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Variscides in the Sudetes and the reworked Cadomian orogen: evidence from the GB-2A seismic reflection profiling in southwestern Poland

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The GB-2A profile shot perpendicular to major fault zones in SW Poland gave first seismic reflection insight, integrated with gravimetric and magnetic ones, into the crustal structure of the NE Bohemian Massif, eastern part of the Variscan belt. Under the West Sudetes there is a domal stack of well reflective, relatively dense, lower crustal rocks, with the Moho easily identifiable at the base of the laminated lower crust. Much poorer reflectors occur in the crust under the Fore-Sudetic Block (FSB)and Fore-Sudetic Monocline (FSM) further NE, with the Moho located in a c. 10 km thick transitional zone between crust and the upper mantle. The wedge-layered internal structure may imply crustal subduction or delamination with the northern block (terrane) pushed over and under the southern one, probably as early as during the Cadomian orogeny which exposed c. 680–540 Ma granodiorites at the surface. The main crustal suture of the A-subduction type is located beneath the Góry Kaczawskie Mts. This domal structure, with particularly well defined NE slope, is a real feature as confirmed also by gravimetric and magnetic modelling. The entire feature probably represents a Cadomian compressional event, then repeated during Variscan times, after Early Palaeozoic crustal extension. Alternatively, the crustal bulge under the Sudetes may represent a suture of two Cadomian terranes. The northern one would be compatible with rifted-off segments of proto-Baltica continental plate. The upper crust is composed of several wedge-like crustal blocks bounded by listric faults dipping generally to the north or north-east. Most important are two zones of this type: a southern zone, coinciding with the Main Intra-Sudetic Fault (MIF) and northern zone, the most important one, corresponding to the Sudetic Marginal Fault (SMF). Their geological history consists of repeated extensional-compressional deformations of a continental crust, accomplished in a dip-slip to strike-slip regime. From Carboniferous times extensional deformation seems to dominate. The Odra Fault Zone (OFZ) is identifiable only by magnetic modelling and cannot be taken as an eastern continuation of the Mid-German Crystalline Rise (MGCR).

INTRODUCTION

Crystalline basement rocks in southwestern Poland are largely hidden below Permian through Cainozoic platform strata. The only exception is a Tertiary horst of the Sudetes Mts., where crystalline basement is exposed (Fig. 1). Together with its concealed continuation in the Sudetic Foreland the basement is considered to be the NE part of the Bohemian Massif. Actually the West Sudetes region is referred to as a crustal block located between the Odra Fault Zone (OFZ) to the NE, the Elbe Fault Zone (EFZ) to the SW, and the Torgau–Doberlug Trough (TDT) on the NW and the Moldanubian Thrust Zone (MTZ) on the SE (Figs. 1 and 2). This block is further subdivided by the NW-trending Sudetic Marginal Fault (SMF) and Main Intra-Sudetic Fault (MIF), and by NNE–trending transcurrent zones, with the earlier WNW–ESE grain clearly overprinted by the NNE–SSW one (East Karkonosze, Niemcza Zone, or Moldanubian Thrust Zone). The SMF subdivides the West Sudetes into Sudetic (Sudetes Mts.) and Fore-Sudetic Blocks, and the Sudetic Block is further parted by the MIF into the Izera–Karkonosze Block (IKB) and Góry Kaczawskie Block (GK). All these fault zones are long-lived features dating back to the Early Carboniferous or Late Devonian. Whether they represent reworked crustal faults, acting first as normal and then reverse fault zones during tectonic inversion, boundaries of far-traveled nappe units, or strike-slip terrane sutures, is a matter of recent controversial interpretations (P. H. Matte *et al.*, 1990; Z.

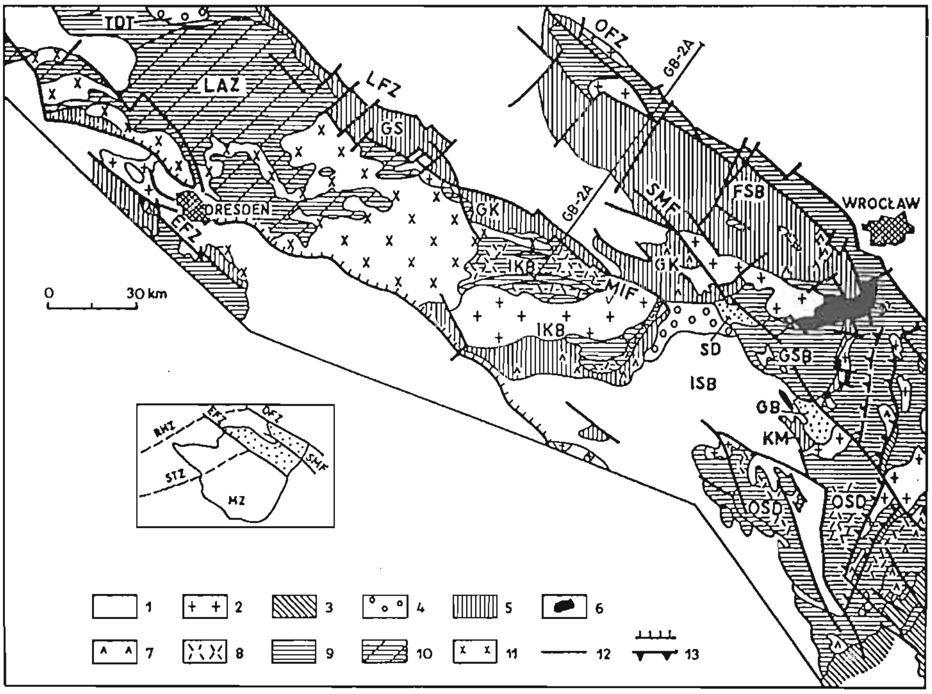

Fig. 1. Geologic sketch of the southwestern Poland and location of the GB-2A seismic profile; inset shows location in the Bohemian Massif and Central European Variscides

1 — Upper Carboniferous–Mesozoic overstep sequences; 2 — Upper Carboniferous granitoids; 3 — Moravo-Silesian metasediments (Devonian–Lower Carboniferous); 4 — Palaeozoic succession: unmetamorphosed; 5 — Palaeozoic succession: metamorphosed; 6 — Sudetic ophiolite (420–370 Ma); 7 — metabasite; 8 — granite (515–480 Ma); 9 — Neoproterozoic–Cambrian succession; 10 — Neoproterozoic Lusatian metagraywacke and other metamorphic rocks; 11 — granitoids (580–540 Ma); 12 — faults; 13 — thrusts; EFZ — Elbe Fault Zone; FSB — Fore-Sudetic Block; GB — Góry Bardzkie; GK — Góry Kaczawskie; GS — Görlitzer Schiefergebirge; GSB — Góry Sowie Block; IKB — Izera–Karkonosze Block; ISB — Intra-Sudetic Basin; KM — Kłodzko metamorphic rocks; LAZ — Lusatian Anticlinal Zone; LFZ — Lusatian Fault Zone; MIF — Main Intra-Sudetic Fault; MZ — Moldanubian Zone; OFZ — Odra Fault Zone; OSD — Orlica–Śnieżnik Dome; RHZ — Rhenohercynian Zone; SD — Świebodzice Depression; SMF — Sudetic Marginal Fault; STZ — Saxothuringian Zone; TDT — Torgau–Doberlug Trough

Szkic geologiczny południowo-zachodniej Polski z zaznaczoną lokalizacją profilu GB-2A; prostokąt: położenie SW Polski w obrębie masywu czeskiego i waryscydów środkowej Europy

1 — pokrywa górnokarbońsko-mezozoiczna; 2 — granitoidy górnokarbońskie; 3 — zmetamorfizowane skały dewońsko-karbońskie strefy morawsko-śląskiej; 4 — niezmetamorfizowane skały sukcesji paleozoicznej; 5 — zmetamorfizowane skały sukcesji paleozoicznej; 6 — ofiolit sudecki (420–370 Ma); 7 — metabazyty; 8 — granity (515–480 Ma); 9 — sukcesja neoproterozoiczno-kambryjska; 10 — neoproterozoiczne metaszarogłazy łużyckie i inne skały metamorficzne; 11 — granitoidy (580–540 Ma); 12 — uskoki; 13 — nasunięcia; EFZ — strefa uskokowa Łaby; FSB — blok przedsudecki; GB — Góry Bardzkie; GK — Góry Kaczawskie; GS — Zgorzeleckie Góry Łupkowe; GSB — blok Gór Sowich; IKB — blok karkonosko-izerski; ISB — depresja śródsudecka; KM — metamorfik kłodzki; LAZ — strefa antyklinalna Łużyc; LFZ — strefa uskokowa Łużyc; MIF — główny uskok śródsudecki; MZ — strefa moldanubska; OFZ — strefa uskokowa Odry; OSD — kopuła orlicko-śnieżnicka; RHZ — strefa reńsko-hercyńska; SD — depresja Świebodzic; SMF — sudecki uskok brzeżny; STZ — strefa saksońsko-turyngska; TDT — niecka Torgau–Doberlug

Cymerman, M. A. J. Piasecki, 1994; A. Żelaźniewicz, in press). Crustal similarities or differences with other parts of the Bohemian Massif and Variscides are still disputed, especially in view of the presence of Neoproterozic rocks (680–540 Ma) believed to represent a part of the Cadomian orogen. Counterparts of tectonostratigraphic units occurring in the West Sudetes can be found further west in the Bohemian Massif (F. Kossmat, 1927; W. Franke *et al.*, 1993).

In F. Kossmat's (1927) classic subdivision of Variscan Europe the Rhenohercynian Zone (RHZ) contained low-grade metasediments of Devonian–Carboniferous age, the Saxothuringian Zone (STZ) was distinguished by the presence of low-medium grade metasediments of Palaeozoic age, and the Moldanubian Zone (MZ) was a realm of high-grade metamorphic rocks, with yet older metasediments of unknown but generally Precambrian age unconformably covered by unmetamorphosed Lower Palaeozoic (e.g. Barrandean). These zones were thought to represent external, internal and central parts of the Variscan orogen, respectively. It is easy to trace the Saxothuringian Zone with its Palaeozoic metasediments eastward to the West Sudetes as proposed originally by F. Kossmat (1927) and recently confirmed by W. Franke *et al.* (1993). However, it is more difficult: (1) to identify in the Sudetes the eastern continuation of a Variscan magmatic arc located in the west at the Mid-German Crystalline Rise (MGCR) (Figs. 1 and 2); (2) to find distinguishable relicts of Saxothuringian and Rhenohercynian oceans and sutures, or (3) to demonstrate a large-scale inversion of tectonostratigraphic units owing to major tectonic allochtonism (A. Żelaźniewicz, in press). Thus a need for 3-D reconstructions helped by seismic data is appealing. Particularly important is a question of provenance of middle and lower crust.

Does it represent a mix of Gondwana-borne terranes accreted during the Palaeozoic to Baltica or Laurussia consequent upon subduction of the intervening Tornquist Ocean (G. J. H. Oliver *et al.*, 1993; Z. Cymerman, M. A. J. Piasecki, 1994), or mostly Neoproterozoic continental crust that was stretched in Early Palaeozoic times and then strongly reworked during Late Devonian–Early Carboniferous inversion and convergence (A. Żelaźniewicz, in press)?

The first seismic reflection transect in southwestern Poland was performed with the intention of unravelling crustal structure in this region. This paper describes and interprets the structure along the c. 100 km long seismic reflection profile named GB-2A, shot in 1994 (Figs. 1 and 2). Both unmigrated and migrated time sections (Figs. 3, 4 and 5) are used in combination with refraction data and all integrated with gravimetric and magnetic data projected onto the surface geology. The results are compared with the results of the neighbouring DEKORP 2S and in particular DEKORP MVE-90 (East) profiles in SE Germany. The aim is to determine the structure of the crust in Polish section of the European Variscides, and integrate this section with the overall Variscan framework.

CHARACTERISTICS OF GEOLOGICAL UNITS ALONG THE TRANSECT

The GB-2A profile runs across the Izera–Karkonosze Block, Main Intra-Sudetic Fault, Góry Kaczawskie, Sudetic Marginal Fault, Fore-Sudetic Block, Odra Fault Zone and enters the Fore-Sudetic Monocline (Fig. 1).

IZERA–KARKONOSZE BLOCK

Izera–Karkonosze Block (IKB) exposes at the surface granites and gneisses containing three narrow belts (1.5 km) of mica schists dipping steeply (80–50°) northward. The granites are 515–480 Ma old (A. Korytowski *et al.*, 1993; G. J. H. Oliver *et al.*, 1993; S. Phillipe *et al.*, 1995) S- to I-type peraluminous, calc-alkaline rocks. In general the schists represent Neoproterozoic–Cambrian succession (A. Żelaźniewicz, in press), intruded by Late Cambrian–Early Ordovician granites. These granites also intruded the c. 540 Ma Lausatia (Zawidów, Leśna) granodiorite, one of a suite of late to post-orogenic granitoids of a Neoproterozoic Cadomian cycle. The origin of the c. 500 Ma granites is linked with an enigmatic magmatic arc (G. J. H. Oliver *et al.*, 1993; A. Żelaźniewicz, W. Franke, 1994), or with an overall extensional setting within existing continental crust (A. Żelaźniewicz, in press). The mica schist belts are complex shear zones embracing fragments of primary country rocks as well as mylonites derived from the Izera granite (A. Żelaźniewicz, 1996). Actually these WNW- to W-trending schists belts are geometrically and kinematically consistent with the strike-slip sinistral and dextral history of generally steep to vertical mylonitic zones intersecting the granite. Although both Neoproterozic and Lower Palaeozoic (meta)granites have rather low potential for seismic reflectors, the schist belts might be detectable, especially if they have listric geometries.

MAIN INTRA-SUDETIC FAULT

The Main Intra-Sudetic Fault (MIF) is a major, subvertical fault zone separating the Izera–Karkonosze Block (IKB) from the Góry Kaczawskie Block (GK). It is patchily exposed along a c. 25 km long border zone up to 1.5 km wide. Its kinematic history is roughly consistent with that of other subvertical shear zones occurring within the Izera gneisses. An important component of dextral transpression brought the Góry Kaczawskie low-grade rocks over the Izera–Karkonosze Block by southward and south-westward thrusting concomittant with c. 340 Ma (H. Maluski, pers. comm.) greenschist metamorphism of the Kaczawa complex and prior to intrusion of the Variscan Karkonosze Granite at c. 330–325 Ma (J. L. Douthu *et al.*, 1991). If not listric, the MIF is unlikely to be seen on a reflection profile because of its steepness. Traces of transpressional thrusts may, however, be expected.

GÓRY KACZAWSKIE

The Góry Kaczawskie (Kaczawa Mts.) Unit is made of Paleozoic rocks of an Ordovician–Lower Carboniferous succession metamorphosed under greenschist facies at c. 340 Ma that overprinted a ubiquitous(?) relict product of an earlier blueschist event waning at 360 Ma (H. Maluski, pers. comm.). About 1000 m of Ordovician siliciclastic sediments of continental derivation (Z. Urbanek *et al.*, 1995) are associated with up to locally 300 m thick, shallow-water carbonate (algal) buildups (S. Lorenc, 1983) and bimodal volcanogenic rocks with a within-plate geochemical signature. The Silurian sequence is condensed (c. 100 m), mostly developed as pelagic clayey and siliceous shales, which are conformable with Ordovician strata (Z. Baranowski *et al.*, 1990). The Devonian is also represented by a c. 100 m of condensed silicic shales. Upper Devonian and especially Lower Carboniferous turbidites and melanges contain, in a shaly matrix, olistoliths (> 1 km) derived from the Ordovician–Devonian portion of the Kaczawa complex. This heralded the closure of the Palaeozoic basin which remained undisturbed by any earlier event temporally consistent with the Acadian, Caledonian, or Ligerian orogeny occurring elsewhere. The Ordovician–Upper Devonian sequence remained essentially undeformed and unmetamorphosed till Late Devonian–Early Carboniferous. Structures associated with downbuckling of the Palaeozoic pile in the Góry Kaczawskie to the depth necessary for blueschist metamorphism at a pressure of 6–10 Kb (R. Kryza *et al.*, 1990) and blueschist metamorphism cannot be identified, despite widespread occurrences of glaucophane massively

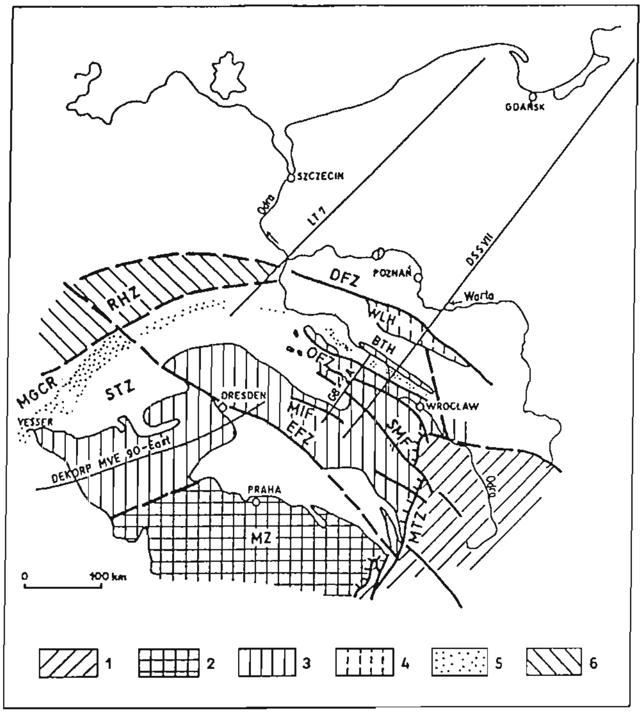

Fig. 2. Tectonic sketch of northern part of the Bohemian Massif and adjacent areas and location of selected seismic profiles in Western Poland and Eastern Germany

1 — Moravo-Silesian basement of Cadomian age; 2 — Moldanubian Zone; 3 — Saxothuringian Zone in outcrops; 4 — Saxothuringian Zone in subsurface (basement highs); 5 — zone of magnetic highs; 6 — Rhenohercynian Zone; BTH — Bielawy-Trzebnica High; DFZ — Dolsko Fault Zone; MGCR — Mid-German Crystalline Rise; MTZ — Moldanubian Thrust Zone; WLH — Wolsztyn-Leszno High; other explanations as in Fig. 1

Szkic tektoniczny północnej części masywu czeskiego i obszarów przyległych, pokazujący lokalizację wybranych profili sejsmicznych w zachodniej Polsce i w Niemczech

1 — kadomskie podłoże strefy morawsko-śląskiej; 2 — strefa moldanubska; 3 — strefa saksońsko-turyngska w odsłonięciach; 4 — strefa saksońsko-turyngska w wyniesieniach podłoża pod pokrywą permomezozoiczną; 5 — strefa dodatnich anomalii magnetycznych; 6 — strefa reńsko-hercyńska; BTH — wyniesienie Bielaw-Trzebnicy; DFZ — strefa uskokowa Dolska; MGCR — środkowoniemieckie wyniesienie krystaliczne; MTZ — moldanubska strefa nasunięć; WLH — wyniesienie Wolsztyna-Leszna; pozostałe objaśnienia jak na fig. 1

overgrown by later actinolitic hornblende. Common is an overall southern (SE and then SW) vergence of folds and thrusts developed under the greenschist conditions and this, possibly, can be traced on the seismic image.

SUDETIC MARGINAL FAULT

The Sudetic Marginal Fault (SMF) at the GB-2A transect cuts through the Góry Kaczawskie complex parallel to strike (Fig. 1). The SMF forms the NE border of the Sudetes Mountains Block and defines the southwestern boundary of the Fore-Sudetic Block (FSB). There is no Permo-Mesozoic cover in the FSB as compared with the Sudetes and thus the SMF is considered persistent long-lived feature active from at least Late Carboniferous time till the Recent. Quaternary sinistral strike-slip (K. Mastalerz, J. Wojewoda, 1993) is, however, of minor importance because outcrop pattern evidence from the Góry Sowie Block dissected by the SMF with insignificant horizontal displacement along this fault points to mainly dip-slip movements, yet with sense changing between normal and reverse. During Permo-Mesozoic times the FSB was permanently in an elevated hangingwall position relative to the Sudetes. The present footwall position of the FSB with respect to the SMF was effected by Miocene-Pliocene block movements elevating the Sudetes Mts. as a brittle horst. Although steep at the present erosional level, the SMF may continue deeper into the crust as a listric feature. Despite its clear impact on morphology the fault plane is nowhere exposed being hidden under Cainozoic deposits.

FORE-SUDETIC BLOCK

In western part of the Góry Kaczawskie, the Palaeozoic basement is extensively covered by Permo-Mesozoic rocks of the North-Sudetic Depression and it reappears close to the SMF and NE of it in the Fore-Sudetic Block (FSB). Combined outcrop and subcrop data show that the Góry Kaczawskie complex extends at least to the Odra Fault Zone (Fig. 1). Its FSB part consists of low-grade rocks identical with those exposed in the Sudetes and bearing the same Ordovician-Lower Carboniferous stratigraphic signature (J. Jerzmański, L. Teller, 1971; M. Chorowska, 1982; see also S. Cwojdziński, A. Żelaźniewicz, 1995). Details of stratigraphy are, however, still unsatisfactorily known, which renders tectonic interpretation difficult. In inlier outcrops scattered over the FSB almost flat-lying foliation is axial planar to E-trending southerly vergent folds refolding earlier tight to isoclinal folds seen only in relicts of unknown attitude.

The E-trending folds are commonly accompanied by an intersection lineation. Later cleavage is connected with more brittle overprint also suggestive of south-westward vergence. Greenschists found in boreholes in the NE part of the FSB, close to the Odra Fault Zone make an arcuate trend and are closely akin to low-grade metabasic rocks in the Góry Kaczawskie (J. Jerzmański, 1991). A similar kinematic pattern is seen across the Kaczawa complex outcropping in the Sudetic Block and mostly subcropping in the Fore-Sudetic Block. It suggests N-dipping seismic reflectors produced by convergent, compressional structures.

In the FSB, almost on the line of the GB-2a transect (Fig. 1), there is an inlier of the IKB-type gneisses near Wądroże Wielkie. However, its contacts with the Kaczawa phyllites are hidden under the Cainozoic and whether this is a window, klippe, or brittle basement horst remains unclear. In the case of shallowly dipping thrusting some reflectors can be expected to occur on the seismic profile.

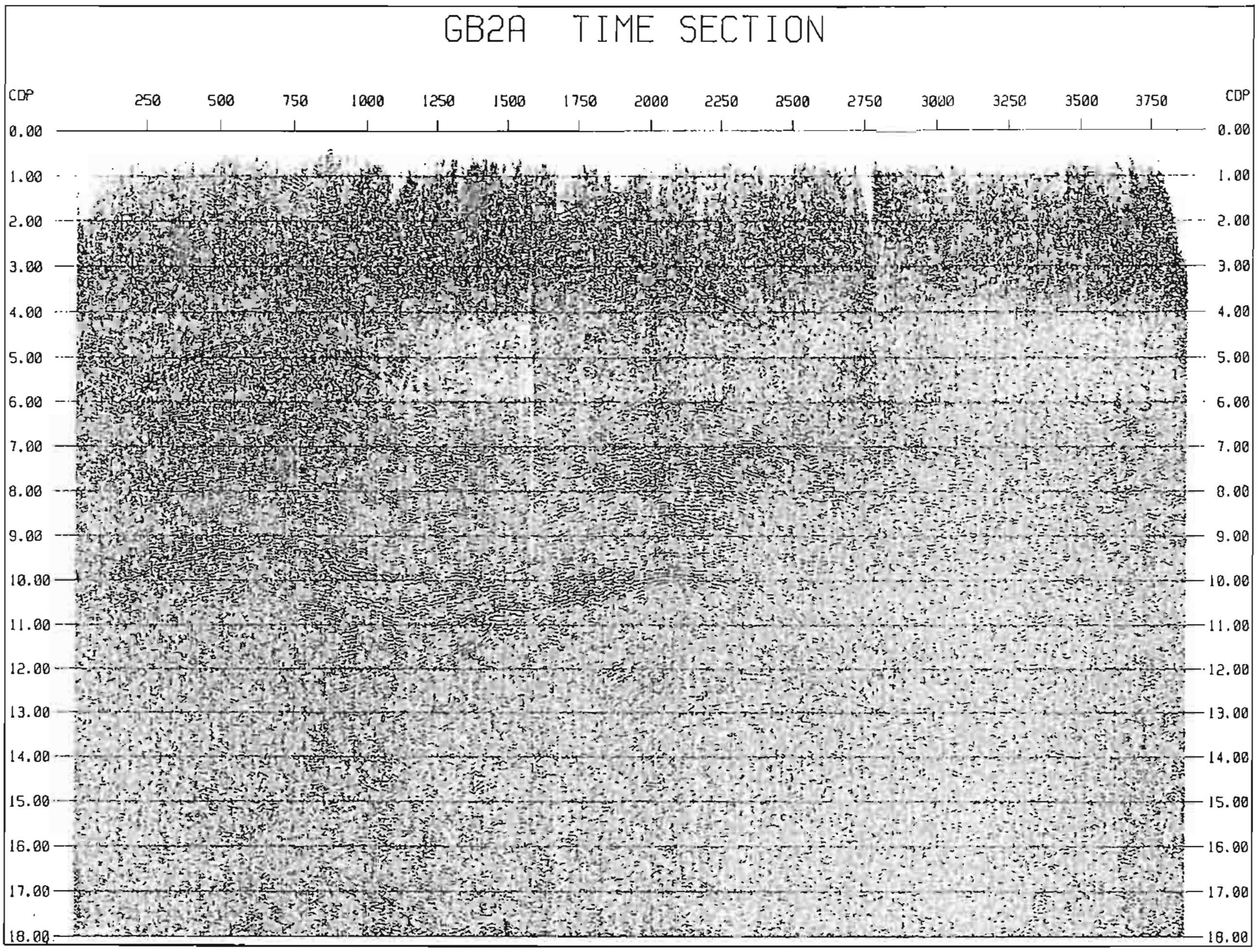

Fig. 3. The GB-2A reflection seismic profile: unmigrated

Refleksyjny profil sejsmiczny GB-2A bez migracji

ODRA FAULT ZONE

The Odra Fault Zone (OFZ) is another major fracture, active at least since Late Carboniferous time, with significant uplift during the Permian and Triassic of a narrow (5–15 km wide) horst of medium- and high-grade metamorphic rocks (Figs. 1 and 2). Such rocks are unknown from the Góry Kaczawskie complex, which actually abuts against the OFZ, but they are similar to the Kamieniec complex of the Fore-Sudetic Block further east (S. Cwojdziński, A. Żelaźniewicz, 1995). Thus they are likely to be a continuation of the Orlica–Śnieżnik Dome complex *via* the Kamieniec complex and are therefore considered part of Neoproterozoic–Cambrian succession experiencing tectono-thermal events twice, once during the Ordovician and then during Late Devonian–Early Carboniferous times. In the metamorphic horst of the OFZ *c.* 500 Ma orthogneisses are, however, absent or not recognized, which does not exclude their presence there. Rocks of that succession may structurally underlie the Góry Kaczawskie succession.

The once suggested similarity of the OFZ horst comprised of medium-grade metamorphic rocks (Odra metamorphic rocks) to rocks of the Mid-German Crystalline Rise (A. Grocholski, 1982, 1986, 1987) is not substantiated because of the absence of Upper Devonian (meta)granitoids and lack of records of any extensive ductile fault movement. Foliation in mica schists and gneisses dips shallowly to steeply, yet evidence for ductile mylonitization is poor and most recognizable fault-related structures are developed in a brittle or brittle/ductile regime. Drill cores do not show evidence for the crustal-scale dextral Variscan shearing proposed by F. Arthaud and P. Matte (1977).

FORE-SUDETIC MONOCLINE

North-east of the Odra Fault Zone (OFZ) spreads the Fore-Sudetic Monocline (FSM) defined by gently and monoclinally north-easterly dipping (3–5°) Triassic and younger strata (Figs. 1 and 2). The Mesozoic FSM strata overlie Permian to Lower Carboniferous sediments, with marked unconformity at the base of Permian rocks. It is almost unknown what type of rocks actually occur below the Carboniferous (tens of hydrocarbon-prospecting wells have terminated in the Carboniferous rocks). It is unknown if the Góry Kaczawskie (GK) succession continues across the OFZ. There is some positive evidence for this because low-grade metamorphic phyllites of at least Devonian age have been reported from boreholes located immediately NE of the OFZ (M. Chorowska *et al.*, 1978). If so, it means that the GK Palaeozoic succession continues across the OFZ further northward and the OFZ is a post-Carboniferous feature, which excludes any possibility of linking the OFZ metamorphic horst with the Mid-German Crystalline Rise (Figs. 1 and 2). This horst would then represent only a basement inlier bordered by mostly brittle faults of Permo–Mesozoic age and leave open a possibility of continuation of mid/high-grade rocks further north as well.

DATA ACQUISITION AND PROCESSING

PARAMETRES OF THE FIELD SURVEY

The deep reflection data in the Sudetes along the 107 km long profile were acquired in 1994 by Geophysical Research Enterprise. Seismic sources consisting of 10 to 30 kg dynamite were detonated in 1 to 3 boreholes at depths of 12 to 30 m. Data were recorded using a 96 channel SN338HR instrument with transmission limits 8–62.5 Hz. The digital data sampling rate was 4 ms, the recording time 18 s. The shotpoints and receivers were arranged in an end-on spread configuration with a 500 m offset between the shot and the nearest geophone. Channel interval was 50 m and each channel consisted of group of 24 geophones. Shooting every station gave nominal 48 fold stacked data along the line.

DATA PROCESSING

The GB-2A section presented in this paper was processed in two stages. The first one included all prestack processes and stack itself. The second one contained poststack processes. The first stage accomplished by the Polish Geological Institute (S. Cwojdziński *et al.*, 1995) employed standard processing procedures in following sequence: (1) demultiplexing, (2) static corrections, (3) bandpass filtering, (4) trace editing, (5) muting, (6) spherical divergence corrections, (7) preliminary velocity analysis, (8) normal moveout correction, (9) preliminary stack, (10) second more detailed velocity analysis, (11) normal moveout correction with new velocities, (12) stack. Because there was significant culture noise over the whole line trace editing was an important and laborious point.

The second stage was realized at the Cambridge University (BIRPS group) in November 1996. The processing sequence included: (1) resampling to 8 ms, (2) F-K filtering, (3) predictive deconvolution (time variant), (4) Butterworth bandpass filtering (time variant), (5) finite difference depth migration. Different migration algorithms were tested and the finite difference method produced the most acceptable results. Constant velocity migration tests were also carried out. The velocity model from International Refraction Profile VII was used as the first aproximation for the migration velocity field. International Refraction Profile VII was shot about 30 km to the south-east from GB-2A and is approximately parallel to it (A. Guterch *et al.*, 1975, 1986). This model was then modified to reduce overmigration effects and to take geological information into consideration. The final section is presented here (Fig. 4). This depth migrated image can be interpreted with greater confidence than the corresponding time section since the depth migration process returns reflectors to a sub-surface location which is corrected for the effects of the chosen overlying velocity field, and automatically converts two way travel time to depth, elimating the distorting effects of lower velocity sedimentary layers and permitting accurate determination of dip angles for reflectors. With a well defined velocity field many of the distortions and overmigration effectes inherent in migration followed by a separate depth conversion can be eliminated. However, the resulting depth image is critically dependent upon the accuracy of the chosen velocity model for the crust. In this case the velocity model is based upon DSS data and therefore should be a reasonably accurate representation of the crustal structure.

GEOMETRY OF REFLECTORS

The GB-2A reveals a typical almost transparent upper crust and a laminated lower crust, with dense sets of shallowly dipping reflectors under the Sudetes and less well defined reflectors in the lower crust of the Fore-Sudetic Block (FSB) and Fore-Sudetic Monocline (FSM) (Figs. 5 site **a**, and 9). The Moho at the base of the laminated crust is better expressed below the Sudetes than below the Fore-Sudetic Block. Further north the Fore-Sudetic Monocline probably has a gradual crust-mantle transition, with few reflectors in a relatively thick, northwards thinning lower crust. The whole crust generally thickens southward to 36 km under the Sudetes. It thins to 30–28 km beneath the FSB and FSM, being elevated by a dome- or ramp-like structure along a shallowly dipping feature (Fig. 5 site **b**). NE of the Main Intra-Sudetic Fault there seems to occur a highly transparent middle crust between 9 and 16 km depth, which is thickest beneath the Góry Kaczawskie and thinnest below the Odra Fault Zone. In the Sudetes this apparently transparent middle crust is disrupted by a symmetric dome or a stack of densely packed reflectors. Once projected upwards the dome axis probably coincides with the surface trend of the Main Intra-Sudetic Fault (MIF). In the upper crust over the stack, there are mostly NE dipping listric

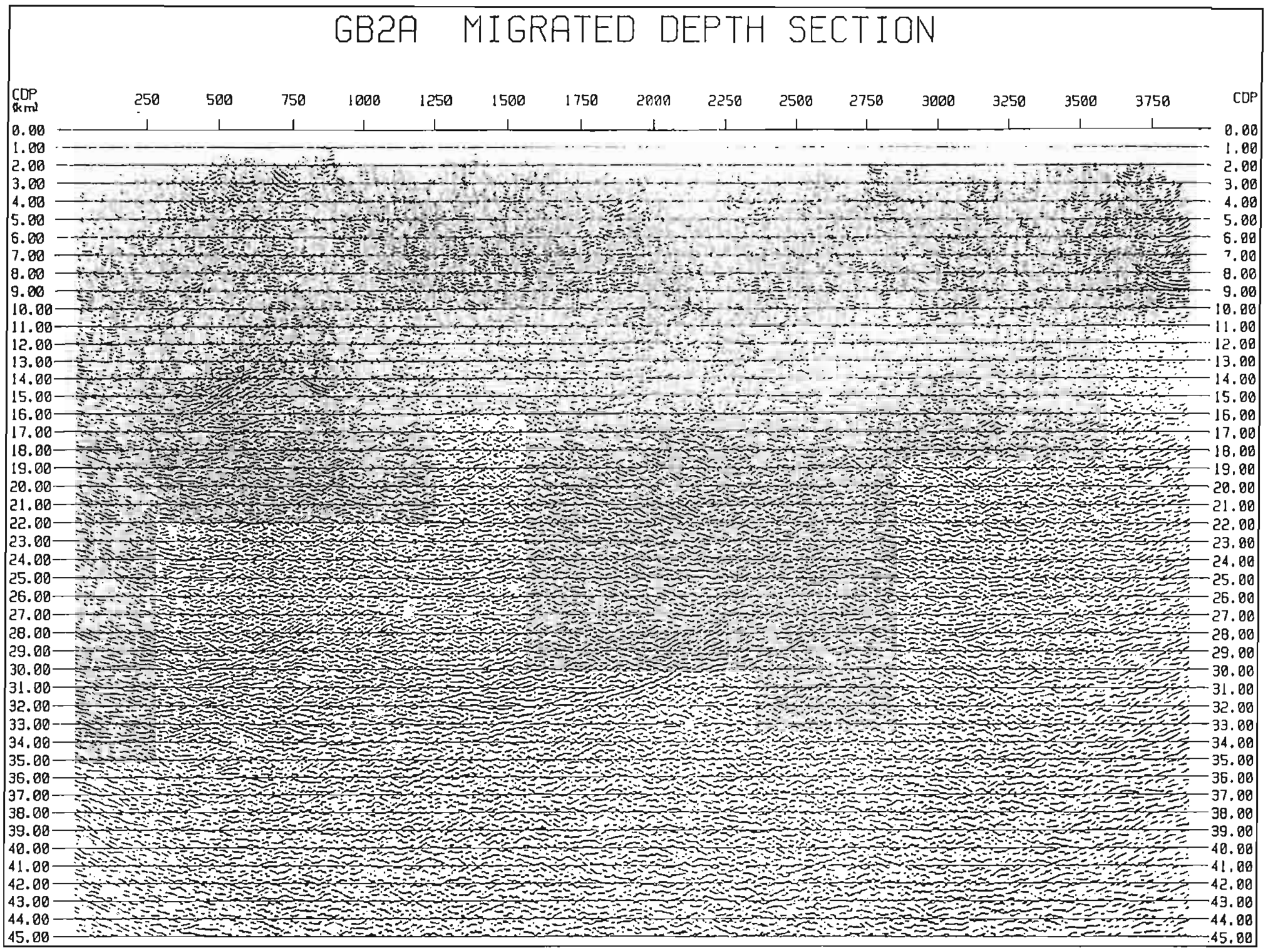

Fig. 4. The GB-2A reflection seismic profile: depth migrated

Refleksyjny profil sejsmiczny GB-2A po migracji głębokościowej

and steep features coalescing or rooting in the transparent middle crust under the Góry Kaczawskie (Figs. 5 and 10). The Main Intra-Sudetic Fault itself is seen on the seismic image as a listric feature possibly rooted in the middle crust (Fig. 10).

Less reflective upper crust occurs SW of the Main Intra-Sudetic Fault, in the domain most likely occupied by the Variscan Karkonosze Granite which extends beneath the Izera gneisses and dies out against the dome of arched reflectors. The N-dipping reflectors over the dome continue to the Góry Kaczawskie side. The listric features are joined by steeper reflector dipping in the opposite direction, which resembles the geometry of faulted and extended crust in a rift zone. Steep shear zones incorporating mica schist of the former envelope of the Izera metagranite are poorly seen as listric features on the unmigrated section (Figs. 3 and 5 site **c**) and they are not recognizable on the migrated section (Figs. 4 and 10).

The Sudetic Marginal Fault clearly coincides with a bunch of northward dipping reflectors which seem to crosscut the transparent zone under the Fore-Sudetic Block (Figs. 3, 4, 5 site **d**, and 10). They may even link with another dome-like feature of more densely packed reflectors, which thins out into the transparent middle crust under the Odra Fault Zone. Here, in the Fore-Sudetic Block–Fore-Sudetic Monocline border zone, the upper mantle is shifted upward by 5–6 km and forms a gentle bulge whose southern slope concides with a S-dipping feature throwing down Moho under the Sudetes along a low-angle normal fault. A discrete roll-over structure can be envisaged on the unmigrated profile (Fig. 5 site **e**), whereas a subducted feature is the alternative suggested by the migrated version (Figs. 4 and 10). At the base of the lower crust in the hanging wall of this crustal feature, i.e. under the Sudetic Block, a dense pack of subhorizontal reflectors suggests a transitional zone between the crust and the mantle (Fig. 5 site **f**).

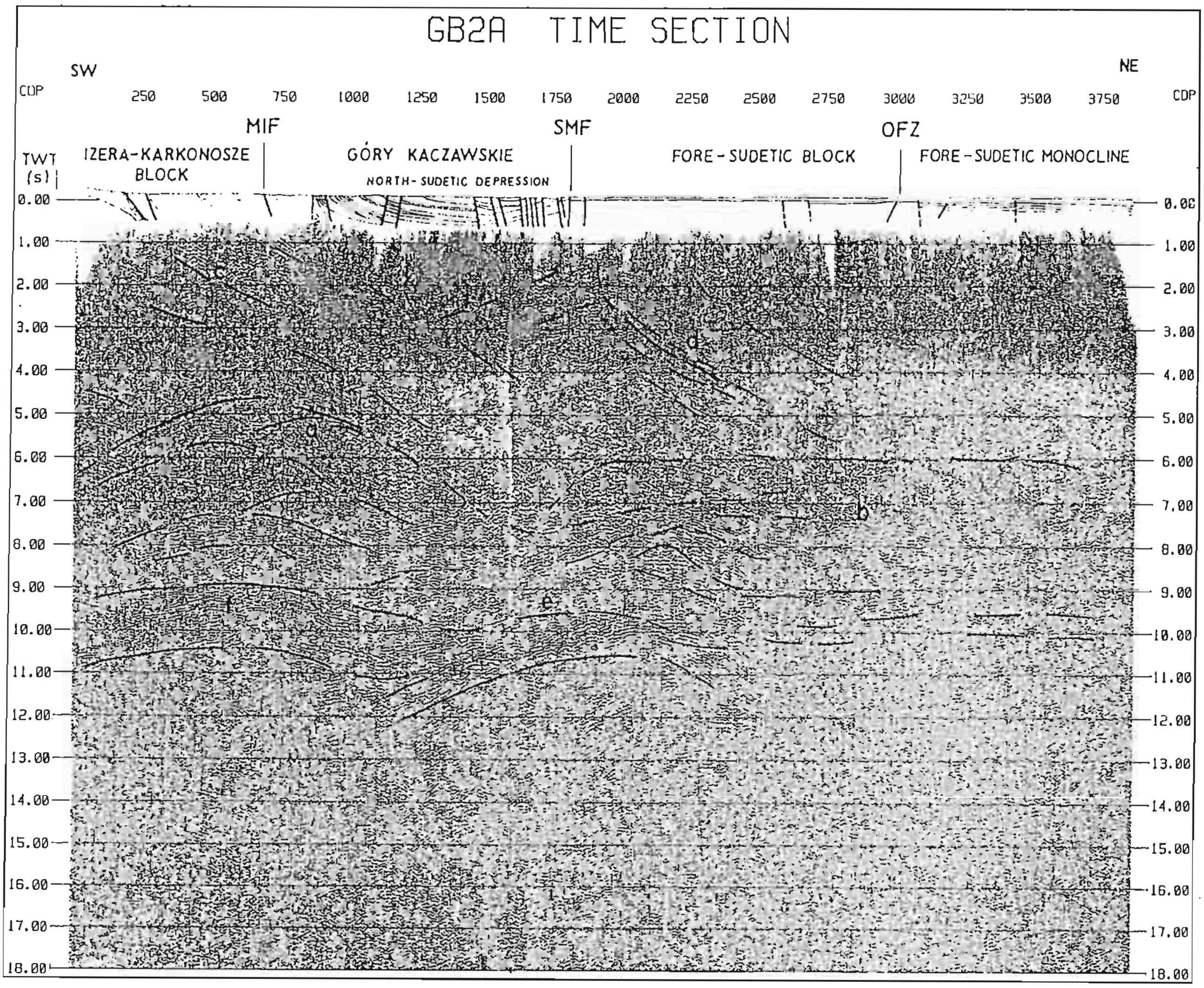

Fig. 5. The GB-2A reflection seismic profile unmigrated: interpreted
Explanations as in Fig. 1; for letter symbols see text

Refleksyjny profil sejsmiczny GB-2A bez migracji: interpretacja
Objaśnienia jak na fig. 1; oznaczenia literowe patrz tekst

RESULTS OF REFRACTION AND POTENTIAL FIELD STUDIES

EARLIER DATA

Earlier data along the DSS International Profile VII, parallel to GB-2A (Fig. 2), refraction data found Moho at the depth of 29–30 km in the Wielkopolska Block. It is bounded by the Dolsk Fault Zone (DFZ) and Odra Fault Zone (OFZ), and coincides with the Fore-Sudetic Monocline. A peculiar "transitional" zone, 3–6 km thick, occurs here in the lower crust immediately overlying the Moho (A. Guterch *et al.*, 1975, 1991). It is characterized by seismic velocities of 7.5–7.8 km/s. A similar "transitional" zone is found beneath the Odra Fault Zone. The latter is a c. 20 km wide horst of medium-grade metamorphic rocks intruded by Variscan granites and elevated on steep Permo–Triassic faults. This transitional zone here is 8 km thick, yet Moho occurs also at a depth of 30 km. The Sudetic crust on the contrary is thicker by c. 5 km, with Moho occurring also at a depth of 35 km, and is much richer in reflectors than crust under the Fore-Sudetic Monocline. However, refraction data do not point to crustal discontinuities.

Refraction data from the DSS VII International Profile were used to develop the velocity model along the GB-2A (Fig. 8). The model suggests a dome of denser lower crustal rocks under the Sudetes and a sag of less dense upper and middle crustal rocks under the Fore-Sudetic Block, which suggests extensional-compressional structures.

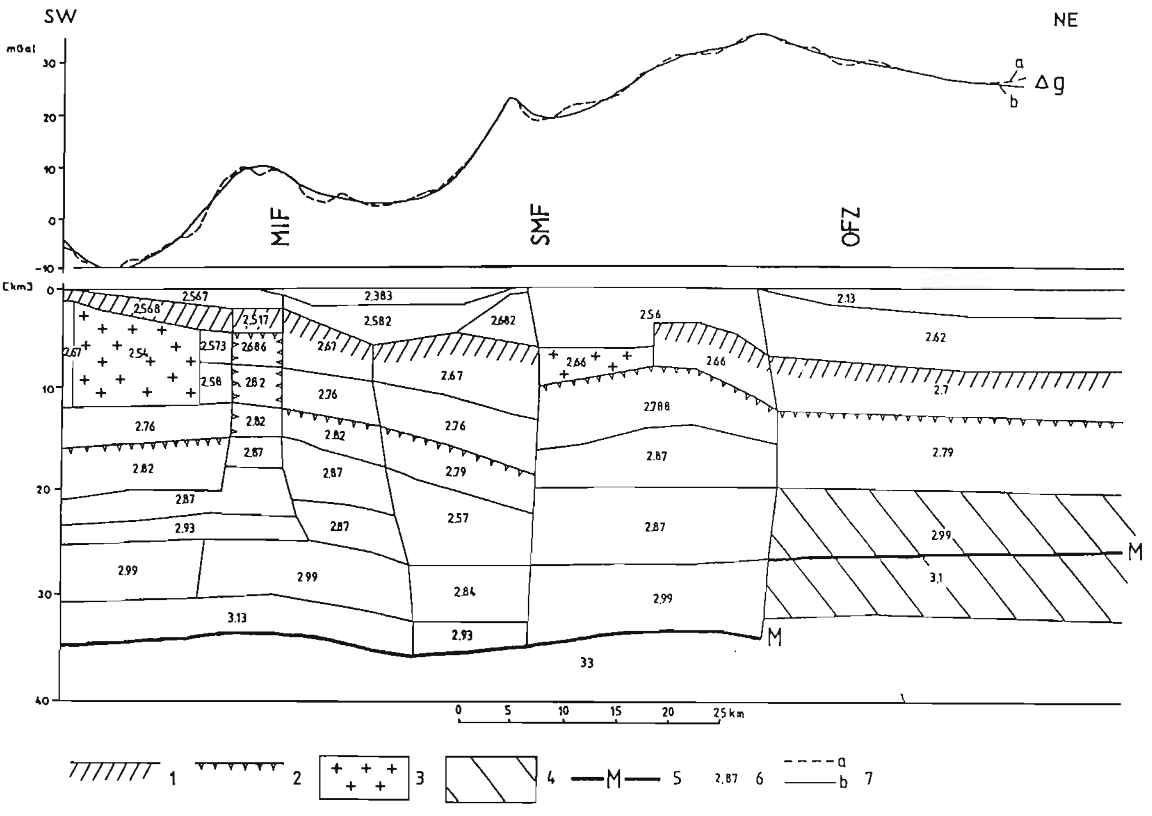

Fig. 6. Gravimetric modelling along the GB-2A profile

1 — theoretical gneiss basement; 2 — high of denser basement; 3 — granitic body; 4 — crust-mantle transitional zone; 5 — Moho; 6 — assumed densities; 7 — Δg curves: a — observed, b — computed; other explanations as in Fig. 1

Modelowanie grawimetryczne wzdłuż profilu GB-2A

1 — teoretyczne podłoże gnejsowe; 2 — wypiętrzenie cięższego podłoża; 3 — ciało granitowe; 4 — strefa przejściowa skorupa-płaszcz; 5 — Moho; 6 — przyjęte gęstości skał; 7 — krzywe Δg: a — obserwowane, b — wyliczone; pozostałe objaśnienia jak na fig. 1

From gravimetric data it is known that area of the GB-2A transect has its NE tip located on the southern slope of a regional positive anomaly (Krosno–Ostrzeszów) which originates in the pre-Permian basement (C. Królikowski, A. Grobelny, 1991), while its SW termination occurs in the centre of Izera–Karkonosze gravimetric low (–10 mGal). Generally gravimetric gradients stretch in the NW–SE direction, normal to the GB-2A transect. The Izera–Karkonosze low is produced by the c. 328 Ma (Rb-Sr) old Karkonosze granite and by older, c. 500 Ma Izera granites. The Karkonosze granite abuts against the MIF to the east (Fig. 1) and has a relatively steep interface with the Izera granite to the west, where the latter is at least 1600 m thick, according to borehole data. NE of the Main Intra-Sudetic Fault, in the vicinity of Bolesławiec, there is a hypothetical granitoid body underlying the Góry Kaczawskie and Fore-Sudetic Block, within the inferred footwall or the zone of the Sudetic Marginal Fault. Both the Main Intra-Sudetic Fault and Sudetic Marginal Fault coincide with discrete positive Bouguer anomalies (Fig. 6). The Main Intra-Sudetic Fault itself, although marked by a Bouguer anomaly, does not appear in the pattern of regional and residual gravity anomalies. NE of the Main Intra-Sudetic Fault gravimetric anomalies are positive, rising north-easterly and eventually exceeding 30 mGal in the northern part of the Fore-Sudetic Block, south of the Odra Fault Zone. This coincides with subcrops of greenstones drilled beneath the Cainozoic near Środa Śląska and Prochowice toward Pyszczyn (J. Jerzmański, 1991), but does not link with the Sudetic ophiolite which is exposed at the surface in the vicinity of the Góry Sowie Block and makes a distinct re-entrant of generally denser crust from the north into less dense crust on the south.

North of the Odra Fault Zone, in the Fore-Sudetic Monocline region, Bouguer anomalies are even higher, pointing to the presence of a still hypohetical mafic body (S. Cwojdziński *et al.*, 1991), which at the depth of 5000 m is inferred to form a discontinuous belt deflecting southward along the boundary between the West Sudetes and Moravo–Silesian Zone. Medium-grade crystalline rocks and granites occurring in the OFZ (= Odra metamorphics) separate this mafic body from the greenstones of the Góry Kaczawskie (Fig. 1). Further NE, near Wschowa, there is another gravimetric anomaly (60 mGal), whose origin is, however, poorly understood because of lack of any surface control (Fig. 2). The gravimetric highs and lows here may be caused by either differences in the depth of Moho, or by differences in the composition of the crust.

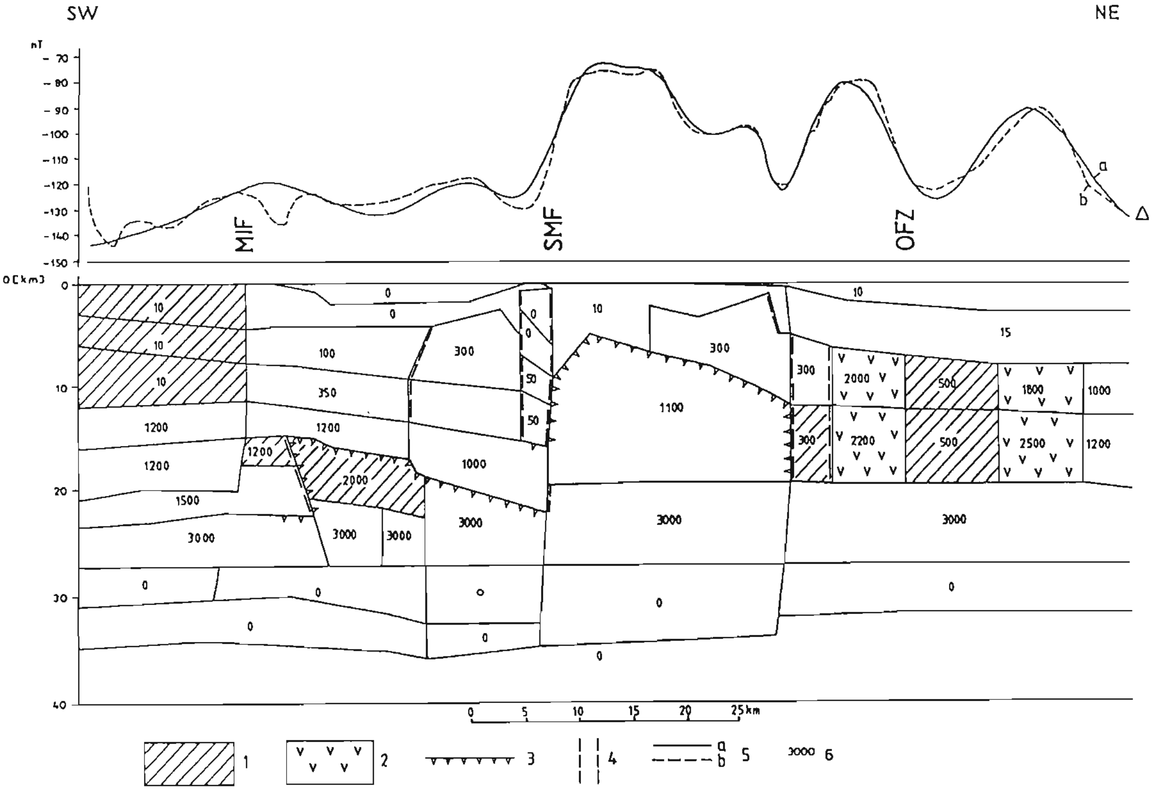

Fig. 7. Magnetic modelling along the GB-2A profile

1 — body of low magnetic susceptibility; 2 — body of high magnetic susceptibility; 3 — basement high of rocks of increased magnetic susceptibility; 4 — boundaries of high magnetic gradients; 5 — ΔT curves: a — observed, b — computed; 6 — magnetic susceptibility in SI units; other explanations as in Fig. 1

Modelowanie magnetyczne wzdłuż profilu GB-2A

1 — ciało o niskiej pobudliwości magnetycznej; 2 — ciało o wysokiej pobudliwości magnetycznej; 3 — wypiętrzenie podłoża o wysokiej pobudliwości magnetycznej; 4 — granice wysokich gradientów magnetycznych; 5 — krzywe Δ*T*: a — obserwowane, b — wyliczone; 6 — pobudliwość magnetyczna w jednostkach SI; pozostałe objaśnienia jak na fig. 1

The granite-gneiss basement of the low-grade Palaeozoic succession is modelled for the Góry Kaczawskie at the depth of 3–4 to 5–6 km in SE and NW part of the Góry Kaczawskie, respectively (A. Pepel, G. Koff, 1992; A. Pepel, S. Cwojdziński, 1994). By backstripping and transforming the gravimetric data a tentative reconstruction of the crustal structure at a depth of 5000 m was generated, which suggests a significant number of granite bodies (S. Cwojdziński *et al.*, 1991). Based on geophysical data, S. Cwojdziński (1992) discussed both thin-skinned and thick-skinned collisional models for the Sudetes, predicting N-dipping crustal faults south of the OFZ.

RECENT GRAVIMETRIC AND MAGNETIC MODELLING ALONG THE GB-2A PROFILE

GRAVIMETRIC MODELLING

Figure 6 shows a two-dimensional density-depth model of the crust along the GB-2A transect based on existing, semi-detailed, gravimetric survey, geological and seismic results, prepared on the basis of data presented by A. Pepel (1995). The model was constructed using the results of the International DSS Profile VII projected onto the GB-2A profile. Generally the observed gravity anomaly curve shows a distinct increase north-eastwards, with a maximum above the NE part of the Fore-Sudetic Block (FSB) near the boundary between the FSB and Odra Fault Zone (OFZ). This gravitational effect can be explained by the presence of a transitional zone in the lower crust with a layer of assumed density of 2.99 g/cm^3 at the depth of 25 km. The Moho, interpreted here as the upper boundary of a layer with density of 3.30 g/cm^3, lies at a depth of 34–35 km under the Sudetes and most of the Fore-Sudetic Block, while it is elevated to a depth of 28–27 km under the NE part of the FSB and further north under the Fore-Sudetic Monocline, with a 10 km thick transitional zone.

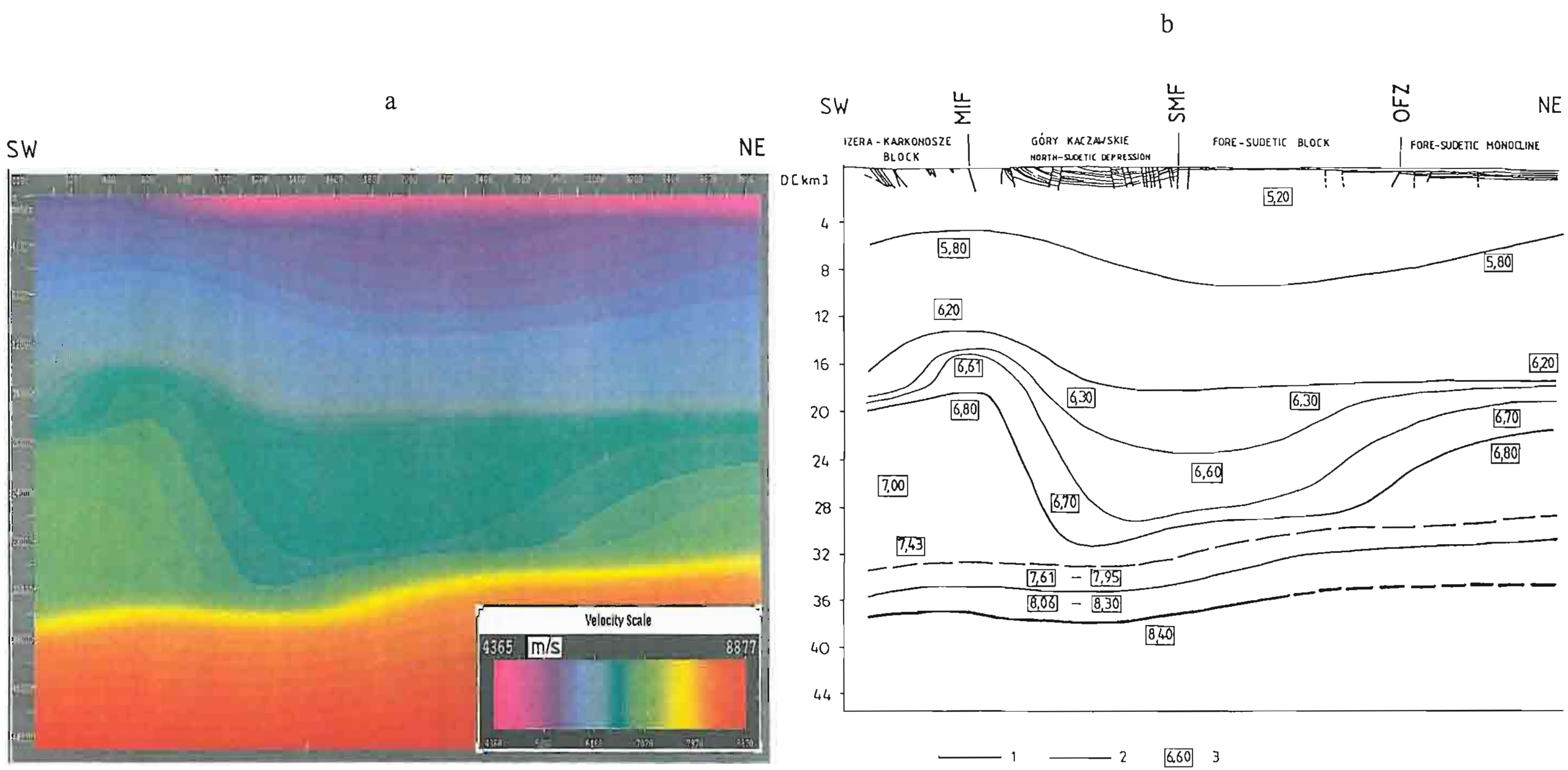

Fig. 8. Velocity model for the crust along the GB-2A seismic profile: **a** — coloured scheme, **b** — velocity model with surface geology
1 — Moho; 2 — boundaries of main crustal blocks; 3 — seismic velocities; other explanations as in Fig. 1

Model prędkości fal sejsmicznych dla skorupy wzdłuż profilu GB-2A: **a** — schemat kolorowy, **b** — schemat z naniesioną sytuacją geologiczną znaną z powierzchni
1 — Moho; 2 — granice głównych bloków skorupy; 3 — prędkości fali sejsmicznej; pozostałe objaśnienia jak na fig. 1

A

B

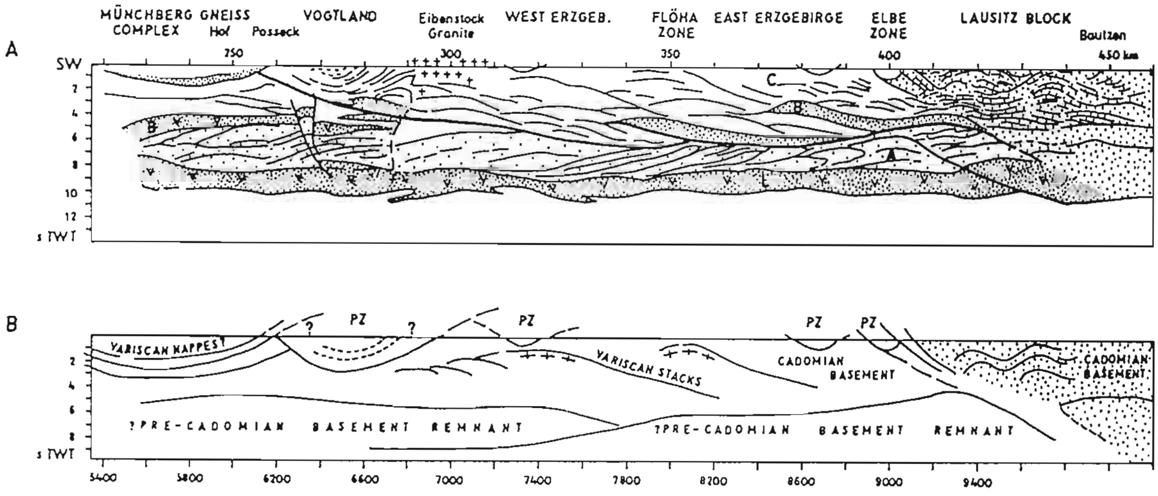

Fig. 9. Geologic interpretation of crustal structure along the DEKORP MVE-90 (East) profile (DEKORP Research Group (B), 1994); stratification of the crust is due to tectonic deformation; **A** — compressional structures in the Saxothuringian Zone; **B** — Cadomian and Variscan elements of the crust

Layer A is transparent and probably preserves older tectonic features; layers **B** have strong reflective lamellae, probably mylonites and shear bands developed during Hercynian compressional stacking episode; layer C is a transparent uppermost crust, which lacks noticeable reflectors due to widespread granitization; layer L — high reflective layer in the lower crust; PZ — Palaeozoic metasedimentary succession?; dots — diverse crustal blocks; crosses — Eibenstock Granite

Interpretacja budowy skorupy wzdłuż profilu DEKORP MVE-90 (East) (DEKORP Research Group (B), 1994); warstwowanie skorupy jest wynikiem deformacji tektonicznych; **A** — struktury kompresyjne w strefie saksońsko-turyngskiej; **B** — kadomskie i waryscyjskie elementy skorupy

Warstwa **A** jest sejsmicznie przezroczysta i przypuszczalnie składa się ze starszych struktur tektonicznych; warstwa **B** jest silnie refleksyjna i zawiera mylonity oraz strefy ścięciowe powstałe w trakcie waryscyjskiej kompresji i nasuwania; warstwa **C** jest sejsmicznie przezroczysta głównie wskutek rozległego tworzenia się granitów waryscyjskich; warstwa **L** jest silnie refleksyjną dolną skorupą; PZ — skały paleozoiczne (baseny lub jednostki allochtoniczne?); kropki — różne bloki skorupy; krzyżyki — granit Eibenstock

The gravity model assumes a drastic change of the crustal structure near the NE margin of the Sudetic Block and under the FSB, with no significant role played by the Odra Fault Zone, but with a well marked impact in the upper crust from the Sudetic Marginal Fault and the Main Intra-Sudetic Fault. Strong, horizontal density gradients occur in these two major fault zones. A domal structure, inferred from the seismic data, in the middle crust under the Sudetes and the SW part of the FSB is also well recognizable in the density pattern.

In the upper crust two blocks of uplifted denser basement are assumed. One occurs under the Izera–Karkonosze Block–Góry Kaczawskie boundary in the MIF zone reaching the crustal level as high as 5–6 km below surface. The other is much wider and deeper in the Fore-Sudetic Block (Fig. 6). In the middle crust this basement shows densities of 2.82–2.87 g/cm^3 characteristic of mafic gneisses and some metabasites. The local negative anomaly under the Góry Kaczawskie unit is interpreted as caused by shallow granite/gneiss basement, at least in part probably of the Izera gneiss type that (re)appears at the surface in the Wądroże Wielkie inlier. Two low density, probably granitic, bodies are responsible for the negative anomaly under the Izera–Karkonosze Block (Karkonosze granite) and the northeastern Góry Kaczawskie (Bolesławiec granite; continuation or counterpart of the Strzegom granite).

MAGNETIC MODELLING

The magnetic modelling along the GB-2A is based on a semi-detailed magnetic survey and was prepared by A. Pepel (1995). The depth/rock susceptibility model refers to the observed ΔT curve which shows much more diverse magnetic properties of the rocks in the Fore-Sudetic Block and Fore-Sudetic Monocline areas as compared to those of the Sudetic Block (Fig. 7). Shallow basement of higher magnetic susceptibility is typical of the Fore-Sudetic Block. Distinct diferrences in magnetic properties are observed near the Odra Fault Zone. These are probably caused by mafic, steeply dipping bodies in the deeper basement located on both sides of the Odra metamorphic horst (= Odra Fault Zone). The southern body is represented by greenstones of basaltic tuff and lava derivation, found in boreholes near Środa Śląska and Prochowice, representing the continuation of the Góry Kaczawskie metavolcanic rocks to the Fore-Sudetic Block (J. Jerzmański, 1991). The northern body, occurring to the NE of the Odra Fault Zone, is more enigmatic as known but from magnetic data. On the magnetic map this produces a discontinuous belt of discrete anomalies possibly linking to the west with those assigned to the Vesser complex (Fig. 2). A deep-seated body of increased magnetic susceptibility may be responsible for local magnetic anomaly in the Main Intra-Sudetic Fault (MIF) zone. The model predicts its presence at a depth of 15–22 km, but well off the MIF zone. A big body of low magnetic susceptibility corresponds with Izera and Karkonosze granites in the Izera–Karkonosze Block. Blocks of strong horizontal magnetic gradient and vertical boundaries are distinctly connected with the three major fault zones transected by the GB-2A profile (OFZ, SMF, MIF). Contrary to the gravity and seismic data the Odra Fault Zone is only portrayed by magnetic measurements. Approximately established blocks in the upper and middle crust along the GB-2A profile roughly coincide in the gravimetric and magnetic models, and the two well portray a domal structure in the crust under the Sudetes found on the seismic image.

COMPARISON WITH NEIGHBOURING DEKORP PROFILES

The GB-2A profile may be considered an overlapping continuation of the DEKORP MVE-90 (East) profile to the north-east, but shifted c. 100 km to the south-east (Fig. 2). Because of an arcuate trend of major Variscan units, the Saxothuringian Zone and Lusatian Anticlinal Zone contain the exposed 680–540 Ma Cadomian basement cross-cut by the DEKORP MVE 90 profile (DEKORP Research Group (B), 1994) are also intersected by the GB-2A profile. Thus similarities of crustal structures along the two profiles may be expected. Both show the same intricate crustal architecture, with the c. 14–15 km thick granite-granodiorite-gneiss upper layer and evident N-dipping reflectors (Fig. 9). In the DEKORP profile these emerge at the surface as sets of Lusatian faults and Saxonian faults at the Elbe Zone. The upper layer is, however, generally less reflective than the lower layer comprising amphibolite and gneisses at the top and metabasite or mafic granulite at the base, with Moho located at 36–30 km. In the lower layer subhorizontal megalenses of less intense reflections occur. In the DEKORP MVE-90 profile less reflective crustal lamina, with mostly southerly dipping shallow reflectors, is located between the Moho and a mid-crustal level characterized by a more densely packed bunch of subhorizontal reflectors. This mid-crustal level is interpreted as a tectonic unconformity and detachment separating possibly the pre-Variscan lower crust stacked to the north/north-east to form the Variscan upper crust overwhelmed by SE-vergent listric thrusting and far-traveled nappes (P. Bankwitz, E. Bankwitz, 1994). Accordingly it is supposed that the crustal architecture along the DEKORP MVE-90 and DEKORP 2S profiles is that of multi-level structure with possibly a pre-Cadomian(?) basement remnant in the lower crust and Cadomian upper crust in the Saxothuringian Zone capped by Palaeozoic sedimentary rocks in localized basins (Fig. 9). Two different(?) segments of Cadomian crust have been convergent along the Elbe Fault Zone, with the Lusatian Block thrust over the Erzgebirge Block during Variscan and Mesozoic compression (DEKORP Research Group (B), 1994). However, the Elbe Fault Zone has even older, Proterozic foundations (P. Bankwitz, E. Bankwitz, 1994) and represents long-lived crustal fractures. Variscan convergence left the hangingwall Lusatian Block undeformed, but caused severe thrusting in the footwall Erzgebirge Block of the Saxothuringian Zone (STZ). The STZ has been pierced by younger granite stocks (Eibenstock, Floha, etc.) rooted in the lower crust and identified by virtue of less reflective domains. The Cadomian crust of the STZ was strongly reworked during Hercynian times, which is one of the most important features of the Erzgebirge Block (and the whole STZ). The Erzgebirgian crust seems to continue as far as the Frankonian line, where it is distinctly offset.

NE of the Elbe Fault Zone, the upper crust contains domed reflectors, which resemble the Izera (Sudetic) sector of the GB-2A transect, though the domes here are more gentle, located much higher in the crust and do not extend to the lower crust. The GB-2A profile contains part of the Lusatian Block and it is the very block that houses the domed lower crust.

INTEGRATED INTERPRETATION OF THE GEOLOGIC STRUCTURE OF THE CRUST

Having integrated all kinds of available geophysical and geological data at least two alternative models of the crust in SW Poland can be constructed. Both take into account the same set of input information featured above and draw on (1) the presence of Cadomian crust in the IKB, (2) structure on the GB-2A profile inferred from the velocity model related to the nearby DSS VII International Refraction Profile (Fig. 8), (3) seismic velocity model of the crust along the southwestern section of the LT7 profile in Western Poland (A. Guterch *et al.*, 1994).

The Cadomian crust, continuing from Lusatia, is also directly exposed at the surface in the western Izera–Karkonosze Block (IKB). However, despite vast outcrops of granodiorites, there are gravimetric highs in Lusatia, whereas the IKB and Góry Kaczawskie (GK) regions are characterized by gravimetric lows extending to the Erzgebirge across the Elbe Fault Zone (Fig. 2). Also a magnetic low is characteristic of the whole IKB and GK, while positive anomalies are seen in Lusatia. Thus the main reason for the negative anomalies in IKB and GK must lie in the massive occurrences of granites

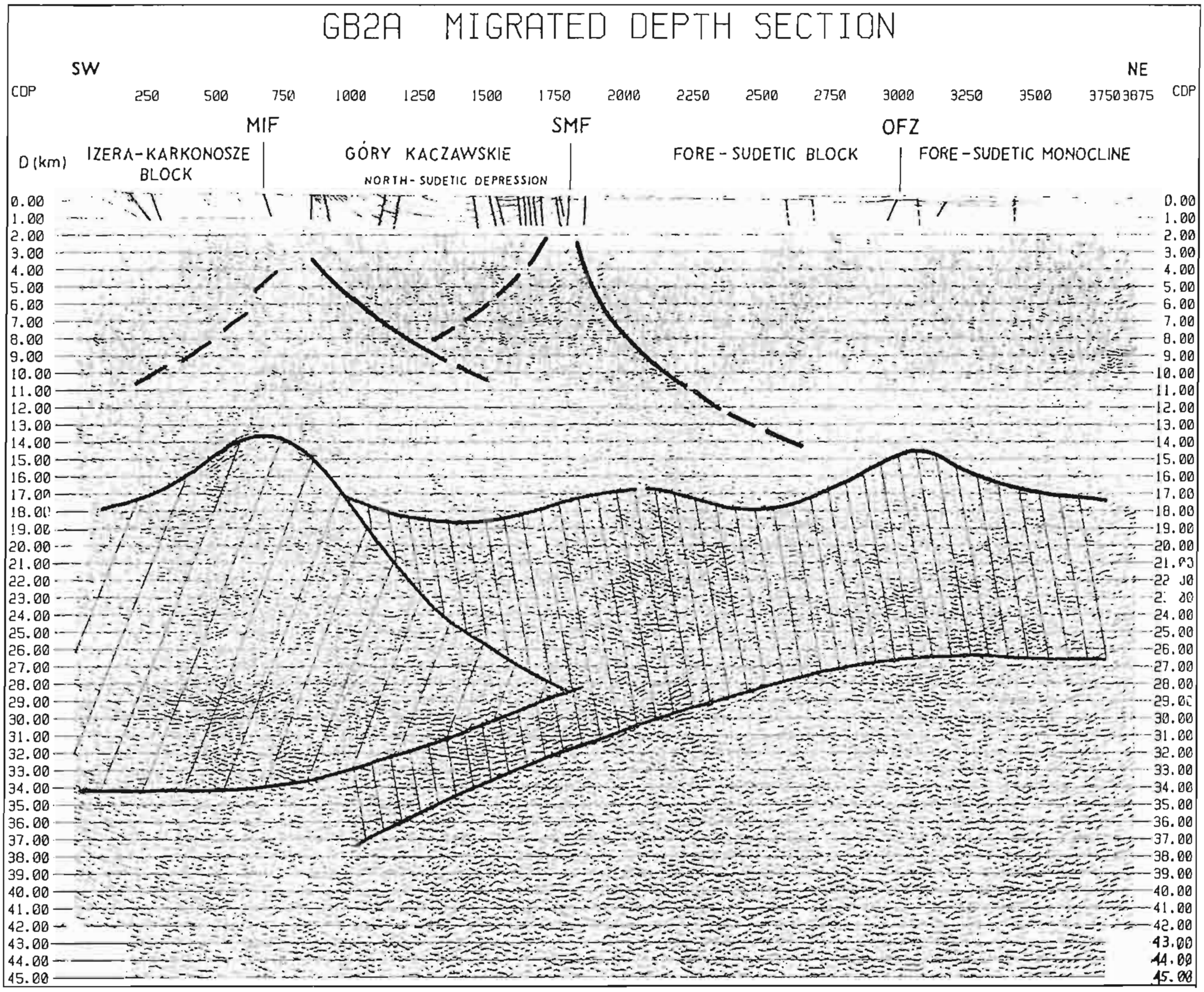

Fig. 10. Depth migrated section with interpretation of a deep-crustal structure
Different ruling denotes crustal blocks described in the text; explanations as in Fig. 1

Profil GB-2A po migracji głębokościowej z interpretacją głębokoskorupowych struktur
Skośne liniowanie oznacza bloki skorupy opisywane w tekście; objaśnienia jak na fig. 1

produced during Variscan orogeny, connected with a heat pulse(s) not suffered by Lusatia. Thus the Cadomian crust is exposed in Lusatia which has remained almost untouched by Palaeozoic thermal processes, but it has been strongly reworked in the IKB (and other Sudetic units) owing to vast intrusions of granites at 515–480 and 340–300 Ma. Accordingly, the IKB–GK crust should be similar to that of the Erzgebirge at Eibenstock or Floha sections, where seismic reflectors in both upper and lower crust are hardly legible due to the presence of unreflective granite plutons which apparently originated in the lower crust. However, in the IKB–GK section such diffuse reflectors occur only in the upper crust, to which the Karkonosze Granite has to be confined, without the possibility of rooting it in the lower crust. To the contrary, the middle and lower crust under IKB–GK consists of densely packed arched reflectors forming a kind of dome. The cause of these reflectors is unknown; either rheological/lithological boundaries, or flat-lying ductile shear zones are equally conceivable. The latter may be considered owing to their presence reducing P-wave velocities as found in the Kola Superdeep Borehole (B. J. Carr *et al.*, 1996).

The presence of a discrete updoming of the lower crust (≈ metabasites and mafic granulites; 6.6–7.2 km/s) under the Sudetes, associated with pronounced downbuckling of the mid-crust (≈ gneisses and amphibolites; 6.3–6.6 km/s) under the Fore-Sudetic Block (FSB) is strongly suggested by seismic velocity structure (Fig. 8). The lower crustal rocks seem to occur at 14–15 km depth under the Sudetes, and at 28 km depth under the FSB, and again shifted to c. 16 km depth and considerably reduced under the Fore-Sudetic Monocline (Figs. 3–5, 8 and 10). A dome of denser lower crustal rocks (metabasites, mafic granulites) under the middle of the

Sudetes adjacent to a crustal "basin" of lighter rocks (≈ gneisses and amphibolites) in the present-day seismic structure of the Sudetes permits two models (Fig. 11A, B). One is a model of two lithospheric plates arranged in a "crocodile" manner, with the northern plate being subducted and obducted southwards (flake tectonics) (largely Cadomian) (see R. Meissner, P. Sadowiak, 1992). The other is a model of extended lithosphere on crustal listric faults, with sediments accumulated in hangingwall basins and then inverted on the same crustal faults (Cadomian and Variscan structures developing in a similar geodynamic setting) active throughout the Phanerozoic times. The third model is a combination of the previous two, i.e. the Cadomian flake effect is taken over by a Palaeozoic extension-compression regime (Fig. 11C). The provenance of the two colliding Neoproterozoic plates is unclear. Gondwana is one of the possible ultimate sources. The other, however, is an ancient continental lithospheric fragment which was moved off the East European Craton along the future Teisseyre-Tornquist line during Neoproterozoic (1.4–1.0 Ga) rifting of pre-Baltica. Evidence for Baltica-borne rocks in the severly reworked basement of the Sudetes comes from U-Pb and Pb-Pb ages of inherited zircons found in c. 500 Ma (meta)granites and in the Góry Sowie metasediments (see A. Żelaźniewicz, in press).

The boundaries between Cadomian terranes occur in the middle of the Sudetes and roughly coincide with the Sudetic Marginal Fault–Main Intra-Sudetic Fault area (Figs. 1, 2, 10 and 11). Hence the Sudetic ophiolite, which is adjacent to the Góry Sowie Block (GSB) but not linked with the Palaeozic succession (A. Żelaźniewicz, in press), might represent the Cadomian (Neoproterozoic) oceanic crust and collision products that were exposed at the surface together with diapiric gneisses and migmatites of the GSB subjected to heating and migmatization by Middle Devonian (= Eovariscan) times (M. Bröcker *et al.*, 1997). The composite model (Fig. 11C) seems to best fit the surface geological, structural and geochemical data and thus is favoured in this paper. Also it is internally consistent with all palaeomagnetic data released so far for the Sudetes, suggesting proximity of the Sudetic rocks (Izera–Karkonosze Block, Sudetic ophiolite, Góry Bardzkie) to Avalonia in Early Ordovician times and from 450 Ma onwards to Baltica (M. Jeleńska *et al.*, 1995, in press; J. Nawrocki, A. Żelaźniewicz, 1996). Some difficulties in reconciling these data with some palaeogeographical models do not dismiss the internally consistent Sudetic data, but simply point to considerable inaccuracies of the proposed reconstructions for central Europe (*cf.* A. Żelaźniewicz, in press). Denser rocks of the southern ("Sudetic") plate seem to represent crust other than that of the northern ("Fore-Sudetic") plate. The Cadomian sutured crust was subjected to rifting and extension during the Palaeozoic. This allowed for bimodal ensialic volcanism grading to N-MORB with the maximum crustal attenuation in the Góry Kaczawskie as well as East and South Karkonosze. The Izera–Karkonosze Block recorded the Early Palaeozoic extension by means of a swarm of basic dikes geochemically akin to volcanic rocks of the Góry Kaczawskie and intruded into a footwall passive margin of the main extensional fault zone (A. Żelaźniewicz, 1994). The zone had oblique strike-slip sinistral WNW–ESE kinematics with a strong normal component. No seismic features extending from the surface down to the Moho are in evidence.

The age and lithospheric (palaeogeographical) plate provenance of this updomed lower crust is unknown. The lower and middle crust underneath, arranged in large-scale S-dipping intracrustal wedges may possibly preserve Cadomian or older lithospheric features related to southward subduction. Such structures are found along strike on the DEKORP MVE 90 profile in Lusatia, where the Cadomian Lusatian Block thrust over the Cadomian crust exposed in the STZ (DEKORP Research Group (B), 1994).

Discrete gravimetric and magnetic highs are also widespread in the Fore-Sudetic Monocline (FSM). The FSM crust is characteristically composed of two main layers: an upper one with velocities 5.7–6.3 km/s occurring between 3–18 km and a lower one characterized by 6.5–6.8 km/s between 18 and 30–35 km.

Palaeozoic extension and largely intraplate basin development were accomplished on the roughly N-dipping crustal faults reworking the Cadomian crust. Late Variscan inversion and convergence produced a domal stack of reflectors within previously extended crust and downbuckled the Moho in the Sudetic sector (Figs. 8 and 10). The same features were utilized subsequently by normal faulting connected with the formation of the Central Polish Basin during Permo–Mesozoic times. A bunch of inclined reflectors in the upper crust north of the Sudetic Marginal Fault marks the boundary between the Sudetic Block (SB) and Fore-Sudetic Block (FSB). In the seismic image this boundary appears the most important crustal listric fault zone in SW Poland, with the FSB thrust over the SB. Such a geometry of crustal features does not show the expected northern orogenic polarity for the Variscan orogen but agrees well with the ubiquitous evidence of southward (back?) thrusting operating during the Late Carboniferous–Permian and then repeated during the Late Cretaceous. Meanwhile these faults probably allowed the Mesozoic extension.

The Fore-Sudetic Block–Fore-Sudetic Monocline Block differs distinctly from the Sudetic Block by the absence of a distinct middle crust and much poorer reflectivity. The latter contains subhorizontal sets of stacked anastomosing reflectors produced by repeated N–S buckling or successive N- and S-vergent shortening. The "consolidated" crust level rises to shallow levels near the Odra Fault Zone and then deepens. At the Sudetic Marginal Fault section, especially on the unmigrated version of the GB-2A profile, in the lower crust a discrete roll-over structure on the northern slope of the mantle swell (Fig. 5) also points to localized late extension triggering an uprise of post-orogenic granite masses (Strzegom–Sobótka and other massifs). The extensional setting was probably connected with the late Variscan collapse, which followed the northward verging shortening during the main Variscan event.

Listric segments are, however, unclear and the Main Intra-Sudetic Fault (MIF), sometimes speculated as the Baltica–Gondwana Plate suture left behind the south-subducted Tornquist ocean (G. J. H. Oliver *et al.*, 1993; see A. Żelaźniewicz, W. Franke, 1994) is not seen. The step-wise down-faulting of the crystalline basement underneath the Kaczawa

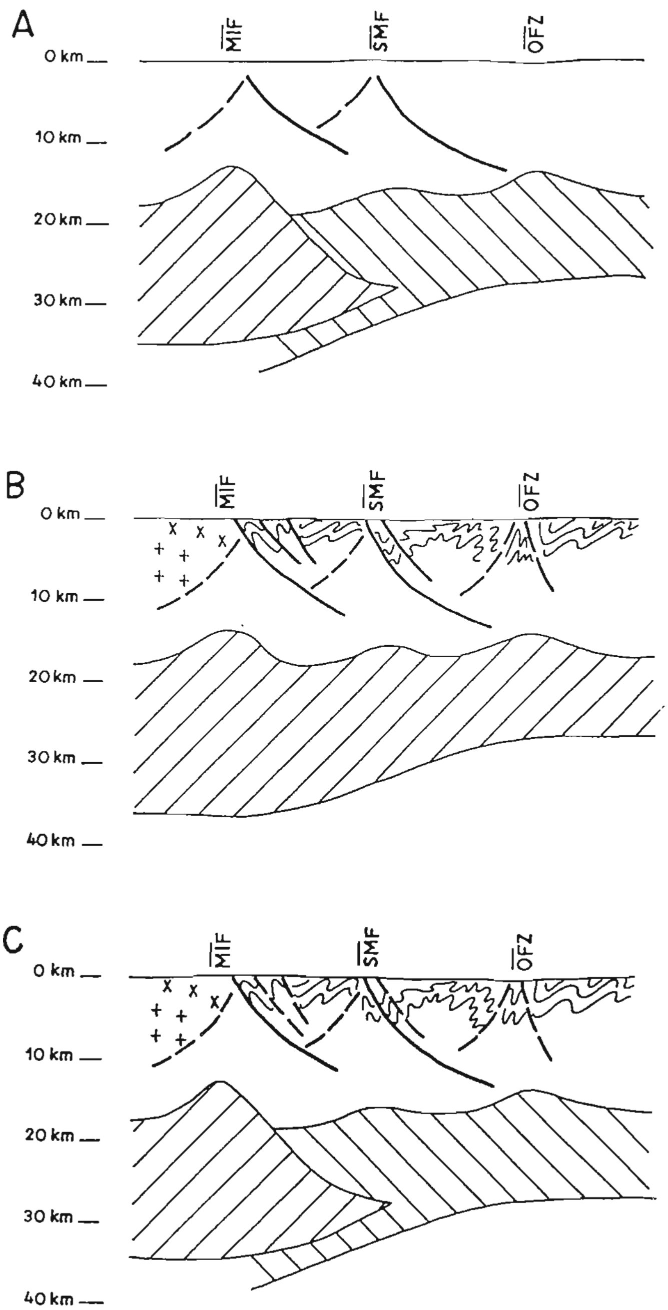

Fig. 11. Feasible models of crustal structure in southwestern Poland: **A** — flake model for lower crust of Cadomian age; **B** — extended-shortened crust model with Cadomian lower crust and Palaeozoic upper crust; **C** — composite model of Cadomian "crocodile" structure in the crust attenuated during Early Palaeozoic and reworked during Late Palaeozoic tectonic inversion on N-dipping major faults

Oblique ruling — blocks of Cadomian lower crust; blank — Cadomian upper crust; x — 515–480 Ma granitegneiss; + — 330–300 Ma granite; folded pattern — metasediments of inverted Palaeozoic basin; other explanations as in Fig. 1

Możliwe modele budowy skorupy w południowo-zachodniej Polsce: **A** — model złuszczeniowy z dolną skorupą wieku kadomskiego; **B** — model skorupy wielokrotnie rozciąganej i skracanej: dolna skorupa wieku kadomskiego, górna skorupa wieku paleozoicznego; **C** — złożony model kadomskiej struktury „krokodylowej" w skorupie wycienionej we wczesnym paleozoiku i przebudowanej w trakcie późnopaleozoicznej inwersji wzdłuż dużych uskoków zapadających ku N

complex units indicated by gravimetric modelling points to the extensional character of the MIF and other NW-trending faults.

F. Kossmat's classic zonation of the Variscan orogen is hardly legible on the GB-2A (Figs. 1–5). Either it has little impact on the whole crust in the Sudetes, or it is a very upper crustal feature which is not resolved by the data. Apart of the Saxothuringian Zone (STZ), the Mid-German Crystalline Rise (MGCR) and the Rhenohercynian Zone (RHZ) should be expected to continue to southwestern Poland. Also the Vesser suture should be identifiable between the MGCR and the remaining part of the STZ further south (Fig. 2). Published interpretations of the DEKORP MVE-90 (East) and DEKORP MVE-90 (West) profiles (DEKORP Research Group (B), 1994; DEKORP Research Group (C), 1994) suggest that a positive magnetic anomaly belt seen in Germany from Schwarzwald to Doberlug does not extinct there but instead deflects to the east and continues, though as a much narrower belt, to Poland where it coincides with positive magnetic anomalies reported from the northern side of the Odra Fault Zone (OFZ) and medium-grade metamorphic rocks uplifted within it (Fig. 2). Given the continuity, consequently the MGCR would have to occur further to the NE, in the Fore-Sudetic Monocline, well below not only the Permo–Mesozoic cover but also Lower Carboniferous flysch and Upper Carboniferous molasse. Accordingly, the Góry Kaczawskie Block (GK) including the greenstone belt of Środa–Prochowice–Pyszczyn (south of OFZ) would represent the Saxothuringian Zone (STZ). The latter conclusion is consistent with most regional interpretations (e.g. W. Franke *et al.*, 1993), except P. Aleksandrowski (1995) who prefers to include the GK into the Rhenohercynian Zone (RHZ). However, then the Odra metamorphic rocks (OM) subcropping under the Triassic in the OFZ basement horst cannot be taken as equivalent of the MGCR despite many recent propositions (F. Ellenberger, A. L. G. Tamain, 1980; A. Grocholski, 1986), but should be treated as a continuation of the crystalline rocks from the eastern Fore-Sudetic Block (FSB). This has already been proposed by S. Cwojdziński, A. Żelaźniewicz (1995) who assigned the OM and FSB rocks to the Kamieniec complex, pointing to a paucity of data for positive verification of the supposed link between OM and MGCR.

Although placing the MGCR under the Fore-Sudetic Monocline (FSM) cover would account for the presence of otherwise mysterious granites there (even north of Poznań), it makes it difficult to explain a Carboniferous cap over the MGCR. This interpretation conflicts with a known geodynamic position of the MGCR in Germany, where it is taken as a magmatic arc shedding clasts into a Late Devonian–Carboniferous foreland basin. Unless it is assumed the MGCR–RHZ boundary is located further north under the FSM and southward backthrusting of the foreland and molasse rocks

Linie skośne — bloki kadomskiej dolnej skorupy; bez ornamentacji — kadomska górna skorupa; x — granitognejsy wieku 515–480 Ma; + — granity wieku 330–300 Ma; linie faliste — zmetamorfizowane skały paleozoicznych basenów po tektonicznej inwersji; pozostałe objaśnienia jak na fig. 1

over the former magmatic arc has occurred, it is impossible to account for such a scenario. South-vergent reflectors identifiable on the GB-2A transect might have represented the backthrusting, but the transect is outside that part of the FSM, which might have contained the MGCR. However, the southward transport is also incompatible with the situation recognized in the RHZ on either side of the Rhine River. Therefore, in our interpretation the N-dipping reflectors in GB-2A are interpreted as Early Palaeozoic normal faults related to ensialic extension, followed by Late Palaeozoic inversion tectonics.

However, having considered the Bouguer anomaly map for Germany published by DEKORP Research Group 2 (P. Bankwitz, E. Bankwitz, 1994) gravimetric anomalies within the STZ are oblique to its external boundaries, thus becoming offset west of German-Polish boundary, and also the RHZ gets very narrow, tapering out just east of Frankfurt near Odra River. According to such an interpretation only the STZ which can be found in Poland (Fig. 2). This would account for why the generally granitic-dioritic (2.62–2.88 g/cm^3) crust shows structures pointing to repeated extension and shortening events, and why the presence of the STZ and RHZ boundary is invisible, nor the signs for the presence of MGCR can be detected on the seismic transect. Accordingly severe doubts are cast upon a commonly assumed direct continuation of the Rhenohercynian orogenic foreland flysch and molasse successions from the Rhineland to Moravo–Silesian Zone.

CONCLUSIONS

The crust of the SW Poland, particularly in the West Sudetes, has a wedge-layered internal structure, which may imply crustal subduction or delamination with the northern block (terrane) pushed over and under the southern one, probably as early as the Cadomian orogeny which exposed c. 680–540 Ma granodiorites at the surface. The main crustal suture of the A-subduction type is located beneath the Góry Kaczawskie. The southern block in the middle crust under the Sudetes consists of intracrustal nappes (slices) stacked at a depth of 10–15 km. This stack occurs at the top of a dome-like structure built of relatively dense rocks characteristic of the lower crust. This domal structure, with particularly well defined NE slope, is a real feature as confirmed also by gravimetric and magnetic modelling. The entire feature probably represents a Cadomian compressional event, then repeated during Variscan times, after Early Palaeozoic crustal extension. Alternatively, the crustal bulge under the Sudetes may represent a suture of two Cadomian terranes. The northern one would be compatible with rifted-off segments of proto-Baltica continental plate. The upper crust is composed of several wedge-like crustal blocks bounded by listric faults dipping generally to the north or north-east. Most important are two zones of this type: a southern zone, coinciding with the MIF, and northern zone, corresponding to the SMF. Seismic data indicate that MIF and SMF are not really occurring as deep-seated, subvertical crustal boundaries but rather they are listric faults. Their geological history is probably quite different from that hitherto presented. From Carboniferous times extensional deformation seems to dominate.

The schists belts with distinct mylonitic component in the Izera–Karkonosze Block are not portrayed on the depth migrated seismic image, probably because of their steepness. Their supposed listric geometries seem unlikely in view of the seismic data. Ductile shearing along these belts developed in strike-slip and normal regimes as evidenced by meso- and microstructural data.

No detachment has been found in the upper crust at the base the Palaeozoic succession of the Góry Kaczawskie. Thus its contact with light, granite-gneiss basement is a sedimentary disconformity, rather than a flat-lying, major tectonic discontinuity. Neither the presence of shallowly dipping thrust has been confirmed in the case of the Wądroże Wielkie inlier, which probably represents a common basement horst. An internal structure of the Palaeozoic succession is not portrayed by the seismic image, whereas weak, N- and S-dipping reflectors produced by extensional-compressional structures in its basement are in evidence. The transpressional thrusts locally recognizable in the field at the Izera–Karkonosze Block–Góry Kaczawskie border zone, are probably too shallow for the seismic resolution.

The Main Intra-Sudetic Fault (MIF) and the Sudetic Marginal Fault (SMF) are recognizable as NE-dipping, listric features on both the unmigrated and depth migrated seismic sections as well as on the gravimetric and magnetic profiles. The listric geometries of the MIF and SMF are confirmed by gravimetric modelling. The SMF is imaged as the most important fault zone of the whole GB-2A profile. Despite its brittle character at the surface, it is a deep-seated ductile shear zone rooted in the middle crust. Owing to the outcrop pattern evidence from the Góry Sowie Block the dominance of dip-slip movements on this zone is undoubted. Both the SMF and MIF are interpreted as persistent crustal features allowing for repeated extension and compression of the continental crust during the Palaeozoic and Mesozoic.

The Odra Fault Zone (OFZ) is well seen only on the magnetic models and remains illegible on gravimetric and seismic profiles. The latter case may be due to the steep attitudes of faults making the OFZ. On the contrary to the SMF and MIF, no more shallowly dipping ductile portion of this zone is imaged on seismic profile. This is partly consistent with a predominatly brittle-ductile nature of the OFZ developing mostly as a Permian–Mesozoic–Tertiary basement horst. Neither seismic nor gravity data permit to interpret mid-grade metamorphic rocks exposed in the OFZ as a continuation of the Mid-German Crystalline Rise to the east.

Generally the crust in southwestern Poland reveals many young features which implies its ongoing activity, with last manifestation of which is extensive Tertiary volcanism, but affecting crust basically composed of Cadomian and older elements.

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WARYSCYDY W SUDETACH I REAKTYWOWANY OROGEN KADOMSKI: WYNIKI SEJSMICZNEGO PROFILOWANIA REFLEKSYJNEGO GB-2A W POLSCE POŁUDNIOWO-ZACHODNIEJ

Streszczenie

Pierwszy sejsmiczny profil refleksyjny GB-2A, o długości około 100 km zlokalizowany w Polsce południowo-zachodniej, został zaprojektowany w celu rozpoznania struktury skorupy ziemskiej tego regionu. Został on wykonany prostopadle do walnych stref rozłamowych o biegu NW–SE przecinających NE część masywu czeskiego: głównego uskoku śródsudeckiego, sudeckiego uskoku brzeżnego oraz strefy uskokowej Odry. Uskoki te są długowiecznymi strukturami skorupowymi, o początkach sięgających wczesnego karbonu lub późnego dewonu. GB-2A przecina kolejno od SW ku NE: blok karkonosko-izerski, Góry Kaczawskie, blok przedsudecki i wkracza na monoklinę przesudecką (fig. 1 i 2).

W artykule zanalizowano zarówno niezmigrowaną (fig. 3), jak i zmigrowaną (fig. 4) wersję profilu sejsmicznego i porównano je z wynikami danych grawimetrycznych i magnetycznych oraz geologii powierzchniowej. Opracowano także model prędkościowy skorupy ziemskiej wzdłuż przekroju GB-2A na podstawie danych refrakcyjnych z VII profilu międzynarodowego (fig. 8) oraz przedstawiono modele grawimetryczne i magnetyczne (fig. 6 i 7). Uzyskane wyniki zostały porównane z rezultatami profili DEKORP 2S i MVE-90 w południowo-wschodnich Niemczech (fig. 9). Dysponując zintegrowanymi danymi geofizycznymi i geologicznymi, skonstruowano alternatywne modele skorupy w południowo-zachodniej Polsce, oparte na tym samym zespole danych wyjściowych.

Skorupa kadomska, odsłonięta w strefie antyklinalnej Łużyc, w bloku karkonosko-izerskim uległa intensywnym, paleozoicznym procesom tektono-termicznym w czasie 515–480 i 340–300 Ma. Stąd możliwe jest tu zacieranie refleksów sejsmicznych przez nierefleksyjne plutony granitoidowe. W przeciwieństwie do sytuacji w Górach Kruszcowych środkowa i dolna skorupa bloku karkonosko-izerskiego i Gór Kaczawskich zawiera łukowato ku górze wygięty, gęsty pakiet refleksów tworzących rodzaj kopuły (fig. 5). Obecność takiej kopuły złożonej ze skał dolnej skorupy (metabazyty, granulity maficzne) i jednoczesne wgięcie w dół skał środkowej skorupy (gnejsy, amfibolity) pod blokiem przedsudeckim sugerowane przez sejsmiczną strukturę prędkościową oraz przez dane grawimetryczne i magnetyczne (fig. 5–8). Skały dolnoskorupowe pojawiają się na głębokości 14–15 km pod Sudetami, 28 km pod blokiem przedsudeckim i ponownie na głębokości 16 km pod monokliną przedsudecką. Kopuła cięższych skał dolnoskorupowych pod Sudetami w sąsiedztwie skał lżejszych w dzisiejszej strukturze skorupy może być wyjaśniona przez dwa alternatywne modele skorupowe (fig. 11A, B). Pierwszy z nich jest modelem dwóch płyt litosferycznych, będących w kontakcie typu krokodylowego, przy czym płyta północna jest subdukowana i obdukowana ku południowi, najprawdopodobniej w wyniku tektoniki kadomskiej. Drugi to model litosfery rozciągniętej od ordowiku po wczesny karbon przez system skorupowych uskoków listrycznych, z paleozoicznymi basenami sedymentacyjnymi założonymi w strefie przypowierzchniowej, ulegającymi następnie inwersji tektonicznej wzdłuż tych samych uskoków we wczesnym karbonie. Model wynikowy (fig. 11C) jest kombinacją obu wspomnianych modeli. Na kadomski efekt złuszczenia nakłada się paleozoiczny reżim ekstensji-kompresji. Pochodzenie kolidujących płyt neoproterozoicznych jest niejasne. Jednym z możliwych źródeł jest Gondwana, innym — fragmenty litosferyczne oddzielające się od kratonu wschodnioeuropejskiego (proto-Baltiki) w trakcie neoproterozoicznego ryftowania wieku 1,4–1,0 Ga. Model ten najlepiej odpowiada istniejącym danym. Jest także zgodny z danymi paleomagnetycznymi, które sugerują bliskość Sudetów w stosunku do Awalonii we wczesnym ordowiku i do Baltiki od 450 Ma. Trudności, jakie model ten stwarza przy nawiązywaniu do obecnie proponowanych rekonstrukcji paleogeograficznych, wynikają z nieprzystawania tych ostatnich do obserwowanych w Sudetach faktów. Połączone wzdłuż szwów tektonicznych mikropłyty kadomskie uległy ryftingowi i ekstensji w paleozoiku. Doprowadziło to do intensywnego bimodalnego wulkanizmu przechodzącego stopniowo do typu N-MORB w Górach Kaczawskich, w południowych i wschodnich Karkonoszach, a także do powstania rojów dajek zasadowych w metamorfiku izerskim.

Wiek i pochodzenie kopulowatej dolnej skorupy są nieznane. Dolna i środkowa skorupa są ułożone w wielkoskalowy klin intrakrustalny zapadający ku S, który może stanowić kadomską lub starszą strukturę litosferyczną związaną z subdukcją skierowaną ku południowi. Paleozoiczna ekstensja, wywołująca powstawanie basenu śródpłytowego, wykorzystywała także uskoki skorupowe zapadające ku N, które przecinały skorupę kadomską. Późnowaryscyjska inwersja i konwergencja są odpowiedzialne za kopułowe spiętrzenie refleksów i wgięcie wgłąb Moho w sektorze sudeckim. Wiązka nachylonych refleksów w górnej skorupie na N od sudeckiego uskoku brzeżnego zaznacza granicę między blokiem sudeckim i przedsudeckim. Strefa ta jest najważniejszym listrycznym uskokiem skorupowym w Polsce południowo-zachodniej, przy czym blok przedsudecki jest nasunięty na blok sudecki. Taka geometria struktur skorupowych nie potwierdza północnej polarności orogenu waryscyjskiego, lecz wskazuje raczej na nasuwanie ku S, być może wsteczne, czynne w późnym karbonie i permie.

Blok przedsudecki i blok monokliny przedsudeckiej różnią się znacznie od bloku Sudetów pod względem poznanej struktury sejsmicznej i cech geofizycznych. Na odcinku sudeckiego uskoku brzeżnego widoczne w dolnej skorupie, na niezmigrowanej wersji profilu GB-2A, struktury typu *roll-over* leżące na zboczu wypukłości płaszcza wskazują na zlokalizowaną, późną ekstensję związaną z kolapsem waryscyjskim następującą po głównym, waryscyjskim wydarzeniu kompresyjnym. Segmenty listryczne są niejasne. Na przykład, główny uskok śródsudecki, interpretowany ostatnio jako szew miedzypłytowy Baltiki–Gondwany, nie jest dobrze widoczny. Dane grawimetryczne wskazują raczej na schodowe uskoki normalne, które obniżają krystaliczne podłoże pod kompleks kaczawski.

Z danych sejsmicznych wynika, iż tradycyjnie sugerowana cylindryczna strefowość orogenu waryscyjskiego, zaproponowana przez F. Kossmata, jest trudna do przyjęcia w całości w Polsce południowo-zachodniej — w każdym razie nie odbija się ona w strukturze całej skorupy, lecz co najwyżej w jej najwyższej partii. Wątpliwości nie budzi jedynie kontynuacja strefy saksońsko-turyngskiej. Przeanalizowane dane geofizyczne przemawiają za tym, iż potencjalny odpowiednik środkowoniemieckiego grzbietu krystalicznego w Polsce powinien leżeć pod monokliną przedsudecką znacznie bardziej ku północy niż zrąb metamorfiku środkowej Odry. Cały obszar bloku przedsudeckiego i co najmniej południowa część bloku monokliny przedsudeckiej wydają się wchodzić w skład strefy saksońsko-turyngskiej. Strefa reńsko-hercyńska w wykształceniu znanym z Nadrenii może w ogóle nie występować na obszarze Polski, lecz wyklinowuje się na wschód od Słubic i Frankfurtu nad Odrą (fig. 2). Ubóstwo danych geologicznych z podpermskiego i brak jakichkolwiek danych z podkarbońskiego podłoża monokliny przedsudeckiej nie pozwalają w tej chwili na jednoznaczną weryfikację tych wniosków. Skorupa ziemska Polski południowo-zachodniej odznacza się skomplikowaną strukturą i polifazową genezą. W skład jej wchodzi wiele młodych, mezozoicznych i kenozoicznych struktur, wskazujących na trwającą aż po pliocen aktywność, wszelako podstawowa skorupa składa się z kadomskich i starszych elementów tektonotermicznie reaktywowanych w fanerozoiku wczesnopaleozoiczną ekstensją i śródpłytowym wycienieniem, a następnie późnopaleozoiczną, waryscyjską kompresją i tektoniczną inwersją.