

COCORP SEISMIC INVESTIGATIONS OF THE SURRENCY BRIGHT SPOT  
BENEATH THE SOUTHERN APPALACHIANS, USA

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*Abstract.* An unusually strong midcrustal reflector, the Surrency Bright Spot (SBS), was found at a depth of approximately 16 km during earlier COCORP profiling in the southeastern U.S. In addition to being very bright, the SBS is notable for being unusually flat and horizontal for about half of its 4 km length. As these characteristics are similar to those of fluid-caused reflections at shallow depths, it has been suggested that the SBS may be caused by in situ midcrustal fluids. If caused by fluid enclosed in fracture porosity in solid rock, the reflection would be expected to exhibit a negative polarity from the top of the porous zone as well as showing anomalous amplitude-versus-offset reflectivity. A series of seismic reflection experiments have therefore been undertaken by COCORP to measure the reflection properties of the SBS. A small reflection seismic experiment with an explosive source was conducted to determine the polarity of the SBS. The experiment consisted of four dynamite shots, each recorded at three receiver stations by Seismic Group Recorders (SGR) borrowed from Amoco Production Company. Comparison of the dynamite records with geophone polarity tests indicate that the SBS is characterized by a positive reflection coefficient at its top. This result itself does not negate the fluid hypothesis - a fluid-fluid interface could cause the positive reflection as well as the 'flat-spot' nature of the reflector. However, modeling indicates that the SBS waveform is most simply interpreted as originating from a circa 120 m thick, high-impedance layer with wavelet tuning contributing to the unusually large amplitude. In this light, a fluid model becomes much more ad hoc. Though the fluid hypothesis is not precluded by this experiment, we feel that the SBS is more likely caused by a mafic or ultramafic layer, either tectonically or magmatically emplaced. A much more extensive experiment was undertaken in the summer of 1990 to obtain 3-component CDP and expanding spread (ESP) profiles over the SBS, as well as crossline and three dimensional control. Initial results show that the SBS is well imaged on all of the P-wave data to 36 km offsets and is visible on some of the S-wave data as well. In the third dimension the SBS is subhorizontal and of comparable lateral extent as on the main profile.

## INTRODUCTION

One of the most striking features yet imaged on COCORP reflection seismic profiles is an extremely bright reflector found beneath the southern Appalachians, termed the Surrency Bright Spot (SBS) (Figs. 1 and 2). The SBS is a relatively small (4 km) reflector lying at 5.8 to 6

sec traveltime (about 16 km depth) in the midcrust. The amplitude of the SBS is about 10 dB greater than the surrounding reflectors; it is certainly one of the brightest reflections imaged by COCORP to date. In addition to its unusually large amplitude the SBS is curious because it is flat and level for half of its length (Fig. 2).

Given these characteristics for the SBS, it has been suggested that the extreme reflectivity is caused by a fluid-filled porous zone (Wille, 1987; Brown and others, 1987). This hypothesis is by analogy with 'bright spots' found on shallow seismic sections; such bright spots are sometimes diagnostic of fluid- or gas-filled porous zones which can also have 'flat-spots' due to the gravitational control on a fluid-fluid interface within the porous zone (e.g., Backus and Chen, 1975; Ensley, 1984). Though the nature of a fluid(s) at the depth of the SBS is unknown, free deep-crustal fluids have been recognized from deep drilling and hypothesized from magnetotelluric studies (Kozlovsky, 1984; Gough, 1986; MacDonald, 1988; Bailey and others, 1989; Hyndman and Shearer, 1989). Presumably any such fluids causing the SBS would be trapped within fracture porosity. A similar mechanism has been suggested to cause a bright reflection beneath the Black Forest in Germany (Luschen and others, 1987). The SBS lies within an hypothesized Late Paleozoic suture zone delineated on the basis of drillhole, magnetic, and seismic reflection data (Nelson and others, 1985). A possible source for the fluids could thus be formational and/or metamorphic waters derived from underthrust sedimentary rocks (e.g., Fyfe, 1986).

To determine the cause of its reflectivity, COCORP has recently reexamined the SBS using a variety of seismic experiments. The first of these was a small dynamite experiment carried out in late 1989, the goal of which was to determine the reflection polarity of the SBS. In addition, seismic wavelet modeling of the dynamite data was carried out to further constrain the SBS geometry. COCORP returned to the SBS in the summer of 1990 for our most elaborate field effort to date. Shear-wave (both transverse and radial) and P-wave expanding spread profiles, crossing S-wave and P-wave common-depth point (CDP) profiles, and a P-wave 3-D experiment were acquired using a 650-channel telemetered seismic system with 8 large vibrators. The goals of these experiments were to further constrain the physical characteristics of the SBS, measure the bulk seismic properties of the crust, and test the applicability of shear-wave vibrators for deep crustal work.

Analysis of the dynamite experiment is currently being completed, and processing of the data from the larger experiment is in its initial stages. This paper describes the results obtained to date.

## POLARITY TEST

A key test of the fluid hypothesis is the polarity of the SBS reflection. The top of a porous zone would presumably mark a downward decrease in velocity and density (Koefoed, 1955; Gardner and others, 1974; Gregory, 1976; Carlson and Herrick, 1990), and thus have negative reflection coefficient. Other hypothesized causes of the SBS reflectivity (e.g., mafic sill or ultramafic body), however, should produce a positive reflection coefficient at the top of the SBS. Unfortunately, seismic reflection data obtained with vibrators, such as the earlier COCORP survey, are plagued

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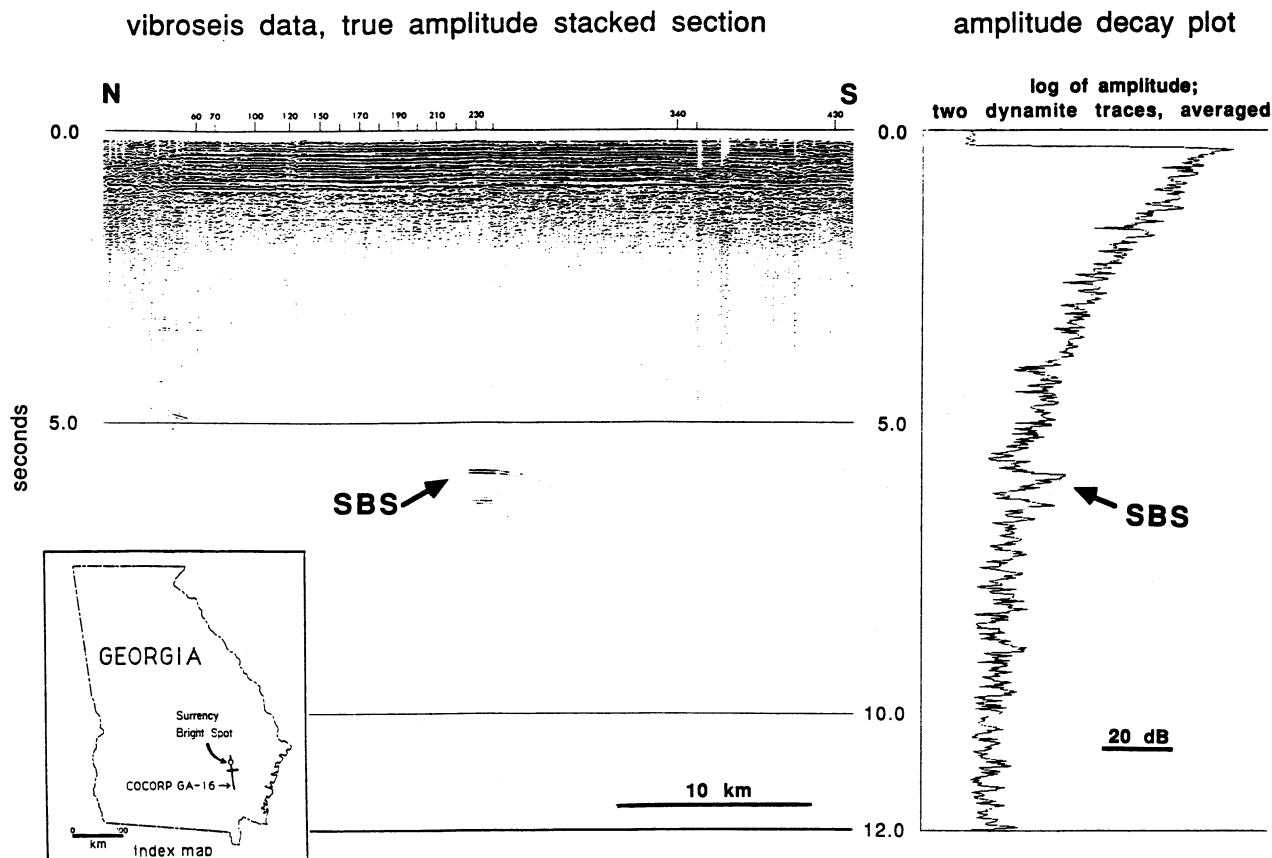


Fig. 1. The Surrency Bright Spot (SBS) as imaged on a true-amplitude version of the original COCORP stacked vibroseis section and on an amplitude decay plot of the dynamite data obtained over the feature. No scaling has been applied to the stacked section; only the shallow Atlantic

Coastal Plain strata and the exceptionally strong SBS are visible. The amplitude decay plot shows that the SBS has an amplitude approximately 10 dB above background levels. Section is plotted at a vertical:horizontal ratio of about 1:1 at 6 km/s.

with uncertainty regarding the reflection polarity because of the complexity of the vibrator source and its interaction with the ground. The polarity was therefore ambiguous on the previously acquired data.

To determine the reflection polarity of the SBS a small seismic reflection experiment was conducted using four dynamite shots as a source. Dynamite can be assumed to have an initial outward motion upon detonation, and thus a compressional wave should be the first arrival at any given subsurface reflector. Charges ranging in size from 11.4 to 20.5 kg (25 to 45 lbs) were placed at the bottom of four 19m holes (Fig. 3) and tamped with coarse sand. Upon detonation, the resulting reflections from the SBS were recorded on three Seismic Group Recorders (SGRs) borrowed from Amoco Production Company. Receiver arrays were 91.5 m (300ft) in length and consisted of 12, 10Hz P-wave geophones. The largest source-receiver offset was 3.5 km; the reflected energy therefore had effectively vertical travelpaths and receiver arrays should not effect the reflected waveforms. A total of 12 traces (4 shots into three receivers) were recorded; static (including uphole) and normal moveout corrections were applied to the traces and they were arranged in CDP order (Fig. 4, center).

The onset of the SBS reflection package is apparent on the recorded data as a sharp negative (leftward on the plot in Fig. 4, center) deflection occurring at about 5.8 sec two-way traveltime (dashed line on Fig. 4). Comparison with tap tests conducted on the geophones and with first (refracted) arrivals in the data show that this negative deflection is in response to an upward geophone motion at the onset of the SBS reflection. The initial outward motion of the explosive source and the

upward geophone motion indicate that the upper surface of the SBS has a positive reflection coefficient; this implies that the SBS is composed of a relatively high-impedance (high velocity and/or density) material.

#### WAVELET MODELING

Though the results of the polarity test imply that the source of the SBS has higher impedance than the overlying material, this does not actually eliminate the fluid hypothesis. It is conceivable that the top of the porous zone is non-reflective, perhaps because of a gradual onset of porosity, and the initial reflection is actually coming from a fluid-fluid boundary within the porous zone. Though this requires two fluids to be present, it is the implication of the 'flat-spot' model proposed for the SBS. Such a fluid model, however, would be characterized by another positive reflection at the base of the porous zone, in contrast to a thin, high-impedance body which would have a negative reflection coefficient at its base.

To distinguish between these two possibilities, wavelet modeling of the traces from the dynamite experiment was undertaken. The modeling procedure consisted of convolving a source wavelet with a reflectivity function composed of 'spikes' representing each of the interfaces. The synthetic models were then compared with the observed field data.

The primary difficulty in this modeling procedure is obtaining a source wavelet. In similar studies, the wavelet has commonly been taken from the first arrivals recorded in the field (e.g., Goodwin and others, 1989). At Surrency, however, there is considerable attenuation of the higher-

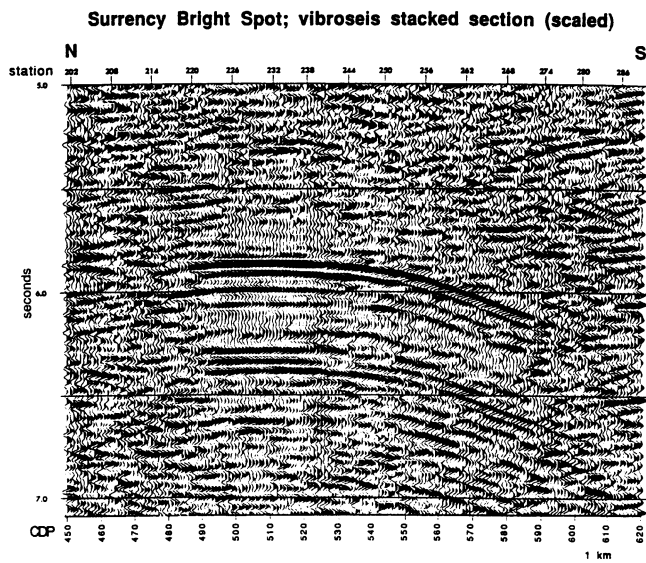


Fig. 2. Detail of the Surrency Bright Spot (SBS) on the original vibroseis stacked section after the application of automatic gain control (AGC). Note the nearly 2.0 km long level portion at the northern half of the SBS and the apparent diffraction tail to the south. The reflection lying approximately 0.5 sec below the SBS is believed to be caused by multiply-reflected energy. Section is plotted at a vertical:horizontal ratio of about 1:1 at 6 km/s.

frequency seismic energy as it propagates through the shallow sedimentary section; hence, the frequency spectrum of the first arrivals is far wider than that of the SBS (Fig. 5). To circumvent this problem, we extracted a minimum-phase wavelet directly from the relevant portion of the seismic trace using a spectral factorization technique (e.g., Claerbout, 1976; Yilmaz, 1987, appendix B-4). This process produces a seismic wavelet with an amplitude spectrum identical to the input trace, but whose phase spectrum has been rearranged to front-load the energy within the trace (Robinson and Treitel, 1980). Examples of such wavelets extracted from different portions of a seismic trace from the Surrency dynamite experiment are shown in Fig. 5A.

Modeling using the wavelet extracted by the above process is valid only if two important assumptions are accepted. First, it is assumed that the dynamite produced a minimum-phase wavelet upon detonation. This assumption is difficult to evaluate, but it is widely believed that explosive sources produce a minimum-phase wavelet (e.g., White and O'Brien, 1974) and it can be shown that any ghosts or reverberations are also minimum phase (Robinson and Treitel, 1980, chapter 11 and appendix 13-1). The second assumption is that the large-amplitude reflection from the SBS is not altering the frequency spectrum of the trace, and thus the wavelet extracted therefrom. In other words, the reflectivity series is random and the amplitude spectrum of the trace is a scaled version of the amplitude spectrum of the source wavelet. This assumption is the basis for all predictive deconvolution and seems justified here given that the amplitude spectrum and wavelet extracted from windows both above (2.0-4.0 sec) and including the SBS (5.0-7.0) are nearly identical (Fig. 5A).

Before modeling, the phase spectrum of the source wavelet must be modified to account for the phase shift introduced by the geophones. The geophones used in the experiment have a damping of 67% of critical, and their phase response can be computed using the equation for a damped harmonic oscillator:

$$\Phi = 180^\circ - \tan^{-1}[2Df_n f / (f_n^2 - f^2)]$$

where  $D$ =damping (0.67),  $f$ = frequency, and  $f_n$ = natural frequency of the geophone (10 Hz). The minimum-phase wavelets extracted from the data

and the same wavelets after applying the geophone 'filter' are shown in Fig. 6 after smoothing with a zero-phase, 4-40 Hz filter to remove high-frequency components introduced by windowing in the wavelet extraction process. The digital recorders and receiver arrays should have a negligible effect on the phase of the recorded signal given the frequency range and incidence angle of the SBS reflection.

Four types of models (Fig. 7, bottom) were used to create synthetic traces for comparison with the observed field records. Based on the polarity test, each of the models has a positive reflection coefficient at the top of the SBS reflector. The first model is a simple boundary (single interface model). Because the amplitude is arbitrary, there is only one permutation of this model. The second model is of a thin, high-impedance layer with a positive reflection coefficient at its upper boundary and an equal but negative reflection at its base. Because the body can have any thickness, a range of thicknesses from 10 msec to 50 msec traveltimes were tried; these traveltimes would represent layers between approximately 30 and 160 m in thickness (assuming a velocity of 6.5 km/sec within the layer). Two variations on a fluid model were also tested. The first of these ('fluid model 1') consisted of a positive reflector at the top of the SBS, as determined from the polarity test, and a second positive reflector of equal amplitude at a later traveltimes representing the base of the porous zone. The second fluid model is the same except that the lower reflector (the base of the porous zone) has only half the amplitude of the upper. As with the high-impedance model, the thickness of the hypothesized body was examined by varying the traveltimes difference between the reflectors from 10 msec to 50 msec.

The results of the modeling exercise for 4 representative CDPs are shown in Fig. 7, and all of the synthetic traces from the best-fitting high-impedance and fluid models are shown next to the field data in Fig. 4. The single-interface model produces a wavelet package which is considerably shorter in duration than the observed SBS reflection sequence (Fig. 7). We thus feel that multiple interfaces are involved in producing the SBS reflection. This was expected because the limited lateral extent of the SBS makes a half-space model unlikely.

The high-impedance model produces a reflection sequence whose duration varies with the layer thickness, as one would expect (Fig. 7). The models with 30 to 40 msec layer thickness produce a reflection sequence very similar in duration, lobe spacing, and lobe amplitude to that of the observed data except that the initial lobe is smaller in amplitude than on the field records. Increasing the thickness of the model body introduces added complexities to the reflection package in the later lobes. Our best approximation to the SBS body was produced with a 36 msec (120 m thick) high-impedance model with a lower reflection amplitude 0.7 times that of the upper (Fig. 4). This model has the added complexity of unequal reflection coefficients on each boundary of the body, but this

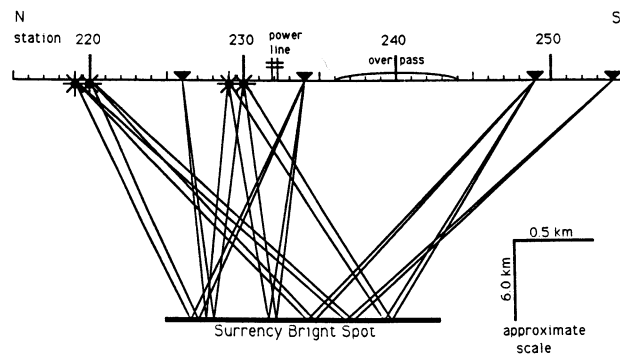


Fig. 3. Diagram of the reflection point coverage of the dynamite experiment along the main north-south profile over the SBS. Receiver locations are shown as triangles, shot locations are shown as asterisks, and the raypaths are shown as straight lines. The source and receiver locations were chosen to maximize the subsurface coverage of the SBS while avoiding the noise associated with the powerline and road overpass.

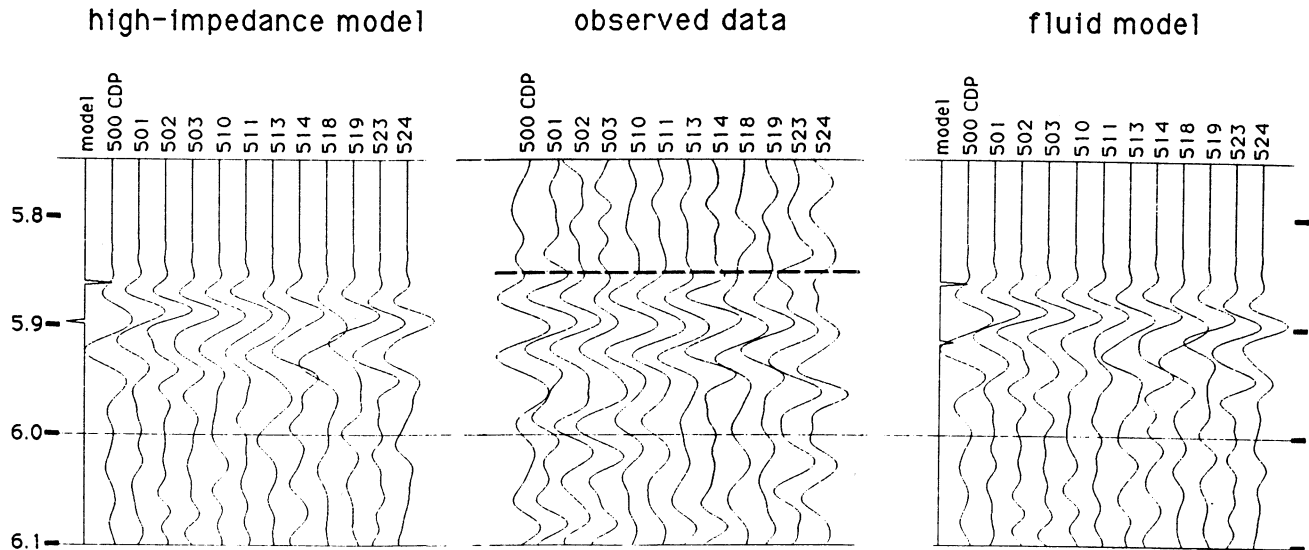


Fig. 4. Single-fold field records from the dynamite experiment, arranged by common-depth-point (CDP) with the same CDP number as the original COCORP profile (Fig. 1). The dashed line at approximately 5.86 sec is the interpreted onset of the SBS reflection package. Note the

leftward deflection of the dynamite traces at this time. The 'high-impedance' and 'fluid' model sections are discussed in the text. Data are scaled to equalize the largest values in each trace.

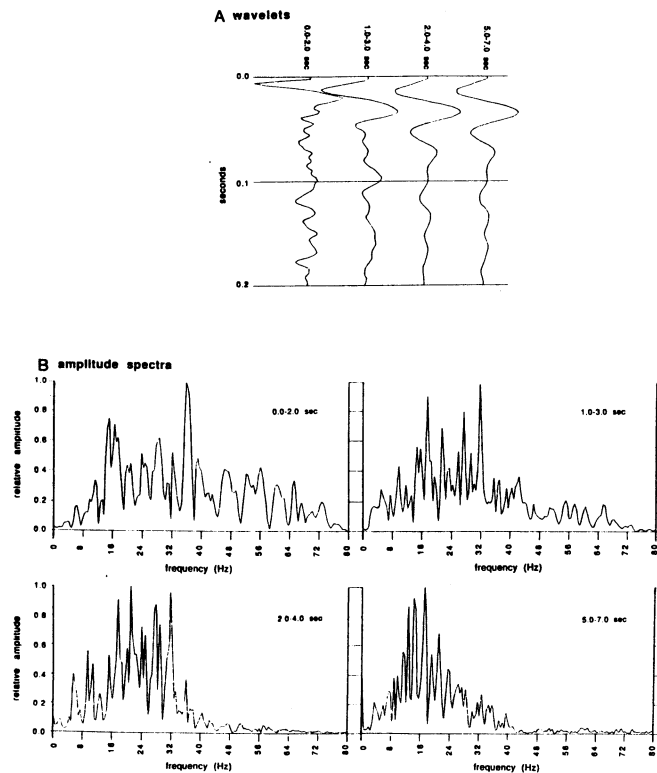


Fig. 5. Seismic wavelets and corresponding amplitude spectra from selected time windows from one trace of the dynamite experiment. Note that the pulse begins as a sharp wavelet with a broad frequency spectrum (0.0-2.0 sec window) but quickly broadens as the higher frequencies are attenuated. Most of the attenuation appears to be occurring in the upper 2.0 sec of traveltime. The wavelets were extracted from the seismic traces using the Kolmogoroff method of spectral factorization (Claerbout, 1976),

could be caused by the presence of several thin layers or a shear zone overlying or underlying the body, thus changing the reflection amplitude on one boundary.

The fluid model containing two equal positive reflection coefficients (fluid model 1) produces a reflection package whose duration is larger than the observed reflection (Fig. 7). Fluid model 2, with a smaller reflection coefficient on the second reflector, produces a reflection which is in good agreement with the observed data when the reflection spacing is about 50 msec. Our best match of any of the fluid models was with a 54 msec

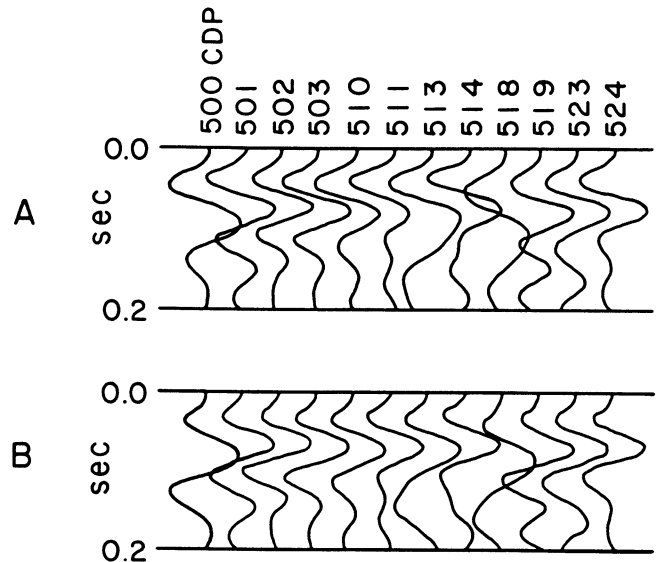


Fig. 6. The minimum-phase wavelets extracted from the dynamite data and the same wavelets after accounting for geophone phase characteristics. The wavelets correspond to the recorded traces (observed data) shown in Figure 4. Data are scaled to equalize the largest values in each trace.

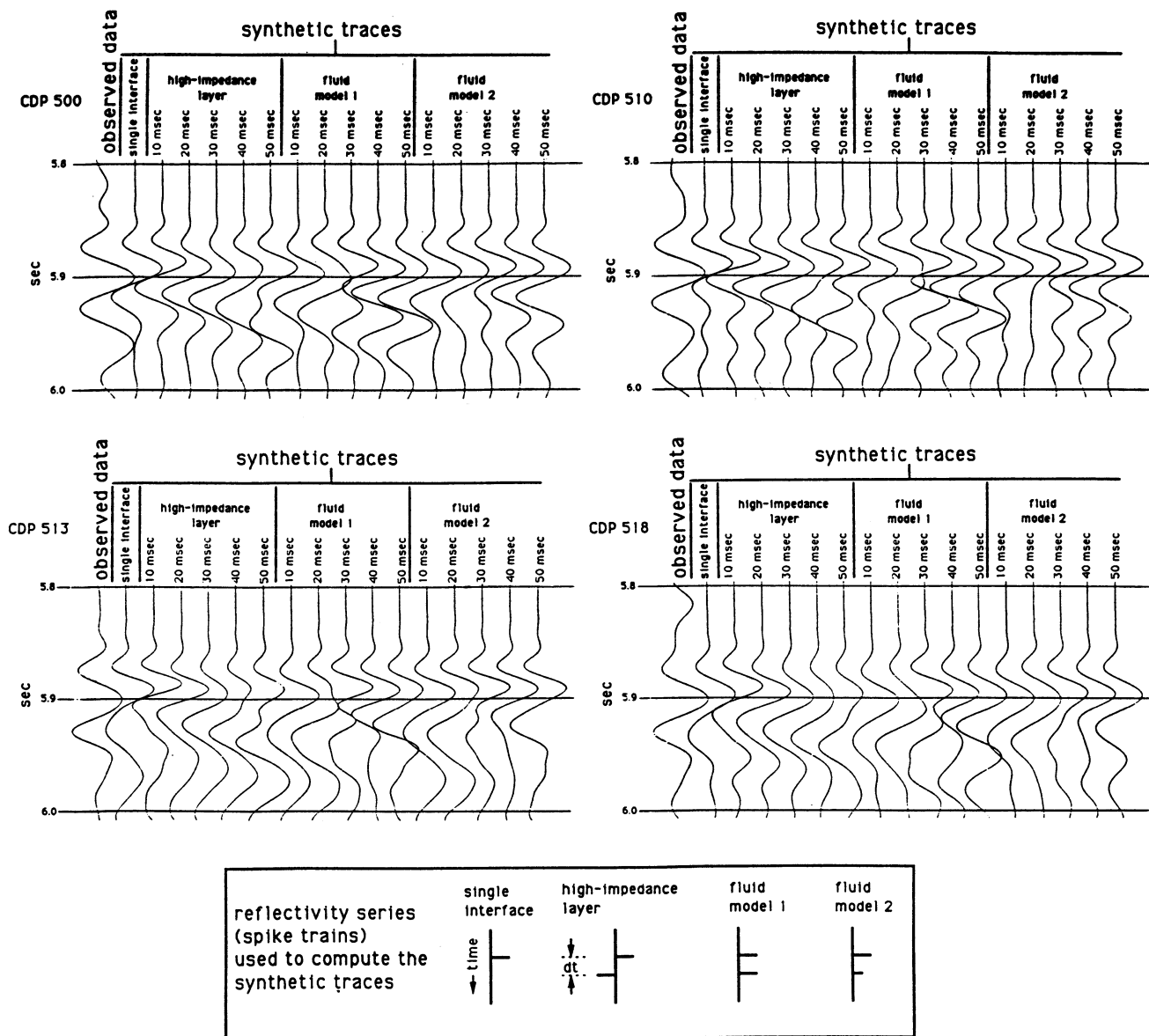


Fig. 7. Results for four CDPs of convolving the geophone-filtered source wavelets with single-interface, high-impedance, and two fluid models. The traveltime differences of the reflectors in the latter three models, which represent thin beds, were varied in 10 msec increments to

simulate different layer thicknesses. The model reflectivity functions are shown in the box at the bottom. Data are scaled to equalize the largest values on each trace.

reflection spacing (about 150 m layer thickness) and a lower reflection coefficient is 0.5 times that of the upper (Fig. 4). The drawback to the fluid hypothesis is that the polarity test requires that two or more fluids be present, and that the top of the porous zone be relatively non-reflective. Though not impossible, these constraints make the fluid model complex in comparison with the relatively simple high-impedance model.

The modeling therefore demonstrates that several interfaces are needed to adequately model the SBS reflection. A reasonable approximation to the SBS reflection package can be obtained using a simple double-interface, 120 m thick high-impedance model, although the amplitude characteristics of the bounding surfaces must be slightly different. The fluid model requires that the upper surface of the porous zone be essentially non-

reflective, that the porous layer be approximately 150 m thick, and that at least two fluids are contained in the porous zone.

Because of its simplicity, we suggest that the SBS is most likely caused by a thin (circa 120 m), high-impedance body lying within the midcrust. Two likely alternatives are a mafic sill, perhaps related to the Mesozoic rifting and associated basaltic rocks in the area, and an ultramafic sliver which was tectonically emplaced during the Late Paleozoic collision between North America and Africa. Either of these could produce reflection coefficients (ratio of reflected to incident wave amplitudes) approaching 0.1 across a single boundary; given the tuning effects of a 30 to 40 msec pair of interfaces the net reflection amplitude could be significantly larger. It must also be kept in mind that the

flatness and horizontal attitude of the SBS also contribute to providing excellent reflecting surfaces.

#### SHEAR AND P-WAVE EXPANDING-SPREAD PROFILES

During the summer of 1990, a much more extensive S- and P-wave, expanding spread profiling (ESP) investigation of the SBS was undertaken by COCORP. ESPs define the reflectivity characteristics of the reflector under a range of illumination angles and, especially when shear-waves are also used, are a sensitive indicator of the material properties of the reflector (e.g., Koefoed, 1955; Ostrander, 1984; Ensley, 1984; Robertson and Pritchett, 1985). ESP and shear-wave analyses are especially sensitive to porous zones and have been used to identify fluids within the shallow crust. Some workers have claimed to have been able to distinguish between differing types of pore fluids (Yu, 1987).

Expanding-spread profiles were collected in all three wave modes (P, SV, SH) out to offsets of 36 km, resulting in incidence angles of nearly 50° at the SBS. Both ESP and normal-incidence CDP profiles were collected in each wave mode by using separate 3-component receiver arrays positioned near the vibrators as well as at large offsets. Four shear-wave (with rotatable pads) and four compressional-wave vibrators were used as sources. A crossline CDP profile in each wave mode and a P-wave 3D experiment were collected to examine the geometry and attitude of the SBS in more detail.

Initial results show that the SBS is extremely well imaged on all of the P-wave data, including the ESP data at all offsets. The 3D and crossline experiments show that in the third dimension the SBS is nearly horizontal and has an extent that is about equal to that on the original profile (about 4 km). The shear-wave reflectivity is more problematic, but a distinct reflection is observed at the predicted traveltime for the SBS on the brute stacks of the shear-wave data. This is among the deepest reflections yet recorded from a shear-wave vibrator source. These preliminary results indicate that in addition to constraining the SBS reflectivity, the COCORP experiment will provide accurate measurements of the  $V_p/V_s$  ratio within the upper and middle crust by observing traveltime differences between the different wave modes.

#### CONCLUSIONS

An analysis of explosion data acquired over the Surrency Bright Spot (SBS) shows that it has a positive reflection coefficient at or near its upper surface. Waveform modeling demonstrates that two or more thinly spaced reflectors contribute to the large reflection amplitude. A simple, 120 m thick high impedance layer, with a positive reflection at its upper boundary and a nearly equal-sized negative reflection coefficient at its base, provides a reasonable match to the observed data when modeled. Such a model could represent a mafic intrusion or thin ultramafic sliver, either of which could produce appropriate reflection coefficients. Fluid models based on analogies with "flat spots" seen on shallow seismic sections can also provide a reasonable match but require a fluid-fluid interface within a ~150 m thick porous zone which has a relatively non-reflective upper surface. We currently favor a mafic intrusion or ultramafic sliver in the midcrust as the most reasonable explanation for the SBS because of its simplicity; additional data collected this past summer should resolve the issue.

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