NORSAR

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6.3 Observed and predicted travel times of Pn and P phases recorded at NORSAR from regional events

6.3.1 Objective

The principal objective of this study is to estimate the absolute travel-time path anomalies of regional seismic phases observed at the Norwegian Seismic Array (NORSAR) with respect to the Earth model AK135 (Kennett et al., 1995) and to determine their relationship to the Earth's three-dimensional (3D) structure.

6.3.2 Reference event phase data

Over the operational period of the NORSAR array (1971-present), phase arrival times for earthquakes and explosions worldwide have been routinely reported to international agencies by NORSAR. These onset time readings were made at different reference sites and sometimes different station codes due to array geometry changes over time, temporary outages of array components, and the installation of the regional array NORES at one of NORSAR's subarray sites. However, since NORSAR first began reporting phase data in 1971, these reports were made primarily from only three reference points (NAO, NOA and NRA0) and most of these phase data are available in a computer accessible form. We associate these NORSAR archived phase reports with a reference event database comprised of explosions and well-constrained earthquakes with global coverage that has been independently assembled by Engdahl (cf., Bondar et al., 2004) and with events at regional distances from NORSAR that are well located by local and regional stations (Hicks et al., 2004). The events in this combined reference event database are usually well recorded at regional and teleseismic distances and the absolute locations and origin times are known to higher accuracy than is typical of even the best global earthquake catalogue. There are currently 1905 events in the global data set, including 1234 explosions with locations known to 2 km or better and 671 earthquakes believed to be accurate to 5 km or better. In this report we will focus on events in the combined database that are within the regional distance range from NORSAR. The process of associating phase arrival times reported by NORSAR with this database required several data preparation tasks:

(1) a phase association script was tested and implemented with the combined regional reference event database (nearly all the events had one or more NORSAR phase reports);
(2) a program was developed to convert the output of the phase association program to a format that could be used as input to the EHB location program (Engdahl et al., 1998), and
(3) the EHB location program was used to convert phase data from each of the NORSAR reference points to residual data (with respect to the model AK135) for the corresponding events in the reference event database.

6.3.3 Event and array clusters

The reference event database contains a number of events globally that are clustered within areas of radius no larger than 100 km. These clustered events in the global database have been validated using the method of Hypocentroidal Decomposition (HDC, Jordan & Sverdrup, 1981) for multiple event relocation. The basic premise of this method is that path anomalies from each station to all observed events in a given cluster are correlated. Thus, multiple event location analysis can produce robust estimates of source-station path anomalies that are far more difficult to extract from single event location catalogs. The set of residuals for Pn and P phases observed at NORSAR relative to absolute hypocenter estimates derived by HDC cluster analysis is used to calculate phase path anomalies at all distance ranges. These anomalies are estimated relative to the 1D reference model AK135. Medians and spreads of groomed residuals for each cluster are calculated for the phases of interest (here primarily P and Pn) at each of the NORSAR reference stations reporting phase arrivals for that cluster. The resulting source-station "empirical phase path anomalies" (the median) are accepted with a minimum requirement of five observations and a spread of <1.40 s for P-type phases (the spread is a robust analog to the standard deviation). The correlation of median phase residuals observed at the NORSAR reference points NAO and NRA0 with respect to NOA for the same event cluster is plotted in Fig. 6.3.1. In spite of some scatter, largely produced by the effect of differences in local structure beneath the array reference points, the correlation is quite good. Hence, for the purposes of this study, cluster medians or single event residual data could be treated as coming from a single NORSAR cluster of reference points, nominally centered at the reference point with the most observations (NOA).

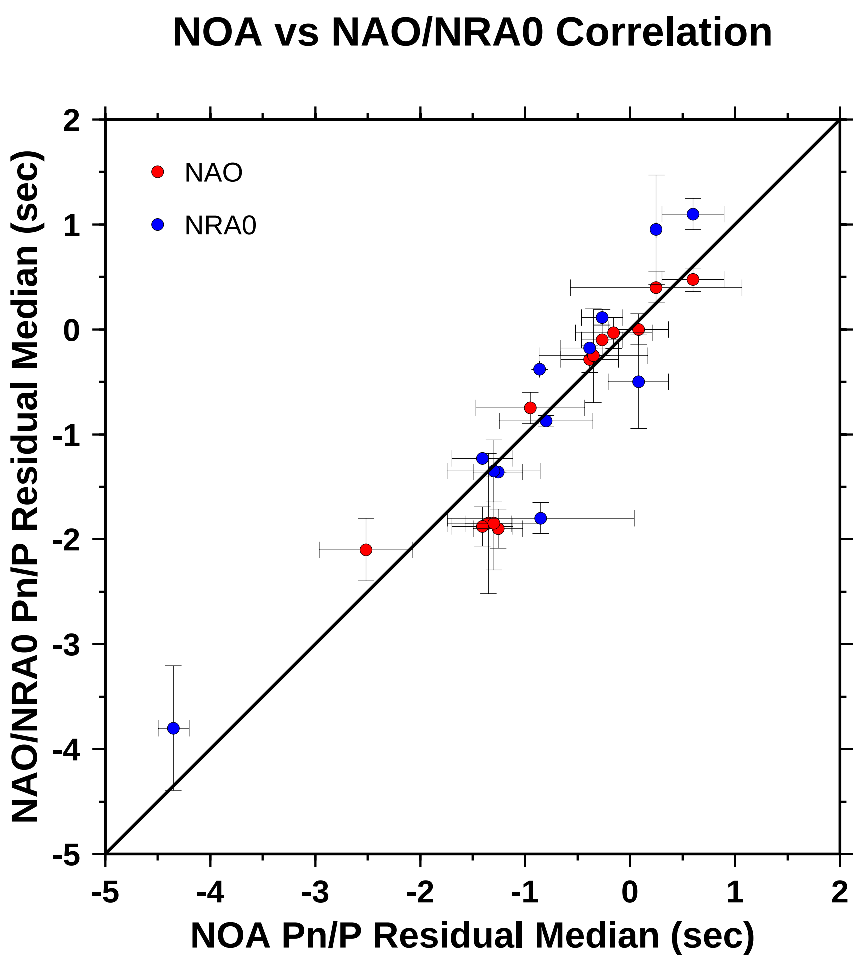

Fig. 6.3.1. Median residual and spread for the phases Pn and P observed from common clusters at the reference points NAO and NRA0 plotted with respect to the corresponding median residual at reference point NOA.

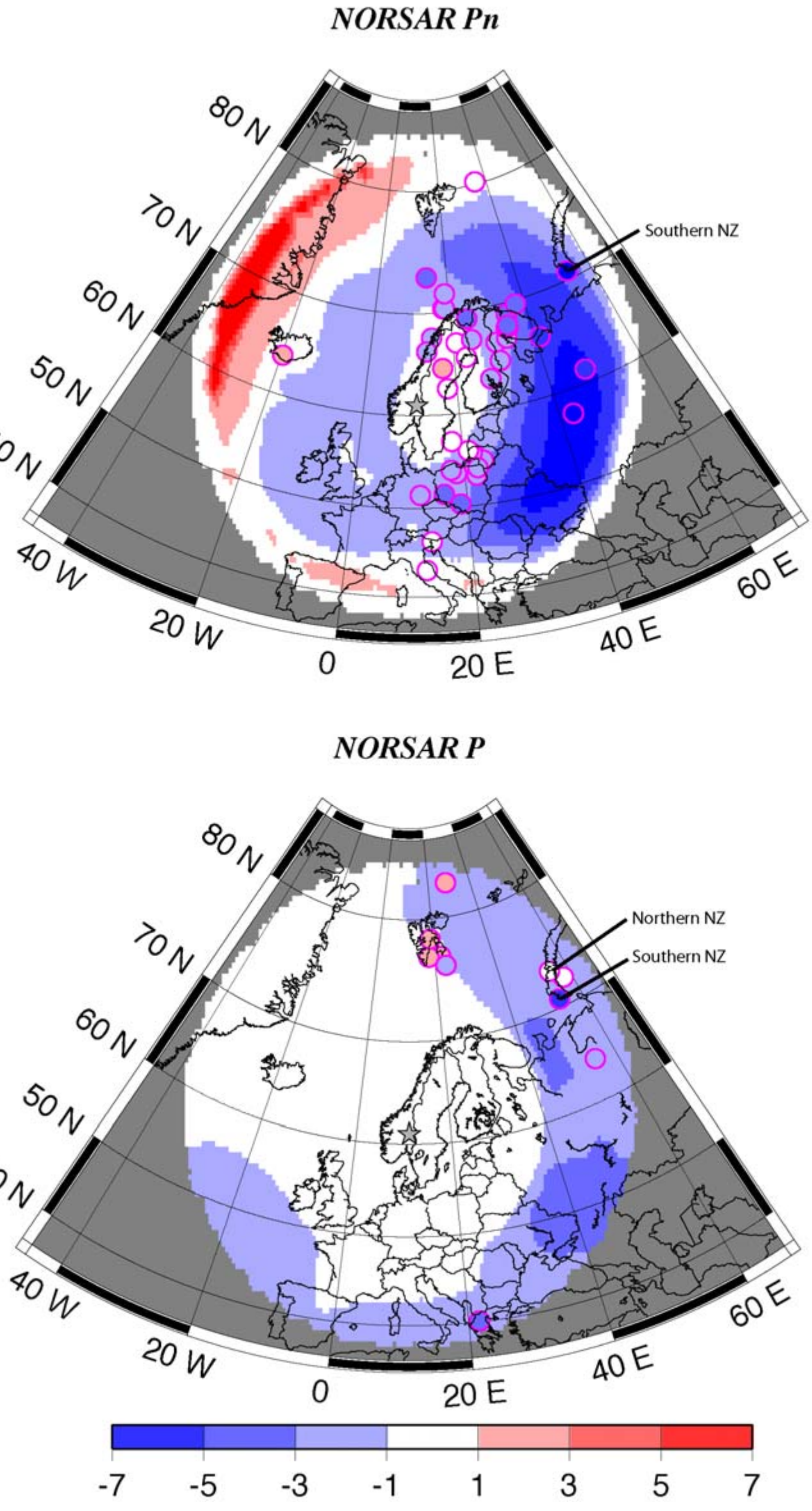

Fig. 6.3.2. Predicted travel time anomalies with respect to AK135 for (a) Pn and (b) P phases centered on the NORSAR reference point NOA and computed for event sources at a depth of 10 km. Bar at the bottom is color coded by the size of predicted anomalies. Observed Pn and P empirical path anomalies are shown as filled circles on the same color scale for qualitative comparison. Path anomalies at the northern and southern Novaya Zemlya test sites are also indicated.

6.3.4 3-D model predictions

Fig. 6.3.2 presents travel time correction surfaces for Pn and P (with respect to the 1D model AK135) for events centered on the NORSAR reference point NOA that was produced using a three-dimensional crust and upper mantle Earth model (CUB) developed by the University of Colorado (Ritzwoller, et al., 2003). This 3D model, based on broadband surface wave group and phase speed measurements, is a Vs model that has been converted to Vp using the thermoelastic properties of an assumed mantle composition. These travel time surfaces depict the predicted travel times from events at a depth of 10 km on a grid of epicentral locations observed at NORSAR and are presented relative to the travel time predicted from the 1D model AK135. For qualitative comparison observed empirical path anomalies for shallow crustal events at regional distances are also plotted. A quantitative comparison is shown in Fig. 6.3.3 where predicted time anomalies for events that could be successfully traced through the CUB model are plotted against observed anomalies. The bounding lines (+/- 2 sec) define the normal range of data based on uncertainties in the 3D model. Later observed P anomalies (near 2 sec) are from shallow focus events near Svalbard where there exists a thick, slower velocity, upper crust not included in the CUB model. The northern and southern Novaya Zemlya (NZ) data points are discussed below.

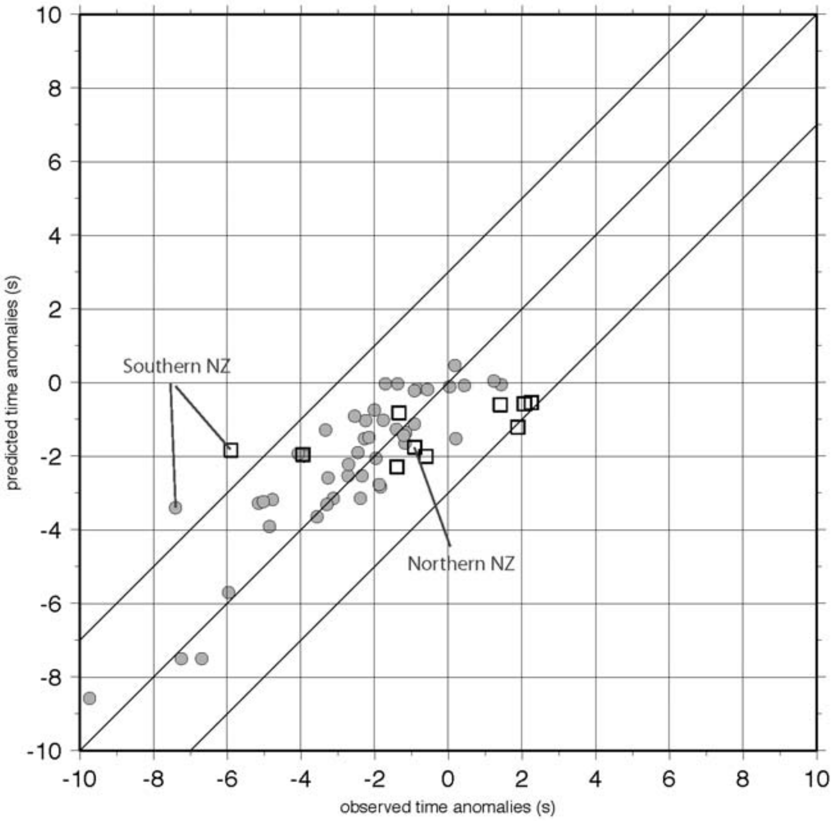

Fig. 6.3.3. Time anomalies for Pn (solid circles) and P (open squares) phases observed at NORSAR plotted with respect to time anomalies predicted by ray tracing through the CUB 3D model. Bounding lines indicate the range (+/- 2 sec) in anomalies that can be a result of uncertainties in the model. P anomaly data for northern Novaya Zemlya test site and Pn and P data for southern test site are also shown.

6.3.5 Discussion

At least with respect to the large-scale features of the correction surfaces, the agreement between the empirical path anomalies and the model-predicted travel times is quite good.

The observed and predicted regional anomalies show strong differences in the P and Pn anomalies observed between explosion source areas in northern and southern Novaya Zemlya, apparently produced by a sharp structural boundary that strongly affects ray paths to NORSAR from these sources. The separation distance between these source areas is on the order of only 300 km, yet the P and Pn median travel time anomalies observed at NORSAR at a distance of about 20 degrees differ by more than 5 seconds (see Fig. 6.3.3). A Pn arrival from the northern Novaya Zemlya source is not predicted by the 3D model while on the other hand the southern source could be interpreted as either a Pn or P phase arrival as shown in Fig. 6.3.3.

These differences between the two Novaya Zemlya sources are also reflected in typical waveforms observed at NORSAR from these test areas (Fig. 6.3.4). The top figure shows a simple Pn waveform observed at NORSAR from the northern test site. The bottom figure, observed at NORSAR from the southern test site, shows a more complex waveform. Ray tracing suggests that for the southern source the first arrival is a Pn wave that has penetrated deeper into the fast lithosphere (a diving ray path) whereas the second arrival is most likely the P wave. The 3D model resolution is only on the order of 400-500 km, so that it is difficult to model these anomalous arrivals without the rays from these source regions encountering a sharper boundary than that presently shown by travel time predictions of the CUB model (see Fig. 6.3.2).

6.3.6 Conclusions

1. For the purposes of this study, residual data from NORSAR reference points can be treated as a single median station cluster residual centered on NOA for single events or event clusters.
2. In the regional distance range P and Pn single event or median cluster residuals generally agree quite well with travel time residuals predicted by the CUB 3D model.
3. There is more than a 5 sec difference in the P median residual observed at NORSAR from the northern Novaya Zemlya test site with respect to the Pn (or P) residual observed from the southern test site, although the separation distance of these test sites is only about 300 km. Residuals predicted by the CUB 3D model, which displays a structural boundary between ray paths from the two test sites to NORSAR partially explains these observations, but a sharper boundary is called for.

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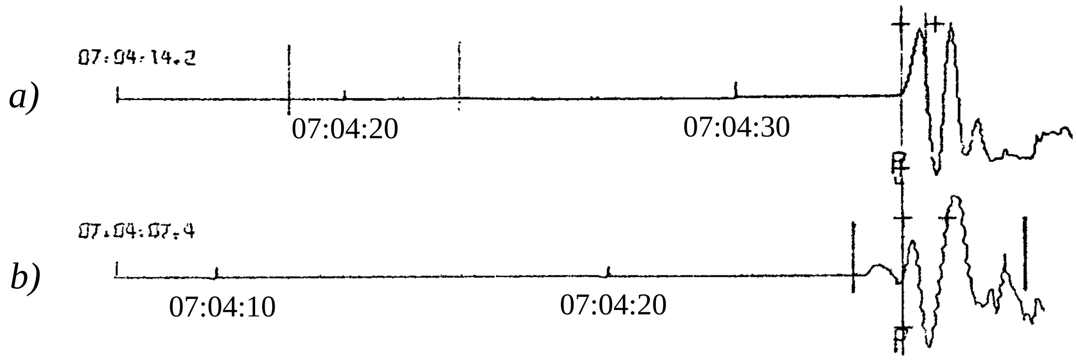

Fig. 6.3.4. NORSAR (NOA) waveforms from events in the (a) northern and (b) southern Novaya Zemlya test sites. Shown are the whole NORSAR array beams as analyzed and plotted on 12 September 1973 (a) and 27 October 1973 (b) in original size. The data were filtered with 3rd order Butterworth band pass filters between 1.4 and 3.4 Hz (a) and between 1.2 and 3.2 Hz (b). Time scale is indicated.

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