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The changing face of deep reflection seismic profiling

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ABSTRACT

The often complex and poor-quality seismic events resolved by deep seismic profiling are generally not dissimiliar to those found on conventional exploration data. Historically however, the processing technology used to image these data has been simplistic, by comparison to exploration studies. This gap in processing technology is generally not viewed as an urgent issue by the crustal geophysics community, who are typically more concerned with broader geological issues. Nevertheless, it would appear that at least on one front, things are going to change. The future of deep seismic profiling is clearly taking two separate paths. On the gross scale, academic researchers are beginning to take time out from their fervent acquisition to review their techniques, their Earth geological models and their perceived future challenges. On the other hand, efforts using deep seismic profiling to place natural resources in a crustal-scale context are rapidly growing in strength, with many such surveys being acquired. These latter studies will become the technical leaders for deep seismic studies, incorporating more advanced processing technologies better known in the exploration industry. The results of these commercially-driven studies should then be of great use to the academic community, providing many previously unattainable insights into the Earth.

INTRODUCTION

Since the Consortium for Continental Reflection Profiling (COCORP) began profiling the Canadian lithosphere in 1975, deep seismic reflection studies have enjoyed a rapid global expansion. In the past, the greatest focus was upon simply acquiring as many datasets from as diverse a set of geological terranes as possible, rather than upon developing and applying advanced acquisition and processing technologies. This approach provided many undreamt of insights into the inner Earth. With the basic skills in hand, deep seismic profiling is now progressing to a new level. The exploration industries have begun realizing that tectonic-scale structures are often important controls upon economically significant features such as intra-basin structures

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and mineralizing zones. In turn, expensive high-resolution deep seismic studies are being funded for the first time. Both LITHOPROBE (Canada) and the Australian Geological Survey Organisation (AGSO) are developing cooperative programs with the exploration industry. Such ventures apply acquisition and processing technologies most similar to those employed in conventional hydrocarbon exploration; close source and receiver spacings, high data redundancy (fold), and a pursuit of high frequency information.

It is my opinion however, that for some time yet, deep seismic studies will continue to operate as two separate thrusts; gross-scale academic studies and studies with a more commercial motive. The flux of technology demanded by the high-resolution studies, to the more regional studies, will therefore be slow and erratic. It is true that a great deal of uncertainties and ambiguities remain in our understanding of the Earth, and thus the academic community have many broad problems to address. In recent times, academics have been organizing symposiums and discussion groups in an attempt to address these unanswered questions. It is apparent that the resulting call will not be for better technology; rather, the call will be for the input of workers outside the seismic domain. Another reason for there being no urgency to speed along the input of newer technology into regional studies is derived from the history of deep seismic profiling, which I briefly discuss below. Practice has shown that the gross-scale features of the outer Earth are best tackled with simplistic processing approaches and novel or unconventional methodologies.

For those that place more emphasis upon doing research more precisely and powerfully, than scouting around simply acquiring more data, it is the commercially-driven surveys that will be the torchbearer for the application of more advanced acquisition and processing techniques to deep seismic studies. I suggest that once several high-resolution, deep seismic datasets have been acquired (and exploration surveys already are regularly recording their data for 8 to 12 s TWT), a significant contribution will then have been made to the general science of "crustal studies". Perhaps then, the academic studies will be more inclined to play catch-up. In the remainder of this paper I briefly discuss, with examples, how deep seismic profiling studies have commonly only required simplistic processing sequences, hence the lack of urgency in applying approaches better known in the exploration community. To place the science of reflection-seismic-based studies in a historical context, I then summarize the most nagging unresolved geological problems. Rather than dwell upon the superior nature of high-resolution commercial datasets, I then discuss how the application of rock physics principles in particular are being used to obtain more useful information from even the most coarsely-sampled data. As these efforts develop in popularity and success, I suggest that the application of other approaches such as 3D acquisition will be better appreciated for the contribution they can make to seismic studies, on any scale.

THE HISTORICAL DEVELOPMENT OF DEEP REFLECTION SEISMIC DATA ACQUISITION AND PROCESSING

Although the most powerful geophysical technique, deep reflection seismic profiling has usually been undertaken at very regional scales. Processing schemes applied to such data are conventionally simplistic, mainly a symptom of the problems in differentiating between (weak) signal and noise. The long-standing attitude has been that complex processing routines can not be used with confidence or reliability. Many of these problems of course relate to the unique characteristics of deep seismic data. Migration has been perhaps the biggest challenge, due to the large aperture inherent in a 12-20 s TWT section (Warner, 1987). Even the fundamental aspects of the seismic method have associated complexities. Of interest to any seismic study, the accurate determination of rock velocities are of fundamental importance. From a regional standpoint, wide-angle refraction seismic profiling is often preferable to reflection seismic profiling, as rock velocities can be better estimated using refraction data. Advanced first-arrival inversion routines (e.g. Hole, 1992) are now able to produce detailed 2.5D tomographic velocity models, even when the acquisition involved irregular and crooked recording geometries. In contrast, the lack of perceptible moveout at depth on CDP gathers makes velocity determination difficult and imprecise. It is not uncommon that refraction data are used to constrain the velocity models input into CDP stacking of reflection seismic data.

Crustal-scale surveys are of course acquired over very large distances, commonly several hundred kilometers, which will usually involve traversing rugged and variable topography. Often these problems are so extreme that remote recording stations are left switched on in (passive) recording mode for several days, while various shots are detonated along the line. The continuous records are then deciphered back at home. This style of recording dictates a coarse receiver station spacing, which in turn dictates that the data will be dominated by long wavelengths and low frequencies. As such, the required processing scheme is relatively simplistic by comparison to that required for imaging of shallow exploration data.

Furthermore, most processing schemes are unique to the particular datasets being processed. An example is the imaging of the major features beneath mid-ocean spreading ridges, where new oceanic crust is formed and rafted away on diverging tectonic plates. Figure 1 shows the oceanic crust to be composed of 3 (seismically) distinct layers: layer 2a (sediments, pillow lavas and extrusives) which varies between 200-500 m thick, layer 2b (sheeted dykes) which is 2-3 km thick, and layer 3 (gabbros) which extends down to the common oceanic crustal depth of 7-8 km. Beneath the mid-ocean ridge (MOR), an upwelling axial magma chamber (AMC) supplies the material required to generate new crust as the plates diverge. The two features commonly of most interest are the variable thickness of the 2a layer (which reveals much about the tectonic evolution of the upper-crust) and the width of the AMC (which reflects the "magma budget", a key control upon the along-axis structure and morphology of the ridge).

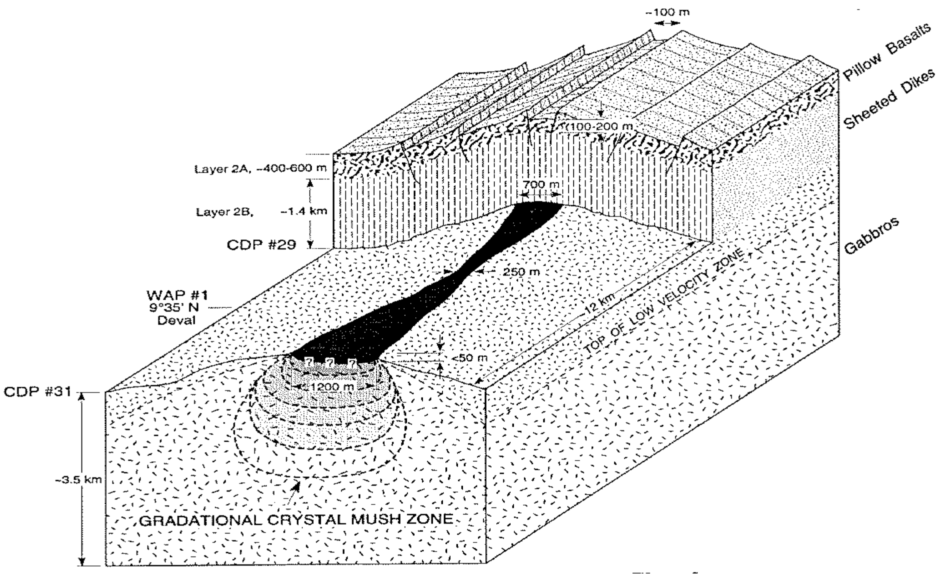

Figure 1: Schematic drawing of the East Pacific Rise mid-ocean ridge. The faulted seafloor forms the top of layer 2a (sediments and extrusives). Layer 2b is entirely composed of sheeted dikes, while layer 3 is predominantly gabbroic. A magma chamber provides the material emplaced between the diverging plates. From Kent *et al.* (1993). andrew1-fig1 [NR]

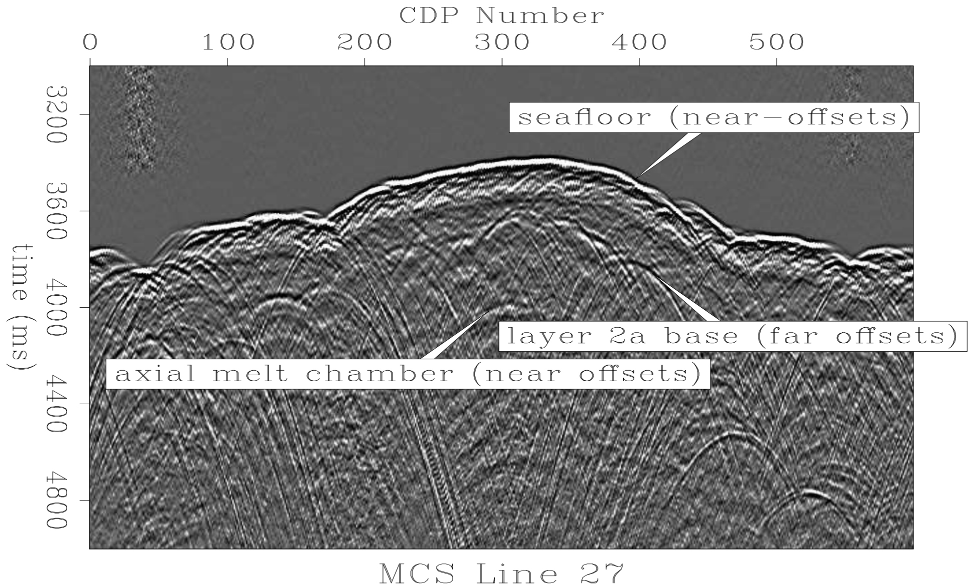

Figure 2: Seismic profile from the East Pacific Rise. The most obvious features resolved after stacking three times with different offset ranges and then merging, are the base of layer 2a (far offsets), the seafloor and top of the AMC (near offsets). Conventional processing was unable to properly image the various features. andrew1-fig2 [NR]

As a pronounced velocity gradient exists within the 2a layer (from 1.5 - 5 km/s), many of the recorded seismic events are from turning ray energy, which is commonly only recorded at offsets greater than 1.5-2 km. Conversely, the best resolution of both the seafloor and the AMC are obtained from near-vertical reflections. Hence, one processing approach successfully used has been to produce 3 separate stacks; 2 using near-offset reflections to image the seafloor and AMC respectively, and 1 using far-offset reflections to image the base of the 2a layer. These 3 stacks are then merged to produce a single output stack (Fig. 2). Such an approach does not favor the subsequent successful application of migration, a problem further compounded by the presence of significant diffraction energy related to seafloor topography, which is often out-of-the-plane.

This is of course only a single, isolated example. Nevertheless, it demonstrates the often unique and simplistic approaches required to image regional deep seismic data.

UNRESOLVED GEOLOGICAL PROBLEMS

When international researchers began formally conducting deep seismic meetings in 1984, they were asking "What are the origins of deep reflections? Can we observe consistent features around the world?." The answer to the last question was generally "Yes, however these features often serve to confuse us." Twelve years later, the issue of crustal reflectivity remains a complex one. Illustrative of some advances, intra-crustal and sub-crustal water is no longer believed to be a primary source of major reflections that it once was. Reflections are now regularly attributed to intrusive sills and basalts, perhaps deformed in structural shear zones. Furthermore, global analysis shows reflectivity can be profoundly modified by successive episodes of lithospheric deformation.

In recent times, the application of rock physics principles to deep seismic data has proven to be a useful technique in understanding the petrology and rheology of the crust, however, significant problems remain. An example is the discrepancy that exists in reconciling the different composition of continental and oceanic crust. Whereas the oceanic crust is fundamentally uniform and predictable in composition, the (much older) continental crust is poorly understood. The chemical composition of the continents is largely intermediate, in striking contrast to the mafic oceanic crust and the ultramafic mantle. Results of modeling the crust as a stochastic medium are consistent with the intermediate model (Levander *et al.*, 1994). The problem is whether these compositional differences are primarily due to different mechanisms of crustal extraction from the mantle or to different mechanisms of differentiation and alteration of newly formed continental crust (Rudnick, 1996).

Answers to many other fundamental questions are also not clear. The fate of subducting slabs in the lower lithosphere has never been determined, yet in an *ad hoc* way the dipping reflections that are infrequently observed in the upper mantle are typically interpreted as representative of such slabs. Many deep reflections are well documented; however, it has never been properly explained why the lower crust is so anomalously reflective and electrically conductive. On this note, the crust/mantle boundary and seismic transition called the "Moho" remains poorly understood. Based on both reflection and petrological considerations, questions have arisen regarding whether the Moho really does represent or coincide with the crust-mantle boundary between rocks of crustal origin and tectonized mantle peridotite, whether in subducted/accreted crust multiple Moho horizons exist, and whether the Moho transition incorporates a large-scale heterogeneous upper mantle "zone". These uncertainties are compounded by the complexity of the recorded seismic wavelets. For example, the seismic Moho is often resolved at different depths by complementary seismic reflection and refraction studies. Seismic modeling ambiguously predicts that both discrete and multi-layered structures can yield the seismic signatures observed on deep data. Such problems need to be solved. Walter Mooney from the USGS has recently shown that the upper-mantle has a surprisingly large control upon near-surface processes. Therefore, these formerly obscure deep geological features are suddenly more significant than they once were.

RECENT DEEP SEISMIC DATA IMPROVEMENTS

In an isotropic media, the 21 anisotropic elastic rock parameters reduce to only 2 elastic rock parameters (bulk and shear moduli), each of which are simply a function of density, and P-wave and S-wave velocities. Detailed volumes of work using measured crustal velocities (e.g. Christensen & Mooney, 1995) are now leading to accurate constraints upon the petrology and mineralogy of crustal and upper-mantle rocks. Former "outsiders" such as geochemists and petrologists are now able to integrate their skills with the results of seismic-based studies. A particular project of interest involves the attempted identification of the deep source regions of xenoliths; lower-crustal and mantle rocks that have been rafted to the surface within magma uprisings. Having identified the physical properties of such rocks found at the surface, the challenge is to identify such parameters at great depths.

The use of AVO phenomena in deep seismic studies has been historically hindered by a lack of confidence in the validity of applying the concept to sparsely recorded, poor-quality data. In recent years however, AVO studies have been successfully applied to infer intra-crustal "melt zones" (e.g. Makovsky *et al.* 1996), transitions in the petrology of igneous intrusions and the presence of intra-crustal water.

Obviously at the crustal scale, anisotropy can be profound. Rather than being considered a hindrance however, crustal studies often rely upon the presence of anisotropy to infer useful observations. Historically, three of the most important mineralogies in the lower-crust/upper-mantle (to crustal geophysicists) have been olivine-rich rocks such as harzburgite, peridotite and dunite (orthorhombic mineral structure and hence anisotropic), eclogites (highly metamorphosed anisotropic rocks) and garnets (cubic mineral structure and hence isotropic). In extending oceanic crust near diverging plate boundaries, strain-related alignment of the olivine-rich rocks perpendicular to the ridge axis imposes a strong anisotropy. All of these examples relate to gross-scale applications. As the quality of recorded reflection seismic data improves, the use of anisotropy measurements at a more local scale will conceivably increase in application. Furthermore, the establishment of correct velocity models and structural geometry depends upon the accurate incorporation of anisotropy parameters, so it is expected that many detailed seismic profiling efforts will look to the developments in anisotropic data processing.

Geophysicists and geologists these days want to resolve both the shallow and deep geology together, such that the deep controls upon shallow structures can be established. This quest then demands the acquisition of high frequencies as well as the lower frequencies that have historically sufficed. Even at the most regional scale (using teleseismic data), the recording of higher frequencies should be of great use, conceivably using receivers anchored in boreholes that have been drilled into consolidated rock. Such acquisition of higher frequencies would allow the recording of lower magnitude earthquakes than is presently possible (at present, it is difficult to remotely record earthquakes with $M < 5$). As the number of global earthquakes varies roughly as the exponential inverse of magnitude, such recordings would create a wealth of new information.

At a simpler level, much of the challenge in using deep reflection seismic data is an interpreter's problem. Often the data quality is so poor that the interpreters find it less ambiguous to produce "line drawings", in which the dominant seismic events are traced by hand, effectively removing the contribution of the weaker signal and noise. This simplistic "coherency" filter is an indication that there exists great scope for the development of more powerful and automated coherency filtering techniques. Application of techniques such as "skeletonization" (Cook & Vasudevan, 1996) and fractal-based data dissemination already hint at the usefulness of such approaches. Coherency filtering is still in its relative infancy in commercial exploration data processing (e.g. Schwab *et al.* 1996), so it appears that this is one area in which the application of new industry technology will quickly follow in the deep seismic profiling domain.

What are the processing developments that hold most promise for the future? Historically, due to the prohibitive logistical and financial obstacles, 3D acquisition has never been undertaken. At present, Scripps Institution of Oceanography (University of California, San Diego) is acquiring the first 3D survey over the overlapping spreading center of the 9°N segment of the East Pacific Rise, Pacific Ocean, which will obviously incur processing problems never before encountered in crustal studies. These problems will open the way for the design and application of routines such as DMO and pre-stack migration. Certainly, the imaging of such a complex structure is going to be a challenge. As consortium experiments between academia and industry focus more upon natural resource regions, the associated larger budgets will allow a previously unattained standard of acquisition: close receiver spacing (of the order of 40 m), high data fold, accurate surveying and thus refraction statics computations, and source parameters designed to generate high-frequency signals. Hence, such datasets will more closely resemble conventional exploration datasets than has been the case in the past. In fairness to academia, the industry will never acquire data in geologically interesting areas like the Himalayas. Nevertheless, there would appear to be little reason to deny that industry surveys will conceivably provide many high-quality images of the deep geological features that have beguiled crustal geophysicists for so long. In turn then, academia will look to industry to lead the way.

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