On the efficacy of recent crustal images of the Indian shield from receiver functions

The availability of broadband digital data has significantly improved our ability to 'see' the crust–mantle domains with more precision than hitherto possible[1–8]. Modern seismological tools such as the receiver functions (RFs) are used to generate crust–mantle images that permit finer interpretations of their evolution and structure. Recent efforts to obtain crustal images of the Indian shield using RF analysis are one of the latest additions in this direction[9–13]. While admitting the efficacy of these new tools, it is important to recognize the limitations starting with data quality to interpretations. Clearly, this topic deserves a much more rigorous treatment than what can be done in a short correspondence. Here we wish to restrict our discussion to two recent papers by Gupta *et al.*[9,10], hereafter referred to as GA and GB respectively, that have presented new images of the crust beneath the southern Indian shield comprising mainly the western Dharwar Craton (WDC) and the eastern Dharwar craton (EDC) using the RF approach. Major conclusions by GA and GB, based on crustal multiple phases (*Pps* and *Pss*) and direct *P*-to-*S* converted phases at the Moho (*Ps*; see Figure 1) can be summarized as follows: (a) the Mid-Archaean segment (3.4–3.0 Ga) of the WDC is underlain by an anomalously thick crust (43–52 km) with felsic-intermediate average composition; (b) EDC, the adjoining late Archaean (2.7–2.5 Ga), is much thinner (33–40 km) and Poisson's ratio varying between 0.23 and 0.26; (c) GB concludes that the southern Granulite Terrain (SGT) is characterized by a thick crust (42–60 km) and the Poisson ratio varies from 0.25 to 0.28. Studies on the thickness of the lithosphere using teleseismic residual data presented by GA suggest that the velocity in WDC is higher and its thickness is about 60–80 km more than the 200-km-thick EDC.

Obviously, these observations have important implications on the evolution and dynamics of the Indian crust and it is necessary to understand the limitations of the techniques used. In particular, we must pay attention to the quality of the basic data and processing strategies adopted. Here, we provide a brief review of the techniques followed by these authors in developing these crustal images, paying attention to the potential sources of errors.

What is a receiver function

A seismic signal (time series or seismogram) that essentially contains the effects of local structure (primarily crust) beneath a station devoid of effects due to source complexities and path effects is termed as RF (Figure 1). Owing to the large velocity contrast across a discontinuity (e.g. Moho, Lehmann, etc.), part of the steeply incident teleseismic *P*-wave energy becomes converted to an *SV* wave (e.g. *P*-to-*S*-converted wave from the Moho) and forms part of the *P*-wave coda. Besides the direct/primary *P*-to-*S* conversion, there are also many multiple reflections and conversions that occur between the surface and the interface. The *P*-wave and its multiples dominate the vertical component (*Z*), while the *P*-to-*S* conversion and its multiples are registered prominently on the horizontal radial (*SV*) component. Therefore, to isolate *P*-to-*S* energy (that contains information about Moho, in our case here) from that of *P*, we need to indulge in appropriate component rotation to arrive at the *SV* component time series or seismogram (Figure 2). The effects related to source, mantle propagation and instrument response are

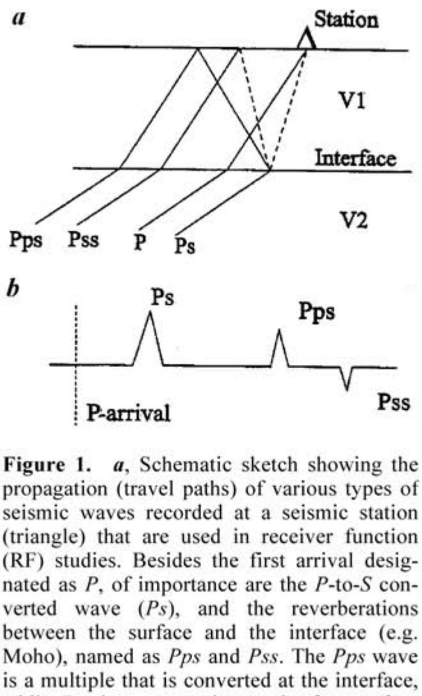

Figure 1. ***a***, Schematic sketch showing the propagation (travel paths) of various types of seismic waves recorded at a seismic station (triangle) that are used in receiver function (RF) studies. Besides the first arrival designated as *P*, of importance are the *P*-to-*S* converted wave (*Ps*), and the reverberations between the surface and the interface (e.g. Moho), named as *Pps* and *Pss*. The *Pps* wave is a multiple that is converted at the interface, while *Pss* is a conversion at the free surface and reflected by the interface. The *S*-paths are stippled lines and *P*-paths are solid lines. Note that both *Pps* and *Pss* have three legs of travel, while the *Ps* has only one leg between the interface and the station. Also, the *Pps* wave travels only one leg as *S*-wave (after conversion from a *P*-wave) and *Pss* has only one leg as a *P*-wave and two as *S*-wave. Naturally, after the first arrival *P*, *Ps* arrives followed by *Pps* and then *Pss*. ***b***, Typical RF sketch showing the *Ps*, *Pps* and *Pps* arrivals. Note the size and polarities of the amplitudes of these waves and their corresponding delayed arrivals after the *P*-arrival. Vertical stippled line marks the first arrival *P*-wave.

suppressed by deconvolving the vertical component (on which *P*-wave energy dominates) from the *SV* component, i.e. by 'dividing' the latter by the vertical component. This deconvolved time series is termed as RF on which the major features are *S*-wave arrivals related to primary *P*-to-*S* conversion from the Moho (*Ps*) and its multiples reflected between the earth's surface and the Moho (*Pps* and *Pss*). *P*-wave energy on the radial (*SV*) component that is coherent with energy on the vertical component, will be compressed by the deconvolution into a single spike at zero lag time, which is often referred to as 'direct P-arrival' (see Figure 2). All subsequent arrivals (*Ps*, *Pps*, *Pss*, etc.), after this direct *P*, have times calculated relative to this large coherence peak.

Issues in interpreting RFs

The radial RFs (*SV* or *Q*) for a homogeneous plane parallel earth are generally simple and coherent and can easily be modelled in terms of shear velocity and depth to the interface. The transverse component (*SH* or *T*) is devoid of any energy. It is well-known that the earth's crust carrries the thermo-tectono imprints of a variety of geodynamic processes that impart the observed geologic diversity after having successfully resisted plate recycling processes preserving their identities unlike most the deeper domains of the earth's interior. Therefore, presence of a heterogeneous crust should not come as a surprise over certain scale lengths. Regions encompassing 'geologic suture zones', lateral faults or geologic contacts and presence of strong lateral heterogeneities by way of volcanic vents, rift-pillows are some examples where the assumption of homogeneous plane parallel layers breaks down. Scattered energy from such crustal heterogeneities would often interfere with the direct converted phases (*Ps*) and degenerate the multiple phases (*Pps*) leading to their ambiguous registration on the seismograms resulting in inaccurate estimation of crustal parameters using information from these phases. In tectonic regions with possible presence of strong lateral heterogeneities receiver functions may show a strong azimuthal dependence (e.g. Langston[14–17]; Cassidy[18]). In tectonic regions with possible presence of strong lateral heterogeneities, RFs may show a strong azimuthal dependence[14–18]. Therefore, it is critical to show data as a function of azimuth to identify such possible scenarios and to enable us devise appropriate strategies to extract the crustal parameters as accurately as possible.

It is important to note that while departures from horizontal, plane-layer-assumption due to lateral discontinuities significantly perturb the *SV* RFs[19], effects due to aspherical nature of the underlying medium (e.g. dipping layers, anisotropy, etc.) can yield substantial energy in the transverse RFs (*SH* RFs) besides registration on the *SV*. The effects of dipping layers on receiver functions have been examined by Langston[15,17]; Cassidy[18] and few others not listed here.

Dipping layers and azimuthal coverage

A dipping structure under the station affects RFs both in delay times and amplitudes (Figure 3). The delay times and amplitudes of the radial (*SV* or *Q*)-component RFs vary as a function of both back-azimuth and epicentral distance.

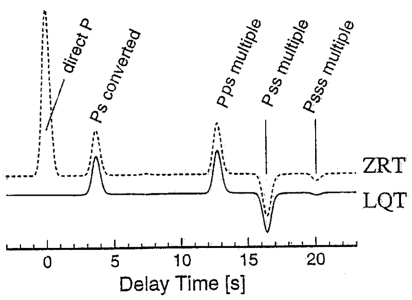

Figure 2. To derive RF from three-component seismograms (N-S, E-W and *Z* records) at a seismic station, as discussed in the text, appropriate component rotation and deconvolution have to be applied to the records. We show two types of component rotations that are in vogue. Rotation of the recorded three-component seismograms into *ZRT* or *LQT* systems is roughly equal to a 2D (*ZRT*) and 3D (LQT) rotation. Note that Gupta *et al.*[9,10] use *ZRT* rotation system, while Kumar *et al.*[11] and Sarkar *et al.*[13] use *LQT* rotation coordinate system. Also, note that *Ps*, *Pps* and *Pss* times are delay times with reference to zero-time lag in both the systems.

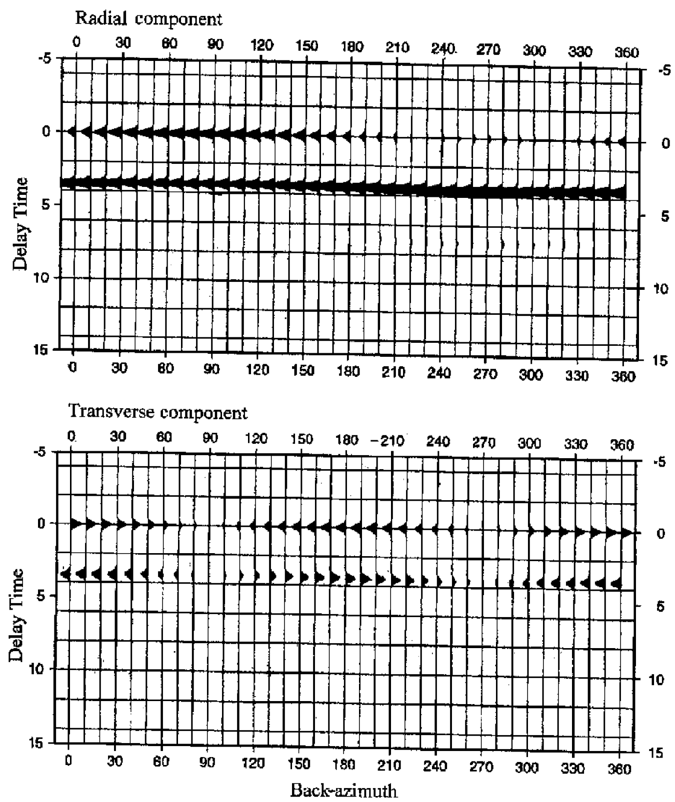

Figure 3. 2D synthetic radial and transverse RFs showing the effects of dipping interfaces and their diagnostics, as described in the text. The computations are made for a Moho with a strike of 180° and dip of 15°. Note the swerve in *Ps* phase close to 5 s in the radial RF showing clear azimuthal dependence, and change in amplitude and polarity of the *Ps* phase in transverse RF and its periodicity.

The largest azimuthal variation in the amplitudes of tangential RFs can be used to determine the dip direction of the dipping interface. The tangential RFs have the largest amplitudes in the direction of strike of the dipping interface and tend to approach zero in the dip direction. An important feature of a simple dipping layer is that tangential RFs reverse their polarities when the back-azimuth crosses the dip line. Hence, in order to detect the presence or absence of dipping structures beneath a region, data over a wide back-azimuth range are essential. Also, display of RFs in azimuth/slowness section is likely to bring out all the diagnostics of the aspherical structure, which would enable us to plan appropriate strategies to account for dip effects, etc. while determining the crustal parameters. In the absence of good azimuthal coverage, presence of dipping layers cannot be detected, as the associated observations are strongly dependent on azimuth and slowness. The RFs would then miss the critical azimuth/slowness range, where the diagnostics of the dip becomes well pronounced. This leads to large errors in estimates of depth to the Moho.

The power of multiples and potential sources of errors

The trade-off between crustal velocity and thickness is one of the classical problems using reflected/refracted waves. RF analysis to obtain crustal thickness values (*H*) uses *Ps* times with sufficient velocity information at a station or one nearby, to overcome this problem to some extent. Since the differential times are used in the analysis, the results are less sensitive to the absolute *P*-velocities (V_p). However, the estimates of crustal thickness (*H*) can be highly dependent of Poisson ratio (*s*) [related to V_p/V_s]. Fortunately, this ambiguity can be resolved using Moho reverberation phases (*Pps*, *Pss*) that arrive later, which provide additional constraints, so that both *H* and *s* can simultaneously be estimated from *Ps*, *Pps* and *Pss* times. This, in essence, is what the Zhu and Kanamori[20] method exploits using *SV* RFs. The real power of RFs lies in this time-to-depth transformation using crustal multiples (*Pps*, *Pss*) to determine Poisson ratio and depth to Moho at a location. Zandt *et al.*[21] have demonstrated that multiple reverberations within the crust, if well observed, can be used together with directly converted waves to accurately constrain *H* and *s*. Obviously, the *ability to determine these two crustal parameters (H and s) depends critically on the quality of the crustal multiples generated at the Moho, their unambiguous identification and accuracy of their pick times*.

Problems in observation

Unequivocal identification of multiples suffers from a variety of causes that can be summed as due to scattering and interference effects. As the multiples (*Pps*, etc.) travel three times longer in the crust compared to the *Ps* waves (Figure 1), they are usually weak and scattered, and this often leads to their mis-identification. Degeneracy of direct-converted phases or their multiples occurs due to scattering from crustal heterogeneities, scattered energy from lateral faults, discontinuities or geologic contacts, etc., so that the assumption of horizontal plane layers is no more valid. The issue of the sampling of the Moho reverberations and reasons for their poor observation can be grasped from simple calculations as below. Our calculations suggest that a *Ps* converted phase (for incoming ray with a slowness of 6.4 s/deg), at the base of a 40 km thick crust with an average Vp of 6.5 km/s samples a lateral distance of 4.8 km. Its corresponding *Pps* and *Pss* multiples sample distances of 16.8 and 21.7 km respectively. Such increased lateral sampling by multiple phases could result in their degeneration and hence lead to more ambiguous determination of Poisson's ratio beneath a station. This becomes more acute in the vicinity of any 'special' geologic structure described above. It is also obvious from above that increase in crustal thickness would result in more lateral distance sampling by the multiples that could further degenerate their registration.

Stations located in regions with surface geology that have high-velocity contrast between exposed geology (e.g. sediments, traps, etc.) and basement rocks and laterally varying geometries, generate reverberations that mask the later conversions[19,20]. Intracrustal conversions, *P*-to-*S* conversions from some shallow upper mantle discontinuities also contribute to this problem. Presence of such spurious, but apparently coherent phases, often smears the maximum in the *H*–*s* domain and leads to multiple local maxima. It is therefore, important to note that the H-*s* determination is indeed influenced by various factors and critically rests on the researcher's assessment of their (*Ps*, *Pps* and *Pss*) fitness for the *H*–*s* analysis using methods like those of Zhu and Kanamori[20].

Strategies to reduce ambiguity in multiples identification

To overcome some of the above discussed problems, individual RFs are usually stacked to obtain a stacked radial (*SV*) RF trace and then subjected to further analysis. It is however important to realize that the multiples (*Pps*, etc.) have significant moveout with respect to the *P*-wave (Figure 4) and will thus stack incoherently. This results in broader pulses and lower amplitudes in the RF stacks thereby further reducing the ability to extract relevant crustal information from these inherently weak signals[22,23]. Further, while amplitudes of *Ps* and its multiples (*Pps*, etc.) largely reflect the contrast in *Vs* across the Moho[24], presence of a gradational Moho could also result in feeble multiples. Lack of coherent multiples and broadening of the *Ps* phase could be attributed to a dipping Moho, but interference by multiples from a weaker, shallow interface can also broaden the *Ps*. It is therefore evident from the above that strict data quality criteria need to be applied to select records with reasonably good S/N even for the multiple phase (*Pps*), besides the *Ps* and stack traces after applying moveout correction to individual RFs to optimally enhance the desired signals. Recognizing that *Ps* and *Pps* have different moveouts (Figure 4), this characteristic criterion[8] is now routinely employed to distinguish between converted and multiple phases and moveout corrections to both the phases are performed separately. Such a data-handling strategy certainly enhances multiple phase (*Pps*) correlation and its coherence in the stacked trace (Figure 4). Such an approach would enable assessing the quality of the multiples and the direct converted phases based on which one could assign a quality factor to the data and arrive at a decision regarding suitability of the RFs for H-*s* determination.

The effect of moveout depicted in Figure 4 for a model by Yuan *et al.*[23], could represent one end-member and appears to be exaggerated compared to a typical Precambrian shield model. The former model consists of a 58 km thick crust with a low average V_p of 6.1 km/s compared to a 40 km crust with V_p of 6.5 km representative of shield environment. For any thinner crust with higher V_p the effect of moveout would obviously be less. In which case the stacks would show more energetic and coherent multiples enabling us to use the ZK technique effectively. If the stacks still yield feeble *Pps* phase inspite of smaller moveout, this leads to ambiguous determination of the crustal parameters by any technique.

Sensitivity of the *Pps* phases to *H–s* variations

As a first step to understand the interrelationship between crustal thickness *H* and Poisson's ratio *s* for a given *Ps* time with an average V_p of 6.5 km/s and a fixed slowness of 6.4 s/° we present the influence of Poisson's ratio on crustal thickness in Figure 5. It is evident that a crustal thickening of about 8 km can easily be accounted with a change (reduction) in Poisson's ratio from 0.30 to 0.25. In other words, a given *Ps* time can be explained either by a relatively thick crust (thicker by about 8km) associated with smaller *s* (0.25) or a thinner crust with 0.30 Poisson's ratio. Therefore, errors in determination of *s* due to poor *Pps* would also have bearing on estimated *H*. Some deeper insight of the influence of *H* and *Vp/Vs* on the *Ps* and *Pps* phase is summarised below.

Synthetic RFs for a reference slowness of 6.4 s/° over a range of *H* between 48 and 68 km and Poisson ratio between 0.24 and 0.31, assuming an average V_p of 6.1 km/s reveal the sensitivity of the RF data to variations in Poisson ratio (V_p/V_s to be precise) and crustal thickness (*H*) (see Figure 4 *a* and *b* of Yuan *et al.*[23]). Their analyses reveal that increase in both V_p/V_s ratio and in *H*, delays the arrival times of all the phases (*Ps*, *Pps*, etc.) in the RFs. The delay of the *Pps* phase caused by increase in V_p/V_s ratio equals the delay of the *Ps* phase. Lastly, the delay of the *Pps* phase mainly due to increase in crustal thickness is more significant than that of the *Ps* phase (see Figure 4 *b* of Yuan *et al.*[23]). They also conclude that, in case only the *Ps* phase is used to compute *H* over a range (0.24–0.31) of Poisson ratios, the error in estimation of *H* is about 14 km. However, if multiple phases are clearly observed and used, they constrain the crustal parameters more accurately[23].

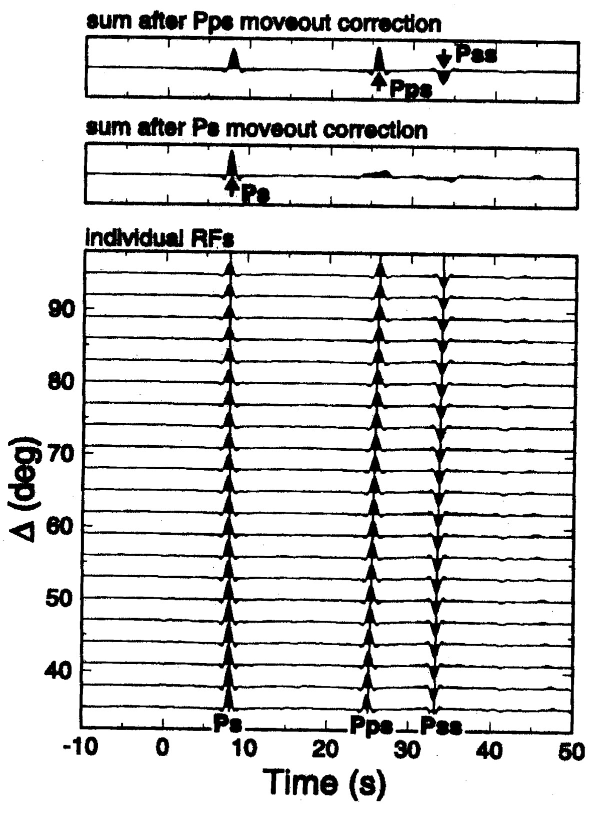

Figure 4. Display of individual RFs (RF-section) with respect to distance in degrees for a synthetic model and the effects of moveout. (Bottom frame) RFs at various distances showing the registration of *Ps*, *Pps* and *Pss* phases. The moveout of these seismic phases with distance is apparent (look along the vertical lines through each phase) and the multiples *Pps* and *Pss* arrivals are more inclined compared to the primary conversions, *Ps*. Naturally, if these are stacked, the multiples would be more incoherently stacked compared to *Ps*. Now, for these moveouts, corrections need to be applied separately for *Ps* and *Pps*. (Middle frame) Sum or stack trace of individual RFs after applying only a *Ps* moveout correction. Stacked *Pps* arrival in this trace is barely visible. This is the situation in a synthetic case, ponder over the state of real records with ambient noise, interference from scattered arrivals and arrivals from shallower discontinuities, etc. (Top frame) *Pps* moveout-corrected sum trace. After Yuan *et al.*[23]. The effect of move-out appears to be exaggerated in view of a thick crust (58 km) with low *Vp* (6.1 km/s), a model not representative of the south Indian shield. It is now important to remember that for a thinner crust (say 40 km) with a higher *Vp* (6.5 km/s) the effect of moveout is obviously small. Our computations using the above thinner model for a fixed Poisson's ratio of 0.25 show a moveout of 0.3 s for *Ps* and 1.3 s for *Pps* over a distance range of 30–90 degrees. In such case the stack traces should show more energetic and coherent multiples (phases), contrary to what is presented by the authors in GA and GB. Therefore, poor registration of the *Pps* multiples in south India could be due to poor quality data and less number or due to complex structure beneath most of the stations. Either way our contention that most stations are not fit to be subjected to ZK technique receives support.

Qualitative assessment of data and results

Keeping the above discussion in view, let us examine how these issues are relevant in the analysis by GA and GB.

The RF stacks presented from the WDC–EDC are noisy and seem to suffer from some natural constraints imposed on the multiples, as discussed. Importantly, as no moveout correction is applied to the individual traces, these problems with observation and good registration of multiples get further accentuated leading to their poor S/N as seen from the stacks presented in GA. Additionally, the quality of *Pss* in WDC and *SGT* cannot be assessed as the time-window of the stacks at many key stations shows only *Ps*, *Pps* and perhaps ends just before the *Pss* arrivals. It is relevant to note that the *H*–*s* analysis makes use of information from all the three phases. As a consequence of greater difficulty in observing *Pps* and *Pss* compared to *Ps*, down-weighing the former compared to the latter (0.2 and 0.1 against 0.7) while using the Zhu and Kanamori[20] algorithm, can result in a significant loss of sensitivity and precision in the *H*–*s* measurements[21]. Weights as high as 1.0/1.5/1.5 for *Ps*/*Pps*/*Pss* are often used in *H*–*s* analysis to yield robust estimates of crustal parameters. Hence a lot of research involving strict data-selection procedures, on applicability of suitable filters to data at each station (e.g. different filters for *Ps* and another range for multiples) and weighing parameters that optimally resolve the crustal parameters, reliability of phase identification (especially of *Pps*, *Pss*) their correlation among individual RFs, application of moveout correction, feel for when and where a particular technique is applicable, assumes importance in RF analysis. The degree of adherence to such measures is clearly reflected in the quality of the RFs and more certainly leads to discarding many poor-quality stations from the analysis[5,11,22,23]. *The moral is, not all stations/data can be modelled.*

A simple way to test the reliability of identification and pick times of *Ps* and the multiples (*Pps* and *Pss*) is to examine the *Ps* – *P* (*Ps* differential time) and *Pss* – *Pps* difference times. These difference times should roughly be equal. As *Pss* arrivals are not shown for WDC and SGT stations, this much desired comparison between the difference times based on data and on arrival times presented in Table 1 is not possible. However, such an exercise can be carried out by the reader for other terrains.

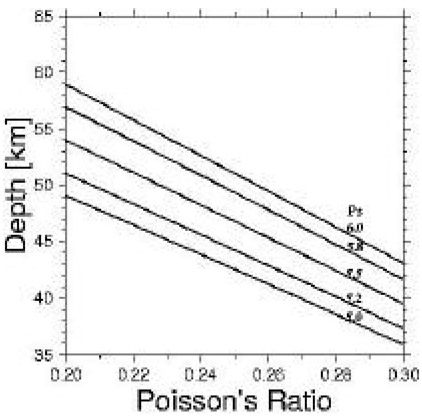

Figure 5. Figure shows the influence of Poisson's ratio on crustal thickness for fixed values of *Ps* times that range from 5.0 s to 6.0 s and which encompass the *Ps* times of the WDC and SGT. Computations are carried out for a fixed slowness of 6.4 s/° assuming an average velocity of 6.5 km/s.

To recognize potential problem stations we tried to point out the discrepancies in the mismatch or absence of the multiples at the times predicted by the crustal parameters derived in GA and GB. Stacked RFs for good quality stations (A in Table 1) do tend to show measurable amplitudes close to the predicted times, even without moveout corrections. Presence of the relevant phases close to the predicted times is in fact, one simple way of validating the results of ZK method, since it is not a very robust method in the presence of weak multiples. It is relevant to recall that since the average *Vp* in the south Indian shield is large (6.5 km/s), the effect of moveout would obviously be less[25]. In which case, the phases should stack more coherently and the stacks from this region should have (show) clearer multiples (phases), contrary to what is presented in GA and GB. Our calculations for a 40 km thick crust with an average *Vp* of 6.5 km/s over a 30–90° distance range for a fixed Poisson's ratio of 0.25 yield 0.3 s and 1.3 s moveout times for the *Ps* and *Pps* phases respectively. Therefore, presence of weak *Pps* or its absence can be reconciled by either attributing it to the poor quality of the data or by invoking presence of complex structure that results in poor *Pps* registration. In either case application of ZK method to extract crustal parameters remains questionable.

At stations where there is a large mismatch between the expected and actual arrival times of the multiple phases, we tried to bring out the bias in the estimated parameters presented by the original authors (using *ZK*), by simply translating the difference in *Pps* and *Ps* times, using the formulae presented in numerous publications[21,26]. As expected, for good quality stations (A in Table 1), the difference in crustal thickness (*H*) and Poisson's ratio estimates from *ZK* and the analytical method is always very small, while it tends to be large for poor quality stations (designated B&C in Table 1) where multiples are either weak or absent. We were surprised to find that there are large discrepancies at many stations sited on the WDC and SGT. This raised some doubts on the reliability or representative nature of the estimated *H*, *s* values arrived at by the original authors. Such a coincidence in discrepancy of estimates and data quality as well, cannot be fortuitous but something real that warrants an explanation.

Interestingly, both GA and GB make H-*s* estimates at all the stations, even at those that did not register clear and observable *Pps* multiples (see Figure 3 of GA and Figure 2 of GB). Also it is evident that RF data at a few key stations in GA and GB defy the results of Yuan *et al.*[23]. This prompted further investigation. As a first step as mentioned earlier, using the estimated crustal parameters [entries H(G), *s*(G) in Table 1] presented in GA and GB along with the corresponding slowness values (see Figure 2 of GB), we re-computed the arrival times of *Ps*, *Pps* and *Pss* phases [see Table 1, entries *Ps*(cal), *Pps*(cal)] and compared them with those marked by the original authors [entries *Ps*(obs), *Pps*(obs) in Table 1]. At many locations mismatch in phase times is more than 2 s reaching as high as 4 s and at few other stations no phases were visible (e.g. MTP, PCH, GOA, KSL, KDM) at the predicted times. As a second step, we assumed that the marked phases by the original authors are true and properly identified by them. We re-picked these (phases) times after appropriate magnification of the relevant figures of GA and GB. We are satisfied by our picking accuracy, as our picks on an average, deviate by about 0.15–0.2 s from those presented in GA. The time–depth transformation of these picks [entries *Ps*(obs) and *Pps*(obs) in Table 1] with appropriate slowness values from GB/GA using the formulae of Zandt *et al.*[21] and Zhu and Kanamori[20] yielded our (*H*, *s*) values designated as *H*(*R*) and *s*(*R*) in Table 1.

Our estimates of *H*, *s* are at large variance with those reported by the original authors at many stations especially in the WDC and SGT. These discrepancies coincide remarkably with stations that have no observable *Pps* multiple, or presence of apparently coherent arrivals close to *Pps*, suggesting their unsuitability for *H*-*s* analysis (e.g. KSL, DHR, DVG, KBC and GOA on WDC; LTV on EDC; PCH, MTP on SGT), contrary to what is attempted by the authors. This could be one possible reason to account for this discrepancy. Predictably, stations (GDP on WDC; SLM and KDR on Cuddapah Basin; MBN on EDC; KIL and NND on the Deccan Volcanic Province) with weak and broad *Pps* or *Ps* or with coherent phases in the vicinity of the *Pps* phase, the crustal parameters reported in GA and GB and their re-estimates (by us) naturally differ substantially (Table 1). At most of these stations, the Poisson's ratio measurements seem to differ significantly. Hence measurements at these stations are largely unreliable. Also, stations TMK, GBA on EDC and GRR on WDC with multiple local maxima in their *H*–*Vp*/*Vs* plots, (see Figure 4 of GB); CRP (character of stacks in GA and GB differ), MYS (very poor *Ps*), both on the WDC; PUN, KRD (noisy stacks with feeble *Pps*), are stations with dubious quality and their results remain suspect. Recognizing such discrepancies and based on the nature of *Ps* and *Pps* registrations, we assigned qualities to the stations (Table 1). A majority of stacks from the WDC and SGT, at the key stations in particular, conspicuously suffer in quality due to a variety of reasons stated above, resulting in unreliable results. Similarly, nearly half the data from the Deccan Volcanic Province (DVP) and most from Godavari graben (GG) are basically flawed for the same reasons. It is important to underscore the utility of a 'standard-way' in data and results presentation. The time window of the stacks should cover at least both the multiples (*Pps* and *Pss*). The *Vp*/*Vs* and *H* windows presented in GA and GB are over a narrow restricted range contrary to the normal practice of using larger windows. Even within these narrow ranges of their

Table 1. Bold face three-letter codes are essentially most of the key stations that either appear in the profiles presented in GA and GB or are mentioned in them. Station qualities: A = clear registration of *Ps* phase and its related multiples; B = stations with clear *Ps* but related multiples (*Pps*, etc.) are weak and barely detectable; C = combination of: i) clear *Ps* with no observable multiples; ii) Poor *Ps* and poor *Pps* with no clear H–*s* maxima; iii) apparently coherent arrivals close to the *Pps* with multiple maxima in the H–*s* plots. Definitions of various entries in the table are as under. Assuming that the derived crustal parameters (*H*, *s*) by the original authors (designated with 'G' in the brackets) to be true, we simply recalculated the *Ps*(cal) and *Pps*(cal) times (see Table 1 in the relevant entries/columns) using the simple analytical fomulae already mentioned in the text adopting the corresponding slowness values from GB. Entries *Ps*(obs) and *Pps*(obs) correspond to the times of phases marked by the original authors. Assuming that these marked phases, *P*(obs & *Pps*(obs)), by the original authors as correct and properly identified by them, we performed a time-depth transformation of these picks [entries *Ps*(obs) and *Pps*(obs) in Table 1] with appropriate slowness values from GB/GA using the formulae of Zandt *et al*.[21] and Zhu and Kanamori[20] to obtain our estimated H–*s* values designated as *H*(R) and *s* (R) in Table 1. Note that, while results from non-italic boldface stations (quality C) are unreliable, those in *italics* (quality B) can give large errors in the crustal parameters estimates. Interestingly, majority of the stacks from WDC and SGT; the anomalous terrains in GA and GB; are of poor quality and hence results from these terrains remain largely unreliable

Station	*H*(G)	*s* (G)	*H*(R)	*s* (R)	*Ps*(obs)	*Pps*(obs)	*Ps*(cal)	*Pps*(cal)	Quality and Remarks
Godavari Graben									
KDM	44	0.25	35.2	0.32	5.38	15.71	5.15	18.07	*C* (no *Pps*), unreliable
Southern Granulite Terrain									
MDR	40	0.24	40.5	0.23	4.57	16.14	4.61	16.05	*A*
TRV	35	0.25	35.7	0.26	4.28	14.75	4.1	14.37	*A*–*B* (noisy stack)
KOD	43	0.25	43.5	0.25	5.25	17.29	5.2	17.1	*A*–*B* (noisy stack), error prone
PCH	39	0.26	51.1	0.17	4.97	19.11	4.87	15.66	*C* (no *Pps*), unreliable
MTP	60	0.28	48.4	0.29	6.65	20.05	8.0	24.6	*C* (bad *Ps*, *Pps* picks), unreliable
Western Dharwar Craton									
KSL	46	0.25	53.8	0.2	5.66	20.55	5.56	18.29	*C* (bad *Pps* picks), unreliable
GDP	51	0.24	53.4	0.21	5.78	20.55	5.98	20.09	*C* (broad, poor *Ps*, broad *Pps*), unreliable
MYS	48	0.26	48.8	0.27	6.34	19.84	5.99	19.27	*C* (bad *Ps* phase), unreliable
GRR	51	0.25	51.3	0.25	6.2	20.38	6.17	20.28	*B*–*C* (multiple maxima in *H*–*s* plats), error prone
CRP	44	0.26	45.2	0.26	5.67	18.17	5.49	17.66	*B*–*C* (*Pps* in GA and GB different), unreliable
TPT	45	0.25	45.2	0.26	5.53	18.81	5.27	18.48	*A*–*B* (small *Pps*), marginal
KBC	42	0.24	42.9	0.24	4.86	17.46	4.77	17.1	*C* (no *Pps*), unreliable
NTR	41	0.25	40.2	0.26	4.97	16.47	4.87	16.59	*A*–*B* (small *Pps*), marginal
DVG	42	0.24	46.7	0.21	5.01	17.94	4.93	16.55	*C* (noisy, weak *Pps*; broad *Ps*), unreliable
DHR	43	0.27	45.2	0.26	5.58	18.08	5.54	17.44	*C* (noisy, weak *Pps*), unreliable
GOA	42	0.25	–	–	5.09	–	4.99	17	*C* (bad trace, no *Pps*, poor *Ps*), unreliable
Cuddapah Basin									
SLM	34	0.25	32.5	0.28	4.23	13.77	3.98	13.96	*B*–*C* (broad *Pps*), error prone
CUD	35	0.25	34.4	0.26	4.2	14.31	4.1	14.37	*A*
KDR	39	0.24	45.9	0.2	4.81	17.52	4.58	15.37	*C* (no *Pps*), unreliable
Eastern Dharwar Craton									
KOL	33	0.25	32.6	0.27	4.13	13.71	3.86	13.55	*A*
BGL	35	0.25	33.9	0.27	4.25	14.21	4.1	14.37	*A*
TMK	35	0.28	33.8	0.29	4.57	14.5	4.52	14.8	*B* (broad *Pps*, multiple maxima), unreliable
GBA	34	0.25	32.9	0.28	4.25	13.9	3.98	13.96	*B* (multiple maxima), unreliable
LTV	35	0.25	34.1	0.26	4.15	14.15	4.1	14.37	*C* (no *Pps*), unreliable
MBN	34	0.25	33.3	0.27	4.12	13.9	3.86	13.84	*B* (weak *Pps*), marginal
BKR	33	0.24	32.7	0.26	4.05	13.09	3.99	13.12	*A*
HYB	33	0.25	34.1	0.24	3.98	13.41	3.99	13.12	*A*
Deccan Volcanic Province									
PUN	35	0.26	36	0.26	4.31	14.88	4.23	14.5	*B*–*C* (broad weak *Pps*), error prone
KRD	36	0.26	36.4	0.26	4.42	15.1	4.35	14.92	*B*–*C* (poor *Pps*), error prone
KIL	36	0.24	35.4	0.27	4.35	14.74	4.09	14.65	*B* (weak *Pps*), marginal
NND	36	0.24	35.2	0.27	4.35	14.68	4.09	14.65	*B* (weak *Pps*), marginal

presentation, we still see parts of a few local maxima closures in their picture frames, even at their ‘good’ stations. Presentation of data and results in longer time windows and broader parameter ranges would help in better appreciation of the results obtained by the authors.

In the absence of RF sections we are unable to verify both the presence and nature of the marked phases especially of the *Pps* and *Pss* multiples that are so vital for *H–s* estimates by any method. Due to non-availability of data from almost all the stations to us, we are not in a position to perform ZK ourselves on permissible stations.

The major point in favour of GA and GB is that they document a clear 1–1.5 s difference in *Ps* time between the EDC and WDC. The WDC seems to be underlain by a thicker crust. In light of all the above arguments, the relevant question is, How thick?. Sarkar *et al*.[13], suggest a 7–8 km thicker-than-EDC crust beneath the WDC. Results of GA and GB show an anomalously thick crust (> 44 km) beneath 6 stations in WDC with at least 3 in excess of 50 km. Owing to poor constraints on Poisson’s ratio estimates due to weak/no *Pps* registrations in the WDC and its direct bearing on crustal thickness as evident from Table 2, we feel that these parameters in WDC and SGT could have been over estimated. As also clear from Table 2, that highlights the influence of Poisson’s ratio on crustal thickness, for a given *Ps* time with an average *Vp* of 6.5 km/s and a fixed slowness of 6.4 s/deg, a crustal thickening of about 8 km can be explained with a change in Poisson’s ratio from 0.30 to 0.25. In other words, a given *Ps* time can be explained either by a relatively thick crust (thicker by 8 km) with smaller Poisson’s ratio (0.25) or a thinner crust with 0.30.

We try to demonstrate the influence of a broad *Ps* or *Pps* pulse, or their total absence or influence of coherent arrivals close to the designated *Pps* on the crustal parameter (H, *s*) estimates by a few examples (Figure 6) from GA and GB.

Examples:

- Clear *Ps* and clear *Pps* at HYB on EDC shows up as a simple and clean *H–Vp/Vs* closure at about 33 km–1.73 (*s* = 0.25) region.
- Broad *Pps* at TMK on EDC/WDC border gets reflected as unclear closures in *H–Vp/Vs* plots and that too multiple closures [one around 44 km–1.66 (*s* = 0.215) region and the other around 35 km–1.8 (*s* = 0.276) region]. What could be the optimal pair of estimates?
- GOA is an example of a typical WDC station with null *Pps* energy (no multiple phase). The data provided by other researchers for this station consists of 44 receiver functions. The station is of quality C in view of poor/no multiples. The ZK was performed with average *Vp*(6.5 km/s) and weights (7-2-1/*Ps*, *Pps*, *Pss*) as described in GB. The *H–s* energy plot documents the typical manifestation of absence of *Pps* (or a weak *Pps* if identifiable) by way of elongated linear energy contours with multiple maxima, one around 30–35 km; 0.30-above region and the other between 35 and 40 km; 0.26–0.30 region. One could have preferred the values 38.5; 0.287 for H and *s* as the crustal parameters. Compare these multiple closure ranges, the preferred estimates and those reported by GB (42 km, 0.25). These station data and results highlight the possible range in estimates of the crustal parameters in the absence of *Pps* multiple or its poor registration and recognition. The same would be true for all WDC and SGT stations in particular (e.g. DHR, KBC, MTP, PCH, etc.) and to all stations in general with either no *Pps* phase or its poor registration.

Even stations with reasonable *Ps* and *Pps* but with relatively energetic arrivals close to the designated *Pps* phase are prone to errors in estimation of the crustal parameters by way of presence of multiple maxima in *H–s* (*Vp/Vs*) plots making it difficult to choose the optimal parameters. For example station GRR has two possible maxima, one is clear and the other is close to the top edge of their figure also showing a closure trend. The clear maxima preferred by the original authors in GA and GB shows values 51 km–0.25 while the other showing the tendency for presence of another maxima is around 45–47 km with a *Vp/Vs* over 1.8 (*s* = 0.276).

The above examples besides clearly supporting our various contentions with regard to applicability of the ZK method to extract crustal parameters also lend support to our station quality classification and possible errors in *H–s* estimates at various locations in the WDC and SGT.

Why and how this data is flawed

The Southern Granulite Terrain

In light of the above, an attempt shall be made to dwell in some detail on some glaringly poor quality data. Station MTP is located on the exhumed granulites with highest reported crustal parameters (*H*, *s*) of 60 km and 0.28 (see Figure 3 of GB). The stack trace is noisy with a low-amplitude broad *Pps* multiple and small *Ps*. The weak *Pps* multiple is picked slightly early compared to the larger multiple at KSL or GDP (see Figure 2 of GB), while the *Ps* is considerably delayed (about 7.0 s). As *H* and *s* at MTP (60, 0.28) are highest in the data presented, both *Ps* and *Pps* should have maximum delays compared to any station. Though the *Ps* fulfils this condition, surprisingly *Pps* defies it, suggesting that this phase is wrongly picked in the stack trace and translates in a similar fashion while estimating the parameters. This spurious behaviour of MTP is also reflected as multiple local maxima in the *H–s* plot (see Figure 3 of

Table 2. Table form of Figure 5. All the model parameters remain the same as in Figure 5. Look at the combinations of *H–s* pairs which yield the same *Ps* times. Note the range in *Ps* times and the corresponding ranges in Poisson’s ratio and crustal thickness values

	P-to-S Conversion times (s)				
	5.0	5.2	5.5	5.8	6.0
Poisson’s ratio	Crustal thickness (km)				
0.2	49.1	51.0	54.0	56.9	58.9
0.23	45.2	47.0	49.7	52.4	54.2
0.25	42.5	44.3	46.8	49.4	51.1
0.27	39.8	41.5	43.9	46.3	47.9
0.29	37.2	38.7	40.9	43.2	44.7
0.30	35.9	37.3	39.5	41.6	43.1

GB). As expected, it can be seen from Table 1 that the re-estimated parameters (48.4, 0.29) from the observed pick times (marked in GA and GB) vary substantially from those reported (60, 0.28) by the authors. It is also interesting to observe that no observable phases seem to exist in the MTP stack trace at the computed *Ps* and *Pps* times based on the crustal parameters reported in GB. This station should have been discarded from modelling on these counts. Yet the authors claim to have successfully performed a *H–s* grid search. Similar arguments can be extended to few other key stations as well, especially to those located in the SGT.

The Eastern Dharwar Craton

A cursory look at figure 3 of GA suggests that data from almost all stations located in the EDC, with the possible exception of KDR and LTV (*Pps* almost absent), are of high quality. Note that the *Ps* amplitude at LTV is also small compared to other EDC data, but the stack trace is simple in form like the other EDC stations. Data from this region are clearly simple and clean because of the simplicity of the underlying crust.

The Western Dharwar Craton

Station KSL on the WDC suffers severely from a bad *Pps* pick time, making the results rather unconvincing. Conceding that the estimated parameters (46, 0.25) are 'representative' of the data, the *Pps* multiple must arrive around 18 s against a pick of around 20 s, a difference of about 2 s (Table 1). If the pick at 20 s in GA were indeed correct, it would result in a Poisson ratio of 0.2 and not 0.25, as reported. The Moho depth would shift to 53.8 km. There is yet another coherent phase around 16 s. If this were identified as the *Pps* phase, then the crustal parameters would be something else. To reduce such ambiguity, it is therefore essential to identify and present the complete data till at least the *Pss* phase. Presence of a few coherent phases (close to the predicted *Pps* arrival) in the stack trace of KSL (see Figure 2 of GA) perhaps leads to multiple local maxima (see Figure 4 of GA), even in the narrow (~ 16 km) *H* range shown. Also, the *Pps* time at KSL is near identical to that at GDP and GRR (another mid-Archaean station). Since the reported Poisson ratios at GRR and KSL and observed *Pps* times are identical (see Figure 3 of GA), they should make an interesting comparison in light of the analyses of Yuan *et al.*[23]. However, thickness (*H*) at GRR is 51 km against 46 km at KSL. This substantial difference in only *H* at GRR should delay the *Pps* more than the *Ps*. To the contrary, the *Pps* remains the same as at KSL (see Figure 3 of GA), but the *Ps* seems to have changed substantially, defying simple calculations as well as model predictions. If we concede that the KSL multiple pick is totally off, then how do we reconcile the measurements at GRR and GDP, which report the same thickness (51 km) with marginal difference in Poisson ratio (0.01), for considerable difference (~ 0.5 s) in their observed *Ps* arrivals? The *Pps* multiples at GRR and GDP have near-identical arrival times. A difference of about 0.01 in *s* alone at GRR and GDP cannot cause a clear difference of 0.5 s in *Ps* as observed (see Figure 2 of GB). Therefore, either GDP or GRR times appear to be in error, warranting a re-estimation of these parameters at both the stations. From the quality of the *Ps* registered at GDP, the estimates at this station appear to be in error. With the maximum *Ps* delay time (close to 6 s) and perhaps the *Pps* as well, GRR should ideally yield the highest *H* and *s* values in this region, in WDC. Thus, most of the key stations on which rest the profound claims of GA, suffer from serious data quality and treatment deficiencies and we believe that the data from MTP, KSL, GDP and perhaps GRR need to be examined again.

Stations located on the Closepet Granite Chitradurga Schists (CG/CT) also suffer from lack of clear sharp multiples and are unlike their EDC counterparts. Most of the stations lie in the vicinity of CG, a postulated suture between the WDC and EDC, and near Chitradurga thrust, an alternative WDC–EDC boundary. At least beneath the CG, existence of an upper crustal scattering zone (5–15 km depth) that acts as a wave-guide, is inferred from waveform and F–K modelling of explosion data recorded at the GBA array[27]. Such a scattering zone

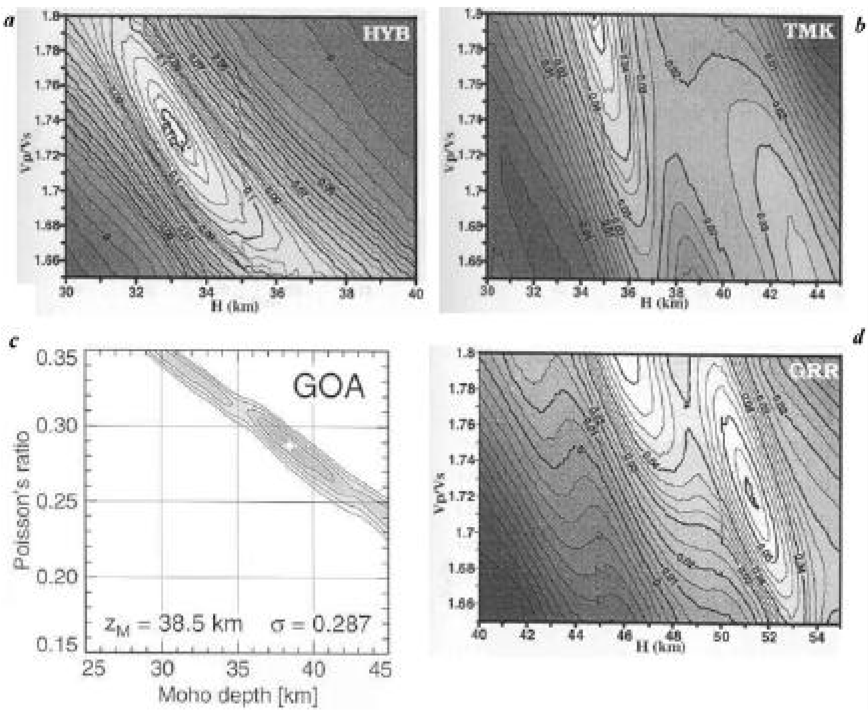

Figure 6. Examples of the nature of ZK energy contours showing clean, ambiguous and multiple closures depending on the quality of either *Ps* or *Pps* phases. ***a***, Clean and clear *Ps* and *Pps* at HYB gets reflected as well constrained parameters. ***b***, Broad *Pps* at TMK shows up in terms of unclear and multiple closures. ***c***, Null *Pps* phase at GOA manifests as elongated linear energy contours with multiple maxima. ***d***, Presence of relatively energetic arrivals in the vicinity of designated *Pps* results in multiple maxima. Cases ***b–d*** become difficult to choose the optimal pair of crustal parameters that explain the data. All figures except ***c*** are published as such in GA and GB.

is likely to be covered by the length sampled by multiples, a region with clear departure from the assumption of a uniform crust that is so central to the *H*–*s* grid search method. Hence absence of energetic *Pps* or broadening of it at locations that 'see' this zone, comes as no surprise. Stations TMK, KBC indeed show the expected behaviour of weak multiples and the resulting multiple local *H*–*s* maxima (see figures 3 and 4 of GA). Clearly, these stations are not ideal for RF analysis and one may have to adopt different strategies to overcome these natural constraints[21]. One may examine the approach followed by Rai *et al.*[12] to render credibility to model data from EDC. Work by Kumar *et al.*[11] and Sarkar *et al.*[13] may provide some useful guidelines in the Indian context.

Inadequate data to detect effect of dipping layers

Another problem with the data used by GA and GB is the poor azimuthal coverage, which is key to the detection of dipping layers. It is evident from figure 6 of GA that the azimuthal distribution of earthquakes recorded by their mobile network at any given time is quite limited, with a traditional large bias to eastern azimuths and sparse events beyond 120° azimuth. Since the events between 30 and 95° distance are suitable for RF analysis, only a limited number of events (10–12) are available for the studies. Thus, on an average, we shall be left with about 5–8 events per station sampling an entire azimuth range of about 240°, roughly between south east and north. Such a small sample of data over a large azimuth range is arguably woefully short to observe the effect of dipping structures. Therefore, it becomes extremely important to show data in RF sections along azimuth/slowness to appreciate the claims of authors for the absence of dipping Moho in their region of study.

It is relevant to mention that essentially the same research group subjected the same data from the EDC, WDC and SGT regions to seismic anisotropy studies. Their analyses reveal aspherical structure effects in the RFs modelled as anisotropy in the crust[28]. Clear observable energy in tangential component of the RF, in addition to radial energy, arising out of split in *Ps* (Moho *Ps*) waves is reported and modelled as due to crustal anisotropy in the range 0.1–0.25 s in Dharwar and Granulite terrains of India. Therefore in the transverse RFs, discernible, observable and measurable energy is indeed present, contrary to the impression given in GA.

Summary of observations

The main points of our presentation can be summarized as under:

Importance of moveout correction in RF analysis and its bearing on unambiguous identification of crustal multiples is clearly brought out in this study.

The critical dependence of *H*–*s* values on the quality of multiples is succinctly brought out and demonstrated with examples from GA and GB.

Possible sources of errors in the results of GA and GB due to poor quality of their data are identified.

The reliability of crustal parameters presented at 32 locations by GA and GB is discussed. We conclude that majority of the stations on WDC and SGT in particular, suffer severely from poor quality of multiples and consequently result in large errors in parameter estimates. At a few locations, these errors reach in excess of 10 km for *H* and 0.05 for *s*. Among the 19 key stations mentioned in GA and GB, only four turn out to be of quality *A*. Incidentally, even at stations with an assigned quality *A* or *B* in the WDC, their results can be dubious for other reasons discussed in the text. Almost all the data from WDC need to be re-examined.

The new claim in GA and GB of 'a mid-Archaean anomalous thick crust' in WDC laments for more authentic and reliable datasets and is still waiting to receive unequivocal support.

The conclusion 'WDC and SGT are thicker than EDC at crust levels' though lacks in quality of data and rigour of analysis, only supports the earlier results[13,29] that are, albeit, feebly documented (magnitude-wise), perhaps arrived at through less fashionable probing tools but with relatively convincing means bestowed with data integrity and analysis.

The azimuthal coverage of the RFs in GA and GB is grossly inadequate to document effects of aspherical earth structure to detect presence of dipping layers in the study region.

In summary, it is imperative to conclude that most of the profound geodynamic statements made in these works are at best still at a conceptual level, waiting to be translated into reality based on the integrity of the data, perhaps reserved for the near future. The results presented in the recent works[9,10] clearly suffer from lack of natural flair and strength of the data. The scope to impart a semblance of rigour and vitality to published results mainly lies in how best the data selection and reduction procedures are employed and to what levels the modelling skills/ efforts can be raised to after data-generation.

1. Bostock, M. G., Hyndman, R. D., Rondenay, S. and Peacock, S. M., *Nature*, 2002, **417**, 536–538.
2. Kind, R. *et al*., *Science*, 2002, **298**, 1219–1221.
3. Kumar, M. R., Ramesh, D. S., Saul, J., Sarkar, D. and Kind, R., *Geophys. Res. Lett*., 2002, **29**.
4. Li, X. *et al*., *Geophys. Res. Lett*., 2003, **30**, 1334.
5. Ramesh, D. S., Kind, R. and Yuan, X., *Geophys. J. Int*., 2002, **150**, 91–108.
6. Simmons, N. A. and Gurrola, H., *Nature*, **405**, 559–562.
7. Vinnik, L. P., Kumar, M. R., Kind, R. and Farra, V., *Geophys. Res. Lett*., 2003, **30**, 1415.
8. Yuan, X., Ni, J., Kind, R., Mechie, J. and Sandvol, E., *J. Geophys. Res*., 1997, **102**, 27,491–27,500.
9. Gupta, S., Rai, S. S., Prakasam, K. S., Srinagesh, D., Chadha, R. K., Priestley, K. and Gaur, V. K., *Curr. Sci*., 2003, **84**, 1219–1226.
10. Gupta, S. *et al*., *Geophys. Res. Lett*., **30**, 2003, 1419.
11. Kumar, M. R., Saul, J., Sarkar, D., Kind, R. and Shukla, A. K., *Geophys. Res. Lett*., 2001, **28**, 1339–1342.
12. Rai, S. S., Priestley, K., Suryaprakasam, K., Srinagesh, D., Gaur, V. K. and Du, Z., *J. Geophys. Res*., 2003, **108**, 2088.
13. Sarkar, D., Kumar, M. R., Saul, J., Kind, R., Raju, P. S., Chadha, R. K. and Shukla, A. K., *Geophys. J. Int*., 2003, **154**, 205–211.
14. Langston, C. A., *Bull. Seismol. Soc. Am*., 1977, **67**, 713–724.
15. Langston, C. A., *Bull. Seismol. Soc. Am*., 1977, **67**, 1029–1050.
16. Langston, C. A., *J. Geophys. Res*., 1979, **84**, 4749–4762.
17. Langston, C. A., *J. Geophys. Res*., 1981, **84**, 3857–3866.
18. Cassidy, J. F., *Bull. Seismol. Soc. Am*., 1992, **82**, 1453–1474.
19. Abers, G. A., *Bull. Seismol. Soc. Am*., 1998, **88**, 313–318.
20. Zhu, L. and Kanamori H., *J. Geophys. Res*., 2000, **105**, 2969–2980.
21. Zandt, G., Myers, S. C. and Wallace, T. C., *J. Geophys. Res*., 1995, **100**, 10,529–10,548.

22. Chevrot, S. and van der Hilst, R. D., *Earth Planet Sci. Lett.*, 2000, **183**, 121–132.
23. Yuan, X., Sobolev, S. V. and Kind, R., *Earth Planet Sci. Lett.*, 2002, **199**, 389–402.
24. Owens, T. J., Zandt, G. and Taylor, S. R., *J. Geophys. Res.*, 1984, **89**, 7783–7795.
25. Sarkar, D., Chandrakala, K., Padmavathi Devi, P., Sridhar, A. R., Sain, K. and Reddy, P. R., *J. Geodyn.*, 2001, **31**, 227–241.
26. Last *et al.*, *J. Geophys. Res.*, 1997, **102**, 24,469–24,483.
27. Krishna, V. G. and Ramesh, D. S., *Bull. Seismol. Soc. Am.*, 2000, **90**, 1281–1294.
28. Rai, A., Priestley, K., Rai., S. S., Srinagesha, D. and Gaur, V. K., *Geophys. Res. Abs.*, 2003, **5**, 10842.
29. Ramesh, D. S., Srinagesh, D., Rai, S. S. and Prakasam, K. S., *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 1992, **101**, 283–298.

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Response:

The paper 'On the efficacy of recent crustal images of the Indian shield from receiver function' by D. S. Ramesh is essentially a comment on our paper[1]. Even a cursory reading of his comments would make it clear that these barely deal with the contents of our paper published in *Current Science*[2], and create a misleading impression of our *GRL* paper when read without that context.

In fact, Ramesh had sent similar criticisms of our *GRL* paper to the *GRL* editor in August 2003, simultaneously with his submission to *Current Science*. Our reply to his comments was reviewed by both the *GRL* editor and other *GRL* reviewers. They agreed with our conclusion that 'the analysis procedure is sound and results . . . robust', and rejected Ramesh's criticisms.

It is intriguing that Ramesh should have chosen to submit his comments on a paper whose substantial contents appear in *GRL*, to *Current Science*, ignoring the possibility that a reading of his comments by researchers and students, without the benefit of a ready reference to the former, would create a grossly distorted assessment of our results. We believe that it is to forestall such distortions, that scientists and publishers adhere to the well-accepted ethical practice of pointing their criticisms directly to the journals where the original paper appears.

However, for the benefit of readers to make their unbiased assessment we are submitting below our reply to the comments.

We refer to comments of Ramesh[3] on the data, analysis and conclusions of Gupta *et al.*[1]. Ramesh points out five problems with the work of Gupta *et al.*: (i) the quality of the conversions, (ii) flaws in identification of the phases, (iii) flaws in analysis, (iv) flaws in processing strategies, and (v) errors in estimate of crustal thickness (H) and Poisson ratio (we actually determine V_p/V_s (k)). We take each of these points separately.

(i) We have worked on receiver function (RF) data from a large range of environments from central Asia to the central Pacific, and the south Indian data are amongst the highest quality RFs we have experience with. They are in general both simple and of high signal-to-noise ratio. We are intrigued at their being summarily branded as unreliable and of poor quality without any explicit basis. In our opinion, the data are authentic and we fail to understand how Ramesh[3] would have them made 'more authentic'.

(ii) The analysis procedure we follow is that of Zhu and Kanamori[4]. Ramesh states that there are flaws in our phase identification, perhaps not appreciating that we make no phase identification. As stated by Zhu and Kanamori (p. 2973), one of the advantages of this algorithm is that it does not require the picking up of arrival times of different converted phases. We apply the Zhu and Kanamori algorithm to find the maxima in H–k space and use these to determine the crustal structure.

(iii) As to the comments about flaws in our analysis, we have tested our computer codes on synthetic waveforms and find no flaws in the analysis. Ramesh refers to a statement we make about the tangential component amplitude. 'The authors in Gl report lack of observable energy in the transverse RFs and rule out the presence of dipping structure. Paradoxically, the same transverse RFs were inferred to have observable energy that is modeled in terms of anisotropy[5]. The tangential receiver functions for a number of the stations discussed in Gupta *et al.*[1] are plotted in Rai *et al.*[6]. The comment in Gupta *et al.* referred to by Ramesh concerns the station MTP, not studied by Rai *et al.*[5] (abstract in a meeting programme volume 2003). The quoted comment from Ramesh is therefore quite out of context, because discussion in that meeting presentation by Rai *et al.*[5] (of which four of us were co-authors), primarily concerned a dataset from the stations in the Pan-African granulite terrane of southernmost India and Sri Lanka, not data from MTP or any other station in the western Dharwar craton. To quote Gupta *et al.*[1] out of context and Rai *et al.*[5] without knowing the contents of the meeting presentation, is misleading. Ramesh criticizes the 'unconventional way of presentation of data and results . . .' (Figure 3 in Gupta *et al.*[1]), but does not clarify as to what is unconventional in it. The broad structure of the south India shield is known from a number of controlled source experiments; results of fourteen of these are used in making the Moho contour map in Gupta *et al.*[1]. The H-scale is at least $\pm$ 5 km and the k at least $\pm$ 0.05 about the Moho depth and k values cited in Gupta *et al.*[1]. These plots were made in such a way as to let the reader see the spread about the cited values, not to hide other larger peaks. Ramesh goes on to mention the presence of other 'local maxima' in the H vs k plots. Gupta *et al.*[1] do not claim that the crust consists of a uniform layer over a mantle half-space; we know from Rai *et al.*[6] and subsequent inversion of the RFs discussed by Gupta *et al.*[1] that the crust contains some internal structure and these can lead to local maxima. Zhu and Kanamori[4] comment that 'in principle, these phases have different moveout with ray parameter from those of Moho *PpPms* and *PsPms* + *PpSms* so that their energy will not be stacked coherently in $s(H, k)$. However, the presence of these phases often smears the $s(H, k)$ maximum and sometimes causes other local maxima. In the case of multiple peaks in $s(H, k)$, information on the crustal thickness and V_p/V_s ratio from nearby stations or other sources can help to resolve the ambiguity'. We follow this practice.

(iv) Ramesh criticizes our choice of the phase weights in application of the Zhu and Kanamori[4] technique, and the fact that we did not migrate the receiver function to a common distance before forming the RF stacks. Choosing the phase weights is somewhat subjective. In this, we also chose to follow Zhu and Kanamori in weighting the *Ps*, *PpPms* and *PsPms* + *PpSms* phases as 0.7, 0.2, 0.1 respectively. We tested the effects of different choices of weights on the resulting estimates of H and k and found that reasonable choices of weights had little effect on the resulting crustal model. Zhu and Kanamori (p. 2973) give their reasoning for this weighting: 'These values are chosen to balance the contributions from the three phases. Among them, the *Ps* has the highest SNR so it is given a higher weight than the other two. We also set $w1 > w2 + w3$ because the latter two phases have similar slopes in the H–k plane'. Another reason for down weighting the multiples is that they sample a different part of the crust than does *Ps*. In addition, *PsPms* + *PpSms* consists of two phases which may not sample the structure in the same way and is normally a weak phase. When comparing RFs for events at greatly different epicentral distances, correcting for normal moveout is required but this is not necessary when events from nearly the same distance are stacked. Gupta *et al*.[1] (pp. 1–2) state that the stacks were over small distance and azimuth bins (both 5°). The moveout correction is to normalize the RFs to a common distance, but since our RFs are from a small distance range (± 2.5°), this correction is unnecessary. Stacking over small distance and azimuth bins is standard practice in RF analysis and has been discussed in a number of earlier publications[7,8]. For an event at 60° epicentral distance and recorded on the south Indian crust, the moveout for ± 2.5° is ± 0.02 s for *Ps*, ± 0.08 s for *PpPms* and *PsPms* + *PpSms*. The sample interval of the data is 0.05 s. So the peak broadening caused by ignoring the phase moveout is negligible. Correcting the RFs for events at greatly differing epicentral distances for normal moveout of *Ps* would cause the multiples to stack incoherently, exactly what we wish to avoid; hence the choice of the narrow stacking bins.

(v) Regarding error estimates of H and k, Ramesh fails to note that the H values from the eastern Dharwar Craton stations discussed in Gupta *et al*.[1] were analysed further in Rai *et al*.[6]. The eastern Dharwar Craton RFs in that study were jointly inverted with the local surface wave phase velocity to determine the crustal structure, not just the Moho depth. This joint inversion provides much tighter constraints on the crustal structure because the weakness of the one dataset (e.g. the time–depth trade-off of RFs) is compensated for by the strength of the other dataset (e.g. control on the average crustal velocity of short-period surface waves). The results of the formal inversion for the data from the eastern Dharwar Craton are in good agreement with the H values for the same stations in Gupta *et al*.[1]. Since the publication of Gupta *et al*.[1], we have inverted the western Dharwar Craton RFs for the crustal structure and find no discrepancy greater than 2 km in H between the two techniques.

Therefore, the data analysed are good, the analysis procedure is sound and the results presented in Gupta *et al*.[1] are robust. We have taken Ramesh's[3] criticisms of a 'lack of natural flair' to heart, while his other criticisms would be clearly seen to be unsubstantiated.

1. Gupta, S. *et al*., *Geophys. Res. Lett*., 2003, **30**, 1419.
2. Gupta, S. *et al*., *Curr. Sci*., 2003, **84**, 1219–1226.
3. Ramesh, D. S., *Geophys. Res. Lett*., 2003, (submitted to *GRL* and rejected by editor).
4. Zhu, L. and Kanamori, H., *J. Geophys. Res*., 2000, **105**, 2969–2980.
5. Rai, A., Priestley, K., Rai, S. S., Srinagesha, D. and Gaur, V. K., *Geophys. Res. Abs*., 2003, **5**, 10842.
6. Rai, S. S., Priestley, K., Suryaprakasam, K., Srinagesh, D., Gaur, V. K. and Du, Z., *J. Geophys. Res*., 2003, **108**, 2088.
7. Owens, T. J., Zandt, G. and Taylor, S. R., *J. Geophys. Res*., 1984, **89**, 7783–7795.
8. Cassidy, J. F., *Bull. Seismol. Soc. Am*., 1992, **82**, 1453–1474.

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