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Moho depth and V_P/V_S variations in the Kope Dagh region from analysis of teleseismic receiver functions

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Abstract
In this study we use the P receiver function technique to determine the Moho depth and V_p/V_s ratio for 8 short period stations of Qochan and Mashhad seismic networks and map the variations of Moho depth under Kope Dagh region. It is shown that a receiver function can provide a relatively good point measurement of Moho depth under a short period station. The crustal thickness estimated from the delay time of the Moho P-to-S converted phase trades off strongly with the crustal V_p/V_s ratio. The ambiguity can be reduced significantly by incorporating the later multiple converted phases, namely, the PpPs and PpSs+PsPs. We use a stacking algorithm which sums the amplitudes of receiver function at the predicted arrival times of these phases by different crustal thicknesses H and V_p/V_s ratios (zhu & kanamori,2000). This transforms the time domain receiver functions directly into the H-V_p/V_s domain without need to identify these phases and to pick their arrival times. The best estimations of crustal thickness and V_p/V_s ratio are found when the three phases are stacked coherently. Applying this technique to 8 stations in Kope Dagh region reveals that the Moho depth is approximately 45 km on average and varies between 41 and 49 km. Thick and thin crust are found under the southern and northern Rang, respectively. These results are in good agreement with the geology and tectonic setting of this region.

Key words: Receiver function, Kope Dagh, Ps converted phase, Crust, Teleseismic wave

تغییرات عمق موهو و نسبت Vp/Vs در منطقه کپه داغ با استفاده از تحلیل تابع انتقال گیرنده امواج دورلرز

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چکیده
در این تحقیق از روش تابع انتقال گیرنده دورلرز P برای به‌دست آوردن عمق موهو ونسبت Vp/Vs برای ۸ ایستگاه کوتاه‌دوره از شبکه لرزه‌نگاری مشهد و قوچان استفاده شده است. همچنین تغییرات عمق موهو و نسبت Vp/Vs را زیر منطقه کپه‌داغ رسم کرده‌ایم. این تحقیق روشن‌ساخته است که روش تابع انتقال گیرنده می‌تواند روش خوبی برای اندازه‌گیری عمق موهو در زیر یک ایستگاه کوتاه‌دوره باشد. ضخامت پوسته‌ای از تاخیر زمانی فاز تبدیلی P به S به‌دست می‌آید که این زمان تاخیر توازنی قوی با نسبت

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Vp/Vs پوسته‌ای دارد. این ابهام می‌تواند به‌طور عمده با داخل کردن بازتاب‌های تکراری با نـام‌هـای PpPs و PpSs+PsPs کـه دیرتر می‌رسند، کاهش یابد.

از یک الگوریتم برانبارش استفاده می‌کنیم که دامنه‌های توابع انتقال گیرنده را در زمان‌های رسید پیش‌بینی شده از این فازهـا بـا نسبت‌های Vp/Vs و ضخامت‌های پوسته‌ای (H) گوناگون جمع می‌کند (زو و کاناموری، ۲۰۰۰). این الگـوریتم تـابع انتقـال گیرنـده حوزه زمان را مستقیماً به حوزه H-Vp/Vs تبدیل می‌کند بدون آنکه به مشخص کردن این فازها و همچنین پیک کردن زمـان‌هـای رسید مربوط به آنها نیازی باشد. بهترین برآورد از ضخامت پوسته‌ای و نسبت Vp/Vs هنگامی به‌دست می‌آیـد کـه سـه فـاز بـا هـم برانباشت شوند.

کاربرد این روش برای داده‌های مربوط به ۸ ایستگاه در منطقه کپه‌داغ، میانگین عمق موهو را تقریبا ۴۵ کیلومتر و تغییـرات آن را بین ۴۰ تا ۴۹/۵ کیلومتر نشان می‌دهد. موهوی عمیق‌تر در زیر منطقه جنوبی یافت شده است و پوسـته نـسبتا نـازکی در زیـر منطقـه مرکزی مشاهده شده است. نتایج به‌دست آمده همخوانی خوبی با زمین‌شناسی و زمین‌ساخت منطقه دارد.

واژه‌های کلیدی: تابع انتقال گیرنده، کپه داغ، فاز تبدیلی Ps، پوسته، امواج دورلرز

1 INTRODUCTION

The Mohorovicic discontinuity (Moho), which separates Earth's crust from the underlying mantle, represents a major change in seismic velocities, chemical compositions, and rheology. The depth of Moho is an important parameter to characterize the overall structure of a crust and can often be related to geology and tectonic evolution of the region. In Kope Dagh region, much efforts have not been made to determine the Moho depth. Nowroozi et al. (2007) mapped the crustal thickness variation in north-east of central Iran and Binalud zone by stacking broadband phases recorded by temporary stations. In general, there is agreement among these studies that the average crustal thickness in Kope Dagh is ~46 km where thick and thin crust are found under the southern and northern Rang respectively.

The limitation of techniques of various degrees imposed by the trade-off between the crustal velocity and the thickness. The trade-off can be very severe for those using Moho wide-angle reflection and refraction (PmP and Pn) travel times because these waves usually travel >100 km laterally within the crust. They are much more sensitive to lateral velocity variations than to the Moho depth variations. Using the differential travel time between PmP and the first P arrival can reduce the dependency on the upper crustal velocity, but the result is still strongly influenced by the lower crustal velocity (Richards-Dinger and Shearer, 1997). In addition, picking the secondary PmP arrival is not easy and can sometimes be ambiguouse. For studies using local earthquakes as energy source the source location brings in additional uncertainty in the Moho depth estimation. Vertical seismic reflection experiment can reveal fine-scale variation of deep crustal structure, provided that the energy sources are strong enouph to illuminate the Moho. However, the cost of such surveys is often very high, and their spatial coverage is very limited. An alternative and more effective technique of estimating Moho depth is to use teleseismic receiver functions (Langston, 1989; Ammon and Zandt, 1993; Zhu and Kanamori, 1994; Baker et al., 1996; Ichinose et al., 1996; Lewis et al., 1999).

Owing to the large velocity contrast across the discontinuity, part of the incoming teleseismic P wave energy will convert into Sv wave at the Moho. By measuring the time separation between the direct P arrival and the conversion phase, the crustal thickness can then be estimated. The estimation provides a good point measurement at the station because of the steep incidence angle of the teleseismic P wave. Furthermore, since the direct P arrival is used as a reference time, it can be shown that the result is not sensitive to crustal P velocity.

Receiver function analysis requires digital three-component seismic stations that are usually not available in large numbers for a specific region. This used to be drawback of the technique compared with other methods such as using Pn and PmP travel times where good spatial coverage can be achieved by using large numbers of local earthquakes and short-period vertical component stations. In this paper we will first discuss the methodology of using teleseismic receiver functions to estimate Moho depth and the associated uncertainties. We will use a developed receiver function stacking algorithm to transform the time domain waveforms into the depth domain which gives the best estimations for both the crustal thickness and Vp/Vs ratio. Then we apply this technique to all available stations and generate a map of Moho depth variation in Kope Dagh.

2 METHOD

The teleseismic receiver function represents the structural response near a recording station to the incoming teleseismic P wave. It is obtained by removing the source time function from raw teleseismic records using deconvolution. Details on the computation can be found elsewhere(Langston, 1977; Owens et al., 1984). In our study we use a modified frequency domain deconvolution which is implemented by dividing the spectrum R(ω) of teleseismic P waveform by the source spectrum S(ω) (zhu & kanamori,2000):

$$r(t) = (1+c)\int \frac{R(\omega)S^*(\omega)}{|S(\omega)|^2 + C\sigma_0{}^2} e^{-\frac{\omega^2}{4\alpha^2}} e^{i\omega t} d\omega \tag{1}$$

where S*(ω) is the complex conjugate of S(ω). The Gaussian-type low-pass filter $e^{-\frac{\omega^2}{4\alpha^2}}$ is added to remove high-frequency noise. The quantity $c\sigma_0^2$ (also called water level) is used to suppress "holes" in the spectrum S(ω), thus stabilizing the deconvolution. Here we use the auto correlation σ_o^2 of S(t) to normalize the water level so that c can be selected from a narrow range for different sized earthquakes. The 1+c factor is used to compensate the amplitude loss due to the water level. In single station applications the vertical component recording is often used as the effective source time function (Langston, 1977). For an array of stations the source time function, which is common to all stations, can be better estimated by stacking all vertical component recordings for each event. An obvious advantage is that the source time function is much smoother so that its spectrum is less singular. One can also obtain the vertical component of the receiver function which adds more information about the structure.

The first-order information about the crustal structure under a station can be derived from the radial receiver function which is dominated by P-to-S converted energy from a series of velocity discontinuities in the crust and upper mantle. Because of the large velocity contrast at the crust-mantle boundary, the Moho P-to-S conversion (Ps) is often the largest signal following the direct P.

The time separation between Ps and P can be used to estimate crustal thickness, given the average crustal velocities (Zhu and Kanamori, 2000),

$$H = \frac{t_{p_s}}{\sqrt{\frac{1}{v_s^2} - p^2} - \sqrt{\frac{1}{v_p^2} - p^2}} \tag{2}$$

where p is the ray parameter of the incident wave. An advantage of this method is that because the P-to-S conversion point is close to the station (usually within 10 km laterally) (Zhu and Kanamori, 2000), the estimation is less affected by lateral velocity variations and thus provides a good point measurement. One problem is the trade-off between the thickness and crustal velocities. However, since tp_s represents the differential travel time of S with respect to P wave in the crust, the dependence of H on Vp is not as strong as on Vs (or more precisely, on the Vp/Vs ratio, k). For example, using a Vp of 6.3 km/s and Vp/Vs ratio of 1.732 for a 30-km-thick crust, one gets, $\Delta H = \frac{\partial H}{\partial V_p}\Delta V_p = 4.3\Delta V_p(km)$

which means that the uncertainty of H is <0.5 km for a 0.1 km/s uncertainty in Vp. However, the thickness is highly dependent on the Vp/Vs, as shown by, $\Delta H = \frac{\partial H}{\partial k}\Delta k = -40.2\Delta k(km)$

i.e., a 0.1 change in k can lead to about 4 km change in the crustal thickness. This ambiguity can be reduced by using the later multiple converted phases which provide additional constraints

$$H = \frac{tp_p p_s}{\sqrt{\frac{1}{v_s^2} - p^2} + \sqrt{\frac{1}{v_p^2}}} \quad (3)$$

$$H = \frac{t(p_p s_s + p_s p_s)}{2\sqrt{\frac{1}{v_s^2} - p^2}} \quad (4)$$

So that both k and H can be estimated (Zhu, 1993; Zandt et al., 1995; Zandt and Ammon, 1995). In real situations, identifying the Moho Ps and the multiples and measuring their arrival times on a single receiver function trace can be very difficult due to back ground noise, scatterings from other velocity discontinuities. To increase the signal/noise ratio (SNR), one can use multiple events to stack their receiver functions. Since we are mainly interested in estimating crustal thickness, we propose a straightforward H-k domain stacking defined as

$$s(H,k) = \omega_1 r(t_1) + \omega_2 r(t_2) - \omega_3 r(t_3) \quad (5)$$

where r(t) is the radial receiver function, t_1, t_2 and t_3 are the predicted Ps,PpPs, and PpSs+PsPs arrival times corresponding to crustal thickness H and Vp/Vs ratio k, as given in (2)-(4). The ω_i are weighting factors, and $\sum \omega_i = 1$. The s(H,k) reaches a maximum when all three phases are stacked coherently with the correct H and k. Advantages of this algorithm are that (1) large amounts of teleseismic waveforms can be conveniently processed; (2) there is no need to pick arrival times of different conversion phases; (3) average crustal model is obtained by stacking receiver functions from different distances and suppressed; and (4) uncertainties can be estimated from the flatness of s(H,k) at the maximum. Using the Taylor expansion of s(H,k) at the maximum and omitting the higher-order terms, one gets the variances of H and k:

$$\sigma_H^2 = 2\sigma_s / \frac{\partial^2 s}{\partial H^2}, \quad (6)$$

$$\sigma_k^2 = 2\sigma_s / \frac{\partial^2 s}{\partial k^2}, \quad (7)$$

where σ_s is the estimated variance of s(H,k) from stacking.

3 STUDY REGION AND DATA

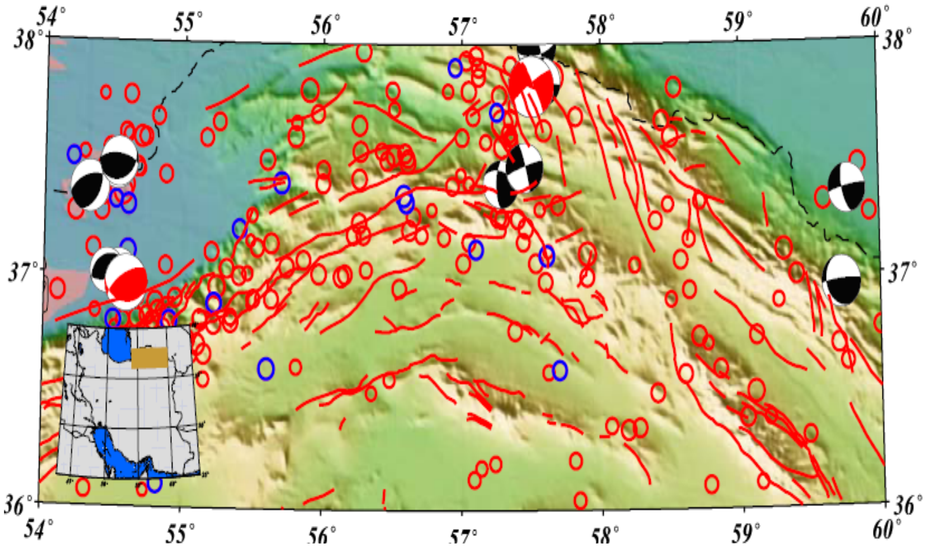
The Kope Dagh fold belt as a part of Alpine-Himalayan mountain belt in western Asia, constitutes the northeastern border of the Iranian plateau and lies on the southwestern margin of the Turan (Turkmenistan) continental crust, forming its epi-Hercynian (Early Kimmerian) cover (Berberian, 1981; Nabavi, 1983). It represents up to 10 km thick Mesozoic and Tertiary sediments, deposited in a subsiding sedimentary basin during the Mesozoic extensional phase, which were folded during the last phase of Alpine orogeny (Tchalenko, 1975; Berberian, 1981; Nabavi, 1983). The Kashaf-Rud depression separates the Kope Dagh ranges in the north from Binalood ranges in the south. The Binalood ranges, tectonically are considered as the eastern prolongation of the Alborz ranges (Alavi, 1992) and its northern boundary is considered to be the Paleo-Tethys suture zone (Sengor, 1987; Alavi, 1992). The Binalood ranges dates from the paleogene-Neogene, whereas the Kope Dagh range was formed later during the Neogene-Quaternary (Tchalenko, 1975). The Kope Dagh and Binalood mountain ranges together from a mountain belt about 600 km long and up to 200 km wide (Tchalenko, 1975) forming the Kope Dagh major seismotectonic province.

Kope Dagh constituting a part of northern limit of the Alpine-Himalayan mountain belt and its formation is the result of Arabia-Eurasia convergence movements. Structurally. It is homologous to the Zagros which forms the corresponding southwestern limit of the belt (Tchalenko, 1975). Although the Kope Dagh basin did not evolve into an oceanic crust, the thickness of the Mesozoic sediments implies that its crust was strongly stretched and thinned along normal faults at that time (Berberian, 1981). The Kope Dagh can be distinguished from the Alborz and Central Iran by the lack of powerful Eocene volcanism and, in fact, of any igneous activity, by relatively simple folding style, and by the fact that the Kope Dagh folds were essentially produced only by the latest Alpine movements in Pliocence to Pleistocene time (Stocklin, 1974). The Kope Dagh fold-thrust mountain belt is elevated by northward thrusting in the north and southward thrusting in the south of the range. The geological observation is also supported by the fault plane solutions of the earthquakes along the northern margin (1984.10.05 Ashkhabad earthquake) and the southern margin (1963.03.31 Esfarayen earthquake) of the belt (Berberian, 1981). The Kope Dagh and Binalood ranges are incised by a post-Alpine fault system which consists mainly of NNW-SSE right-lateral and NE-SW left-lateral strike-slip faults, as well as some minor sub-longitudinal thrusts referred to as diagonal fault system. The most important of the NNW-SSE faults (in length and in total displacement) are found in the Bakharden-Quchan zone which is a key element in regional seismicity (Tchalenko, 1975).

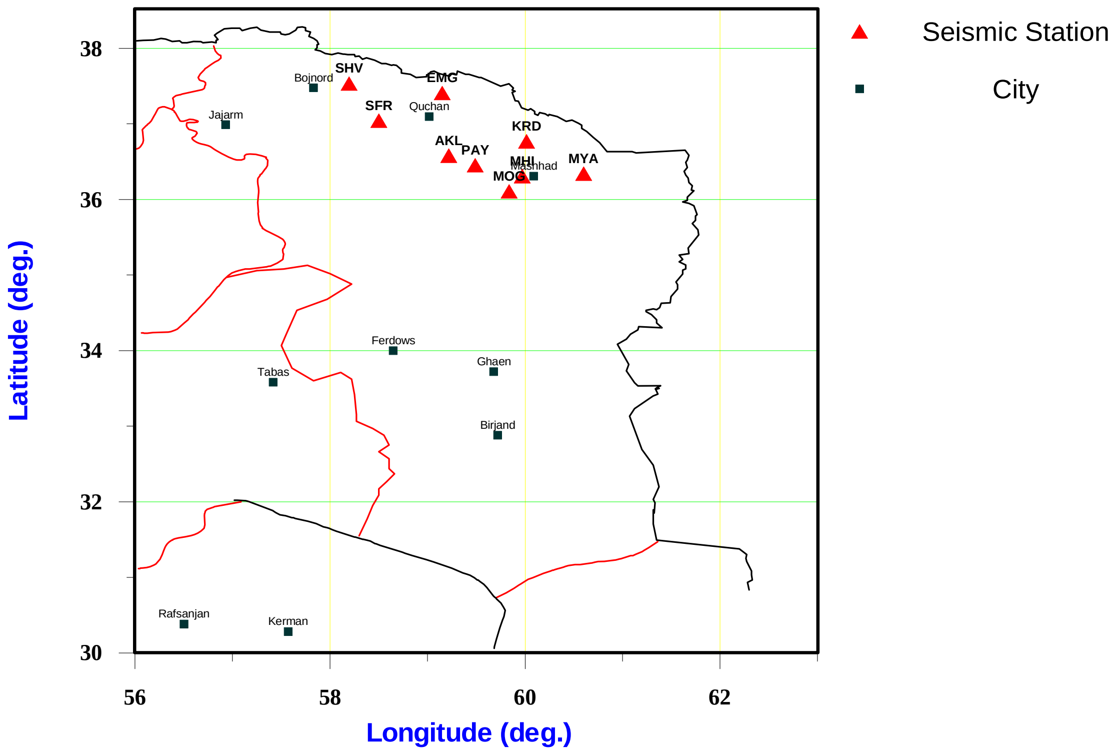
To the northeast, the Kope Dagh is separated from the stable Turan shield by a fault zone called Main Fault Zone (Tchalenko, 1975), which makes an abrupt northeast topographic front and follows the seismicity northwest to the Caspian Sea (Jackson and McKenzi, 1984; Priestly et al., 1994). The Main Fault Zone was associated with the major earthquake of 1948.10.05, M_s=7.2, near the city of Ashkhabad. The mechanism of the Ashkhabad earthquake was pubished by Rustanovich and Shirokova (1964) and Mckenzi (1972), that show a thrust mechanism with an almost vertical nidal plane striking ESE and a shallow plane dipping SW (McKenzi, 1972; Jackson and McKenzi, 1984). Though the fault plane solution of this event is supported with the results of leveling (Rustanovich and Shirokova, 1964), the available fault plane solutions for this event are considered to be badly constrained (Jachson and McKenzi, 1984). Several authers associated the linearity of the abrupt topographic scrap with right-lateral strike-slip motion on Main Fault Zone. Measurement of sheared underground irrigation tunnels (qanats) on Main Fault Zone apparently indicates right-lateral displacement, in some places at rates of about 3 ~ 8 mm/ a (Trifonov, 1978; Jackson and McKenzi, 1984), and farther northwest, focal mechanism solution of the earthquake of 1984.02.22 is consistent with right-lateral strike-slip movement on this trend (Priestley et al., 1994). Elsewhere in the Kope Dagh there is certainly thrust faulting on faults parallel to the regional fold axes and with NE directed slip vectors. The Kope Dagh may perhaps be another example of the partitioning of strike-slip and thrust motion that is postulated to occur in the Alborz mountains (Priestley et al., 1994).

The abrupt cut-off of seismicity NE of the Kope Dagh, combined with the slip vectors, indicates that considerable crustal shortening must be taking place in the Kope Dagh , as Iran is compressed against the Turan shield (Mirzaei, N., et al., 1998). Geographic position of stations and epicentral location, tectonics and seismicity in Kope Dagh is showen in Figure 1.

Waveforms of 200 teleseismic earthquakes recorded by 8 stations in the Qochan and Mashhad seismic networks are retieved from data archives at the IGUT. The actual number of events for individual station varies from 20 to 56, depending on the length of recording period and background noise level of the global earthquakes between 2005 and 2007 with magnitude >5.5 and distance range from 30° to 90° to the center of the network. The abundance of earthquakes within this distance range makes Kope Dagh a favorable place for study using teleseismic waveforms.



(a)



(b)

Figure 1. (a) Epicentral location, tectonics and seismicity in Kope Dagh. (b) position of stations in Kope Dagh(triangulars).

4 DATA PROCESSING

We use a time window of 35 s in length, starting 5s before the P onset, to cut the P waveform from raw velocity records. To utilize data recorded at different types of seismometers, the instrument responses have to be deconvolved. Then, the two horizontal components N and E are rotated to radial (R) and tangential (T) directions.

To isolate the converted Ps wave from the direct P wave, the ZRT components are rotated into an LQT (P-SV-SH) ray-based coordinate system, The L component is dominated by the P wave, while the Q and T components contain mainly the converted S wave energy. To eliminate the influence of the source and ray path, an equalization procedure is applied by deconvolving the Q and T component seismograms with the P signal on the L component (Sodoudi et al., 2004).

The resulting Q component data are named P receiver functions and are mainly composed of the P-to-S converted energy and contain information on the structure beneath a seismic station. The arrival time of the converted Ps phase in receiver functions depends on depth of the discontinuity, whereas the amplitude of the converted phase depends on the S-wave velocity contrast across the discontinuity. The converted Ps phase and crustal multiples (PpPs, PpSs and PsPs) contain a wealth of information concerning the average crustal properties such as the Moho depth and the Vp/Vs ratio.

The delay times of the primary converted Ps phase from the Moho and its crustal multiples can be used to determine the crustal thickness by a given average crustal P velocity. In presence of clear multiples, the Moho depth and Vp/Vs ratio can be computed using the stacking method of Zhu and Kanamori (2000).

This algorithm stacks the amplitudes of receiver functions at the predicted arrival time of the Moho conversion (Ps) and its multiples (PpPs and PpSs+PsPs) for various crustal thicknesses H and Vp/Vs ratios. The time domain receiver functions are then plotted by means of crustal thickness versus Vp/Vs ratio. Regarding the higher signal to noise ratio of the primary converted phase (Ps) in comparison to its multiples, amplitudes of phases are weighted and stacked using (5).

As an example, stacking 56 receiver functions for station MYA gives a crustal thickness of 42 km with a crustal Vp/Vs ratio of 1.75 (Figure2).

Station KRD has a total of 42 receiver functions. Crustal thickness under the station is estimated to be 45 km with a crustal Vp/Vs ratio of 1.81. The predicted Moho Ps arrival time agrees with the receiver function profile which shows a strong converted phase at 6 s following the direct P arrival. This phase has the expected increase of amplitude and time delay with ray parameter for a primary converted phase. (Figure3). The receiver function profile also shows clear Moho Ps phase. The 45 km represents an average crustal thickness near this station.

There are other apparently coherent phases after the Moho Ps in the above receiver function profiles. They could be generated by P-to-S conversions from some upper mantle discontinuities, or they might be the multiples of intracrustal conversions. In principle, these phases have different moveout with ray parameter from those of Moho PpPs and PpSs+PsPs so that their energy will not stacked coherently in s(H,k). However, the presence of these phase 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 Vp/Vs ratio from nearby stations or other sources can help to resolve the ambiguity.

Altogether, we obtained Vp/Vs ratio measurements of 6 stations. The other stations have very complicated site responses so that their receiver functions are overwhelmed by P-to-S conversions in the shallow crust. Most of these stations are located in sedimentary basins where the high-velocity contrast between the sediments and basement rocks and laterally varying, basin geometry generate large basin reverberations that mask the later Moho conversions. The final thickness and Vp/Vs ratio results, along with the corresponding Moho Ps arrival times, are listed in Table1. The crustal Vp/Vs ratio ranges from 1.66 to 1.81 with the average of 1.79 on average; the crustal thickness of Kope Dagh is 45 km on average. However, there is a wide range of values from 42 to 50 km. The results were then combined and showed Moho depth variation of Kope Dagh in Figure 4.

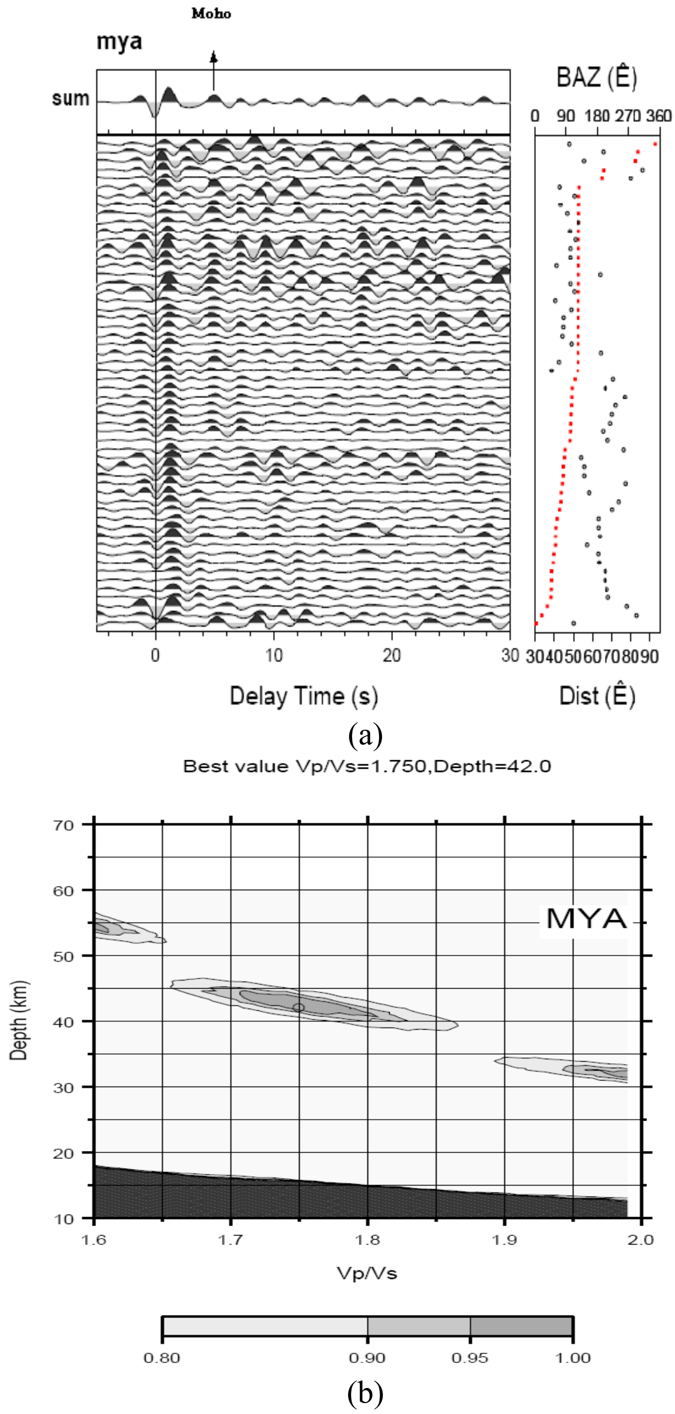
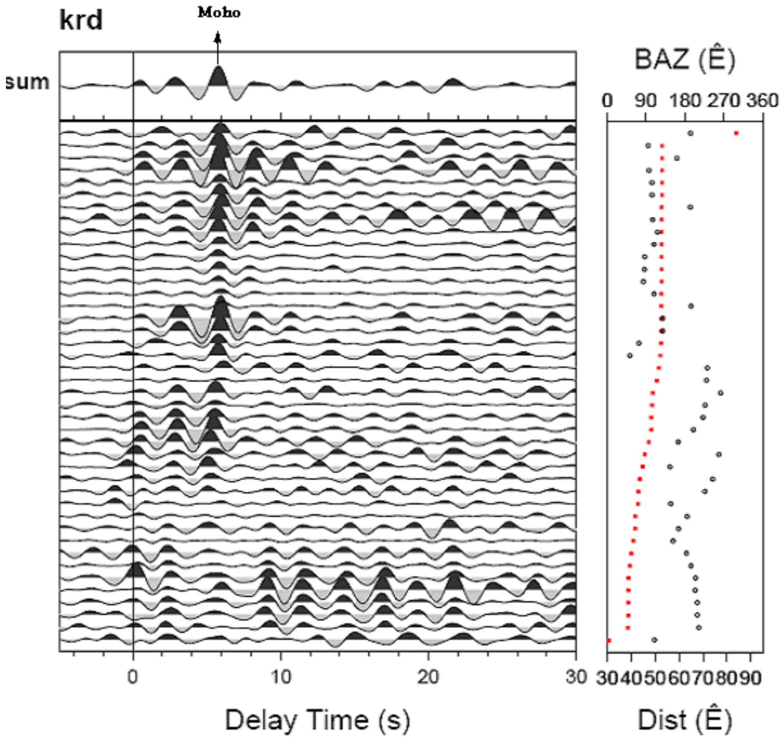


Figure 2. (a) Receiver functions of Moho converted phases by the estimated crustal thickness and V_p/V_s ratio in MYA station. (b) The Determination of Moho depth using Zhu & Kanamori (2000) method. The best estimate of the crustal thickness is 42 km with a V_p/V_s ratio of 1.75.



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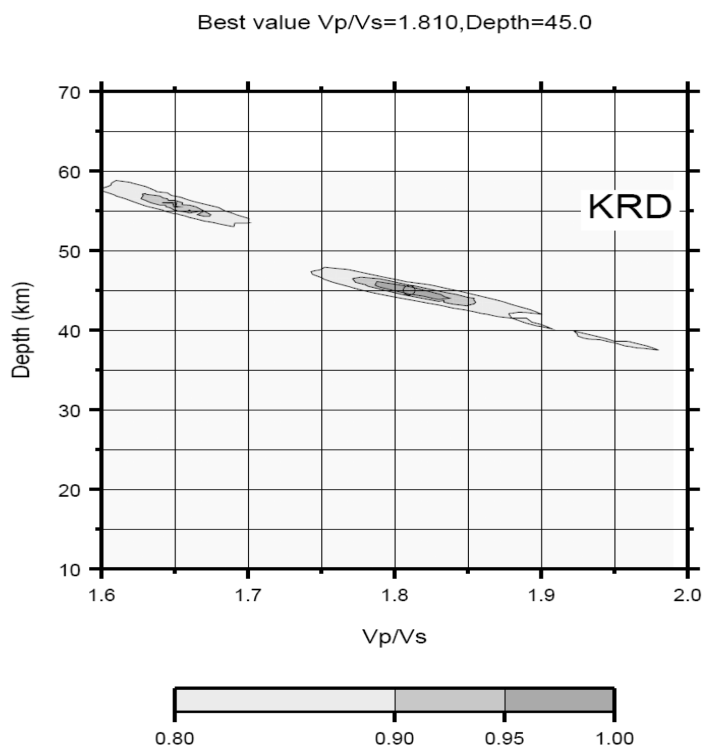

(b)

Figure 3. (a) Receiver functions of Moho converted phases by the estimated crustal thickness and V_p/V_s ratio in KRD station.(b) The Determination of Moho depth using Zhu & Kanamori (2000)method. The best estimate of the crustal thickness is 45 km with a V_p/V_s ratio of 1.81.

Table 1. Location of short-period stations and its values of Moho depth.

H, km	t_{Ps}, s	Elevation, m	Longitude	Latitude	Station
46	6.14	2565	58.6514	37.4097	EMG
47	6.17	1925	57.6950	37.5342	SHV
41	5.55	2448	58.0000	37.0436	SFR
43	5. 58	1150	59.4717	36.3083	MHI
45	6.12	2245	59.5201	36.7716	KRD
49	6.3	2100	58.996	36.45	PAY
42	5.41	1684	60.1021	36.3414	MYA
45	6.12	2577	59.3391	36.108	MOG

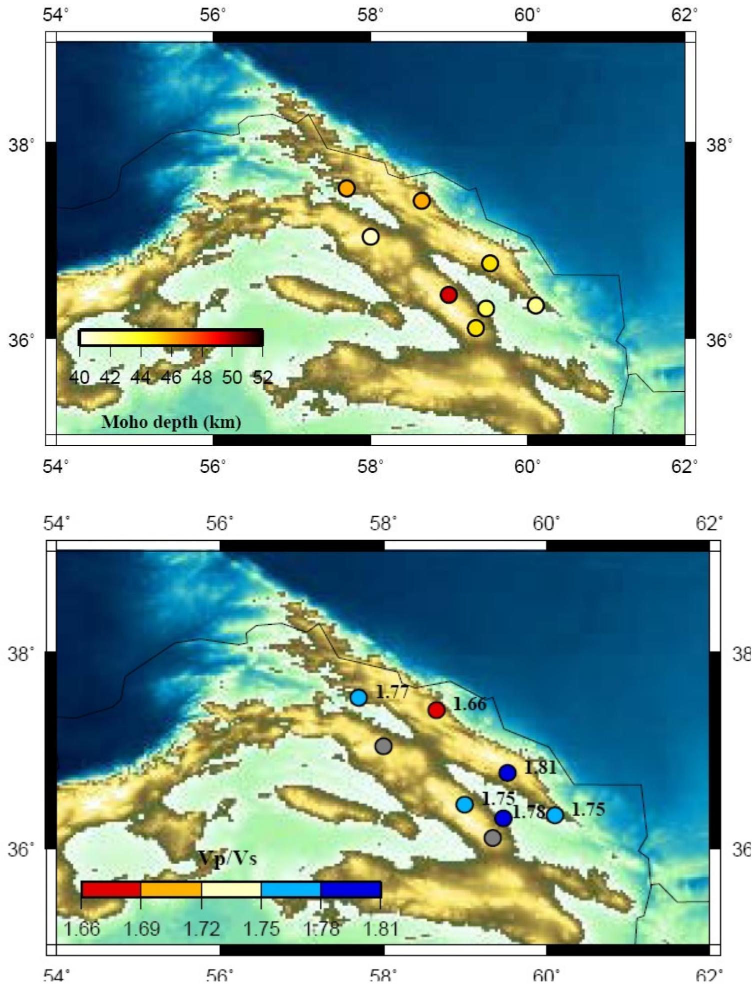

Figure 4. (Up) Moho depth variation in Kope Dagh region, (Down) Vp/Vs variations in Kope Dagh.

5 DISCUSSION AND CONCLUSIONS

As we have shown above, the largest uncertainty of crustal thickness estimation from teleseismic Moho P-to-S conversions is associated with crustal V_p/V_s ratio. Unfortunately, crustal V_p/V_s ratio is among the least constrained parameters from both laboratory and field measurements. It is thought tht the average composition of the continental crust is close to andesite or diorite (Anderson, 1989). Laboratory measurements of the Vp/Vs ratio of diorite at crustal pressures range from 1.75 to 1.79 (Carmicheal, 1982). Using Ps and PpPs arrival times on receiver functions, Zandt and Ammon (1995) estimated Poisson's ratios of diffrenet types of continental crust. The global average is 0.27 which corresponds to V_p/V_s ratio of 1.78. For the Mesozoic and Cenozoic belts they obtained a lower ratio (1.732) with large variations. In our study the average V_p/V_s ratio over all stations is 1.79 , which is close to their global average. We believe that these measurements from directly stacking receiver functions are more robust than the estimates derived from Ps and PpPs arrival times. The later phase, which has a longer path through the crust than the primary conversion and has one extra reflection on the surface, is sensitive to lateral structural variations such as a dipping Moho or surface topogeraphy. For example, a Moho dipping 5° can delay or advance the PpPs arrival by 2 to 3 s depending on updip or downdip propagation of the incoming wave. Our stacking algorithm using receiver function from different directions and distances helps to reduce the effect of lateral variation.

The estimated V_p/V_s ratios vary from 1.66 to 1.81 , and the spatial variation is coherent in general.

Our Moho depths agree with previous results. For example, crustal studies from analysis of teleseismic receiver functions by Nowrouzi et al. (2007) in north-east of central Iran and Binalud zone. Nowrouzi et al. (2007) estimated crustal thickness variation in Binaloud zone using teleseismic events recorded by the temporary broadband stations. The overall patterns in their result and ours are quite similar, despite the fact that these two results are from completely different data sets. The PmP technique relies on picking the PmP arrivals correctly and using a background P velocity model. The Moho depth trades off with lower crustal P velocity. On the other hand, the receiver function results mainly depend on the average crustal V_p/V_s ratio. The good agreement of these two results suggests that our estimates of crustal V_p/V_s ratio are appropriate.

In summary, we found that the receiver function technique is an effective way of determining Moho depth and crustal V_p/V_s ratio. It can provide a good point measurement under a short-period station and is not sensitive to crustal P velocity. Crustal thickness estimated only from the time delay of Moho Ps phase trades off strongly with crustal V_p/V_s ratio. The ambiguity can be reduced significantly by incorporating the later multiple converted phases. Applying a new stacking technique to 8 short-period stations in Kope Dagh shows that the Moho depth is approximately 45 km on average and varies between 41 and 49 km. Thick and thin crust are found under the southern and northern Rang , respectively. These results are in good agreement with the geology and tectonic setting of this region.

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