoir. Near- (5.48 m) and far-field (14.83 m) signatures are recorded from a Bolt airgun with a chamber volume of 20 in^3 and the shock gun with its 300 in^3 chamber filled with helium. Both guns were fired at 1500 psi into the omnidirectional ball hydrophones which are positioned directly below the source. The air-gun signatures are sampled at50 000 samples/s-and the shock gun at 100 000 samples/s.

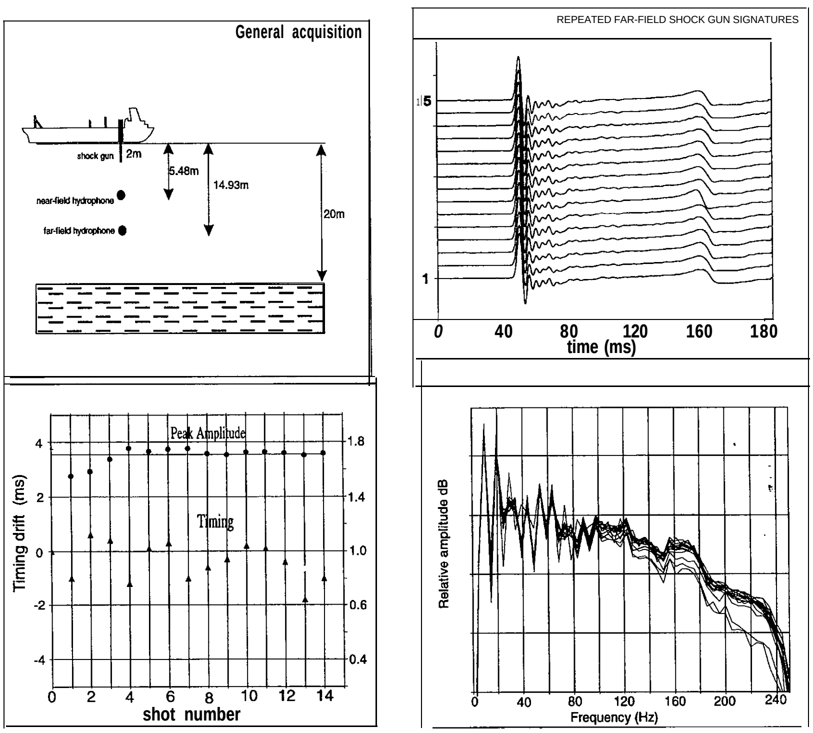


Figure 2. Repeated far-field signatures for the shock gun at 1500 psi in the Wraysbury tests, together with time breaks, amplitudes, and spectra. The signatures are sampled every 1/20 ms. The standard deviation for the timing is 0.70 ms, and 0.058 bar-m for the amplitudes.

Shock gun fired in a vertical hole. A shot hole with a 20-cm diameter was drilled to 3 m. The upper 1.5 m is lined with a l-cm thick plastic pipe to prevent possible collapse which occurs as a consequence of the large gas volume following the initial shock wave. The recorded wavefield is now visually simplified due to the lack of bubble pulse energy. We also found that the shock gun activated with helium at 1500 psi produced timing drift with a standard deviation of 0.51 ms (Figure 3a). Although, as expected, this was larger than the previous tests, the shift remained within a satisfactory tolerance.

Figure 3b shows the average frequency content for compressional- and shear-waves generated from the four test cases. There is a clear 10-Hz peak in the surface and shear-wave spectrum for the three sources shot in the water pit. By comparison, the shock gun in land deployment possesses a similarly positioned but smaller peak and a similar peak *P*-wave amplitude. Only part of this overall reduction in amplitude is related to the additional offset for this source. Note that the shock gun in land deployment appears to produce additional shear-wave amplitudes in the range of 20 to 40 Hz that are not present in the other modes of deployment. This is also evident from the frequency spectra in Figure *4* for the 3-C VSI?

In our land deployment, shear waves are generated directly from the source as a consequence of interaction between the shock wave and the confining borehole. The exact dynamics of this process and the relationship between the free-space shock wave behavior and the resultant seismic wavefields, require further modeling. In particular, it would be of value to determine the equivalent force system for the force. This would help to make accurate predictions of the seismic wavefield in modeling studies, analyze offset conversion efficiency by more accurately defining its radiation pattern, and guide future modifications. For example, if the shock gun has a major explosive component and the shot hole may be assumed open, the resultant displacement of the far-field may be simulated by the explosion and a vertical dipole acting in the isotropic solid medium. (See "The equivalent force system of a monopole source in a fluid-filled open borehole" by Ben-Menahem and Kostek, GEOPHYSICS, 1995.) Alternatively, if the physical interaction is more akin to an outward radial pressure distributed over the cylindrical wall, then the shear waves may be represented by two horizontal and orthogonal linear dipoles. (See Seismic *waves — radiation, transmission and attentuation* by J. E. White, McGraw-Hill, 1965). In reality the strong impulse to the bottom of the borehole (a vertical force?), the directional variation of the shock which loads the wall, an additional "dragging" component against the borehole wall due to the boundary layer, and the response of the surrounding near-surface materials mean that the mechanism remains an issue open to further investigation.

It is believed that under certain near-surface conditions the instantaneous nature of the shock somehow helps to stiffen the surroundings to create a more efficient conversion into shear-wave energy to higher frequencies — as seen in Figure 3b. The energy output may be promoted by multiple reflections of the incident shock wave within the water column.

Changing the gun characteristics. A major attribute of the shock gun is that the shock wave is very controllable; i.e., the velocity and pressure are very predictable given initial conditions defined by the specific heats, temperature, and pressure of the gaseous constituents. It also possesses a relatively simple structure and could, in principle, be tailored to tune into particular external conditions to maximize the energy coupled to the earth and the frequencies generated. Here we list and explain some known adjustable features and detail their particular constraints.

Outlet tube size and geometry. The shock formation distance and boundary layer growth tend to restrict the low-pressure tube length. Beyond a particular threshold, pressure reduction will eventually reduce the propagating shock wave to a fully choked turbulent flow, and the shock velocity departs from its ideal curve. A larger-diameter tube does mean that the boundary layer growth is less influential but makes the device more cumbersome. The current gun is a trade-off between these two factors. The tube diameter also affects the output ratio for the radial to axial velocity and hence can

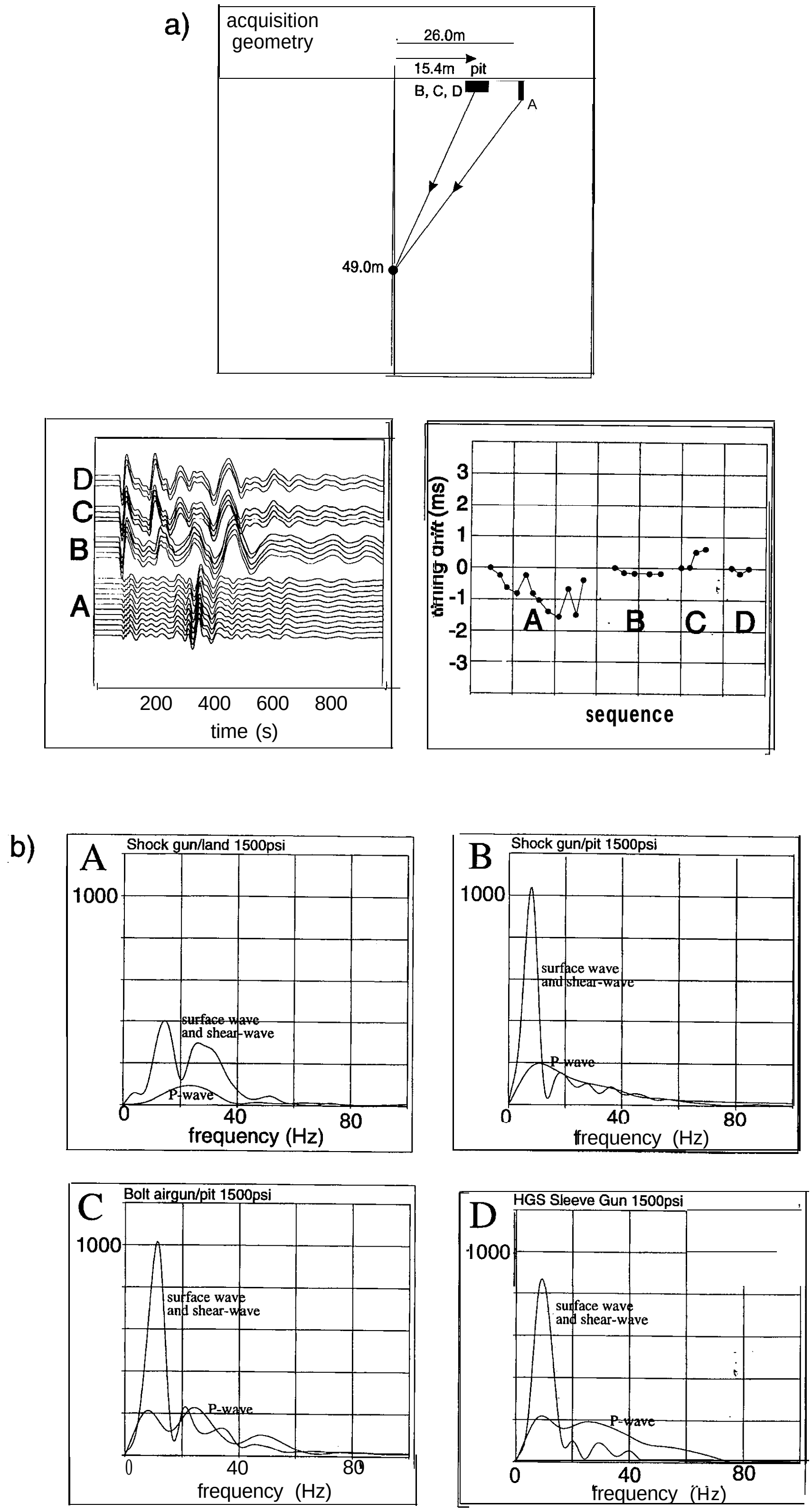


Figure 3 (a) Repeated signatures with corresponding time breaks for different sources at the Shell test site. A = land deployment of the 300 in^3 shock gun (2-m shot hole); B = 300 in^3 shock gun in water pit; C = 120 in^3 Bolt airgun in water pit; D = 150 in^3 sleeve gun in water pit. Standard deviations for timing drift are 0.51 ms, 0.18 ms, 0.35 ms, and 0.12 ms, respectively. (b) Comparison of P-wave and S-wave amplitude spectra for sources in (a), evaluated by taking the Fourier transform of a short window around the relevant arrival (thus avoiding the bubble pulse).

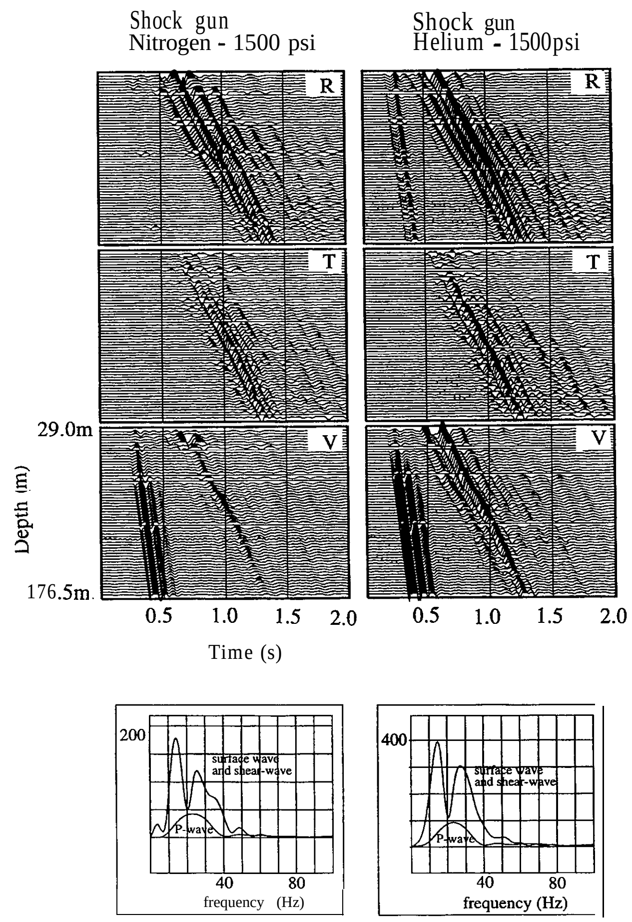


Figure 4. Rotated 3-C data recorded at a depth of 176.5 m in a VSP configuration at the Shell test site. The shock gun is operated on land at an offset of 23 m, with two different gases at 1500 psi. The lower part of the diagram shows the resultant amplitude spectra.

be used to adjust the degree to which the side wall is loaded, thus preventing collapse or changing the equivalent force mechanism. Placing a steel plate in the shock tube itself will spin and deflect the shock wave so that it can be directed at a desired angle against the borehole or containing wall.

Type of gas. It is well known that replacing the helium by a heavier gas such as nitrogen will reduce the overall velocity and pressure amplitude of the generated shock wave. In the shock gun this substitution affects the recorded wavefield as shown in Figure 4, where the gun is operated in a water-filled borehole with both gases at 1500 psi. The difference in overall energy content is noticeable for both the compressional and shear waves. The frequency spectra also show a decrease in the higher-frequency content for the nitrogen. Using mixtures of helium and nitrogen is not a viable solution to the reduction in output energy as the peak amplitude drops off rapidly as more nitrogen is introduced into the mix. The gun was originally designed for helium, the use of air being expected to affect the timing stability. It is felt, however, that this could be improved in future designs.

Gus pressure. The current shock gun can be operated at any pressure in the range of 1000-2000 psi. Experiments in the marine setting have identified a near-linear relationship between peak amplitude measured on a near-field hydrophone and gun pressure. The effect of operating pressure on the shock wave in the down tube is well understood, showing a general reduction of velocity and pressure with decreasing helium pressure. In experiments where we have directly measured the propagation of the shock wave within the tube, we have found that reducing the gas pressure from 1500 to 800 psi reduced the shock amplitude by 50% and the shock velocity from 1000 m/s to 750 m/s.

Hole orientation and its implications. The exact mechanism for shear-wave generation by the shock wave and control of this characteristic form an important part of future developments. Taking the system to be simulated by the equivalent-force systems proposed above, the source may be assumed to generate a shear-wave polarization aligned parallel to the shot-hole axis (of course, this is an idealization as the medium may be neither isotropic nor homogeneous). Thus it is possible to change the alignment of the emitted shear-wave polarization by changing the azimuth of the hole inclination. Multicomponent-source data can thus be created by inclining the shot hole along in-line and then cross-line directions, creating ground motion in orthogonal directions. This concept was tested in field trials at a test site in Marolles, near Paris. This consists of shooting near- and far-offset VSPs with a circular distribution of outwardly inclined shot holes at each source location. The holes are drilled with a portable drilling rig mounted on a tracked vehicle. The unit is capable of drilling at angles between 0 and 60”. The recordings from the common receiver groups display a distinct variation which may be linked to a source-polarization change resulting from the shot-hole orientation. As a test of the multicomponent control, we select two sets of multicomponent recordings from orthogonal shot hole azimuths. These are then used in an attempt to numerically simulate the traces expected for the other source hole azimuths (Figure 5). This helps determine the degree of control and predictability, and whether the data could be used in a procedure such as the Alford rotation. Although the overall fit appeared visually satisfactory there is an azimuthal variation in the frequency content and finer structure of the shear waves which is suggestive of a complicated near-surface response. Additional tests indicated that the average timing drift of 1.70 ms from the inclined hole arrangement is more pronounced than for the previous orientations.

Possible applications. Some potential practical uses for this method include:

As a standard seismic source. On land, due to its compact size, it could allow access to environmentally sensitive areas. The weight, size, and cost also make it attractive for VSPs in remote areas. Also, it may be used where explosives have complications due to political sensitivities. The ability of the device to position the origin of a large energy source at the bottom of a long, predrilled borehole has advantages in many applications; indeed, for VSPs this device may be more desirable than either marine air guns operated in a large pit or buried air guns. We also maintain (as do others) that concerns over drift can be relaxed for VSP applications, because time breaks may be taken from a monitor borehole or a buried reference point. However, for surface seismic, the natural concern is over the conditions of the hole after each activation and its effect on the timing. To put this into perspective using a simple calculation, we consider one spectral component of the signal and stack it with another slightly misaligned component from a separate trace. The resultant amplitude obtained from the stacking procedure may exceed 98% of the desired amplitude at 40 Hz if the drift is no more than 1.60 ms; this is adequately met for the land deployment using a vertical water-filled hole but marginal for the inclined hole.

A possible multicomponent VSP source. Multicomponent VSPs yield important information on the rock matrix, stress, and fractures from analysis of seismic anisotropy. A critical component is the ability to control and change the source polarization; this is required for accurate seismic anisotropy estimation using Alford rotation and its variants. However, such surveys (and their surface-seismic counterparts) are not routinely acquired, primarily due to a shortage of appropriate multicomponent equipment. This global distribution has a strong impact on the survey cost for a land VSI? This was brought home by the recent experience of one of the authors in costing equipment rental, shipment, travel, and field crew for VSP acquisition in Asia. In principle, a near-offset multicomponent VSP can be shot in 1-2 days (when fully set up).

However, the sources could not be leased for less than two months. The expense of the survey outweighed its value, and the project was canceled. There are many other, less dramatic examples where this cost equation would equally apply. In

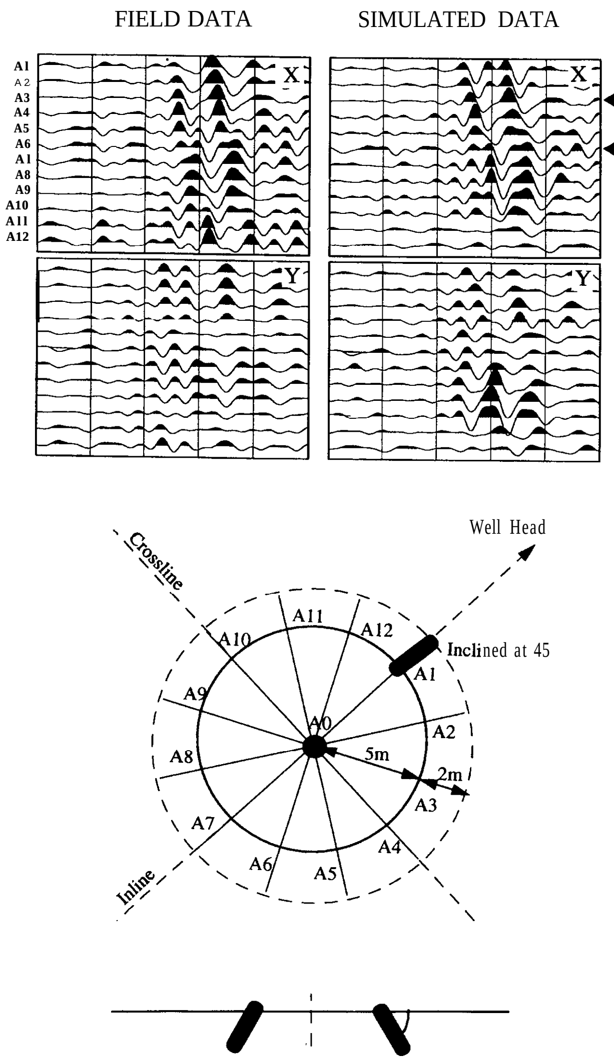


Figure 5. The Elf test site at Marolles. Top left = horizontal component (X and Y) seismograms recorded for the near-offset VSP configuration with an offset of 27 m into a receiver depth of 1710 m. Each trace corresponds to a shot from the shock gun activated in shot holes inclined at 45" and arranged in a circular shot pattern with 10-m radius at 30" azimuthal intervals (bottom). Top right = Horizontal component traces simulated from the observed data by using recordings from two of the orthogonal source azimuths (arrowed).

remote areas, where large truck-operated sources are difficult to maneuver, this situation is exacerbated. Thus, although we recognize the benefits of multicomponent surveying, they are often outweighed by more basic issues. A device is needed to fill the gap, and the ability of the shock gun to operate in inclined holes and create the necessary directional behavior for seismic anisotropy is appealing. Here, just as in standard VSP, the timing drift may be corrected by a shallow borehole monitor allowing complete near-surface correction. Thus, provided directional behavior exists, a multicomponent subsurface response can be estimated. There are, of course, alternatives for generating shear waves such as using air guns activated in pits, or a standard source near to walls or trenches; however, there is usually insufficient control of the source direction. One way to illustrate the overall requirements for multicomponent surveys is to group commonly available sources on a graph of perceived (our estimated) multicomponent flexibility (Figure 6) versus depth of penetration. Future work could extend the existing location of the shock gun on this graph into the top right of this figure.

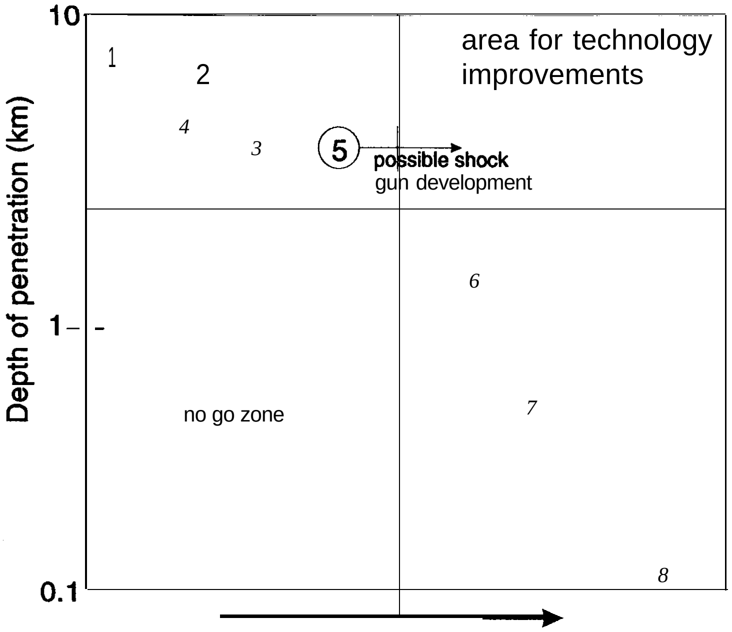
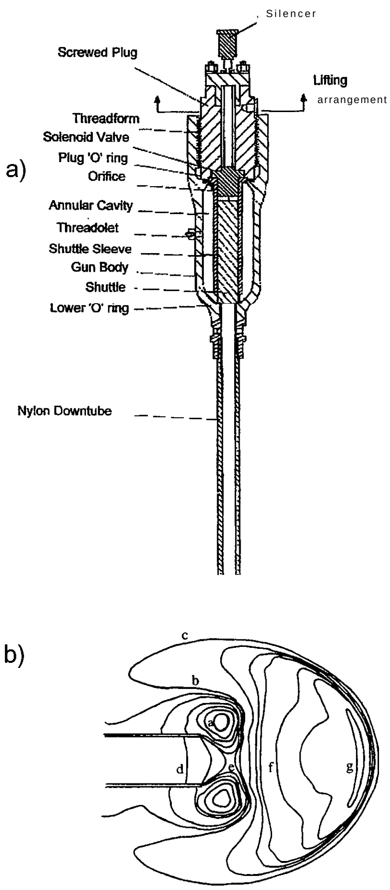


Figure 6. Our perceived multicomponent flexibility of existing "shear" sources against the depth of penetration. Current devices fall into either lightweight with near-surface applications, or heavy with seismic depths. The shock-gun concept may help develop a lightweight source in the area required for future widespread applications: 1 = explosive trench; 2 = P & S vibroseis (20-30 tons); 3 = Omnipulse airgun (20 tons); 4 = Marthor weight drop P & SH (20 tons); 5 = shock-gun source (2 tons); 6 = mini-ribroseis (l-4 tons); 7 = portable vibrators; 8 = hammer devices.

Appendix

This figure is a schematic design (a) of the shock gun which shows the main features of the generating mechanism, and (b) isobars predicted for the flow field created by the shock wave emerging from the gun tube into ambient air. Pressure in bars: a = 145, b = 100, c = 145, e = 80, f = 110, and g = 120.



Future developments. The data in this article were taken from six VSP data sets generated with a prototype shock gun. The experience has helped us to identify a number of fundamental improvements needed to fully exploit the gun's potential. These include:

Shock gun redesign: (a) reduce gun mass; (b) improve access to internal components; (c) allow variable internal gas volumes; (d) optimize helium efficiency (a heated helium driver would boost shock energy and a combustion-driven shock would allow a reduction of gas consumption); (d) ruggedize connections; (e) reduce firing pulse energy.

Permanent integration onto an all-terrain vehicle: (a) mounting mechanism to allow simple angled deployment and tapered tube (perhaps telescopic) for mounting / positioning in hole; (b) combined drilling unit/ shock gun on a dual-purpose vehicle; (c) universal tractor mounting to allow low-cost deployment.

In addition, a key feature of the shock gun is its controllability and flexibility, which make the device, or one based on a similar concept, a strong candidate as a basis for future seismic-source developments. However, further tests and modeling are required. In general, the nature and behavior of the nonlinear shock wave interaction with the borehole fluid and solid surroundings are not properly understood and cannot be easily related to seismic efficiency at present. This requires 3-D modeling of the shock wave propagation on high-powered computers. Such studies could help determine when to adjust the shock-wave focusing/ directional control or alter the coupling mechanism and how to properly control the shear-wave polarization. E

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