THE NATURE OF INTERMEDIATE-DEPTH SEISMICITY IN THE CENTRAL ANDES

Peter GIESE[(1)] and Günther ASCH[(2)]

(1) Geophysical Department, Freie Universität Berlin, Malteserstr. 74-100, D 12249 Berlin, Germany
(2) GeoForschungsZentrum Potsdam, Telegrafenberg, D 14473 Potsdam, Germany

KEY WORDS: Central Andes, intermediate-depth seismicity, phase transformations

INTRODUCTION

Intermediate-depth seismicity is a very typical feature along subduction zones. The detailed shape of this seismic zone may differ from region to region, but there exists some common characteristics. In this contribution the nature of the intermediate depth seismicity is discussed comparing the situation along the converging zones of the Andean belt and in the Japan and the Kuril-Kamchatka arc system. In both regions the intermediate-depth seismicity is localised in the oceanic crust and in the uppermost mantle as well. Therefore the seismicity must be related to two different metastable phase transformations that are associated with the emission of seismic energy. The different shape of the seismic active zone is mainly dictated by the different converging rates, about 1 cm/a along the Japan and the Kuril-Kamchatka arc system and 10 cm/a for the Andean arc.

THERMAL STRUCTURE OF THE DOWNGOING SLAB

For the study of the metastable phase transformations that are going on in the descending slab, the knowledge of the temperature field in the downgoing slab is of importance. The main parameters controlling the temperature distribution are: the rate of subduction; the age, thickness and dip of the descending slab, frictional heating along the shear plane between the upper and lower plate, the conduction of heat into the slab from the deeper lithosphere and asthenosphere, and the heating of the top of the slab caused by the induced convecting corner flow in the upper plate.

A simple method for an approximate steady-state temperature calculation has been proposed by MOLNAR and ENGLAND (1990) and PEACOCK (1993).Here the method proposed by PEACOCK (1993) has been applied and extended for a depth depending shear stress and variable dip angle. In addition heating of the top of the slab by the induced corner flow has been taken into consideration.

For the following considerations two temperature gradient zones are of importance. In the upper zone, mainly situated in the oceanic crust immediately beneath the shear plane between the upper and lower plate, the temperature decreases with depth. The lower gradient zone in the uppermost oceanic mantle shows a positive temperature gradient. The width of the resulting temperature inversion is strongly controlled by the convergence rate. A low convergence rate of about 1-2 cm/a is associated with an inversion zone of some ten kilometre width, as it is observed in the Japan and the Kuril-Kamchatka arc. A high convergence rate of about 10 cm/a causes an inversion zone of only few tens kilometres thickness, as it is the case along the Central Andean subduction zone.

METASSTABLE PROCESSES IN THE DOWNGOING SLAB

The upper 8-10 km of the downgoing slab is composed of basaltic and gabbroic rocks forming the oceanic crust. The underlying oceanic mantle is made up by peridotitic rocks with olivine and pyroxene as main components. Therefore two different metastable processes must be considered for the explanation of intermediate-depth seismicity.

The metamorphic evolution of the subducted oceanic crust can be described by calculated P-T-paths and a model of metabasalt phase transformation (PEACOCK 1993). Fig. 1 presents the corresponding phase diagram. In steady-state subduction zones with moderate to low rates of frictional heating and a dip of 20°-30° most of the subducted oceanic crust moves along the low-T and high-P path from the blueschist into eclogite field in the depth interval 70-120 km.. This path is associated with the release of a relative large amount of fluids (up 5.9 wt %), which cause hydraulic fracturing of the overlying rocks. The association between the injection fluids and hydraulic fracturing of rocks and the emission of seismic energy is evidenced experimentally. In contradiction in flat subduction the cooling of the downgoing slab is only moderate and the transformation runs along the high-T and low-P path which enters the eclogite field through the epidote-blueschist and amphibolite facies fields with small release of fluids.

An other process must be considered for the generation of seismicity in the uppermost mantle. KAO and LIU (1995) have studied the double seismic zone along the Japan and Kuril-Kamchatka arc. Here the upper and lower seismic zone are separated more than 30 km. Thus the lower zone is situated in the uppermost mantle and a process must exist, which refers to mantle composition. They propose as the most likely candidate for such a process decomposing of Al-rich enstatite to Al-poor enstatite plus garnet. Like the transformation process olivine to spinel that is associated with the emission of seismic energy, the same is assumed for the enstatite process. Fig. 2 shows the corresponding phase diagram, derived by KAO and LIU (1995) from petrologic, geothermal and seismological data. It should be noted, that the critical phase boundary is situated along a low-P and high-T path below 80-100 km depth in the temperature range 400°-500°C. This is just the same temperature interval of the upper gradient zone in the downgoing slab (Fig.1).

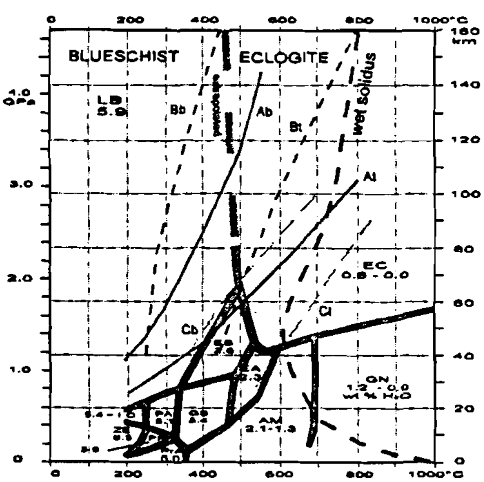

Fig. 1: P-T–diagram of metamorphic facies based on experimental and theoretical phase diagrams compiled by PEACOCK (1993).

At, Bt, Ct :P-T–path of the top of the oceanic crust, model A, B, C

Ab, Bb, Cb :P-T–path of the base of the oceanic crust, model A, B, C

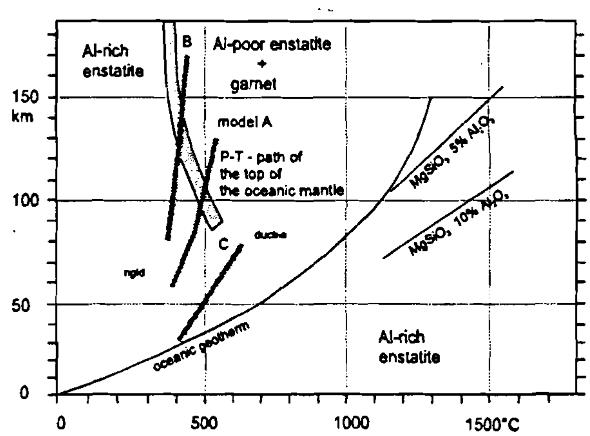

Fig. 2: P-T–diagram of the emstatite system (based on KAO and LIU 1995). The grey zone as seismically active phase is derived from the seismological and geothermal situation along the Japan and Kuril-Kamchatka arc system. It is assumed that this diagram can be applied to other subducting systems as well.

PISCO 94

Aiming to study the detailed structure of the intermediate-depth seismicity a network of about 25 mobile seismic stations were installed in the Precordillera and the Western Cordillera of the Central Andes operating between February and May 1994. The network operated in a continuous mode within an area of 200 km (W-E) x 250 km (N-S). About 50-100 events per day could be recorded in the magnitude range -0.5 to 4 (local magnitude scale). The accuracy of localising is ±2 km. Most of the events could be located in the depth range 75 to 120 km. Fig. 2A, B shows two sections derived from the high resolution PISCO 94 experiment, showing different pattern of seismicity.

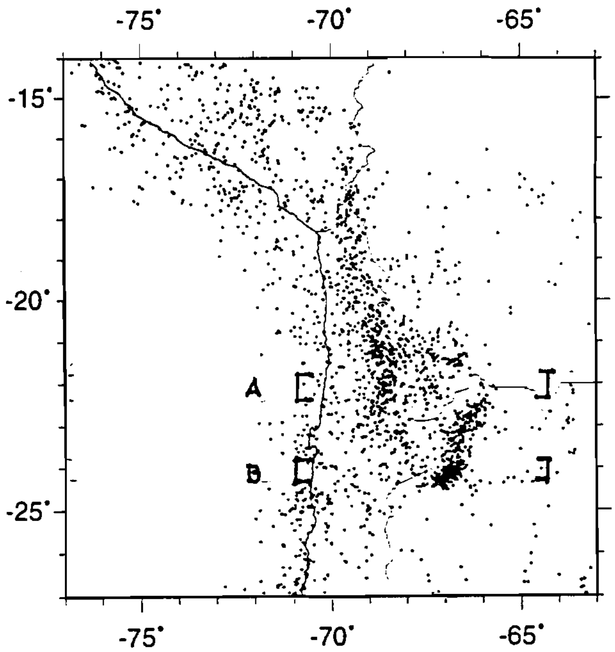

Fig. 3: Seismicity pattern in the Central Andes, based on the PDE catalogue.

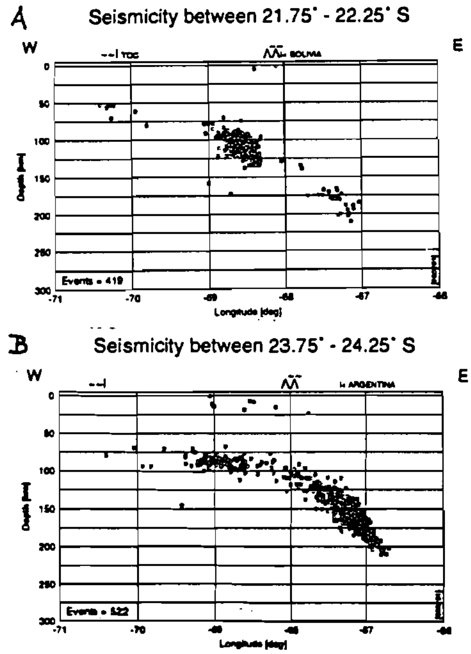

Fig. 4A,B: Two sections through the Central Andes showing the varying shape of the intermediate-depth seismicity

P-T PATHS AND SEISMICITY IN THE CENTRAL ANDEAN CONVERGING SYSTEM.
Aiming to match the observed seismicity with the metastable phase diagrams described above three thermal models with varying subduction parameters were calculated. Following parameters were used:

Table 1

	model A	model B	model C	
convergence rate	10	10	10	cm/a
dip of the subduction plane	17°	20°/40°/60 km	15°/8°/40 km	
thermal cond. crust/mantle	2.5./2.0	2.5./2.0	2.5./2.0	W/m·K
diffusity	1	1	1	10^{-6} m^{-2}
mantle heat flux	0.050	0.050	0.080	W/m²
frictional heating (1)	60 / 50	40 / 50	40 / 50	km / MPa
corner flow heating (2)	400°/70-200	400°/70-200	0	°C/km

(1) frictional heating increases linearly with depth, given max. depth (km)and max. stress (MPa)
(2) heating of the top of the slab by the induced corner flow, given the temperature increase(°C) and in the corresponding depth interval (km).

The transitional phase boundaries depicted from the phase diagrams are plotted in Fig. 5A, B, C. These transitional zones may have a width of at least 50°-100° C and 0.1-0.2 MPa (3-6 km). In addition the subducted slab may show deviations from the plane structure thus an actual thickness for the transitional phase zones of at least 10 km may result.

Fig 5A should be compared with Fig 4A. The seismicity is concentrated in the depth interval between 80 and 120 km. In Fig 4B, lower section, the seismicity is strechted between 80 and 200 km depth.
The corresponding model in Fig. 5B shows that the transitional phase boundaries are situated between 80 and 160 km. In the third case (Fig. 5C), the flat subduction, there a strongly reduced or even no seismicity in the intermediate-depth level because in both phase diagrams the descending slab moves along the high-T–low-P path associated with only small release of fluids.

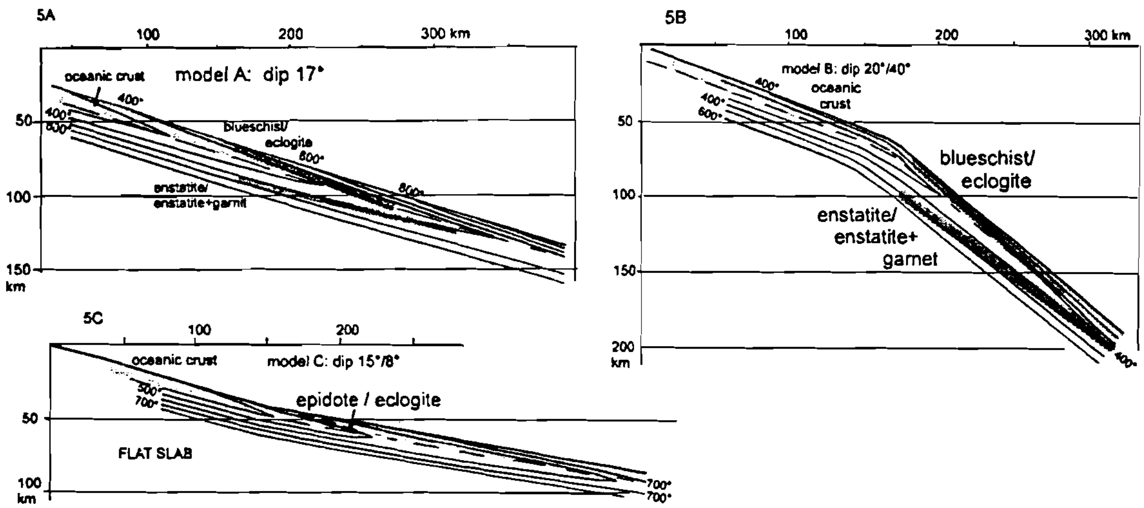

Fig. 5A,B,C The geothermal structure in the downgoing slab (parameters see table 1)
model A: dip 17°; model B: dip 20°/40°; model C: dip: 15°/8°

CONCLUSIONS

The nature of intermediate-depth seismicity is caused by metamorphic processes going on in the upper and lower temperature gradient zone in the downgoing slab. Considering seismological data, geothermal calculations, and petrologic considerations the intermediate-depth seismicity in the Central Andes is explained by two different metastable phase transformations, which occur in the oceanic crust resp. in the uppermost mantle. Both processes are associated with the emission of seismic energy. The different shape of the seismically active zone in the Central Andes can be modelled by variations of the parameters controlling the temperature field in the downgoing slab. The same processes take place along the Japan and Kuril-Kamtchatka arc system. A clearly recognisable separation of both zones depends on the thermal structure in the downgoing slab, which is dictated by the converging rate.
This project is funded by the Collaborative Research Programme "Deformation processes in the Central Andes"

REFERENCES

Kao, H. and L. Liu (1995): A hypothesis for the seismogenesis of a double seismic zone Geophys. J. Int., 123, 71-84.

Peacock, S. M. (1993): The importance of hlueschist → eclogite dehydration reactions in subducting oceanic crust. Geological Society of America Bulletin, 105,184--194.

Molnar, P. and P. C. England (1991): Temperature, heat flux, and frictional stress near major thrust faults, J.of Geoph. Res. , 95,433-4