in 1978 was not even 10 cm, and there were known systematic errors as well. In contrast, the accuracy of all systems is now better than 1 cm, and the goal of the CDP is to be routinely achieving 1 mm accuracy in all systems by the mid-1990s. This will require substantial funding for technology development within the next few years.

Comparing space geodynamics in 1978 with the prospects for the 1990s, we are on the brink of having available two revolutionary new measurement systems: GPS, which must still be regarded as an experimental technology not yet fully operational, and the Geodynamics Laser Ranging System (GLRS) to be available late in the 1990s. The first and second generation GPS receivers developed in the early 1980s made it possible to use facilities for measuring crustal deformation that were highly mobile and that cost a few hundred thousand dollars per unit instead of at least $1 million for the much more cumbersome mobile VLBI and SLR facilities.

The third generation GPS facilities now being developed cost less than $100,000 and will use much simpler data processing algorithms; within 2–3 years GPS systems will be placed on a single VLSI chip housed in a unit that could be transported by a small child and that will cost less than $15,000. At this price per unit, it becomes possible to greatly densify GPS measurements in both space and time. One can also anticipate semipermanent deployment of arrays of such GPS receivers as an alternative to continually moving a few units from site to site.

GLRS, which puts the laser in space and the retroreflectors on the ground, will reduce the cost of measuring crustal deformation drastically, even below that of GPS operations. Once the reflectors are in place, no further movement of field crews is necessary. Data analysis will be done by the EOS project, and baseline length and length changes will be provided directly to scientific investigators, perhaps even in the form of maps and tables transmitted via fax machines. GPS, VLBI, and SLR measurements would be needed to tie together regional GLRS grids in tectonically active areas; therefore, these systems will continue to play an important role in the Geodynamics Program.

Finally, the development of more accurate and more efficient analysis techniques for all types of space geodynamics data is of crucial importance. NASA regards data analysis as part of its technology development responsibilities.

Gravity and Magnetic Field Missions

A surprisingly large number of space missions with geophysical and geodetic objectives are now approved or planned by various space agencies for flights in the 1990s. For gravity these include TOPEX-Poseidon, ERS-1, ARISTOTELES, the Superconducting Gravity Gradiometer Shuttle Experiment, Gravity Probe-B, Mini-Lageos (small laser ranging satellites, including the CNES Stella), laser altimeters on the polar platforms of the EOS project, a topographic mapping mission, and the Superconducting Gravity Gradiometer Mission. In geomagnetism we are planning the Scout-launched Electromagnetic Field Explorer, the Magnetic Field Explorer-/Magnolia mission in cooperation with CNES, tethered magnetometers on the EOS polar platforms, tethered magnetometer deployments from the space shuttle, and the Polar Orbiting Geophysical Survey satellite to measure total field intensity in cooperation with USGS and the British Geological Survey. To take advantage of the overlapping objectives and measurement capabilities of these missions, the NASA Geodynamics Program is considering proposing an International Decade of the Geopotential Fields or some other method of focussing attention on the opportunity for obtaining definitive measurements of the magnetic and gravity fields.

The broad outline of NASA's geodynamics activities for the next decade seems reasonably clear at present, and a formal program plan will be written during the next year in consultation with cooperating agencies and organizations. The opportunities of the next decade are evident; whatever specific form the international projects in space geophysics and geodynamics take, NASA looks forward to contributing to major new advances in these scientific disciplines.

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A Modern Perspective on the Conrad Discontinuity

PAGES 713, 722-725

Robert K. Litak and Larry D. Brown

Department of Geological Sciences and Institute for the Study of the Continents, Cornell University, Ithaca, N.Y.

We thought that the methods used to explore the deep interior of the Earth would apply to exploration of the crust. But surprisingly this is not the case. The crust is more complicated in structure than the deep interior.

E. Wiechert, 1926

Introduction

V. Conrad in 1925 postulated that seismic energy propagated in a lower crustal layer with a velocity intermediate between that of the upper crust and mantel. That suggestion led to the idea of a universal or at least pervasive midcrustal velocity discontinuity, a concept that soon became widely, albeit not universally, accepted. As early studies of earthquake records were supplanted by data from controlled-source refraction surveys, references to the "Conrad discontinuity" in the continental crust became common in the literature.

As more and increasingly detailed data have been collected, the nature and even the existence of this feature has been called into question. However, some results of deep seismic reflection profiling seem to indicate a distinction between upper and lower crust, which suggests that a midcrustal boundary may indeed exist in some areas. In light of these developments and the continuing debate over the nature of the continental crust, it is appropriate at this time to examine the historical development of the concept of the Conrad discontinuity and the objections and responses and how recent data affect perspectives on the Conrad discontinuity.

Historical Aspects

One of the most fundamental contributions of seismology is the recognition of the layered structure of Earth. Near the turn of the century, mapping of surface exposures led many geologists to view Earth as a complex heterogeneous structure. In the early 1900s, however, seismological evidence was discovered that pointed to the existence of Earth's core [*Oldham,* 1906; *Gutenberg,* 1915]. In 1910 Mohorovičić recognized two separate P arrivals on a record produced by a near earthquake and interpreted that observation as evidence for a velocity discontinuity now considered the crust-mantle boundary. In addition, the development of universally applicable travel-time tables [*Jeffreys and Bullen,* 1935] became a powerful argument for the spherical symmetry of Earth. (Later, the discovery of the inner core [*Lehmann,* 1936] lent additional impetus to layered Earth models.) The great impact of these discoveries led to the recognition of seismological studies as a powerful tool for determining Earth's structure.

Against this background of discovery of stratification in the deep Earth, *Conrad* [1925] examined earthquake records from an event in Tauern, Austria. He observed another P arrival, which he labeled P*, and interpreted it as propagation along a midcrustal interface, analogous to Pn traveling along the crust-mantle boundary. He thereby inferred the existence of a midcrustal velocity discontinuity and calculated the lower crustal velocity to be 6.3 km sec^{-1}. Subsequent development of thought concerning this second-order discontinuity would attempt to follow the same lines as thinking about the "Moho," although it soon became clear that there are significant differences between the two, as discussed below.

Jeffreys [1926] reached a conclusion similar to Conrad's, based on evidence from the Jersey and Hereford earthquakes (Figure 1), inferring a P* velocity of 6.5 km sec^{-1}. Furthermore, he interpreted that discontinuity to be the boundary between a granitic upper crust and a basaltic lower crust and named the upper crustal arrival Pg (for granitic). In his analysis Jeffreys introduced the assumption, made strictly for computational convenience, that the crust is made up of constant-velocity layers, a model that perhaps came to be viewed too literally.

Additional reports of P* arrivals by *Conrad* [1928] (Figure 2), *Gees* [1937] (Figure 3), and others began to trickle in. In the 1930s Japanese data seemed to confirm the existence of the Conrad discontinuity, but were later found to be in error [*Lapwood,* 1955]. Further research indicated a wide discrepancy in depth to the elusive Conrad [*Reich et al.,* 1951], as well as ambiguity concerning the number of intracrustal discontinuities [*Byerly,* 1956] (Figure 4). By the middle of the century it was becoming clear that this variability made simple interpretations exceedingly difficult, and inconsistent results on the crust in California, Japan and New Zealand implied "substantial differences in structure for different parts of the world" [*Jeffreys,* 1952, p. 80]. Nevertheless, the general picture of a two-layered crust continued to persist in the literature. It is important to realize that this fact can be partly attributed to the early success of seismology in generating layered-Earth models, with perhaps some additional contribution from the personal stature of the eminent scientists involved in its early development.

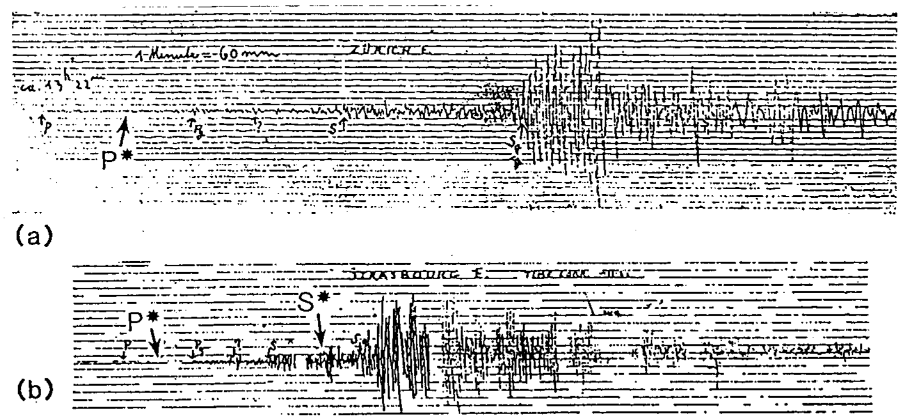

Fig. 1. Records of the Jersey earthquake of July 30, 1926, from (a) Zurich (7.0° distance) and (b) Strasbourg (6.2°). Note the quality of the P* arrival in each case and the existence of a larger, unknown arrival between Pg and S. In (b) the trace has been inked in by hand for clarity. After *Jeffreys* [1952].

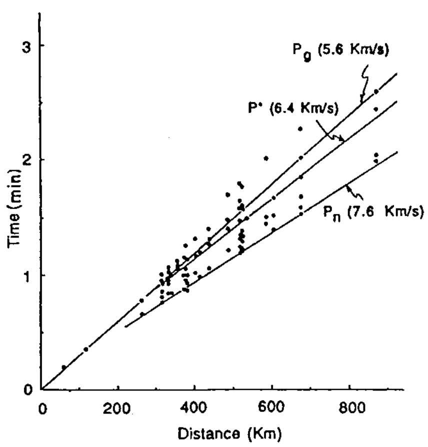

Fig. 3. Unreduced travel-time curves corresponding to Pg, P*, and Pn for North Brabant earthquake of November 20, 1932. Points represent interpreted arrivals at different stations. Note that the scatter of points, many of which are somewhat ambiguous second arrivals, allows considerable latitude in the identification of intermediate crustal layers. After *Gees* [1937].

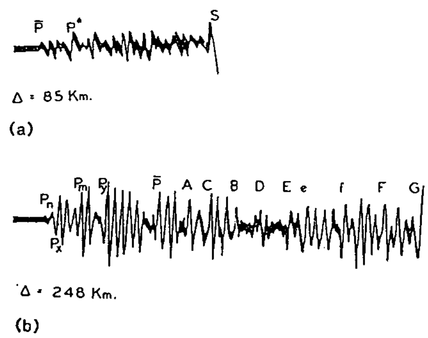

Fig. 4. (a) A "textbook" example of a good P* arrival from a California earthquake. Note several other apparent phases of similar amplitude. (b) Interpretation resulting from a conscientious attempt to pick every phase on a seismogram from California. Although this may represent a valid identification of seismic arrivals, it is questionable whether such an approach will provide consistent and meaningful results. Such difficulties called into question the number, depth and universality of intracrustal discontinuities. From *Byerly* [1956].

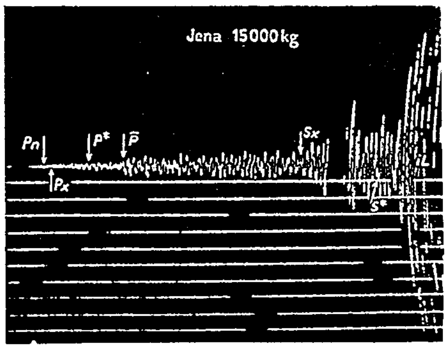

Fig. 2. Record of the Schwadorf earthquake of 1927 showing interpretation of upper mantle and crustal arrivals. Note the emergent character of P energy. P* and S* were inferred to be evidence for the Conrad discontinuity. From *Conrad* [1928].

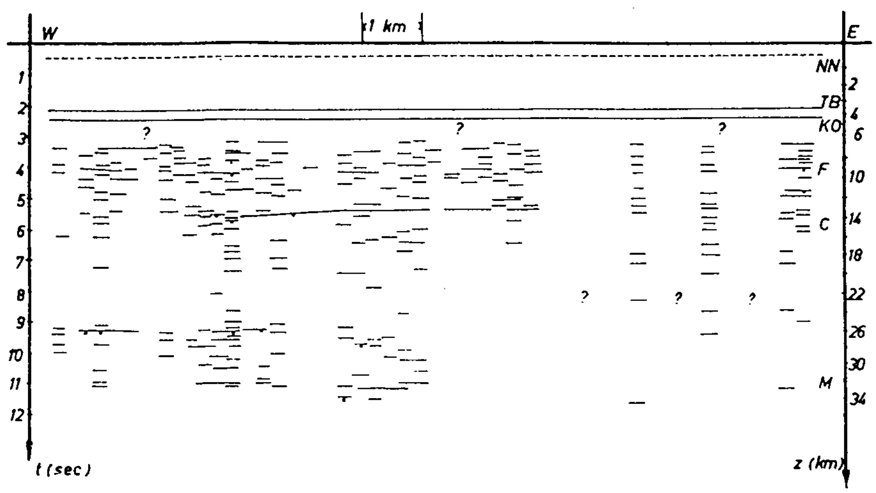

Fig. 5. Line drawing of an early reflection profile. M, Moho; C, Conrad; F, Förtsch discontinuities. Horizontal exaggeration is approximately 6:1. After *Liebscher* [1964].

Early Objections

As Earth science advanced, it became apparent that the simple two-layered crustal model was inadequate. Reservations about the universality of the Conrad discontinuity were voiced early, and objections became more frequent and vociferous as time progressed. As early as 1939 *Schmerwitz* [1939] blamed P* on high-velocity but discontinuous inclusions. Jeffreys, whose early work was instrumental in popularizing the Conrad, remarked that "the failure of later special studies to give series of observations of these pulses led me to have some doubt about whether the readings represented anything more than accidental alignments of points on a graph of (time) against (distance)" [*Jeffreys*, 1952, p. 75].

In addition, some question arose as to whether the Conrad was geologically meaningful or merely a mathematical convenience. In 1956 *Byerly* [p. 146] stated that the "concept of the (Conrad) discontinuity is justified primarily in that it reduces from graphical integration to algebra the methods of computation of the depth of the (Moho)," imputing an almost arbitrary computational significance to the Conrad. Nevertheless, he went on to express belief in existence of an oceanic crust-type basaltic layer beneath the continents. *Richter* [1958, p. 284] expressed doubt about the applicability of the term 'Conrad' to North America "since it is nearly certain that the detailed structure of the crust differs radically from region to region."

James and Steinhart [1966], in an insightful discussion, anticipated much of the criticism that would subsequently be leveled. They cited laboratory measurements, as well as the complexity of seismograms and surface geology, and concluded that "the high degree of inconsistency between results in respect to number, depths, and velocities . . . suggests that the idea of worldwide or continent-wide intracrustal discontinuities is untenable" [p. 321]. Their conclusion was based partly on early reflection work in Germany (Figure 5), which had previously been interpreted as evidence for an additional discontinuity. James and Steinhart recognized that the significance of numerous reflections was in the heterogeneity that they indicated and that it was counterproductive to try to force those data into simple models with a small number of major pervasive discontinuities.

Refraction Seismology

After World War II controlled-source refraction surveys enjoyed a rapid increase in popularity. Crustal models based on those early experiments were often simple two-layered models, with the main variations being the depth to the Conrad and Moho and the velocity of the lower crustal layer. As methods have improved, resulting crustal models have become increasingly elaborate; yet these models often involve variations on the theme of a horizontally layered crust, for example, *Mueller* [1977] (Figure 6).

Considerable complexity and lateral variation is apparent in *Meissner*'s [1986] compilation of crustal models (Figure 7). Nevertheless, the common features of pervasive horizontal layering and an essential midcrustal boundary owe an evident legacy to Conrad. With the exception of Cenozoic collision zones and rift areas, Meissner generally finds a pronounced differentiation between upper and lower crust, especially where basement age is Paleozoic to Mesozoic. He suggests that age-dependent processes may have homogenized the old cratons. It is interesting to note that earlier data appeared to indicate that the Conrad could be clearly defined in shield areas of Canada and the U.S.S.R. [*Meissner*, 1977].

Although the Conrad discontinuity is primarily a European phenomenon, scattered reports of Conrad-type features have been received from many parts of the world. Several Canadian studies have emphasized a midcrustal velocity discontinuity, for example, *Hall and Brisbin* [1965]; *Cumming et al.* [1979]. Due to the distance from Europe and the somewhat higher velocity (~7 km sec^{-1}) calculated for the lower crust in Canada, some workers have referred to this feature as the Riel discontinuity [*Clowes et al.*, 1968]. Implicit in this distinct nomenclature is the uncertainty of whether or not it corresponds to the European Conrad.

The theme of regional crustal variability has been accorded increased emphasis by sev-

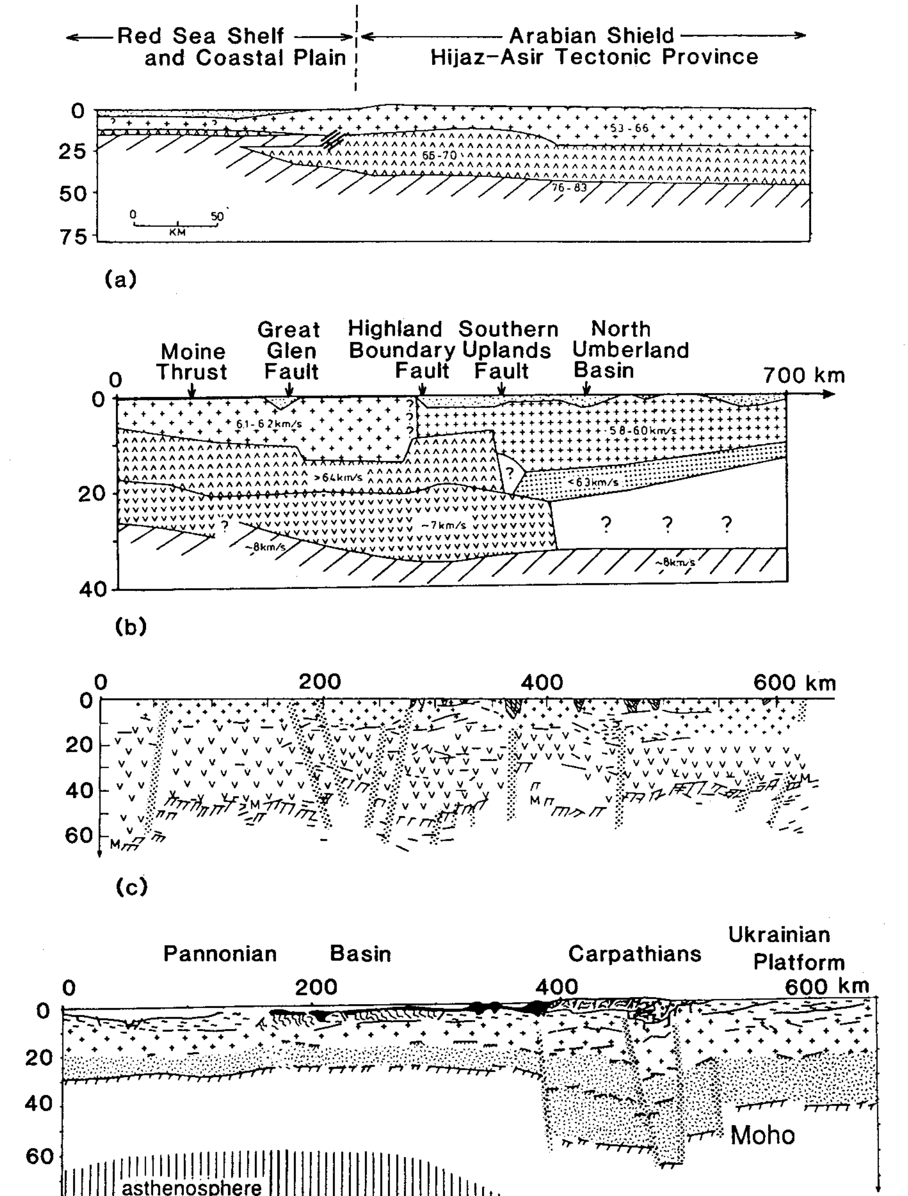

Fig. 7. Seismically derived crustal models from (a) Saudi Arabia, (b) Great Britain, (c) the Ukraine, and (d) Hungary. Scales are in kilometers and are variable. After *Meissner* [1986].

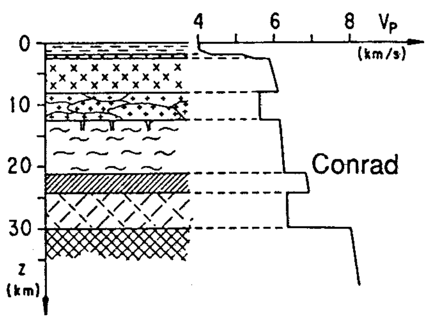

Fig. 6. Schematic model of the continental crust featuring elaborate layering in one dimension. Here, the Conrad discontinuity has degenerated into a thin, high velocity tooth. After *Mueller* [1977].

eral workers. Interpretations of the Conrad ranging from a major first-order discontinuity to a minor second-order transition in velocity have led *Berry and Mair* [1980] to state that "the Conrad discontinuity does not appear to be a fundamental property of the Earth's crust," while *Mueller* [1987] also stressed that the "detailed structure of the crust differs radically from region to region." Thus, increasing sophistication in refraction methodology seems to have presaged a trend away from the simple picture of a universal midcrustal discontinuity, while retaining some aspects of this interpretational style.

Reflection Seismology

The advent of deep reflection surveys quickly transfigured the debate over the nature of intracrustal boundaries. While early reflection surveys were interpreted as evidence for features such as the "Förtsch discontinuity" [*Liebscher*, 1964] (see Figure 5) and the "Sub-Conrad discontinuity" 7.5 km below the Conrad [*Glocke and Meissner*, 1977], it soon became clear that those data were in fact indicative of numerous minor, localized discontinuities [*James and Steinhart*, 1966; see previous discussion]. Based upon an early profile collected by COCORP (the Consortium for Continental Reflection Profiling), *Oliver et al.* [1976] presented a model of the crust for Hardeman County, Texas, characterized by extreme heterogeneity. This heterogeneity led *Oliver* [1978] to assert that, due to the findings of reflection seismology, the term Conrad discontinuity "should probably be abandoned." In another study, *Berry and Mair* [1977] indicated that the crust as revealed by reflection profiles is too complex and heterogeneous to fit into simple layered models.

Smithson has been one of the most outspoken and frequent critics of the traditional two-layered crustal model, for example, *Smithson* [1978], and has stated that "seismic velocities, crustal refraction studies, and deep crustal reflections all show that the lower crust is highly heterogenous and that it cannot be gabbroic." In his model of the continental crust, there are so many discontinuities that it is difficult to single out one as more important than another. Of course, if a locally large body of intermediate to mafic rock is favorably located with respect to a seismic refraction line, a "Conrad" arrival could be expected.

Prompted in part by reflection results, *Mereu and Ojo* [1981] created a simple crustal model with smooth random lateral inhomogeneities superimposed upon a linear velocity gradient (Figure 8). They then showed that rays traced through this model would produce a travel-time plot remarkably similar to that expected from a two-layered crust. They state that such a model might also be expected to yield reflection results similar to those observed, although it seems likely that steeper velocity gradients (that is, more local heterogeneity) would be required to produce many of the sharp reflections seen. This study demonstrated that the traditional interpretation of different travel-time branches corresponding to distinct horizontal layers is not necessarily applicable if the crust has appreciable heterogeneity. Thus the growing evidence for crustal heterogeneity began to make the concept of the Conrad discontinuity seem obsolete.

Yet even as many have come to discard the term "Conrad," the growing body of reflection data has led some to generalize a crustal model that seems to reincarnate the two-layered crust. Numerous reports of a nonreflective upper crust overlying a reflective lower crust, for example, *Matthews and Cheadle* [1986] (Figure 9), have generated much discussion concerning this apparent dichotomy, for example, *Mooney and Brocher* [1987]. Since this "layered lower crust" is often observed in areas where extension has been the most recent significant tectonic event, it may be that lower crustal layering is a relatively young feature related to extension [*Meissner and Wever*, 1986; *Matthews and Cheadle*, 1986]; (however, *Hobbs and Peddy* [1987] cast doubt on this interpretation). Several workers have hypothesized that the onset of layering in the lower crust indicates the transition from brittle behavior to ductile stretching, for example, *Meissner and Kusznir* [1986]; igneous intrusion may also be involved [*Furlong and Fountain*, 1986].

The suspicion that there is something special about the midcrust is also fueled by several reports of anomalous high-amplitude reflection packages at midcrustal depths [*Brown et al.*, 1980; *de Voogd et al.*, 1986], as illustrated in Figure 10. These "bright spots," which occur in several distinct geographic areas, have generally been interpreted as magma bodies or other fluids [*Brown*, 1987a], prompting questions as to whether a rheological barrier to upward migration of fluids may exist at the midcrust. *Brown* [1987a, b] has speculated that such a ponding effect may be related to the brittle-ductile transition, although it seems perhaps more likely that fluids would accumulate at the base of a ductile zone, rather than the top.

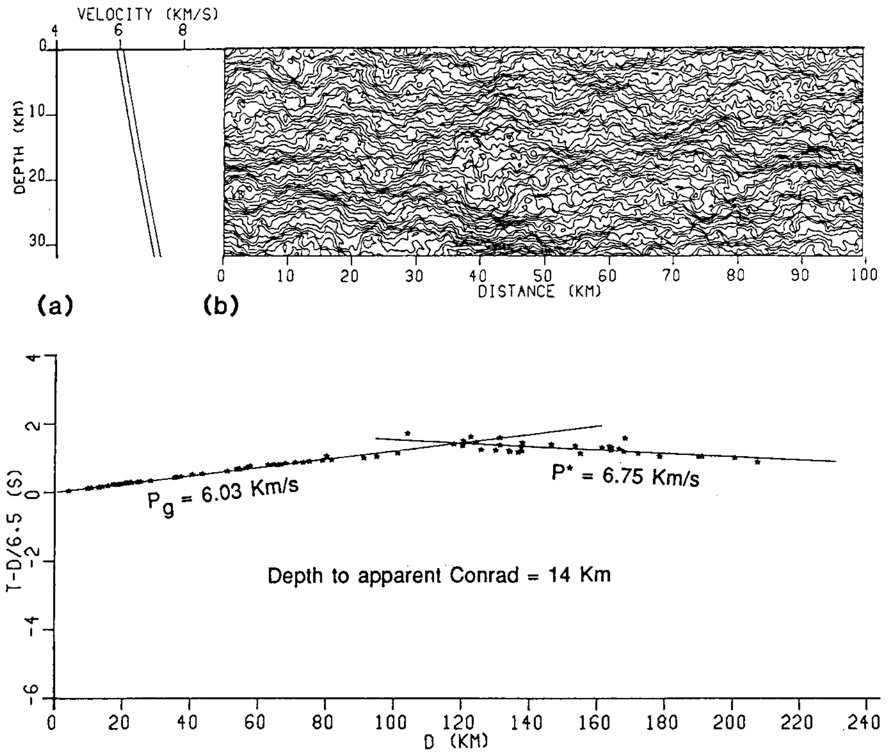

Fig. 8. (a,b) Simple crustal model featuring smooth random inhomogeneities superimposed on a linear velocity gradient. (c) Resulting travel-time curves. Stars denote arrival times. Note appearance of two linear segments with crossover distance of 120 km. Compare to Figure 3. After *Mereu and Ojo* [1981].

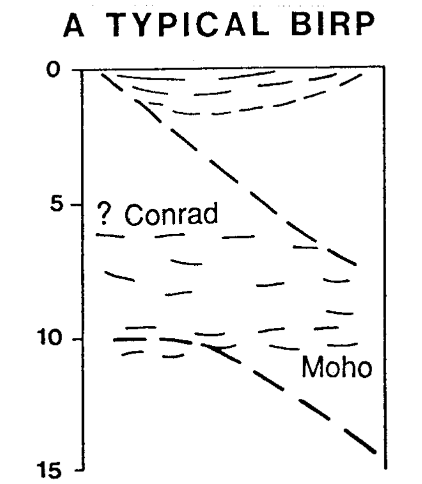

Fig. 9. Cartoon of "typical" BIRPS (British Institutions Reflection Profiling Syndicate) reflection profile. Dipping events terminate in a reflective lower crust that lies under a nonreflective upper crust. Vertical scale is two-way travel time in seconds. After *Matthews and Cheadle* [1986].

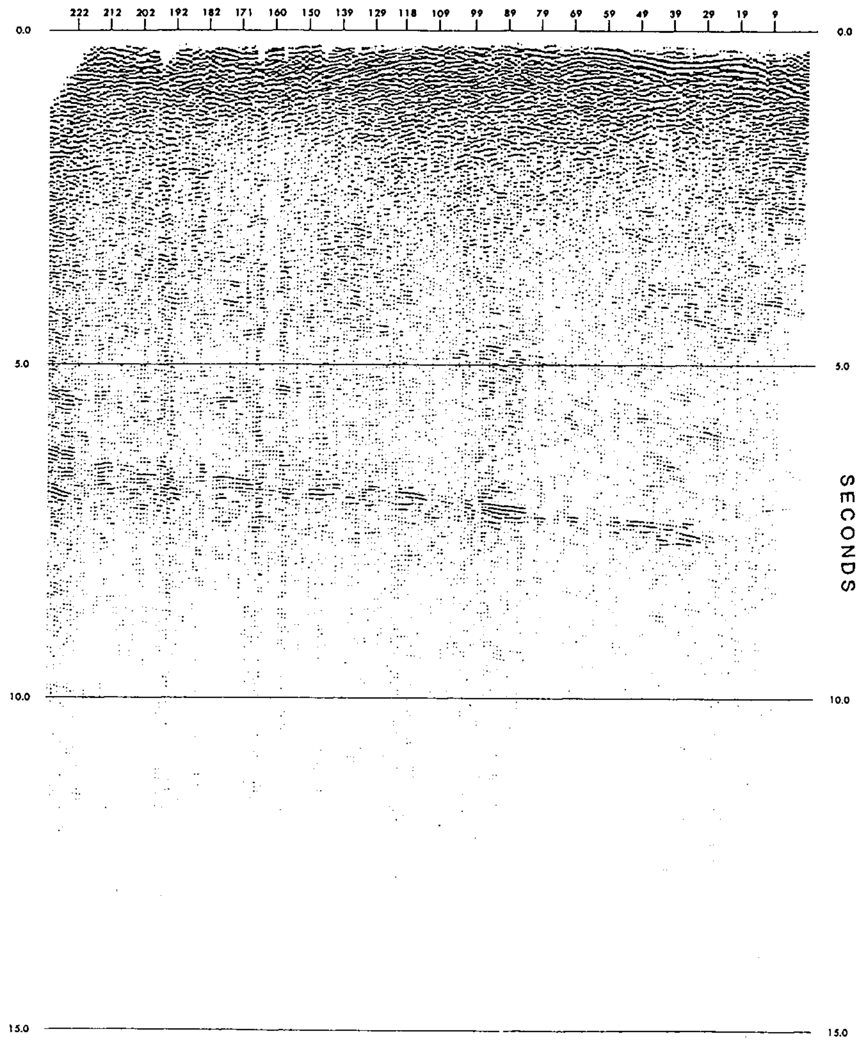

Fig. 10. True amplitude stack of COCORP New Mexico line 2A featuring a midcrustal "bright spot" believed to be caused by a magma body. Vertical scale is in two-way travel time; no vertical exaggeragion for a velocity of 6 km sec^{-1}.

Regardless of the causes of such features, the question remains as to whether any of them should be interpreted as corresponding to the Conrad. Although the *DEKORP* (Deutsches Kontinentales Reflexionsseismisches Program) *Research Group* [1985] and *Finlayson et al.* [1984] have reported a rapid increase in velocity associated with the onset of a reflective lower crust, for the most part unequivocal coincident refraction data are relatively scarce [see *Mooney and Brocher,* 1987]. It is also worth noting that while the Moho is often identified with a strong, relatively continuous reflection or group of reflections, this is rarely true of the Conrad. Furthermore, and most important, there are so many counterexamples to the reflective-nonreflective generalization that they could easily be considered the rule rather than the exception. Inspection of COCORP data alone reveals areas where the whole crust is reflective, for example, *Latham et al.* [1988], areas where the whole crust is nonreflective above a reflective Moho [*Nelson et al.,* 1985], and areas where a reflective upper crust overlies a relatively nonreflective lower crust, for example, *Potter et al.* [1986] (Figure 11) —in short, every conceivable combination. (It is significant that, in the last example, broad zones of reflectivity occupy substantially different levels over relatively short distances). Thus it may be misleading to relate midcrustal anomalies, where they occur, to an entity with the semantic baggage now associated with the Conrad.

Geological Significance of the Conrad

Although many observations suggest diversity in the midcrust, there are clearly distinct features in certain areas at midcrustal depths. A number of hypotheses have been advanced to explain such features where they have been associated with the Conrad discontinuity. Perhaps best-known among these is Jeffreys' original division of the continental crust into granitic and basaltic (or gabbroic) components. Although this traditional view of a gross petrologic distinction is consistent with the composition of some xenoliths [*Kay and Kay,* 1981], it appears to be much too simplistic in light of modern seismic and geologic observations and may conflict with petrologic considerations [*Ringwood and Green,* 1966]. In addition, the only experiment to directly test the hypothesis of a lithologic discontinuity, the Kola superdeep well in the Soviet Union, is notable for its negative result. In an area where seismic refraction results were interpreted as indicative of a major discontinuity, no sharp lithologic boundary has been found [*Clarke et al.,* 1986]. Thus while it is almost certain that (high-velocity) mafic material is more abundant in the lower crust, the hypothesis of a universal compositional discontinuity now seems considerably less attractive than it once did.

The concept of the Conrad as a metamorphic boundary between upper crustal amphibolite and lower crustal granulite has somewhat more support [*Mueller,* 1977]. *Percival* [1986] has suggested that the Kapuskasing uplift represents a midcrustal exposure where tonalitic gneisses of amphibolite facies grade into more granulitic lower crustal rocks, producing a velocity contrast of about 0.3 km sec^{-1}.

Yet another ubiquitous midcrustal boundary has also been postulated: the distribution of earthquakes within the continental crust provides evidence for a brittle-ductile transition at a midcrustal level, since the lack of hypocenters in the lower crust is consistent with ductile behavior in that region [*Sibson,* 1982; *Chen and Molnar,* 1983]. Perhaps a relationship between the Conrad and the brittle-ductile transition can be speculated on, but it is difficult to see why a transition from brittle to ductile behavior, in and of itself, should be responsible for a substantial velocity increase. An association between the brittle-ductile transition and the Conrad is perhaps more plausible if the former is considered a more fundamental quality and is responsible for conditions (such as magma ponding) that may give rise to a midcrustal refraction.

The difficulty of ascribing the Conrad to a single one of these presumably universal features clearly lies in reconciling such ubiquitous mechanisms with such inconsistent seismic observations. Perhaps this can be accomplished by invoking regional differences in these processes to produce subtle and variable velocity changes. Modern results, however, indicate that the continental crust has had a long (for the most part) and complex history and has been subjected to numerous episodes of collision, rifting, heating, cooling, and other processes. These considerations make variations of simple two-layered models decidedly less appealing and may lead one to wonder whether the diversity of seismic results in fact indicates diverse origins for midcrustal anomalies. One such possible origin has been proposed by *Clowes and Kanasewich* [1970] in a study of seismic attenuation. Their results suggest that, in at least one area, midcrustal reflections can be explained as a "sill sandwich" of alternating high and low velocity layers. This is consistent with later observations of strong layered reflections in the midcrust, but it is questionable whether such a mechanism can be a general explanation for reports of the Conrad.

Another, perhaps related, possibility involves the presence of fluids in the crust. Fluids are becoming increasingly recognized as having a major effect upon the physical properties of the crust [*Fyfe,* 1986; *Oliver,* 1986]. Whether this effect is related to an upper crustal low-velocity zone [*Berry and Mair,* 1980], the Conrad, or both, is an intriguing possibility. In fact, in the only instance where

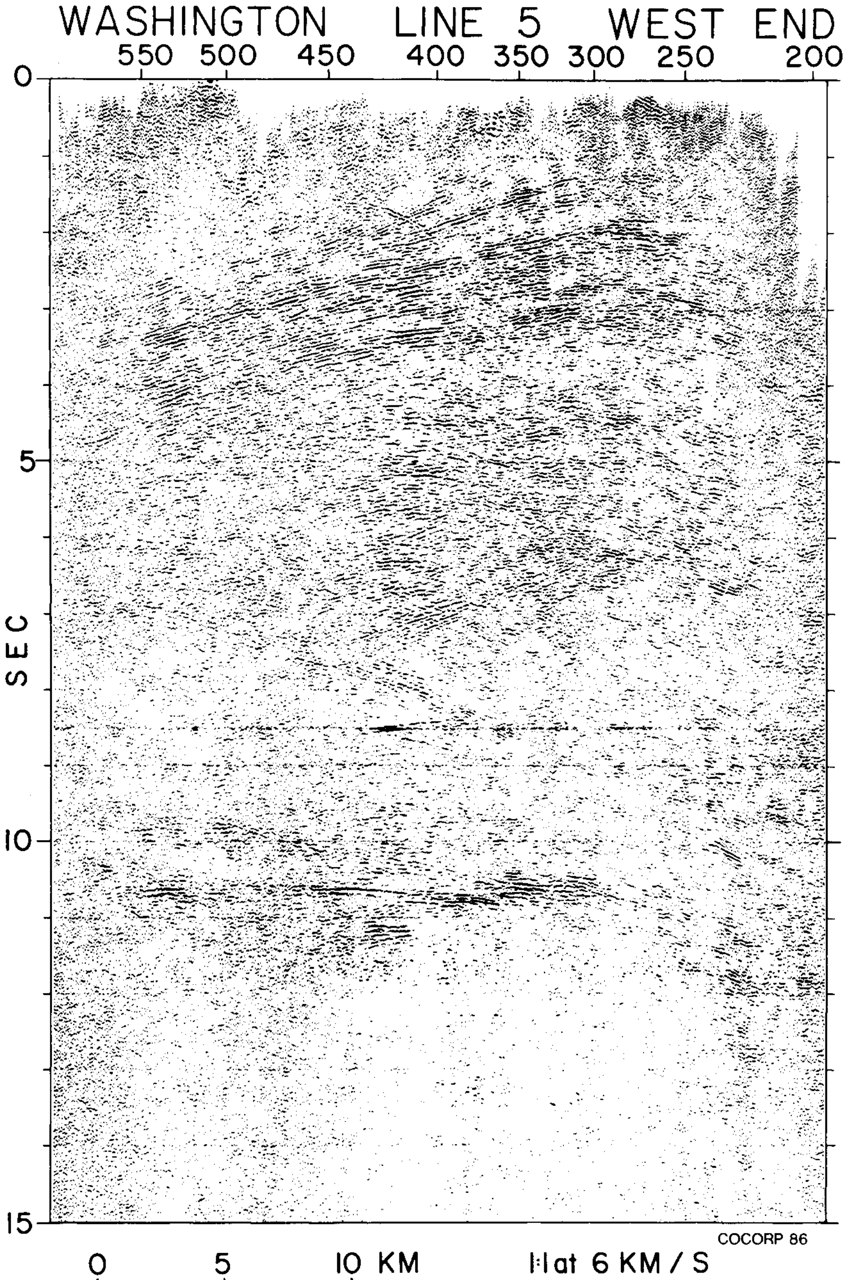

Fig. 11. West end of COCORP Washington line 5 in northeastern Washington [state] featuring a reflective upper crust and strong Moho reflections. From *Potter et al.* [1986].

rocks have been sampled through the Conrad (the Kola well), the discontinuity was found to coincide with the base of a "zone of disaggregation" related to overpressured fluids [*Kozlovsky,* 1984]. Highly reflective midcrustal "bright spots" may also be related to fluids [*Brown,* 1987a]. Thus fluids in the crust may be highly significant where they occur; however it is not clear how fluids in the midcrust could cause a Conrad-type refraction.

Conclusion

It is quite possible that all, or at least several, of the above mechanisms may be responsible for observations which, taken individually, might suggest a Conrad discontinuity. That is, local variations in petrology, rheology, metamorphic grade, and fluid content may each contribute to reports of a midcrustal anomaly called the "Conrad discontinuity." The variable and elusive nature of the Conrad suggests that, where it is observed, it is a feature of regional or local extent and diverse origins. Of course such variability might cause one to consider whether the Conrad discontinuity is itself a concept that has outlived its usefulness and no longer has geological significance. Clearly the idea of a ubiquitous boundary between a vastly different upper and lower crust is no longer viable; moreover a search for "the" model of the continental crust whether using refraction, reflection, or other methods is probably misguided. By the same token, it cannot be denied that there are numerous and complex processes occurring within the continental crust, any number of which could give rise to a genuine and observable midcrustal refraction, and that lower crustal velocities are generally higher than those in the upper crust. Whether the term "Conrad discontinuity" should be retained is perhaps a matter of semantics. Yet the observations of midcrustal anomalies, and the diversity thereof, are critical to understanding the origin and nature of the continents.

Finally, it should be recognized that the current controversy concerning midcrustal discontinuities in no way diminishes the important contributions to earth sciences made by V. Conrad and other seismological pioneers. Indeed, modern insights on the nature of the continental crust enhance their legacy of crustal exploration.

Acknowledgments

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