IMPROVED FOCAL DEPTH DETERMINATION FOR USE IN NUCLEAR-EXPLOSION MONITORING

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ABSTRACT

Seismic event location remains as one of the important discriminants for separating natural tectonic and explosive events. However, in order to be useful for discrimination purposes, the uncertainties associated with seismic locations must be well defined, and this has proven to be difficult to accomplish to the required degree of accuracy. In particular, high-confidence estimation of focal depths remains as an outstanding monitoring problem. Over the past several years, we have been pursuing a research program that is directed toward the development of improved detection and identification procedures for the depth phases pP and sP, as well as formulation of a new algorithm for computing more reliable confidence intervals on focal depth estimates determined from P-wave first arrival times. With regard to depth phase identification, we have investigated the utility of a fully automatic network stacking algorithm that maps the International Data Centre (IDC) post-P detection times at a station into candidate depth phases using the pP - P and sP - P delay times predicted by the IASPEI-91 travel-time tables for that epicentral distance and then combines the individual station results as a function of candidate source depth. This automatic algorithm has now been applied to data from about 150 Reviewed Event Bulletin (REB) events in the Hindu Kush and in the Hokkaido and central Honshu regions of Japan, as well as the region surrounding the Chinese Lop Nor test site. Prominent candidate pP and sP peaks have been identified in the resulting network detection stacks for a majority of these events, including some with mb values as low as 3.7 and depths as shallow as 20 km.

This algorithm has now been implemented in a software module that interacts directly with the standard IDC analyst review station (ARS) and is currently being delivered to the RDSS at the Center for Monitoring Research (CMR) for full-scale evaluation and testing. We have also begun to investigate the applicability of calibrated regional S - P arrival-time information to the estimation of independent event origin times for use as constraints in the hypocenter location process. Although the detailed nature of the trade-off between focal depth and origin time can be complex in practical applications to small events for which few data of limited azimuthal distribution may be available, an ability to independently constrain origin time can often lead to significantly improved focal depth estimates. In particular, differences between origin times determined from regional S - P times and the corresponding origin times determined from standard hypocenter location codes with focal depths constrained to zero can be used to infer focal depth bounds that are useful for event screening purposes. For this reason, we have been collecting regional seismic data recorded at selected International Monitoring System stations from samples of earthquakes with well determined focal depths located in the Hindu Kush and in the Hokkaido and central Honshu regions of Japan and are developing calibrated S - P travel-time relations for use in the determination of independent origin times. Preliminary results suggest that this approach can consistently identify, with a high degree of confidence, subcrustal events as being too deep to be explosions.

OBJECTIVES

The objectives of this research program are to determine more reliable estimates of the uncertainties associated with the different focal depth estimation procedures and to increase the number of events that can be identified as earthquakes on the basis of focal depth through the implementation of new and improved analysis tools. This is being accomplished through the development of improved procedures for identifying and using the teleseismic depth phases pP and sP, the incorporation of regional S-P based origin time constraints into an improved depth estimation algorithm, and the development of more robust statistical hypothesis tests for use in event screening. This effort includes the implementation and large-scale testing of these new algorithms on the Research and Development Support System (RDSS) at the CMR.

RESEARCH ACCOMPLISHED

During this initial year of the contract, the effort has focused on the continuation of the development of improved tools for the detection and identification of the depth phases pP and sP and on the preliminary evaluation of the use of calibrated regional S-P time intervals to constrain event origin times for use in focal depth determination. With regard to depth phase identification, we have been attempting to improve the frequency and reliability of the identification of the depth phases pP and sP through the use of network beam forming (Murphy *et al*, 2000). In our approach, post-P arrivals observed at each station for a given event are mapped from functions of delay times with respect to P to functions of source depth using the pP-P and sP-P delay times predicted by the IASPEI-91 travel-time tables for the various station distances. These functions of depth for all the stations in the detecting network are then added together to identify arrivals consistent with the predicted depth phase move-outs over the entire range of potential source depths. That is, the observed delay times of all post-P arrivals with respect to P are translated into equivalent focal depths under the hypothesis that they are either pP or sP arrivals. Those arrivals that are consistent with such hypotheses should then show up as peaks on a stacked network depth function. In the present application, difficulties associated with the variability of observed short-period signals between widely separated stations are avoided by stacking unit amplitude boxcar functions centered on the post-P detection times, which are automatically determined at each station by front end signal processing procedures. One advantage of this approach is that not only is it fully automatic, but it includes only signals that have triggered a detection, which should help to minimize the inclusion of questionable arrivals in the analysis. Figure 1 shows an example of the application of this algorithm to the automatic post-P detection times for the Hindu Kush earthquake of 1998/02/14. It can be seen that the network detection stack in this case shows a pronounced peak at a depth corresponding to the published REB depth for this event, indicating the presence of a good candidate pP phase that should be further reviewed by the analyst. This automatic algorithm has now been applied to data from over 200 REB events located in the Hindu Kush, Lop Nor, Hokkaido and central Honshu regions identified on the map of Figure 2. Prominent candidate pP and sP peaks have been identified in the resulting network detection stacks for a majority of these events, including some with mb values as low as 3.7 and depths as shallow as 20 km, indicating that this algorithm can provide the analyst with information useful for the confident identification of additional pP and sP phases.

In order to make this depth phase stacking procedure available for large-scale testing and further evaluation on the RDSS at the CMR, the algorithm described above has now been formally integrated into the Analyst Review Station (ARS) software employed at the IDC and US NDC. In this implementation, the analyst initiates a fully automatic process from the ARS that causes all of the post-P detection times for the current event to be recovered from the automatic detection files and passed to the depth phase stacking module, where they are converted into their corresponding depth traces, stacked, and presented back to the analyst in an X-Window display. This interactive interface to ARS is illustrated in Figure 3, which shows the pP, sP, and pP + sP depth phase stacks for the Lop Nor region earthquake of 1999/01/27. Note that the sum of the pP and sP stacks shows a pronounced candidate depth phase peak near the published REB depth of about 18 km for this earthquake. In this implementation, by clicking on this or any other candidate peak with the mouse, the analyst initiates a process by which the corresponding waveforms are brought up in the standard ARS display with the data time aligned on the predicted pP times corresponding to the selected trial depth. These data can then be further processed using the bandpass filter routine or any of the other signal processing algorithms available in the ARS. A sample of the resulting ARS display for this selected Lop Nor region earthquake is shown in Figure 4, where it can be seen that there are multiple candidate pP and sP arrivals at the arrival times predicted for that selected trial depth. Moreover, in this case the strong variation of the pP/P amplitude ratios over wide ranges in distance and azimuth permit the analyst to identify pP and sP arrivals with high confidence, thereby enabling this event to be confidently screened out as a natural earthquake.

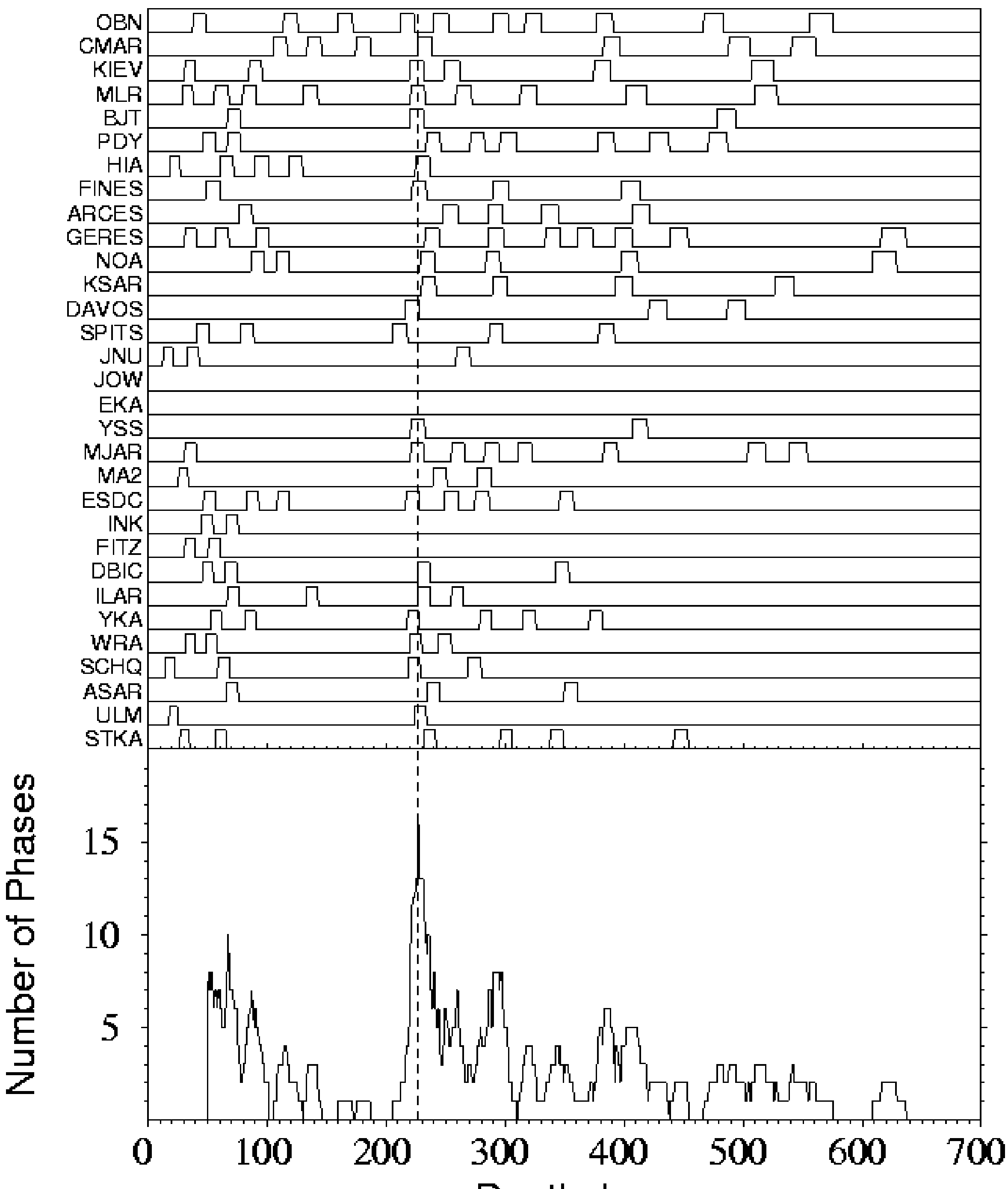

Figure 1. Network detection stack of pP for the Hindu Kush earthquake of 1998/02/14, m_b = 5.03. The dashed vertical line coincides with the REB depth estimate of 226 km.

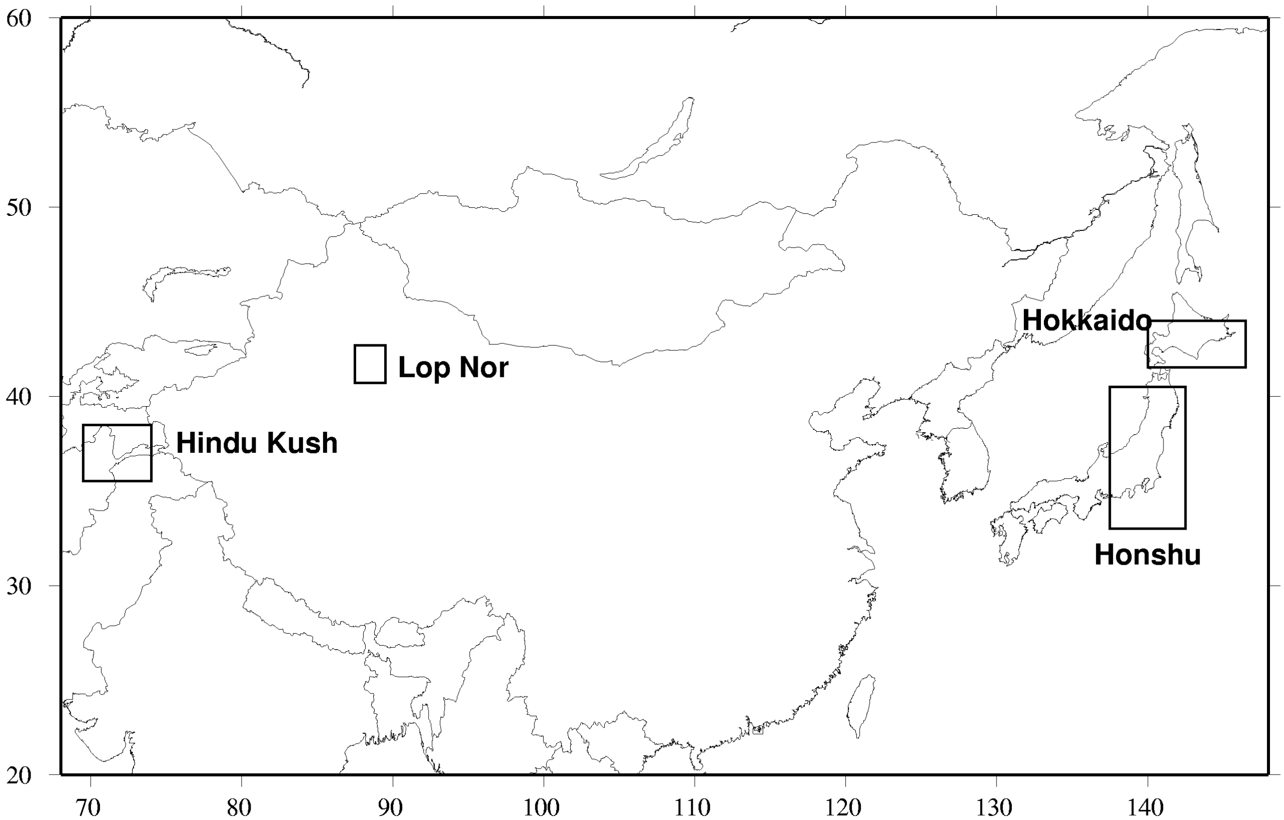

Figure 2. Map locations of the events in the Hindu Kush, Lop Nor, Hokkaido and central Honshu regions used in the evaluation of the depth phase stacking algorithm.

The utility of this RDSS implementation is currently being further tested in analyst review of data recorded from a large sample of Lop Nor region events.

We have also begun to investigate the applicability of calibrated regional S-P arrival time information to the estimation of independent event origin times for use as constraints in the hypocenter location process. It is well known that there exists a trade-off between focal depth and event origin time in the hypocenter location problem. Although the detailed nature of this trade-off can be complex in practical applications to small events for which few data of limited azimuthal distribution may be available, an ability to independently constrain the event origin time can nonetheless lead to significantly improved focal depth estimates. More specifically, if S-P differential time information is available from well-calibrated regional stations, it can be used to provide useful, independent estimates of the event origin time for use as constraints in the hypocenter location process. That is, if t_0 is the event origin time and t_P and t_S are the observed arrival times of P and S waves that have traveled essentially the same path to a station at distance Δ from the event, it follows that:

$$\begin{aligned} t_P &= t_0 + T_P(\Delta, h) \\ t_S &= t_0 + T_S(\Delta, h) \end{aligned} \qquad (1)$$

where h denotes the focal depth and T_P, T_S are the travel-time functions for P and S arrivals as a function of epicentral distance and focal depth. It follows that we can relate the origin time to the observed S-P time interval as

$$t_P - t_0 = \frac{1}{\left[\frac{T_S(\Delta,h)}{T_P(\Delta,h)} - 1\right]}(t_S - t_P) \qquad (2)$$

or

$$t_0 = t_P - \frac{1}{\left[\frac{T_S(\Delta,h)}{T_P(\Delta,h)} - 1\right]}(t_S - t_P) \qquad (3)$$

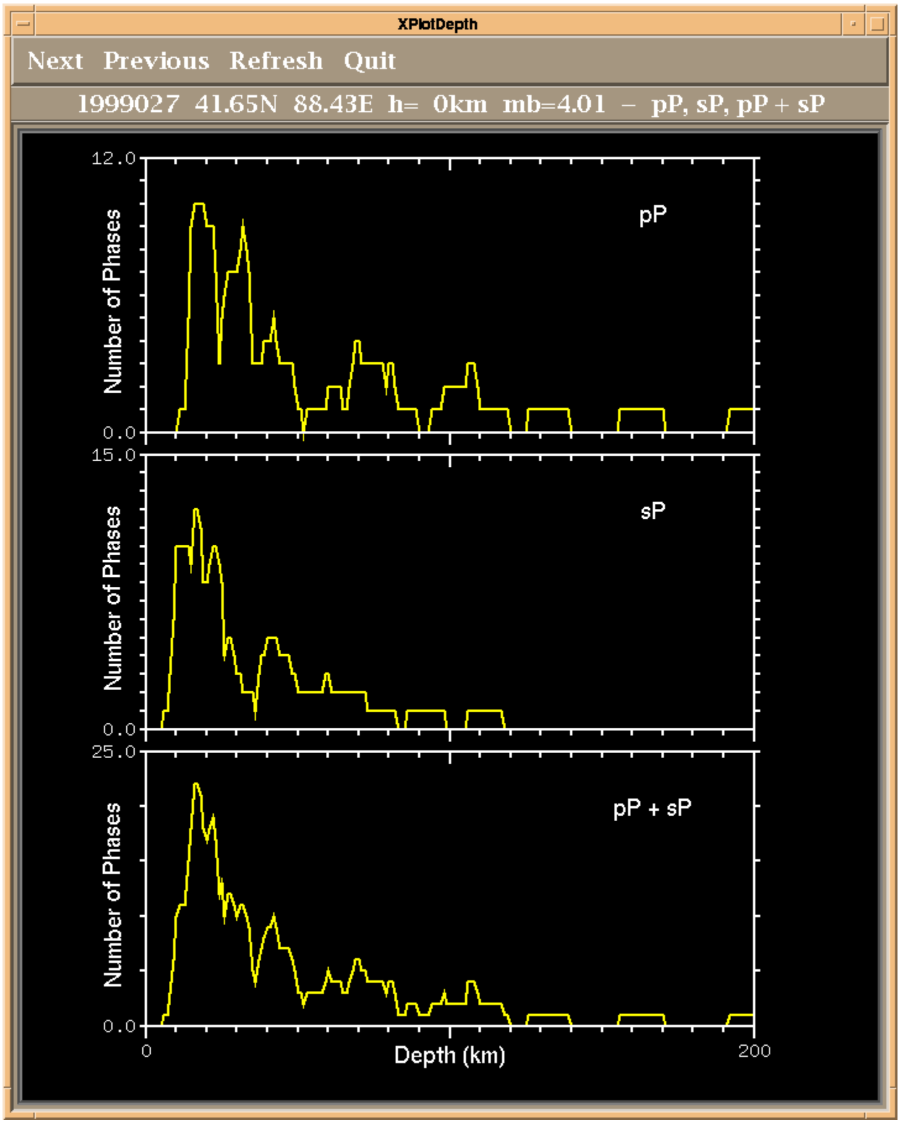

Figure 3. Network detection stacks of pP (top), sP(middle) and their sum (bottom) for the Lop Nor region earthquake of 1999/01/27.

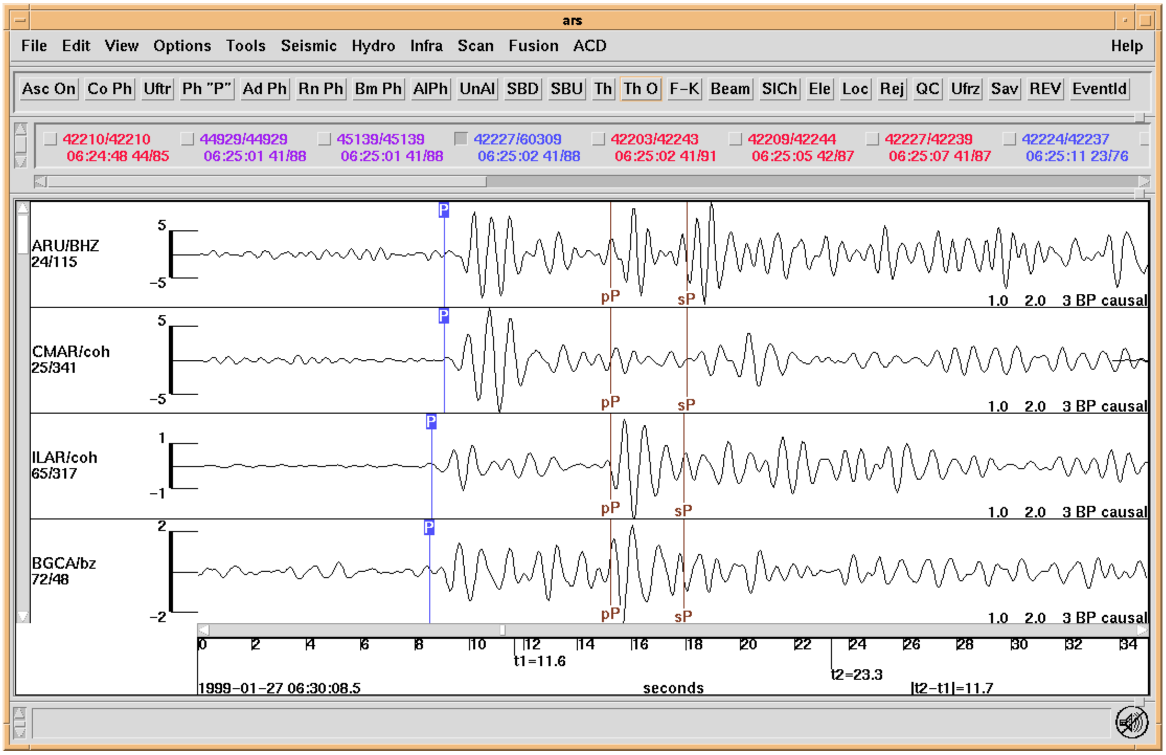

Figure 4. ARS Display of bandpass filtered waveforms for the Lop Nor region earthquake of 1999/01/27, shown time aligned on the predicted pP arrival times corresponding to the selected candidate depth (i.e. 18 km) from Figure 3.

Now, if the travel paths for the observed P and S arrivals are the same and the ratio of compressional (α) to shear (β) wave velocity along these paths is constant, independent of Δ and h, then (3) can be simplified to

$$t_0 = t_P - \frac{1}{\left[\frac{\alpha}{\beta} - 1\right]}(t_S - t_P) \qquad (4)$$

which is the relation originally proposed by Wadati some 75 years ago. It follows that if the average ratio α/β along paths to a selected regional station from events in a specified source region can be determined, then the event origin time can be estimated from observed P and S arrival times. Our focal depth hypothesis test is formulated by comparing this S-P-based origin time estimate, t_0(S-P), with the corresponding teleseismic-based origin time, $\tilde{t}_0\,(h = 0\text{ km})$, determined with the depth constrained to zero. Substantial differences in these two estimates provide evidence of significant focal depth. In particular, since from the IASPEI-91 tables $\tilde{t}_0\,(h = 10\text{ km}) - \tilde{t}_0\,(h = 0\text{ km}) \approx$ 1.5 seconds and the measured variability of $t_0\,(\text{S} - \text{P}) - \tilde{t}_0\,(h = 0\text{ km})$ for well-located events recorded at calibrated regional stations is on the order of ± 3.5 seconds, we have assumed for preliminary analysis purposes that differences of $t_0\,(\text{S} - \text{P}) - \tilde{t}_0\,(h = 0\text{ km})$ greater than about 5 seconds provide high confidence that the event depth is greater than 10 km and, consequently, that the event can be confidently screened out as a natural earthquake source.

We are currently evaluating this hypothesis test using regional data recorded from events in the four source regions of Figure 2 for which the event depths have been well constrained by validated depth phase observations. For this application, P and S arrival times were determined at selected regional stations for well located events and the resulting $t_P - t_0$ and $t_S - t_P$ time intervals were used to evaluate the calibration constant in equation (2), where t_0 denotes the origin time from the well constrained hypocenter solution. Origin times for events recorded at each calibrated station were then estimated from observed $t_S - t_P$ intervals and compared with corresponding constrained teleseismic origin time estimates, $\tilde{t}_0\,(h = 0\text{ km})$, to test for significant focal depth. This process is illustrated for a sample of Honshu events recorded at station MJAR in Figure 5, where the determination of the calibration constant (left) and its application in a focal depth hypothesis test (right) are shown. It can be seen that, in this case, almost <u>all</u> the events with validated focal depths of greater than 50 km can be screened out as being too deep to be explosions with high confidence. The dashed line in the right-hand panel of this figure denotes the value of $\tilde{t}_0\,(h) - \tilde{t}_0\,(h = 0\text{ km})$ predicted as a function of focal depth by the teleseismic IASPEI-91 travel-time values, and it can be seen that the observed data show some systematic deviations from this relation that may indicate variations in the regional station calibration constant as a function of epicentral distance and focal depth that will need to be further evaluated. In any case, this hypothesis test clearly shows promise for applications to event screening on the basis of focal depth.

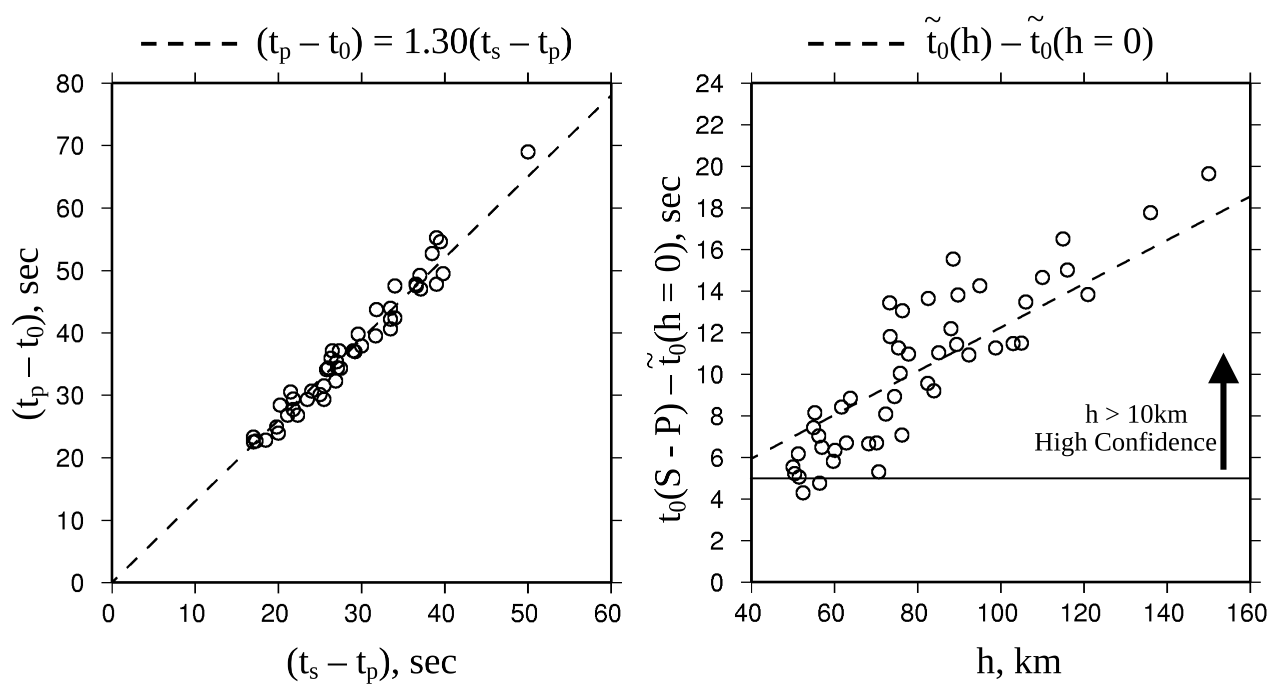

Figure 5. Application of the S-P origin time hypothesis test to data recorded at regional station MJAR from selected Honshu earthquakes. The left panel illustrates the estimation of the regional station calibration constant, while the right panel shows the results of the hypothesis test as a function of focal depth for a sample of well-located events.

CONCLUSIONS AND RECOMMENDATIONS

The first year of a three-year research investigation directed toward the development of improved focal depth estimates for use in event screening has now been completed. A principal result of this investigation has been the formulation and testing of an automated procedure for stacking raw P wave detection data to identify candidate pP and sP depth phases for further review by the analyst. This algorithm has now been formally integrated into the Analyst Review Station (ARS) software employed at the IDC and US NDC and delivered to the RDSS at the CMR for further evaluation and large-scale testing. Work was also initiated on the formulation of a depth hypothesis test based on the application of calibrated regional S-P time intervals to constrain event origin time. Preliminary applications of this test to selected well located events in the Hindu Kush and Honshu source regions have indicated that it shows promise for use in event screening.

REFERENCE

Murphy, J. R., R. W. Cook, and W. L. Rodi (2000), Improved Focal Depth Determination for Use in Seismic Monitoring of Underground Nuclear Explosions, *Maxwell Technologies Final Report* MSD-DFR-00-16621.