Chapter 79.24 Germany

German National Report
Part B – Reviews of Research by Subjects

Contents

1 Modern Broadband Seismology

by Rainer Kind
GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany

Many analog earthquake recordings have for a long time been restricted to short periods (1 sec and shorter) and long periods (15 sec and longer) in order to minimize the 6 sec microseismic noise. Only after digital recording and processing became possible, broader period ranges have been recorded more regularly. Modern broadband seismology has already a long tradition in Germany. Early work has been done in East and West Germany (Berckhemer 1971, Teupser und Unterreitmeier 1977).

1.1 The Graefenberg Array

http://www.szgrf.bgr.de

The Graefenberg Array (GRF) was the world's first major digital broadband installation (Harjes and Seidl 1978). The 13 stations of the GRF array are located within an area of about 50 x 100 km east of the city of Nuremberg. It became full operational in April 1980, although continuous recordings of the first subarray are available since 1976. The first commercially produced Wielandt-Streckeisen broadband seismometers have been installed at the GRF Array (Wielandt and Streckeisen 1982). A summary of the GRF activities (including examples of research using broadband data) after ten years of its operation is given by Buttkus (1986). The array is operated by the Seismologisches Zentralobservatorium (SZGRF) which is part of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). It is supported by the Deutsche Forschungsgemeinschaft (DFG).

1.2 The German Regional Seismic Network

http://www.szgrf.bgr.de

The German Regional Seismic Network (GRSN) has been installed between 1991 and 1996 by the German Universities supported by the DFG and BGR (Hanka 1991). It forms a modern national seismograph network with 16 open stations distributed over the whole country and central data archiving at the SZGRF in Erlangen. Here the first Streckeisen STS-2 broadband sensors with extended high frequency range were installed and the open station concept was realized, where all users could directly log into the station for data retrieval.

1.3 The Geoforschungsnetz of the GFZ

http://www.gfz-potsdam.de/geofon

The global Geoforschungsnetz (GEOFON) project has been founded by the GFZ in 1992 (Hanka and Kind 1994). Presently (summer 2001) about 45 broadband stations contribute to the network. Most stations are operated in close cooperation with seismological institutions in host countries. The data are transmitted to GFZ and archived at Potsdam. In addition, the GFZ operates a pool of mobile seismic stations including at present about 70 broadband sensors.

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2 Free oscillations

By Gerhard Mueller
University Frankfurt, Frankfurt, Germany

Since 1972, the Black Forest Observatory (BFO) in the southwest of Germany records the deformations of the earth over a broad frequency band, from seismic waves over free oscillations to tidal deformations. At a depth of 150 m, it is one of the quietest observatories world-wide for long-period motions which are recorded with broadband seismometers, a tidal gravimeter, borehole pendulums and strainmeters. Continuous research with the data is performed at the observatory and guarantees and improves data quality. A few highlights from the free-oscillation research at BFO are mentioned in the following.

The fundamental mode of radial oscillations, oSo, was studied in the late seventies. The period of this mode was determined with a precision that strongly exceeds the precision of all other spheroidal and toroidal modes (Zuern, Knopoff and Rydelek 1980). The attenuation of oSo, i.e. the quality factor of this mode, was measured very reliably as well (Knopoff, Zuern, Rydelek and Yogi 1979).

Low-order fundamental spheroidal (oSn) and toroidal (oTn) oscillations, for n = 2,3,4, are difficult to observe because of the elevated noise background at their long periods. This is particularly true for the toroidal oscillations. Widmer, Zuern and Masters (1992) were the first who safely identified oT2 in the BFO strainmeter records of a strong 1989 earthquake.

Large volcanic eruptions produce vertical atmospheric oscillations above the volcano with well-defined frequencies. On the ground and in the earth these oscillations generate for hours Rayleigh waves (spheroidal oscillations) which are strong enough to travel to teleseismic distances. Widmer and Zuern (1992) detected these waves at BFO for the 1991 eruption of Mount Pinatubo and gave the explanation. This is one example of non-seismic generation of free oscillations. Another example are permanently existing spheroidal oscillations of very low amplitudes. Probably they are of meteorological or oceanographic origin (Suda, Nawa and Fukao 1998). They have also been found at BFO.

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3 Surface Waves in Germany, Second Part of the Century

By Peter G. Malischewsky
Friedrich-Schiller University, Jena, Germany

Because of political reasons the seismological research in Germany in the second part of the 20th century is characterized by independent developments in Western and Eastern Germany, repectively. Nevertheless, in this period interesting results concerning seismic surface waves were achieved in theoretical and practical aspects as well. S. Müller (1962) systematically investigated the general theory of propagation processes with normal dispersion and found a new technique to display directly the group travel time as a function of frequency. He also contributed to structural investigations in Germany by using short-period (Schneider et al., 1966) and long-period (Knopoff et al., 1966) surface waves. A special result of these studies was the preliminary clarification of the alpine underground which has had a great resonance in that time and stimulated more detailed investigations. Seidl and S. Müller (1977) published a comprehensive review article about seismic surface waves which covered both theory and practice.

The early surface wave investigations in Eastern Germany by Güth (1964) using the classical phase and group velocity methods were improved by Neunhöfer (1985), who obtained new geological results concerning the structure in the northern and southern part of Eastern Germany. Beyond that Neunhöfer (1985) thoroughly studied secondary effects connected with surface wave propagation like multi-pathing, anisotropy and attenuation. The experimental proof of the existence of a vertical Love-wave component in presence of anisotropy should be mentioned. A special secondary effect, the reflection and refraction of surface waves, was thoroughly investigated by Malischewsky (1973). His combination of Rayleigh and Love modes to an uniform eigenfunction system was adopted in the international literature. Malischewsky (1987) presented also for the first time a theory of surface waves in disturbed media with the incorporation of conceptions of wave-guide physics and quantum mechanics.

Wielandt (1980, 1993) obtained very interesting and new theoretical results concerning the polar phase shift of Rayleigh waves and the structural interpretation of non-plane waves. The latter study has considerably changed our understanding of surface wave propagation over networks of stations. Together with Friederich and Stange (Friederich et al., 1993) he obtained also important results concerning the multiple forward scattering of surface waves. Stange and Friederich (1992) clarified fundamental questions in connection with guided wave propagation across sharp lateral heterogeneities. Worth mentioning is also a proof for the completeness of surface-wave eigenfunctions by Besserer (1996). Meier et al. (1997) systematically studied the reflection, refraction, and scattering of seismic surface waves for tomographic purposes. For the first time, he succeeded in obtaining tomographic pictures of the Tornquist zone and other discontinuities in Middle Europe with reflected and scattered surface waves. New results concerning the seismic exploration with coal-seam waves, which are closely connected with surface waves, were presented by Dresen (1997).

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4 New seismic phases

By Gerhard Mueller
University Frankfurt, Frankfurt, Germany

Since about 1960, the advent of networks and arrays of identical analog and digital seismic stations facilitated the detection of weak seismic phases which either were unknown before or were expected, but not observed. Familiar examples are the steep-angle reflection PKiKP from the inner core or underside reflections from mantle discontinuities. In a few cases, German seismologists contributed to such detections.

In synthetic S-wave seismograms with mantle and core phases, Kind and Mueller (1975) found an unexpected arrival, related to the core phase SKS. It was identified as a wave with a similar path, but with an additional segment of P-wave diffraction, Pdiff, on the mantle side of the core-mantle boundary (CMB), either before entrance into the core (SPdiffKS) or after exit from the core (SKPdiffS). After identification, the phase was found in observed seismograms. About 20 years later, the time and amplitude differences of this phase relative to SKS were used to study the seismic wave velocities directly above the CMB. One result was the identification of ultra-low-velocity zones (e.g. Garnero and Helmberger 1996).

To which extent the lowermost mantle, zone D”, has a discontinuity or thin transition zone at its top, is a seismological theme since almost 20 years. Arrivals in long-period S-wave seismograms between S and ScS have been interpreted as giving positive evidence for a discontinuity, but the evidence is rather marginal than overwhelming. Weber and Davis (1990) and Weber (1993) studied broadband data from the GRF array and found clear reflections from a reflector about 300 km above the CMB below northern Siberia. The evidence was strongest for the P-wave reflection PdP, and this identification relied heavily on the slowness determination for PdP and the regular phases P and PcP. PdP has occasionally been found also in data from other arrays.

Teleseismic Pn phases with velocities around 8.1 km/s and epicentral distances up to about 3000 km have been repeatedly observed in oceanic and continental regions. Particularly clear and dense observations were reported by Ryberg, Fuchs, Egorkin and Solodilov (1995) on a long-range seismic profile in the former Soviet Union, with wave generation by so-called peaceful nuclear explosions. In a strict sense, this identification is not a new phase, but its unprecedented quality puts it on this level. The character of Pn is well explained by multiple scattering in a randomly heterogeneous lithospheric structure below the Moho (Ryberg and Wenzel 1999).

Seismologists in the former Soviet Union were the first who suggested methods to study (1) crustal and mantle discontinuities with P-to-S converted waves (Vinnik 1977) and (2) lithospheric seismic anisotropy with the birefringence of SKS and SKKS (Vinnik, Kosarev and Makeyeva 1984). In a close cooperation with German seismologists in the eighties, in particular at the Graefenberg array, these methods were intensively applied to data (e.g. Kind and Vinnik 1988, Kind, Kosarev, Makeyeva and Vinnik 1985). This contributed much to popularize these methods which by now are routine techniques to map crustal, lithospheric and upper-mantle structures.

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5 The Reflectivity Method for Computing Theoretical Seismograms

By Rainer Kind
GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany

Since the complete analytical solution of the problem of propagation of elastic waves in a half-space by Lamb (1904), there was only little progress towards layered models until the age of computers. A complete numerical solution for a stack of layers with an explosion point source above was developed by Fuchs (1968) using the matrix formalism of Haskell (1953) for generalized reflection and transmission coefficients and integration over the angle of incidence.

A parallel development was the wavefield decomposition into generalized rays (Helmberger, 1968; Mueller, 1968). Fuchs and Mueller (1971) combined both techniques into an efficient scheme which they called ‘Reflectivity Method’. In this form the reflectivity method was applied over decades around the world to seismic refraction studies.

Mueller (1973) has added to the reflectivity method an Earth flattening approximation which enabled in many cases application to spherical models. Kind (1978) has extended the reflectivity method for the case of a buried source using an analytical formulation of Harkrider (1964). This version permitted application to earthquake records including depth phases and surface waves. Later many different versions of the reflectivity method were generated, allowing the computation of various partial responses of a layered medium (e.g. Kennett 1983). Mueller (1985) wrote a very useful tutorial on the reflectivity method. More recently Wang (1999) published a version with many options for efficient computations in difficult cases.

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6 Controlled Source Seismology

By J. Mechie
GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany

Crustal seismic studies using controlled sources began in Germany with the recording of the Helgoland shot in 1947 and the Haslach shots in 1948 at wide-angle distances (Schulze 1947, Reich et al. 1948, 1951). Subsequently, between the late 191950s and the early 1970s a network of seismic refraction profiles was built up mainly in southern Germany using quarry blasts as sources. From this network of profiles the crustal structure especially in southern Germany was well delineated (Giese et al. 1976). Further, for the first time a portion of the uppermost layer of the continental mantle was discovered to be anisotropic in nature following the time-term analysis by Bamford (1977) of the Pn wave recorded throughout the network of seismic profiles in southern Germany.

Also in the 1960s, in the former East Germany, a network of seismic refraction profiles was completed to determine the structure of the crystalline basement under the North German Polish Basin. These measurements were carried out by the oil industry with 100 m geophone spacing. Thus good results were obtained, but as these were classified publication was not possible. Beginning in the late 1960s seismic refraction measurements were also carried out in the former East Germany along profiles along which studies were also made using converted waves from earthquakes. This joint technique in which the refraction measurements provided the velocity model and the converted waves provided interface information was known as the ZEMLJA method and originated in the former Soviet Union. Again the measurements were carried out by the oil industry and thus the focus was on the North German Polish Basin (Lange 1973, Jacobs et al. 1981).

In the field of deep crustal reflection studies, an early cooperative program between the prospecting industry and the universities deserves to be mentioned. For at least 10 years after 1958 the recording time of routine seismic prospecting surveys was extended from 5 to 12 s. A statistical interpretation of the number of reflections as a function of two-way travel-time revealed for the first time using deep reflection studies, the Moho reflection and mid-crustal reflections (Dohr and Fuchs 1967). At the same time as data were being collected methods were being developed also in Germany to interpret these data. One significant advance which occurred at the end of the 1960s was the development of the reflectivity method (Fuchs and Müller 1971) so that amplitudes (i.e. the full wavefield) and not only travel times could be interpreted.

During the 1970s a number of long-range (up to about 2000 km) seismic profiles were carried out in Europe (e.g. France in 1973, LISPB in Britain in 1974, ALP in 1975 and Fennolora in Sweden in 1979) often involving leading participation from German institutes (e.g. Sapin and Prodehl 1973, Bamford et al. 1978, Miller et al. 1982, Guggisberg et al. 1991). The aim of these profiles was not only to study crustal structure but also to examine the structure of the mantle lithosphere. From these profiles the picture of the mantle lithosphere as a stratified series of high and low velocity layers emerged (e.g. Hirn et al. 1973, Kind 1974, Cassell and Fuchs 1979). This picture has now been refined during the 1990s following joint analysis by German and Russian scientists of the Peaceful Nuclear Explosion (PNE) data collected over the past 30 years in the territory of the former Soviet Union (Tittgemeyer et al. 1996, Ryberg and Wenzel 1999). During the 1970s and 1980s seismic refraction profiles were also carried out in the former East Germany to determine the crustal structure of the southern and central part of the country. These measurements were carried out under the auspices of the former Central Institute for Physics of the Earth using three-component digital recorders (Bormann et al. 1985, 1987, Schulze and Bormann 1990, Schulze and Lück, 1992). Towards the end of the 1970s a near-vertical incidence reflection test profile was carried out across the North Variscan Deformation Front (NVDF) near Aachen. This profile imaged a strong reflector at 3-4 km depth dipping slightly to the SSE. This reflector was interpreted as the main thrust fault associated with the NVDF (Meissner et al. 1981).

During the 1980s much effort also in Germany was put into completing the European Geotraverse (EGT). The final result of the wide-angle seismic work carried out in this project was a picture of the crust and lithosphere along a N-S trending profile across Europe from the North Cape in Norway, through Sweden, Denmark, Germany, Switzerland, Italy, Corsica and Sardinia to Tunisia (Ansorge et al. 1992)

The early 1980s also saw the start of DEKORP (DEutsches KOntinental Reflexions Program) with several deep reflection lines across the Variscan terranes of Germany (Meissner and Bortfield 1990). As a result of DEKORP a deeper understanding of the structure and evolution of the Variscan mountain belt in central Europe was obtained with the various Variscan terranes exhibiting different styles of reflectivity depending on their tectonic and thermal development (see e.g. Meissner and DEKORP Research Group 1991). For example, west of the Rhine river the main thrust associated with the North Variscan Deformation Front was observed near Aachen in a thin-skinned tectonic setting. In contrast east of the Rhine river no thin-skinned tectonics were observed, but the original thrusting and interfingering of crustal units seems to be better preserved here. The results obtained from the extended and heated Variscan terranes have greatly contributed to the picture that such terranes are mostly comprised of a transparent upper crust, a reflective lower crust and a transparent mantle.

Within the framework of the KTB (Kontinentales Tiefbohrprogramm) in Germany in the 1980s, several coincident near-vertical incidence and wide-angle reflection profiles were carried out (Lüschen et al. 1987, DEKORP Research Group 1988, Harjes et al. 1997) and one 3-D near-vertical incidence reflection survey centered at the deep drill hole was completed (Buske 1999). As a result of the coincident near-vertical incidence and wide-angle reflection measurements, considerable effort was put into modelling the reflective properties of the lower crust (e.g. Wenzel et al. 1987). In the 1990s much of the work under the DEKORP banner has been undertaken outside Germany including the URSEIS95 project in the Urals (Berzin et al. 1996, Echtler et al. 1996) and the ANCORP96 project in the Andes (ANCORP Working Group 1999). In the Urals some of the deepest reflections (45 s two-way travel-time equivalent to about 170 km depth) ever imaged by the near-vertical incidence reflection method were observed (Knapp et al. 1996) while in the Andes the deepest ever image of a subduction boundary (80 km depth) by the same method was achieved. In 1999 the TRANSALP project from Germany through Austria into Italy was completed, while in 1996 a reflection profile across the North German basin was carried out (DEKORP-BASIN Research Group 1999).

Mainly during the 1980s and 1990s German groups participated often as leading partners in many international seismic projects in many parts of the world. Notable examples include the Afro-Arabian rift system (Mechie and Prodehl 1988, Makris et al. 1991, Prodehl et al. 1994, Fuchs et al. 1997, DESERT Team 2000), the Andes (Wigger et al. 1994, Schmitz et al. 1999), the Urals (Carbonell et al. 1996, Stadtlander et al. 1999), Tibet (Zhao et al. 2000), the north Atlantic/Iceland region (Gebrande et al. 1980), the continental margin of Namibia (Bauer et al. 2000), the Baltic Sea/Gulf of Bothnia region (BABEL Working Group 1993a, b), the northeastern Pacific (Ye et al. 1997), and along the Pacific margin of central and south America (Hinz et al. 1996, Ye et al. 1996, von Huene et al. 1997, Flueh et al. 1998, Patzwahl et al. 1999).

Within the framework of the URSEIS95 project complimentary wide-angle data demonstrated the presence of a 15-18 km thick crustal root beneath the central part of the southern Urals orogen. Wide-angle seismic data collected in the central Andes (northern Chile, northern Argentina and southern Bolivia) by German groups since the 1980s have delineated the crustal structure of this part of the orogen including a 65-70 km thick crust under the Altiplano and the Western and Eastern Cordilleras. The wide-angle seismic data collected in the Kenya rift in 1985, 1990 and 1994 revealed significant lateral variations in structure both along and across the rift. The crust thins along the rift axis from 35 km in the south to 20 km in the north corresponding to an increase in extension from south to north. Across the rift margins there are abrupt changes in Moho depth (5-10 km) and uppermost mantle velocity (7.5-7.7 km/s beneath the rift itself and 8.0-8.1 km/s beneath the rift flanks). At present German groups are still very actively involved in various seismic projects throughout the world including Tibet, the Andes, Rumania, Indonesia and the Middle East.

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