Processing and modelling of short-offset seismic refraction—coincident deep seismic reflection data sets in sedimentary basins: an approach for exploring the underlying deep crustal structures

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SUMMARY
We present a new approach to extract deep crustal velocity structure from short-offset seismic refraction sections acquired over sedimentary basins. A coincident deep seismic near-vertical (NV) reflection stack section is used to constrain the derived crustal structure. The high-amplitude free-surface multiples, often found on refraction sections due to high velocity gradients in shallow sedimentary layers, are routinely modelled for velocity and Q structure of the sedimentary strata. These multiples almost completely mask most of the arrivals, including reflected phases from crustal interfaces. By application of velocity filtering with a rejection band that includes the apparent velocity of the free-surface multiples, they can, however, be significantly attenuated. The relatively weak signals, notably the deep crustal reflections in the subcritical (SC) range, can thus be well developed. This approach is demonstrated here by application to a short-offset refraction section in two steps: initially, the free-surface multiples are modelled for obtaining the sedimentary basin velocity structure, later they are substantially attenuated by velocity filtering to enhance the weak SC reflections, further modelled for the velocity structure of the deep crust underlying the west Bengal sedimentary basin, India. The stack section obtained by processing the deep seismic NV reflection data set, coincident with the short-offset refraction section, is consistent with and well substantiates the derived model of the crustal velocity structure in the region.

Key words: attenuation, coincident seismic reflection and refraction data sets, free-surface multiples, seismic modelling, subcritical reflections, velocity filtering.

1 INTRODUCTION
Near-vertical (NV) common-depth-point reflection profiling and wide-angle (WA) reflection–refraction profiling are the two most successful techniques of the controlled source seismology for exploring the crustal and subcrustal lithosphere. These two techniques, employing different frequencies, reveal different aspects of the structure of the Earth’s interior (Fuchs 1986). NV reflection sections delineate structural images revealing the deep tectonic processes and evolution, while WA refraction data provide models of the velocity, Q structure and possible composition of the interior. There exists a substantial range of the subcritical region (SC) between the NV and WA ranges (Fig. 1). The information in the subcritical (SC) region is, however, not routinely used because of the inherently low amplitudes of the signals in that range. In sedimentary basins, which are mostly the exploration targets for hydrocarbons, the structure and composition of the sediments and their basement are of primary interest. The seismic data acquisition in those regions is, therefore, often limited to 5–6 s of recording times by the NV, and out to only 50–60 km recording distances by the WA profiles. Necessary data sets for deep crustal structure in those regions have to be obtained by specially designed experiments of the NV and WA profiling with extended acquisition parameters. While NV reflection imaging to deep crustal depths can be accomplished by extended recording times and multichannel processing, however, refraction profiling to long offsets—required to sample the deep crust—can only be possible if significantly large explosions are used as the energy sources. We present here an approach for utilizing the hidden information in the SC region of deep crustal depths available as SC reflections on short-offset refraction sections in sedimentary regions. We illustrate this approach by processing the short-offset seismic refraction data in the west Bengal sedimentary basin, India, and deriving the underlying deep crustal velocity structure. The reflection stack section obtained from the coincident NV deep seismic data set further substantiates the derived crustal velocity structure in the region.

2 GEOLOGY AND TECTONICS
The Bengal delta, comprising the Indian and Bangladesh provinces, is one of the largest pericratonic foreland basins in the world. The western part of this delta is referred as the west Bengal basin. The
The very high-amplitude multiples almost completely mask all other lower amplitude signals, especially weak reflections from the deep crust in the SC range. In order to develop the useful reflected signals in this range, clearly the multiples have to be significantly attenuated by an appropriate processing of the record sections. However, prior to such a processing, we model the multiples by generating reflectivity synthetics (Kind 1985; Mueller 1985) to infer the velocity structure of the sedimentary section along a northern segment of the Palashi-Kandi N–S refraction profile in the west Bengal sedimentary basin (Fig. 2). The reflectivity method is particularly suitable for reliable amplitude modelling of the present data set including the multiples because there are no significant lateral variations of the shallow structure being investigated (Kaila et al. 1996). Figs 4(a) and 5(a) illustrate the high-amplitude multiples quite dominant in the short-offset refraction record section from SP15 along the N–S deep reflection profile coincident with the refraction profile investigated here.

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4 MODELLING FREE-SURFACE MULTIPLES
Kaila et al. (1996) proposed a velocity model to the crystalline basement depths for the northern part of the west Bengal basin along the N–S refraction profile. It reveals a number of sedimentary layers above the crystalline basement along with a low velocity layer (≈4.0 km s⁻¹) corresponding to the Gondwana sediments underlying the Rajmahal Traps (≈4.6 km s⁻¹). Further, a deep well located near Palashi (Fig. 2) provides the additional control confirming presence of the sub-Trappean Gondwana sediments. A layer of 5.2–5.3 km s⁻¹ velocity, corresponding to the Proterozoic Singhbhum rocks is also delineated in the refraction section.

The sedimentary section overlying the Traps, delineated by Kaila et al. (1996), however, does not indicate high velocity gradients in the shallow layers as required to generate the observed high-amplitude multiples. Therefore, the velocity structure inferred by them, from modelling of only refraction and WA reflections,
Figure 2. Location map showing seismic refraction profiles and the surface geology in the west Bengal basin, India. Roman letters (I–IV) indicate different profiles recorded in the area. Thick line (IV) indicates the N–S profile along which the coincident reflection and refraction data are recorded between SP14 and SP17 discussed in the present study. The key map shows the regional tectonic setting of various plates.

Figure 3. Schematic ray diagrams for the multiple refractions from the three high-velocity-gradient sedimentary layers (a) The Whispering Gallery (WG) phase consists of high-order free-surface multiples and direct arrival in the top sedimentary layer. (b) free-surface multiples from the second layer and (c) free-surface multiples from the third layer. $M_i$ indicates multiple refractions, $j$th multiple from the $i$th layer.

appears to be inconsistent with prominent features of the recorded wavefield, especially the multiples well observed in several record sections in the region. A more viable model is attempted here by additionally modelling free-surface multiples (considered as ‘signal’), constraining the high velocity gradients and inferring a plausible Q-structure of the shallow sedimentary layers. In the next step, the multiples are significantly attenuated (rejecting as ‘noise’) and the record sections thus processed appear to develop the hidden SC reflections from deeper interfaces. The SC reflections so developed are then used for modelling the deep crustal velocity structure. It may be mentioned here that a velocity model for the deeper crust in the study region is not obtained earlier, as the refraction sections from all the shot points are only limited to smaller offsets suitable for mapping the crystalline basement. While refraction data sets were acquired along four profiles (I–IV) in the region (Fig. 2), a 30-km-long segment of deep reflection profiling was also obtained, coincident with the N–S refraction profile, between SP14 and SP17, investigated here. The crustal velocity structure obtained in the present study, by modelling the SC reflections, is compared with the stack section derived from the deep seismic NV reflection data set and the velocity model is checked for its consistency with the coincident reflection and refraction data sets.

The observed record section from SP15 (Figs 4a and 5a) on the middle of the coincident reflection–refraction segment reveals the high-amplitude multiples which are dominant throughout the range. While none of the possible reflection phases are observable, even the primary refraction phases from relatively low-velocity-gradient layers of 5.2–5.3 km s$^{-1}$ and 6.0 km s$^{-1}$ velocity appear with only low amplitudes. The velocity model from the Palashi deep well (Das et al. 1993) is taken as the starting model for traveltime modelling of various shallow refraction phases. After obtaining a first arrival traveltime fit (by adjusting layer velocities and thicknesses), the velocity
An approach for exploring deep crustal structures

gradient in each of the successively deeper layers is adjusted, starting from the shallowest layer, to fit the high-amplitude secondary phases modelled as multiples. Thus, traveltime fits to the observations including the multiples, are obtained. Reflectivity synthetic seismograms are computed for a number of competing traveltime models until an acceptable fit of both the traveltimes and amplitudes of various phases is achieved. Fig. 6(a) shows the traveltime fits for the preferred model and these computed traveltime curves are found to well simulate various observed phases. It can be seen from Figs 5(a) and 6(a) that the WG, M2j, M3j phases, especially with high amplitudes, are well modelled as the multiples of refractions in the shallow three layers with velocity gradients of the order of 0.6–0.7 km s$^{-1}$/km. The other modelled features, quite consistent with the observations, include: (a) the traveltime offset between the first arrival refraction branches of the Rajmahal Traps ($P_f$, $\sim$4.6 km s$^{-1}$) and the 5.3 km s$^{-1}$ layer (attributed to the sub-Trappean low velocity layer of the Gondwana sediments of $\sim$4.0 km s$^{-1}$) and (b) the basement refraction ($6.0$ km s$^{-1}$) appearing as the first arrival from $\sim$20 km recording distance (Fig. 5).

It is well known that seismic waves are attenuated, especially at higher frequencies, due to the anelastic structure of the propagating medium. The anelasticity is represented by the reciprocal of the seismic quality factor $Q$, thus lower $Q$ values imply higher attenuation. The seismic quality factors for $P$ and $S$ waves, $Q_p$ and $Q_s$, respectively, strongly depend on the medium physical properties and the rock types. Depending on the medium properties, the $Q_p/Q_s$ ratio can vary significantly, $<1$ to $\gg1$. Although it is not attempted here to obtain accurate values for $Q_p$ and $Q_s$ in each layer from the present data sets, we considered a wide range of $Q_p/Q_s$ ratios in the sedimentary section. The synthetic seismograms computed for a $V_p/V_s$ ratio of $\sqrt{3}$ and a $Q_p/Q_s$ ratio of 9/4 reveal the envelope of the WG phase having a group velocity of $\sim$1.0 km s$^{-1}$ (Fig. 4b), corresponding to the shear conversion phases from the shallow layers. The WG phase in the data has a velocity of $\sim$1.8 km s$^{-1}$ (Fig. 4a), which is the surficial $P$-wave velocity used in the input model for obtaining the synthetics. This discrepancy between the velocities of the observed and synthetic WG phase is recognized here by the reflectivity modelling, for the $V_p/V_s$ and $Q_p/Q_s$ ratios used. These model details are usually not brought out by ray-synthetic calculations (e.g. Sarkar et al. 1995) due to inherent limitations of the method.

Hwang & Mooney (1986) earlier found a similar discrepancy for the WG phase in their reflectivity synthetic seismogram computations. Clearly, two alternatives are possible to resolve this apparent discrepancy: either the surficial $S$-wave velocity should be too low, as used by Hwang and Mooney (1986); or, $Q_s$ can also be too low to attenuate the shear phases substantially as seen in the observed section. In the absence of any evidence for anomalously low $S$-wave velocities in the region, we considered here the second possibility of a significantly low $Q_s$ in the shallow layer. Such low $Q_s$ attenuates the shear converted phases substantially and the WG phase of $\sim$1.8 km s$^{-1}$ is simulated consistent with the observations.

A large number of synthetics are computed for various $Q_p/Q_s$ ratios which indicate that this ratio in the shallowest layer is on the order of at least $\leq 10$ (for $Q_p$ $\sim$ 50–100 and $Q_s$ $\sim$ 5–10). Fig. 4(c) shows one of the best fitting plausible models obtained by the reflectivity synthetics in which the WG phase is quite well simulated consistent with the observations.

Fig. 7 shows a comparison of the inferred velocity model (Fig. 7b) with that of the Palashi deep well (Fig. 7c), indicating very high velocity gradient in the sedimentary section. A line drawing prepared for the prominent reflections of the stack section (Fig. 7a) correlates very well with the velocity boundaries shown in the Palashi well data (Fig. 7c). A comparison of the velocity model with the line drawing of the stack section in the region further substantiates the fine-
Figure 5. (a) As Fig. 4(a) showing dominant high-amplitude multiples, (b) same record section after velocity filtering (rejection band 1.5–4.5 km s\(^{-1}\)), note the deep reflections are developed by attenuating the multiples, (c) a clearer view of the processed section given in Fig. 5(b) at larger offsets. Computed traveltime curves of the SC reflections from the deep crust and the Moho are shown in the processed sections (b) and (c).
Figure 5. (Continued.)

Figure 6. (a) Traveltimes modelling of refracted and free-surface multiples for velocity structure of the sedimentary section, (b) same after velocity filtering (see Fig. 5b) to fit deep crustal reflections mostly in the SC range.
structure inferred here from velocity modelling of the refraction observations. However, the earlier model (Fig. 7d) for the sedimentary section in this region as given by Kaila et al. (1996) does not indicate high velocity gradients in any of the shallow layers, contrary to the clear observations of the strong free-surface multiples.

5 DEVELOPING SUBCRITICAL REFLECTIONS FROM THE DEEP CRUST AND THE NEW APPROACH

The multiples, after being used as ‘signal’ as discussed above for constraining the velocity structure of the shallow sedimentary section, are further treated as ‘noise’ and significantly attenuated. The relatively weak SC reflections hidden in the secondary arrivals can thus be developed. As the frequency of the reflection signals in this range may not be very different from that of the ‘noise’, we consider velocity filtering to be the most effective tool to discriminate and attenuate the high amplitude low velocity multiples. We apply the velocity filtering (Emmert et al. 1963; March & Bailey 1983) in the frequency-wave number (F–K) domain using the CGG-GEOMASTER seismic data processing software package. It is clear that velocity filtering is quite a common procedure routinely applied to multichannel seismic data, both in the narrow-angle and WA experiments for shallow and deep crustal studies (e.g. Klemperer 1989; Samson & West 1992, 1995; Minshull 1993). We utilize here this processing with advantage especially for attenuating the multiples, thereby developing the weak SC reflections from the deep crust for the first time. Our new approach is demonstrated by application to a short-offset seismic refraction section recorded from SP15 on the N–S profile for developing weak SC reflections from the underlying deep crust in the west Bengal sedimentary basin.

We propose here a new approach in that the multiples can be utilized initially to determine models of the velocity and Q structure of the sedimentary section as described earlier. Further, they can be significantly attenuated by application of velocity filtering (with appropriate rejection band of apparent velocity of the multiples) to develop the relatively low-amplitude SC reflections from the deep crust, and to infer the velocity models. Figs 5(a) and (b) illustrate the record section before and after application of velocity filtering (rejection band 1.5–4.5 km s$^{-1}$), the latter revealing a number of secondary phases ($P_{18–25}$) of varying amplitude and lateral coherence, possibly the deep crustal reflections mostly in the SC range (see also Fig. 5c, showing the phases more clearly at larger offset range). In the present study, a striking evidence of noise removal and enhancement of SC reflections is thus well demonstrated. Further, these reflections are used to retrieve complete information from the recorded wavefield which was not possible earlier because it was hidden by free-surface multiples. Traveltime fits to the correlated reflections in Fig. 5(b) are shown in Fig. 6(b), and the inferred 1-D crustal $P$-wave velocity model is shown in Fig. 8. The crustal velocity model obtained here compares fairly well with that inferred to the south of the present study region from WA reflection–refraction data sets (Rao et al. 1999).

In the study region deep crustal reflections can be expected in the SC range. It is likely that relatively sharp interfaces, required to generate the SC reflections, may be developed in sedimentary regions subjected to recent tectonic activity. The reflection coefficients are about 0.3 for sedimentary basins whereas they are about 0.1 for crystalline rocks of the shield regions (Smithson & Johnson 1989). Further, the velocity models obtained from reflections in the SC range may be more appropriate to those regions by virtue of the short offsets involved. In the SC range, the subsurface is sampled nearer to both the source and the recording arrays, unlike in the
An approach for exploring deep crustal structures

Figure 8. Crustal velocity structure inferred by modelling SC reflections (Fig. 6b), comparing fairly with the model derived from the WA data towards south of the study region.

WA range where the source and the recording arrays are separated by large distances. As regards the reliability, it may be mentioned that inherent ambiguities concerning correlation and interpretation of secondary phases on refraction sections remain similar in any range of observations, even in the WA range. Therefore additional constraints, preferably from coincident NV reflection stacks may enhance the reliability of the inferred models as illustrated in the following.

6 CONSTRAINTS FROM THE COINCIDENT DEEP CRUSTAL REFLECTION STACK SECTION

The crustal velocity-depth model obtained here by modelling the SC reflections is checked for its consistency with the coincident NV reflection data. Deep crustal seismic reflection common midpoint (CMP) data were acquired along a 30 km long segment in the west Bengal basin, coincident with the refraction/WA reflection data of the N–S Bishnupur-Kandi profile between shot points SP14 and SP17 (Fig. 2). The CMP data were acquired with the shot and geophone intervals of 80 m using the parameters given in Table 1.

![Table 1. Data acquisition parameters.](https://example.com/table1)

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Energy source              | Dynamite               |
| Shot hole depth            | 20 m                   |
| Geophone interval          | 80 m                   |
| Spread length              | 9.6 km                 |
| Number of channels         | 120                    |
| Sampling interval          | 4 ms                   |
| Frequency range            | 3.5–64 Hz              |
| Anti-alias filter          | 64 Hz (72 db/octave)   |
| Recording instrument       | DFS-V (Digital Field System) |
| Geophones                  | 4.5 Hz (L-1B)          |

![Reflection Profile](https://example.com/reflection_profile)

| Reflection Profile:         |                      |
|----------------------------|----------------------|
| Shot interval              | 80 m                 |
| Nearest channel at         | 80 m                 |
| Farthest channel at        | 9.6 km               |
| Spread configuration       | End-on               |
| Record length              | 20 s                 |
| Theoretical foldage        | 60                   |
| Charge per hole            | 35 kg                |
| Profile length             | 30 km                |

The seismic reflection data are processed by the sequence shown in Table 2 (Vijaya Rao 2003). All noisy traces are edited and a near-trace gather is examined for assessing the quality of the data. Spherical divergence correction and refracted-first-arrival mute are applied at the pre-stack processing stage. The shot gathers consistently revealed high-amplitude coherent noise events, which are generated due to the high velocity gradient present in the shallow sedimentary layers, similar to those illustrated in the refraction/WA reflection data, masking the useful reflections. The coherent noise is attenuated by velocity filtering in the shot domain, thereby enhancing the signal-to-noise ratio of the useful reflections. In order to suppress possible multiples from the sedimentary section, spiking deconvolution is applied. As the elevation differences in the region are negligible, bulk statics are applied to the data. CMP gathers are stacked after applying the NMO correction. A time-varying filter with 5–25 Hz frequency band for the shallow (0–3 s TWT) and a lower frequency band (3–15 Hz) for the deeper parts (TWT > 3 s) is applied to the stack section, providing a better display of both the
shallow and deeper reflections. The post-stack processing further consisted of F–K filtering, predictive deconvolution and coherency filtering.

The final stack section (Figs 9a and b) obtained up to ~15 s two-way-time (TWT) delineates the basin configuration, the underlying Archaean basement and the Moho. The seismic stack section (Fig. 9a) displays prominent reflectivity in the top 3 s TWT representing the various sedimentary layers. Depths to various layers derived from the refraction data set (by fitting the SC reflections) are converted into TWTs and compared with the deep crustal reflection stack section (Figs 9a and b). The layers corresponding to the Rajmahal Traps, the Gondwana sediments and the crystalline basement coincide well with the prominent reflection bands in the stack section. The crystalline basement appears south dipping, consistent with the structural map obtained by Kaila et al. (1996).

The depths to various boundaries in the deeper crust, derived from P18–P25 and the PMP phases recognized in the processed refraction sections (Figs 5b and c) are correlated with the corresponding reflection bands in the stack section of the NV reflection data set. The predicted TWTs of the deep crustal boundaries inferred from the velocity model (Fig. 8) are shown in the stack section (Figs 9a and b). The prominent reflection band at 10.5–12.5 s TWT (Fig. 9b) indicates that the transition between the crust and upper mantle has complex reflectivity. Termination of this reflection band at ~12.5 s

Figure 9. (a) NV reflection Stack section for 0.0–7.5 s TWT, and (b) for 7.5–15.0 s TWT. The reflector depths from the crustal velocity-depth model inferred from the present study are converted into two-way times and compared with the stack section. Reflections from 0 to 2 s TWT represent the shallow sedimentary layers. P11, P14 and P15 represent the Rajmahal Traps, Gondwana sediments and the crystalline basement. P18–P25 phases represent reflections from the intracrustal boundaries in the region. A good correlation of the inferred reflectors (see Fig. 8) with the reflection bands in the stack section is clearly evident.
TWT is interpreted as the Moho boundary that coincides with the Moho at 36 km depth inferred from the velocity model given in Fig. 8 (see the TWT of the \(P_M \) phase). Some of the intracrustal reflection bands on the stack section at TWTs predicted for the inferred velocity boundaries do not, however, appear to be continuous on the line. This is possibly due to the low-velocity groundroll and other noise or even due to varying nature of the reflectors that may be gradational rather than being sharp throughout. Further, deep crustal boundaries with small velocity contrasts are not well represented as prominent reflection bands in the NV stack section. It may be mentioned here that \(P_{20} \)–\(P_{23} \) phases are due to the boundaries with relatively small velocity contrasts (Fig. 8). Therefore, these phases are less prominent in the stack section. On the other hand, boundaries with relatively large velocity contrasts are reasonably well represented in the stack section (e.g. \(P^{24} \), \(P^{25} \) and the Moho). Therefore we believe that the inferred velocity model (Fig. 8) is consistent with the NV reflection stack section (Figs 9a and b).

7 DISCUSSION AND CONCLUSIONS

In the present study, the free-surface multiples are initially used as ‘signal’ and later rejected as ‘noise’ at different processing steps to constrain the high-velocity-gradients in shallow sedimentary layers, and to further develop the SC reflections modelled for the deep crustal velocity structure. A flow chart of the proposed approach, especially applicable to short-offset seismic refraction sections in sedimentary regions as illustrated here (with high velocity gradients being quite common), is given in Fig. 10.

The shallow velocity structure derived from the present study indicates a large number of layers representing various lithological boundaries. A comparison of the velocity structure with the lithostratigraphy of the region suggests that the top layer with 1.75–1.85 km s\(^{-1}\) velocity represents the unconsolidated sediments and 2.1 km s\(^{-1}\) may represent the Holocene alluvium present in the region. The layers with 2.6 km s\(^{-1}\), 2.4 km s\(^{-1}\) and 3.1 km s\(^{-1}\) velocities possibly represent the Pliocene, Miocene and Oligocene formations, respectively. They also correspond to the high-amplitude reflection bands at 0.6–1.2 s TWT revealed on the stack section. The 3.6 km s\(^{-1}\) and 4.1 km s\(^{-1}\) velocities are of the Eocene and Paleocene formations represented by the Sylhet limestone in the region. The 4.7–5.0 km s\(^{-1}\) velocity layer represents the Rajmahal Traps and the 4.0–4.2 km s\(^{-1}\) velocity layer represents the Gondwana sediments. The crystalline basement is mapped as the 6.0 km s\(^{-1}\) velocity boundary. A reasonably good correlation is evident between the derived velocity layering and the NV reflection stack (Figs. 9a and b) in the entire crustal section down to the Moho. The crustal thickness estimate obtained in the present study is ~36 km and the TWT of the \(P_M \) phase coincides with the prominent reflection band at ~12.5 s. The nearest available estimate of the Moho depth, towards south of the Palashi well, is ~37 km (Rao et al. 1999), which is consistent with our results.

A comparison presented here of the velocity stratification in the deep crust - inferred from the SC reflections—with the reflection

![Figure 10. Flowchart for processing short-offset seismic refraction sections in sedimentary regions by the new approach proposed here to explore the underlying shallow (A) and deep (B) crustal velocity structure. Availability of coincident NV reflection stack section and deep well control in a nearby region further constrain the inferred models.](https://academic.oup.com/gji/article-abstract/163/3/1112/594868)
bands consistently displayed on the processed NV crustal image enhances credibility of the proposed approach. Deep crustal velocity models can therefore be reliably inferred even in the absence of more appropriate refraction profiling at long offsets. This is achieved by processing and developing the hidden, but plausible, SC reflections on relatively short-offset refraction sections. Coincident NV reflection images certainly help checking viability of the derived models.

SC reflections are not routinely used for modelling the deep crustal velocity structure. The approach we propose here is particularly useful in regions that are unfavourable for utilizing large energy sources—required for recording long-offset refraction/WA reflection data sets sampling the deep crust. Especially in sedimentary basins, seismic refraction profiling tends towards short-offset lines sufficient for basement mapping, while reflection profiling is also usually available. Therefore, SC reflections well revealed on the processed record sections at short offsets can form a good alternative data set to extract the deep crustal structures, especially validated by the coincident NV reflection data set. Although NV reflection stack sections cannot directly provide reliable models of the deep crustal velocity structure, they can certainly help validate a model derived otherwise. In the present case, the crustal velocity model inferred from the SC reflections is checked for its consistency with the NV reflection stack section. Turning to the examples presented to illustrate this approach, we are convinced that the SC reflection phases from the deep crust are well recognized. SC reflections from deep crustal boundaries of sharp velocity contrasts can be recognizable, although they are of relatively low amplitudes compared to the amplitudes of the WA reflections. The inferred reflector depths, including the Moho, correlate reasonably well with the NV reflection stack, particularly those with large velocity contrasts.

We suggest that short-offset seismic refraction sections in the sedimentary regions can be processed with advantage by this approach, for attenuating the multiples and developing the SC reflections, which can in turn be used to derive models of the underlying deep crustal velocity structure in the absence of, or even prior to, more appropriate but expensive crustal scale experiments. By this, we believe, it closes the known gap between NV and WA reflection seismology.

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