A THREE-DIMENSIONAL MODEL OF SEISMIC VELOCITIES BENEATH NORTHERN CHILE FROM LOCAL EARTHQUAKE TOMOGRAPHY

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INTRODUCTION

In the last two decades, structural information about the deep interior of the earth in local, regional and global scale has been drawn extensively from travel-time tomography experiments. Depending on the kind of station network used, two- or three-dimensional (2- or 3-D) models of the p- and s-wave velocity structure are obtained. Tomographic models are in most cases calcutated as deviations to an a priori one-dimensional (1-D) reference model. Thus the method is particularly useful for imaging extended lateral inhomogeneties. Velocity anomalies are mainly caused by differences in density and aggregate state of rocks, both influenced by temperature and pressure. The Cental Andes are, due to the plate collision, characterized by various geophyical anomalies. One of them is the huge amount of seismic activity on and within the subducting plate, making it possible and attractive to apply local earthquake tomography.

METHOD

In geophysical investigations the physical properties of a targeted volume are often not directly measurable. One has to observe the effects at the surface and calculate back or invert for these properties, in order to get a model of their distribution in space beginning with simple approximations. In travel-time tomography the differences in arival times of earthquake-generated seismic waves at seismometer stations form the set of observed data. Deviations of seismic velocities at discrete points in space with respect to a starting model are the model parameters to invert for. In case of local earthquake tomography the hypocentral coordinates depend on the velocity structure and thus belong to the unknown (model-) parameters too. The linearized hypocenter-velocity-inverse problem is generally ill-posed (or mixed-determined) and according to Levenberg-Marquardt solved iteratively using the damped least squares (DLSQ) technique. The linearization by a Taylor series expandation requires a proper a priori model. Kissling et al. (1994) demonstrated, that the so called minimum 1-D model, which is itself a DLSQ solution of a simultaneous 1-D inversion, is well suited for routine earthquake locations in comparison to estimated 1-D models and gives much more accurate results when used as starting model in the 3-D inversion. The 3-D inversion procedure is performed by the routine SIMULPS12 (Evans, Eberhart-Phillips & Thurber, 1994). The parametrization of the 3-D model is given by nodal planes in x-, y- and z-direction. Velocities are interpolated between the points of intersection. Distances between these planes depend on the station network characteristcs, on the amount and spatial distribution of events and on the dimensions of structural features wished to be resolved. Toomey and Foulger (1989) pointed out the importance of properly considering both model resolution and model fidelity to avoid poorly resolved model parameters as well as spatial aliasing caused by a sparse parametrization. Tests with artificial data, various subsets of data and various model parametrizations are carried out to refine the final 3-D velocity model and to unmask possible artifacts.

TARGETS OF THE TOMOGRAPHIC INVESTIGATION

The Chilan part of the Central Andes offers very good conditions for a temporary seismological experiment, including local earthquake tomography, with respect to the quantity and quality of data and the existence of targets of special interest. Like other regions of plate collision and subduction, it shows a characteristic distribution of seismic activity. A large number of earthquakes occur at the contact zone of the Nazca plate and the continental plate as well as within the subducting Nazca plate down to more than 600 km depth. Due to fast (> 9cm/a) and moderatly steep subduction, the subducted oceanic plate remains colder as the surrounding material. This thermal anomaly should be expressed in a positive velocity anomaly close to the Wadati-Benioff zone, as similar studies in other subduction zones found out. Related to the subduction is the existence of the volcanic arcs. The recent volcanic arc (Western Cordillera) is characterised by an increased heat flow density, a volume of high electric conductivity, a short wavelength gravity minimum (Götze et al., 1994) and a zone of anomalous high attenuation. These anomalies evaluated together are an indication for a volume of partial melted rocks, which is usualy outlined by lower seismic velocities. The crustal seismic activity is much smaller and could not be mapped previously due to the lack of strong earthquakes.

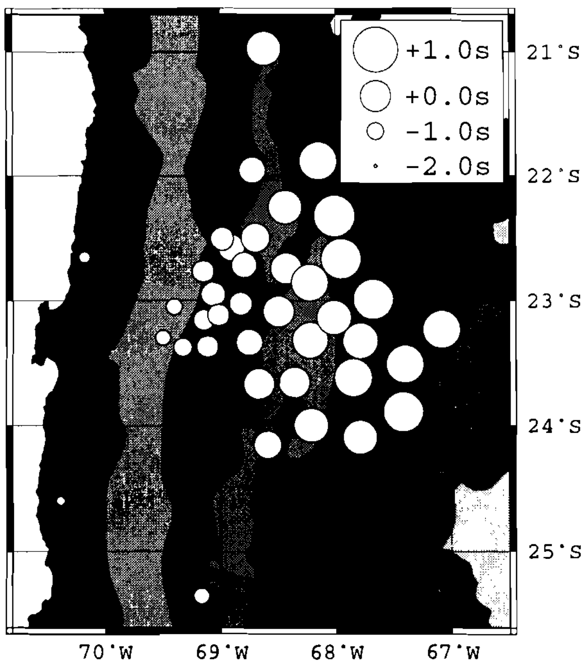

Fig. 1
The PISCO'94 and CALAMA'94 network stations drawn with circle sizes according to their average travel-time residuals from 1-D inversion

DATA FROM THE PISCO'94 EXPERIMENT

This study takes advantage of the dense and sensible seismological network of the PISCO'94 (Projecto de Investigacion Sismologica de la Cordillera Occidental) experiment, which was operated from January to May in 1994 as part of the Collaborative Research Center 267 "Deformation processes in the Andes" between 21°S to 25°S and 67°W to 70°W (Fig. 1). It combines active and passive seismological measurements. Continuous digital registration of the network stations with 100 samples per second guaranteed a high level of data quality and quantity. The arid climate, caused by the cold Humbold current, and the very low population density promote low noise registrations. Thus a few hundred crustal events of lower magnitudes, including natural earthquakes, mining blasts and shots, and about 5000 earthquakes within the subducting plate could be observed in a 100 days period. Additional data from the temporary seismological network CALAMA, which was operated in April 1994 by the Universidad de Chile, Santiago, is available thanks to a data exchange. Two subsets of high quality data were selected for the inversion procedures: 450 events with more than 10000 p- and s-wave readings for the 1-D inversion and 930 events with more than 20000 p- and s-wave readings for the 3-D inversion.

RESULTS OF THE 1-D AND 3-D INVERSIONS

The obtained minumum 1-D model with average station residual reflects the extremely thickened crust in the Central Andes. Typical subcrustal velocities of nearly 8 km/s are reached only beneath 70 km depth. Normal upper crust and middle crust velocities can be seen down to 40 km depth and rather high lower crust velocities between 40 km and 70 km depth. The station residual pattern shows a strong trend to higher velocities from the Western Cordillera towards the trench, which might be caused by the thinning of the crust in this direction and/or fast waves, that are propagating along the cold subducting plate. The station residuals are consistent within the morphostructural units.

The Volume of acceptable model resolution in 3-D is described by the resolution matrix and several tests and is, as expected, limited to the crust and mantle beneath the denser part of the network and above the Wadati-Benioff zone. The minimum horizontal and vertical seperation of nodes is 25 km and 10 km, respectively. Horizontal and vertical sections through the actual 3-D model outline four prominent anomalies:

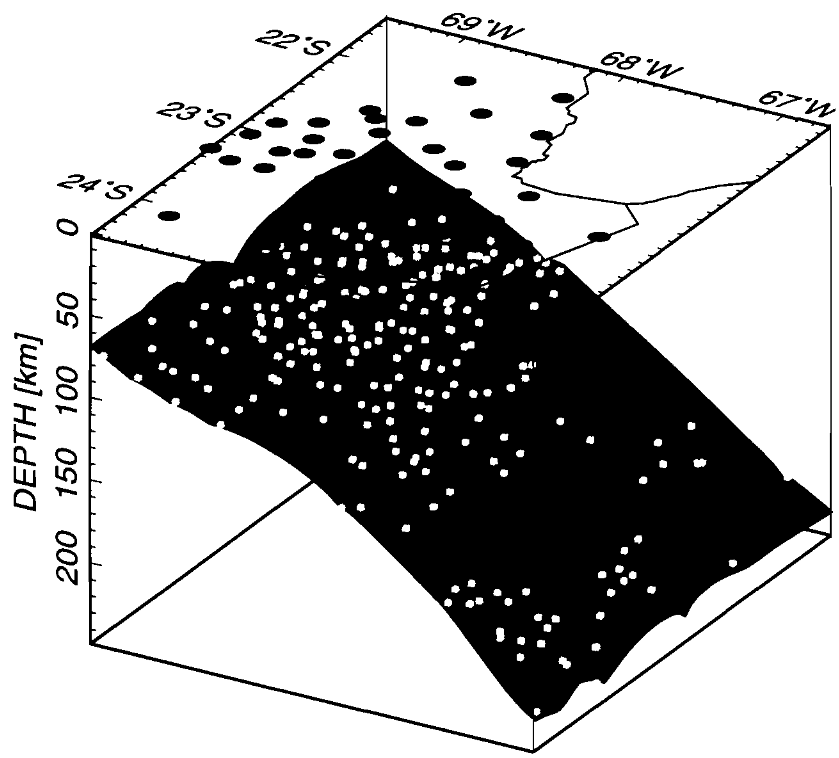

Fig. 2
The top surface of the Wadati-Benioff zone as given by interpolation through the uppermost slab earthquakes of a subset of high quality data

- -1- A narrow zone of lower velocities following the western edge of the recent magmatic arc down to about 65 km, considering previous studies interpreted as partial melts
- -2- A layer with moderately lower velocities beneath the Precordillera, eventually a remnant of the last period of volcanic activities
- -3- High velocities related to the Wadati-Benioff zone, interpreted as cold oceanic lithosphere
- -4- A body of high velocities beneath the Salar de Atacama next to a local short wavelength gravity maximum

Less prominent anomalies have to be discussed in detail. A comparison with 2-D models from the controlled source measurements of the PISCO'94 experiment might support some of them.

The high quality slab earthquakes relocated in the 3-D inversion procedure contract the top of the seismic activity to a clearly shaped plane. Fig. 2 shows an interpolated plane through the uppermost slab earthquakes in each 1/8° sector. At about 68°W the Wadati-Benioff zone becomes slightly steeper towards the east.

CONCLUSIONS

Especially when the complexity of the true crustal structure limits the interpretation of one- and two-dimensional methods, the obtained tomographic images, though they have to be interpretated very carfully as artifacts might remain undiscovered, offer important 3-D structural information in crustal scale. On the other hand, tomographic results can hardly be evaluated without additional information from other studies. The coordinated studies of different geoscientific disciplines within the Collaborative Research Center 267 "Deformation processes in the Andes" offer the possibility of a compilation of all the different kind of geophysical, geological and petrological data available and will lead to a refined model of the anomalous crust and upper mantle in the area of investigation.

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