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Deep Seismic Reflection and Refraction Profiling

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Definition

Deep Seismic Reflection and Refraction Profiling
Classically, multichannel recording, along a measurement line, of (mostly) seismic P-waves, artificially generated using large energy sources, after these have traveled deep thru the earth's crust (and upper mantle). Later developments include multicomponent recording enabling analysis of shear waves. Deep reflection profiling is mostly done using vibrators (on land) or air guns (in water) at near-vertical distances (8–12 km) to image the structure of the crust and upper mantle. Wide-angle reflection/refraction profiling uses large explosions and recording distances (200–300 km), primarily to obtain velocity information down to the upper mantle.

Synonyms
► Active source seismology; ► Controlled source seismology; ► Deep seismic sounding; ► Explosion seismology; ► Wide-angle reflection/refraction profiling

Notational Notes
Below, all capitals (e.g., DSRRP) will be used for acronyms and italicized phrases within double quotes (e.g., "*Seismic Noise*") will refer to articles elsewhere in *this* volume.

Introduction

Vibrations caused by earthquakes are known to travel great distances and provide valuable information about the internal structure of the earth. Explosions and other artificial sources could also be used to generate such waves. Man-made *earthquake* signals have several advantages of their own, e.g., their location – both in space and time – is precisely known. Further, due to relatively shorter distances of observation, higher frequencies are better preserved and allow a better resolution of the subsurface structure. Development of *marine seismics* has extended the coverage of this technique to offshore regions too.

As a science, *deep seismics* is positioned between exploration seismics and seismological studies. With the shared theory of wave propagation in (visco)elastic media, similar instrumentation, and computer-intensive processing/interpretation techniques, there is increasing *overlap* between these two approaches. Improvements in data acquisition and processing have extended the depth range of exploration seismics from basin level downwards and now cover the entire continental crust down to *Moho* and the upper mantle region immediately below it (50–100 km). Such studies are called deep seismic sounding, long-range reflection-refraction, wide-angle crustal-seismics, etc. depending upon their focus. The acronym *DSRRP*, derived from the title, will denote studies using seismics to study the (continental) crust, including active and passive continental margins, and the upper mantle of the earth, using man-made and natural sources.

There are several good resources about the general theory of wave propagation in elastic media (e.g., Aki and Richards 2002) and exploration seismics (e.g., Sheriff and Geldart 1995 and "► Seismic Data Acquisition and Processing"); special topics pertaining to the latter in the context of DSRRP will be elaborated whenever needed.

Basic Principles

Figure 1 illustrates the principle of the seismic experiment using a simplified earth model. Here, a horizontal boundary

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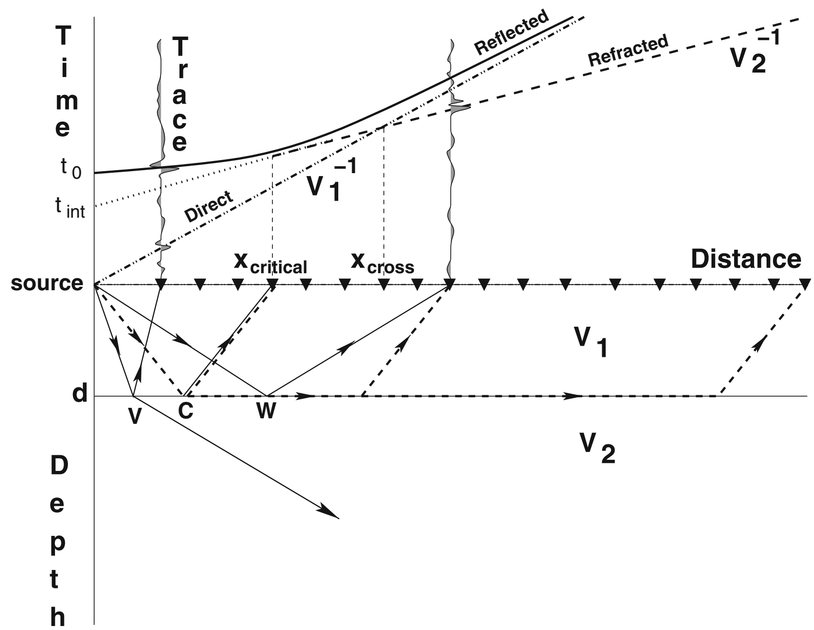


Deep Seismic Reflection and Refraction Profiling, Fig. 1 Schematics of a multichannel seismic experiment to image the earth (layer of wave speed V_1 overlying a half-space of wave speed V_2). Energy travels from the source through the medium and is recorded by the receivers (filled triangles), planted in the ground, as *seismic traces*. Dash-dots represent energy *directly* traveling from source to the receivers along the surface, continuous lines show *reflections* from the layer boundary, and dashes indicate energy *critically refracted* along the boundary. The upper half uses the same patterns to show the *travel times* of these three phases. Letters *V*, *C*, and *W* indicate points representing (near) vertical, critical, and wide-angle incidence of energy on the boundary

separates the top layer of velocity (actually wave speed) v_1 and thickness *d* from a half-space of velocity v_2, with $v_1 < v_2$, mostly valid within the earth. Wave energy, generated at the source, travels through the media and is recorded by many (usually hundreds of) receivers on the surface as *seismic traces*, their collection being a *seismic record*. Plot of a record – amplitudes as a function of recording distance versus travel time – shows distinct spatiotemporal *alignments*, representing different wave types (*phases*), three of which are sketched in the figure. Depending upon their travel path, the phases show up in the record as *first* or later arrivals and carry information about some properties of the medium. The amplitudes of these phases – and their variation with the recording distance (*offset*) – yield additional information about material properties of the medium, e.g., *density*, *elasticity*, etc.

The subject matter of this article forms an extension of exploration seismics. Sheriff and Geldart (1995) and Liner (2004) provide good coverage of its various aspects, e.g., theory and data acquisition, processing, and interpretation. More detailed treatment of these topics is provided by Aki and Richards (2002; theory of wave propagation), Vermeer (2002; data acquisition), and Yilmaz (2001; data processing). DSSRP-specific modifications/extensions to the standard field and processing procedures will be described later. Based on Fig. 1, a brief overview of some key concepts from *seismics* – relevant to DSRRP – follows.

Linear arrivals represent the travel times of both *direct* and *refracted* arrivals, if v_1 and v_2 are constant, the slopes (dt/dx) being inversely proportional to the corresponding velocities. Using these, and the *intercept time* (t_{int}, Fig. 1) of the refracted arrival, the layer thickness *d* can be calculated.

Critical distance is the minimum recording distance for observing the refracted wave. According to Snell's law, only when the energy is incident on the boundary at the critical angle $\left(= \sin^{-1}\frac{v_1}{v_2}\right)$ will it be refracted *along* the boundary, will propagate with the velocity v_2 of the lower medium, and will keep sending energy back into the upper medium according to Huygens' principle.

Crossover distance denotes the distance, beyond which the faster refracted phase overtakes the direct wave ($v_2 > v_1$) and becomes the first arrival; the latter can also be used to determine the thickness *d*. In a layered earth with velocities increasing with depth, refraction arrivals from deeper boundaries become the first arrival after their respective crossover distances. *Historical note*: A. Mohorovicic used the overtaking of the direct P-phase from an earthquake by a faster (refracted) one, which he called P_n, to infer the thickness of the earth's crust and the presence of a higher-velocity medium underneath (IGCP-559 2010a); the boundary defining the base of the crust has since been named *MOHO* in his honor.

Reflections represent that part of wave energy incident upon a layer boundary, say at the point "V" in Fig. 1, which will be transmitted back into the upper medium, according to Snell's law. The *reflected* arrival is hyperbolic in shape, with its apex at time t_0, corresponding to the vertical two-way time ($= 2d/v_1$) from the source down to the boundary and back. Reflection amplitude is sensitive to the (contrast of) material properties across the boundary and the incidence angle and provides valuable additional information regarding the media.

Supercritical incidence occurs, as the recording distance increases, with the incidence angle changing in Fig. 1 from (near) vertical (e.g., point "V") through the critical incidence (e.g., point "C") to supercritical (e.g., point "W"). Note that the reflection hyperbola becomes asymptotic to the linear arrival belonging to the layer above but never crosses it. This relationship also holds in a multilayered situation with increasing velocities.

Wide-angle incidence implying large recording distances (compared to the target depth) sees a sharp increase of *reflection coefficient* and enables imaging of crustal boundaries with small contrasts. The quantity $t_x - t_0$ (Fig. 1), called normal moveout (NMO), can be measured well in this region and helps velocity estimation. The seismic signal window gets compressed though at large offsets due to the geometry (kinematics) of the travel time curves (Fig. 1, top).

Modern DSRRP represents an integration of the *near-vertical* and *wide-angle* modes of seismic investigation. While near-vertical multichannel reflection seismic (NMRS) provides powerful tools for structural imaging developed for the exploration industry, wide-angle reflection-refraction (WARR) is valuable for constraining the velocities of the crustal units and thus provides the geological framework.

Data Acquisition

Seismic field measurements need three components, viz., man-made *source* to produce seismic energy (usually at the earth surface or within water), which then propagates within the earth, *receivers* (usually also at the surface) to pick up a part of this energy returning back after reflection/refraction/diffraction (scattering in general) from within, and *recorder* to store the received signals (nowadays after digitization); see "▶ Seismic Data Acquisition and Processing" for details.

Sources used in DSRRP have to be stronger than those in exploration, as the distances traveled by the seismic waves – both vertically and especially horizontally – are much larger. Such sources including quarry blasts using several kilotons of TNT – sometimes under water – were recorded over long distances, often across international boundaries (Steinhart and Meyer 1961; György 1972; Kaila et al. 1978). Calibrating and monitoring of nuclear explosions necessitated several long-distance (mostly) refraction profiles, with nuclear explosions as sources (see "▶ Seismic Monitoring of Nuclear Explosions"). Later, very long-range crustal seismic measurements were carried out in the Soviet Union using dedicated *peaceful nuclear explosions* (Pavlenkova and Pavlenkova 2006). Although chemical explosions continue to be used for WARR studies, powerful hydraulically driven mechanical vibrators on land and large compressed air sources (air guns) under water are preferred nowadays for NMRS; these have sufficient energy to return signals back to the surface from Moho and upper mantle.

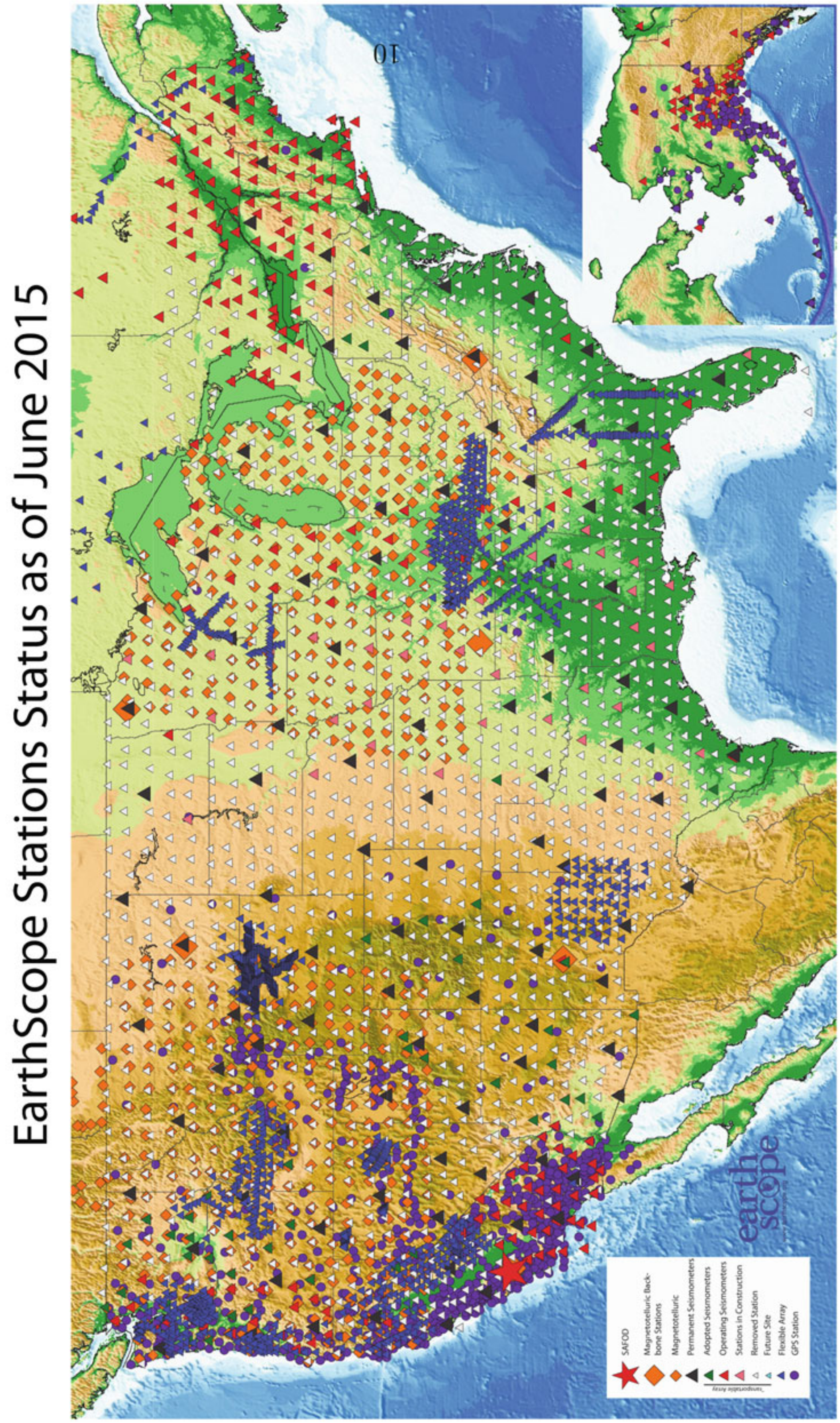
Receivers used in DSRRP are similar to those used in seismology and in exploration seismics but need some special characteristics. Long measurement profiles imply deployments over a large distance/area, often necessitating standalone capabilities, especially for power supply and storage capacity; see Mereu and Kovach (1970), in which mention is also made of an early German effort (MARS-66) using a portable four-channel analog tape recorder. Modern DSRRP receivers digitize in real time and can often be programmed to record at certain pre-arranged time windows (see Texan in the references). For near-vertical land/marine deployments, standard industry equipment is used; these are frequently cable-free and use radio communication for data transfer.

Time-of-shot recording was the weakest link in DSRRP – especially for WARR deployment, covering distances of several hundred kilometers. Early experiments used short-wave radio link or the parallel recording of a continually broadcasting radio transmitter. Availability of GPS-based time signals and high-quality internal clocks has mitigated this problem.

Field Layouts

Receiver arrays were utilized early on for long-range refraction-seismic studies for their directivity vis-a-vis possible nuclear test sites – some becoming permanent installations, e.g., NORSAR (Norway), GBA (India), and WKA (Australia). Recently, the Program for Array Seismic Studies of the Continental Lithosphere (see PASSCAL in the references) has made hundreds of identical instruments available, enabling temporary deployment in several countries. Using these, with fixed and portable deployments recording both active and passive sources, a 15-year observation has been completed in the USA. See Fig. 2 and USARRAY and EarthScope in the references.

Multichannel near-vertical land/marine studies use standard industry equipment and deployments (see also "▶ Seismic Data Acquisition and Processing"), the main difference being a much longer recording time (15–30 s or longer). When using vibratory sources on land, long sweep and listening times are needed too. If the continental crust is covered by a shallow water layer (e.g., British Isles), marine data acquisition offers twin advantages of speed and better signal-to-noise ratio, enabling better imaging.



Deep Seismic Reflection and Refraction Profiling, Fig. 2 Plot of EarthScope stations – permanent and temporary – including those of USARRAY. For details, see legend in the inset. Full resolution original at http://www.earthscope.org → Research → Maps → EarthScope Overall Maps (Archive) → June 2015. (Figure courtesy of www.earthscope.org)

DSS-DSRRP onshore-offshore recorded earlier from near-vertical outward till at least the p_n-phase (refraction below Moho) was recorded as the first arrival (Gamburtsev 1952). Outside the Soviet Union, this technique was first extensively used in India starting 1972, to study the tectonic framework of the subcontinent (Reddy et al. 1999) and was later adapted for sub-basalt (*Deccan Trap*) exploration. Many DSRRP investigations nowadays combine the two modes – an industry standard *common midpoint* profile (NMRS) is frequently interspersed with a few widely spaced explosions, observed at large distances (WARR). Variations include two-ship marine recording and simultaneous onshore-offshore measurements, useful for investigating continental/accretionary margins.

Special Processing and Interpretation Tools

Processing of DSRRP data followed initially the standard industry scheme. Soon, however, the special needs of deep seismic data were realized. Consequently, schemes using modules newly developed by the industry/academia were established, and older data were frequently reprocessed, often resulting in *improved* images and interpretation (Cook and Vasudevan 2006).

Line drawings were used initially to prepare DSRRP data for migration and interpretation. NMRS signals are generally weak and laterally discontinuous and embedded in a noisy background. Lines were therefore drawn on the paper section to form more or less continuous alignments – taken to represent boundaries for interpretation. The process was strongly subjective. This approach paralleled interpreting WARR data with long refraction segments, which neglected signals with limited lateral continuity.

Coherency filter was proposed to mitigate this. Kong et al. (1985) formulated a procedure to *automatically* identify *signals* present in the seismic section. Using the concept of *phase coherency*, it uses a few user-defined parameters, to yield *repeatable* results, and can detect *weak but laterally continuous* signals in the presence of incoherent noise – although it does not preserve (relative) amplitudes. Some form of coherency filtering is nowadays commonly used for processing NMRS data.

Noise reduction versus amplitude preservation is, however, an important issue because modern processing techniques can use amplitude information to advantage. An example of amplitude-preserving noise reduction is provided by Kumar et al. (2011), wherein curvelets are used to suppress incoherent seismic noise.

Statistical processing of DSRRP data, for objective high-grading using a coherency criterion, was proposed by Hansen et al. (1988), based upon statistical hypothesis testing. It provided some estimate of the robustness of the results, albeit at the cost of additional computation time. Vasudevan and Cook (1998) introduced the concept of *skeletonization* to delineate regions of the deep crust based upon their seismic signature; van der Baan (2000) included local signal statistics for high grading the signals.

Attempts have also been made to treat the entire deep-reflection wave field as backscattering from a random medium (Hurich 1996; Hurich and Kocurko 2000; Pullammanappallil et al. 1997) and analyze it to extract parameters describing the medium (see below).

Vertical vis-a-vis horizontal tectonics used preferentially could lead to different interpretations of the same data. DSS profiles in György (1972) and later literature (e.g., Kaila et al. 1979) frequently contain intra-crustal normal faults. With the paradigm shift associated with the formulation of plate tectonics, some of these may need to be revisited. Gibbs (1986) illustrated this by using a DSS section sans the earlier interpretive lines for an alternate interpretation.

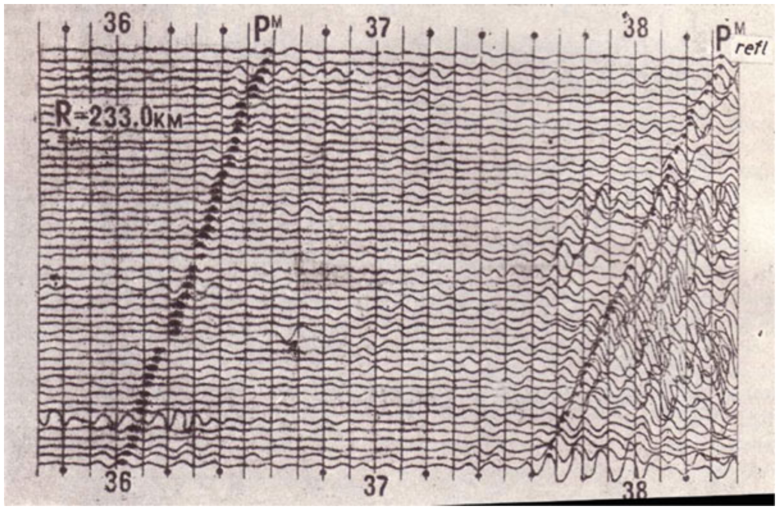
Main Results

NMRS recordings from 12 to 15 s contain coherent reflected energy from down to 35–45 km, depending upon the presence/absence of sedimentary cover. Crystalline crust appears to be much more reflective than assumed earlier, although there are transparent zones too. In general, the mature continental middle crust is less reflective than the lower crust – probably indicating differences in their rheology (brittle vs. ductile). Intra-crustal dipping reflective zones – of both thrust and normal fault types – are encountered frequently. At times, these cut through the Moho into the upper mantle as *frozen* evidence of paleo-subduction. Moho appears frequently as the termination of *diffuse* reflectivity, the boundary itself occasionally showing sharp displacement (sign of strength).

WARR recordings can be modeled with longer boundaries separating tectonic/velocity blocks at a regional scale. These also provide occasional evidence of *sharp* offsets in crustal boundaries including Moho; the latter seems, in some cases, to be *doubled*.

The role of deeper structures – especially *deep faults* – in controlling the evolution of shallower geology, e.g., deposition, deformation, fluid movement, etc., is being increasingly appreciated. The knowledge gained is of economic significance – for understanding *systems* associated with economic accumulation of hydrocarbons and minerals and to help steer search for them.

Early DSS(RP) in Eastern Europe has been nicely summarized in György (1972), from which Fig. 3 is taken. It shows a part of a long-offset (≈233 km) DSS profile recorded in Ukraine in the 1960s, as part of extensive DSS surveys in Eastern Europe, which had established the



Deep Seismic Reflection and Refraction Profiling, Fig. 3 DSRRP data recorded in Ukraine in the 1960s. Both refracted and reflected energy is clearly visible at a distance of about 233 km and is correlatable trace to trace with a geophone spacing of 100 m. The first arrival, here marked P^M, is the head wave from Moho (P_n), and the strong later phase, marked P^M_{refl}, is the wide-angle reflection from the base of the crust. (Figure courtesy of *Geophysical Transactions* from György (1972, p. 50))

Deep Seismic Reflection and Refraction Profiling, Table 1 Some (inter)national DSRRP efforts

Acronym	Location	Period	Remarks
COCORP	USA	1975 onwards	Pioneered near-vertical imaging
BIRPS	UK	1981–1998	Marine seismic imaging
DEKORP	Germany	1983–1997	Deep drilling (KTB)
LITHOPROBE	Canada	1984–2003	Multidisciplinary
ECORS	France	1983–1991	IFREMER (marine)
MONA LISA	UK	1993	On/Off -shore
IBERSEIS	Spain	2001	Spanish universities and institutes
SEAL	*E. antarctica*	2002–2004	Japan
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INDEPTH	China	1992 onwards	USA and other countries
ANCORP	Chile	1996	Germany and other countries
KRISP	Kenya	1985–1994	European and US universities
BEST	Russia	2002	Denmark and Poland
BABEL	Baltic Sea	1989	European groups, On/Off -shore
EAGLE	Ethiopia	2003	European and US universities
SINOPROBE	China	2008–2012	Multidisciplinary
. . .			

observability of deep refracted and reflected phases in the wide-angle range. High apparent velocity of the refracted P_n-phase (first arrival at large offsets) and its relationship with (later) reflected phase help identify the base of the crust as their origin. Some figures in the above reference also show near-vertical reflections from the Moho.

György (1972, pp. 44–68) includes on page 66 a contour map of the Moho depth below Ukraine, the detail of which, although debatable, is impressive, especially considering its vintage. It is based on an astounding 6000 line km of DSS profiling with a dense network, following the methodology described in Gamburtsev (1952). The contours indicate depths between 22.5 and 55 km, with rapid lateral variations at places. The latter were interpreted as *deep faults* displacing the Moho.

(Inter)national consortia in DSRRP started in 1975, when an industry crew measured a reflection profile in Texas, using a vibratory source, with a recording time of 15 s (Finlayson 2010b). A large amount of data has since then been collected/analyzed in several national academic industrial collaborations – Table 1 provides a partial overview; see also IGCP-559 (2010c) for more details.

Recently, some international DSRRP experiments have studied specific geological problems, e.g., Himalaya and

Tibetan Plateau (Zhao et al. 1993), active continental margin in Central Andes (ANCORP Working Group 2003), and structures in East Antarctica from SEAL geotransect (Kanao et al. 2011). Such transects are often multidisciplinary in character, e.g., Palomeras et al. (2011).

International biennial symposia have been organized (roughly) every 2 years since 1984 to showcase the data and discuss the results from DSRRP surveys. The publications resulting from these meetings provide a historical record of the progress of DSRRP – with respect to both technological advancement and scientific knowledge: Barazangi and Brown (1986a, b), Matthews and Smith (1987), Leven et al. (1990), Meissner et al. (1991), Clowes and Green (1994), White et al. (1996), Klemperer and Mooney (1998a, b), Carbonell et al. (2000), Thybo (2002), Davey and Jones (2004), Snyder et al. (2006), Heikkinen et al. (2011), Rawlinson and Goleby (2012), Santosh et al. (2014), Carbonell et al. (2016), Rawlinson et al. (2017), and Malinowski et al. (2019). Some additional information is also available in IGCP-559 (2010b).

(Re)processing, synthesis, and interpretation of the vast amount of DSRRP data – near-vertical and wide-angle – are not easy. The data quality depends upon the geological settings and the data acquisition technique and parameters used. Uniform processing of this dataset of mixed quality/vintage is necessary though for regional syntheses and interpretation, to understand the internal architecture of the continental crust (e.g., Phinney and Roy Chowdhury 1989; Cook and Vasudevan 2006).

Results from DSRRP contain several surprising features – some of which are still being interpreted – and have yielded new insights into the processes that shape the continental crust. Below are some of these highlights; the acronyms referring to the consortia/projects are explained in Table 1.

Imaging deeper with multichannel exploration seismics began in 1975. The COCORP consortium – the acronym is reported to have been coined past midnight at a bar in Mexico – pioneered the use of industry standard sources (vibrators), recording layout (NMRS), and processing for deep seismic profiling on land and obtained useful signals from depths of 40–50 km, by using 4–5 vibrators simultaneously and extending the recording time (Oliver et al. 1976). Later, similar studies confirmed that the crust underlying the basement possesses variable reflectivity, including some *transparent* regions. Moho, the base of the crust, often showed up on such images as the termination of a zone of diffuse reflectivity, and not as a long and sharp boundary inferred from earlier (refraction) studies.

One of the early surprises of the COCORP lines was the discovery of a mid-crustal zone of strong reflectivity below southern Georgia, USA; the *surrency bright spot* was reconfirmed during a later survey (Pratt et al. 1993). Such zones have since been reported in other surveys too, e.g., the *Quebrada Blanca Bright Spot* (QBBS) in Andean subduction zone (ANCORP Working Group 2003) and below the Dnieper-Donets paleorift (Pylypenko et al. 2011). The possible causes of this strong reflectivity remain controversial (see below).

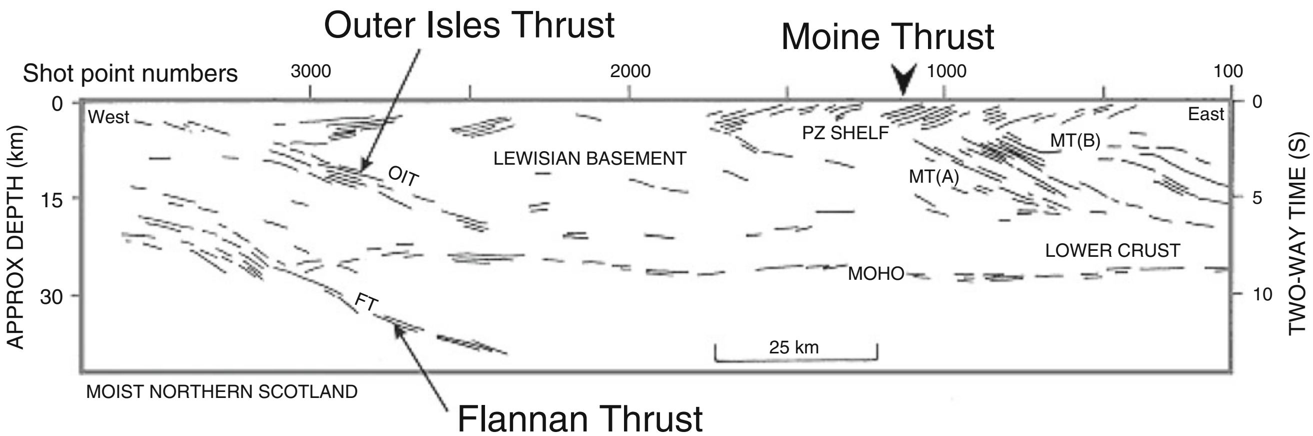
Besides WARR recordings of quarry blasts, Germany had an early start in near-vertical recordings of deep reflections and statistical evaluation of their amplitudes (e.g., Dohr 1957; Dohr and Fuchs 1967). More recently, their DEKORP program has included investigations across active collisional zones, e.g., Alps (Gebrande et al. 2006) and the Andes (ANCORP Working Group 2003). For details, see DEKORP in the references.

Marine seismic imaging of the continental crust was seized upon to (partly) alleviate the unfavorable *signal-to-noise ratio* (SNR) for deep seismic data acquisition on land, e.g., noise from traffic, industry, etc. – although marine seismics has its noise sources too. Phinney (1986) used data from a 48-channel marine survey (recorded by USGS during 1973–1979) over the Long Island Platform. The original stack sections of lines 36 and 23, reprocessed to 12 s, showed clear evidence of a rich crustal architecture, with half grabens, wedges, and other tectonic features indicating both compressional and extensional phases of a Wilson cycle.

Existence of known – and expected – hydrocarbon-bearing structures had attracted marine seismic exploration activity in the 1970s and 1980s to the waters around the British Isles. The latter, surrounded by North Sea and the northeast margin of the Atlantic Ocean, are a part of the European continental shelf. Starting 1981, this situation was utilized to great advantage by the BIRPS consortium – essentially by extending the marine seismic exploration recording time to 15 s. The very first profile, MOIST (recorded by the preceding BURPS group), contained strong reflections from the lower crust, Moho, and upper mantle (see Fig. 4), which could be connected to surface geology on land (Smythe et al. 1982), and even prompted correlation of tectonic evolution across the Atlantic (Brewer and Smythe 1984).

Later BIRPS profiles, e.g., WINCH (Brewer et al. 1983), provided evidence for shallower/younger tectonics being controlled by older/deeper crustal structures. The DRUM profile extended the recording to 30 s. The density of coverage and the quality of data allowed Flack and Warner (1990) to map deep reflections in 3D and enabled Chadwick and Pharaoh (1998, p. 268) to produce a contour map of Moho beneath the UK, which may be compared with a similar map below Ukraine (György 1972, p. 66) mentioned earlier.

Integrated transects, using additional geophysical tools, e.g., magnetotellurics, electromagnetics, and geochronology, characterized the LITHOPROBE program in Canada. It took advantage of the geology to investigate both ancient processes, e.g., assembly of continents and modern crustal dynamics of active subduction, detachment, and imbrication.



Deep Seismic Reflection and Refraction Profiling, Fig. 4 Annotated line drawing interpretation of the MOIST profile data, showing coherent reflections from throughout the crustal column. Moho shows up as a more or less continuous boundary. Several dipping thrust-like features (e.g., Outer Isles Thrust) can be seen at all depth ranges, which also include transparent zones. One dipping reflective zone (Flannan Thrust) is seen to penetrate through the Moho into the upper mantle. (Figure from Finlayson (2010a); see Brewer and Smythe (1984) for details)

For example, the Kapuskasing Uplift, one of the few lower crustal exposures on earth surface, was imaged in the KSZ transect (Percival et al. 1989), whereas the transects SNORCLE and SC examined younger mountain building processes (e.g., Clowes et al. 1983).

Relating to the ground truth, the strength of exploration seismics, is the Achilles' heel of DSRRP (and seismology). Superdeep drill holes provide the only opportunities of directly correlating observations to the rock properties; the German DEKORP program was able to utilize this in a symbiotic manner.

DEKORP played an important role in the site selection phase of the German superdeep drilling program, KTB, which was set up to drill ≈10,000 m down through an ancient geodynamic suture – see Emmermann and Lauterjung (1997) for an overview of KTB. Later, besides providing a reference point for the seismics at the drill site, the KTB program has yielded direct evidence of shear zones, anisotropy, and substantial amounts of fluids deep in the crust; the analysis of the latter has provided new insights into their origin and role in controlling/influencing geodynamic processes.

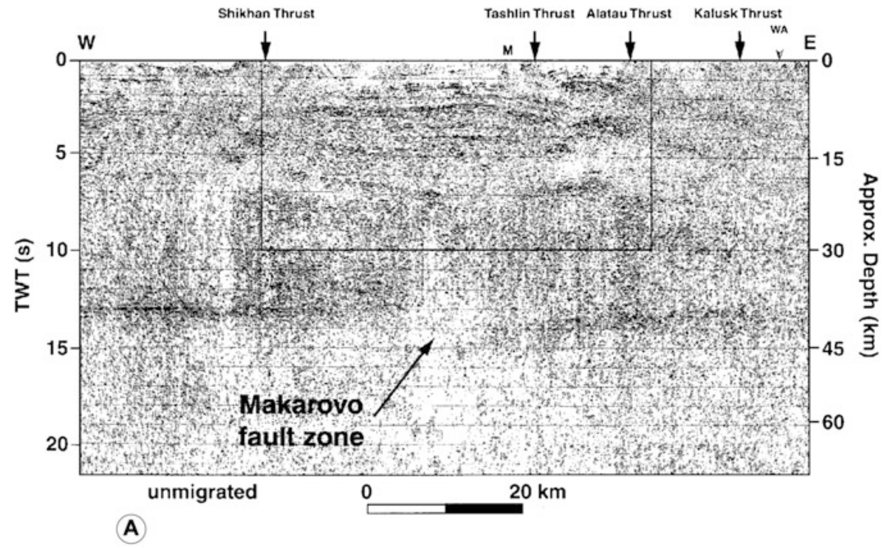
The Russian super-deep drilling program in the Kola Peninsula (Smythe et al. 1994) reached the record depth of 12,200 m and also provided valuable *ground truth* regarding the macrostructure of the mature continental crust and the origin of crustal reflectivity.

Upper-mantle reflectivity-frozen subduction has also undergone a paradigm shift as a result of DSRRP investigations. Reflections from upper mantle were already reported by György (1972). DSRRP has provided vivid proof that reflective zones may extend into the upper mantle and has helped understand their structure. Dipping reflectivity in this region has provided information regarding paleotectonics and may – in some cases (see Fig. 4) – be evidence for paleo-subduction (see also BABEL Working Group 1990; Morgan et al. 1994).

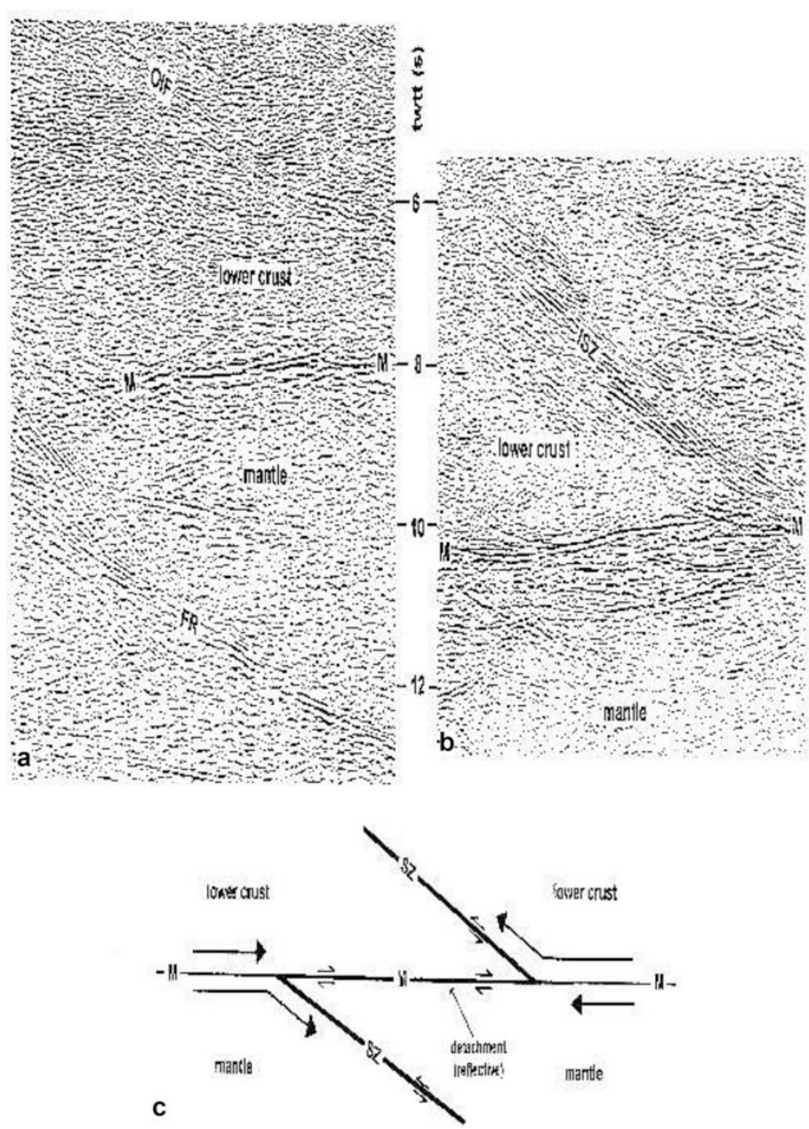
Rheology of crust, Moho, and upper mantle depends upon their composition and in situ physical conditions. Intra-crustal faulting, affecting even the Moho, was already inferred by György (1972) and Kanasewich et al. (1969). DSS data from the Indian shield (Kaila et al. 1979) was used by Roy Chowdhury and Hargraves (1981) to infer constraints about the thermo-tectonic evolution of the early earth. With improved acquisition/processing, such features are now regularly reported from different parts of the world.

(Near) vertical offset in the Moho, inferred at many places from teleseismic, gravimetric, and other geophysical observations, is now often imaged in NMRS. This has important bearings regarding the *nature* of Moho. This first-order seismic boundary is often thought to be a surface that re-equilibrates after tectonic events above (e.g., thrusting) or below (e.g., underplating). DSRRP images contain counter examples too, showing that Moho topography can survive later orogenic cycles, e.g., BABEL Working Group (1990) and Diaconescu et al. (1998). The reason for this behavior is not well understood.

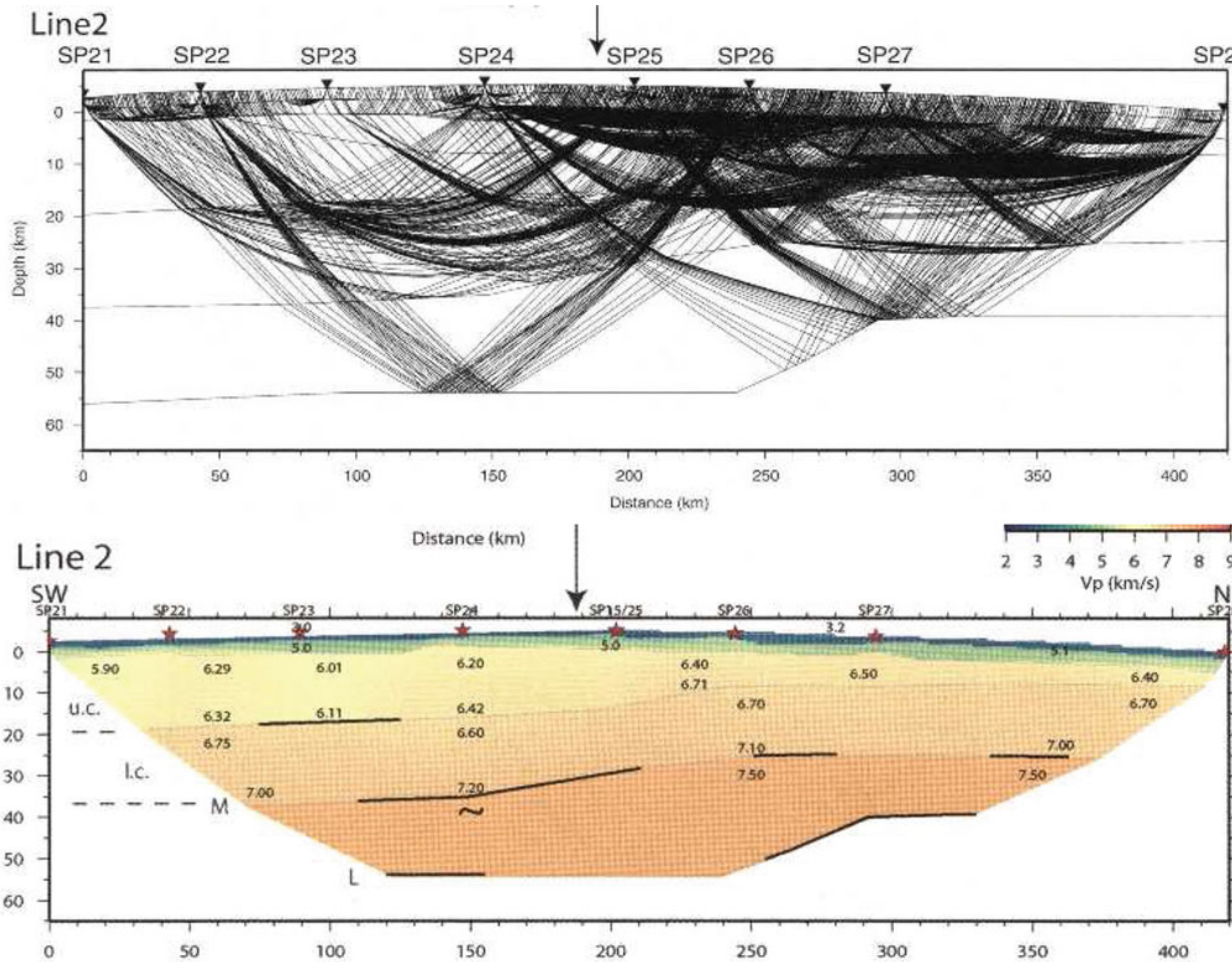
The thermal- and the stress- regimes in the lower crust and upper mantle determine the interaction between the two during the formation of Moho as the boundary layer. Chadwick and Pharaoh (1998) interpret a DSRRP line by associating increased reflectivity of the Moho *there* to its being a detachment surface resulting from low-angle shear (Fig. 6). Local *doubling* of Moho is seen especially in some WARR data – its evolutionary mechanism remains unclear though.



Deep Seismic Reflection and Refraction Profiling, Fig. 5 Unmigrated seismic section from URSEIS profile across southern Urals. (Figure from Diaconescu et al. (1998), with permission from *Geology*). Moho (older than 1 billion years) is bright on the left and is offset sharply in the middle of the figure (Makarovo fault zone) by ≈5 km. Migrated image of the boxed upper part (not shown) contains laterally continuous stratification over this fault zone



Deep Seismic Reflection and Refraction Profiling, Fig. 6 Schematic representation of low-angle shear near Moho (**c**) with parts of BIRPS seismic sections GRID (**a**) and NEC (**b**). (For details, see Chadwick and Pharaoh (1998); figure courtesy of *Tectonophysics*)



Deep Seismic Reflection and Refraction Profiling, Fig. 7 Velocity modeling by ray tracing for the EAGLE project (in the Ethiopian rift). Note the variable coverage of the ray tracing (above) and the *smooth* result, with a few long segments, in the final P-wave velocity model (below) – both these characteristics are typical for WARR data analysis. (For details, see Maguire et al. (2006); figures courtesy of *Geol. Soc. London*, with permission from the author)

WARR had taken a back seat with the increasing use of NMRS. With progress on some of the processing issues, it has made a comeback following the adage: *structures from reflection and velocities from refraction*. It is, sometimes, a part of onshore/offshore measurements and uses three-component receivers to study crustal anisotropy. Mooney and Brocher (1987) provide a review of earlier coincident WARR studies. Another example is BABEL Working Group (1993). Standalone WARR remains useful at places with difficult logistics; see the KRISP experiment in the Kenyan Rift Valley (Khan et al. 1999).

Deep seismic investigations using nuclear explosions: During 1965–1988, the then USSR carried out a series of very long-range seismic experiments using *peaceful nuclear explosions* (PNEs), supplemented with chemical explosions placed every 100–150 km (Benz et al. 1992). Employing three-component receivers, typically 10 km apart, and recording out to 1550–3000 km (Pavlenkova and Pavlenkova 2006), these datasets provide an invaluable basis for current and future research; QUARTZ, the profile studied most, used 400 three-component receivers, 3 PNEs, and 51 chemical explosions (Morozov et al. undated IRIS communication; see references); analysis of its data has generated new ideas about wave propagation in the lower crust and upper mantle.

Analysis/modeling of WARR data typically starts by picking *travel times* of first and later arrivals that are interesting, the choice being decided by the data quality and the geological aim. Usually, some prominent (mid) crustal reflected/refracted arrivals are identified and *picked*, along with arrivals from Moho, and possibly deeper ones. Methods of deriving crustal models from this data include ray tracing (Zelt and Smith 1992), tomography (Hole 1992), computation of synthetics, etc. (see also "► Seismic Travel Time Tomography"). Frequently, a preliminary *velocity model* is iteratively fine-tuned to obtain a desired level of fit to the observed travel times. There are several schemes for *ray* *tracing*; see "▶ Seismic Ray Theory" and Zelt (1995) for overviews. Of late, amplitude information has also been incorporated in such schemes.

Maguire et al. (2006) contains examples of the different aspects of the procedure in the context of the EAGLE experiment (Fig. 7). Different modeling/inversion schemes yield different results from same input. The DOBREfraction'99 Working Group (2003) provides an example of this. Pavlenkova (2011) has interpreted PNE arrival times to infer upper mantle rheology and suggests layering along the travel paths with boundaries at 100 and 200 km (fluids?).

Analyzing amplitude of DSRRP signals is a crucial step, to differentiate between competing models of the crust. Improvements in the data quality, and careful processing, allow attempts to quantify the material properties that influence the strength of the recorded signals. Properties that are of primary interest are reflection coefficients (RC) across various boundaries, their variation with the angle of incidence (AVO), and the Q(uality) factor along the path (see "▶ Seismic Data Acquisition and Processing" for definitions). These properties are especially important while considering the probable cause(s) of the bright spots, e.g., fluids, intrusions, layering, etc.

Warner (1990) reported RC values of about 0.1 for lower crustal layers and about 0.15 for Moho – both derived from the WAM profile (Peddy et al. 1989). The polarity (sign) of RC is important in differentiating between likely causes of bright spots sometimes seen in DSRRP images. However, even using polarity-preserving processing, it is often only possible to determine relative values of RC. ANCORP Working Group (2003) discusses the issues involved for a couple of strong reflectors – *Nazca and QBBS* – while reporting RC > 0.2 for the latter. Combining NMRS and WARR data, Makovsky and Klemperer (1999) report RC values between -0.3 and -0.4 for the NBS bright spot in the Tibetan middle crust.

Obtaining estimates of Q along the travel path of NMRS signals (relatively high-frequency body waves) is also difficult – the effects due to scattering, conversion, etc. (apparent-Q) cannot be readily separated from the intrinsic attenuation (see also "▶ Seismic Viscoelastic Attenuation"). Combining the two, Hobbs (1990) obtained a value of 500 ± 200 for effective-Q for the lower crust below the WAM profile. Morozov et al. (1998) used the data from the QUARTZ profile mentioned above to obtain a 2D Q-model for the upper mantle below this PNE profile down to a depth of 500 km.

Some Recent Developments

DSSRP has traditionally positioned itself between basin-level seismics (using artificial sources) and deep-earth seismology (using natural sources). Recent methodological advances in the above fields have blurred this distinction. This is exhibited by the themes of the biannual meetings:

Seismix-2010: "Seismic imaging of continents and their margins: New research at the confluence of active and passive seismology"

Seismix-2012: "Advances in seismic imaging of crust and mantle: Preface"

Seismix-2016: "Seismic imaging at the cross-roads: Active, passive, exploration and solid Earth"

These may be contrasted with *seismic probing of continents and their margins*, which, with small variations, was used for almost the first three decades.

Note: most submissions at the latest biannual meeting (Seismix-2018) have not (yet) been published but are available at Seismix-2018-abs (2018). These abstracts (56 talks and 48 posters) further show the maturing of DSRRP – both regarding methodology and inclusion of other geophysical data for a better (geodynamic) interpretation.

Improvements in data acquisition are reported in Seismix-2018-abs (2018, pp. 40, 41) using the newly developed *DAS* (distributed acoustic sensing) technology. Both of these use the data for VSP (vertical seismic profiling) in a mineral exploration setting. Use of *OBS* (ocean bottom seismometers) is reported on page 45 of the same abstract collection to improve lower crustal velocity models and also better calibrate pressure measurements from air gun sources.

Noise as a seismic source is now an exciting field of research and is referred to as *seismic interferometry or daylight imaging*. The basic idea is that *noise* contains useful information. Noise recorded at two locations can, for example, be used to obtain relevant properties of the intervening medium. See Curtis et al. (2006), Wapenaar and Snieder (2007), and Snieder and Wapenaar (2010) for further details and also "▶ Seismic, Ambient Noise Correlation" and "▶ Seismic Noise."

Rawlinson and Goleby (2012) mentioned the use of noise for crustal imaging in their introductory article for Seismix-2010. Ito et al. (2012) use autocorrelation functions of ambient noise to obtain seismic images in a subduction zone. An interesting case of using autonomous recording *nodes* to record noise in between the active recording to obtain better V_s models is reported by Behm et al. (2019).

Inversion – Full/constrained/joint, i.e., the ability to reproduce each wiggle of the seismic observations is the ultimate goal for its interpretation, in terms of the viscoelastic properties of the causative medium (see "▶ Seismic, Waveform Modeling and Tomography"); DSRRP benefits from research in this field. For a quick introduction to this topic, including underlying problems, see Virieux and Operto (2009), Virieux et al. (2017), and Brittan and Jones (2019).

True full waveform inversion (*FWI*) of seismic remains an unattained goal, but some progress is reported by, e.g., Górszczyk et al. (2019), which use both OBS and standard multichannel marine reflection data to optimize the crustal velocity model by a joint full waveform inversion. Rawlinson et al. (2016) use a detailed crustal starting model from ambient noise seismics for a *constrained inversion* in teleseismic tomography.

Multidisciplinary studies have been largely not discussed in this entry, which has focused on P-wave measurements. Availability of high-quality *multi-geophysical* data does enable extraction of additional information though. Shear waves, for example, can provide valuable constraints regarding lithology and composition – see Eccles et al. (2011) for an example.

Nowadays, data from other geophysical surveys, e.g., gravity, magnetic, magnetotelluric, geodetic, etc., are frequently available near the DSRRP transects; these can be used to improve both structural and petrophysical interpretation. See Dong et al. (2013) reporting results from the *SinoProbe* Programme (2008–2012) covering deep lithospheric exploration of China.

Integrating diverse geophysical datasets, however, needs special attention during interpretation, to obtain a model which satisfies all data in some optimal fashion. This approach may be further subdivided into *joint assessment* and *true joint/constrained inversion*.

Palomeras et al. (2011) falls in the first category, so does Yegorova and Pavlenkova (2014), who report inverting for density along the PNE profiles, with their starting model taken from seismic data.

Roberts et al. (2012) is an example of attempting to constrain the final model for a multidisciplinary dataset (seismic refraction, MT, and gravity) using computer emulation.

The road ahead will see DSSRP results being increasingly applied to geodynamic problems related to the continental crust/lithosphere (e.g., Seismix-2018-abs 2018, pp. 20, 75). Better acquisition/processing will result in crustal images/properties with a higher resolution, enabling more nuanced conclusions regarding their evolutionary history. Inroads are already being made into more fundamental questions like *earthquake processes* (Górszczyk et al. 2019).

True joint inversion of disparate datasets will remain a challenging problem – not in the least due to the relative scaling for the different datasets. Syracuse et al. (2017) report results from a joint inversion using P- and S-arrival times and dispersion data from Rayleigh waves from USARRAY deployment and Bouguer gravity anomalies. Several important issues related to FWI of different datasets are mentioned by Seismix-2018-abs (2018, p. 58), e.g., optimal acquisition design, large-scale inversions involving *hundreds of millions* of parameters, problem of nonlinearity, and optimizing high- and low-frequency contents of the result.

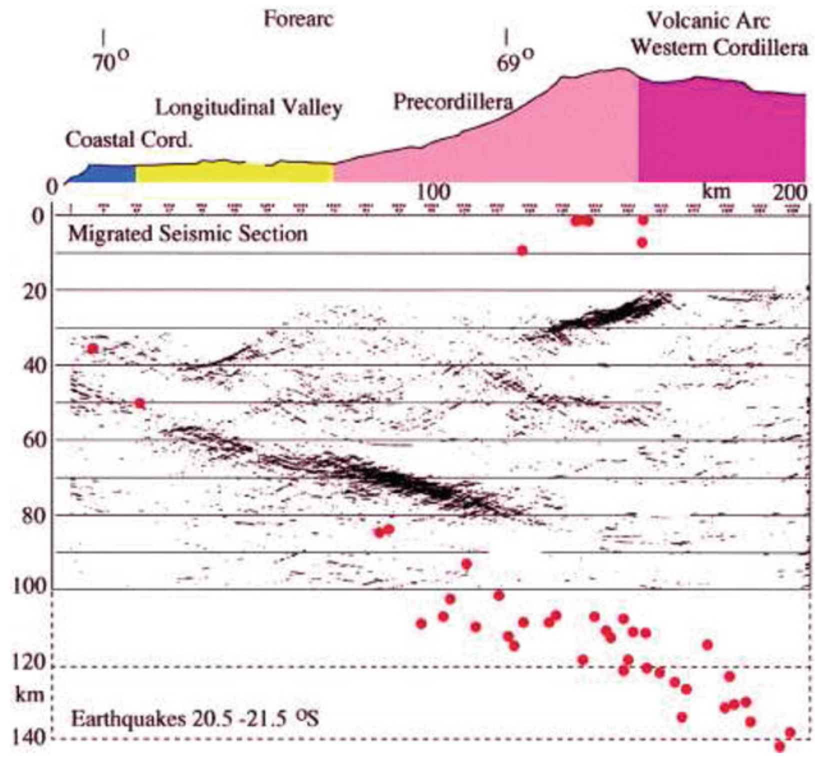
Research Problems

The massive amount of DSRRP data collected during the past half century has produced many new insights but has also brought up some (yet unsolved) problems.

Origin of crustal reflectivity, clearly visible in DSRRP images of mature continental crust, cannot be explained uniquely. Surface exposures of basement rocks mostly show steep dips due to earth's surface being stress-free and explain transparent zones at shallow depths. Starting at intermediate depths, these structures are expected to become subhorizontal and seismically imageable and do reveal layering including strongly reflective zones. Smithson and Brown (1977, Fig. 5) had already proposed a *complex* crustal model with a threefold subdivision based on geo-scientific data. Processes and materials to explain such low- and high-angle deformation, sometimes even affecting Moho and upper mantle, remain a challenge.

Shear zones, decollements, imbrications, laminae, metamorphism (facies changes, mylonitization), sill-like intrusions, and fluids (water, brine, melt, magma) have all been proposed as candidates for crustal (and Moho) reflectivity. Both Kola (Smythe et al. 1994) and KTB (Emmermann and Lauterjung 1997) super-deep drill holes have identified such conditions/structures at depth; extrapolations would point to the presence of crustal fluids in quantities more than that earlier expected, both in bound and free form. See also Meissner et al. (2006), "▶ Continental Crustal Structure" and "▶ Crustal Reflectivity and Magma Chamber."

Bright spots – zones of very strong reflectivity – present an extra challenge. Pratt et al. (1993) investigated the surrency bright spot (Georgia, USA), first assumed to be fluid related due to its flat nature and concluded an (ultra)mafic body instead. Makovsky and Klemperer (1999) inferred 10% (volume) of free aqueous fluids as the cause for the Tibetan bright spot. Figure 8 is an interesting example of two reflective zones, probably with different, but related, origins. Simancas et al. (2003) reported a mid-crustal highly reflective body below SW-Iberia from NMRS observations; later modeling of dense WARR data suggested the presence of high-velocity material. Palomeras et al. (2011) used additional data (heat flow, gravity, etc.) to further study this zone and inferred the presence of sill-like lenses of mantle material.



Deep Seismic Reflection and Refraction Profiling, Fig. 8 Migrated seismic section from the ANCORP line 2 in the Central Andean subduction zone. (Reproduced from http://www-app1.gfz-potsdam.de/www/pb3/dekorp/an-fig/Amline2.gif, with permission from the author). The strongly reflective zone on upper right is the *Quebrada Blanca* Bright Spot (QBBS), and the reflective zone dipping to the right is the Nazca reflector. Superimposed red dots show seismicity in this area of active subduction. (For further details, see ANCORP Working Group (2003))

Origin and nature of (continental) Moho are also not well understood, probably because this boundary – geophysically defined as a first-order transition of P-wave velocity from ≈6.8 to ≈8.2 km/s – does not always have the same evolutionary history. However, DSRRP has replaced the earlier model for (seismological) Moho, consisting of long refraction segments – more or less flat – by a (seismic) boundary with a complex and variable structure. It seems, at places, to be the equilibrium surface established under the deviatoric stress regime after a tectono-thermal event involving the lower crust and upper mantle. At others, it seems to be underplated or overlain by sill-like intrusions, from a later magmatic episode. Elsewhere, Moho is only identifiable as the terminal zone of a diffused lower-crustal reflectivity. At many places, it seems to exhibit enough strength, to retain its earlier structure through later tectonic events; examples include *frozen subduction* (Fig. 4) and *offset Moho* (Fig. 5).

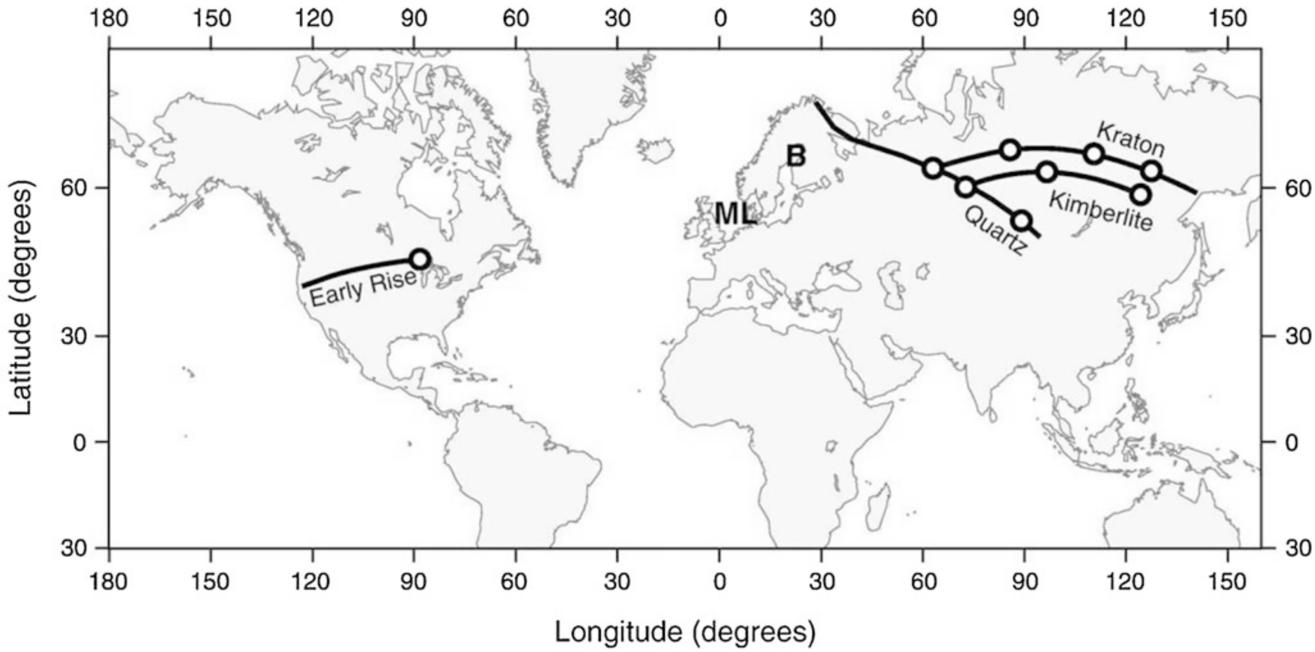
Role of (multiple) scattering in lower crust has attracted attention lately – both to explain observations and to relate to geological evidence. Surface outcrops of Moho (read: lower crustal and upper mantle rocks) are extremely rare in the continental setting, e.g., *Kapuskasing Uplift* (Eastern Canada), Musgrave Range (Central Australia), and *Ivrea-Verbano Zone* (IVZ, Northern Italy). While the first two have been studied by DSRRP (LITHOPROBE transect KSZ and Central Australian Basin transect, respectively), IVZ – although sans seismics – has been extensively studied in the past by geologists, e.g., Zingg (1990), and geophysicists, e.g., Berckhemer (1969).

Recently, statistical analyses of detailed geological maps of several exposed (lower) crustal rocks have yielded the tantalizing possibility of a self-similar (fractal) description of their shapes in terms of typical *horizontal* and *vertical scale lengths*. For the IVZ, a *2D von Karman* distribution of the structure with bimodal petrology has been derived (Holliger and Levander 1992). Holliger et al. (1993) computed synthetics for such a simulation of IVZ and were able to qualitatively reproduce lower-crustal reflectivity observed in NMRS. At large distances (WARR configuration), the synthetics from the random medium contained laterally correlatable events, which could be erroneously used for velocity analysis, migration, etc., a possibility already suggested earlier (e.g., Levander and Gibson 1991; Emmerich et al. 1993).

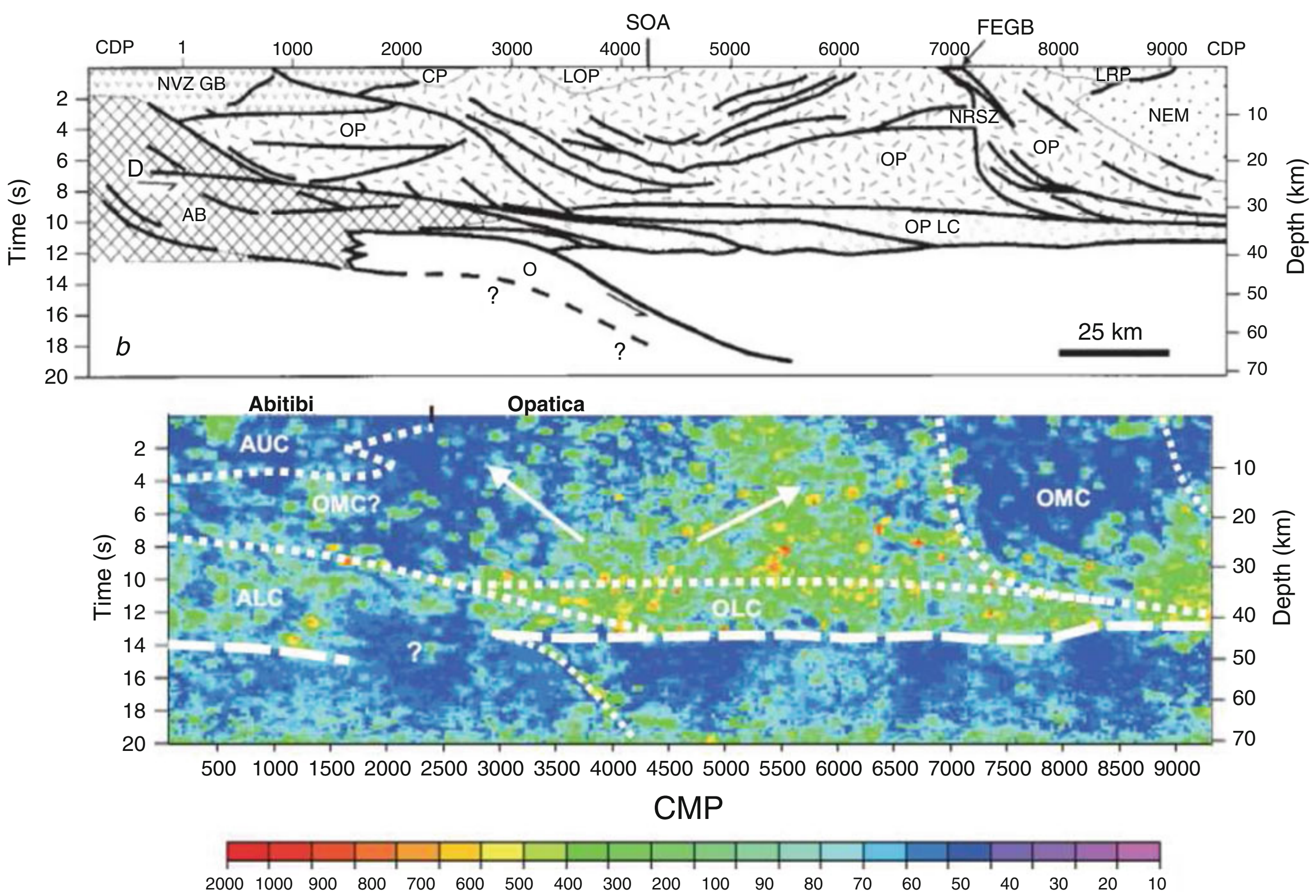
Another explanation offered for increased reflectivity in the lower crust, including transition zones, is lamellar structures with associated wave propagation effects (amplitude, anisotropy); see Meissner et al. (2006) and "▶ Seismic Anisotropy."

Both these possibilities, random heterogeneity and lamination, bring up the role of multiple scattering in the DSRRP wave field and question the propriety of using conventional tools from basin exploration for processing such data. Douma and Roy Chowdhury (2001) used synthetics to show that multiple scattering has a limited effect for a 1D bimodal model of IVZ but also mentioned the need for 2D full-wave numerical simulations.

In the upper mantle too, multiple scattering seems to play an important role. Menke and Chen (1984) had invoked this to explain long-range propagation of P_n-phase from



Deep Seismic Reflection and Refraction Profiling, Fig. 9 Long-range seismic lines used for modeling by Nielsen and Thybo (2006). *Early Rise* used chemical explosives; the other lines used *PNEs*. B and ML mark the locations of NMRS lines *BABEL* and *MONA LISA*, respectively. (Figure courtesy of *Tectonophysics*)



Deep Seismic Reflection and Refraction Profiling, Fig. 10 Above: Tectonic interpretation of LITHOPROBE line AG-48 (Abitibi-Grenville, Canada, taken from Calvert et al. (1995); figure courtesy of *Nature*). Below: interpretation by Carpentier et al. (2011) overlain on their estimation of the horizontal scale length (a_x) of the medium from the seismic data. (Figure courtesy of *Tectonophysics*) earthquakes. More recently, DSRRP data from PNE profiles, e.g., QUARTZ, has shown surprisingly strong propagation of high-frequency (5 Hz) P_n-phase to distances of 3,000 km!

Estimating descriptive parameters of a possibly random medium in lower crust and the upper mantle can be done by modeling or direct estimation. To explain the long-distance P_n-phase in the QUARTZ data, Ryberg et al. (1995) modeled an upper mantle zone of *horizontally stretched*, *randomly distributed velocity anisotropy*. Nielsen and Thybo (2006) modeled a larger dataset (Fig. 9) and inferred random heterogeneity for both lower crust and upper mantle.

Following some earlier work (Hurich 1996; Pullammanappallil et al. 1997; Hurich 2003; Carpentier and Roy Chowdhury 2007), Carpentier et al. (2011) have recently analyzed the data from Line 48 of the LITHOPROBE transect AG statistically. Assuming a 2D *von Karman* medium, they estimated the horizontal scale length of the medium directly from the seismic wave field (Fig. 10), which also shows their interpretation. The comparison with an earlier line drawing-based interpretation (above) illustrates the similarities and differences between the two approaches.

Summary

DSRRP has, over half a century, produced quality images of the continental crust and its margins, revealing their complex structure. These – including some unexpected results, e.g., *frozen subduction* – have contributed significantly to our ideas about the processes, current and ancient, involved in their evolution. As the deep structures, mostly inaccessible, play an important role in the development of the shallower geology, understanding these (*deep faults*) also helps in the optimal exploration of economic resources, e.g., hydrocarbons, ore deposits, etc., and in the study of natural hazards associated with volcanism and earthquakes.

Cross-References

- ► Continental Crustal Structure
- ► Continental Rifts
- ► Crustal Reflectivity (Oceanic) and Magma Chamber
- ► Earth's Structure, Upper Mantle
- ► Lithosphere, Continental
- ► Plate Tectonics, Precambrian
- ► Seismic Anisotropy
- ► Seismic Data Acquisition and Processing
- ► Seismic Imaging, Overview
- ► Seismic Instrumentation
- ► Seismic Monitoring of Nuclear Explosions
- ► Seismic Noise
- ► Seismic Ray Theory
- ► Seismic Tomography
- ► Seismic Viscoelastic Attenuation
- ► Seismic Waves, Scattering
- ► Seismic, Ambient Noise Correlation
- ► Seismic, Waveform Modeling and Tomography
- ► Traveltime Tomography Using Controlled-Source Seismic Data

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