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Mantle Reflections Beneath the Montana Great Plains on Consortium for Continental Reflection Profiling Seismic Reflection Data

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A systematic search for reflections from the upper mantle has been carried out on 2000 km of Consortium for Continental Reflection Profiling seismic reflection data from 14 different sites across the United States. The general observation from these data is the striking contrast between the generally pervasive reflectivity of the crust and the relative lack of coherent reflectivity in the upper mantle, a contrast that cannot always be attributed to lack of signal penetration. In order to image more of the upper mantle section on the seismic data, seismic field files were increased from 16 to 28 s two-way travel time by extended correlation processing. While the results reveal an upper mantle generally devoid of laterally continuous coherent energy, pronounced local reflections, called here the Lonesome Lake Complex, are observed at upper mantle travel times beneath the Montana Plains. Reflections at mantle travel times do not ensure mantle reflectors, as other mechanisms operating at shallower levels in the crust may be responsible for the observed reflections. However, multiple reflections and converted waves from the crust are unlikely explanations for the Lonesome Lake Complex. Although energy from outside the plane of profile cannot be ruled out, circumstantial evidence suggests that these reflections are likely due to intramantle heterogeneity. The Lonesome Lake Complex joins examples of upper mantle reflectivity observed on other deep seismic data worldwide in establishing the mantle as an productive target for future deep seismic surveys.

INTRODUCTION

Unequivocal upper mantle reflections have been virtually non-existent on routine Consortium for Continental Reflection Profiling (COCORP) seismic profiling (Figure 1). Even COCORP experiments conducted specifically to detect mantle structure, such as the Utah test with a listening time of 32-s two-way travel time (TWTT) [*Lundy*, 1988], have also revealed a general lack of coherent subcrustal reflectivity. This is substantially true of most deep seismic surveys recorded onland. Possible upper mantle reflections have been reported from seismic reflection data in the Rhinegraben in Germany [*Fuchs*, 1986], Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) data in Lake Superior [*Behrendt et al.*, 1989] and the Eromanga Basin in Australia [*Moss and Mather*, 1986]. These upper mantle reflections are usually isolated, discontinuous reflections. However, dramatic upper mantle reflections, typified by the Flannan Feature (Figure 2), have been areally mapped by the British Institutions Reflection Profiling Syndicate (BIRPS) group on marine seismic surveys surrounding Great Britain [*Smith et al.*, 1988]. These reflections have been interpreted as localized shear zones associated with North Sea extension [*Warner and McGeary*, 1987; *Klemperer*, 1988]. The common geologic setting of the aforementioned upper mantle reflections suggests that processes associated with crustal extension, such as the development of shear zones, dike and sill intrusions, and crustal underplating, may be favorable to the development of upper mantle reflections.

Motivated in part by the BIRPS results demonstrating that upper mantle reflections might be more common than once presumed, a systematic study to identify upper mantle reflections on selected COCORP data was carried out employing extended correlation techniques to generate seismic records with longer record lengths than originally interpreted. The COCORP data base (Figure 1) represents perhaps the most diverse collection of deep seismic profiles across different tectonic settings and as such presents an excellent opportunity to search for upper mantle reflections beneath diverse geological provinces. Results suggest that mantle reflections were recorded on COCORP seismic data beneath stable craton in Montana and that the upper mantle should be an additional target in future deep seismic surveys. However, since multiple reflections, mode conversions, coherent noise and energy from out of the plane of section might also be responsible for seismic energy at mantle travel times, care must be exercised in interpreting these extended seismic sections.

REPROCESSING

The COCORP data subset reprocessed for this study comprises 25 individual lines from 14 different surveys (Figure 1) covering 2000 km of seismic data, or approximately 20% of the total COCORP data base. The data were reprocessed on COCORP's Megaseis computer system at Cornell University. A standardized processing scheme was applied to the data in order to minimize the introduction of artifacts (see the appendix); line geometries, statics, mutes, and stacking velocities from the original processing were applied. Additional processing techniques were tested on both prestack and poststack data in order to evaluate various approaches to optimizing the reflectivity of the upper mantle section: precorrelation automatic gain control (AGC) [*Coruh*

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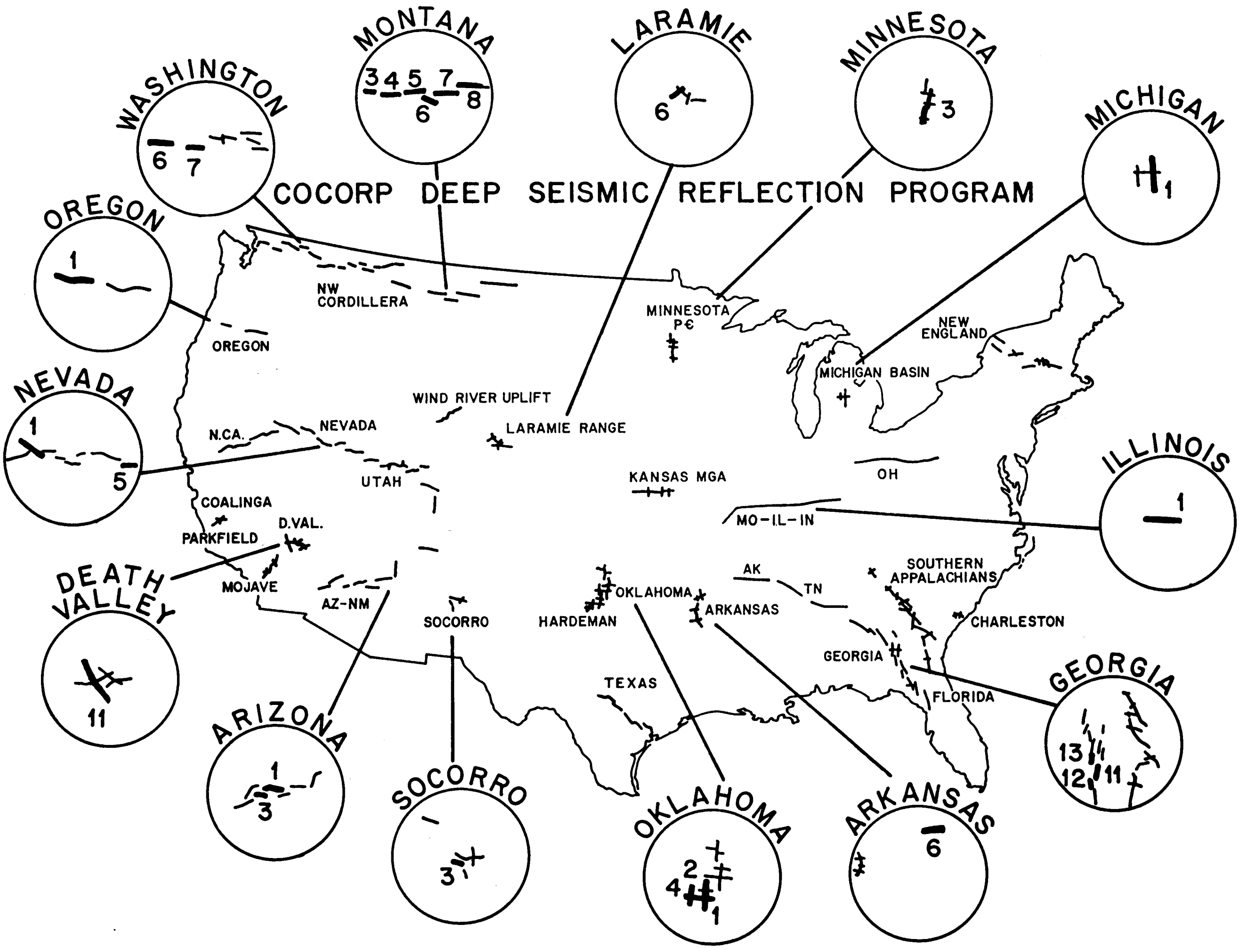

Fig. 1. Location of COCORP surveys completed as of February 1989. Titled circles denote surveys selected for this study, and bold lines within circles denote seismic lines reprocessed.

and Costain, 1983], partial and truncating correlation [*Okaya*, 1989], trace mixing, coherency filtering, correction for spherical divergence, and gain balancing. These tests generally yielded little improvement to the longer travel times and, in some instances, degraded the appearance of the deep seismic sections.

The most effective technique for highlighting relative crust-upper mantle reflectivity contrasts involved gain balancing (prestack) and a slight trace mix (poststack). "True amplitude" sections are usually dominated by reflections from the shallow sedimentary section, revealing little if any deeper reflections. On the other hand, conventional AGC boosts both signal and noise which suppresses any observable contrasts in crust/mantle energy. By muting amplitudes in the shallow section, a greater relative contrast in amplitudes from deeper events was observed upon application of a data length AGC gain. The suppression of the shallow section was achieved by application of a 4-s mute before gain balancing. This method represents a brute force approach to the problem that may be more elegantly achieved by more sophisticated gain balancing techniques that would suppress the shallow amplitudes with respect to the deep amplitudes. All of the seismic sections presented in this paper have had a deep mute applied before gain balancing. A five trace running average mix (trace weights: 0.1–0.3–0.9–0.3–0.1) was applied as a poststack process to suppress random noise and to enhance slightly lateral continuity.

Extended vibroseis correlation is a processing technique designed to utilize more of the field file as output by trading source bandwidth for more record length, resulting in a stacked seismic section with a longer two-way travel time than the listening time of the original survey. This technique was first applied to COCORP data from the Hardeman County, Texas, survey in 1974 [*Oliver et al.*, 1976] and has since been employed in many circumstances to increase record times of shallow seismic data acquired for hydrocarbon exploration to obtain additional information about basement structure [i.e., *Okaya*, 1986; *Rothstein and Trachtman*, 1986]. The technique involves continuing the vibroseis correlation process beyond the normal listening time of the survey, resulting in additional correlated output. However, the increased time is acquired at the expense of a time varying decrease in the bandwidth of the vibroseis sweep (Figure 3). A concise presentation of the theory and practical application of extended correlation processing has recently been reported by *Okaya and Jarchow* [1989].

The amount of increased listening time depends upon three factors: bandwidth, sweep rate, and acceptable limits on wavelet broadening. The first two factors determine the rate of time extension, defined as the sweep time divided by the bandwidth. For example, with a 26-s sweep time, a 12–48 Hz bandwidth, and a 16-s correlated record length (Montana Plains survey parameters), the rate of time extension equals 0.722 s/Hz (Figure 3); thus the seismic record can be extended

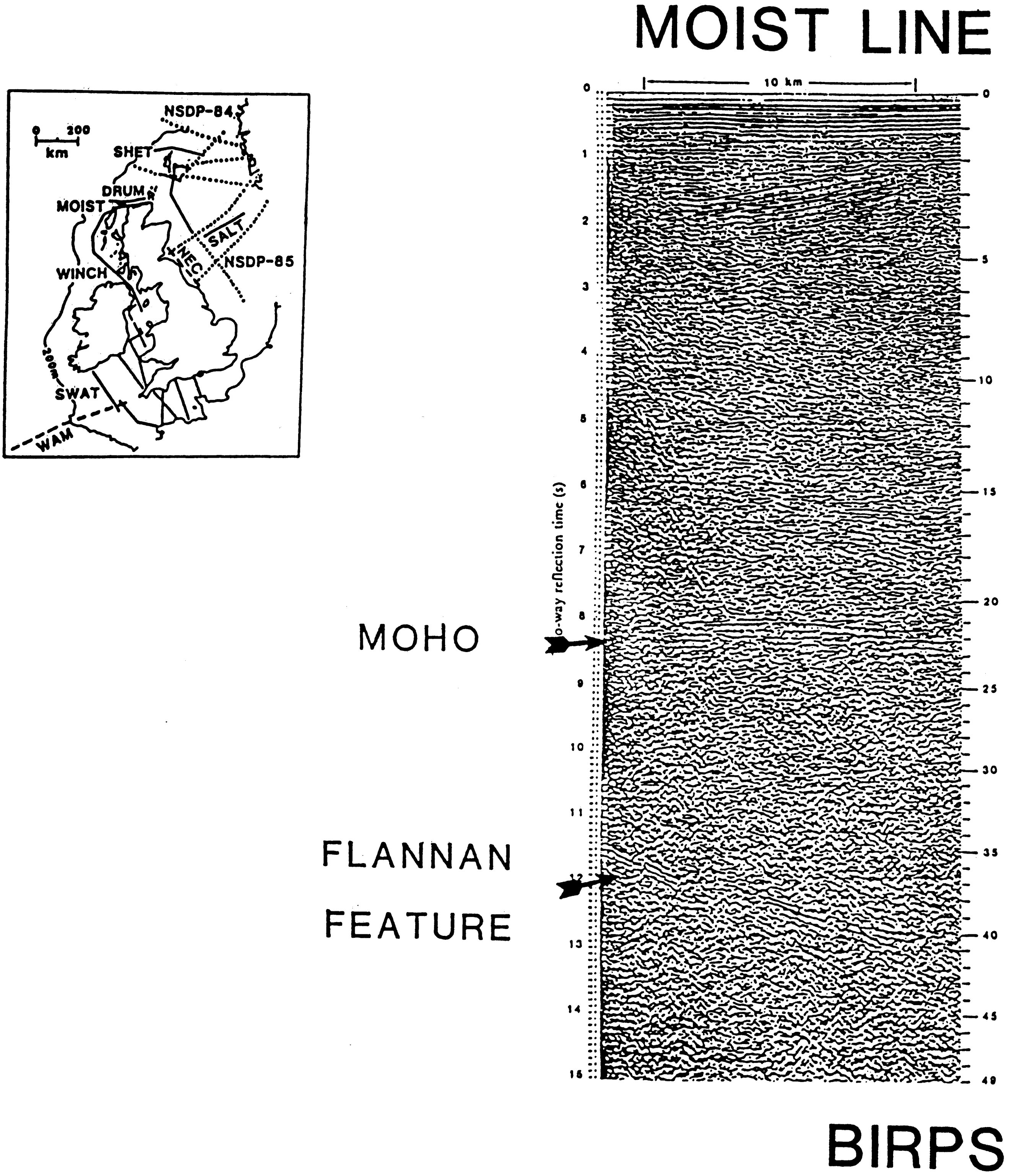

Fig. 2. Upper mantle reflections on BIRPS seismic data. Portion of MOIST line demonstrating dipping upper mantle reflections (Flannan Feature) starting at 11.5 s beneath subhorizontal Moho reflections at approximately 8 s [from *Smythe et al.*, 1982].

to 21.77 s with only a slight decrease in bandwidth to 12–40 Hz. Generally, a two octave bandwidth is considered the lower limit for a vibroseis wavelet to approximate a useful impulsive wavelet [*Lang*, 1977]. As the bandwidth becomes less than two octaves a tradeoff occurs between central lobe breath, ratio of sidelobe amplitude to maximum amplitude, and length of side tail oscillations [*Koefoed*, 1981] which results in a decrease in vertical resolution. In order to preserve as much as the bandwidth as possible, the extended correlation was terminated when the bandwidth decreased to approximately 1.5 octaves.

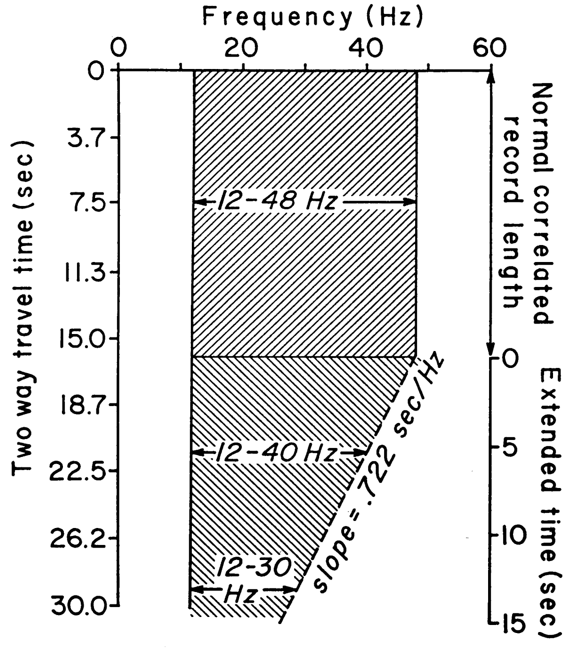

Fig. 3. Changes in bandwidth due to extended correlation for a linear vibroseis sweep of 12–48 Hz with a 16-s listening time and a 26-s sweep length (Montana survey parameters). Full bandwidth is applied in correlation process to 16 s. Extended time is available at a rate of 0.722 s/Hz. A decrease in the sweep bandwidth to 12–30 Hz results in an increase of approximately 13 s extending the correlated record length from 16 to 29 s.

RESULTS

The majority of seismic lines reprocessed for this study show a common reflection pattern for the upper mantle consisting of short, discontinuous energy "randomly" distributed. An example of this reflectivity is seen on Georgia line 11 (Figure 4*a*). Comparison of this seismic section with wind strips (Figure 4*b*), which are active geophone arrays recording the daily background noise levels, suggests that the energy on the stacked section is no more coherent than noise from cultural and/or natural sources. Several departures from the random upper mantle reflectivity were observed on the Oklahoma, Michigan, and Montana surveys; weak, sub-Moho, dipping reflections truncated at the base by horizontal reflections were observed on a portion of Oklahoma line 1 and a sub-Moho transparent zone followed by an increase in randomly distributed reflections was observed on Michigan line 1. These sub-Moho variations in Oklahoma and Michigan are questionable as to their upper mantle nature; the possible Oklahoma mantle reflections are not present on an appropriate crossline and the Michigan mantle reflectivity may well be associated with noise spikes enhanced by the trace mix. Therefore, these examples are not presented here. While there is little evidence to support the Michigan and Oklahoma reflections as true, upper mantle reflections, a reflection package at 22 s on the Montana Plains survey presents a convincing example of possible upper mantle reflections beneath the Montana craton.

COCORP's Montana Plains transect (acquired in 1986) is composed of six seismic lines that run west to east from the front of the Rocky Mountains thrust belt to the western edge of the Williston Basin (Figure 5). The survey traverses the Montana Block, the northernmost of a series of Precambrian age units that are anchored by the Archean Wyoming Province [i.e., *Tonnsen*, 1986]. These blocks have experienced differential uplift throughout the Phanerozoic that has influenced Phanerozoic sedimentation patterns (*Peterson* [1986] and other papers in the same publication).

The interpretation of regional refraction data have yielded a number of velocity-depth models for the Montana region [*Meyer et al.*, 1961; *McCamy and Meyer*, 1964; *Asada and Aldrich*, 1966]. Moho traveltimes calculated from these models ranges between 12.5 and 18.2 s [*Prussen*, 1989]. Figure 6 is adapted from *Prussen* [1989] and shows the comparison between *Meyer et al.* [1961] velocity model and Montana line 4. The relative abrupt cessation of coherent reflections correlates well with the top of the 8.40 km/s region. Thus reflection and refraction data appear to correlate with respect to the Moho in Montana within the uncertainties inherent in velocity estimation.

All six lines of the Montana survey were reprocessed for this study, and most are characterized by a highly reflective crustal section with the Moho generally marked by the cessation of diffuse reflections, rather than a specific prominent reflection zone [*Latham et al.*, 1988]. The exception to this are the prominent Moho reflections on Montana 8 located on the western edge of the Williston Basin. Figure 7 is an example of the highly reflective crust of the Montana Plains imaged on COCORP Montana line 4. The Moho is interpreted by an abrupt cessation of reflections at approximately 14.5 s TWTT. This Moho characterization appears typical of cratonic areas [i.e., *Brown et al.*, 1983; *Serpa et al.*, 1984; *Meissner and Wever*, 1986]. The sub-Moho section is devoid of any coherent energy of more than a few traces in lateral extent. Note that the five trace mix applied to the data would enhance any lateral continuity that might exist, yet no extensive lateral continuity is observed. Observations such as this have lead to descriptions of the upper mantle as

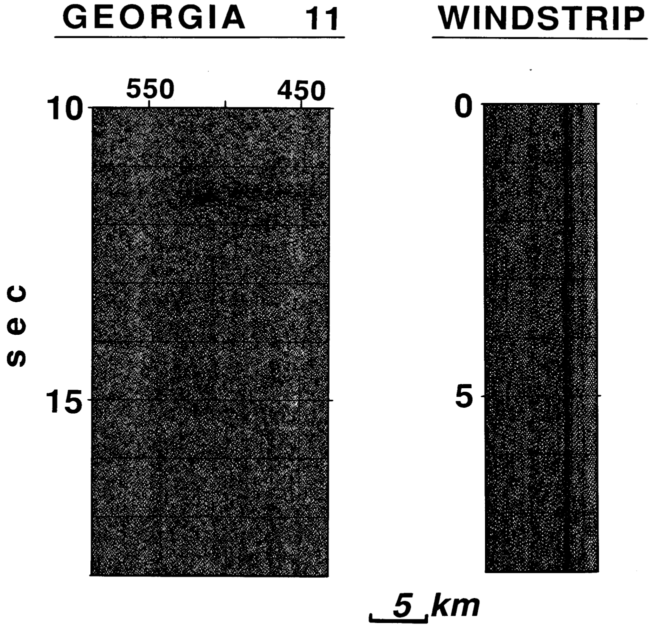

Fig. 4. Comparison of an upper mantle section from Georgia 11 consisting of (*a*) short, discontinuous energy randomly distributed and (*b*) a correlated wind strip. The similarity suggests that much of the deep seismic section may be dominated by random noise from cultural and/or natural sources.

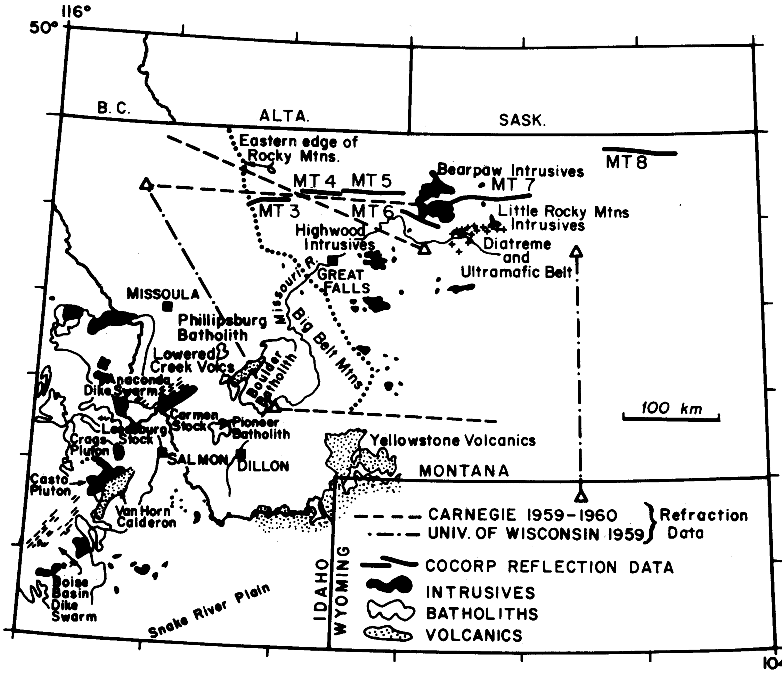

Fig. 5. Location of Montana Great Plains Survey, 1986. All the lines of this survey were reprocessed for this study. The star marks the location of the upper mantle reflections, named the Lonesome Lake Complex. The dashed lines marks the locations of refraction lines in the region. Adapted from *O'Neill and Lopez* [1985].

nonreflective [*Moss and Mather*, 1986], seismically transparent [*Goleby et al.*, 1989], or homogeneous [*Brown et al.*, 1983].

Although the crustal reflectivity remains similar as one proceeds eastward on Montana 5, a prominent, multicycle reflection package is observed between shot points 450 and 550 at approximately 22 s TWTT (Figure 8). These subhorizontal reflections are recognizable over a 9-km lateral extent with a maximum duration of approximately 300 ms. The reflections taper to the west (Figure 9), while the eastern termination of the reflections is diffuse. The multicyclic

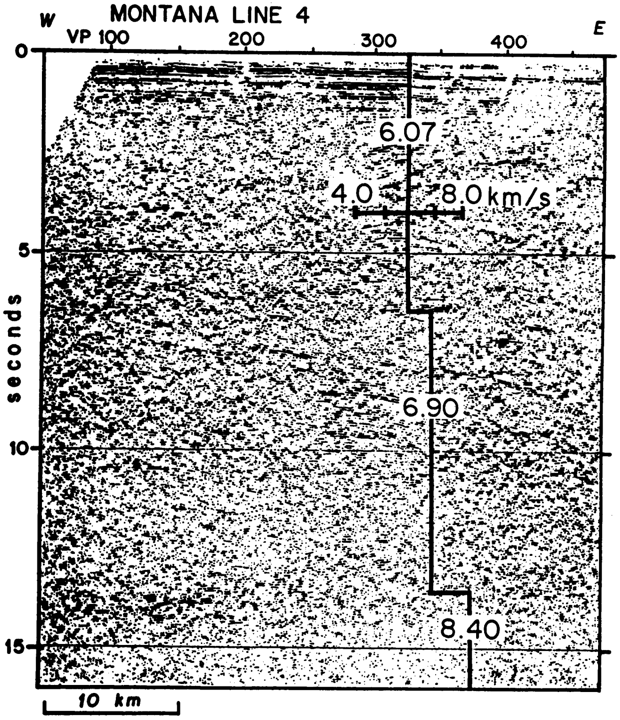

Fig. 6. Refraction velocity model of *Meyer et al.* [1961] superimposed on Montana 4. Adapted from *Prussen* [1989].

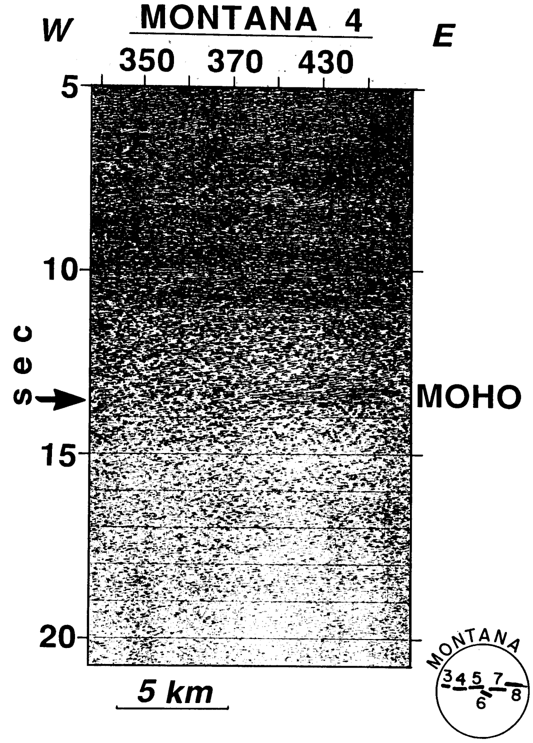

Fig. 7. Montana line 4. This section reveals a nonreflective upper mantle beneath a highly reflective crustal section. The appearance of the short reflection segments dispersed throughout the upper mantle section is due to the five trace mix applied to the stack section.

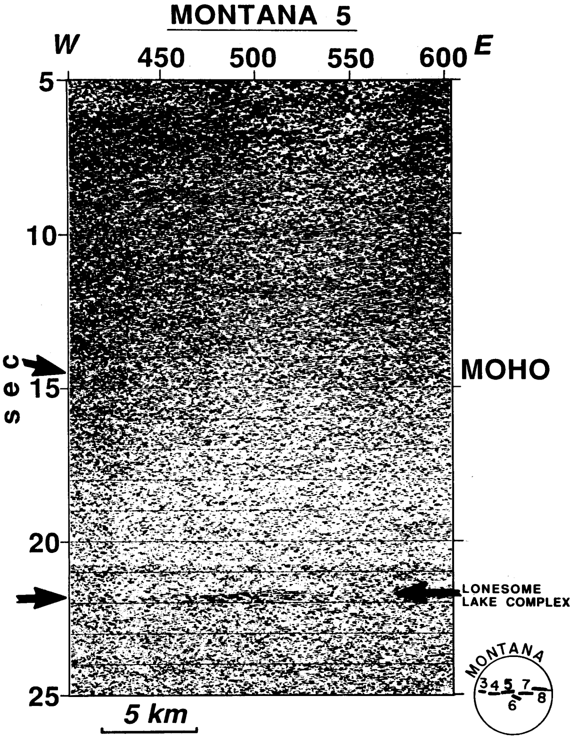

Fig. 8. Montana line 5. Example of coherent reflections observed in an otherwise nonreflective upper mantle. The nonreflective mantle section is similar to that apparent on Montana line 4 located immediately to the west.

appearance of the reflections suggests the presence of localized layering in the upper mantle. Assuming an average crustal velocity of 6.0 km/s and an average upper mantle velocity of 8.0 km/s, a vertical travel path places this feature at approximately 72 km depth, or 27 km beneath the interpreted Moho reflections. This reflection package is here identified as the Lonesome Lake Complex (LLC), after an similarly isolated lake nearby.

The Lonesome Lake Complex is located approximately 50 km west of the Bearpaw Mountains, a middle Eocene volcanic center dominating the local landscape [*Hearn*, 1976]. In turn, the Bearpaw Mountains lie within the Great Falls Tectonic Zone (GFTZ), a northeast trending zone 150–250 km wide extending from southwest Montana to Saskatchewan, Canada, which is interpreted to mark the northwestern boundary of the Archean Wyoming province [*Condie*, 1976]. This zone is characterized by high-angle faults, shear zones, intrusive complexes, volcanics and diatremes (Figure 5) [*O'Neill and Lopez*, 1985]. Geographic proximity, at least, raises the question of whether the LLC is related to the igneous architecture of the GFTZ (representing a crust and upper mantle marked by intrusions), or more specifically associated with the development of the Bearpaw Mountains.

McCamy and Meyer [1964] infer a region of unusually high velocity at approximately 65–68 km depth on a east-west reversed profile acquired south of the Bearpaw Mountains (Figure 5). The top of this highly speculative zone is at the approximate depth estimated for the Lonesome Lake Complex (72 km), a correlation too close to seem fortuitous. *Hearn et al.* [1988] reports that xenoliths from the mafic phonolites in the Bearpaw Mountains contain both undeformed, cumulate-textured peridotites and deformed peridotites. The relationship of these rock suites to the LLC reflections is unclear; however, they reasonably suggest some scale of heterogenity in the Montana mantle. Both mafic layering and shear zones permeated by mafic material are considered viable mechanisms for generating mantle reflections on BIRPS data [*Flack et al.*, 1990]. The possible presence of localized upper mantle heterogeneity based on the refraction data and xenoliths provide at least circumstantial support for an upper mantle origin of the LLC.

The question of signal penetration is an important consideration when dealing with the identification of any deep reflections and can be quantitatively addressed by the use of amplitude and average frequency decay curves. These curves reflect the decay of seismic energy, as a result of scattering, attenuation, and spherical divergence, toward the ambient noise level, which is characterized by a relatively constant value throughout the record length. Decay curves are computed here by taking the log of a low-pass-filtered trace envelope of ungained traces for the amplitude curves and a spatially and temporally averaged instantaneous frequency for the average frequency curves [*Barnes*, 1990]. The intersection of the decaying signal curve with the ambient noise level is generally taken as a guide to the extent of adequate signal penetration [*Mayer and Brown*, 1986]. An important consideration in the use of decay curves is the number of cdp traces summed together as input to the calculations. Decay curves composed of entire lines (Figure 10*a*) reveal relatively smooth curves that represent the mean amplitude characteristics of the crustal section beneath the entire seismic line; decay curves for a subset of the entire seismic line demonstrate greater variance in the amplitude levels and serve to highlight amplitude variations in smaller crustal regions (Figure 11*a*). The trace selection process can be continued down to a single seismic trace, but the advantages of this choice are uncertain. Deep reflections, whether primary or multiple reflections, are generally recognized on

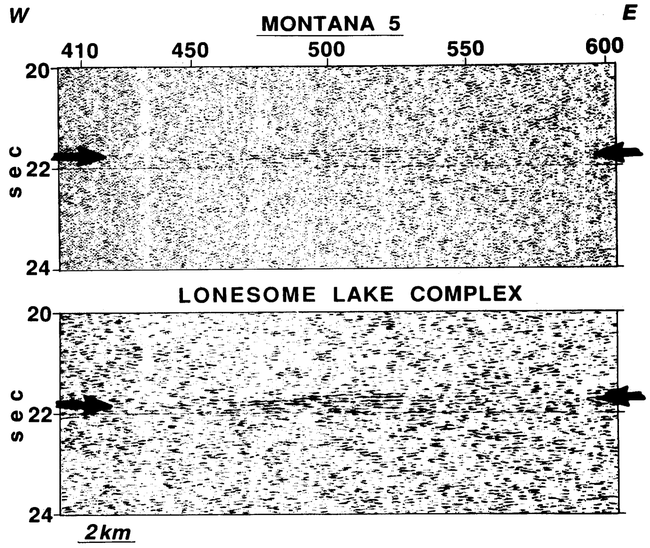

Fig. 9. Closeup of the Lonesome Lake Complex, Montana line 5. The upper display represents a normal final stack section and the lower display has a five trace mix applied with a weighting scheme of 0.1–0.3–0.9–0.3–0.1. The reflections are distinct over 9 km in length and reach a maximum thickness of 300 ms.

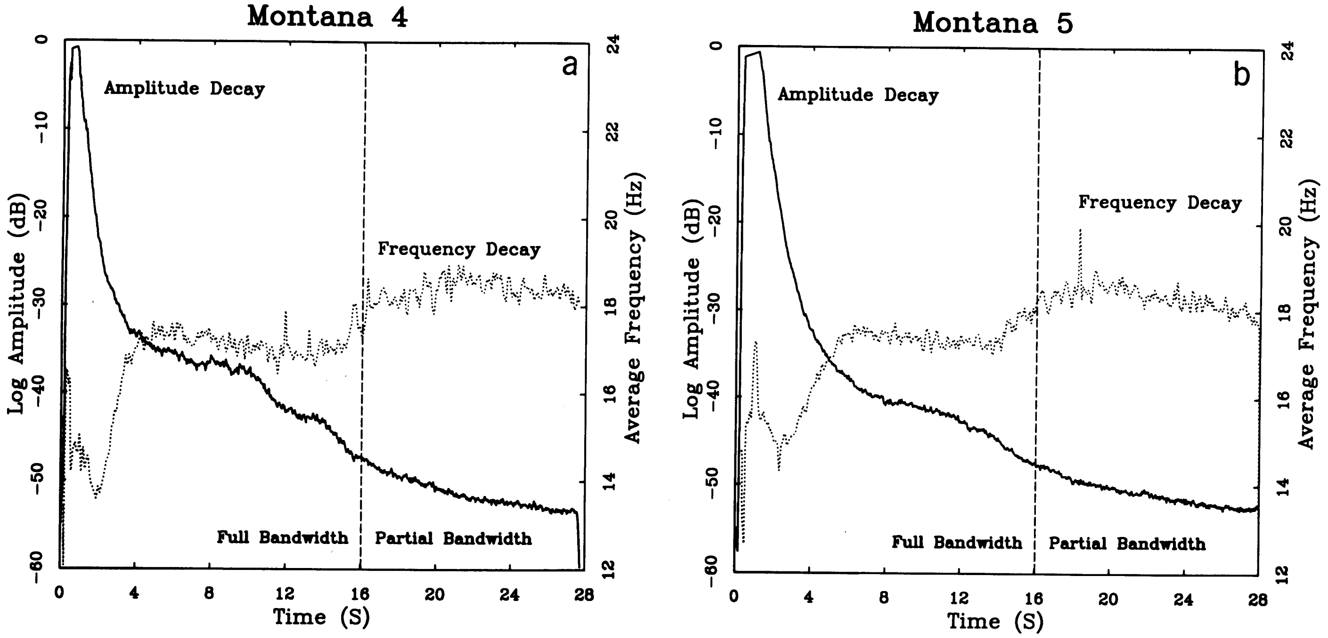

Fig. 10. Decay curves for the entire line. (*a*) Amplitude and frequency decay curves for Montana 4. (*b*) Amplitude and frequency decay curves for Montana 5. Note slight amplitude rise at approximately 22 s for the Lonesome Lake Complex.

seismic data by their relative lateral continuity with respect to background random noise. Thus, in this instance, the obvious choice is a decay curve calculated over the lateral extent of the LLC reflections on Montana 5 (Figure 11*a*).

The amplitude decay curve for Montana 4 seismic line (Figure 10*a*) falls off by 35 dB between 0 and 4 s TWTT. A decay "plateau" with only a 5-dB decrease exists between 4 and 10 s TWTT in the midcrust region. From 10 to 13 s TWTT the amplitudes decrease by 5 dB, and the decay curve levels off slightly at the interpreted Moho travel time. A sharp transition zone characterizes the decay curve near Moho travel times. This is compatible with a cessation of crustal reflections that characterize the Moho on Montana 4 rather than a Moho characterized by a single prominent reflection. Amplitude decay continues beneath the Moho to 16 s TWTT (implying that the ambient noise level has not yet been reached) at which point the observed signal decay is directly associated with bandwidth truncation inherent in the extended correlation processing. Similar crustal decay slopes are present on the amplitude decay curve for Montana

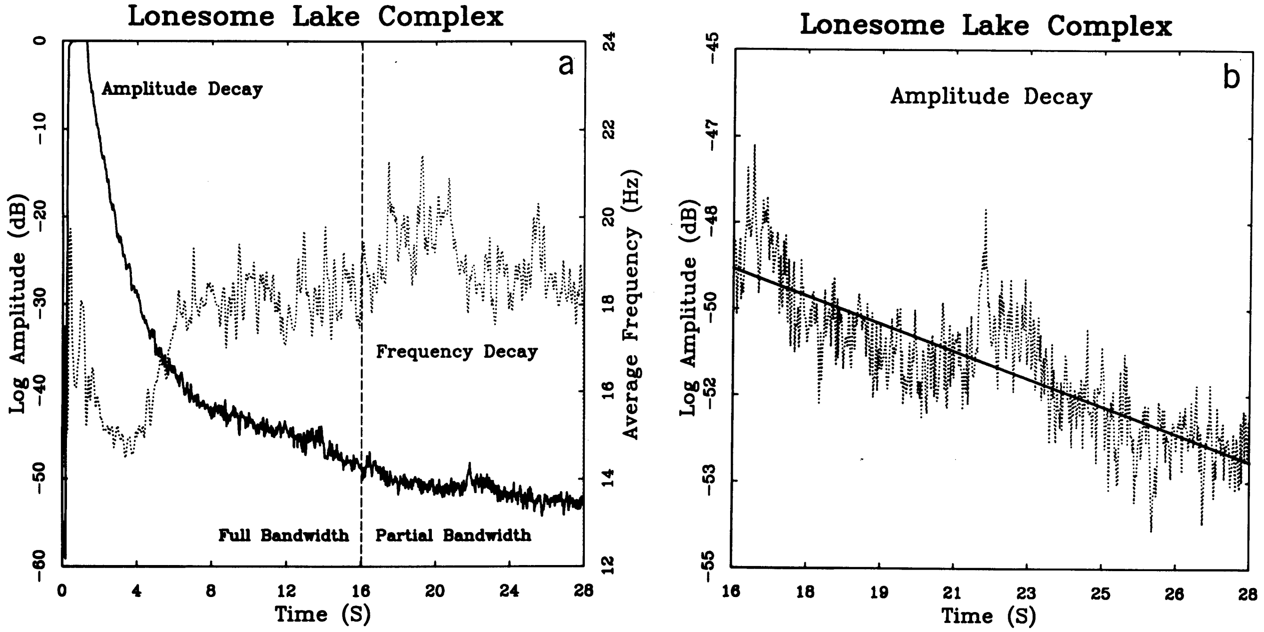

Fig. 11. Decay curves for the Lonesome Lake Complex. (*a*) Amplitude and average frequency curves for 100 CDPs centered on the LLC. (*b*) Zoom of the upper mantle decay section highlighting the amplitude plateau. Straight line represents a linear, least squares fit of the amplitude data and decay due to bandwidth truncation.

5 seismic line (Figure 10*b*), with the LLC appearing as a minor amplitude "plateau" at 22 s on the upper mantle portion of the decay curve. Figure 11*a* details an amplitude decay curve composed of 100 CDPs from Montana 5 centered on the LLC reflections. The amplitude rise associated with the LLC is highlighted in Figure 11*b*; the straight line represents a linear, least squares fit of the decay curve and the decay associated with the bandwidth truncation. The LLC is 2 dB above the line and an amplitude plateau continues for 1.0 s after the LLC reflections. As the LLC is observed to be only 300 ms in time, the amplitude plateau may be the result of multiple reflections generated by possible layering of the LLC, or from within the shallower section. Average frequency decay curves demonstrate a complementary situation to the amplitude curves. Theory suggests that for a truly nonreflective upper mantle section, the average frequency decay curve should decay to the average frequency of the noise level [*Barnes*, 1990]. This situation is observed on Montana 4 and 5 (Figures 10*a* and 10*b*).

The nature of the decay curves for Montana 4 and 5 and the presence of the Lonesome Lake Complex on Montana 5 yield two conclusions: that the upper mantle beneath Montana 4 and 5 is truly nonreflective at seismic wavelength scale (except for the Lonesome Lake Complex) and that sufficient signal penetration is achieved to at least 22 s TWTT (or approximately 70 km depth). The success in achieving such deep signal penetration may well be a consequence of an excellent acquisition environment with long straight roads of uniform surface conditions, efficient vibroseis ground coupling, and little cultural noise.

The Montana Lonesome Lake Complex is suspected to be of igneous origin due to its proximity to the Bearpaws volcanic center and location within the Great Falls Tectonic Zone. Reflection coefficients from the upper mantle events seen on the BIRPS seismic surveys offshore Great Britain [*Warner and McGeary*, 1987] suggest two possible models that could generate the inferred impedance contrasts: a partial melting event resulting in mafic layering within a peridotite matrix, or partially hydrated peridotite, including serpentine, mica, or amphibole. With only an estimate of depth and rough geometry of the LLC known to date, it is premature to suggest which mechanism is responsible for the Montana reflections, as either could apply to the LLC.

DISCUSSION

The general observation of this study is the striking contrast between the pervasive reflectivity of the crust and the almost total lack of coherent reflectivity in the upper mantle imaged on COCORP seismic data. This statement must be qualified as to whether or not this observation represents a geological characteristic of the upper mantle or a signal penetration problem. If the lack of upper mantle reflectivity is of a geological nature, then two possibilities may exist: (1) properties properties of possible mantle lithologies are such that acoustic impedance contrasts are very small, generating very weak reflections at best, as presented by *Warner and McGeary* [1987]; or (2) the upper mantle attenuation factor is low. If, on the other hand, inadequate signal penetration, and not inherent reflectivity, is responsible for the lack of observed coherent upper mantle reflectivity on seismic data, then it is premature to catagorically call the upper mantle nonreflective. The best case for reflectivity versus nonreflectivity due to upper mantle geology can be made by demonstrating adequate signal penetration at depth on the seismic data from the Montana Plains survey.

However, coherent energy at sub-Moho travel times does not necessarily imply mantle reflectors. Other possible explanations include multiple reflections (including long period and peg-leg), mode conversion (i.e., *P* to *S* conversion), source-generated noise, unmigrated energy from shallow depth, energy from out of the plane of profile, and reflected refractions.

Although it was once expected that multiple reflections were a serious problem on deep crustal seismic lines [*Zawislak and Smithson*, 1981], they do not seem to be a general problem [*Jones*, 1985]. Intermediate-order multiples generated within the sedimentary section are not generally recognized as a problem on land seismic data, in contrast to the prominent water bottom multiples often observed on marine surveys. Moreover, common depth point (CDP) stacking appears to be quite effective in reducing their contribution to the stack. However, multiples might contribute more subtly to coherent energy on land seismic data. Energy from intrabasement multiples are even less likely to be observed due to the already small reflection coefficients of expected basement lithologies [*Christensen*, 1965; *Warner and McGeary*, 1987]. Multiple energy may contribute to background noise levels but appears to lack coherence over any appreciable lateral extent.

Shear waves remain an unknown component of the energy on seismic reflection data. Results from vibroseis source studies reveal that shear wave energy comprises approximately 26% of the generated energy [*Miller and Pursey*, 1956], yet this energy has rarely been recognized on deep seismic reflection profiles. Shear waves on COCORP seismic data from Georgia have been identified on the basis of normal moveout and interpreted as due to *P-S* or *SV-P* conversion [*Gremell and Cook*, 1985]. Note that these converted reflections are from shallow depths (approximately 1.5 s TWTT) corresponding to large offset apertures. Although wide-angle seismic experiments periodically image arrivals greater than *PmP* and have been interpreted as converted phases or multiples from within the crust [*Luetgert et al.*, 1987], the small aperture angle of near vertical reflection profiles are unlikely to record shear phases. Shear waves would be expected to be highly attenuated by the CDP stacking based on *P* wave velocities, however, since little moveout is present at mantle traveltimes, they should also stack in.

Misidentification of unmigrated energy (i.e., diffractions) or reflected refractions from the crust as mantle reflections are a more serious concern. Migration should collapse diffractions and most dipping events within the plane of profile to their "true" position. However, three dimensionality of structures, velocity uncertainties, and migration noise could inhibit the proper location of dipping events, leaving the impression of a mantle origin for the reflections.

Energy out of the plane of profile may be the most common ambiguity on deep seismic profiles. Since cross-line control is still relatively rare, identification of reflections from off-line locations is extremely difficult. Additionally, a priori knowledge for the positioning of cross lines is usually lacking for initial surveys in a given area. Although cross-line control is available for many COCORP surveys, few prove to be suitably located over the potential mantle events.

The aforementioned mechanisms are possible explanations for any subbasement reflections observed on any deep seismic data. Additionally, misstacking of the CDP traces due to deep statics associated with lateral variations within the crust can be significant but unobtrusive in its effect. Finally, the highly reflective Montana crust suggests numerous opportunities for mode conversions and/or multiple generation to produce nonprimary reflections at deeper travel times. Yet only the coherent reflections of the Lonesome Lake Complex are observed at upper mantle travel times along the Montana Plains transect and argues for its viability as a true upper mantle reflection.

CONCLUSIONS

Reprocessing of over 2000 km of COCORP seismic surveys by the technique of extended correlation reveals that the upper mantle is generally nonreflective. However, it is unclear whether or not this represents a case for homogeneity in the upper mantle or a problem of adequate signal penetration with depth. The latter appears to be a prevalent situation at deep travel times. However, in one case, localized, prominent coherent upper mantle reflections (Lonesome Lake Complex) superimposed upon a genuinely nonreflective upper mantle, not associated with a lack of signal penetration, was observed beneath the Montana Craton. This feature is suspected to be of igneous origin, due to its proximity to the Bearpaw Mountains volcanic center and general position within the Great Falls Tectonic Zone. Amplitude and average frequency decay curves of the Montana seismic profiles quantitatively demonstrate a nonreflective upper mantle section and adequate signal penetration down to approximately 70 km along the western portion of the Montana Plains survey. The Lonesome Lake Complex demonstrates that upper mantle reflections are observed beneath cratons.

In spite of the rare occurrences of the upper mantle reflections worldwide, the upper mantle is a clear frontier for deep seismic profiling of the lithosphere. The importance of identifying upper mantle reflections and their influence on establishing boundary conditions for lithospheric deformation has been well demonstrated around the British Isles by studies from the BIRPS group and others; extension of the subcrustal lithosphere may well be represented in the structure of the overlying sedimentary basins. The extensive mantle reflections around the British Isles represent the majority of upper mantle reflections observed to date; more will undoubtably be found. Long regional transects offer the best opportunity for maximizing the identification of possible upper mantle reflections. In fact, where vibroseis sources are employed, the upper mantle section can be imaged at no additional acquisition costs through the use of extended correlation techniques. Crosslines are critical for defining the three-dimensional structure of the reflectors and eliminating other explanations for the reflections, such as energy out of the plane of profile. However, placement of cross lines is impossible without prior location of mantle targets by reconnaissance work. As only a small portion of the COCORP data set was considered in this study, the remaining data should be reprocessed. Future efforts should address the question of adequate signal penetration at depth with source tests, varying type of source and energy levels, and source-receiver array configurations to ensure necessary conditions for imaging upper mantle reflectors.

APPENDIX: GENERALIZED PROCESSING SEQUENCE

- Demultiplex
- Vibroseis correlation
  - Resampled from 4 to 8 ms
  - Correlation extended to 28 s
- CDP gather
- Statics
- Velocity analysis
- Mute
- Trace equalization
- Deconvolution
- Normal moveout
- Stack
- Frequency filter
- Trace balance
- Trace mix
  - Five-trace running average
  - Traces scaled by 0.1, 0.3, 0.9, 0.3, 0.1
- Display

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