

Exploration of the continental basement by seismic reflection profiling

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The structure of the continental crust and uppermost mantle is being explored with higher resolution than previously attained through application of the seismic reflection profiling technique of the petroleum industry. Crustal structure is diverse, and features such as faults, unconformities, magma bodies, and the crust-mantle boundary have been delineated.

SOME four billion people derive their livelihood from this planet, so society's need for a thorough understanding of the Earth and a comprehensive inventory of potentially accessible Earth resources seems obvious. Yet except for mining prospects and districts, and the sedimentary basins that are the habitat of petroleum, there is little detailed or direct knowledge of subsurface Earth structure and composition at depths greater than a few tens or hundreds of metres. In most areas, deep rocks of the crystalline basement can be described only in general terms based on indirect evidence. Their genesis and evolution remain largely unknown.

The reasons for this remarkable state of affairs are partly economic and partly historical and organisational. They are also partly technological although there are means for improving substantially, if not ideally, our knowledge of the crystalline basement. Better mapping and improved field and laboratory studies of surface rocks, drilling for informational purposes, study of xenoliths of basement origin, and further application of a variety of geophysical methods are all feasible and promising. The article focuses on potentially the most productive and the most sophisticated geophysical technique—seismic reflection profiling—and its application to studies of the basement. This does not mean that other methods are not valuable; in general, they provide complementary information. The seismic reflection profiling technique discussed here should not be confused with the seismic refraction technique that is conventionally used for exploration of the crust, or with the Russian DSS method, which uses both refraction and wide-angle reflections.

During 1976 world expenditure on seismic reflection profiling was well over one billion dollars. Essentially all of this money was spent on exploration for petroleum. Continuing effort on this scale by the petroleum industry has resulted in, and is the result of, development of the technique of echo ranging in the Earth to a very high level of sophistication. In recent years, the industry has produced such innovations as non-explosive sources, digital field recording for movable listening arrays of thousands of detectors, computer processing of immense quantities of digital data, and powerful new methods of analysis and interpretation that have greatly enhanced understanding of the stratigraphy and structure of sedimentary basins. Modern reflection profiling bears little resemblance to the simple one shot—one detector method initially employed in the 1920s.

Within the past few years in several different countries, successful attempts have been made to apply these modern techniques, with appropriate modifications, to exploration of the continental basement and hence greater depths (for a review see ref. 1). Here, the term 'basement' refers to crystalline rocks typically lying below the sedimentary veneer that is some 0–10 km thick. The continental basement rocks of interest here extend through the base of the crust at some 35–45 km and into the underlying mantle to depths of 50 or so km, the current limit of the method. Although rocks of the deep continental basement

have been explored with some success previously using various geophysical techniques, the new efforts based on reflection profiling offer far greater resolution of structural detail and much better information on other properties that are currently unknown or poorly known. Because of the potential of this much improved, yet rarely applied, observational capability in seismology, the potential of other geophysical and geological methods, the great extent of the basement, and the direct and informative relation of the deep continental basement to the near-surface rocks, the continental basement must be considered one of the major scientific frontiers of modern geology.

The method

The principle of the seismic reflection profiling technique is deceptively simple. A disturbance at or near the surface of the Earth generates elastic waves that propagate through the Earth and are detected and recorded by sensors at the surface near the source. Although other kinds of waves are sometimes useful, most information comes from the compressional waves that travel along near-vertical paths and are partially reflected at buried sub-horizontal interfaces between rocks of contrasting impedance. The travel time of a pulse propagating along such a path is perhaps the prime information gathered, but the amplitude, phase, frequency content, and apparent surface velocity of the signal are also valuable.

The source and receivers are moved together along a line and the experiment repeated at closely spaced intervals so that subsurface reflecting horizons may be traced, and a profile or section obtained in a similar manner to that of a marine echo sounder. The basic travel-time data must be ultimately converted to depths and reflectors properly positioned; hence it is necessary to know or to measure the spatial distribution of velocities along the profile. One common method for velocity measurements uses reflected waves travelling along paths that are somewhat off the vertical. Thus, a single source might be detected and recorded by many sensors distributed over distances ranging from near zero to significant fractions of the depth of the deepest reflecting horizon.

Furthermore, because the sources generate kinds of waves (surface waves, shear waves, waves with complex paths, diffracted waves) in addition to the nearly vertical travelling compressional waves that are normally the signal, arrays of many source elements and arrays of many receivers are commonly used to discriminate against the unwanted waves as well as background noise. Some data are also collected off the line, to permit the waves propagating out of the plane of the section to be identified.

In practice, there are numerous variations of the technique which depend on a large number of factors, such as local terrain, local propagation phenomena, economics, available hardware, characteristics of the particular target, and noise conditions.

As an example, a field procedure sometimes used in the

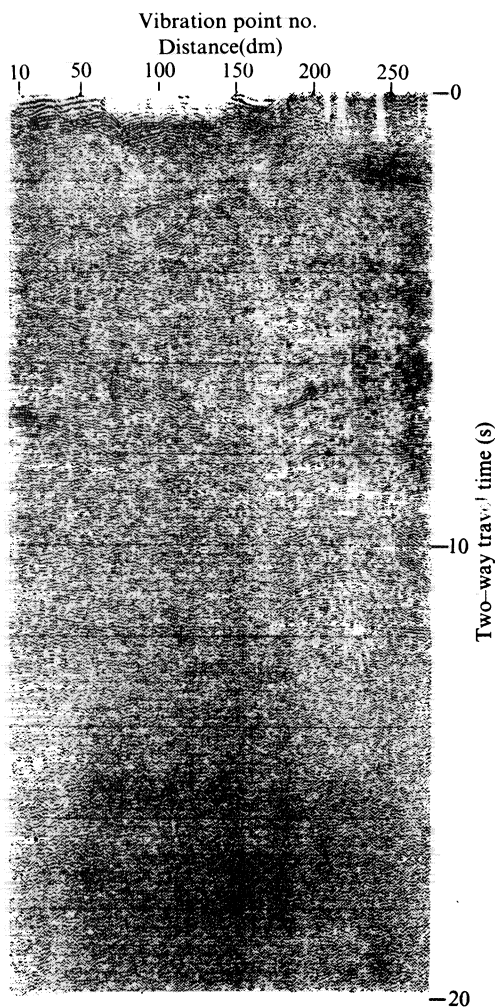


Fig. 1 Seismic section for line 1, Rio Grande Rift (see Fig. 3).

COCORP project is described in some detail in the following. (COCORP is consortium for continental reflection profiling, and the project is the major US effort to apply the seismic reflection profiling technique of the petroleum industry to study of the deep basement of the continents. The procedure represents a compromise among various factors including acquisition of maximum possible information, economics, and logistics.)

COCORP uses the VIBROSEIS technique developed by the Continental Oil Company. Instead of an impulse generator such as an explosion, weight drop, or compressed air gun, a truck-mounted vibrator serves as a source element. Each vibrator imparts a peak vertical force of some 13 tons over about 20 ft² of the Earth's surface; the force is near-sinusoidal in time but of slowly varying frequency. The signal thus resembles a radar 'chirp' in character, though not in frequency. Typically the duration of vibration is 20 s, and the frequency varies linearly from 8 to 32 Hz over the interval. Cross correlation of the recorded signal with the input produces a record resembling that from an impulsive source, subject, of course, to restrictions of bandwidth and other properties of the VIBROSEIS source and the propagation. The advantages of the method include flexible and precise control of source character, elimination of drilling to implant explosives, avoidance of legal restrictions on explosives and the explosive hazard, and efficient coupling of source energy into elastic waves without great loss through rupture or other non-linear effects near the source. VIBROSEIS has been used widely and successfully on land by the petroleum industry for many years.

In a typical COCORP survey, stations in the field are spaced at 100-m intervals. Five vibrators operate synchronously 16 times at equally spaced intervals between stations, and the resulting signals are appropriately summed. Thus, 80 sweeps are injected into the earth per station interval and combined to form

a source array 100 m long.

The receiving array includes 96 stations and is thus almost 10 km long. At each station a small spread of about 30 detectors, spaced to discriminate against natural and source-generated noise, is summed and recorded as one of 96 channels. Once the 80 sweeps at one station are recorded, the sources and the 3,000-element listening array are, in effect, moved 100 m along the line and the entire process repeated. Thus, along a line a few tens of kilometres in length, information travelling along tens of millions of rays is used in the analysis, a high level of redundancy that can be very advantageous. The data are recorded digitally in a form that will accommodate a very large dynamic range.

A further advantage is gained by computer processing the data. A wide variety and large number of methods including frequency and wavelength filtering, construction of synthetic seismograms, proper spatial positioning (migration), beam-forming, and various signal enhancement techniques are commonly applied depending on the particular problem. One powerful method, called common depth (or common reflection) point stacking, is based on combination of data from rays incident upon a particular reflection point at slightly different angles. Under favourable conditions signals are much enhanced. COCORP typically uses 12, 24 or 48-fold common depth point stacking. In the sense that information from segments of many rays passing through a common zone is combined, the method resembles X-ray tomography.

Although seismic reflection data appear in other useful forms such as velocity profiles and contour maps, the end product is typically a section with distance as the abscissa and travel time, or depth, as the ordinate. For the casual observation, and to a first approximation, this may be thought of as a section through the Earth. It is misleading to carry this view too far, however. A detailed interpretation of the data requires an understanding of wave propagation, field procedures and data processing, and a knowledge of related geological and geophysical data for the area. This report is too brief to present detailed analysis or interpretation of data. Instead two sections are shown and described in general terms, and some conclusions based on studies to date are presented after a discussion of current efforts to explore the continental basement. (For a more detailed description of seismic reflection profiling techniques and interpretation as found in the petroleum industry see refs 2-5.)

Seismic exploration of the continental basement

A proper strategy for exploring a major frontier of the Earth sciences must include a judicious blend of several factors including the nature, scope and scale of the scientific problems, capability of the method, economics, expertise of personnel, and logistics. In an effort to achieve this blend, the COCORP project operates as follows. Many scientists from industry (largely the petroleum industry), government agencies, and universities participate in committees to advise on technical, scientific, and administrative problems. Cornell University acts as the operator or prime contractor. The field work is conducted by large geophysical contracting companies. Data are processed through routine stages, and available at modest cost, so that further specialised processing and interpretation are facilitated.

The choice and nature of sites for such surveying are critical. Six sites have been surveyed to date in the US. The first site in Hardeman County, Texas, was selected for favourable seismic and field conditions in initial testing of the method, and with little regard for the geology. Later sites, two in the Rio Grande Rift near Socorro, New Mexico, one crossing the boundary fault of the Wind River Mountains in Wyoming, one across the Franciscan basement-continental basement boundary in the Great Valley of California, and one across the San Andreas fault in California, were selected because of geological problems of special interest. A recognised problem of regional or crustal scale, as opposed to local or surficial scale, is found at each of these sites. Typically, a few lines of reflection profiling totalling some tens of kilometres have been carried out at each site. In all cases the results have been highly encouraging. In the longer term, however, it is planned that longer lines traversing the entire continent will be explored, so that problems of still larger

scale will also be investigated. Applying this method of exploration to studying the modern basement is so new, and the region to be studied so vast and varied, that one must anticipate a period of rapid learning and development in the early stages of the project.

Two examples of the data

Figures 1 and 2 show two sections obtained by the methods described above for the locations in the Rio Grande Rift area^{6,7} indicated by 1 and 2A in Fig. 3. The reproductions do not do justice to the original data but some of the major features can be seen. The abscissa for Figs 1 and 2 is the distance in kilometres times 10; the ordinate is two-way travel time. Multiply by three to convert time to approximate depth in kilometres.

In Fig. 1, the upper 1–1.5 s of data for the western two-thirds of the profile show nearly horizontally stratified sediments of the rift valley. The sediments are broken into horsts and grabens by normal faults. It is only this portion of the section that would be studied in normal petroleum exploration, and in much greater detail. Below these sediments is the crystalline basement which outcrops east of the bounding fault as seen at about station 180. Some shallow Palaeozoic sediments that overlap the basement at the eastern end of the section are indicated by events at <1 s.

Principal interest here is in information from greater depths. In some areas of the section, such as from ~1 to 3 s and between stations 10 and 75, there is a paucity of reflected data as indicated by the lack of short horizontal lineups. The rocks of such zones must be relatively free of acoustic heterogeneities. In this same range of times near the centre of the section are some horizons that dip to the west and may be faults. To the east (right) are additional basement structures.

Beneath the bounding fault through most of the record there is a zone lacking in reflected energy, possibly because of intrusives associated with the boundary. To the east (right) considerable structure in the basement is apparent, and at ~12 s there is a strong reflector that, based on time, corresponds to the top of the mantle. This reflector cannot be traced across the entire section, although it might be correlated with reflectors to the west at about the same time.

There is little reflected energy on this section at times greater than 12 s. At the western end of the profile there is a strong reflection at 7 s with an associated diffraction. This event corresponds to a horizon identified as the top of a magma body by Sanford⁸. Other profiles in the Rift show additional evidence for this mid-crustal body of molten rock. (For more detailed discussion of these data, see ref. 7).

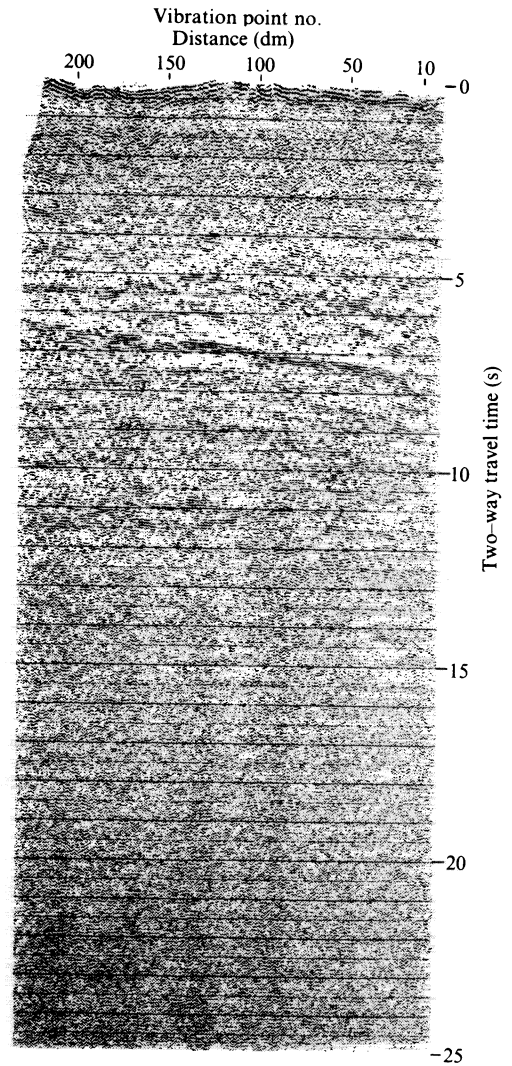
Figure 2 shows a section for line 2A (Fig. 3) that begins slightly south of line 1 and continues southwards. Some of the major features are (1) the sediments showing much less structure than is the case for line 1 because line 2A is more nearly parallel to the geological structure, (2) a transparent zone in the upper basement between the base of the sediments and almost 4 s; (3) a strong reflector corresponding to the magma body at about 7 s and dipping to the north; and (4) a zone of reflected energy between about 11 and 12 s presumably corresponding to the top of the mantle.

The above qualitative and cursory descriptions obscure the great potential for obtaining more quantitative information by careful study, computer modelling, and other forms of analysis, but they provide a first impression of the type of data now available on the crust and illustrate the much improved resolution and vast potential of the technique.

Although seismic reflection profiling of the deep continental basement is relatively new, and only a tiny fraction of the basement has been surveyed at present, some conclusions can be drawn, although they must be held subject to revision as more data are acquired. The following points are based largely on COCORP experience, but they are compatible with similar observations elsewhere (see ref. 1 for a review and citations)^{6,7,9–13,16}.

(1) The continental basement at any particular site some tens of kilometres in dimension is typically heterogeneous on the scale of less than one or a few kilometres. Reflections from within the basement are only infrequently continuous for more than a few kilometres. Diffractions, reflection character, and transparent

Fig. 2 Seismic section for line 2A, Rio Grande Rift (Fig. 3) for coordinates.



zones further attest to this heterogeneity. While layered models such as the classical but already outdated granite–basalt crust or those based on seismic refraction data may be useful for interpretation of some seismic data, they can only be approximations in a gross sense to the geology of the crust. The deep crust seems to be, not surprisingly, like rocks with a history at depth but which are now at the surface (see also ref. 14).

(2) On a larger scale, there is great variation from site to site in the character of the seismic reflection profiles; consequently such variation must exist in the basement geology. With the exception of some features of the seismic profiles in the Rio Grande Rift, many of which show the magma body at a depth of about 18–20 km and some consistency at Moho depths, there is little similarity and great difference in seismic sections from one site to another. In Hardeman County strong diffractors are found in a quantity not observed elsewhere, and there are also shallow basement reflectors of unusual length of continuity, at least 17 km. The San Andreas fault in California shows up as a series of diffractors to depths of ~10 km, while deep reflectors are discontinuous across the fault zone. In the Wind River Mountain area the major thrust can apparently be traced to depths of almost 25 km. Many other deep reflectors corresponding to faults or other horizons may be seen. The Great Valley line shows fewest deep reflectors, perhaps because the Franciscan basement is so badly deformed. At any rate, there is little similarity from one site to another and ample evidence for de-emphasising universal models of the continental crust. It follows therefore, that a wealth of new knowledge of the structure of the crust must be available using the reflection technique.

(3) There is no evidence for a single consistent mid-crustal reflecting horizon corresponding to the Conrad discontinuity, a

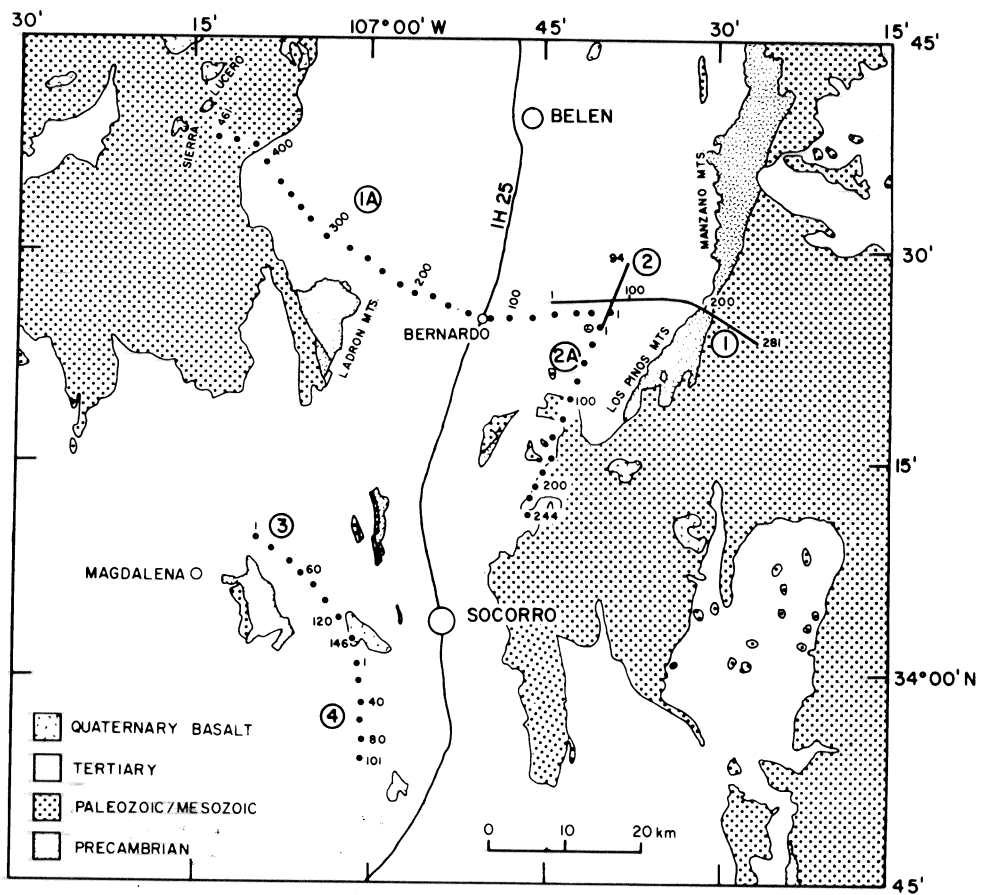
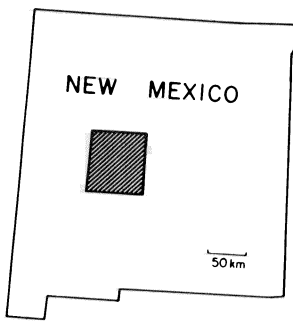


Fig. 3 Map of section of Rio Grande Rift in New Mexico showing locations of seismic lines. Solid lines 1 and 2 indicate locations where data for Figs 1 and 2 were taken. Dotted lines 1A, 2A, 3 and 4 show other lines that were surveyed but not discussed in this paper.

term that should probably be abandoned.

(4) In existing data the Mohorovicic discontinuity does not generally appear as a single simple reflector. Instead there is commonly a band of reflected energy. A possible interpretation is the laminated sort of boundary proposed by Meissner¹⁵ and perhaps suggested by exposures of the lower crust–upper mantle in the Ivrea zone.

(5) With the abundant evidence from geology and geophysics indicating heterogeneity throughout the crust, it would be remarkable if the mantle directly below the crust were homogeneous.

(6) At particular sites the method reveals features of the basement that, in nature, are geological (as opposed to geophysical) such as active magma bodies, faults, unconformities, folds, intrusions, and perhaps brecciated zones, as well as boundaries between rocks of different acoustical impedances. Detailed discussions of such sites can be found elsewhere^{9–13,16}.

(7) Continued application of the seismic reflection profiling technique including modern developments should provide a wealth of new knowledge and lead to a much enhanced understanding of the continental basement, a major frontier of modern earth science.

The results from the COCORP project depend on numerous participants from universities, government laboratories, and industry. This research was supported by the NSF.

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