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Abstrakt. Sejsmiczne badania refleksyjne, zwłaszcza tzw. pionowa sejsmika refleksyjna stały się od początku lat osiemdziesiątych XX wieku głównym narzędziem badawczym skorupy ziemskiej, a także górnego płaszcza litosfery. Realizacja w ciągu ostatnich 20 lat wielu dużych, często międzynarodowych, projektów sejsmicznych umożliwiła uzyskanie ogromnej ilości informacji, które są zwykle interpretowane przy uwzględnieniu paradygmatu tektoniki płyt. Jednakże interpretacje te napotykają na znaczne trudności. Po pierwsze, trudne do wyjaśnienia jest zagadkowe podobieństwo struktury sejsmicznej skorupy kontynentalnej występującej pod różnymi genetycznie i wiekowo geostrukturami, a także jej symetryczność.

Podobieństwo refleksyjności sejsmicznej w różnych środowiskach geologicznych wskazuje na: (1) decydujący wpływ właściwości reologicznych litosfery na charakter refleksyjności oraz (2) wspólny proces tektoniczny odpowiedzialny za jej ukształtowanie. W zależności od warunków termicznych skorupa kontynentalna podlegająca deformacji kruchej sięga do głębokości 10–20 km. Poniżej tej granicy, odpowiadającej temperaturom 300–400°C, zaczyna się strefa odkształceń podatnych, w której dominuje płynięcie stanu stałego. Granica między strefą deformacji kruchej i podatnej jest nieostra, jej szerokość zależy od potoku cieplnego, a także od litologii. Kolejną granicą reologiczną jest powierzchnia Moho. W istniejących tam warunkach termicznych górny płaszcz podskorupowy odkształca się w sposób kruchy. Sejsmika refleksyjna potwierdza te zachowania reologiczne. Między lepkością litosfery kontynentalnej, a refleksyjnością sejsmiczną obserwuje się ścisły związek. W górnej skorupie krystalicznej, która ogólnie jest przezroczysta sejsmicznie, na wszystkich profilach występują nieliczne pakiety refleksów związane z dyslokacjami, na ogół o geometrii listrycznej, nachylone w różnych kierunkach i wypłaszczające się wraz z głębokością. Dolna skorupa jest zdominowana przez, penetratywne w skali dolnej skorupy, struktury subhoryzontalne, wiązane przez większość badaczy z deformacjami z płynięcia. Na granicy skorupy górnej i dolnej znajduje się strefa przejściowa, wydzielana niekiedy jako skorupa środkowa. W strefie tej zanika większość dyslokacji listrycznych. Występują tam śródskorupowe struktury wielkosoczewkowe, podkreślane przez pasma refleksów. Górny płaszcz podskorupowy charakteryzuje się przejrzystością sejsmiczną. Rzadko występują tam pasma refleksów zapadające w głąb pod niewielkimi kątami, odpowiadające wąskim strefom uskokowym. Tym samym, z reologicznego punktu widzenia, dolna skorupa stanowi warstwę „słabszą", zamkniętą między sztywnymi sferami górnej skorupy i litosfery podskorupowej. Proces deformacji tektonicznej, prowadzący do wykształcenia laminacji refleksyjnej, jest niezależny od petrologicznej stratyfikacji skorupy.

Przedstawiony w modelu wielowarstwowej struktury litosfery kontynentalnej piętrowy rozkład naprężeń odpowiedzialnych za powstanie struktur sejsmicznych nie może być efektem działania mechanizmu tektoniczno-płytowego. Podstawowe cechy tych struktur, tj.: (1) piętrowy rozkład pól naprężeń i typów deformacji, (2) ich prawdopodobnie młody wiek i (3) przenoszenie naprężeń od dołu ku górze, wskazują na proces tektoniczny związany z ekspansją Ziemi. Tylko ekspansja wnętrza planety i związane z nią zmniejszanie się krzywizny przypowierzchniowych sfer Ziemi mogła doprowadzić do powstania takiego rozkładu naprężeń. Zasadnicza teza pracy nawiązuje do koncepcji wpływu zmian krzywizny ekspandującej Ziemi na procesy tektoniczne — idei wyrażonej wcześniej przez Hilgenberga (1933), Rickarda (1969), Jordana (1971), Careya (1976) i Maxlowa (1995, 2001). W górnej skorupie wypłaszczanie przejawia się w pierwszej fazie utworzeniem kompresyjnych struktur skorupowych opisywanych przez tektonikę płyt jako struktury ze złuszczenia (*flake tectonics*) lub kliny tektoniczne, a także procesy delaminacji skorupowej. W miarę narastania ekspansji struktury kompresyjne są zastępowane na niektórych obszarach przez struktury ekstensyjne. Dalsza ewolucja geologiczna może prowadzić zarówno do dalszego rozciągania, aż do rozerwania ciągłości skorupy kontynentalnej, jak i — w wypadku konsolidacji obszaru — do pojawienia się kolejnej fazy kompresji wynikającej z dostosowywania się sztywnej, górnej skorupy do nowej, mniejszej krzywizny Ziemi (inwersja tektoniczna). Struktury z wypłaszczania odpowiadają tym, które tektonika płyt opisuje jako rezultat tzw. tektoniki membranowej. Rozpatrywana w planie tektonika

z dostosowania tłumaczy także: występowanie struktur przesuwczych, transpresyjnych i transtensyjnych, dowodzone paleomagnetycznie poziome rotacje bloków oraz powstawanie oroklin pasm fałdowych itp.

W świetle proponowanej interpretacji geologicznej struktury sejsmiczne litosfery kontynentalnej obserwowane na licznych profilach refleksyjnych odzwierciedlają różny stan naprężeń tektonicznych. Między dolną a górną skorupą oraz między skorupą a płaszczem podskorupowym mamy do czynienia ze strefami planetarnych i regionalnych odspojeń śródskorupowych. Naprężenia rozciągające są transferowane od strony płaszcza Ziemi ku skorupie. Zjawisko to jest właśnie tym, czego możemy oczekiwać w wyniku ekspansji Ziemi.

Słowa kluczowe: sejsmiczne profilowanie refleksyjne, proces wypłaszczania, struktury sejsmiczne, litosfera kontynentalna, reologia, wielowarstwowy rozkład naprężeń, geotektonika globalna, ekspandująca Ziemia.

Abstract. Seismic reflection investigations, in particular the so-called near-vertical reflection seismics, have been the main research tool of the Earth's crust and the upper mantle since the 1980s. Many international research seismic projects have been performed over the last 20 years, and have provided a lot of data commonly interpreted with the use of the plate tectonics paradigm. However, these interpretations face many difficulties. Firstly, it is difficult to explain the enigmatic general similarity of the seismic structure of the continental crust under various geostructures that are different in age and origin; similarly, its commonly observed geometrical symmetry is an area of contention.

Resemblance of seismic reflectivity in various geological environments indicates (1) the crucial influence of rheological properties of the lithosphere on reflectivity and (2) the common tectonic process responsible for development of seismic reflectivity. Depending on thermal conditions, the brittely deformable continental crust occurs to a depth of 10–20 km, which corresponds to temperatures of 300–400°C. Below this depth, there is a ductile deformation zone dominated by the flow of solid state matter. Obviously, the boundary between the brittle deformation zone and the ductile deformation zone is not sharp. Its width is dependent on both the heat flow and the lithology. Another rheological boundary is the Moho surface. The subcrustal upper mantle is brittlely deformable under the thermal conditions existing in this zone. Reflection seismic analysis confirms this rheological behaviour. There is a strict relationship between the viscosity of the continental lithosphere and seismic reflectivity. Sparse reflection packets related to fault zones (mostly of listric geometry) are observed in all the profiles in the crystalline upper crust, which in general is seismically transparent. These fault zones dip in different directions and flatten downwards. The lower crust is dominated by subhorizontal structures which are suggested by most authors to represent flow deformations. A transitional zone, sometimes referred to as the middle crust, occurs at the lower/upper crust boundary. Most listric fault zones die out within this part of the crust. It contains intracrustal large-scale lenticular structures, marked by reflection bands. The subcrustal upper mantle is characterized by a transparent seismic structure. Therefore, from the rheological point of view, the lower crust is a "weaker" layer closed between the rigid upper crustal zones and the subcrustal lithosphere. Reflection lamination results from a process of tectonic deformation that is independent of the petrological stratification of the crust.

Multilayered stress distribution, proposed in the model of the continental lithosphere, is responsible for the formation of seismic structures, and cannot be an effect of the plate tectonic mechanism. The major features of these structures include: (1) a layered distribution of the stress field and deformation types; (2) a relatively young age of deformations; and (3) probable upward transmission of stresses. These features suggest the involvement of a tectonic process associated with the expansion of the Earth. The expansion of the Earth's interior, accompanied by a decrease in the curvature of near-surface layers, could give rise to observed stress pattern. The main thesis of the work is the idea of the influence of curvature changes (flattening) of the expanding Earth on tectonic processes. This idea was earlier expressed by Hilgenberg (1933), Rickard (1969), Jordan (1971), Carey (1976) and Maxlow (1995, 2001). In the upper crust, the first phase of flattening is manifested as the formation of compressional crustal structures described in plate tectonics as flake structures or tectonic wedges, and also as crustal delamination processes. As expansion accelerates, compressional structures are replaced by extensional structures in some areas. The subsequent geological evolution may proceed both towards further extension until the crust breaks, or, in the case of the consolidation of the area, towards another compressional phase which can result from the adjustment of the rigid upper crust to a new, smaller curvature of the Earth (tectonic inversion). Flattening structures correspond to the ones which are described by plate tectonic theory as resulting from so-called membrane tectonics. Flattening tectonics also explains numerous strike-slip, transpressional and transtensional structures, palaeomagnetically determined lateral rotations of blocks, the formation of oroclines and foldbelts, etc., commonly described in recent literature.

In the light of the proposed geological interpretation, the seismic structures of the continental lithosphere observed in reflection seismic profiles reflect different states of tectonic stresses. Planetary and regional intracrustal detachments occur at the lower/upper crust boundary and crust/subcrustal mantle boundary. Extensional stresses are transferred from the upper mantle towards the crust. This phenomenon is what we can expect to be the result of the Earth's expansion.

Key words: seismic reflection profiling, flattening process, seismic structures, continental lithosphere, rheology, multilayer stress distribution, global geotectonics, expanding Earth.

INTRODUCTION

For the last 30 years, modern geotectonics has been dominated by plate tectonics. This theory (as a term commonly used in the Earth sciences) is a combination of much older ideas on subcrustal convection currents (Ampferer, 1906) and continental drift (Wegener, 1915, 1924). Its original principles were created during the early 1960s and based on research results of modern ocean floor, interpreted with the silent assumption that the Earth's dimensions have been constant throughout geological time. This assumption was in Le Pichon's mind (1968) as he wrote: "if the Earth is not expanding, then there should exist another plate margin along which the plates are shortened or destroyed". It was assumed that such areas where newly formed oceanic lithosphere is plunging into the mantle (in a process called subduction) are located in the Benioff zones along island arc systems or volcanic-plutonic belts on active continental margins. Somewhat earlier, Heezen (1960) thought that the discovery of a vast global system of ocean-floor spreading as well as suggestions arising from several different and independent research methods that all the modern oceans are young and came into being during Mesozoic–Cenozoic times, indicate the possibility of the entire planet having expanded through geological time. However, Heezen's proposal was not taken up by the scientific community. Between 1961 and 1970, the principles of plate tectonics were published in several basic papers (Dietz, 1961; Hess, 1962; Isacks *et al*., 1968; Le Pichon, 1968; Morgan, 1968; Le Pichon *et al*., 1976). The history of the creation and development of plate tectonics theory is currently presented in most textbooks (in the Polish literature, see e.g. Chain, 1974; Dadlez, Jaroszewski, 1994; Mizerski, 1999; Mizerski, Orłowski, 2001), many popular publications (in Poland, see e.g. Mizerski, 1986, 1998; Cwojdziński, 1989) and in press articles, scientific conferences abstracts, and museum exhibitions. Nowadays, plate tectonics is integral to geology in the minds of those who are professionally concerned with the natural sciences.

Nevertheless, an alternative theory, that of the expanding Earth, is still being developed at some scientific centres; however, it plays a secondary role in modern geotectonic science. This theory is based on the same facts which were the principles for the construction of plate tectonics theory, except for the assumption that the Earth has constant dimensions. There are increasingly more first-order facts and many regional and local observations which seem to show that expansion of the Earth is a real process which could have controlled the geological evolution of our planet (cf.: Cwojdziński, 1984, 1989, 1990; Oberc, 1986; Koziar, 1991a).

One set of data which could indicate that the expansion of the Earth is a reality is the information about the seismic structure of the continental lithosphere provided by comprehensive, often international geophysical research projects which are based, in particular, on reflection seismic methods. I am of the opinion that the seismic structure of the continental lithosphere unambiguously indicates that the lithosphere gradually adjusts to the Earth's curvature, which is decreasing with time. This adjustment process could be acknowledged as one of the most powerful geotectonic phenomena; it controls the evolution of the Earth along with other processes such as ocean-floor spreading, rifting and mantle diapirism.

The aims of this paper are as follows:

— to analyse seismic profiles across the lithosphere from various regions of the globe with different geological histories;

— to show the previous geological interpretations of these profiles;

— to put forward proposals for the creation of a new interpretation of deep crustal seismic reflection data based on the expanding Earth theory.

SEISMIC PROFILES OF THE CONTINENTAL LITHOSPHERE

SEISMIC REFLECTION INVESTIGATIONS — A NEW RESEARCH TOOL

Seismic reflection investigations, in particular the so-called near-vertical reflection seismics, have been the main research tool of the Earth's crust and the upper mantle since the 1980s (e.g. Dohr, 1989; Blundell, 1990; Klemperer, Peddy, 1992). This method yields excellent results and is used for the exploration of reflection horizons deeper than those associated with sedimentary basins. Thanks to this method, it has been possible to trace deep seismic structures across the entire crust of the Earth, and to relate them to surface geological structures or subsurface ones penetrated by drillings. Reflection seismics is also a useful tool for studying the complex structure of the crust. Many international research seismic projects, led by consortiums such as COCORP, LITHOPROBE, DEKORP and BIRPS, have been performed over the last 20 years, and have provided a lot of data commonly interpreted with the use of the plate tectonics paradigm. However, these interpretations face many difficulties. Firstly, it is difficult to explain the enigmatic general similarity of the seismic structure of the continental crust under various geostructures that are different in age and origin; similarly, its commonly observed geometrical symmetry is an area of contention (Cwojdziński, 1991a, c).

THE GEOLOGICAL SIGNIFICANCE OF SEISMIC REFLECTORS

Ultimately, the geological nature of seismic reflectors imaged on seismic profiles has not been explained, and still appears controversial. Shallow, "basinal" reflection seismic sections seem to be clear for interpretations: individual reflections correspond to lithological boundaries, in particular where sedimentary rocks differ considerably in their lithologies (confirmed by borehole data). The properties of rocks, such as porosity and water saturation, can also be of certain significance. The interpretation of deeper reflection seismics is not so simple. In the early days of this method, the reflection seismic data was used to interpret in lithological terms; e.g. Fuchs (1969) stated that reflections from deeper crustal zones are generated as seismic waves which are reflected from alternating packets of thin layers of rocks showing higher and lower seismic velocities. Thus, reflections in the crust have the same genesis as reflections in sedimentary rocks. Such packets are often associated with tectonic discontinuities, in particular in those areas where they are correlatable with well-known faults, thrusts or detachments. The results of deep continental boreholes drilled in the Kola Peninsula and Bavaria area showed that there can be another possibility of interpretation (Minc *et al*., 1987; Emmermann, Lauterjung, 1997). Neither of these boreholes reached the expected depths; however, they allow the statement to be made that the drilled seismic reflection bands are composed of narrow breccia and cataclasite zones representing migration paths for strongly mineralized waters. Although these results refer to relatively shallow reflections, they seem astonishing. The obtained results require confirmation; nevertheless, they indicate that the nature of reflectors can be quite different than thought, at least in the upper crust.

In the case of the lower continental crust, the situation is somewhat different (Mooney, Meissner, 1992). There are several hypotheses concerning the origin of lower crustal seismic reflectivity. Some of them are supported by the results of drilling investigations or studies of exposures, and obviously refer to reflections which occur in the upper crust, although their character is typical of the lower crust. These reflections are associated with planar intrusions of magmatic rocks (Juhlin, 1988), and are induced by small-scale lamination of rocks from highly metamorphosed complexes. The seismic properties of the latter (Mooney, Meissner, 1992) show that the inner lamination of these complexes is a more essential factor than contacts between tectonic units for the generation of reflections.

Other reflectors, confirmed by correlation with surface structures, are represented by fault zones, in particular mylonitic shear zones, showing middle and upper crustal petrological features. In this case again, it is the inner lamination of these zones, not the contact surfaces between them, which produces these reflections. However, it should be born in mind that there is an essential limitation in the use of the reflection seismic method, which results from the minimum thickness of the objects possible to be identified. According to data cited by Klemperer and Peddy (1992), the thickness must be at least 1/4 of the seismic wavelength, and is inversely proportional to frequency. With the normal seismic velocities and frequency used in seismic investigations, this means that the minimum thickness of "seismic layers" distinguishable in seismic profiles is 75 m thick. Thinner objects can be revealed on seismic sections as a diffraction hyperbole, i.e. upward-bent arched reflections.

A REVIEW OF SEISMIC REFLECTION PROFILES

Geological interpretation of deep seismic profiles has been employed to study most continental geostructures. Most synthetic reports concerning seismic investigations refer to division into compressional, extensional and strike-slip structures, correlating them with tectonic structures observed on the Earth's surface. These structures are distinguishable in crustal blocks of various ages — on Precambrian platforms, and within Caledonian (early Palaeozoic), Variscan (late Palaeozoic) and Alpine (Mesozoic and Cenozoic) deformation zones. Most such seismic research projects were performed on continental areas of North America, Europe and Australia. The major transects cross geological structures of different ages, because transect lines were often designed in order to explore known or suspected tectonic sutures, variable in character, which separate crustal blocks of various ages of deformation processes in the near-surface zone.

The following subchapters of this report critically describe the major seismic geotransects done over the last 20 years, and consider the possibility of a different interpretation of the origin of these seismic structures. On account of the above-mentioned arguments, this review will be presented according to geographical regions.

NORTH AMERICAN CONTINENT

The core of the North American Continent is Precambrian platform composed in its northern part by the Canadian and Greenland Shields, of Archean and early Proterozoic consolidation age. This old continental core is encircled by younger orogenic belts: to the north-east and south-east, these are the late Proterozoic Grenville belt, the Palaeozoic foldbelts of Greenland and the Appalachian Caledonides; to the west, this is the great, polygenic and polyphase fold system of North American Cordillera. Fragments of late Palaeozoic orogens also occur to the north in Canadian Arctica, and along the Mexican Basin (Wichita Mountains).

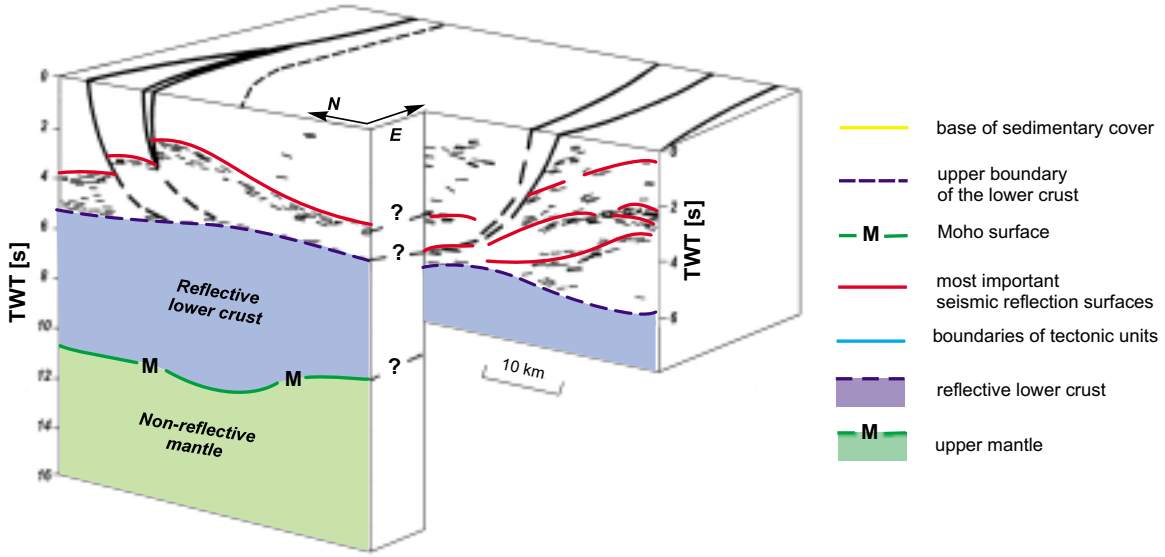

Fig. 1. A block diagram showing the principle features of the crustal structure of the Abitibi belt (Canadian Shield) (Clowes, 1993; modified)

Note the shifts of upper crustal lenticular seismic structures due to listric faults observed on the surface

Several large seismic projects supported by a range of geophysical-geological investigations were devoted to the problems of the North American crustal structure. These projects were primarily realized by an American consortium of COCORP and the Canadian LITHOPROBE, and included several transects crossing geostructural elements of different ages. The transects led to the statement that there is a frequent spatial relationship between tectonic structures observed on the surface and intracrustal structures identified at different depths.

The Abitibi–Grenville transect (Fig. 1) was carried out within the framework of the LITHOPROBE programme. It crosses the classically developed Abitibi greenschist belt in the central part of the Archean crust of the Canadian Shield. The upper crust of this area is poorly reflective but it shows the occurrence of single, slightly inclined reflection packets, locally interrupted by downward-continued listric faults bounding the rocks of the Abitibi belt at the surface (Clowes, 1993). These faults steeply dip to a depth of 10 km; below this, they seem to flatten and disappear at the top of the lower crust. The lower crust displays a laminated structure and is interpreted as a stratified complex of felsitic and mafic granulites with large anorthosite lenses. The Moho surface coincides with a zone of weaker lower crustal reflectivity. This zone occurs at 11–11.5 s TWT, which corresponds to a depth of 35–38 km.

One of the subprojects of the LITHOPROBE project explored the early Proterozoic Trans-Hudson tectogens, located in central Canada; these are a component of the Proterozoic tectonic belts binding together the Archean continental cores (Lewry *et al*., 1994). This longitudinally running 800 km long transect crosses the entire tectogens. Its ends terminate at the Archean fringe of the Trans-Hudson Zone, partly rejuvenated as a result of subsequent tectonothermal processes. In this seismic profile (Fig. 2), the crust shows high-reflectivity down to the Moho surface, where the reflectivity rapidly disappears. The Moho topography shows a small swells (roots) in the marginal western part of the Trans-Hudson Zone, which corresponds to a domal culmination of dome-like convex upward reflection bands. Archean basement rocks occur at the surface within Proterozoic mylonitic rocks. West of this culmination, westwards dipping seismic reflections are predominant, whereas to the east, eastward dips are most common. These seismic reflections define a large-scale lenticular to wedge-like structure of the crust. The Trans-Hudson Zone as a whole is represented by a huge lenticular crustal block bounded by shear zones. These zones separate the block from clinoform crustal structures of neighbouring blocks that are shifted in relation to the Trans-Hudson Zone. As stressed by Lewry *et al*. (*op. cit*.), there is no correlation between the steeply dipping foliation and lithological stratification observed at the near-surface, and the gently dipping reflection surfaces in the upper crust.

In the western part of the American–Greenland Platform (West Canadian Basin), reflection seismic investigations were carried out within the framework of the LITHOPROBE project along a grid of seismic reflection profiles arranged perpendicular to one another (N–S and W–E) with data acquisition to 18 s TWT. Beneath a sedimentary infill of the basin, there are the Proterozoic crystalline rocks of the Hudson Province. The profiles are characterized by the presence of the so-called Winagami Reflection Sequence (Ross, Eaton, 1997, see Fig. 2) — a grid of remarkable subhorizontal reflections which occur as waveforms at depths of 3–7 s TWT, i.e. in the upper and middle crust. The entire sequence is parallel to the horizontal seismic lamination corresponding to the sedimentary rocks of the West Canadian Basin (down to 2 s TWT); however, the se-

quence is not associated with the laminated lower crust. The Winagami Reflection Sequence is developed identically on all the perpendicular profiles, as evidenced from investigations which covered an over 600 × 200 km area. In its western part, the reflections of this sequence clearly cut the eastward-dipping, 15 km thick packet of upper crustal reflections associated with a regional ductile shear zone that separates Proterozoic terranes. According to Ross and Eaton (*op. cit.*), the reflection sequence is genetically related to several levels of intrusive dyke sheets occurring within the crust; however, the discrete seismic structure observed between the Winagami reflections, often lenticular in appearance, can suggest a connection of subhorizontal surfaces with a general radial, subhorizontal extension of the crust.

The GLIMPCE reflection seismic profile, 350 km long, runs across Huron Lake, in the Grenville Front that separates the Archean and early Proterozoic terranes of the Canadian Shield from the middle Proterozoic Grenville tectogen (Green *et al.*, 1988; Clowes, 1993). The entire zone is conspicuous by the repeated and episodic occurrence of magmatic and tectonic events during the Archean and Proterozoic (Green *et al.*, *op. cit.*), as well as by the presence of a number of regional shear zones which are boundaries between crustal blocks. In the middle part of the profile, corresponding to the Grenville Front tectonic zone, there is a 30 km thick stratified belt of densely arranged reflections. They dip eastwards at an angle of 35° close to the Grenville Front, and up to 25° further to the east (Fig. 3). This belt used to be related to a huge mylonitic complex (Green *et al.*, 1988, Clowes, 1993), and it separates two crustal domains of different age but essentially of a similar seismic structure. This structure is composed of a complicated grid of arched reflections observed from 2–3 s TWT down to the Moho surface at 12–13 s TWT. Such crustal domains of large-scale lenticular structure tend to be remarkably bent downward; this one underlies a reflection belt of the Grenville Front. The Earth's crust of this zone is composed of mutually shifted clinoform domains.

Seismic and geological investigations performed as part of the LITHOPROBE project along the south-eastern margin of the North American Platform, focused on examining the Appalachian seismic structure of eastern Canada, and its relationship to the Grenville basement at the contact zone between the Grenville Block and the so-called Avalonia microcontinent (Clowes, *op. cit.*). The BURGEO transect crosses south-western New Foundland (Fig. 4) with a typical seismic structure: the entire crust shows bidirectionally dipping (at angle of 20–30°) narrow reflection sets dividing the crust into clinoform blocks which are inserted one into another. Some of the reflection sets seem to correspond to tectonic lines identified at the Earth's surface, but this relationship is not always unambiguous. The seismic structure is the same along the entire profile, irrespective of the near-surface geological structure. In the south-eastern part of the transect, arched, listric reflection bands correspond to near-surface extensional structures associated with the opening of the Atlantic. The Moho surface corresponds to a narrow belt of subhorizontal reflections that terminate at the top of the non-reflective upper mantle.

The COCORP profiles also transect the Appalachians, a region which is a perfect example of seismically well-explored Palaeozoic tectogen representing the result of a series of orogenic events that affected its area from the Ordovician through to the Permian.

The ADCOH seismic profile (Fig. 5), discussed by Klemperer and Peddy (1992), is conspicuous by a very distinct subhorizontal reflection band at 2–3 s TWT; this corresponds to the Palaeozoic shelf deposits that horizontally overlie the Grenville basement. A number of flat-dipping reflections which occur within the crust above the seismic discontinuity are associated with thin-skin tectonics of the upper, allochthonous structural level. There are normal fault-bounded tectonic troughs of the basement immediately beneath the thrust allochthonous units. No signs of compression which could have resulted in the formation of the great, west-verging Appalachian thrusts can be observed here. The seismic reflectivity of the lower crust is weak, although there are local large-scale lenticular structures which show no connections with near-surface structures. The interpretations of the Appalachian geological structure presented by various authors (Harris *et al.*, 1982; Brown *et al.*, 1986; Coruh *et al.*, 1988; Evans, 1989; Hall, Quinlan, 1994) indicate the occurrence of two tectonic styles in this structure — thin-skin tectonics, discussed above (e.g. Southern Appalachians), where the allochthonous "skin" is up to 10 km in thickness; and thick-skin tectonics, found in deeper crustal zones up to a depth of 30 km. This was illustrated well in a seismic profile across the oceanic foreland of the Middle Appalachians (Phinney, 1986). The weakly reflective upper crust is composed of large gneiss and migmatite lenses separated by narrow zones of shear suture zones. The reflection bands tend to continue downward and become denser in the lower crust, indicating its large-scale lenticular to wedge-like structure, except in a narrow belt of horizontal lamination at the Moho zone. In another seismic profile crossing the Appalachians of New England (Brown *et al.*, 1986), there is a stacking and wedging of the lenticular crustal structure at the margin of a rigid block of the Appalachian Grenville basement. The Virginia I 64 profile (performed by the USGS) shows a similar seismic structure (Coruh *et al.*, 1988, see Fig. 2) with characteristic undulations of major reflection bands delimiting large-scale lenses which are stacked to form NW-verging imbrications, i.e. they are directed towards the North American Continent. Moreover, the entire crust becomes remarkably thinner eastward, towards the Atlantic. The asymmetric seismic structure of the Appalachian crust was formed at the boundary of the two crustal domains: the old, repeatedly reactivated Precambrian crust of a continental craton, and the young Atlantic ocean crust.

Summarizing the results of the COCORP, USGS, LITHOPROBE and British investigations of the crustal seismic structure along the Appalachian/Caledonide orogenic belt, Hall and Quinlan (1994) emphasize its overall similarity along the whole fold-and thrust system. This similarity involves the occurrence of crustal domains which dip in two opposite directions (NW and SE) and divide the crust into a number of clinoforms. The boundaries between the crustal blocks can commonly be correlated spatially with the boundaries of tectono-stratigraphic zones on the surface. In areas composed of crystalline rocks, dipping reflections continue towards

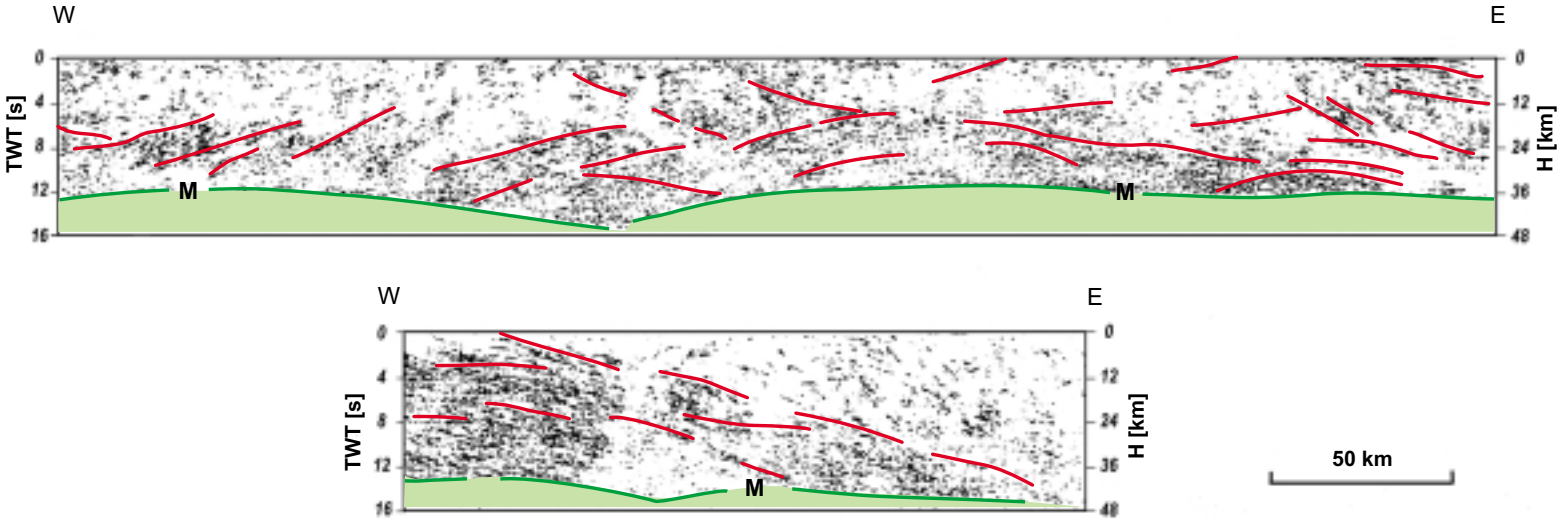

Fig. 2. The seismic transect across the Trans-Hudson Tectogen in the Canadian Shield (after Lewry *et al.*, 1994; modified)

Major seismic crustal structures are marked; the lower drawing is a continuation of the upper one; for explanation see Figure 1

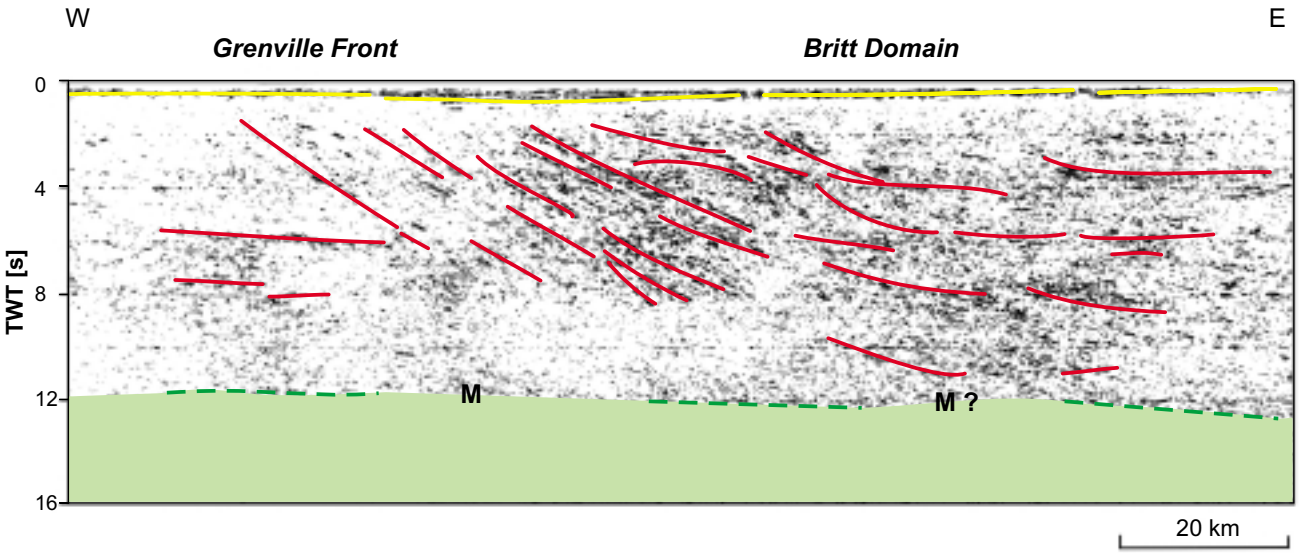

Fig. 3. A migrated section of the GLIMPCE reflection seismic profile perpendicular to the Grenville Front (Canadian Shield) (after Green *et al.*, 1988; modified)

For explanation see Figure 1

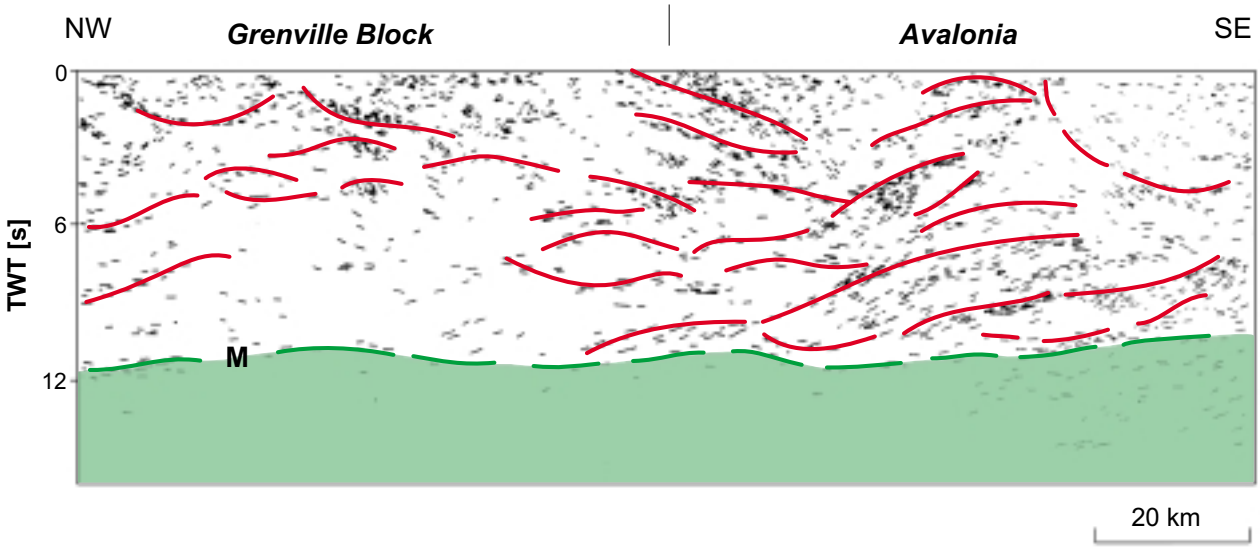

Fig. 4. The BURGEO transect in eastern Canada crossing the contact between the Grenville Block and the Avalonia terrane (after Clowes, 1993; simplified)

For explanation see Figure 1

the surface into mylonitic zones; hence the conclusion that these result from ductile shear deformations. The existing interpretations suggest that the formation of such structures is genetically related to a varying polarity of the subduction processes responsible for a collisional asymmetry; however, Hall and Quinlan (1994), for example, are of the opinion that the delamination process during collision is responsible for opposedly-dipping shear domains in the crust. Therefore, this is the product of a single geotectonic process. According to Heck (1989), the recent seismic image of the Appalachian crust indicates extensional processes related to the Mesozoic evolution of this area. Younger tectonic processes are superimposed on older ones, blurring even more prominent geological events.

The compilation of reflection seismic profiles from offshore eastern Canada (line 85-3 LITHOPROBE) and offshore western Ireland (the WAM profile of the BIRPS project) permits the reconstruction of the crustal seismic structure on both sides of the early Cretaceous North Atlantic rift (Keen *et al.*,

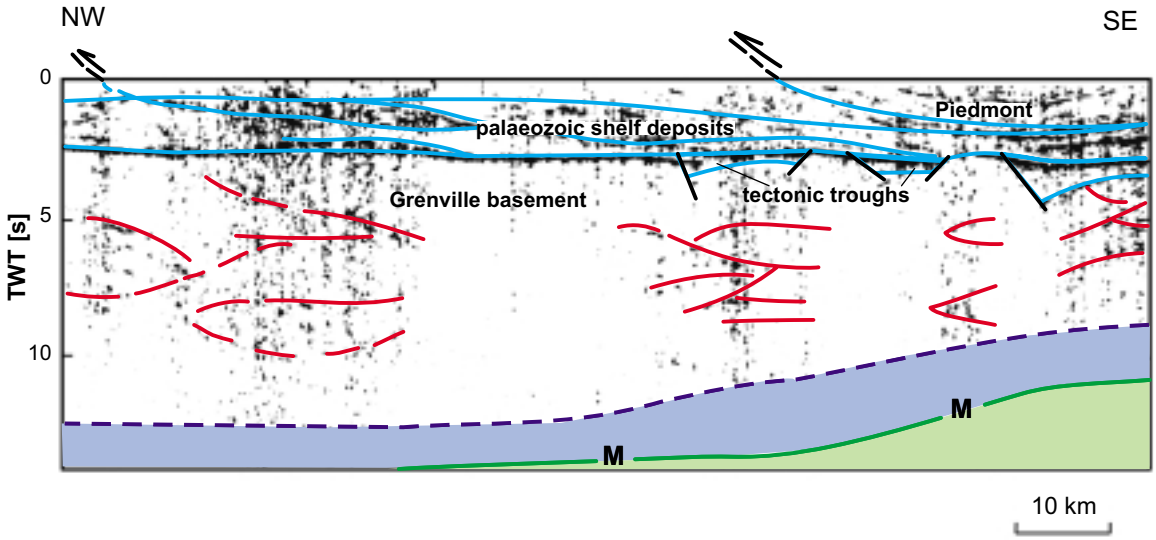

Fig. 5. The ADCOH seismic profile across the Southern Appalachians, with its geological interpretation (Klemperer, Peddy, 1992; supplemented)

For explanation see Figure 1

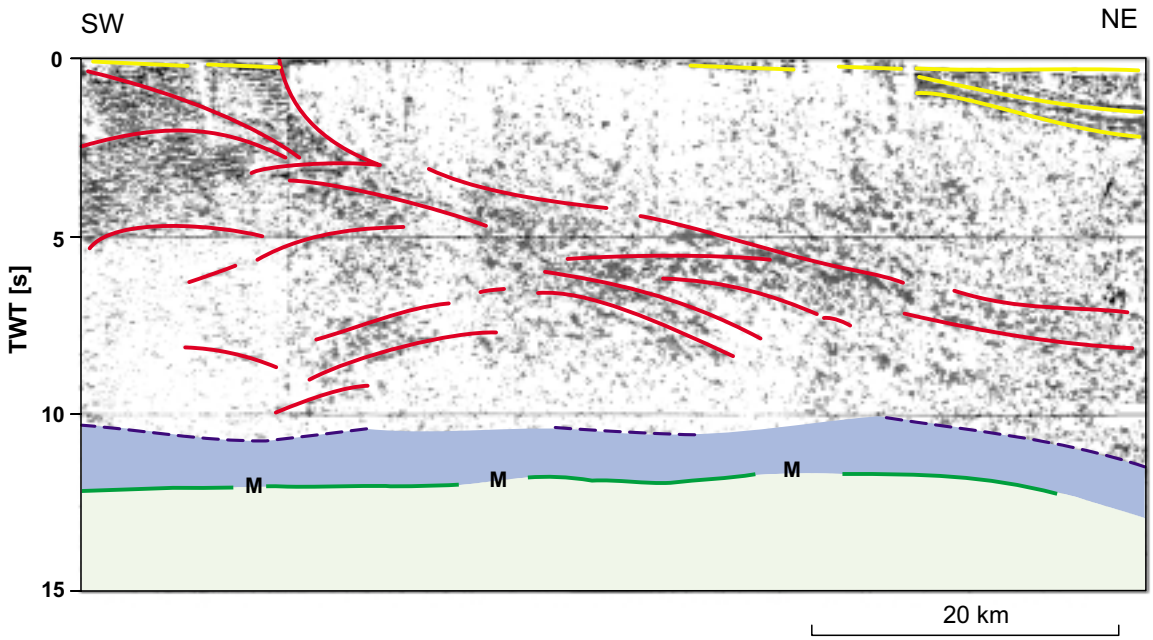

Fig. 6. The COCORP reflection seismic profile crossing the Wind River Block (Smithson *et al.*, 1978; modified) with major crustal structures shown

For explanation see Figure 1

1989, see Fig. 2). The reconstructed rift zone shows the presence of a 7–8 km thick laminated lower crust; its thickness decreases at the rift margins. This crust is domally uplifted at the top of a mantle diapir. The thickness of the crust decreases from 28–30 km along the rift margins to 10 km in the centre of the rift zone. The upper crust contains a few seismic structures: these form sets of waveform reflections or reflections dipping at 20°. Some of the reflections observed close to the rift borders can represent normal frame faults. These structures formed due to symmetrical extension of the continental crust in the pure shear field.

The COCORP and LITHOPROBE profiles also transect the meridionally stretching North American Cordillera fold--and-thrust belt, which has a complicated geological structure.

One of the first COCORP seismic transects crosses the Wind River Range of the Rocky Mountains in Wyoming (Smithson *et al.*, 1978). This range is composed of Precambrian crystalline rocks, and is uplifted along a Tertiary thrust of the same name. The COCORP reflection seismic profile (Fig. 6) indicates that the bounding fault of the Wind River dips at an angle of approximately 30° to a depth of 15 km. According to the geological interpretation of the seismic data (Klemperer, Peddy, 1992), the Precambrian block is thrust upon horizontally resting Mesozoic rocks. The entire crustal structure shows typical crustal tectonics. However, an analysis of seismic images indicates that the bounding fault of the Wind River is rather a normal fault, complementary in relation to the northeasternwards- and flat-dipping intracrustal fault zone which gradually passes into the middle crust. In the middle crust (between 6 and 9 s TWT), narrow bidirectionally dipping reflection zones are observed. They form a kind of a large-scale lenticular seismic structure which was not revealed in previous interpretations. A "layer" of the laminated lower crust is visible within a zone immediately adjoining the Moho surface, at a depth of 11–12 s TWT.

LITHOPROBE geophysical transects longitudinally cross the Cordillera of West Canada (Clowes, 1993). Together with some of the COCORP profiles, they provide insight into the crustal structure of this area where tectonic processes took place on the Archean–Lower Proterozoic crystalline basement and date back to the early Proterozoic. An example of a longitudinal LITHOPROBE transect (Fig. 7), crossing part of the North American Cordillera, shows an even and flat, eastward-dipping (at 1°) Moho surface, with an underlying, variable thickness, laminated lower crust, and a complex seismic structure of the upper crust reaching a depth of 10–11 s TWT. This structure is conspicuous by the presence of waveform and arched reflection bands, which are often associated with surface structures. Both the reflection bands (gently dipping towards the west and marking — according to Cook *et al.*, 1987, 1988 — tectonic zones that separate the North American Cordillera nappes), and extensional listric faults (reaching as deep as the middle crust at a depth of 20 km), are observed in this profile. Antiforms of metamorphic core complexes occur between the listric faults. The entire complex seismic structure of the upper crust corresponds neither to the flat-lying lower crust nor to the Moho surface.

The overall analysis of the Cordillera crustal structure shows its double symmetry, manifest in the west-verging main seismic structures of the Eastern Cordillera and the intramontane superterrane, and in the east-verging Coastal Range seismic structures. Analysed in detail, e.g. in the Rocky Mountains (Green *et al.*, 1993), the structure shows the presence of west-dipping detachment surfaces at depths of 20–30 km, and

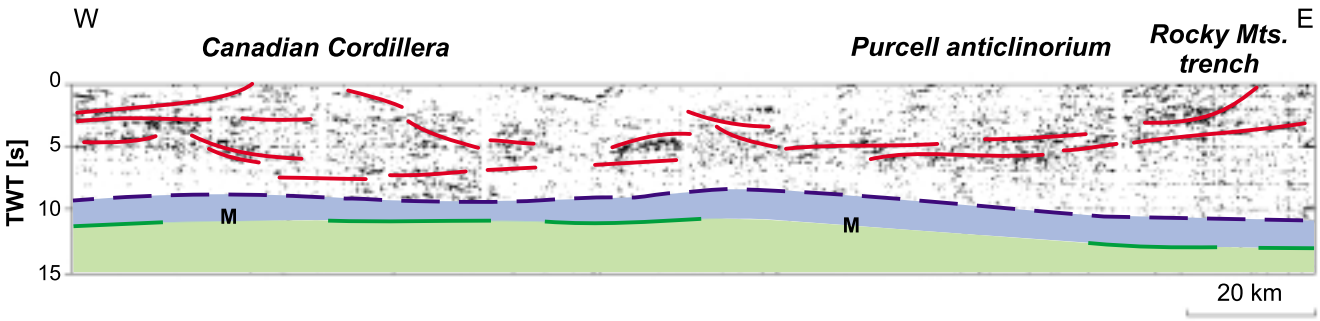

Fig. 7. The LITHOPROBE geophysical transect crossing part of the North American Cordillera (Green et al., 1993; modified)

For explanation see Figure 1

mutually wedging crustal "lenses" in the upper part of the crust, 4–5 km long and 1–1.5 km thick. In most papers, the North American Cordillera system is interpreted as a subduction--oblique collisional orogen, formed along the western margin of the North American Continent. However, many seismic profiles show that extensional structures are dominant. For example, the COCORP profiles of Oregon 1 and 2 (Keach *et al*., 1989), transecting the Coastal Mountains and the Cascade Range, in front of the convergence boundary between North America and the Juan de Fuca Plate, prove the presence of a system of normal faults in the upper crust; these faults divide the mountains into a series of mutually shifted blocks (*op. cit*.). Reflection profiles of the Middle Cordillera run along the Canada/USA border near the Lewis thrust (late Palaeocene–early Eocene) and show the occurrence of lenticular reflection packets in the upper crust (2–6 s TWT). These packets are discontinuous due to extension. Van der Velden and Cook (1994) assume that this extension was associated with the formation of the Rocky Mt. Trough, superimposed on earlier thrust structures.

EUROPEAN CONTINENT

The East European Platform of the old Precambrian basement, which was ultimately consolidated during the Dalslandian epoch, is the core of the European Continent. Theplatform covers half of the continent's area. The platform's crystalline basement appears at the surface forming the Baltic and Ukrainian Shields. To the east, the platform is adjoined by a late Palaeozoic fold system of the Ural Mts. To the south-west, the East European Platform is bordered by a prominent fault system of the Tornquist–Teisseyre Zone, and to the north-west, by the Scandinavian Caledonides. The western reach of the platform is not precisely defined, due to the thick sedimentary cover. The so-called Trans-European Fault Zone is the boundary of a Precambrian crust wedge that stretches as far as the British Isles. South of this wedge, younger foldbelts occur. This prominent tectonic lineament of the Trans-European Fault Zone separates two distinct and different geotectonic provinces: the East European Platform from Central and Western Europe, where young Permian–Mesozoic sedimentary basins developed between uplifted zones of Precambrian (Cadomian) and Palaeozoic basement, commonly blocky in character. These zones are represented by fragments of the Caledonian and Variscan tectogens.

BABEL was the most important project of reflection seismic investigations done on the East European Platform (Babel, 1992). Geophysical investigations were performed along 10 transects of a total length of nearly 2300 km; the aim was the exploration of the crustal structure of the Precambrian Baltic–Belarus Shield along the axes of the Baltic Sea and Botnian Bay. The BABEL profiles from Botnian Bay provide insight into the crustal structure of the boundary zone between the Archean crystalline complexes and early Proterozoic Svecofennides. The profiles crossed the famous Skellefte–Vihanti/Pyhasalmi (Sweden–Finland) zone of sulphide mineralization (Snyder, 1992). The upper crust, down to a depth of 3–4 s TWT, is characterized by poor reflectivity. Below this depth, down to the Moho surface, which is identifiable by a rapid and almost total decrease in reflectivity, crustal structure is dominated by a dense pattern of variably dipping waveform reflections (BABEL 2, 3, 4). It is important to note that in 3-dimensional space, the lenticular seismic structure of the crust is the same in appearance (Fig. 8). Therefore, it is unjustified to relate the structure to the perpendicularly crossing tectonic structures observed at the surface (Snyder, 1992). The lenticular structures in the BABEL profiles are of two different orders of magnitude: the most common ones, well visible on profiles (Fig. 8), 15–20 km long; and large-scale lenticular structures, visible after the compilation of 2 or more profiles, 150–200 km in length. Variations in the reflection dips in different parts of the profiles have also been observed by plate tectonicians (Babel, 1992), but such interpretations relate the variations to hypothetical zones of tectonic palaeosutures, obviously if the dip direction matches the principles assumed. As stressed by Lindsey and Snyder (1992), crustal reflection bands can correspond to laminated mylonitic zones produced by intense shear processes. Some authors (Heikkinen, Luosto, 1992) relate the dipping crustal reflections to extension and rifting processes.

The BABEL transects of the south-western Baltic Sea cross prominent fault zones which are a boundary between the Precambrian East European Platform (Baltic–Belarus Shield)

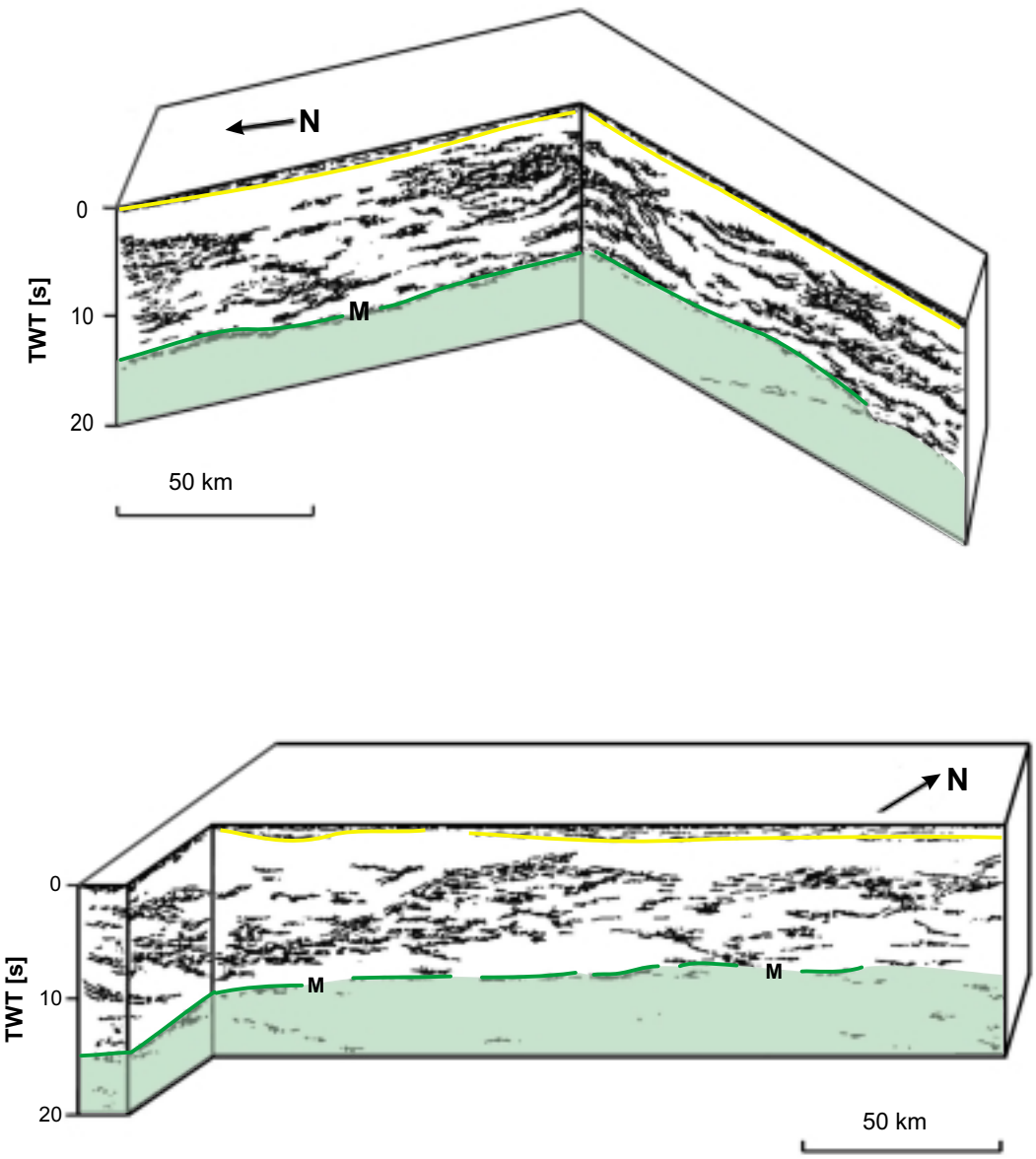

Fig. 8. A block diagram illustrating the seismic structure of the Baltic Shield crust along perpendicular BABEL reflection profiles (after Snyder, 1992; simplified)

For explanation see Figure 1

and the young platform of Europe. These fault zones are: the Tornquist–Teisseyre Zone, which coincides with the south--western boundary of the Precambrian Platform, and trends from Romania as far as the Baltic coasts; the Sorgenfrei–Tornquist Zone, which is an intraplatform branch of the Tornquist–Teisseyre Zone; and the Main Trans-European Fault. The SW–NE-running BABEL A transect (Fig. 9a) was described and interpreted by Meissner (1992) and Blundell (1992). The upper crust is weakly reflective. It contains single bidirectionally and symmetrically dipping reflections, interpreted as low-angle faults. Above these faults, at the near-surface, extensional sedimentary basins are developed. These are the Danish, Sorgenfrei–Tornquist and Hano Bay basins. The intensely laminated lower crust is of variable thickness and shows lenticular swells and pinches. A distinct crustal thickening is observed under the Sorgenfrei–Tornquist Zone. Reflection bands of variable thickness plunge in both directions from the lower crust into the upper mantle. The reflection bands are visible even down to a depth of 16 s TWT. Locally, they cross one another, forming a conjugate set of discontinuity surfaces. That is why the Moho boundary is blurred along some sectors of this transect. In general, the crust of the south-western Baltic is characterized by large-scale lenticular seismic structure, typical of Precambrian platforms (Fig. 9b). The results of refraction and wide-angle reflection surveys (e.g. Graham *et al.*, 1992) also confirm the occurrence of this crustal structure type.

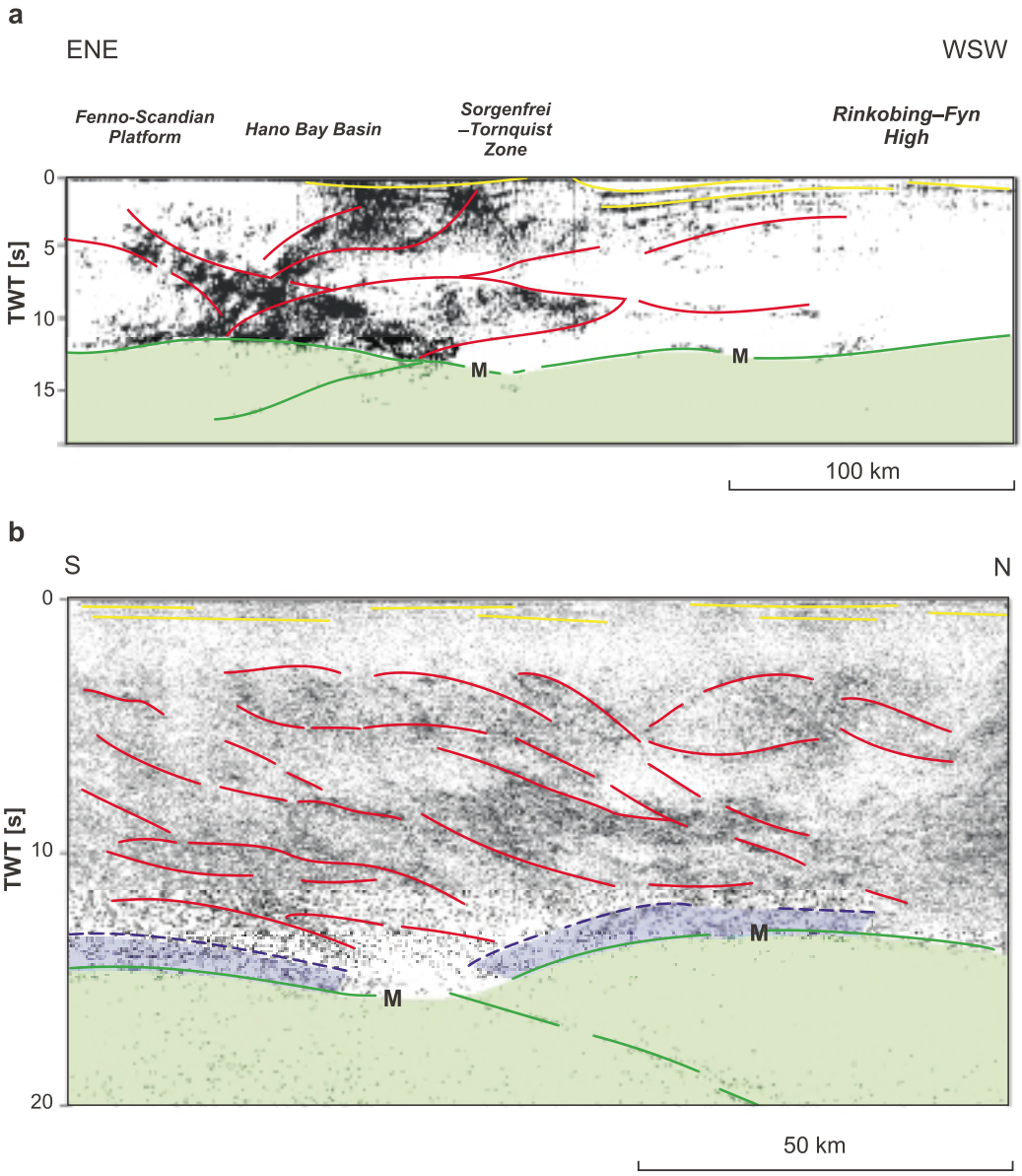

Fig. 9. Deep seismic reflection sections of the BABEL profiles (after Snyder, 1992; modified)

a — Profile BABEL A; **b** — BABEL — Line 4; for explanation see Figure 1

In the Skagerrak area, the crystalline basement of the Baltic Shield is transected by systems of normal faults and tectonic grabens which have developed since the Permian. This area was the subject of deep reflection investigations, which were interpreted by Lie and Husebye (1993). The upper crust is weakly reflective and dominated by bidirectionally dipping reflections, often crossing one another and corresponding to the surfaces of fault zones which divide the upper crust into wedge blocks related to tectonic grabens and half-grabens observed in the near-surface. These surfaces often listrically flatten at 5 s TWT (about 10 km). The middle crust shows a typical large-scale lenticular structure that is similarly developed on profiles crossing one another. The lower crust is a thin (2–3 km), intensely laminated layer spatially associated with the Moho surface. Its seismic image is typical of old, extended continental crust.

The British Isles and their surroundings are an area of tectonic contacts of the Precambrian complexes of Northern Scotland with the Caledonian and Variscan tectogen. The Caledonian tectogen is additionally divided into two "branches" by the Precambrian Midland Massif which is included in the Anglo-Brabant Massif. Plate tectonic interpretations of the accretion of the European Continent suggest that this complex tectonic junction plays a significant role. It is supposed that major collisional sutures between the palaeocontinents of Baltica, Laurentia and Avalonia, and Variscan peri-Gondwanian terranes run across this area.

Marine areas around the British Isles were intensely explored in seismic reflection surveys conducted by the BIRPS research group in the 1980s (Blundell, 1990). A total length of 12,000 km of offshore deep seismic profiles were made at that

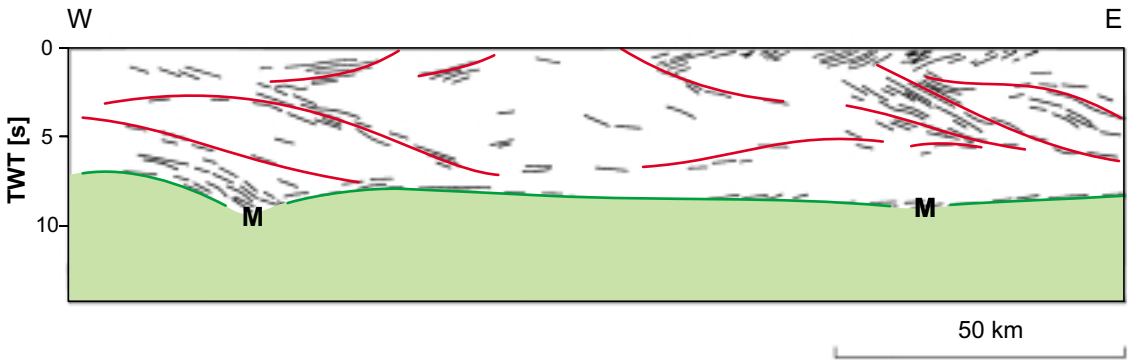

Fig. 10. The MOIST seismic profile running along the northern coast of Scotland (after Smythe *et al.*, 1982; simplified)

For explanation see Figure 1

time. The results of those investigations were discussed in brief by Blundell (1990); they permitted the characterization of the structure of the Earth's crust in areas of different tectonics and consolidation ages. The W–E running MOIST seismic profile is the oldest one located offshore of northern Scotland (Fig. 10). It enabled the reconstruction of the remarkable, reflection, subhorizontal Moho surface at 9 s TWT. This is the bottom bounding surface of a thin layer of the laminated crust, and a layer containing a set of eastward-dipping reflections (at an angle of 20–30° and reaching as deep as the middle crust) and sets of westward-dipping shorter reflections which correspond to fault zones bounding wedge-like sedimentary basins. A single reflection set continues into the upper mantle.

The DRUM profile is parallel to the MOIST profile and runs slightly to the north of it. The seismic structure of the crust is similar, with moderately dipping reflections dominant in its upper part. These reflections correspond to asymmetric crustal blocks resembling a domino pattern and occur above a highly reflective subhorizontal zone in the lower crust. Beneath the Moho surface, distinctly bounding the laminated crust at 15 s TWT, there is another set of horizontal or low-dipping reflections of the upper mantle. It borders a non-reflective zone that wedges out towards the west and is truncated by a prominent set of reflectors. This set gently dips towards the east into the upper mantle down to a depth of 80 km (Fig. 11). According to plate tectonic interpretations (Warner *et al.*, 1996), this struc-

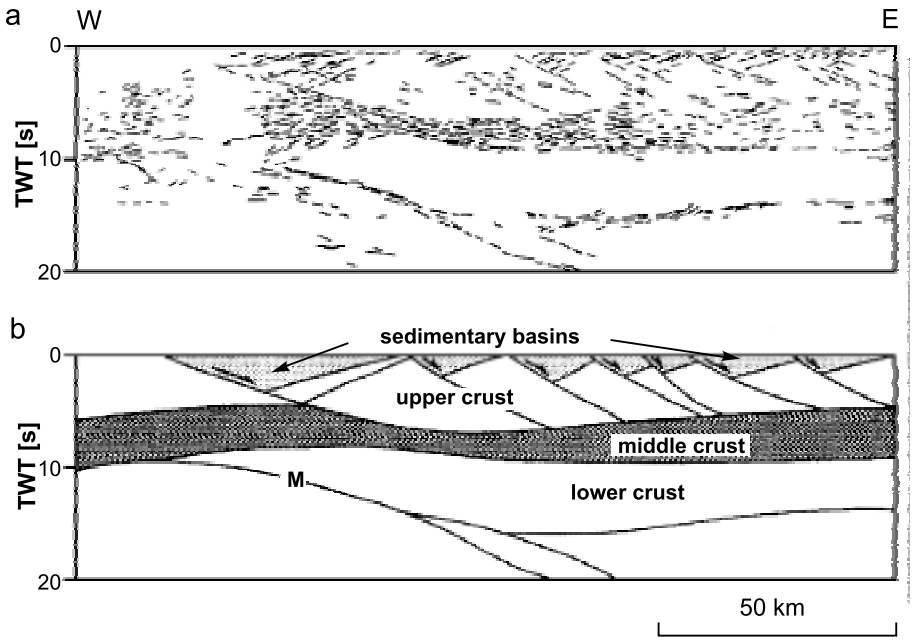

Fig. 11. The northern coast of Scotland

a — the DRUM seismic profile (after Blundell, 1990; simplified); **b** — the crustal structure interpreted by Reston (Blundell, 1990; simplified); the arrows indicate movement along extensional listric faults between which asymmetric sedimentary basins (dotted areas) developed; the listric faults die out within a subhorizontal zone of the middle crust

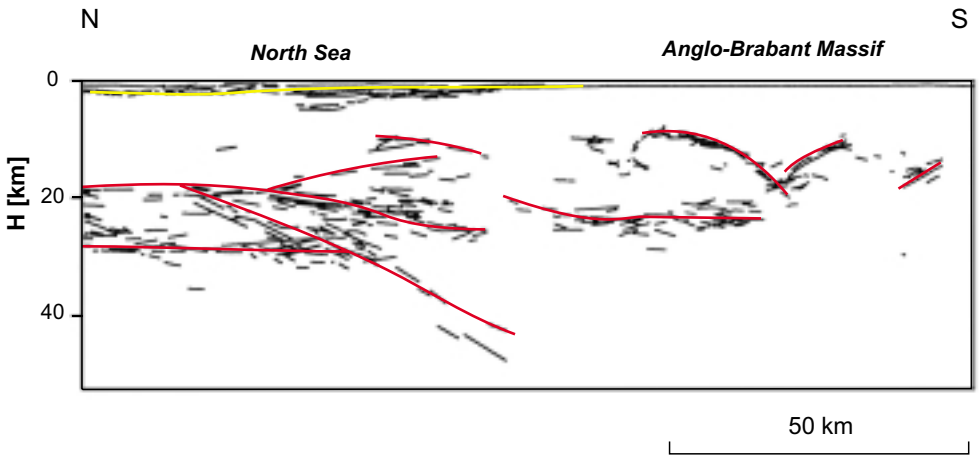

Fig. 12. The MOBIL 7 seismic profile (line drawing), crossing the southern North Sea towards the Anglo-Brabant Massif

For explanation see Figure 1

ture corresponds to a fragment of the subducted oceanic crust composed of eclogite. This crust plunges under the peridotite continental upper mantle and, according to those authors (*op. cit.*), represents a relict of pre-Caledonian subduction.

The MOBIL 7 seismic profile (Fig. 12) crosses the northern boundary of the Anglo-Brabant Massif in the southern North Sea. It shows a lateral transition from the strongly reflective lower crust under the southern North Sea to the weakly reflective crust of the Anglo-Brabant Massif. However, arched or bidirectionally dipping reflections delineating large-scale lenticular crustal structures are observed in both of these sectors of the profile. These reflections are interpreted as large-scale anastomosing ductile shear zones along which crustal extension takes place. This extension is responsible for the formation of near-surface extensional sedimentary basins (Blundell, 1990). Some of the low-dipping reflections reach down into the non-reflective upper mantle.

The NNE–SSW trending BIRPS profile crosses offshore Ireland (WIRELINES) and the so-called Iapetus Suture Zone, which was the effect of the closure of the Iapetus Ocean during the Caledonian orogeny. According to Klemperer (1989), this collisional suture is marked in the profile in the form of a series of distinct lower crustal reflections gently dipping towards the north and terminating at the Moho surface. That author is of the opinion that the theoretical roots of the Caledonian orogen were eliminated by post-orogenic extension and flow deformations within the lower crust. However, this profile shows (Fig. 13) a typical large-scale lenticular to wedge-like seismic

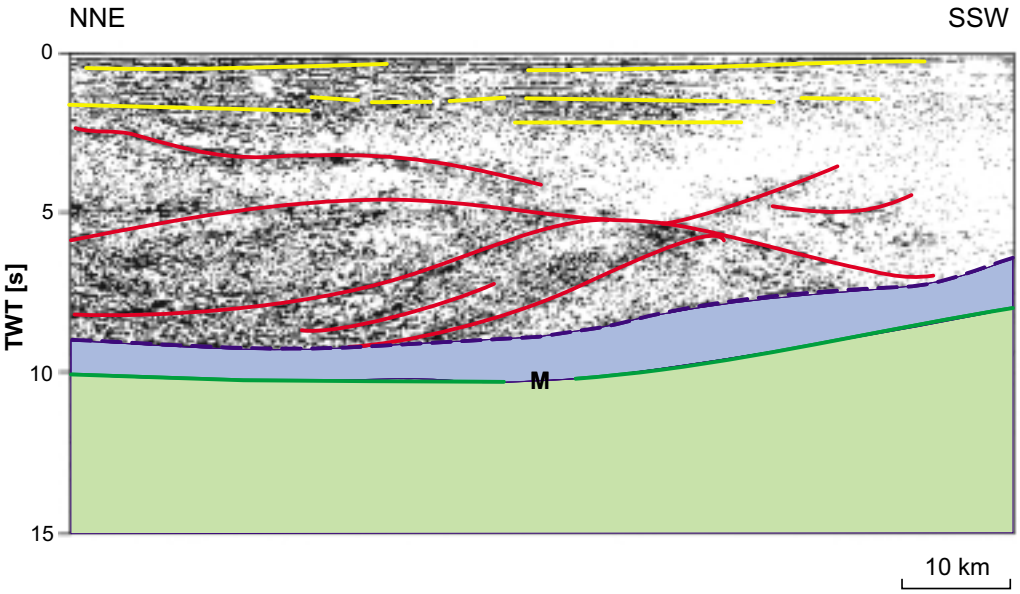

Fig. 13. A reflection seismic profile, offshore west Ireland, crossing the so-called Iapetus Suture Zone(after Klemperer, 1989; supplemented)

For explanation see Figure 1

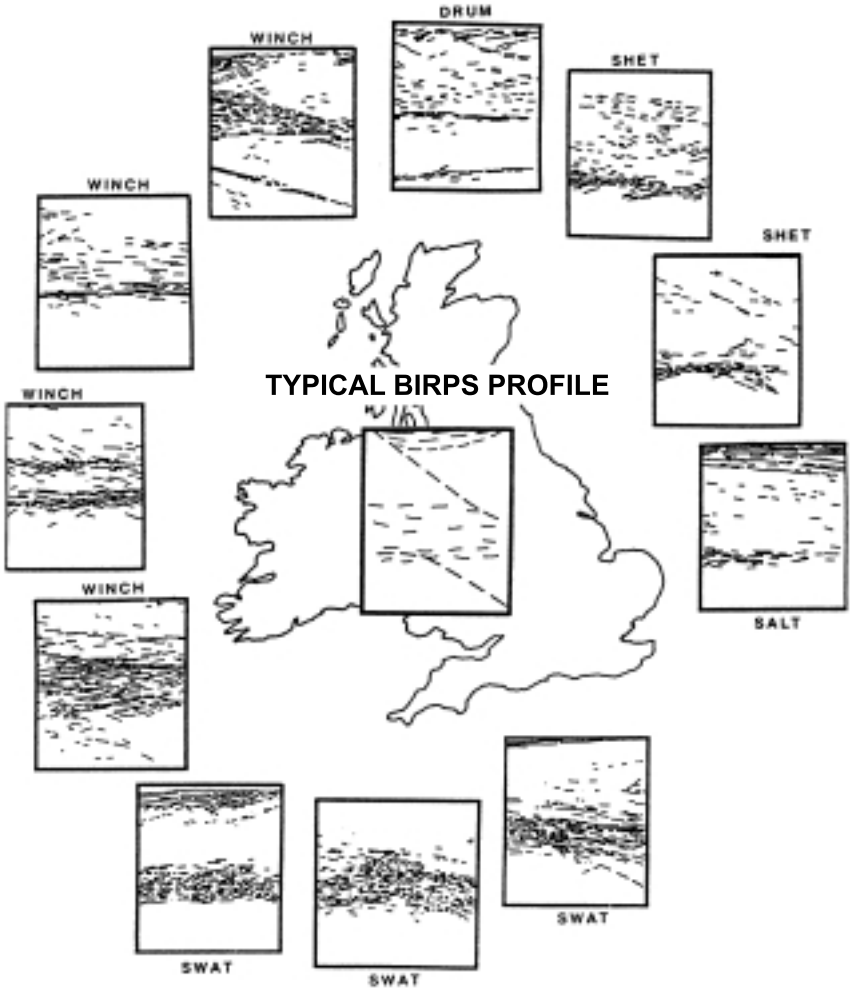

Fig. 14. A schematic, typical seismic profile of BIRPS (after McGeary, 1987) showing the features in common for the crustal and upper mantle seismic structure around the British Isles (shown in the centre)

The drawings distributed around it illustrate examples of typical crustal seismic structures identified in individual transects performed by the BIRPS consortium

structure, delineated by mostly bidirectionally and symmetrically dipping reflection sets. The subhorizontal and dense reflectivity of the upper crust results from the stratification of sedimentary complexes that fill younger basins. Beneath this, flat-dipping extensional detachments are also visible.

Although the BIRPS transects cross geological structures of different ages and origin, there is a range of features common to all the profiles. This fact allowed McGeary (1987) to introduce the term "typical BIRPS" (Fig. 14). Apart from sets of dense reflections which mark stratification of deposits filling near-surface basins, the typical BIRPS profile of the upper crust generally shows low reflectivity and the presence of single, low-dipping reflections commonly corresponding to faults observed on the surface, in particular in the extension zones of Mesozoic and Cenozoic basins. The middle crust is dominated by reflections which divide the crust into lens-like and wedge--like fragments which are locally remarkably shifted in relation to one another. The lower crust in the BIRPS profiles mostly shows a dense subhorizontal lamination, although its thickness varies over a broad range. The reflective Moho surface is commonly associated with an abrupt disappearance of the laminated structure of the lower crust.

BIRPS investigations also provided many results concerning the reflectivity of the continental lithosphere, its age and possible genetic relationships with deformation processes. The geological structure of the areas around the British Isles is dominated by Permian–Mesozoic and Cenozoic lithospheric extension, responsible for the formation of a series of extensional sedimentary basins and divergent continental margins. Older tectonic structures are related to the Caledonian and Variscan epochs. In the southern British Isles, it is also evident that there was Alpine inversion of some of the younger basins. The BIRPS profiles show numerous normal listric faults in the upper crust, which controlled the rotation of the blocks, a process that was simultaneous with the filling of the sedimentary basins. These faults gently merge into the middle-lower crust,

characterized by a dense subhorizontal seismic lamination. The spatial relationships between the extensional structures of the upper crust and the laminated lower crust suggest that the lower crust was also subject to extensional processes. However, tensional stresses could not be transferred from the upper crust down to the lower crust and upper mantle, as postulated by Blundell (1990), but rather in the opposite direction: from the upper mantle towards the upper crust.

Some of the BIRPS profiles also indicate the occurrence of discontinuous structures within the upper mantle. These are represented by rare normal faults, commonly forming a conjugate system. Elsewhere, the upper mantle shows no reflections.

The European Variscides have also been the subject of reflection seismic studies. The Variscan deformation zone of Western and Central Europe is represented by an arched belt extending from Portugal and Western Spain across France and Germany as far as the Czech Republic and Poland. This belt is disturbed by young post-Variscan basins and rift zones. A number of blocks, represented by Proterozoic and Palaeozoic massifs (the Iberian, Central, Armorican, Ardenian–Rhine and Bohemian massifs), mainly uplifted during the Tertiary, occur within this belt. These massifs yield evidence for a polygenic tectonic and magmatic evolution (Dallmeyer, 1995) during the Cadomian, Caledonian and Variscan epochs. The major phases of metamorphic processes and orogenic uplifts occurred during the late Devonian–Carboniferous, as evidenced by both intense flysch and molasse sedimentation, and magmatism. Since Kossmat's studies (1927), the European Variscides have been traditionally subdivided into several belt zones corresponding to different parts of this tectogen. Moving northwards, these are: the Moldanubian, the Saxothuringian, the Rhenohercynian and the Subvariscan zones. The two last zones show distinct external polarity of tectonic processes and vergence of tectonic structures, and have been best explored in Germany. Their equivalents in Southern Europe are represented by dismembered fragments of the Variscan tectogen known from Spain, Corsica, the southern Central Massif, and also from the Balcans (the Rodopes Mts., the Serbian–Macedonian Massif). Variscan structures are also included in some of the Alpine nappes (Raumer, Neubauer, 1993). According to Matte (e.g. 1991), the European Variscan tectogen shows an overall bidirectional symmetry.

Plate tectonic interpretations of the geological structure of the European Variscides suggest that individual zones are of geodynamic significance. The tectonic boundaries between these zones are considered to represent major collisional sutures separating terranes or superterranes of Gondwanian origin. Collisions between them are believed to be responsible for Variscan deformations (e.g. Franke, 1989; Franke *et al*.,1990; Dallmeyer, 1995; Matte, 1986, 1991). Therefore, most of the geophysical transects (reflection profiles) of Europe cross the suspected major collisional zones. These are primarily deep geophysical and geological studies performed by DEKORP. The most important, in terms of exploration of the Earth's crust of the Variscides, were: the NNW–SSE trending DEKORP 2 and DEKORP 4 seismic transects; the DEKORP 3A and B transects, connected in the east with the MVE-90 profile; the DEKORP 9-N and DEKORP 1 transects, connected in the northwest with the BELCORP profile; and the DEKORP 9-S transect, which is the southeastern end of the ECORS transect of France.

The DEKORP 2 reflection seismic profile transects the entire Rhenohercynian Zone of the Rhenish Schiefergebirge Mts., the Northern Phyllite Zone, the Mid-German Crystalline Zone and the southern branch of the Variscides, now mostly hidden under the Mesozoic cover (Behr, Heinrichs, 1987). Its northern part — the DEKORP 2-N profile — crosses the Rhenish Massif, and is one of the most comprehensively analysed seismic profiles in the world (Fig. 15). A very detailed analysis of the DEKORP 2-N profile was given by Franke *et al*. (1990). This profile shows the upper, middle and lower crust, which differ in terms of their seismic structural features. The upper crust reaches to 3–4 s TWT, corresponding in the Rhenish Massif to a thickness of 9–10 km. It is strongly reflective and dominated by waveform and irregular reflections dipping in various directions. The reflection pattern is associated with the tectonic style observed on the surface. It reflects both the open folds of the Subvariscan Ruhr Basin, and the anticlinoria and synclinoria of the Rhenish Slate Mts. The north-verging fold structures are separated by steep fault zones representing thrusts and normal faults. The geological history of all of these fault zones is very long, and their movement kinematics is variable through time (Franke *et al*., 1990). The reflection pattern of the upper crust allows the statement to be made that these fault zones are listric in character. They dip south and gradually flatten downwards, passing into subhorizontal detachment surfaces at 4–5 s TWT. The general seismic image of the upper crust may partly be correlated with the stratigraphic and tectonic structures observed on the surface. The occurrence of numerous north-dipping (i.e. in the opposite direction to the vergence of the tectonic structures observed in the near-surface) reflection bands is also evident. These reflections have not been analysed in previous geological interpretations.

In the DEKORP 2-N profile, the middle crust is represented (Fig. 15c) by a low-reflectivity zone and lenticular pinches, bounded on both sides by high-reflectivity bands. Its upper boundary lies at a depth of 4 s TWT (about 12 km), and its thickness varies from 3 to 6 km. Some of the middle crust reflections are straight and subhorizontal. The seismically transparent zone is correlated with a zone of low seismic velocity or weak inversion of velocity on the refraction profile. Both of its borders are represented by high velocity "layers" (Franke *et al*., 1990; Giese *et al*., 1990). The listric structures of the upper crust seem to be rooted in the highly reflective layer. The geometrically variable seismic structures of the upper crust are undoubtedly truncated by the middle crust. Taking into account Meissner's (1986) and Meissner and Kusznir's (1987) data on the rheological properties of the continental crust at this crustal level, we can state that this is evidence for ductile shear. From the middle crust downwards to the Moho surface, the seismic reflections are subhorizontal and more or less straight. Such a seismic structure probably reflects ductile deformation represented by flattening or simple shear.

The lower crust is of variable character along this profile (Fig.15). In its northern part, under the structures of the Subvariscan zone (Ruhr Basin), the lower crust is seismically transparent. The Moho surface is delineated by discontinuous reflection bands, and gently dips towards the north. This part of the crust distinctly wedges out southwards under the Variscan

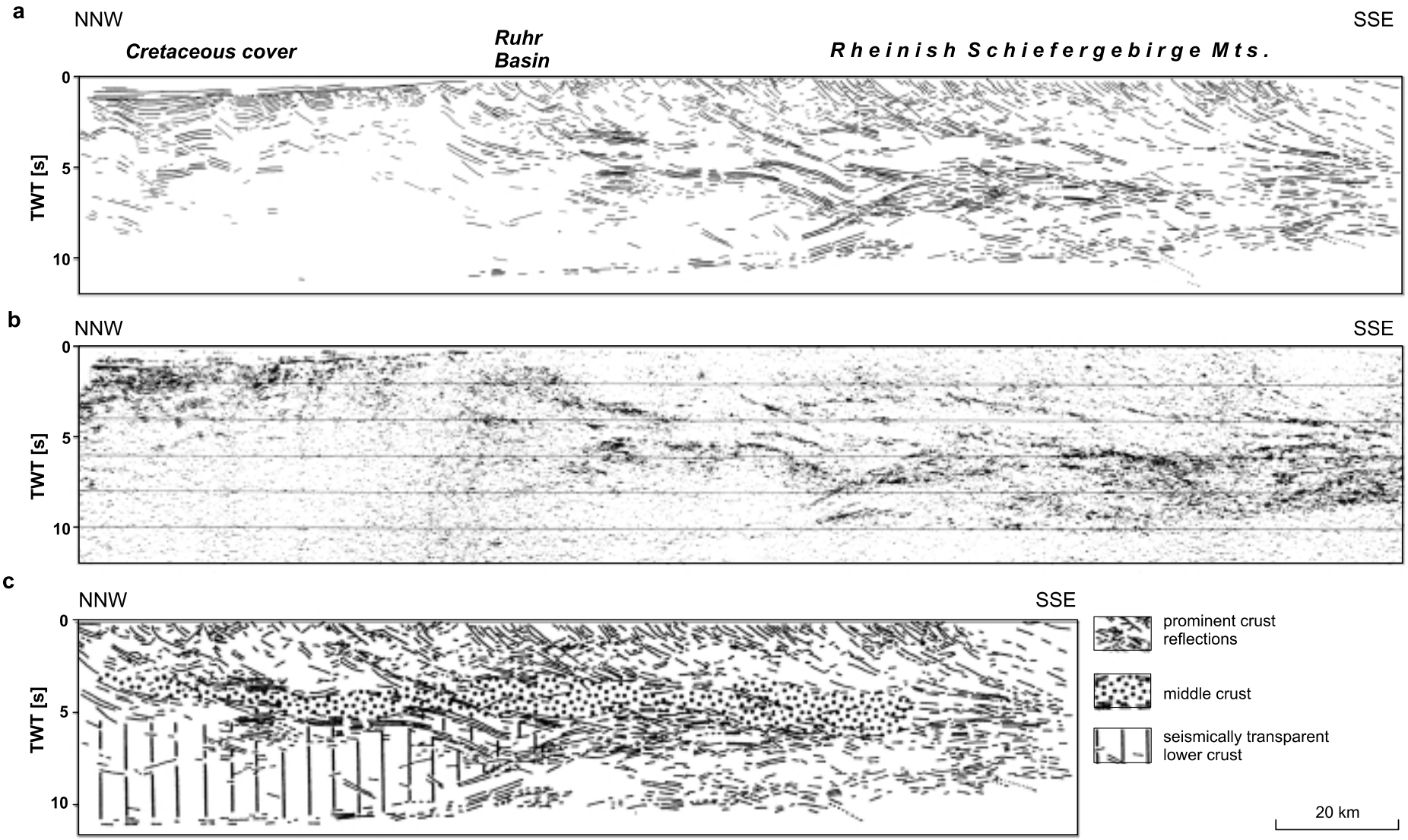

Fig. 15. The DEKORP 2-N reflection seismic profile

a — line drawing; **b** — migrated section; **c** — seismic domains identified in the DEKORP 2-N section, Rheinishe Schiefergebirge Mts. (Franke *et al.*, 1990)

structures of the Rhenish Schiefergebirge Mts., forming a huge intracrustal large-scale lenticular structure, approximately 100 km in length and probably over 15 km thick. Franke *et al*. (1990) considered this structure to represent the crystalline basement of the Precambrian Anglo-Brabant Massif, hidden deep under Variscan structures. In the southern part of the profile, the highly reflective lower crust occurs at a depth of 6–10 s TWT. In this area, reflection bands dip bidirectionally, forming a lenticular seismic structure; however, the lenses are much smaller: 15–20 km in length and 3–4 km in thickness. The Moho surface is interpreted as the lower boundary of the laminated crust. Single, bidirectionally dipping reflections seem to dip beneath the Moho, in the upper mantle.

The authors of the profile's interpretation (Franke *et al*., 1990) underline the fact that the general style of tectonic deformation of the crust largely depends on the rheological gradient — on the downward increase in ductile behaviour. Along the length of this profile, there is no single detachment surface which would represent a sharp rheological boundary. The change in the seismic structure style proceeds within a fairly wide zone in the middle crust. It seems that listric fault zones, typical of the upper crust, are rooted in this part of the crust. The middle and lower crust are involved in a completely different structural pattern — a lenticular to large-scale lenticular structure, typical of many other seismic profiles. Individual lenses seem to wedge out, being mutually shifted relative to each other, although the amplitudes of these shifts are not high. These ductile deformations are accompanied by a grid of presumed conjugate fractures transecting the entire crust and dipping at an angle of approximately 50°. Its origin is difficult to interpret, although Franke *et al*. (*op. cit*.) suggest that they can represent inversion faults. The age of these crustal structures is unknown. It is commonly suggested that they are related to Variscan tectonic structures observed on the surface; however, this hypothesis has not been seismically proved, in particular with regard to the middle and lower crust. The conjugate fractures are certainly younger than the large-scale lenticular structure of the lower crust. They can represent the phase of brittle deformations in the entire crust (*op. cit*.).

The crustal seismic structure of the other DEKORP profiles shows many similarities. For example, the DEKORP 2-S reflection seismic profile, which transects the Saxothuringian Zone and a fragment of the Moldanubian Zone (Behr, Heinrichs, 1987), is characterized by a distinct bipartition — the upper crust, down to a depth of about 4 s TWT, is weakly reflective and difficult to correlate with surface structures (Fig. 16). Below this depth, bands of reflections appear, dipping southwards and northwards at 20–30° to a depth of 6 s TWT. At this depth, they gently approach the top boundary of the laminated lower crust. In the Mid-German Crystalline Rise, they correspond to reflections which form a dome-shaped antiform. Along the entire profile, the lower crust shows high reflectivity marking its lenticular (boudinage) seismic structure. The same seismic image can be observed in the middle part of the profile (Wever *et al*., 1990). In the Moldanubian Zone (the DEKORP 2-S profile — the southern part, and the KTB profiles — the Schwarzwald), the lower crust also shows a distinct lenticular stratification and, as stressed by Wever *et al*. (1990), it does not differ from the crust of the Saxothuringian Zone. Its top boundary with the upper crust is wavy, forming local domal elevations. Its basal boundary is rather flat and coincides with the Moho surface. Rare, crossing reflection bands (dipping at 25°) are visible below the Moho surface in the upper mantle.

The DEKORP 4 seismic profile, running from the Upper Palatinate across the Fichtel Mts. to the Franconian Wald, transects a major geological boundary of the Central European Variscides (Fig. 17). Its general seismic image is similar to that discussed above (Wever *et al*., 1990). The crust, 10–11 s TWT in thickness, is composed of mutually shifted lenticular and wedge-like fragments separated by stronger reflectivity zones. Seismic interpretations, which suggested that in the upper crust, the Moldanubian nappe complexes are thrust over the Saxothuringian Zone (e.g. the Muenchberg gneiss massif), were not confirmed by the KTB deep borehole (Emmermann, Lauterjung, 1997; Harjes *et al*., 1997).

The western part of the European Variscides was explored via the BELCORP and ECORS reflection seismic profiles.

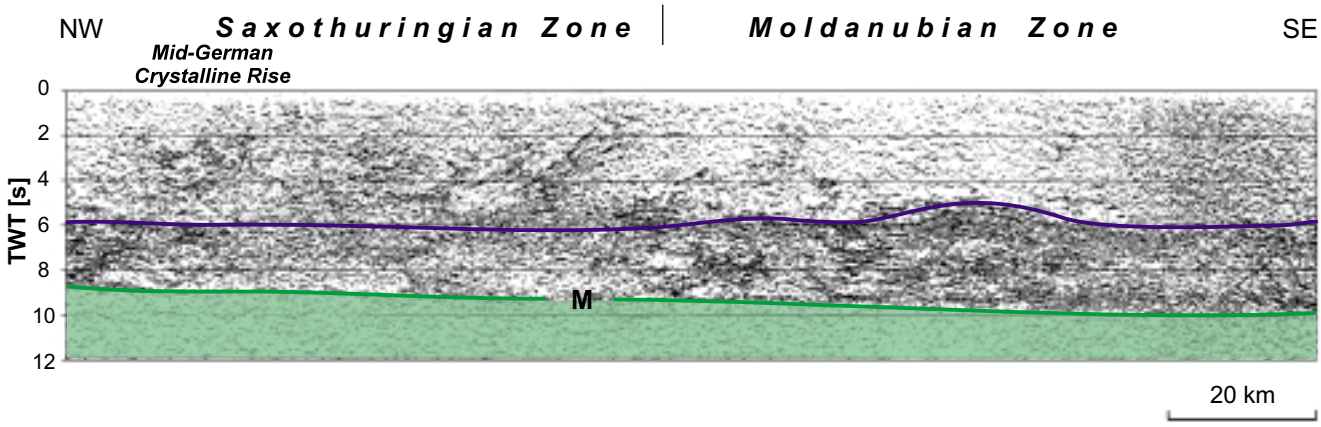

Fig. 16. Part of the DEKORP 2-S reflection seismic profile crossing the boundary between the Moldanubian and Saxothuringian zones (Behr, Heinrichs, 1987; modified)

For explanation see Figure 1

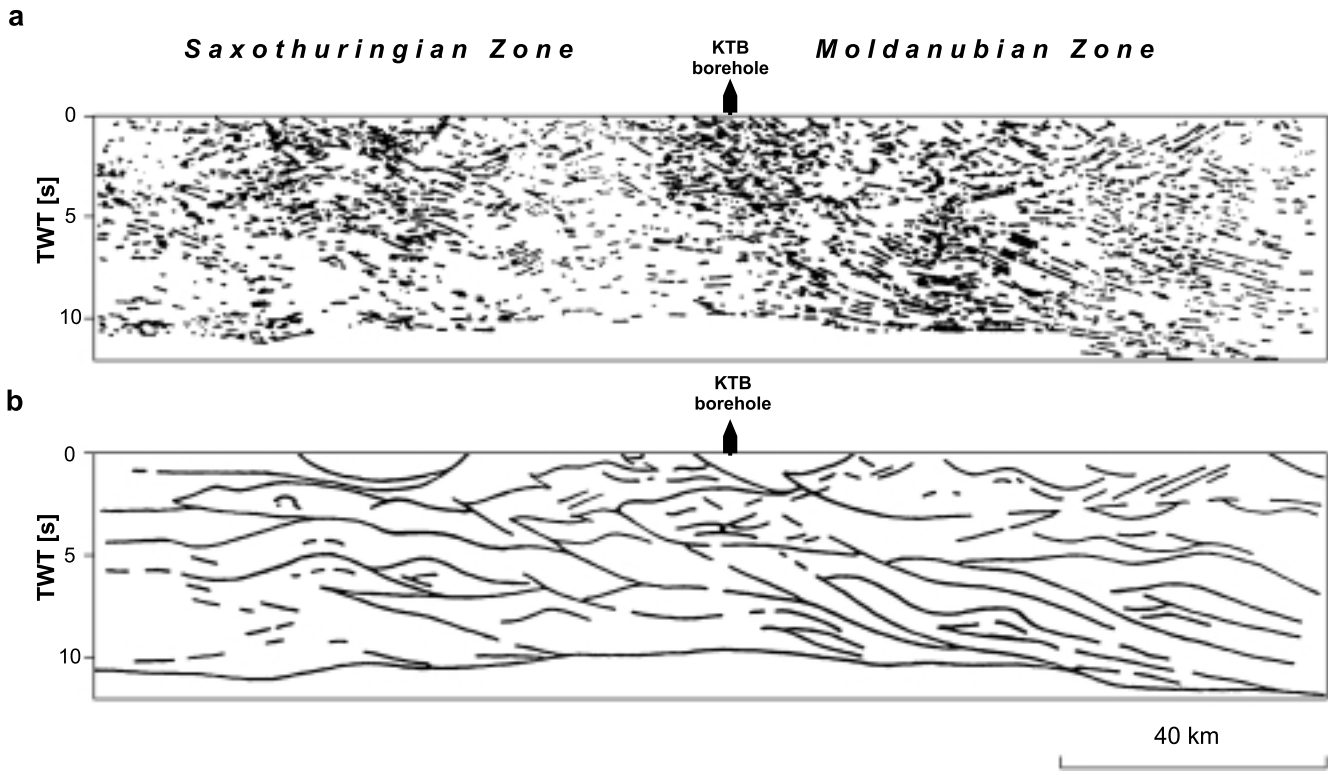

Fig. 17. The contact between the Moldanubian and Saxothuringian zones near the KTB borehole

a — the DEKORP 4 seismic profile; **b** — a model of the seismic structure according to Wever *et al.* (1990)

The ECORS profile is 1000 km long and crosses France from the Variscan Front in the Ardenes through the Paris Basin, Armorican Basin and Bretany towards the Bay of Biscay. This profile has provided the most complete data on the European Variscides. Near vertical reflection data come from 1/3 of the northern and 1/3 of the southern part of the transect. The middle part of the profile is covered by wide-angle reflection data (Fig. 18). The tectonic interpretation of this profile was done by Matte and Hirn (1988). Despite the poorer quality data compared to the DEKORP profiles, it allows the statement to be made that the nearly even Moho surface (the crust under the Paris Basin is thinned) is represented in this profile by a horizontally intensely laminated layer, 3 to 5 km thick. Only in the Brabant Massif is the Moho surface less distinctly marked. The highly reflective lower crust, partly with fragments of the upper crust, is involved in a pattern of flat-dipping, large-scale lenticular crustal structures. These structures seem to dip from both ends of the profile towards the Armorican Zone, forming a symmetric synform, over 600 km in length. At the north-eastern end of the profile, a wedge-shaped structure of the Precambrian Brabant Massif is observed. This structure shows weak reflectivity and is inserted into more strongly reflective zones. A similar syncline-shaped crustal structure is suggested in the interpretations of Matte *et al.* (1990) for the Bohemian and Central massifs.

The western ends of the European Variscides in the southern and southwestern British Isles were explored through reflection seismic profiling along the SWAT profiles (Fig. 19). These profiles were jointly interpreted by the BIRPS and ECORS teams (BIRPS and ECORS, 1986). Although the profiles run across the area of Variscan deformations and are perpendicular to the so-called Variscan Front of south-western England and southern Ireland, they cross a number of Mesozoic extensional basins such as the English Channel Basin, the Plymouth Bay Basin, the South and North Celtic Sea Basins, etc. The main features of the SWAT profiles resemble those of the other transects performed around the British Isles. Dense reflections that correspond to stratified sedimentary deposits of extensional basin fills are underlain by the seismically transparent upper crust, with rare bands of reflections dipping at up to 20°. These reflections are rooted at the topmost portion of the strongly reflective lower crust, variable in thickness, which is sharply truncated at the base by the even Moho surface (at 10 s TWT). The crust shows no evidence of thinning under the maximum depressions of the basin; therefore, these depressions are a result of uniform extension of the entire crust. The sedimentary basins are symmetric or asymmetric, the latter commonly developed on the upthrown sides of low-angle crustal fault zones.

The north-eastern part of the Saxothuringian Zone (Vogtland — from the Franconian Line across the Erzgebirge Mts. to Lausitz) was also seismically investigated. Deep seismic investigations were performed in this area as early as the late 1970s along the EV 01 and EV 02 profiles running

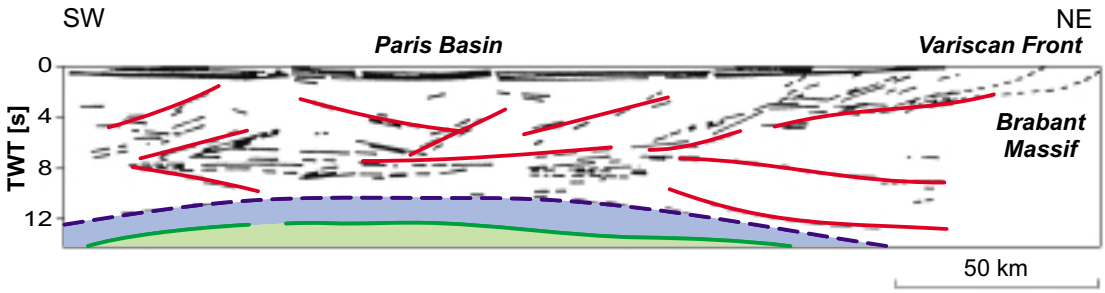

Fig. 18. The ECORS seismic profile across northern France from the Paris Basin to the Variscan deformation front

Line drawing after Bois *et al.* (1987; supplemented); for explanation see Figure 1

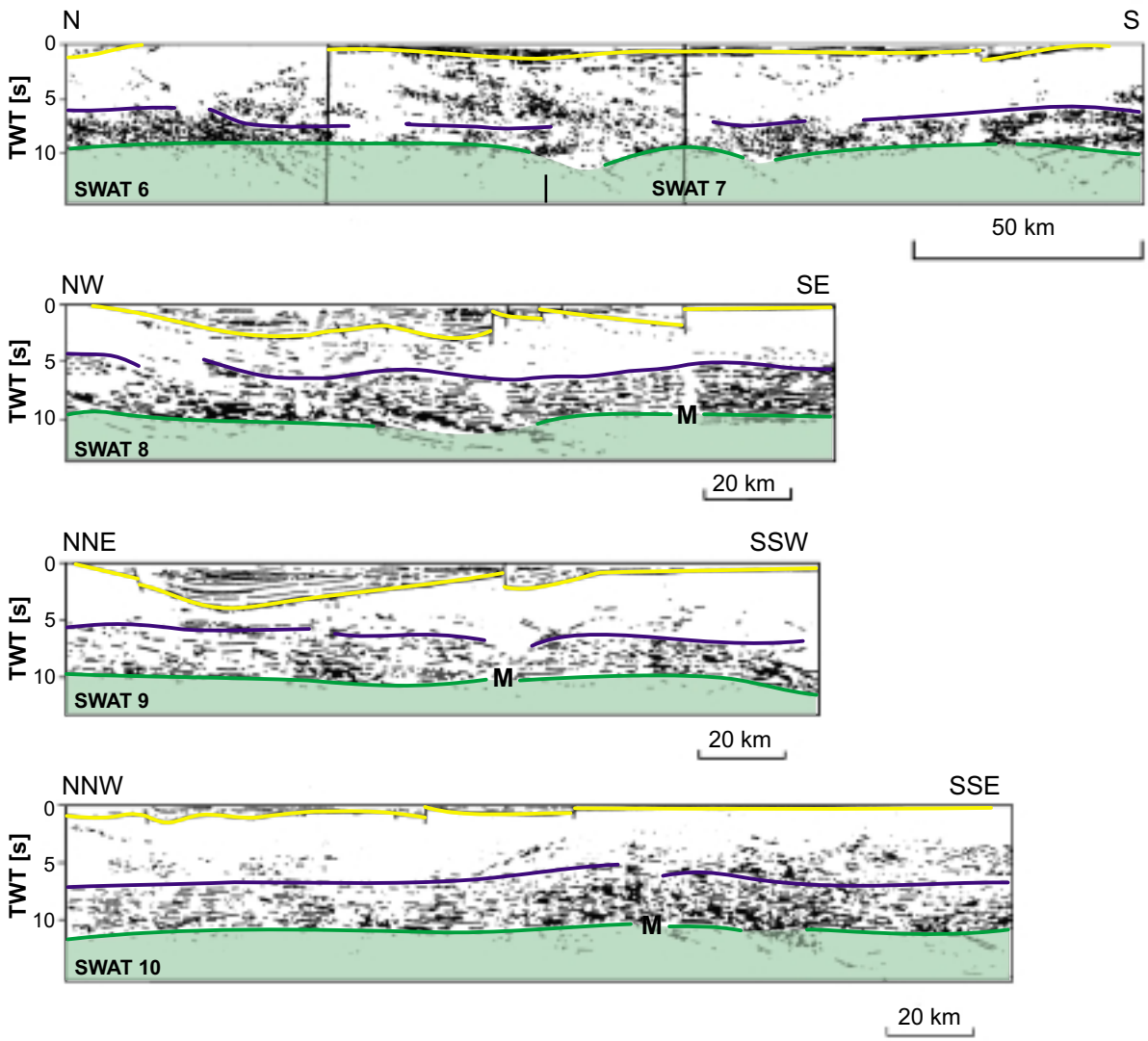

Fig. 19. Selected line drawing seismic profiles of SWAT, running between France and England in an area of extending continental crust (BIRPS and ECORS, 1986)

Note the thick laminated lower crust showing variable thickness, swells and thins, as well as the symmetric reflection bands dipping into the upper mantle; for explanation see Figure 1

NE–SW along the Erzgebirge Mts. Anticlinorium. The results of these investigations were interpreted with the use of potential field modelling by Conrad, Haupt and Bolsche (1994). Despite the much less modern research methods used, these profiles show the subhorizontal large-scale lenticular to layered seismic structure of the crust. Gravity modelling of the Erzgebirge Mts. gravity low, which is bounded by the Franconian Wald and Upper Lausitz gravity highs, suggests the occurrence of a trough-shaped block of light granitogneisses of the Erzgebirge Mts. basement relative to a shallower position of heavier rock complexes occurring to the SW and NE. New data about the crustal structure of this part of the Saxothuringian Zone was provided by the MVE-90 (Ost) reflection profile, which runs more or less parallel to the older profiles and, in the west, is connected through the MVE-90 (West) with the DEKORP 3 profile (with a change in direction from NE–SW to NW–SE) (Durbaum *et al*., 1994). The MVE-90 (Ost) profile trends parallel to the north-western edge of the Bohemian Massif, and generally follows the Vogtland and Erzgebirge Mts. tectonic structures, crossing complexes of Proterozoic and Palaeozoic sedimentary rocks, variably metamorphosed metamorphic rocks and numerous granitoid bodies. This profile also transects several major fault zones: the Franconian Line, the Gera–Jachymov Fault Zone, the Flöha Zone and a system of NW–SE trending Lausitz faults which are a prolongation of the Elbe tectonic zone.

The general seismic-reflection image of this profile (Fig. 20) insignificantly differs from the above-discussed profiles. The continental crust is remarkably stratified, probably as a result of tectonic processes. The upper crust is weakly reflective down to a depth of 3–4 s TWT. Only individual strongly reflective bands which dip at an angle of 35–40° and flatten downwards are interpreted as shear zones (Behr *et al*., 1994). A set of similar NE-dipping structures correspond to faults observed on the surface. These are the Middle-Saxonian, West Lausitz and Lausitz faults (Elbe Zone). Other similar reflections, although difficult to interpret, also occur in this profile. Some of the fault zones are interpreted from changes in the stratification of reflections on the fault sides as subvertical fracture zones, even reaching to the Moho surface (Bankwitz, Bankwitz, 1994). Only around the Münchberg Gneiss Massif do a number of trough-shaped reflection bands occur within the upper crust. These probably reflect a synclinorially-arranged foliation of metamorphic rocks. The intensely and variably reflective middle crust occurs down to a depth of 8 s TWT beneath the upper crust, mostly transparent in appearance and conspicuous by a complex lenticular to wedge-like structure. Individual large-scale lenses, 40–60 km in length and up to 2–3 s TWT thick, show both variable intensity of inner reflectivity and a variable pattern of inner reflections which often mark the second-order lenticular structure. Bankwitz and Bankwitz (1994) distinguished here a number of mutually shifted structural complexes separated by reflection bands, considered by those authors to represent unconformity or intracrustal detachment surfaces. These surfaces are wavy in appearance. A number of listric fault zones, rooted at approximately 4 s TWT, occur in the upper crust. Therefore, as in the DEKORP 2 profile, the middle crustal complexes truncate the upper crustal structures, representing a different deformation model. These structures are generally symmetric along the entire transect, although some of them — interpreted on the basis of the assumed genetic model (Behr *et al*., 1994; Bankwitz, Bankwitz, 1994) — are supposed to show a south-western vergence. The lower crust along the MVE-90 (Ost) profile lies at 8–10 s TWT, and its base truncates the seismic structures of the middle crust. The lower crust is highly reflective and characterized by a variable thickness; towards the north-east, under the Lausitz Block, its thickness increases to 2.5 s TWT and it laterally passes into a lower reflectivity transition zone. Both the top and basal surfaces of this crustal layer are diffusional; the lower one is related to the Moho surface. The characteristic feature of the MVE-90 (Ost) profile is that it crosses large granitoid masses represented by both Cadomian granitoids and orthogneisses, and typical Variscan intrusions. Gravity data indicate the predominance of these rocks in the upper part of the crust. Despite that, the effect of the decreasing reflectivity of the crust is very rare in areas where huge granitoid masses occur. Most of reflections cross granitoid bodies without a change in direction, although their intensity can become weaker. This phenomenon is visible as the interfingering of granitoids with its metamorphic mantle, and the occurrence of autochthonous enclaves (Behr *et al*., 1994). It can also indicate that the reflection bands of the upper and middle crust are younger than the Palaeozoic granitoid intrusions.

The DEKORP 3-B transect runs further to the north-east, roughly parallel to DEKORP 2. It crosses an area covered mostly with Permian–Mesozoic sedimentary deposits (Heinrichs *et al*., 1994). It is connected with the MVE-90 (Ost) transect through the MVE-90 (West) profile. The meridionally trending DEKORP 3-A profile, which runs along the axis of the Hessian Depression (filled with Permian, Mesozoic and Tertiary deposits), branches out from the DEKORP 3-B transect in its northern part. The MVE-90 (West) transect (Fig. 21) crosses the Mid-German Crystalline Rise with fragments of the Northern Phyllite Zone, and part of the Saxothuringian Zone (Vesser Synclinorium, Schwarzburg Anticlinorium, terminating at the Munchberg Complex. Disregarding differences in the geological structure of the deep basement as well as the varying directions of these transects, it is striking that the crustal seismic structure is similar from transect to transect. The crust shows remarkable structural stratification. At shallower crustal depths, down to 0.5–1 s TWT, horizontal reflections are predominant, corresponding to stratification of the platformal sedimentary complex. The upper crust, down to a depth of 3.5–4 s TWT, is characterized by the occurrence of short reflection bands, bidirectionally dipping at angles of up to 30°. The authors of the geological interpretation of this profile (*op. cit.*) named this type of seismic structure "herringbone", due to its similarity to a fish skeleton. Beneath this, as deep as 5–5.5 s TWT, the dipping reflections are arranged in longer bands surrounding weakly reflective or non-reflective lenticular or wedge-like parts of the crust. Heinrichs *et al*. (1994) considered the latter part of the middle crust. However, there is no doubt that these large, mutually shifted crustal structures, often wedging out in the form of crocodile structures, are involved in the upper crustal structural pattern. The laminated lower crust reaches a depth of 10 s TWT. The Moho surface coincides with the base of the seismic lamination. The lamination of the lower crust is less pronounced

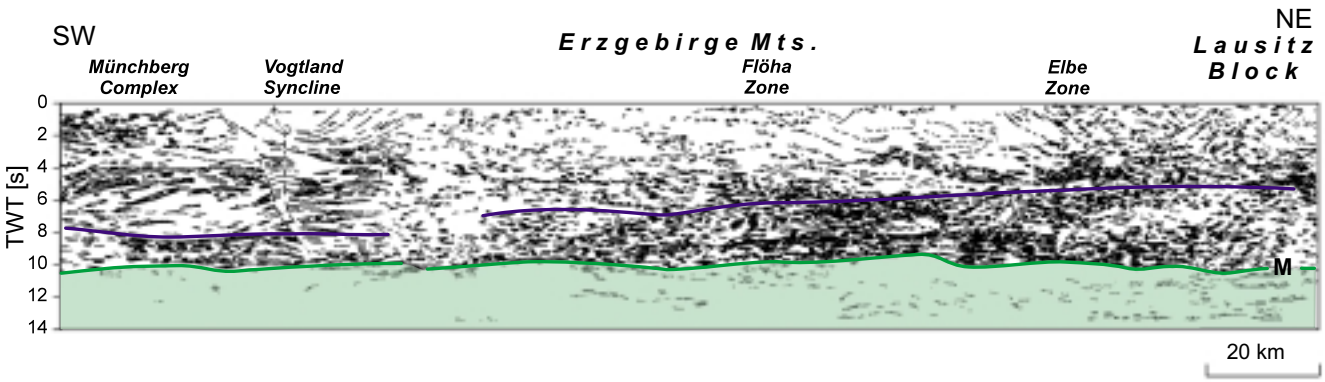

Fig. 20. The MVE-90 (Ost) reflection seismic profile across the Erzgebirge Mts. range

The most prominent reflections are marked with lines (line drawing) (after Behr *et al*., 1994); for explanation see Figure 1

along the DEKORP 3-B/MVE-90 (West) profiles than along the other DEKORP profiles, possibly due to the muffling of seismic waves by a thick sedimentary cover.

The DEKORP 3-A profile shows a similar crustal zonation. Beneath a stratification-related reflectivity zone, there is a zone of common, moderate density reflections, in which short (up to 0.5 km) reflections and waveform reflection belts are visible. These dip multidirectionally at 10 to 30° resembling a conjugate system. In the middle crust, down to a depth of 5.5 s TWT, strong reflection bands occur; they dip subhorizontally, mostly southwards. Some of these bands surround and separate lenticular and wedge-like areas of weaker reflectivity. There are also isolated reflection bands that occur within seismically transparent zones, but such cases are rare. From 5.5 to 9.5–9.8 s TWT, there is a strongly reflective lower crust characterized by seismic lamination. Individual, subhorizontally-arranged strong reflections are 2 to 4 km long. Locally, they dip bidirectionally at 20°. The density of the reflections seems to increase downwards. The reflective Moho surface lies at a slightly shallower depth than in the DEKORP 3-B/MVE-90 profiles (except in the Lower Hessian Depression) — at 27–28 km. Locally, lamination of the lower crust fades away and is laterally replaced by seismically transparent zones. Such zones are poorly correlatable with Tertiary volcanism centres (Heinrichs *et al*., 1994).

The DEKORP 3 and MVE-90 seismic transects also confirm that the reflective Moho surface gently dips under the Bohemian Massif.

The Bohemian Massif was also an object of seismic reflection investigations, initially along the NW–SE trending 9HR seismic profile. This profile transects the south-western part of the Bohemian Massif from the Saxothuringian Zone, through the Marianske Lazne Ultramafic Complex and the Tepla–Barrandien Zone, towards the Moldanubicum of Shumava and the southern Czech Republic (Fig. 22). This profile also shows the presence of similar seismic structures: bidirectionally dipping short reflections in the upper crust (up to 2 s TWT, corresponding to a depth of 6 km) which overlie a layer where symmetric "pinch and swell" structures are dominant (down to

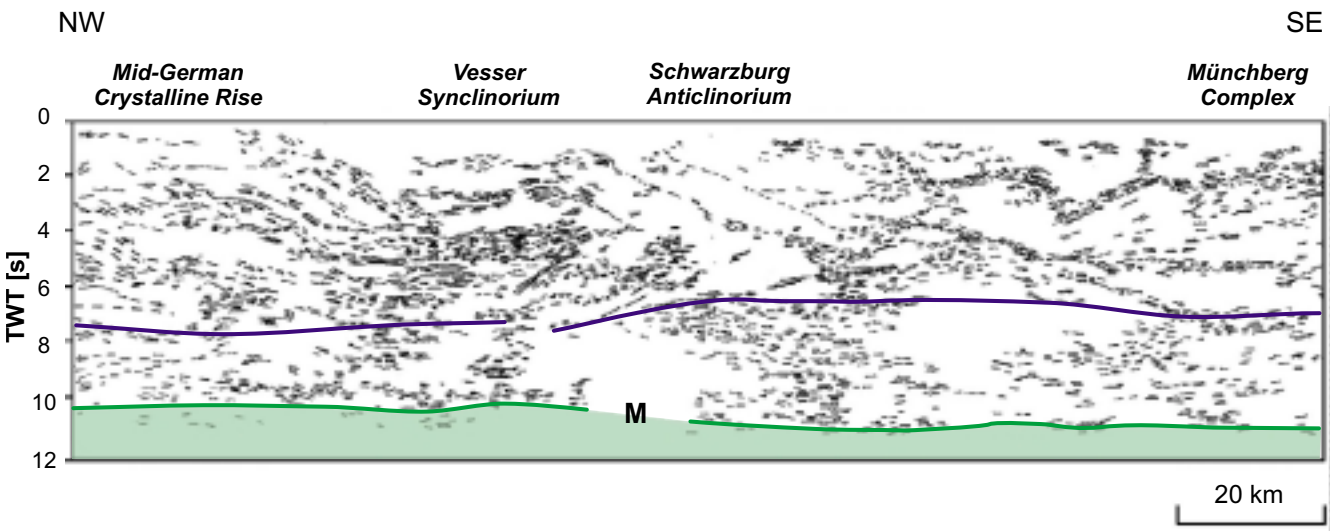

Fig. 21. The MVE-90 (West) reflection seismic profile (after Bankwitz in Behr *et al*., 1994)

For explanation see Figure 1

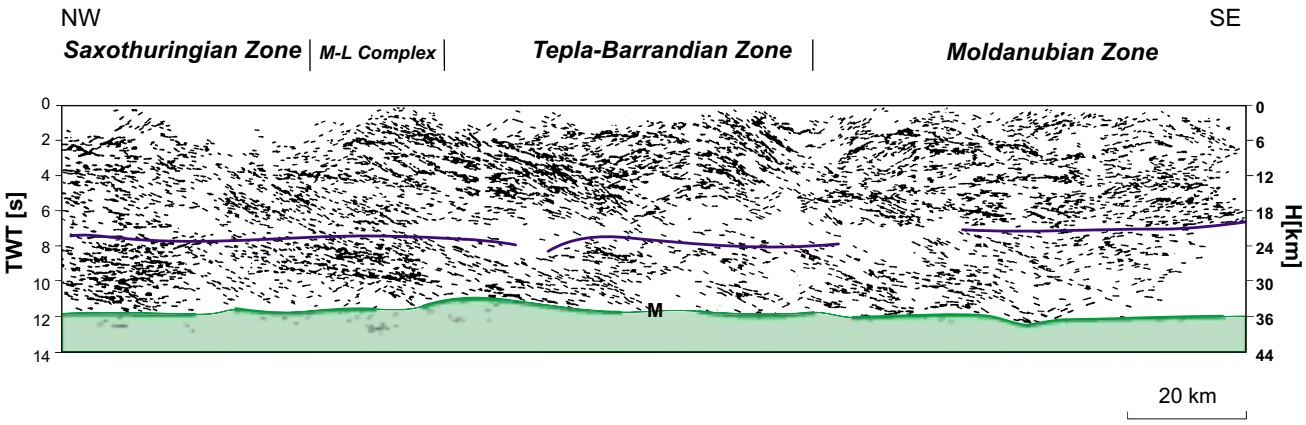

Fig. 22. The 9HR seismic profile crossing the southern Bohemian Massif

M.-L. Complex – the Marianske Lazne Ultramafic Complex; for explanation see Figure 1

a depth of 18–20 km). Beneath this, there is a low reflectivity zone related to the pattern of lenticular structures (down to a depth of 24 km) resting on the laminated lower crust (24–33 km), typically developed under the Saxothuringian and Tepla–Barrandien zones. In the lower crust, under the Moldanubian part of the Bohemian Massif, symmetrically inclined bidirectionally dipping reflection bands occur marking the large-scale lenticular seismic structure. The Moho surface is indistinct in this area, being additionally disturbed by conjugate reflection systems dipping into the upper mantle at angles of 15–20°.

South-western Poland is transected by the GB-2A reflection seismic profile (Cwojdziński *et al*., 1995). Between the towns of Głogów and Świeradów Zdrój, the purpose of this profile was to provide information on the deep structure of the Earth's crust along the NE–SW trending transect more or less perpendicularly crossing several major tectonic lines of the Lower Silesian Variscides, as well as to solve the problem of the occurrence of major tectonic sutures in this area. From the geological point of view, this profile crosses the following areas (from NE to SW): the southwestern margin of the Fore-Sudetic Monocline, the poorly explored tectonic boundary which runs along the so-called Middle Odra Fault Zone between the Fore-Sudetic Monocline and Fore-Sudetic Block, the northwestern part of the Fore-Sudetic Block, and the part of the West Sudetes represented in this profile by the Kaczawa Unit with the North Sudetic Depression, developed within this unit, and the northern part of the Karkonosze–Izera Block.

This profile shows the occurrence of a complex seismic structure of the southern Variscides, generally similar to the seismic structure of the southern German Variscides, observed in the DEKORP 2-S and DEKORP MVE-90 profiles. The major features of the GB-2A profiles are as follows: (1) a strongly reflective lower crust of variable thickness and density of reflections, and with a characteristic lenticular to layered seismic structure; (2) a reflective Moho surface marked by an abrupt loss of reflectivity of the lower crust at 11–12 s TWT, which coincides with the refraction Moho over large distances; (3) the occurrence of a reflective middle crust under some of the geological units, characterized by a zonal seismic structure; and (4) a weakly reflective upper crust with single, low or moderately dipping reflections which, at least in part, correspond to geological structures observed on the surface (e.g. the Sudetic Marginal Fault and the Intra-Sudetic Fault).

In recent years, the DEKORP consortium performed additional seismic transects. These are the NE–SW-trending BASIN 9601 profile between the Harz Mountains and Rügen, with a continuation in the form of the PQ2-005 transect crossing the Baltic Sea, and the perpendicular BASIN 9602 profile (Dekorp-Basin Research Group, 1999, see Fig. 3). The BASIN profiles were performed in order to explore the crust in the area of the most complete development of the Permian–Mesozoic basin of north-eastern Germany. The BASIN 9601/PQ2-005 profile transects part of the Rhenohercynian Zone, the so-called Variscan Deformation Front, Caledonian Deformation Front and Trans-European Suture Zone. Normal faults of the upper crust cut sedimentary deposits of the platform cover. These faults can be observed in the subhorizontal reflection structure down to a maximum depth of 5 km. A series of strong reflections of the middle crust forms subhorizontal, elongate lenticular structures bypassed by strong and wide reflection bands. The inner structure of these lenses is often inconsistent with the surrounding reflection bands. At the bottom of the crust there is a 2–4 km thick reflection band which shows an intense seismic lamination along the entire profile. Its base coincides with the Moho surface at a depth of 30 km beneath the basin of north-eastern Germany, and at a depth of 35 km under its margins. Refraction data indicate seismic velocities Vp = 6.7–7.0 km/s in the laminated layer beneath the basin, suggesting the occurrence of mafic rocks. The crustal structure in the perpendicular NW–SE trending BASIN 9602 profile is highly similar. Both of these profiles represent the continental crust subjected to extensional stresses from the Permian throughout the Mesozoic. The authors of the geological interpretation of these profiles (Dekorp-Basin Research Group, 1999) empha-

size an extensional thinning of the basin crust and the fact that late Cretaceous inversion of the structures (in their opinion related to a crustal shortening) did not markedly affect the extensional structures beneath the North German Basin.

A different tectonic structure is represented by the meridionally /stretched Upper Rhine Graben included in a Tertiary rift system of Central Europe. This structure was formed as the result of lateral extension. The Upper Rhine Graben is crossed by the ECORS/DEKORP 9-S geophysical transects (Brun *et al*., 1991). Seismic data indicate the occurrence of weakly reflective upper crust with rare reflection bands which dip bidirectionally at about 30–35°. The most prominent reflection bands seem to correspond to listric frame faults. The geological interpretation (Echtler *et al*., 1994) states that the laminated lower crust markedly thins. Beneath the graben axis, its top lies 3 km deeper than beneath the flanks. There is also a gentle rise in the Moho surface. Therefore, the laminated lower crust extended by 50%, whereas the extension of the upper crust is estimated at 15% (Echtler *et al*., 1994). A process of detachment of the lower and upper crust at the top of the laminated layer probably occurs in this area.

Summarizing the results of the reflection seismic investigations across the European Variscides, it should be stressed that most of the profiles are of excellent quality. They provide insight into the seismic structure of the continental crust as well as into the long and diverse geological evolution from the Proterozoic to the Tertiary. The characteristic features of the European Variscides are metamorphic complexes representing pT conditions of the middle and upper crust and locally even of the upper mantle (high-pressure complexes), which now occur on the surface. The mechanism of exhumation of these complexes still remains unclear, although the processes responsible for this mechanism must have been recorded in the crustal structure. However, the identification of ages and origin of crustal structures is difficult; they are most often polygenic in character. Undoubtedly, a general change in the structural pattern of the crust occurs at depths of 15–20 km. Structures which occur above these depths can be correlatable to a lesser or greater degree with the tectonic structures observed on the surface, but the seismic structure of the lower crust shows no relationships with the surface structures.

Those existing geodynamic interpretations which are based on the results of reflection seismic investigations and other deep geophysical investigations commonly developed from plate tectonic interpretations of the evolution of the Variscides (Franke *et al*., 1990; Behr *et al*., 1994; Heinrichs *et al*., 1994; Bankwitz, Bankwitz, 1994) with particular regard to the idea of terranes (Meissner, Sadowiak, 1992). All of these interpretations search for evidence of the preservation of compressional structures in the seismic image, in particular in those sectors of the seismic transects which cross major tectonic boundaries of geological units observed on the surface. In the upper crust, these are thin-skinned tectonic ramps (as interpreted along the Variscan front zone at the boundary between the Rhenohercynian Zone and the Anglo-Brabant Massif) or signs of crustal tectonics observed, for example, in the Rhenohercynian Zone (Franke *et al*., 1990). Structures related to plate collisions and terrane docking are represented by intracrustal crocodile structures observed at boundaries between the Rhenohercynian and Saxothuringian zones (along the Mid-German Crystalline Zone), and between the Saxothuringian and Moldanubian zones (Meissner, Sadowiak, 1992). In various geological reconstructions, the structures cover the whole thickness of the crust (Fig. 23). The authors of these interpretations (Franke *et al*., 1990; Meissner, Sadowiak, 1992) claim that the lower crust shows a different seismic structure along the tectonic suture zones on most of the profiles. It "truncates" the base of the upper crust, which is dominated by detachment and thrust structures. Behr *et al*. (1994) also stressed that it is very difficult to distinguish compressional crustal structures from extensional ones on the ground of the reflection pattern. The recently constant thickness of the crust and the presence of extensional structures, in particular in its lower part, has commonly been explained by the assumption of post-Variscan extension (Behr *et al*., 1994) superimposed on an earlier orogenic stacking phase. In my opinion, the seismic structure can be explained exclusively using a model of extensional deformations. In this model, the evident lenticular structures of the middle crust, visible in the upper crust, are considered to represent pinch and swell structures, while the reflection lamination of the lower crust is assumed to be a result of the formation of extensional, conjugate surfaces of pure shear.

The important result of the seismic investigations of the European Variscides was the statement that there is much similarity in the seismic structure of the crust along a number of profiles perpendicular to one another (e.g. DEKORP 3-B and 3-A, MVE-90 (West) and (Ost)). Regardless of the position of the profile relative to the structural pattern of the Variscan Zone, the seismic structure of the crust is similar.

There are also seismic profiles running perpendicular to the Ural Mountain axis. The Uralides are one of the longest Palaeozoic orogens located between the East European Craton and West Siberian Platform. The latter was subject to intense extensional and rifting processes during the Permian, Mesozoic and Cenozoic. The polyphase and polygenic Uralides are composed of 5 main, meridionally-stretched, narrow tectonic zones. The three westernmost zones correspond to the externides, and the two easternmost ones to the internides. The main deformation processes took place during the late Carboniferous and early Permian. In the central part of the orogen, there is the longitudinal Main Uralian Fault, over 2000 km long, which coincides with a boundary between the externides and internides. According to plate tectonicians, this fault is a major collisional suture between the East European Craton and the terranes of the Tagil–Magnitogorsk and East Uralian zones (Zonenshain *et al*., 1990; Perez Estaun *et al*., 1996). Older, Soviet reflection, refraction and wide-angle reflection profiles (Sokolov, 1992) show a large-scale lenticular structure of the middle and lower crust (Fig. 24), as well as the occurrence of abundant symmetrically-dipping short reflections, arched locally in the upper crust. These reflections mark symmetric synforms reaching a depth of 10 km. New reflection profiles, including URSEIS and ESRU, carried out as part of the EUROPROBE project (Perez Estaun *et al*., 1996), indicate that the Main Uralian Fault is manifested as a reflection band gently dipping towards the east and observed down to a depth of 6–7 s TWT. A reflection band related to the top of the crys-

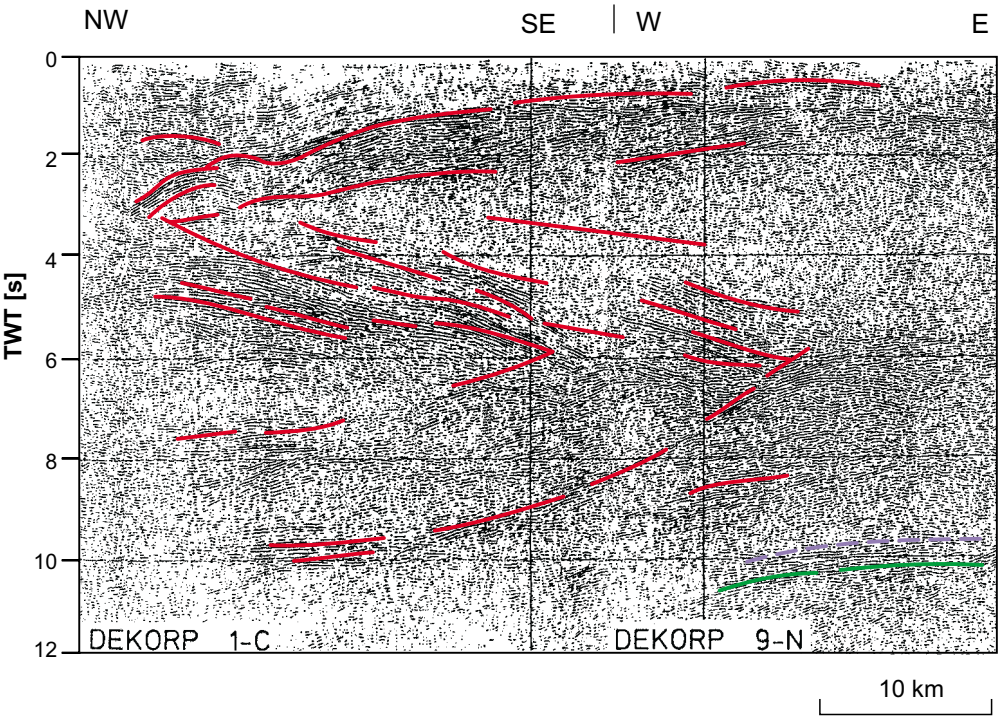

Fig. 23. Crustal seismic structure interpreted as a boundary (Meissner, Sadowiak, 1992) between the Saxothuringian and the Rhenohercynian terranes

Example of crustal wedges forming a typical crocodile structure; in the lower part of the profile, a "layer" of laminated crust is visible; for explanation see Figure 1

talline basement of the East European Platform dips in the same direction. In the eastern flank of the Uralides, crustal reflections dip in the opposite, western direction. The Uralides differ from other Palaeozoic orogens in terms of the presence of crustal roots under their axis. These roots locally reach a depth of 60 km, which is not reflected in the isostatic uplift of the mountain range (Perez Estaun *et al*., 1996).

The Alpine deformation zone of Southern Europe is part of the huge, longitudinal Alpide belt stretching along the continent border of Eurasia in the north, and Africa, Arabia and Dec-an in the south. The European Alpides comprise the Pyrenean Belt and the fold-and-thrust arcs of the Betica Mts., Sardinia and Corsica, the Alps, the Carpathians, the Balcans and the so--called Balcan Alpides, comprising the Dinarides and Hellenides. This complex Alpine Belt includes a number of fragments of old Precambrian and Palaeozoic tectonic structures which occur within intramontane massifs, and actual Alpine thrust (nappe) structures involved in thrust deformations and vergent outwards relative to the fold-and-thrust arcs characteristic of the whole belt. Numerous foredeep and intramontane

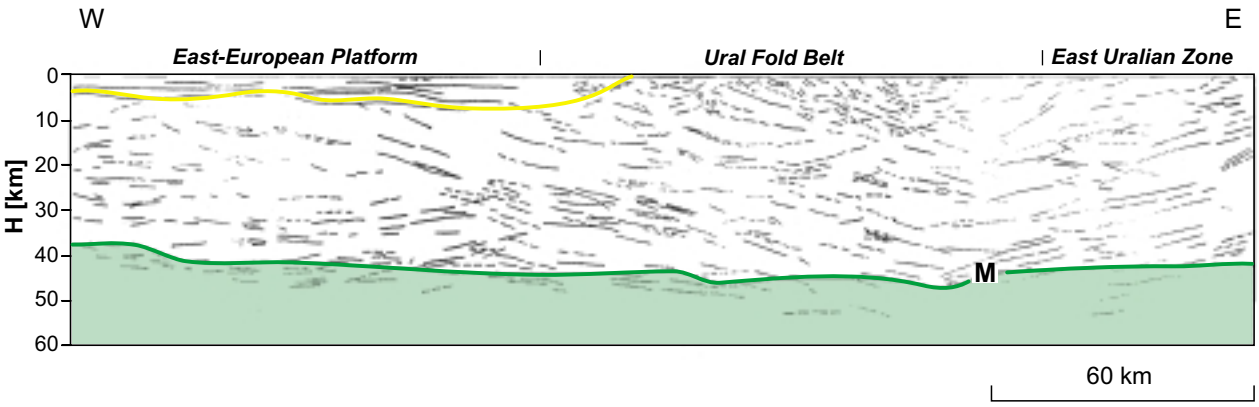

Fig. 24. A reflection and refraction seismic profile across the Ural Mts. along the Yekaterinburg parallel, after Sokolov (1992)

For explanation see Figure 1

basins (e.g. the Po, Panonian and Transilvanian basins) are symmetric structures closed within fold-and-thrust arcs. The youngest elements of the Alpides system are small oceanic basins which opened in the Mediterranean zone during the Mesozoic and Cenozoic. The major deformation phase occurred during the Tertiary and was preceded by Jurassic and Cretaceous tectonic phases.

This complicated orogen was the subject of relatively few reflection seismic investigations.

The Pyrenees are transected by the ECORS seismic profile, 250 km in length, located between the Aquitanian and Ebro basins (Choukroune, 1989). The Pyrenean orogen shows an axial symmetry and fan-like geometry of geological structures, with a narrow metamorphic-granitoid core along a vertical fracture zone — the so-called North Pyrenean Fault (Matte, 1991). The ECORS seismic profile (Fig. 25) shows the crust to have a complicated inner structure and structural stratification. The upper crust shows a remarkable subhorizontal reflection lamination corresponding to sedimentary complexes of both of the foredeep basins, and a series of reflections dipping towards the centre and corresponding to thrust deformations. The lack of reflections in the axial part of the orogen, down to the upper mantle is worth noting. It confirms the existence of a vertical crustal fracture. The middle crust shows a typical lenticular structure of various orders of magnitude. Reflections observed in the flanks of the axial part dip towards the centre of the orogen at 30–35°. The intensely laminated lower crust has a relatively small thickness of 7–8 km, and lies horizontally under both the foredeeps, gently dipping towards the centre in the axial part of the Pyrenees.

This seismic image confirms a tension and strike-slip origin for the Pyrenees belt. Its formation was accompanied by a simultaneous opening of the Bay of Biscay and sinistral rotation of the Iberian Peninsula (Johnson, Hall, 1989).

One of the first complex and deep geophysical transects which crossed the Western Alps from N to S was the refraction European Geotraverse performed in the 1980s. It crosses (from N to S) the Molasse Basin, the Helvetic Nappes, the Aar Massif, the Pennine Nappes, the Insubrian Line, the Southern Alps and the Po Basin. The Alps are an asymmetric two-sided orogen in this profile. The system of external nappes (the Helvetic domain) which are thrust over the forefield, and the system of internal Penninic Nappes with fragments of polymetamorphic rocks of the basement in their cores show the vergence towards the margins of the mountain arc. The system of Southern Alps nappes verges towards the centre of this arc. These two orogenic branches are separated by a narrow metamorphic-granitoid zone characterized by steep foliation and composed of rocks which underwent metamorphic processes during the Palaeozoic.

Refraction seismic surveys (Ye, Ansorge, 1990) show (Fig. 26) the descending Moho surface (an abrupt change in seismic velocities from 6.5–6.6 to 8.2 km/s) under the orogen. The maximum depth of the Moho, 60 km, is observed beneath the Central Alps. The Moho surface shows a remarkable domal elevation beneath the Po Basin (30 km). Seismic velocities in the upper mantle are considerably lower in this area — 7.9 km/s. The boundary surface between a layer of a velocity of 6.2 km/s, and the lower crust, of a velocity of 6.5–6.6 km/s, is flat and lies at a depth of 20–22 km. Therefore, there is a lenticular "pillow" under the central part of the Alps, composed of lower crustal rocks. Data from reflection profiles from eastern Switzerland (the ET, S1, S3 and S5 profiles) and projected into the plane of the EGT profile (Holliger, 1990) allow refraction and reflection seismic information to be correlated (Fig. 27). The reflective Moho surface confirms the occurrence of an orogenic root. The thin lower crust, up to 2 s TWT (6–7 km) in thickness, is distinctly laminated and gently dips towards the south under the orogenic core (Pfiffner *et al*., 1988). In the upper crust, down to a depth of 2–3 s TWT, there are numerous subhorizontal or arched reflections which correspond to the surfaces of nappe thrusts and deformations observed within them, as well as to stratification within the Molasse Basin. The middle crust is conspicuous by a lenticular to wedge-like structure. The occurrence of so-called crustal wedges in the Alpine crust is confirmed by several seismic profiles from western (the W1 to 4 profiles) and eastern (the E1 profile) Switzerland. These profiles are perpendicular to the thrust structures (Green *et al*., 1993). Dense reflections observed in the upper crust down to a depth of 5–6 s TWT are most probably a response to lithological stratification surfaces or shear surfaces related to a stack of nappes. These are slightly dipping (up to 20°) planar structures, several hundred to a few kilometres thick. The thrust verges in the opposite direction relative to the dip of the basal surface. In the middle crust, at 5–15 s TWT, there are reflection bands dipping in two opposite directions at an angle of 25–30°. According to some authors (Mueller *et al*., 1980; Green *et al*., 1993), they mark crustal wedges related to a process of crustal delamination which accompanied the Alpine collision. This collision involved a push of the elongate Adriatic intender into the European continent. This process explains the origin of the Alpine arc on the basis of the plate tectonic theory on continental collisions. The most prominent wedge of this type occurs at 5–8 s TWT, north of the Insubrian Line. Wedges and crocodile structures are also observed further to the north, beneath the system of Pennine Nappes.

Both basal surfaces of the nappes, which often show listric geometry, and the occurrence of wedges and crocodile structures in the crust indicate the existence of intracrustal detachment surfaces on a regional scale, i.e. the occurrence of tectonic delamination processes within the crust. According to Mueller *et al*. (1980), such surfaces can correspond to zones of inversion of seismic wave velocities.

The structural model of the Alps, constructed on the basis of geophysical data, assumes a considerable crustal shortening (Pfiffner, 1990) at the expense of delamination at the middle crust level. Tectonic phenomena, such as the common occurrence of gravity structures, the significance of vertical movements, the symmetry of thrust structures and their fan-like arrangement along the Alpine arc, and the common occurrence of extensional structures which are coeval with major deformation phases both in the forefield and within the orogenic arc, seem to negate the correctness of collisional ideas. Laminated lower crust occurs under almost the entire Alpine belt, except in the area located beneath the orogenic axis where the Moho surface lies at the greatest depth.

The Western Carpathians are transected by the 2T/83, 84 seismic profile, trending from the Magura Nappe across

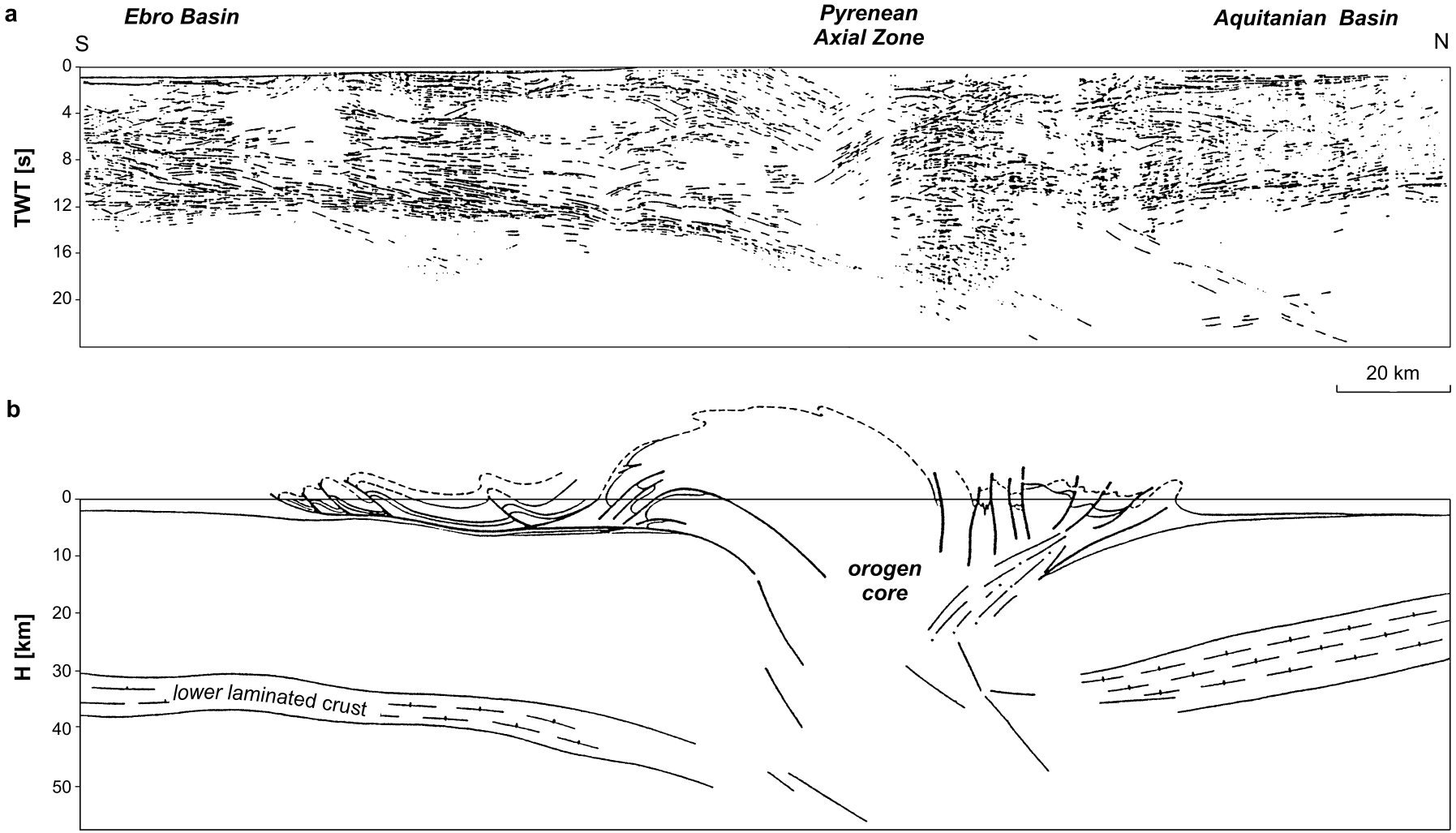

Fig. 25. The ECORS seismic profile across the Pyrenees

a — line drawing produced based on unmigrated reflection data (Choukroune, 1989); **b** — interpretation of a subsurface structure of the Pyrenees after Matte (1991)

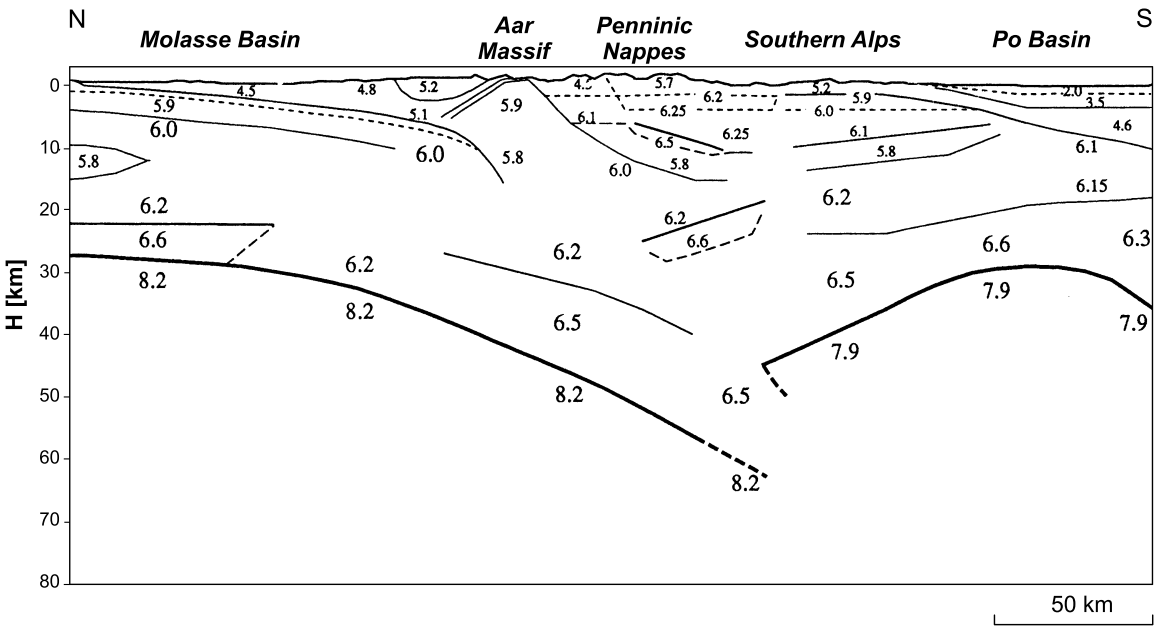

Fig. 26. A meridional crustal section across the Alps along the EGT refraction profile (after Ye, Ansorge, 1990)

Seismic velocities are given in km/s

the Pieniny Klippen Belt and Inner Carpathians (Tatra Mts., Veporides and Gemerides) (Tomek *et al*., 1989; Bielik, 1999). This profile (Fig. 28) shows a lenticular to wedge-like structure typical of many reflection seismic images of the crust. Double reflection bands in the northern and central parts of the profile dip towards the S at 15–20°, fringing weakly reflective zones and marking crustal structures which dip in this direction. The reflection bands occur at 3 to 10 s TWT, and they are "truncated" at the base by the subhorizontal Moho surface. These are therefore too shallow structures to represent crustal fragments of a subducted orogenic forefield.

The characteristic feature of the Carpathian arc is the occurrence of a distinct swell of the asthenosphere beneath the Pannonian Basin. The top of this swell lies at a depth of 60 km. Another, smaller swell of the asthenosphere (depth 80 km) is observed under the Inner Carpathians in the contact zone between the Veporides and Gemerides (Bielik, 1999). These swells represent central spots of radially arranged, outward verging nappe structures.

The Spanish programme of deep reflection seismic investigations (ESCI) included a series of profiles crossing the Iberian coast. These profiles provided an image of the seismic structure

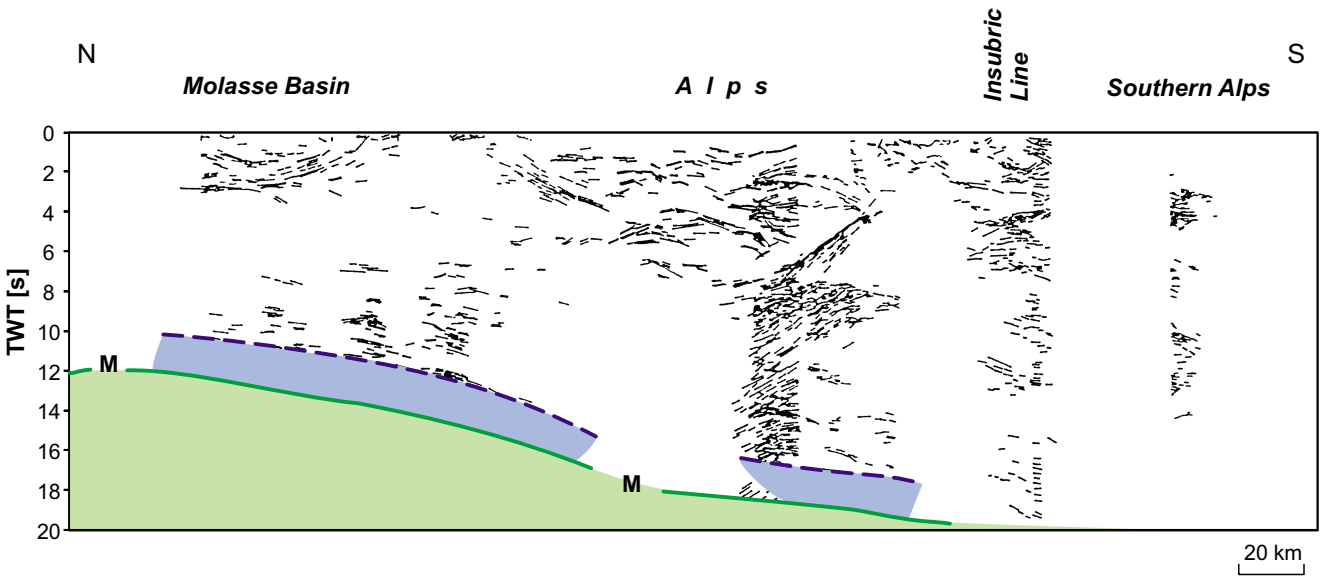

Fig. 27. Part of a reflection seismic profile meridionally crossing the Swiss Alps (Holliger, 1990)

For explanation see Figure 1

of the continental crust, which was subject to extension and thinning along the borders of the young extensional basins of the Mediterranean Sea. The NW–SE-trending Catalonian ESCI profile (Gallart *et al*., 1994) crosses the area from the Ebro Basin through the Catalonian Coastal Range and Valencia Trough, and runs offshore by the Spanish coast towards Mallorca Island. The thickness of the continental crust of the Iberian Peninsula decreases twice from 29–30 km to 15 km over a distance of 100 km. Beneath the coastal area there is a thick (up to 15 km), high-reflective lower crustal layer which continues towards the sea, reducing its thickness from the bottom due to the gently ascending Moho surface, and from the top due to the occurrence of SE-dipping listric faults. Lenticular portions of the lower crust of lower reflectivity are observed within the high-reflectivity layer. In general, the upper crust is seismically transparent, except at the topmost parts (corresponding to the stratification of sedimentary basins). There are also short, bidirectionally dipping reflections. The ESCI--Beticas profiles (Garcia-Dueñas *et al*., 1994) transect the Betica Mts. and run towards the Alboran Sea. Also in this area, the continental crust thins towards the coastal zone. This is manifested in the reflection image by the occurrence of the strongly reflective lower crust with the highly reflective, wavy Moho surface at 10–11 s TWT, and the transparent upper crust with rare reflection bands marking lenticular and wedge-like structures. Some of the dipping reflections correspond to normal listric faults.

AUSTRALIAN CONTINENT

The crystalline basement of the Australian Continent is divided into three major geological regions: the western province is composed of Archean rocks, the central province of Proterozoic rocks, and the eastern province of Palaeozoic rocks. Therefore, successively younger crust is observed moving towards the east. The Great Dividing Range stretches along the eastern margin of the continent and continues towards Tasmania. This range is composed of folded and thrust Palaeozoic rocks, mainly deformed during the Palaeozoic. The youngest, Triassic structures occur along the coasts. The vergence of the structures is westward, towards the continent's interior. The younger, Alpine orogenic belt runs along New Zealand, and is separated from Australia by a young oceanic basin of the Tasman Sea. A number of isolated sedimentary basins are superimposed on the old basement. In western Australia, these basins were established during the Proterozoic (Kimberlay and Hamerslay basins). Throughout the continent there is a number of large, trough-shaped Palaeozoic and Mesozoic basins. The largest one, the Great Artesian Basin, separates the West Australian Craton from the Palaeozoic orogen of eastern Australia. The Great Artesian Basin was formed during the Middle Jurassic and subsequently filled with Mesozoic and Cenozoic deposits. The characteristic feature of Australian geological structure is the long-lasting (hundreds of million years) evolution of basinal structures and their strong relationship with the deep basement.

Extremely interesting results from the point of view of this paper's thesis were derived from a longitudinal transect crossing eastern Australia (Eromanga–Brisbane), described by Finlayson (1993). Deep seismic profiling was performed along the 1,100 km long line across eastern Australia between 1980 and 1986. This transect shows the continental crust of the East Australian Craton with the Lower Palaeozoic Thomson and Lachlan tectonic zones, and the Variscan New England Tectogen in the eastern part of the transect. Vast Palaeozoic and Permian–Mesozoic basins and intracratonic troughs are observed in the near-surface zone. Thus, the Eromanga–Brisbane seismic transect provides much information on the crustal seismic structure of tectonic units of different ages and origin. The interesting feature of this profile is that Finlayson (*op. cit*.) published it giving an interpretation referring to the curvature of the present-day Earth's surface.

A general feature of the western part of the reflection profile is the presence of a seismically transparent upper portion of the approximately 40 km thick continental crust, and the occurrence of a reflective lower crust (Fig. 29). Seismic lamination is observed at the boundary between these two layers. According to Finlayson (1993), this lamination is related to a rheological zonation marking a series of boundary surfaces of large intracrustal tectonic detachment zones. The reflectivity of the lower crust is manifested either by subhorizontal lamination that occurs within a "layer" of gradual thickness changes (from 15 to 20 km), or by a "large-scale lenticular" structure marked by reflection bands passing by lenticular portions of the non-reflective crust. The non-reflective upper crust practically disappears in the eastern part of the profile. The crust characterized by lenticular seismic structure locally reaches 30 km in thickness, with its top approaching close to near-surface structures. The crust observed beneath the intracratonic basins which form troughs filled with Permian deposits (the Surat Basin with the Taroom Trough beneath) shows the strongest reflectivity.

The Moho surface is commonly marked by an abrupt disappearance of lower crustal lamination or by a narrow (2–3 km thick) transitional zone composed of densely-spaced, short, subhorizontal reflections. The latter mainly occurs under those parts of the crust which show a large-scale lenticular structure, and is interpreted as a zone of subhorizontal basic intrusions within the lower crust rocks (O'Reilly, Griffin, 1990).

Finlayson (1993) interpreted the geological structure of the crust on the Eromanga–Brisbane seismic profile, and distinguished a series of subsurface structures which are represented by listric faults terminated at various crustal levels, intracrustal ramps, and subsurface stratified sequences. These structures are probably related to the geological structure of the near-surface. This interpretation was done under the influence of the plate tectonic model of the geological evolution of eastern Australia. For example, deep fracture zones, dipping almost exclusively towards the west, were identified in the profile as a result of the *a priori* assumed direction of subduction of the palaeo-Pacific plate under the Australian Continent. That author also related individual crustal structures to different phases of geological evolution of the area, and identified compressional, strike-slip and extensional structures. However, the results of seismic profiling show the occurrence of large, intracrustal, mostly symmetric and bidirectionally dipping discontinuity surfaces. The tectonic activity of this area

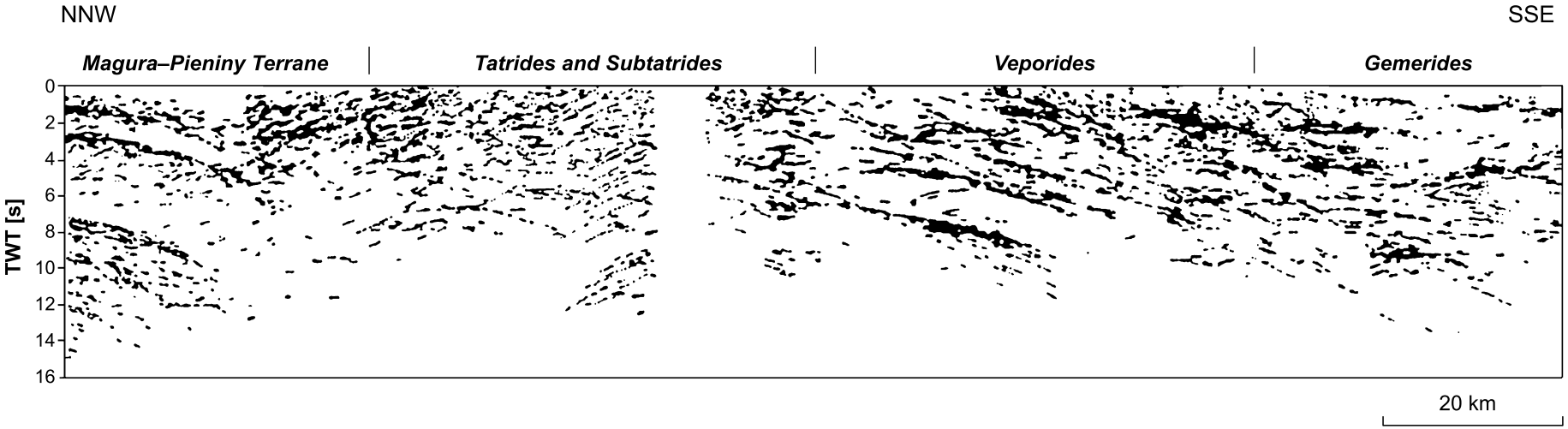

Fig. 28. Deep seismic transect 2T/83.84 across the Polish and Slovak Carpathians (after Tomek *et al.*, 1989; simplified)

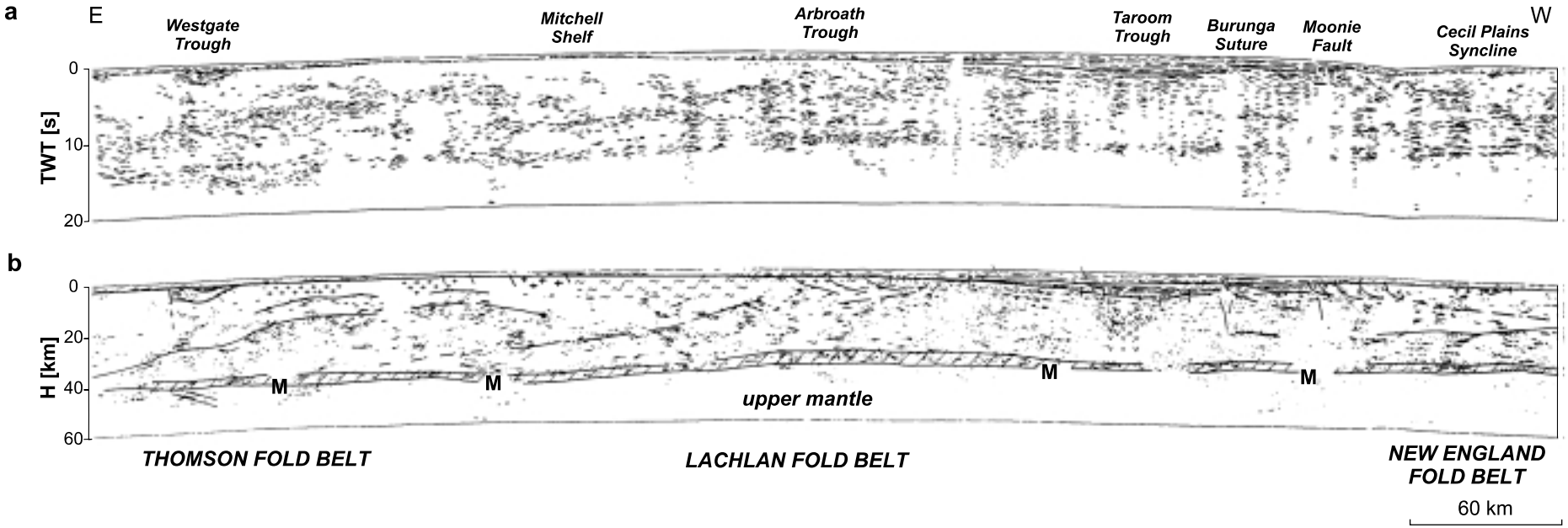

Fig. 29. The Eromanga-Brisbane seismic transect (Australia) (a) and the geological interpretation of Finlayson (1993) (b)

Profile corrected for the Earth's curvature

dates back to the early Palaeozoic. A cratonic stage of its evolution with repeated reactivation of older discontinuous structures has continued since the Triassic. This area belongs to those portions of the continental crust which were subject to extension, as evidenced by the great extent of intracratonic basins filled with horizontally lying deposits. A similar crustal seismic structure is observed in areas of numerous intracratonic basins explored via reflection seismic surveys, usually carried out during hydrocarbon-prospecting projects (the Bowen Basin in north-eastern Australia, the Gippsland Basin offshore Victoria State, the Cobar Basin in central New South Wales etc. — Goleby *et al*., 1994). Most of these basins developed in response to the process of pure, extensional shear which manifests itself in the occurrence of major listric detachment surfaces observed in the crust. Such surfaces fade away at approximately 5–6 s TWT (depth 20 km).

THE SEISMIC STRUCTURE OF THE CONTINENTAL LITHOSPHERE — DATA SYNTHESIS

The seismic structure of the continental lithosphere has recently been widely discussed. The major problem of this discussion is the dependence of seismic structure on the age and geological structure of the area examined. Does the present-day seismic structure reflect geological processes that occurred during the formation of individual tectonostratigraphic units? Or is it the result of a global process? There is no doubt that reflection seismic profiles display many features in common for the entire Earth, irrespective of various differences, as evidenced by the data presented in this paper. The seismic image is not significantly affected by the acquisition and data collection parameters. Similarity in the seismic reflectivity of various geological environments indicates that: (1) the rheological properties of the lithosphere exert the essential effect on reflectivity; and (2) there is a single tectonic process responsible for this reflectivity.

THE RHEOLOGICAL PROPERTIES OF THE CONTINENTAL LITHOSPHERE

Recent investigations, in particular refraction seismic surveys, indicate that the continental crust has a layer-block structure, and great variability in terms of rheological properties, depending on crustal thickness, composition, age and geological processes. The present-day continental crust is a result of the formation of the lightest, outer geosphere due to the chemical differentiation of the Earth's mantle during the Precambrian. This process, confirmed by many scientists (cf. Rudnik, Sobotowicz, 1984; Taylor, McLennan, 1985), was of magmatic and magmatic-metamorphic character, and resulted in the formation of Archean cores and Proterozoic complexes of crystalline socles of both modern cratons and the mobile belts and basins of Palaeo-, Mezo- and Cenozoic. The occurrence of fragments of the old Precambrian basement within younger orogens and within the basement of younger sedimentary basins is a common phenomenon all over the Earth. The conclusion is that the dominant portion of the continental crust was formed during the Precambrian (Glikson, 1983), and that since that time, it has only undergone tectonothermal rejuvenation processes. The Precambrian crust was the base for all younger geological processes. According to geochemical data, interpreted in terms of the plate tectonics theory, 75% of the continental crust was formed during the Archean over 2.5 Gy ago, and most of the remaining 25% during the Proterozoic (Taylor, McLennan, 1985). Therefore, the idea of considerable Palaeozoic and Mesozoic growth of new continental crust along active lithospheric plate margins is incorrect (Ellam, Hawkesworth, 1988).

The upper crust is available for direct observation. Its average chemical composition is granodiorite (Taylor, McLennan, 1985), and it is 10 to 15 km thick. The upper crust is generally separated from the lower crust by the Conrad seismic discontinuity, where seismic wave velocities increase from 5.2–6.0 km/s, typical of the upper crust, to 6.7–7.0 km/s. This discontinuity lies at depths of 10 to 20 km, although it is locally absent. Therefore, the thickness of the upper crust is highly variable, ranging from 20 to 30 km (75% of the total crust volume). Its chemical composition has not been ultimately defined. Information on the pressure and temperature of the lower crust, geochemical data and studies of xenolites indicate the predominance of granulite complexes similar to andesite in chemical composition, although more basic garnet granulites can occur locally in deeper crustal zones. Geochemical data indicate that the lower crust is composed of rocks similar to the upper mantle in composition. Easily fusible components were melted out of these rocks. These components, granodiorite in composition, make up the recent continental upper crust. The general chemical composition of the continental crust has not changed since the end of Archean (2.5 Ga) (Taylor, McLennan, 1985). The Moho surface is detectable by seismic methods as a distinct boundary showing a rapid increase in seismic wave velocities to 8.0–8.3 km/s. Moreover, its interpretation as a homogenous and common lithological-chemical boundary now appears to be incorrect. Seismic data indicate that the Moho surface is heterogenous, and in places represents a transitional zone, up to 5 km thick, within which rapid increases in seismic wave velocities are dominant. These rapid increases show that the zone has a layer structure. Similarly, variable seismic wave velocities within the subcrustal part of the upper mantle (7.9 do 8.3 km/s) indicate its heterogeneity.

These general features of the continental crust are superimposed by many differences in geological properties, depending on the kind of geotectonic structures which are characterized by different types of crust (Pavlenkova, 1979; Belousov, Pavlenkova, 1989). On old Precambrian cratons, the 40–45 km thick continental crust with an average seismic velocity (Vp) of 6.5–6.8 km/s, is composed of 3 layers; their average thicknesses range from 10 to 15 km, and their Vp = 6.0–6.4, 6.5–6.7 and 6.8-7.4 km/s, respectively. The platform crust includes

a zone of lower seismic velocities, relative to the layer above. Its detailed analysis indicates (Pavlenkova, 1979) that this zone, up to 1.5 km thick, lies at depths of 13–15 km. Lateral heterogeneities which show vertical and diagonal boundaries, typical of the upper crust, disappear within this zone, replaced by horizontal heterogeneities. According to Pavlenkova (*op. cit*.), this zone is represented by a highly ductile crustal "layer" where the horizontal plastic flow of matter is possible. Palaeozoic platforms *sensu lato* are characterized by lower crustal thicknesses (25–30 km), lower average seismic velocities (Vp = 6.2–6.4 km/s) and the two-layer structure ignoring the sedimentary layer) composed of the granitogneiss layer (Vp = 6.0 km/s) and the lower crust (Vp= 6.5–6.6 km/s, sometimes up to to 7.0–7.3 km/s). The Moho surface is relatively even, and any gradual variations in the crustal thickness are at the expense of its lowermost layer.

The continental crust under orogenic belts is 50 to 70 km thick and shows an average seismic wave velocity of 6.1–6.8 km/s. The amplitude of the orogenic "roots" ranges from 10 to 20 km. These roots are commonly represented by the middle and lower crustal layer. The crust here shows a considerable variability, and the presence, at various depths, of horizontally arranged (locally slightly inclined) lenticular or stratified zones of lower seismic velocities and intervening layers of higher velocities (Pavlenkowa, 1979; Vitte, 1983).

The continental crust of foredeep basins and intercontinental rift zones is developed differently (Pavlenkova, 1979; Belousov, Pavlenkova, 1989). Beneath old aulacogens located on Precambrian platforms (e.g. the Dniepr–Donietsk Aulacogene), the crust is 35 to 40 km thick, and the amount of its thinning, relative to the surroundings, is by 10 to 20 km (Levin, Khayn, 1987, 1990). This crustal thinning is mostly at the expense of the granitogneiss layer. Palaeozoic sedimentary basins are conspicuous by their crustal thickness of 25 to 30 km, and average velocities of 6.4–6.5 km/s. A thinning of the upper crust is also observed there. The 25–30 km thick crust beneath young Mesozoic and Cenozoic basins is composed of a sedimentary complex, up to 20 km thick, and the 10 km thick lower crust (e.g. Pannonian Basin). The average velocity is 6.5–6.8 km/s. There is no granitogneiss layer in these areas. This type of crust shows many features transitional between the continental/oceanic crust (Vitte, 1983).

Horizontal and vertical heterogeneities are also observed within the upper mantle of the continental lithosphere. These are mainly detectable with the use of deep seismic soundings (Rezanov, 1978; Egorkin *et al*., 1987). Characteristic variations in the properties of the subsurface zone, depending on age and geological structure, are also observed there. Under old platforms, seismic velocities either increase slowly with depth (Baltic Shield) or there is a 20–40 km thick zone of lower velocities (by 0.2 to 0.4 km/s, relative to the surroundings) at depths of 40–60 km beneath the Moho surface (Moscow Syneclise, Canadian Shield). In general, these zones are indistinct and relatively thin. Much thicker and prominent "layers" of lower seismic velocities occur in areas of young orogens and rift zones. Beneath the Coastal Range of the Cordillera, such a zone extends from a depth of 30 km down to over 200 km, and the decrease in seismic velocities is by as much as 0.8 km/s, while in the Rocky Mts., it is from 40 km down to 140 km, and the decrease in seismic velocities is by 0.5 km/s. Also, investigations of absorption of seismic waves by the upper mantle indicate lateral changes in its properties. The mantle has low absorption properties beneath cratons, whereas beneath young orogens (e.g. Tibet), rift zones (e.g. Baikal) and marginal basins (e.g. Ochock Sea), there are zones of strong absorption of seismic waves, indicating the presence of low density and plastic mantle masses lying shallow under the crust.

Many years' seismological studies of the upper mantle of Siberia (Egorkin *et al*., 1987) allowed the statement to be made that the mantle shows a layer-block structure. Several subhorizontal zones of lower seismic velocities occur in this area down to a depth of 300 km. They are variable in thickness, with seismic velocities of 8.1–8.3 km/s, except in the shallowest layer where seismic velocities range from 8.0 to 8.1 km/s. This layer shows considerable swells, and locally in areas of Mesozoic–Cenozoic riftogenesis (e.g. West Siberian Plate), it occurs just below the Moho surface. The average seismic wave velocities down to a depth of 120 km are also lower in these areas than beneath old cratons. However, the lower velocity zone that occurs beneath Precambrian cratons at depths of about 250 km is commonly related to the astenosphere and shows higher seismic velocities than those which correspond to the partly liquefied matter of the mantle (Egorkin *et al*., 1987). The upper mantle of the continental lithosphere also displays a similar structure in other regions (Fuchs, 1979).

A comparision of tomographic lithospheric thicknesses with a tectonic map of the world (Abbott *et al*., 2000) confirms the existence of lithospheric roots under old Precambrian cratons, 250 to 370 km thick. At the same time, the results of seismic investigations (Dziewoński, Anderson, 1984; Woodhouse, Dziewonski, 1984; Pavlenkova, 1979, 1990) clearly confirm the existence of huge mantle "roots" under the continents, reaching as deep as the mantle/outer core boundary. The continental lithosphere seems to be permanently connected with its deep mantle basement (Fig. 30).

From the rheological point of view, the continental lithosphere is a system developed as a result of both the varied rheological properties of the rocks composing its individual complexes, and the variable tectonic stresses which operate at different lithospheric levels. Recent investigations of vertical changes in rheological properties are based on data about the principles which govern deformations of the components constituting the lithosphere. These data are verified by geophysical models of the lithospheric structure of various geotectonic units (e.g. Kirby, 1983; Meissner, Strehlau, 1982; Ranalli, Murphy, 1987). In general, the rheological properties of rocks depend on their lithological features and are a function of temperature and pressure and, therefore, of depth. The most significant forms of rheological behaviour are brittle and ductile, depending on the resistance of rocks to crack and creep. Rheological profiles of the lithosphere (Ranalli, Murphy, 1987) illustrate changes in the depth-related creep resistance of the rocks which compose the lithosphere. The profiles are different in various geotectonic units. They require a brief discussion that is important for the analysis of seismic structures identified in the lithosphere. In the cool sialic crust of old Precambrian platforms, brittle deformations occur in its upper part down to a depth of 25 km, and below the Moho surface to a depth of 80 km. The lower crust

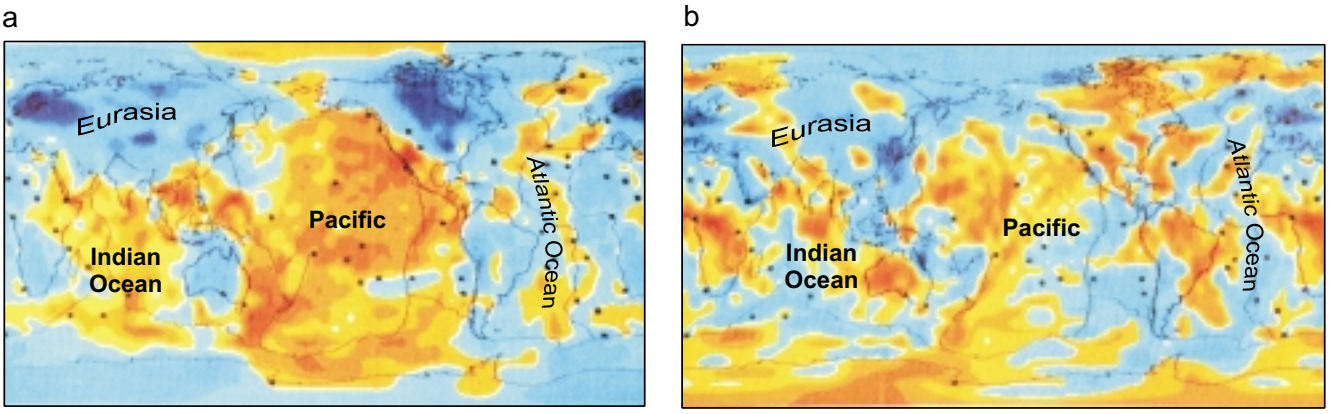

Fig. 30. Deeply rooted continents from seismic tomography data (Anderson *et al.*, 1992)

a — at a depth of 230 km; **b** — at a depth of 490 km; rigid and "cool" continental roots (blue regions) are distinct at a depth of 230 km, beneath the hypothetical top of the asthenosphere; they are mostly also recognizable at a depth of 490 km; under the modern oceans, there is hot and plastic upper mantle matter (orange regions); the dots are the hotspots

(25–40 km), like the upper mantle from a depth of 80–100 km downwards, tends to deform ductilely. Precambrian platforms, composed of three lithologically different "layers": a quartz--granitoid upper "layer", a transitional middle and a basite lower "layer", are basically deformable brittlely along with the upper mantle down to a depth of 80 km (Ranalli, Murphy, 1987). Only thin ductile layers can occur in these areas at the lower crust/upper crust boundary and at the base of the lower crust. In the case of thick (up to 60 km), cool crust, ductilely deformed zones occur at the lower crust/upper crust boundary, at the base of the lower crust, and in the upper mantle below a depth of 100 km (Ranalli, 1984, Ranalli, Murphy, *op. cit.*).

Under high heat-flow conditions, the crust shows a considerably lower thickness (about 30 km); if it is composed of the sialic layer, then brittle deformations are observed down to a depth of 15 km. The rest of the lithosphere behaves ductilely except in a narrow zone along the Moho surface. Low creep resistance of rocks is achievable at a depth of 40 km. In the case of the thin, two-layer crust, intracrustal ductile zones with intervening brittle zones occur at depths of 10–15 km and 27–30 km. A brittle deformation zone is also observed in the upper mantle immediately beneath the Moho surface (Ranalli, Murphy, *op. cit.*). The results of rheological property modelling assesments of the lithosphere correlate well with geophysical data, in particular with those concerning the depths of occurrence of seismic shocks, seismic wave velocities and electric conductivity. Low seismic velocity zones are commonly associated with a decrease in the resilience of the composing rocks. This phenomenon can be induced not only by anomalously high temperatures and the presence of water, but also by tectonic stresses. Subhorizontal ductile zones which are predominant in both the crust and upper mantle of the continental lithosphere (Ranalli, Murphy, 1987) can be a common result of appearing or disappearing tectonic stresses.

Rheological stratification of the lithosphere is a real fact. Its geological significance has been differently interpreted. However, its effect on tectonic deformations has always been stressed, in particular on the formation of intracrustal, most frequently flat or listric detachment and thrust zones, as well as flakes resulting in a tectonic thickening of the crust. It should also be emphasized that lithospheric stratification is a recent process, and therefore it is genetically related to the latest stage of the geodynamic evolution of the lithosphere (like *in situ* stresses). Obviously, we cannot preclude the existence of relict structures of this type.

Summarizing discussion, the following conclusions can be drawn:

1. The continental lithosphere shows a number of lateral and vertical heterogeneities genetically related to the geothermal regime, mineral composition and presence of tectonic stresses.

2. These heterogeneities are spatially related to surface tectonic geostructures. The various depth extents of these relationships are observed. On the continental scale, the mantle "roots" of these structures reach the lower mantle or even the mantle/core boundary: in the case of Precambrian platforms, they go down to a depth of 400 km, and in intraplatform basin-type structures (syneclise), orogenic belts etc. down to a depth of 140–150 km.

3. The lithosphere is dominated by subhorizontal structures represented by alternating zones of higher and lower seismic wave velocities, except upper crust that has been deformed brittlely, and where the immediate continuation of discontinuous surface structures is commonly observed.

4. All the heterogeneities identified using geophysical methods correspond to zones of different rheological properties and represent rheological stratification of the lithosphere.

LITHOSPHERIC RHEOLOGY AND SEISMIC REFLECTIVITY

The values of the strength parameters of upper crustal rocks increase with depth, reaching their maxima at a depth of approximately 10 km (Byerlee, 1978). Depending on thermal conditions, the brittely deformable continental crust occurs to a depth of 10–20 km, which corresponds to temperatures of

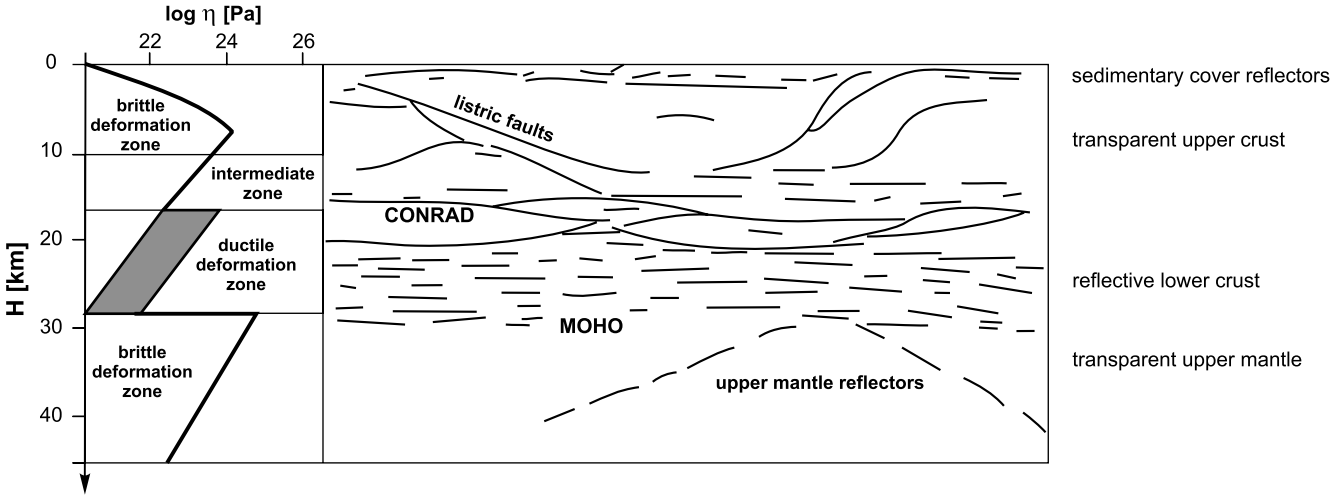

Fig. 31. The seismic reflectivity of the crust and upper mantle in relation to the strength parameters (plasticity) of the continental lithosphere (after Mooney, Meissner, 1992; modified and supplemented)

The shadeded area covers the range of strength parameter variability within the lower crust

300–400°C. Below this depth, there is a ductile deformation zone dominated by the flow of solid state matter. Obviously, the boundary between the brittle deformation zone and the ductile deformation zone is not sharp. Its width is dependent on both the heat flow and the lithology. Another rheological boundary is the Moho surface. It has been assumed that a mineralogical change involving the disappearance of feldspars and the appearance of olivines causes the subcrustal upper mantle to be brittlely deformable under the thermal conditions existing in this zone (Ranalli, Murphy, 1987). Reflection seismic analysis confirms this rheological behaviour. There is a strict relationship between the viscosity of the continental lithosphere and seismic reflectivity (Fig. 31). Sparse reflection packets related to fault zones (mostly of listric geometry) are observed in all the profiles in the crystalline upper crust, which in general is seismically transparent. These fault zones dip in different directions and flatten downwards. The lower crust is dominated by subhorizontal structures which are suggested by most authors to represent flow deformations. A transitional zone, sometimes referred to as the middle crust, occurs at the lower/upper crust boundary. Most listric fault zones die out within this part of the crust. It contains intracrustal large-scale lenticular structures, marked by reflection bands.

The subcrustal upper mantle is characterized by a transparent seismic structure. Gently dipping reflection bands, corresponding to narrow fault zones, are rare. Therefore, from the rheological point of view, the lower crust is a "weaker" layer, as stressed by Meissner and Strehlau (1982), closed between the rigid upper crustal zones and the subcrustal lithosphere. The important rheological feature of the continental crust is the lack of any correlation between the intracrustal velocity boundaries that separate zones of different petrological composition and the boundaries of the laminated lower crust. Reflection lamination results from a process of tectonic deformation that is independent of the petrological stratification of the crust.

THE CLASSIFICATIONS OF SEISMIC STRUCTURES

Many classifications of seismic structures observed in the crust and upper mantle of the continental lithosphere have been proposed. They are based not only on the depth of occurrence, geometry and age of the crust, but also on the origin and structure. Changes in the rheological properties of the crust with depth lead to differently developed seismic structures occurring at various crustal levels. Therefore, depth-related classifications are usually associated with geometry-related ones. Seismic structures of two or three crustal levels are commonly distinguishable, referred to as the lower and upper crust, or as the lower, middle and upper crust. The two-level structure is characteristic of most of the seismically examined fragments of continental crust, in particular in cratonic areas and Proterozoic and younger intracontinental basins.

The upper crust contains structures such as normal and reverse listric faults, nappe stacks, intracrustal ramps, upper crustal detachments, fan-shaped faults, etc. In many cases, upper crustal reflection structures correspond to tectonic structures observed on the surface. The lower crust is dominated by subhorizontal structures represented by reflection lamination or a flattened, symmetric lenticular structure. Both of these crustal levels commonly show no relationships with each other, although upper crustal reflection structures locally continue across the entire crust, and are sometimes truncated by the Moho surface. Some authors also attempt to relate selected tectonic structures known from the surface with seismic structures that reach as deep as the subcrustal mantle. However, the results of these attempts are not convincing. In most cases, the upper crust is separated from the lower crust by a subhorizontal discontinuity surface in which listric faults are rooted. This zone, spatially related to the top of laminated lower crust, is commonly interpreted as

the major detachment surface along which mutual shifts of crustal blocks take place.

The Earth's crust of some of the Variscan tectogens (Rhine Massif, Erzgebirge Mts.) shows a distinct tripartition. Between the upper and lower crust, both characterized by typical seismic structures, another crustal layer is observed — the middle crust. This crustal layer is conspicuous by the presence of large-scale lenticular and augen-lenticular structures. Reflection bands pass by lenticular portions of weaker reflectivity. The characteristic feature of these large-scale lenticular structures is that they contain reflections and reflection packets arranged diagonally relative to the reflection bands which pass the structures by. Middle crust of such a structure is a transitional zone where reflections related to the tectonic structures of the upper crust gradually disappear. Signs of crustal tectonics such as flakes, crocodile structures, intracrustal sutures, etc. are also observed in this part of the crust.

The attempts to introduce a classification of seismic structures according to depth of occurrence and geometry resulted in the creation of a seismic image model of the typical BIRPS profile (McGeary, 1987) (Fig. 14), and a crustal model of the Variscan orogen (Allmendinger *et al*., 1987). These models are based on the so-called line drawings created by a subjective or digital analysis of time seismic sections. These models are highly similar, although the latter is affected to a greater extent by the *a priori* assumed tectonic interpretation of the orogen. There is also a classification based on reflection density versus a TWT unit (Wever *et al*., 1987). Such a classification was applied for the continental crust in Germany. It permitted the identification of three major types of reflectivity: (1) the crust of intracratonic sedimentary basins is characterized by intense reflectivity of its top parts, related to the stratification of sedimentary complexes, and equally intense reflectivity of the laminated lower crust of relatively small thickness; (2) the crust of rift zones shows strongly reflective lower crust of considerable thickness and weakly reflective upper crust; and (3) the crust of Palaeozoic massifs is conspicuous by two maxima of reflection density — a broader one in the lower crust, and a narrower one in the mid-upper crust — separated by a lower reflectivity zone in the form of the middle crust.

A structural classification of crustal structures was given by Klemperer and Peddy (1992). Looking at the crustal seismic image, they sought equivalents of compressional, extensional and strike-slip structures typical of various geotectonic units observed on the Earth's surface. Compressional structures are represented by thin-skinned thrust structures, crustal thrusts and seismic structures related to collisional suture zones. These are the crustal wedges commonly described in recent papers, and also crocodile structures. The latter are most frequently observed across the entire thickness of the crust, contrary to the others, which are associated with the upper crust. The lower crust has a different seismic image and, according to Klemperer and Peddy (1992), is younger since its (probably extensional) structures diagonally truncate upper crust structures. Therefore, the analysis performed by those authors leads to the conclusion that the presumed compressional structures of the upper crust are mostly accompanied by extensional structures of the lower crust. It should also be stressed that the examples of interpretations of the seismic images of orogenic belts given by those authors are commonly based on observations of near-surface tectonic structures. The authors of these interpretations only considered those reflections which are consistent with the overall orogenic vergence pattern, disregarding those seismic structures whose location or direction of inclination does not fit the assumptions. There are many such interpretations.

According to the classification of Klemperer and Peddy (*op. cit*.), extensional seismic structures are primarily represented by normal listric faults. They dip at 60–75° at the near-surface, and are directly distinguishable in seismic profiles from the lateral displacements of reflection bands. They gradually flatten downwards, passing into subhorizontal structures of the middle or lower crust. The lower portions of listric faults are directly documented by reflection seismic data. Detachment structures, which separate zones characterized by different styles of extensional deformation resulting from crustal rheology, occur at this crustal level. Flat intracrustal detachments commonly merge with a system of upper crustal listric faults. These are represented by zones of brecciation and hydrothermal changes, up to 500 m in thickness. Rotated blocks, separated by steep normal faults (domino faulting), are observed in the upper crust above these detachment zones. Such structures are referred to as thin-skinned low-angle extensional faults. Examples of these structures have commonly been cited from the North Sea and the Great Valley in the western USA (the Basin and Range Province). Klemperer and Peddy (*op. cit*.) claimed that these structures are a result of simple shear. They are also locally observed within orogenic belts where the occurrence of evident extensional structures is interpreted as the effect of the reactivation of earlier compressional structures in an extensional stress field, resulting in postorogenic collapse. The typical laminated lower crust occurs beneath the zones of extensional detachments. With several exceptions, it is a global structure. Seismic structures related to the process of continental lithospheric extension, observed in rifting zones and at passive continental margins, confirm a gradual decrease in lithospheric thickness. The crustal thinning factor is 1.8 to 2.0, and up to 3.5 in rift zones. Seismic data confirm the process of plastic extension of the continental lithosphere, which proceeds at the expense of the upper crust — plastic thinning is observed in the lower crust. The continuity of the upper crust is broken by a system of normal listric faults. The plastic thinning of the continental crust is sometimes not associated with crustal fractures.

A seismic image of strike-slip structures is discussed by Klemperer and Peddy (1992) with regard to the BIRPS profiles from the Great Glen Fault in Scotland, and to the ECORS profiles crossing the Bray Fault, Northern France, and the Pyrenees. It is characteristic that reflections which dip towards a strike-slip show a fan-like arrangement, forming a flower structure. The crustal fractures alone are invisible in seismic profiles due to their high dip angles. The essential feature of this seismic structure is that the laminated lower crust is bidirectionally inclined towards this crustal dislocation.

Another classification of seismic structures refers to the age of the continental crust in which the structures are observed. This classification is based on the assumption of a gradual growth of the continental crust due to the plate tectonic process.

Thus, the age of formation of a specified crustal fragment can be derived from the age of the tectonometamorphic and magmatic processes in the upper crust available for direct study. Thus, structures of the Precambrian crust, seismic structures of old (Proterozoic and Palaeozoic) orogenic zones, seismic structures of young (Mesozoic and Cenozoic) orogens, and structures of recent extension areas can be distinguished (Mooney, Meissner, 1992). According to Gibbs (1986), seismic structures may have persisted in the continental crust since the Precambrian. In the 1980s, the Precambrian crust was considered to be weakly reflective, the reflective Moho surface poorly marked, and the laminated lower crust absent over most areas. However, seismic transects from Canada, Australia and the Baltic Shield show that the Precambrian crust exhibits all those geometric types of seismic structure which are observed within the Phanerozoic crust, i.e. the Precambrian crust displays features formerly assigned only to a younger crust (Meissner, 1986). Nevertheless, the thickness of the Precambrian crust is considerably larger and commonly contains mostly short reflectors down to a depth of 50 km. The reflective Moho surface is marked by the disappearance of crustal reflectivity and coincides with the refraction Moho. Crocodile and wedgeform structures are often observed within Precambrian cratons. This fact led to a number of "collisional" models being proposed to explain the origin of the Precambrian crust. Such structures are genetically related to zones of collisions between microplates. The accretion of these microplates is believed to have resulted in the formation of the present-day continental cratons. However, the general seismic image of the Precambrian crust indicates its higher rigidity.

The Earth's crust of old orogens was studied in areas of the Grenville tectogen, the Appalachians, the Scottish and Scandinavian Caledonides, the European Variscides, the Uralides and the Great Dividing Range in Australia. Flakes, crustal wedges, subhorizontal detachment surfaces of the lower crust, intracrustal wedgeform structures and subhorizontal lenticular to wedge-like structures are observed in those areas. According to Klemperer and Peddy (1992), zones of presumed Palaeozoic collisional sutures are marked by wide reflection zones crossing the entire crust at angles of 30–35°. These are considered to represent a trace of displacement of one continental fragment under another during collision. However, such proto-Atlantic (Iapetus) sutures transected by the BIRPS seismic profiles in Scotland and the COCORP profiles in the southern Appalachians prove that, both on either side of the "sutural" belt and within this belt, symmetric sets of bidirectionally dipping reflections occur; these do not fit the assumed collisional model.

Except in the Uralides, no crustal roots occur under old orogens where the Moho is a horizontal surface. Strongly reflective lower crust is also common. Therefore, there is a characteristic superposition of contrasting tectonic processes in the upper crust (where at least a part of the seismic structures is related to compression) and in its lower part (where extension is the dominant process). Many authors underline difficulties in distinguishing between compressional and tensional seismic structures (e.g. Behr *et al*., 1994). The latter are commonly interpreted to be a result of post-orogenic extension superimposed on earlier compressional structures. Meanwhile, within old orogens, where flat thrusts of considerable extent (i.e. classical thin-skinned structures) are observed (the Appalachians, the Scandinavian Caledonides, the Variscan Front in the Brabant Massif), typical extensional structures such as grabens and half-grabens occur within the crystalline basement under the subhorizontal detachment surfaces of upper crustal nappes. The thrusting of a nappe stack does not change the tension character of these basement structures.

The continental crust of young orogens is characterized by the occurrence of orogenic roots in a state of isostatic balance with the surface morphology. The orogenic root of the Alps is 20 km thick, while that of the Himalayas is 30 to 40 km thick. These roots are also observable in reflection seismic profiles. The Moho surface and laminated lower crust gradually dip towards the orogenic centre. Simultaneously, the reflectivity of the lower crust disappears under the core of young orogens. A pillow-like, seismically transparent zone occurs in this area (Alps, Pyrenees). The upper and middle crust show a complicated reflection image: wedges, crustal lenses, delamination surfaces and, in the uppermost part, thrust stack-related reflections. The structure of young orogens is commonly characterized by thick-skinned tectonics, although thin-skinned tectonics is observed in the Cordilleras. The crustal deformation style of young orogens is very similar to that of structures observed within the Precambrian crust, as noted by Mooney and Meissner (1992). It should be added that the style is also similar to that of the structures of old orogens.

The recently extending continental crust was examined using reflection seismic methods in western Europe (sedimentary basins, the Upper Rhine Graben, the North Sea, the Iberian Peninsula coasts), western North America and along passive continental margins. The lower crust of these areas is highly reflective below a depth of 10 km, in contrast to the transparent upper crust and upper mantle. The Moho surface is mostly flat and is commonly considered to represent a young structure, formed due to extension (Klemperer, Peddy, 1992; Mooney, Meissner, 1992). The processes responsible for the formation of Moho surface include the metamorphism and deformation of the lower crust under conditions of ductile extension. The transparent upper crust is cut by normal listric faults and subsurface (mostly low-angle) extensional detachments. Rotated blocks, domino-faulting structures, syntectonic sedimentary basins, etc. occur between and above these structures.

The genetic classification of Blundell (1990) unites data on the geometry of seismic structures, on crustal thickness and on the geological evolution of the crust. It divides the continental crust into three major types: (1) "weak" crust subjected to extension — for example, that of the Great Valley (the Basin and Range Province) with a characteristic set of extensional structures: normal faults, rotation of crystalline basement blocks, and anastomosing ductile shear zones; (2) "weak" crust extended at the first stage of its evolution and subsequently subjected to compressional stresses — for example, that of the Appalachians which show a characteristic thin-skinned structure; and (3) "strong" crust formed as a result of compressional stresses and containing a range of crustal structures, subsurface stacking of crustal thrusts, etc. This type of the crust can be subjected to post-genetic extension which does not disturb older compressional structures, as claimed by Blundell (1990).

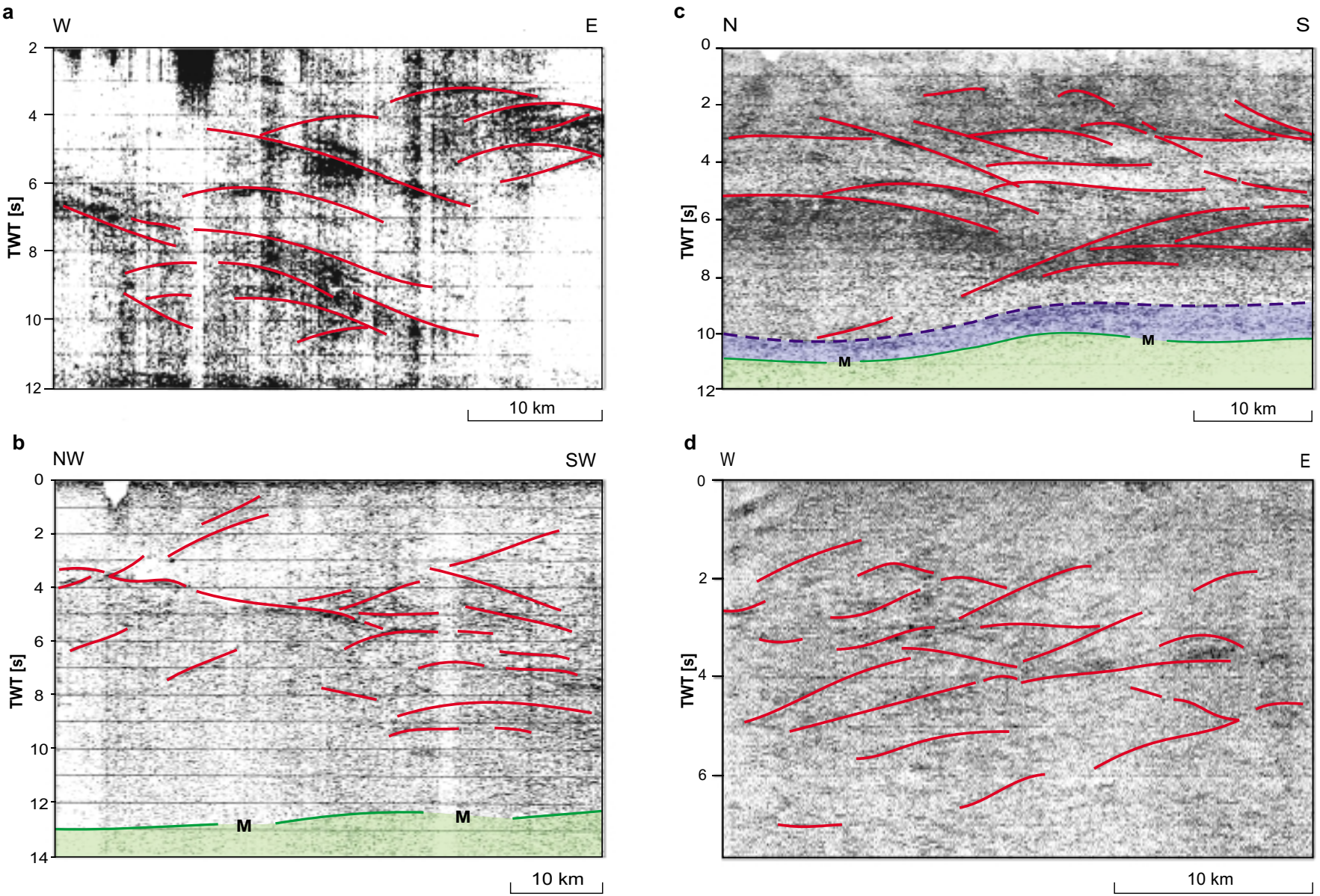

Fig. 32. Examples of seismic images of the continental crust of various tectonostratigraphic units

a — Precambrian crust, Arunta province in central Australia (Goleby *et al.*, 1990); **b** — Appaliachian crust (after Spencer *et al.*, 1989 – modified); **c** — crust under the Variscides – the Rhenohercynian Zone, part of the DEKORP 2-N profile; **d** — the crust under the Eastern Canadian Cordillera, Rocky Mts. trough (Green *et al.*, 1993); for explanation see Figure 1

Blundell's (1990) essential question refers to the problem of the seismic structure of the continental crust. The question is: did the lower crustal shear zones form initially as a result of imbricate stacking of thrusts due to syn-orogenic (syn-collisional) compression with subsequent reactivation and transformation into anastomosing ductile shears during crustal extension, or did the process proceed the other way round?

To summarize, it is striking that continental crust structures of different ages, geological features and tectonic units show many similarities irrespective of the criteria applied for the classification of the crustal seismic structures (Figs. 32, 33). The seismic images of the upper and middle crust of old Precambrian platforms (Fig. 32a), Palaeozoic tectogens (Fig. 32b, c) and Cenozoic tectogens (Fig. 32d) are similar. Throughout all of these areas, the upper crust displays a lenticular to wedge-like and lenticular structure at the upper/lower crust transition. The Moho surface is more or less distinctly accompanied by laminated lower crust. It is also striking that the crustal seismic structure of Palaeozoic orogens (Fig. 33a) is similar to that of younger ones (Fig. 33b), although the characteristic lenticular structure of the Alps occurs at shallower depths than the Variscan orogen of Central Europe.

The similarity of seismic structures along all of the geophysical transects indicates that their origin is related neither to geological processes observed on the Earth's surface nor to the tectonic evolution of a given area. Their origin must be associated with a powerful, global tectonic process superimposed on the lithosphere of diverse rheology.

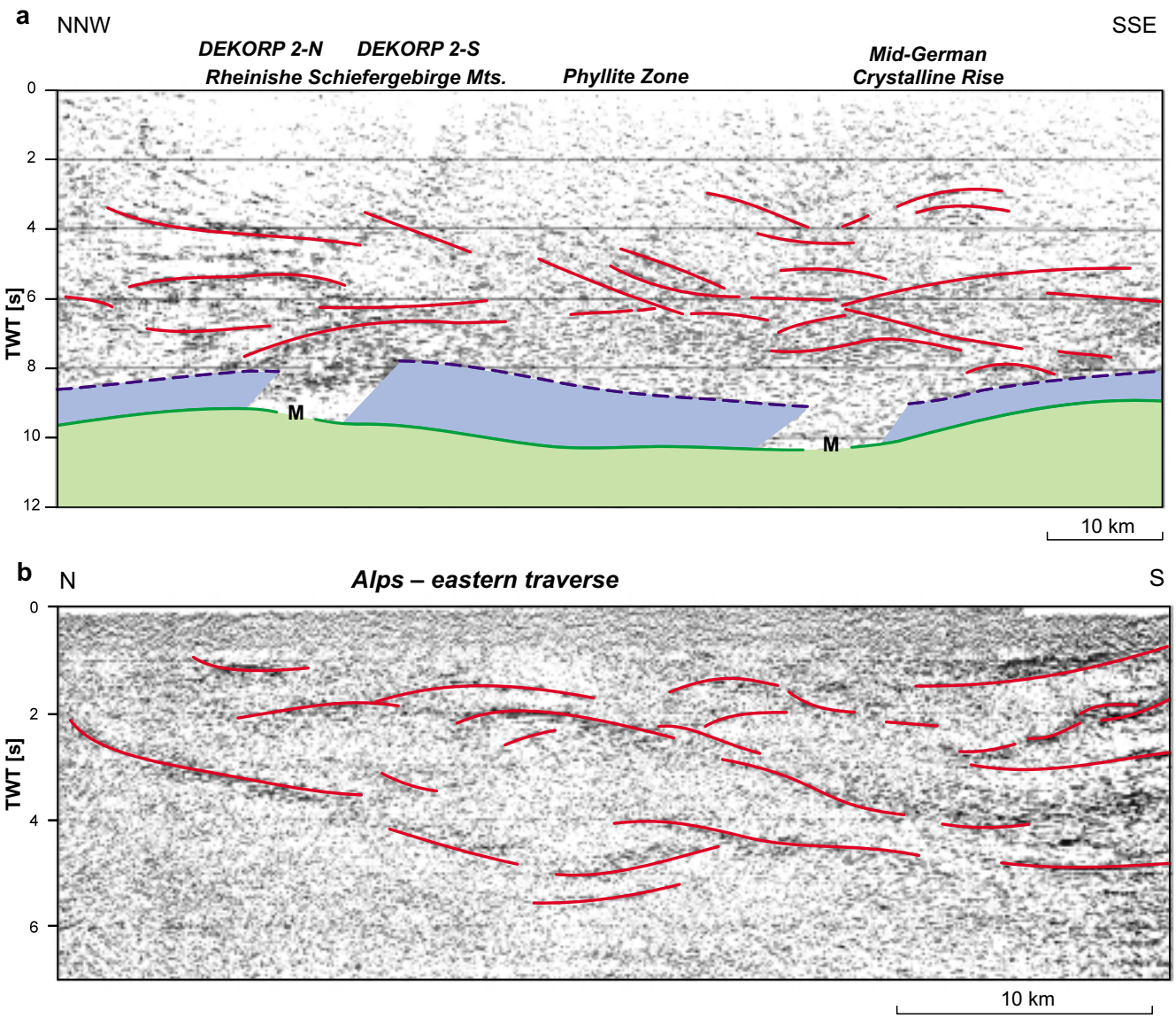

Fig. 33. Seismic images of the crust within orogens of different ages

a — the Variscan crust of Central Europe; **b** — the Alpine cust of the Swiss Alps; for explanation see Figure 1

THE MULTILAYER STRUCTURE OF THE CONTINENTAL LITHOSPHERE

Repeated geophysical investigations of the continental lithosphere have shown its multilayer structure. The stratification of the continental lithosphere is undoubtedly related to differences in the chemical and petrographical composition of individual "spheres", as perfectly evidenced by seismic velocity data (e.g. Pavlenkova, 1979; Belousov, Pavlenkova, 1989). This lithospheric stratification has old Precambrian foundations and is marked by the occurrence of subhorizontal discontinuity surfaces such as the Conrad and Moho surfaces. Subsequent tectonothermal events also affected the lithologies of individual layers, through processes such as intracrustal magmatism or eclogitization of the lower crust. Reflection seismic investigations also permitted the exploration of the inner structure of individual layers of the crust and upper mantle, indicating that they dramatically differ in their seismic structure. Reflection seismic work revealed different styles of deformation within the individual crustal layers of various continents. The boundaries of deformation levels do not always correspond to lithological boundaries. In general, four levels, which differ in deformation style, can be distinguished (Fig. 34). These are:

— the upper crustal level,

— the lower crustal level,

— the Moho surface zone,

— the upper mantle level.

Since the boundaries of these levels are well correlatable with data concerning the present-day rheological properties of the crust and subcrustal lithosphere (Fig. 31), there is a logical conclusion that the seismic structure of the continental lithosphere is, to a large extent, a result of sub-recent and recent tectonic stresses, but not a structure inherited from inactive old deformations.

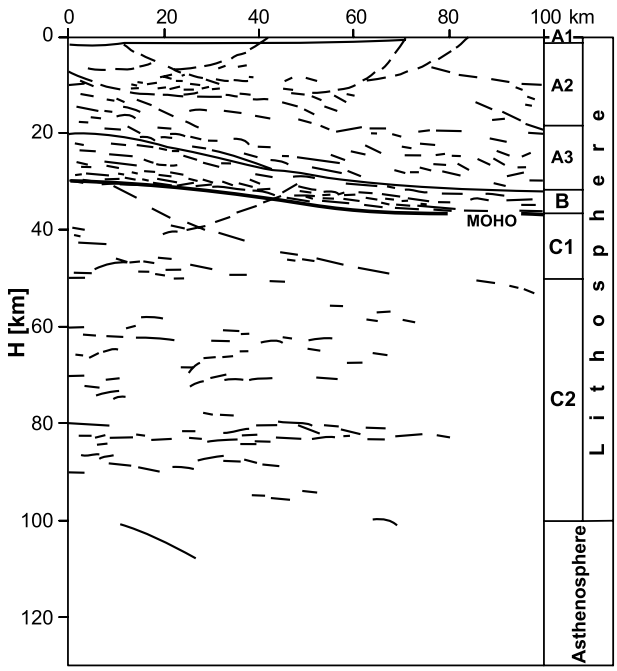

Fig. 34. A synthetic seismic profile of the continental lithosphere showing its subdivision into deformation levels

A1 — the sedimentary cover of the crust, A2 — the upper crust, A3 — the transitional zone, B — the lower crust, C1 — the subcrustal upper mantle, C2 — the upper mantle

UPPER CRUST

The continental upper crust is the best explored lithospheric layer, although direct observations refer only to its shallowest fraction, down to a depth of 4,000–7,000 m. The deepest drilling investigations of the Kola and Bavaria boreholes enabled its penetration to a depth of 10,000 m. All the remaining portion, down to the top of the laminated lower crust, has been penetrated using geophysical methods, including reflection seismics. The trend among geologists to relate the upper crustal structure to the tectonic structure observed on the surface is absolutely justifiable; however, the present analysis suggests that these attempts are not convincing. Geologists working on the interpretations of seismic images commonly take into consideration only some of the reflections observed in seismic profiles, ignoring others. The resultant image of the relationships between surface tectonic structures and the crustal seismic structure is not always reliable.

As a research tool, reflection seismic studies do not provide direct information on geological surfaces which dip at more than 30°. Despite this limitation, our knowledge on the seismic structure of the continental upper crust allows an objective reconstruction of its geological structure. In general, the upper crust is weakly reflective, except at the near-surface parts of sedimentary basins where the seismic lamination corresponds to depositional stratification. The upper crustal seismic structure is marked by reflection bands separated by weakly or non-reflective zones. Two distinct crustal levels which differ in seismic structure can be identified: the upper and lower level (Fig. 34). The upper level is dominated by symmetrically or asymmetrically dipping fault zones which commonly show listric geometry. These zones divide the crust into mutually shifted wedgeform blocks. In the case of symmetrically dipping discontinuity surfaces, the characteristic bowl-like arrangement of reflector bands of a lateral extent of up to 20–30 km occurs in the upper part of the crust down to a depth of 8–10 km. Listric faults are commonly related to fault zones observed on the surface and represented by steep thrusts, inversion faults, and normal or strike-slip faults. They gradually fade away downwards and disappear within a zone of dominant,

subhorizontally oriented, large-scale, lenticular structures of the lower level of the upper crust. This level is sometimes referred to as the middle crust. Not everywhere does the crust show such a structure. The mid-crustal layer is locally absent, and the listric faults of the upper crust gradually merge into the reflective laminated lower crust. Crocodile structures, resulting from the pushing of two wedgeform crustal fragments into each other, are also characteristic of the upper crust.

The geological significance of these discontinuity surfaces was elucidated thanks to very deep exploratory boreholes in the Kola Peninsula (Kol'skaya Sverkhglubokaya SG-3) (Minc, *et al*., 1987) and in Bavaria (KTB) (Emmermann, Lauterjung, 1997). Each of the two boreholes penetrated zones of low-dipping seismic reflections which were originally interpreted as surfaces related to thrust deformations. These deformations were thought to be synchronous with Precambrian orogenic processes in the Kola Peninsula, and with Variscan processes in Bavaria. What these boreholes revealed was a surprise to research teams, due to the narrow microfractured and porous cataclasite zones encountered within the zones corresponding to the reflection bands of the upper crust. These cataclasite zones were "pathways" for highly pressurized, strongly mineralized waters. They are most probably related to neotectonic and recent tectonic stresses, the result of relaxation of subhorizontal tangential stresses under brittle deformation conditions. Interesting results of *in situ* stresses from the SG-3 borehole are given by Minc *et al*. (1987). Down to a depth of 8 km, upper crustal rocks occur in a zone of increasing *in situ* stresses. Below this depth narrow (up to 50 m) anomalous decompression zones of open porosity and pore water migration were observed. Similar results were derived from the KTB borehole, which was drilled in an area of different geological structure.

Deformation under upper crustal geological conditions involves rigid displacements along brittle fault zones. These zones are detachment surfaces along which rock masses are displaced, though not necessarily over large distances. As depth increases, the deformations acquire features of transitional, brittle-ductile deformations, and become ductile deformations at the lower crustal level. The so-called Conrad seismic discontinuity is commonly assumed to occur at the lower/upper crust boundary, coinciding with a rapid change in seismic wave velocities. This discontinuity was originally associated with a change in lithology or degree of metamorphism (Wever, 1989). However, the results of the SG-3 borehole analysis (1987) indicate that a dramatic change neither in lithology nor in degree of metamorphism can be observed at the Conrad seismic discontinuity. The elastic properties of rocks of different compositions equalize with increasing depth (Minc *et al*., *op. cit*.). The main factor affecting their variability is the state of stress.

In this situation, the Conrad seismic discontinuity is associated with the top of the laminated lower crust (Wever, 1989), and seems to correspond to the change from a brittle or brittle-ductile type to a ductile deformation type. It can be considered as one of the major subhorizontal detachment surfaces in the continental lithosphere.

LOWER CRUST

A particular role seems to be played by the lower crust which commonly occurs both in areas of recent extension (Allmendinger *et al*., 1987; Barazangi, Brown, 1986; Blundell, 1990) and under tectogens of different ages. In many areas, it is also observed in Precambrian cratons. Therefore, it is important to explain the origin of the lower crustal seismic structure. Seismic lamination in this crustal layer is caused by densely arranged, mostly subhorizontal, short reflections. Reflection packets are locally inclined, arched or wavy (Mooney, Meissner, 1992).

The top of the laminated lower crust lies at a depth of 20–30 km over most areas, locally at 12 km (Fig. 34). Its sharp base is interpreted as an equivalent of the Moho surface. The thickness of the laminated lower crust is variable. Over a distance of several tens of kilometres, it often shows a number of swells and thins. The Moho surface, associated with the base of the seismic lamination, does not always strictly correspond to the Moho surface, represented by an abrupt increase in seismic wave velocities (Wever, 1989). The reflective lower crust occurs as three major forms: (1) as a uniform laminated layer at depths from 6 to 10 s TWT; (2) as a laminated layer with a more weakly reflective band dividing the laminated crust into the lower and upper part; and (3) as a narrow belt of very strong subhorizontal reflections which accompany the Moho surface. Each of these cases shows no relationships between the lower crustal seismic structure, the upper crustal structure and surface geology.

As regards its inner structure, the lower crust is essentially different to the other continental lithospheric layers. According to Klemperer and Peddy (1992), the structure was formed as a result of a crustal process, controversial in nature. Investigations of the origin of the seismic lamination have been conducted on the basis of: (1) synthetic seismograms constructed for assumed models (Reston, 1990a; Blundell, 1990); (2) structural studies of highly metamorphic rock complexes formed under lower crustal temperature and pressure conditions (Ramsey, 1980); and (3) seismic data that confirm the occurrence of plastic deformations in the lower crust (Reston, 1990a).

The origin of seismic lamination is commonly explained by the extensional process of pure shear affecting the lower crust (Matthhews, Cheadle, 1986; Reston, 1990a). High electric conductivity of the lower crust indicates the presence of free water, and inclines some authors to relate reflection lamination to subhorizontal water-bearing zones (Warner, 1990). There is also a popular concept of mafic sills intruding from the upper mantle into lower crustal rocks (Allmendinger *et al*., 1987; Warner, 1990). It is interesting that all of these genetic models are not at odds with one another — they correspond to a crustal layer deformed by tensional stress.

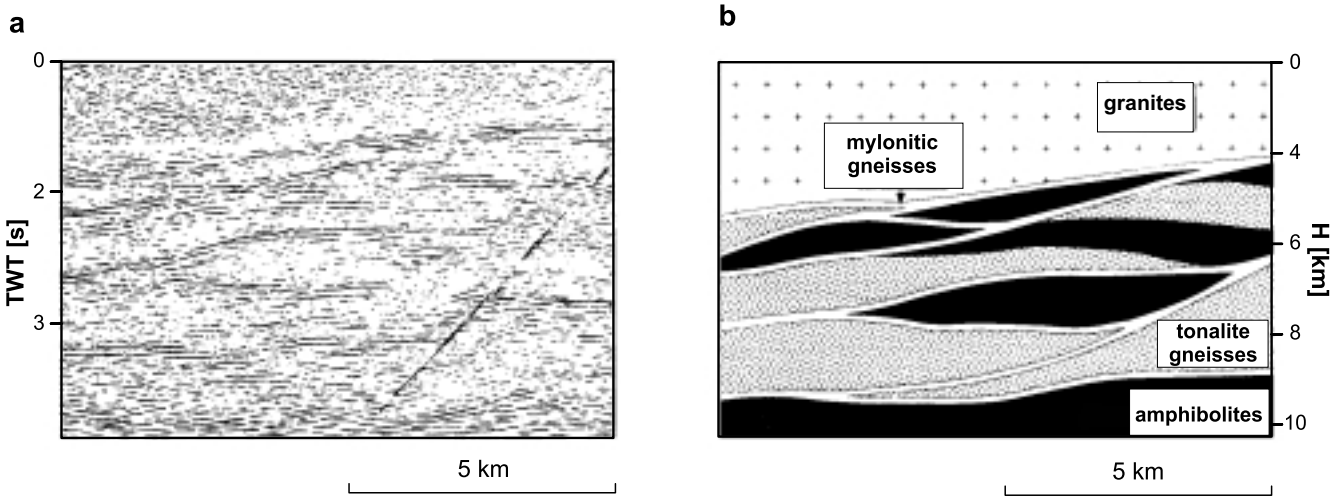

Fig. 35. A structural model of the reflective lower crust, by Norton (Blundell, 1990)

Lenticular portions of crystalline rocks, bypassed and separated by anastomosing shear zones, are responsible for this reflective image

Norton (*vide* Blundell, 1990) constructed a model of the lower crustal structure by a comparison of a reflection seismic image from deeper levels of the Moine thrust (depth 4–8 km), northern Scotland, with the geological setting in the surface zone of this thrust (Fig. 35). The laminated seismic structure is explained by a model of densely packed, elongate, lenticular bodies; shorter and thicker lenses show upward-arched reflections on seismograms.

According to Reston's interpretation (1988), the reflectivity of the lower crust, manifested by the occurrence of non-reflective lenticular "bodies" bypassed by narrow bands of strong reflections, can be best explained as resulting from the formation of large-scale, anastomosing, ductile shear zones in the lower crust. These zones are associated with extensional processes in the lower crust. A gradual transition from concentrated normal fault zones in the upper crust to dispersed shear zones in the lower crust corresponds to a transition from brittle to ductile deformation. This process occurs at various depths and in different ways, depending on the rheological properties of the rocks. Therefore, simple shear deformations along fault zones are predominant in the upper crustal zones of extension, whereas in the lower crust, a system of anastomosing simple shear zones creates an overall pure shear effect. A very significant feature is shown by Blundell (1990) in a graphic scheme illustrating a type of extension within the crust (Fig. 36). The lower crustal structure is identical in both perpendicular cross-sections. This indicates a nearly isotropic extension in all directions, contrary to the upper crust, where deformation is anisotropic and concentrates along certain zones.

Thus understood, the laminated lower crust acts as a wide detachment zone separating the upper crust from upper mantle. In the plate tectonic model, it is necessary to assume that tensional stresses are transferred from the upper crust downwards, resulting in the formation of the laminated lower-crustal structure. However, the analysed data indicate that the stresses were transferred in the opposite direction, i.e. upwards. Tensional stresses are varied at different lithospheric levels. The reflective lower crust was formed as a result of a global system of tensional stresses which are dominant in this continental lithospheric layer.

Lower crustal processes of extensional deformation, responsible for seismic reflectivity, can occur according to pure or simple shear mechanisms or as a combination of these two (Reston, 1990a). The final effect, however, is a symmetric lenticular structure indicating isotropic extension of this lithospheric layer with a predominance of the pure shear process.

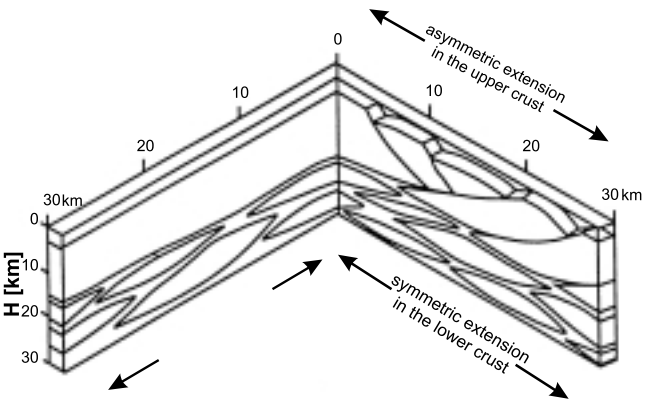

Fig. 36. A scheme illustrating the extension of the lower crust according to Blundell (1990; supplemented)

Isotropic extension in the lower crust is accompanied by asymmetric extension in the upper crust

THE MOHO SURFACE

The Moho surface was defined long ago by refraction seismic investigations as an original petrological boundary between rocks contrasting in terms of their density and chemical composition. In reflection seismic interpretations, this surface is related to the base of the laminated lower crust (Barton *et al*., 1984). So defined, the Moho surface shows much lateral variation (Blundell, 1990). In areas of recent extension (MOIST — Fig. 10, DRUM — Fig. 11a), the Moho is commonly represented by a strong, almost continuous reflector. Elsewhere, the Moho surface is an indistinct, discontinuous zone of reflection bands at the base of the laminated lower crust. Locally, mostly in old cratons, the Moho surface coincides with a narrow belt of reflections without the typical laminated lower crust, although this type of crust is also observed under the Precambrian portions of continents. A small thickness of the laminated crust is probably a result of greater crustal rigidity. The Moho surface is commonly considered to represent a younger structure (e.g. Dohr, 1989; Klemperer *et al*., 1986; Jarchow, Thompson, 1989; Mooney, Meissner, 1992; Klemperer, Paddy, 1992).

UPPER MANTLE

In general, the upper mantle of the continental lithosphere is seismically transparent. However, many prolongated-recording time reflection seismic profiles show the presence of discrete low-dipping reflection bands which gradually pass upwards into the laminated lower crust. These bands do not displace the reflective Moho surface, although, as stated by Reston (1990a, b), locally, there is a spatial relationship between extensional faults in the upper crust and reflection bands in the upper mantle (e.g. DRUM profile — Fig. 11). Such bands commonly dip symmetrically in both directions. Data on the character of deformation responsible for the formation of these bands in the subcrustal lithosphere are derived from reflection images, investigations of upper mantle xenolites and experimental studies and investigations of highly metamorphosed ultramafic rocks. There is a dominant view among contemporary research workers that upper mantle reflection bands reflect the occurrence of localized shear zones which accommodate most of the deformations within the subcrustal lithosphere (Reston, 1990a, b). Reston (1990b) is of the opinion that upper mantle reflections, observed in the crustal basement of the North Sea, are associated with extensional structures such as reversed extensional listric faults, which fade away at the Moho surface. This boundary can therefore be considered a detachment surface along which relative movements between the crust and subcrustal mantle occur. Almost identically developed upper mantle reflection bands, observed beneath old cratons (e.g. BABEL — Figs. 8, 9), are sometimes interpreted as traces of ancient subduction surfaces, yet there is no proof of it. Balling's (2000) reinterpretation of the BABEL and MONA LISA reflection profiles additionally shows that subhorizontal reflections, marking large-scale lenticular structures, again occur in the subcrustal lithosphere at depths of 50 to 100 km. Their geometry resembles that of lower crustal structures. The latter, however, are much smaller. From the rheological point of view, these structures appear in a succeeding layer of lowered rigidity.

THE GENERAL MODEL OF THE CONTINENTAL LITHOSPHERE

The results of seismic investigations of the multilayer structure of the crust and subcrustal mantle under the continents can be the basis for creating a general model of the continental lithosphere. The overall knowledge on the seismic structure and the physical nature of reflection bands allows deformation types to be related with individual lithospheric layers. And so:

1. The continental upper crust contains both typical compressional and extensional structures. Compressional structures, referred to as flake structures in the plate tectonic theory, are represented by tectonic wedges, crocodile structures, subhorizontal or inclined detachments at various crustal levels, steep thrust structures, and thrust stackings. In the classical plate tectonic interpretation, all of these structures are related to subduction processes and the resultant collision. A repeated rejuvenation of discontinuous structures through superimposition of compressional and extensional, and transpressional and transtensional processes, is the commonly occurring phenomenon observed on the surface. The prominent upper crustal structures are listric faults. These are steep or vertical at the near-surface, and pass downwards into a detachment surface/zone at the upper/lower crust boundary. Multiphase displacements of varying kinematics take place along these fault zones. In general, compressional structures occur in the upper crust in areas where the crystalline basement is composed of Precambrian continental crust. In areas of recent extension, in rift zones, under young extensional basins, along continental shelves subjected to extension, and over all those areas where the continental crust thins, characteristic extensional structures occur in the upper part of the crust. These structures are represented by normal faulting, tectonic rotation of blocks above basal detachment surfaces, domino faulting and metamorphic core complexes. Irrespective of their character, upper crustal deformations lead to the formation of non-penetrative structures on a crustal scale, and simple shear is the dominant mechanism.

2. In the lower crust, isotropic extension is the dominant process under conditions of ductile (plastic) deformation. It manifests itself in the formation of symmetric lenticular structures representing penetrative structures, if considered on a crustal scale. These give rise to reflection lamination in seismic images (cf. Blundell, 1990; Reston, 1988). The topmost part of the lower crust separates two deformational domains and acts as a planetary detachment (decoupling) surface. The major deformation mechanism is pure shear, although simple shear can also locally occur.

3. In the subcrustal mantle of the continental lithosphere, extensional deformation processes are again concentrated within narrow, commonly symmetric and discontinuous structures gradually passing upwards into the reflective lower crust, due to changes in the rheological properties of mantle matter. The Moho surface is another rheological-structural boundary at which the crust is tectonically detached from the upper mantle. In the lower part of the lithospheric mantle, extension can again result in the formation of subhorizontal penetrative structures genetically similar to the structures of the laminated lower crust.

The seismic structures of the continental lithosphere, observed in a number of reflection profiles, reflect different types of deformations in individual layers. The various parameters affecting these layers, such as the thickness of individual layers and the type of shear, depend on rheological conditions, which are in turn influenced by the pT conditions in the lithosphere.

THE SEISMIC STRUCTURE OF THE CONTINENTAL LITHOSPHERE IN THE LIGHT OF THE EXPANDING EARTH THEORY

According to the thesis presented in this paper, the presently observed seismic structure of the crust and upper mantle is being shaped out primarily by the process of the flattening of the outermost zone of our planet, forced by the "swelling" of the Earth's interior. Hence, an overall similarity of seismic structures can be observed along transects crossing different geostructures. Multilayered stress distribution, proposed in the model of the continental lithosphere, is responsible for the formation of seismic structures, and cannot be an effect of the plate tectonic mechanism. The major features of these structures include: (1) a layered distribution of the stress field and deformation types; (2) a relatively young age of deformations; and (3) probable upward transmission of stresses. These features suggest the involvement of a tectonic process associated with the expansion of the Earth. The expansion of the Earth's interior, accompanied by a decrease in the curvature of near-surface layers, could give rise to such a stress pattern (Fig. 37). The main thesis of this paper is the idea of the influence of curvature changes of the expanding Earth on tectonic processes. This idea was earlier expressed by Hilgenberg (1933), Rickard (1969), Jordan (1971), Carey (1976) and Maxlow (1995, 2001).

However, before it is possible to interpret the presented data on the seismic structure of the continental lithosphere in the light of the expanding Earth theory, it is necessary to discuss the history of creation and development of this, largely disregarded, geotectonic theory, and to show its modern image, as well as to describe the phenomenon of curvature changes in the outer zones of the expanding globe and its theoretical effect on geological processes.

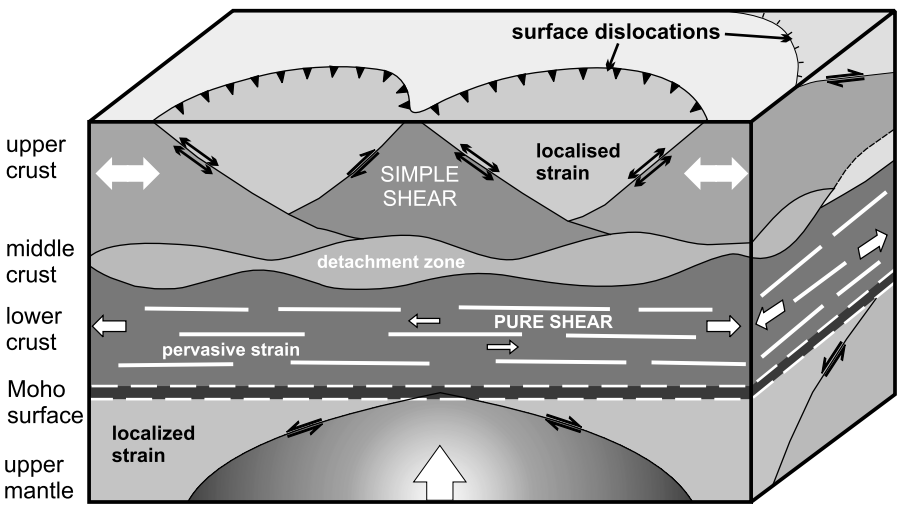

Fig. 37. The probable stress pattern, types of deformation and character of strain in different individual layers of the continental crust and upper mantle

THE DEVELOPMENT OF THE IDEA OF EXPANDING EARTH

All the major geotectonic ideas were born in the 19th century. They rapidly developed throughout the 20th century. The theory of an expanding Earth is no exception. In 1888, J.O. Jarkowski (Yarkovskii, 1888, 1889), a Russian rail engineer of Polish origin, published a report entitled "Hypothèse cinétique de la gravitation universelle en connexion avec la formation des éléments chimiques" in a local paper. This publication was rediscovered as late as the 1990s (cf. Koziar, Ciechanowicz, 1993). It assumes the possibility of a constant increase in the volume of planets due to an increase in the matter mass inside them. As a result of this process, the planets expand. Working in the same period, Green (1857, 1887) published papers suggesting the possibility of the Earth's expansion. Carey (1976) presented the most complete analysis of the historical development of the expansion idea from its conception to the mid-1970s. In Polish geological literature, the development of this idea was described in brief by Cwojdziński (1984, 1989) and Dadlez and Jaroszewski (1994).

The development of modern geotectonic theories commenced with the continental drift theory, best expressed by Wegener (1915, 1924). The concept of Pangea — a supercontinent covering all the present-day continents during the late Palaeozoic, and surrounded by an ocean (Panthalassa) — was also the starting point for the development of the expanding Earth idea. In the 1920s and 1930s, the first papers showing reconstructions of the position of the continents on a globe of smaller diameters were published. The first geologist who proposed such reconstructions was Lindemann (1927) of Germany. He assumed that the breakup and dispersion of Pangea was triggered by the expansion of the Earth. Since that time, several stages have been observed in the history of research on the expanding Earth. The expansion of the Earth was considered by some geologists as an alternative concept to that of the constant radius of the planet during its geological evolution — this idea resulted from the interpretation of geographical and geological data. The global expansion process was modelled by many scientists, most commonly, though not only by geologists, while analyses of the possible reasons for such expansion were published in papers by physicists, astrophysicists and astronomers, among others.

THE EXPANSION OF THE EARTH AS AN ALTERNATIVE CONCEPT TO THAT OF CONSTANT RADIUS OF THE PLANET

This research direction is an exciting case story about how geologists and geophysicists came to the expanding Earth theory, based on different global and regional observations. The first step, as mentioned above, was made by Wegener (1915), who created his idea of the late Palaeozoic Pangea, which subsequently broke up as a result of continental drift. As the amount of data on the geological and geophysical structure of continents and oceans grew, new arguments appeared in favour of the expansion idea. At the beginning, evidence was searched for on the continents. For example, it was noticed that the land bridge theory, so popular at the end of the 19th century, which was to explain the palaeontological relationships between recently distant continents, can be well explained with the assumption of the Earths radius having been smaller, and close contacts having existed between all the continents in the geological past (cf. Koziar, 1985). Egyed (1956) performed a detailed analysis of the extents of shallow epicontinental seas from the Precambrian until the recent, assuming that the volume of the World Ocean waters had changed during that time by no more than 4%. He discovered that the area of shallow epicontinental seas has continuously decreased, meaning that the area occupied by the oceans has increased. This led to the conclusion that the Earth has expanded and allowed the calculation to be made that the Earth's radius increased by 0.5 mm per year, with the assumption of its constant and steady increase. Although Egeyed's arguments are mostly out-of-date today, he was the first research worker who came to the idea of expansion on the basis of different and independent observations.

Carey (1958), using cartographic projections, reconstructed Wegener's Pangea on an Earth of the present-day diameter, and proved the occurrence of gaps which could not be evidenced by any geological data. The same reconstruction on a globe of a smaller diameter eliminates such problems.

The 1950s brought about a rapid inflow of information on the structure of the oceanic floor, and the discovery of the global system of oceanic ridges that resulted in the theory of the ocean-floor spreading. Heezen (1960) analysed the consequences of the discovery of the linear zones of oceanic lithosphere accretion and wrote: "I have recently suggested that the Earth is neither shrinking nor remaining at the same size; rather, it is expanding!". Although those observations, confirmed by various independent research methods (cf.: Coulomb, 1969, 1973; Vacquier, 1972, 1976), seemed to be the basis for a broad acceptance of the expansion theory, the principle theses of the so-called new global tectonics, i.e. plate tectonics, were formulated at that time. An actualistic approach to geologic processes, rooted in minds of geologists, was one of the reasons why Heezen's proposal was rejected. The second main reason why "the theory of the non-expanding Earth" was rejected (Koziar, 1991a, 1997) was the lack of any physical explanation for the origin of such a great expansion of the planet during the last 200 My of its evolution.

However, many data which contradict the principles of the plate tectonics theory were also published. Fairbridge (1965) was the first to show that there is a lack of evidence for compression at both oceanic ridges and orogenic belts, which suggests, along with the youth of ocean basins, the expansion of the Earth. Jordan (1966) analysed the contemporary rift system, considering ocean trenches to represent a separate type of rifting basins. He concluded that a common rift expansion exists, one which is recently a dominant geodynamic process. The same research direction was later continued by Tanner (1973), who proved the tension nature of the island arc–ocean trench system. He also showed that it is incorrect to explain

the motion of plates responsible for the formation of subduction zones in terms of plate tectonics, and that the subduction model is in disagreement with the facts observed in island arc–ocean trench systems. It is obvious that the tension character of ocean trenches and the entire trench-island arc-back-arc basin system contradict the basic principles of plate tectonics, and can only suggest expansion of the Earth (cf. Tanner, 1973, Fig. 3; Koziar, Jamrozik, 1994; Pfeufer, 1995).

Waterhouse (1967), analysing the results of oceanic basin age determinations, concluded that the real explosion in Earth expansion was post-Jurassic, neglecting the possibility of earlier expansion.

Barnett (1969) took note of the mutual relationship between the contemporary position of the continents and mid--ocean ridges. According to that author, the ridges represent relicts of the original tectonic lineaments along which Pangea broke up. He made an attempt to create an eclectic combination, with an expansion during the first stage of planetary development, and the lateral drift of continents during the second stage.

One of the key tests for the great dispute on the expansion of the Earth and plate tectonics is provided by the Pacific Ocean (Koziar, 1980, 1985, 1992). Its area would have to have shrunk if the Mesozoic–Cenozoic spreading of the Atlantic and Indian Oceans was to be compensated for, in order to maintain the constant dimensions of the Earth. Meservey (1969) showed that the shrinkage of the Pacific area is unrealistic, and that reconstructions of drifting continents on an Earth of present-day dimensions lead to topological discrepancies. Many subsequent authors discussed the problem of the present-day Pacific Ocean, which, in terms of its age and lithospheric structure, does not differ from the other oceans (Fig. 38). The Jurassic opening of the Pacific is evidenced by the similarity of the Permian, Triassic and Lower Jurassic facies, palaeofauna and palaeoflora between the American continents, Asia, Australia and Melanesia (Avias, 1977; Shields, 1979, 1983). Palaeogeographical, tectonic, geological and palaeobiogeographical data (Shields, 1979, Figs. 3–7, 1983) indicate the geographical proximity of the western coast of the Americas to the eastern coasts of Asia and Australia prior to the Jurassic–Cretaceous breakup of Pangea. Simultaneously, that author rejected the previously postulated concept of Hughes (1975), who realized the geological similarity between Asian and Australian margins and the western coast of the Americas, and located the pre-Jurassic pra-Pacific between the Cordilleras and the continental part of North America. Such a palaeocean, whose existence is necessary to maintain the constant dimensions of a globe, is not evidenced by any palaeobiogeographical data cited by Shields (1979). Therefore, the results of studies of circum-Pacific relationships between the continents suggest the expansion of the Earth. Similar conclusions were expressed by Davidson (1983), who investigated Carboniferous and Permian palaeoflora. Ager (1986) analysed the distribution of Mesozoic brachiopods in the Mediterranean area, and around the Indian and Pacific Oceans, stating the following: "I find it difficult to accept different explanations for the same phenomena which occurred in the various oceans of the Earth. On balance, I prefer to think that all the oceans have been expanding since early Mesozoic times and that therefore the hypothesis of an expanding Earth is inescapable".

Another very significant problem is the nature of the Tethys — a wide and mobile zone separating continental Eurasia from the Gondwanian continents. In the Wegener's Pangea, this is a zone of a Mesozoic continental sea which, in plate tectonic palaeogeographical reconstructions, acquires a clinoform shape as an oceanic area between Laurasia and Gondwana. However, geological data clearly indicate (Meyerhoff, Meyerhoff, 1972; Ahmad, 1983; Carey, 1983a; Čirič, 1983a): (1) the epicontinental type of sedimentation in the Tethys; (2) the close palaeogeographic and palaeobiogeographic relationships between the southern margins of Eurasia and Arabia, Madagascar, Decan and large islands of the Sunda Archipelago. The interpretation of these facts leads to the conclusion that the Earth has expanded (Crawford, 1979, 1982, 1983; Stocklin, 1983; Ahmad, 1983; Cirič, 1983a, b; Carey, 1983a). The Tethys Ocean, arising from the plate tectonics theory, is considered by expansionists as an apparent structure resulting from the so-called "orange peel effect" (van Hilten, 1963; Carey, 1976) which forms as continents are artificially "flattened" on a globe of a larger, present-day size.

The geological evolution of the Mediterranean Basin has similar significance. According to the plate tectonic theory, this basin recently had to be undergoing a shortening as Africa approaches Europe due to sea-floor spreading in the southern Atlantic. Carey (1976) claimed that the development of this basin occurred along a left-lateral strike-slip zone between Laurasia and Gondwana in an extensional tectonic setting. Koziar and Muszyński (1980), having analysed the existing concepts of a regressive and progressive development of the Mediterranean and Black seas, and having compared them with palaeogeographic data, came to the conclusion that these are young extensional basins. A similar model was also constructed by Chudinov (1980), Cirič (1983a), Tassos (1983a), and Panza and Suhadolz (1990). The youth of the small Mesozoic and Cenozoic ocean basins which formed between Europe and Africa, and the simultaneous left-lateral rotation of Africa, as evidenced from the plate tectonic model, is an easily explainable discrepancy if we assume that the Earth expands.

Carey (1976) presented six fundamental facts suggesting the expansion of the Earth. These are: (1) the youth and the age of all the recent ocean floors (Fig. 38); (2) the gaps within the clinoforms observed in all the Pangea reconstructions on the Earth of the present-day dimensions (the Tethys area represents the greatest gap); (3) the polygonal structure of the Earth's surface and the occurrence of hierarchic extensional structures; (4) the dispersion of first-order polygons and their areal increase; (5) the Pacific Paradox; and (6) the Arctic Paradox. All of these arguments are still current. The first of them is absolutely obvious. Arguments 2, 3 and 4 are strictly associated with the problem of the curvature change of an expanding Earth. This problem will be discussed later.

The Pacific Paradox (Carey, 1958, 1976) is the most striking argument. The perimeter of the modern ocean is slightly less than the Great Circle, and extensional processes are observed between the continental masses around the Pacific (Australia–Asia, Australia–Antarctica, Antarctica–South America, South America–North America) (Fig. 38). The area

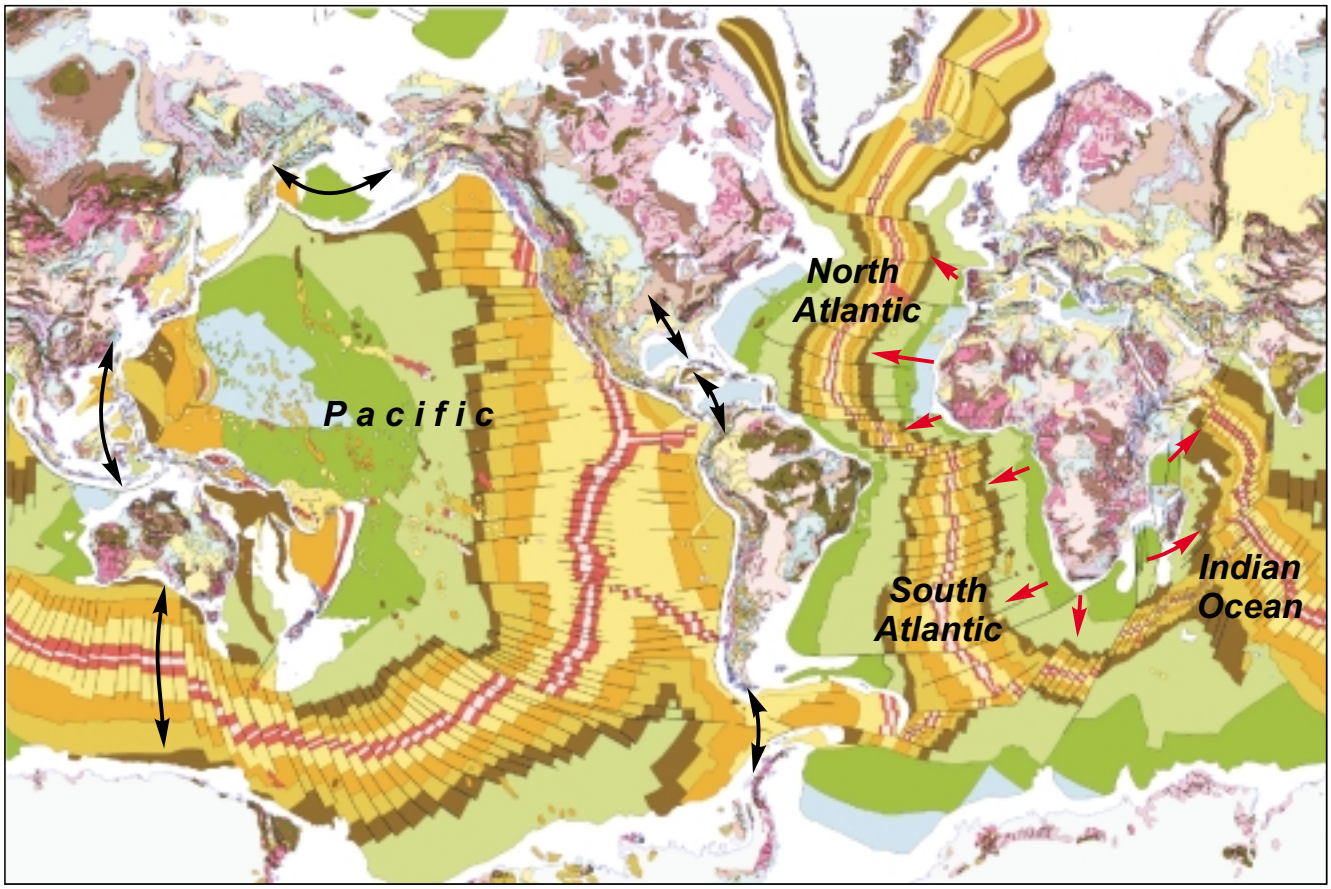

Fig. 38. A Geological Map of the World (Geol. Map of the World, 1990)

The black arrows denote the directions of continental spreading around the Pacific perimeter (Pacific Paradox); the red arrows denote the radial separation of the mid-ocean ridge from Africa

of the Atlantic and Indian Oceans has developed due to sea--floor spreading since the beginning of the post-Palaeozoic breakup of Pangea. In the Earth of constant radius, this process would have to be accompanied by an enormous shrinking of the Pacific area. In the light of the modern geodynamics, such a shrinking cannot occur. This was emphasized by Koziar (1993), who analysed plate tectonic interpretation of the Mesozoic evolution of the Pacific Ocean and proved the geometrical impossibility of such interpretation. He also introduced the term "strengthened Carey's test". It appears that the expansion of the modern Pacific can be proved by dilatancy in only three segments of the circum-Pacific belt. These are the Australian–Antarctic, Antarctic–South American and Middle American segments. In these areas, the present-day extension between the continental blocks is beyond question.

The Arctic Paradox results from the complete discrepancy between the results of palaeomagnetic investigations, which suggest a slow northward drift of all the continents during the Mesozoic and Cenozoic, and the simultaneous "opening" of the Arctic Ocean. Meanwhile, no post-Palaeozoic subduction zone occurs along the Arctic Ocean margin.

Ocean-floor expansion, as the major evidence for expansion of the Earth, was discussed in various aspects by Carey (1976), Chudinov (1976) and Koziar (1980, 1985). Koziar (1980) was the first to point out that the longitudinal extension of the Mid-Atlantic Ridge separating Africa from South America (Fig. 38) — an obvious fact for plate tectonicians too (Wilson, 1965a; Dietz, Holden, 1970) — is evidence that the Earth expands because it is related to the isotropic and homogenous extension of the lithosphere basement. This is a simple explanation of a fact which cannot be easily explained by plate tectonic interpretations, which require the existence of a complex and improbable system of two convection currents responsible for the Atlantic rifting and a simultaneous transversal shift of the oceanic lithosphere (Wilson, 1965a). In the same paper, Koziar (1980) calculated the current annual rate of increase of the Earth's radius to be 2.6 cm, and the rate of increase in Earth volume to be 13,200 km^3. In another paper, Koziar (1985) proved that the idea of Pacific sea-floor spreading reconciles the requirements of modern geotectonics with the 19th century land bridge theory, which explains the close palaeobiogeographical relationships between Asia and Australia, Australia and North America, and Australia/Oceania and South America (cf. Briggs, 1987).

The problem of the opening of the Pacific Ocean was lately discussed by Scalera (1989, 1991), who noticed a similarity between the outlines of the individual continents of the Pacific Rim and the outlines of the oceanic plates: e.g. between Austra-

lia and Nasca, South America and Tassman and the Coral Sea Plate, North America and the NW Pacific. That author analysed suspected causes of this phenomenon and concluded that it can be best explained by the expanding Earth theory, since the ocean-floor structure contains a record of the mutual position of continents prior to the Pacific opening in early Mesozoic times.

Other arguments in favour of the expansion theory were gathered by research workers of the so-called hot spots (mantle plumes), which, according to the research results of plate tectonicians, are rooted deep in the Earth's mantle (cf. Condie, 2001), and, as features uninvolved in the lithospheric plate drift, do not change their positions on an Earth of constant dimensions. Burke, Kidd and Wilson (1973) studied the relative motion of hot spots towards one another and stated that the curve illustrating an increase in distance (along the Great Circle) between two objects selected for the analysis has shown an exponential character for the last 120 My. However, the former authors seem to disregard this fact. Meanwhile, a similar increase is observed for the Earth's radius. Stewart (1976) analysed the increase in distance between mantle plumes through time, and came to the conclusion that this process suggests the expansion of the Earth.

One of the most important tools of plate tectonics, used for reconstructions of the position and drifting of continents and their fragments (microcontinents), are palaeomagnetic methods (cf. Westphal, 1993). According to the followers of the "non-expanding Earth" theory, these methods suggest large horizontal displacements of continental masses as they get closer and move apart, their collisions and rotations. The results of palaeomagnetic research, conducted for over 30 years and used for pre-Mesozoic reconstructions, along with the increasing amount of data, led to the situation that the former regional geology of continents became replaced by microplate, microcontinent and terrane geology.

During the early development of palaeomagnetic studies, the so-called "single meridian method" was proposed to measure the Earth's palaeoradius (Egyed, 1960). Van Hilten (1963, 1964, 1965, 1968) invented a method of using palaeomagnetic data (a compilation of palaeolatitude and palaeolongitude data) to measure the Earth's palaeoradius for the Carboniferous, Permian, Triassic and Cretaceous. He obtained different values, much smaller than recent ones (e.g. R = 5096 km for Triassic of North America, R = 4,803 km for the Permian of Siberia etc.). This approach was criticized by Ward (1963, 1966), who modified this method, and later also by Hospers and van Andel (1967). In the discussion with expansionists, Ward's method was used to calculate the Earth's palaeoradius (McElhinny, Brock, 1975; McElhinny *et al*., 1978; Stewart, 1983) and the results of the investigations, according to those authors, preclude the possibility of the expansion of the Earth. At that time, Smith (1978) published a paper in which he called the publishing day of McElhinny's paper (McElhinny *et al*., 1978) the "black day" of the expansion theory. However, Carey (1961, 1976) proved that this method can yield accurate data on the change in the Earth's size, provided that there is confidence that no deformations occur between the sites of palaeomagnetic measurements during the period between the time for which the measurements were made and the recent. It appears that most of the palaeomagnetic sites on old platforms are separated by extensional deformation zones which show the characteristics of intracontinental basins, aulacogens or rifting zones.

The principle error of palaeomagnetic interpretations is that many palaeomagneticians do not take into consideration the fact that, on an expanding Earth, there is also an increase in the linear distances between the measuring points and the crossings of palaeolongitude lines.

Chudinov (1984) paid attention to this fact, and described and employed a new method of calculating the Earth's palaeoradius (the so-called Tertitzki method) based on a calculation of the magnetic palaeolatitude of the three points of spherical triangles selected for different Precambrian homogenous platforms. The calculations, cited by Chudinov (*op. cit.*) and based on the existing measurement data, indicate the process of planetary expansion (e.g. for the late Cretaceous, the Earth's radius ranges from 4075 to 5100 km). The problem of the interpretation of palaeomagnetic data was also discussed by Scalera (1990a), who invented an original method of computer simulation of the dispersion of continents and their accretion into Pangea on an Earth of present-day and smaller sizes, and performed a computer simulation of the position of synthetic magnetic palaeopoles for all the experimental versions. The comparison of simulation and real data (with the use of Cambrian palaeomagnetic data) led to the conclusion that the early Cambrian Earth's radius was probably about 3,000 km (Scalera, 1990a).

Carey (1976) also proposed other methods of using palaeomagnetic data to prove the expansion process. One of them is the Arctic Paradox mentioned earlier: the geographic palaeolatitudes of all the Circum-Arctic continents show a slow northward movement of continental masses from the Permian until the recent. The only logical explanation for this process is an asymmetric expansion of the planet, which triggers the migration of palaeolatitude parallels across continents (Carey, 1976, Fig. 105; Tanner, 1983, 1990). The expansion of the Earth is also evidenced, according to Carey (1976), by phenomena such as: the double palaeomagnetic equator and the magnetic palaeopole "overshoot" paradox.

Since the conception of the continental drift theory, many attempts to measure the rate of continental drift have been made in order to prove the motion of continents. There have also been measurements which were made to show stability or changes in the Earth's radius through time. In the beginning, these methods were based on astronomic measurements of changes in the position of geographic coordinates. Recently, instrumental investigations are most common. The first measurements were commented and interpreted by Blinov and Kirillov (1978). The results of astronomic measurements show an angular widening of the meridians in the Pacific area with a simultaneous shrinking of the Atlantic and Asian segment. This shrinking is only an apparent phenomenon resulting from a faster spreading of the Pacific. According to Blinov and Kirillov (*op. cit.*) and Blinov (1987), these data directly indicate the expansion of the Earth. Instrumental investigations have recently been based on three different methods of cosmic geodesy (Dadlez, Jaroszewski, 1994) —

Very Long Baselines Interpherometry (VLBI), Lunar Laser Ranging and Satellite Laser Ranging Network (SLRN) — of increasingly better resolution. Synthetic reports on these methods (e.g. Anderle, Malyevac, 1983; Smith *et al.*, 1990) underline the conformity of the results with the expected results of plate tectonics (cf. Dadlez, Jaroszewski, 1994, p. 594). However, the principle error of plate tectonic interpretations relies on the *a priori* assumption of the constant dimensions of the Earth (Blinov, 1987; Koziar, 2002). The results of cosmic geodesy investigations, obtained this way, will ultimately prove that the plate tectonic mechanism does work. However, Carey (1988, 1994) and Koziar (2002) excellently evidenced that the current interpretation of satellite and VLBI investigations is based on the erroneous assumption that the Earth's radius is constant. If a proper equation includes change in radius through time and numerical data from geodesy measurements, then we can obtain a suggestive and convincing result: the Earth's radius annually increases by 2.08 ±0.8 cm. This value corresponds to the rate of expansion calculated from the speed of recent ocean-floor spreading (cf. Koziar, 1991a).

GLOBAL EXPANSION MODELLING

The idea of the breaking up of Pangea due to the expansion of the Earth was initiated by Lindemann (1927) and illustrated for the first time by Hilgenberg (1933) as a series of spherical models. The set of Hilgenberg's globes was made of papier-mache and presented reconstructions of the position of Wegener's Pangea at the end of the Precambrian (massive continental cover around the entire planet, the radius of which was 2/3 of its present value), the middle Jurassic and the early Cenozoic (Fig. 39). It is noteworthy that Hilgenberg (1933) had to assume the occurrence of enormous global shear lines (Scherlinien), along which large fragments of continental masses were horizontally displaced, to obtain the image of the complete "closure" of all the modern oceans on a globe whose radius was 2/3 that of the present-day Earth's. The Hilgenberg reconstruction is characterized by the following: (1) the brilliant observation, 30–40 years before the scientific confirmation of this fact, that all the oceans are young in age; and (2) the necessity of assuming considerable displacements of continental fragments to obtain "Hilgenberg's Pangea" (term introduced by Oberc, 1986) closed on a globe of a smaller radius. Other aspects of Hilgenberg's work will be discussed below.

Fig. 39. The Hilgenberg's model of the expanding Earth (1933) viewed from the Indian Ocean

Keindl (1940) was also of the opinion that Pangea once covered the entire globe and that the oceans represent structures formed through the separation of continents. The title of his work includes the question: *Does the Earth expand?*

Brösske (1962) and Barnett (1962) slightly modified Hilgenberg's model, introducing some changes in the way of closure of the Pacific Ocean. For example, on Brösske's model, with a radius = 55% of the present-day Earth's, the Middle Pacific was closed by Australia, whereas Antarctica was rotated by 180° as compared to its present-day position. These differences, and other variations in the approach to this problem by each of these two authors, were illustrated and discussed by Koziar (1991b).

In the conclusions to the analyses of his models, Barnett (1962) wrote: "It is difficult to believe that chance alone can explain this fitting together of the continental margins". Barnett was also the first scientist who made an attempt to dynamically model the expansion process on an inflated elastic sphere. An original graphic reconstruction of Pangea on an Earth of smaller radius was proposed by Kirillov (1958). Some modifications to this reconstruction were made by Neiman (1962, 1983). In this reconstruction, the Pacific Ocean is closed by strongly rotated Americas, which contact along their present-day western borders. The reconstruction is now of only historical significance, since it ignores the geometry of recent ocean-floor spreading.

By turns, Creer (1965) placed the outlines of the continents on globes of radii of 37 and 27 cm, and also came to the conclusion that the continents match too well, so this cannot be down to chance alone.

Vogel (1983) was another expansion investigator who built his own models based on the outlines of the present-day continental blocks. First, he performed a reconstruction of the Precambrian terrella (60% of the present-day diameter) and Mesozoic terrella (Cretaceous, 72% of the present-day diameter), and then a set of terrellae for diameters = 46, 55, 60, 66, 75 and 85% of the present-day values (Vogel, 1990, 1994), and a globe-within-a-globe reconstruction which allows the present-day position of continents to be compared with that on Hilgenberg's Pangea (Fig. 40). Vogel's models (1983) suggest that the continental masses occupied a constant position relative to their basement, but that the asymmetric expansion of the Earth induced their apparent drift towards the North Pole. Vogel (1994) was also the first to construct two geological globe models: one of them reflects the present-day Earth's diameter (85 cm in diameter) and the second one is 54 cm in diameter (63% of the present-day radius) (Fig. 41). These models enable a comparison of the geological structure along the matching continental edges.

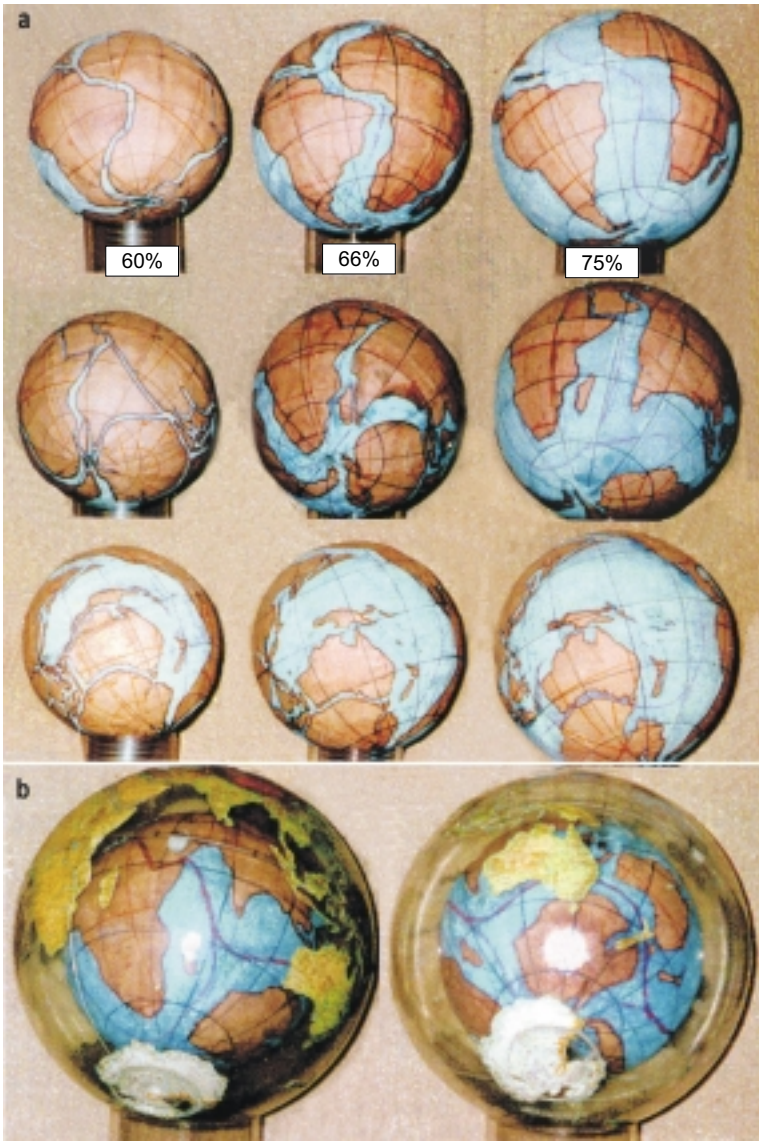

Fig. 40. The expansion of the Earth as illustrated in Vogel's models (1983)

a — reconstruction of the continents' position on an Earth of radius = 60, 66 and 75 % of the present-day radius, viewed from the Atlantic (upper models), Indian (middle) and Pacific (lower) Oceans, respectively; **b** — a globe-in-a-globe model of the expansion of the Earth, shown in order to compare the configuration of the continents on an Earth of radius = 75%

Non-typical reconstructions with the use of various cartographic projections — most frequently azimuthal equidistant projections — were done by Owen (1976, 1983). With mathematical precision, Owen proved that reconstructions of the Mesozoic and Cenozoic positions of continents, based on the analysis of the magnetic anomalies of the oceanic floors for the individual anomalies on an Earth of present-day dimensions, lead to the occurrence of gaps which cannot be explained via the plate tectonics theory. Such gaps are not observed in reconstructions for the period between 180–200 My on a globe of 80% of the modern radius, i.e. with a slightly larger surface curvature. Owen (1976, 1983) assumed an expansion defined by an exponential function of the increase in the Earth's surface area through time. However, he also assumed the existence of the Eo-Pacific. Therefore, the values of the expansion parameters obtained by him were lower than those obtained previously.

Weijermars (1986) made a series of foamed polystyrene models, each 10 cm in diameter, on which he distributed the outlines of the continental blocks and the ages of the oceanic floors for the modern configuration. Subsequently, by removing the oceanic crust belts of given ages, he obtained similar configurations for the periods of 20, 65, 95 and 140 million years ago. It should be noted that all these reconstructions were made on globes of the same diameter, so the author did not model the expansion of the Earth; rather he performed a plate tectonic analysis. The reconstructions conducted in this way resulted in a number of gaps and overlaps which could be suppressed only by the assumption of a slow expansion of the Earth and an increase in the Earth's radius by 94 km during the last 180 My. Obviously, that analysis was

Fig. 41. Vogel's geological globes (Vogel, 1994), showing the modern Earth (left model) and an Earth of radius = 63% of the present-day radius (right model), viewed from the Indian Ocean. The globes show the "closure" of this ocean and the changes in the positions of continents relative to the South Palaeopole

Fig. 42. Maxlow's models of the expanding Earth (2001)

The colours of the stratigraphic units on the continents and ocean floors correspond with those in the Geological Map of the World (Geol. Map of the World, 1990; see Figure 38)

highly affected by the fact that the pra-Pacific, much larger than the recent Pacific Ocean, was illustrated on these reconstructions. Therefore, the results obtained by Weijermars (1986) are not convincing.

Scalera (1988, 1994) employed computer software for his unconventional reconstructions of Pangea on an Earth of changing radius. he reconstructed the position of the continents during the Archean (assumed radius value R = 3,500 km), Palaeozoic (R = 4,300 km) and Mesozoic (R = 5,300 km). He based this on data about the outlines of the tectonic plates and the areas of the different ages of the oceanic floor. The Archean reconstruction shows the significance of changes in the Earth's surface curvature, which are manifested by large shear zones and microblock rotations. As a result, not only the Arctic Ocean and the Mediterranean zone, but also the Indian and Pacific Oceans were reasonably well closed. The Pacific Ocean was closed by North America and Australia connected with Antarctica, which are in contact with South America along their present-day eastern edge. This reconstruction shows the following: (1) there is a constant close relationship through time between India and Eurasia and between Africa and Europe; (2) the Samfrau geosyncline (du Toit, 1937) stretches logically straight across the Gondwanian continents; (3) large, global shear zones between and within the continental blocks run along straight lines (e.g. the Tibet–Baikal–Lena line). For the subsequent reconstructions performed for Jurassic (R = 3800 km) and Cretaceous times (R = 4800 km), Scalera (1994) also used palaeogeographical data.

Maxlow made a series of 11 models of the expanding Earth, in 1:20,000,000 scale, which show the distribution of the continental blocks and oceans for the successive stages of the Mesozoic and Cenozoic evolution of the Earth. Individual models (terrellae) illustrate reconstructions for the following palaeomagnetic isochrones: M38 (205 Ma — early Jurassic), M29 (170 Ma — late Jurassic), M17 (144 Ma — early Cretaceous), M0 (119 Ma — middle Cretaceous), C34 (84 Ma — late Cretaceous), C29 (66.2 Ma — Palaeocene), C25 (59 Ma — Eocene), C15 (37.7 Ma — Oligocene, C6B (23 Ma — Miocene), C3A (5.9 Ma — Pliocene) and C0 (recent) (cf. Cwojdziński, 1998a, b). The idea of these models is simple: oceanic crust belts which were formed during the specified time period were successively removed from the surface of the globe, and the remaining portion of the continental crust, together with older oceanic crust, was distributed on a globe of calculated smaller radius. Maxlow's models (1995) enable the calculation of the so-called Earth's lithospheric budget on an expanding Earth. The plotted graphs of the increase in the area of the oceans through geological time, and the increase in the Earth's radius allow the extremely important conclusion to be drawn that the expansion of the Earth is an exponential function and that expansion did not begin during the Jurassic, when the first lithospheric fragments of the modern oceans appeared, but much earlier during the Proterozoic, about 750 My ago. The original pra-Earth's radius might have been as small as approximately 2,000 km.

Maxlow's models (1995) are an excellent basis for global palaeogeographical, palaeobiological and palaeotectonic considerations. They provide an overview of the scale of the expansion process, and permit the estimation of the role of regional and global shear zones associated with the rotations of the continents during the asymmetric expansion of the Earth. They also permit the evaluation of the scale of changes in the Earth's surface curvature, induced by its expansion.

Luckert (1996) is another author of an expanding Earth model. His model is a computer simulation presented as a video movie. It shows the continuous expansion of the Earth, viewed from several sides: the Atlantic, the Indian Ocean, the Pacific and the North and South Poles. Compared to the previous models, the Pacific area in this reconstruction is closed differently, and the main role is played here by Antarctica, which occupies the central area of Pangea relative to the present-day Pacific. The Pacific coasts of Antarctica adjoin both Americas. During the expansion of this ocean, Antarctica underwent a considerable left-lateral rotation; however that is not confirmed by any geological data. This lack of reference to the results of geological studies is the weakest point of Luckert's model.

Maxlow (2001) recently presented a new interpretation of geological data, constructing 24 models of the expanding Earth. These models show a configuration of geostructures from the Archean/Palaeoproterozoic transition to the Recent +5 Ma (Fig. 42). Pre-Triassic reconstructions, when the modern oceans existed as narrow belts of extending continental crust, were created by Maxlow (2001) through a gradual reduction in the areas of the intracratonic basins and large magmatic complexes. In this way, it was possible to calculate the Earth's original radius to be 1,700 km. This primordial Precambrian Earth represents a planet completely covered by a crust of contemporary Archean and Palaeoproterozoic cratonic centres. Maxlow (2001) assumes that the continental crust, like the oceanic crust, was produced through the lateral accretion of new, younger crust. However, the occurrence of numerous fragments of Precambrian rocks complexes, rejuvenated many times, within younger tectogens and in platform basements, rather suggests a model in which the Precambrian crust was the basement for many younger geostructures (e.g.: Krats, Zapolnov, 1982).

To sum up, the Earth's expansion modelling, regardless of the method used, permits the demonstration that the distribution of all of the continents on an Earth of smaller radius is not only possible but it provides a cohesive image consistent with many independent geological data. Simultaneously, reconstructions for the earliest periods, prior to the Mesozoic oceanic expansion, are possible only if the inner parts of the continents are deformed, allowing the accommodation of a greater curvature of the globe. Even a simple comparison of an expansion reconstruction with a plate tectonic reconstruction for the early Jurassic (Figs. 42, 43) indicates the simplicity of the former and the kinematic improbability of the latter. To maintain the constant size of the Earth, plate tectonic reconstructions must assume the existence of the pra-Pacific. As the Atlantic and Indian Oceans increased their areas, the pra-Pacific was subjected to a shrinking, despite the simulta-

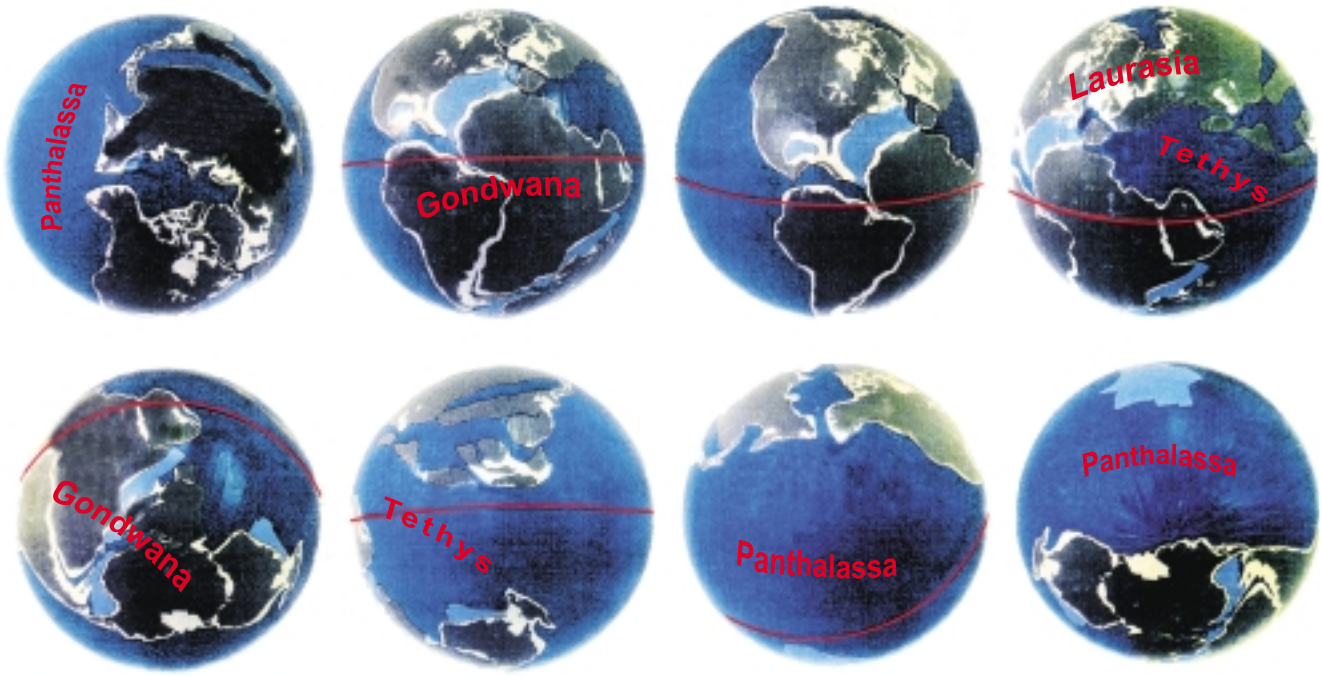

Fig. 43. A reconstruction of the continents' positions during the late Jurassic on a non-expanding Earth (after Scotese, 1994)

The continents are consolidated into a supercontinent corresponding to the All-Ocean of a size exceeding the present-day Pacific Ocean by approximately 30%. Between Laurasia and Gondwana, a clinoform Tethyan break resulting from an "orange peel" effect is visible. Apart from the fragments of late Jurassic oceanic lithosphere (light blue), the rest of the All-Ocean lithosphere would have to have been subjected to subduction during the last 180 My to maintain such a constant size of the planet. Individual drawings illustrate the distribution of continents and oceans viewed from different directions

neous spreading of the young, Mesozoic lithosphere in the centre of the pra-Pacific, coeval with the sea-floor spreading of the other oceans. No other currently acceptable mechanism of lithospheric plate drift can explain the possibility of such a radial expansion of the Pacific Ocean floor with simultaneous consumption along the ocean perimeter.

AN ANALYSIS OF THE POSSIBLE CAUSES OF THE EARTH'S EXPANSION

There has been a search for reasons for expansion ever since the theory was born. So far, the origin of this process is not known what causes that this idea is not accepted. The vicissitudes of Wegener's theory and its rejection for several tens of years by the geological community resulted from the lack of any convincing explanation of the origin of the supposed continental drift. Plate tectonics cannot explain the causes of geodynamic processes in the lithosphere either; however, most geologists consider that the idea of mantle convection currents (though variably understood) explains the origin of the lateral displacements of the lithospheric plates. Although many phenomena, recently observed at the Earth's surface (e.g the position of the mid-ocean ridge system around Africa and Antarctica, the location of hot spots), directly contradict the existence of such a system of convection currents (*vide*: Carey, 1976; Koziar, 1991a), followers of the plate tectonics theory consider this problem to be solved. There have lately been attempts to explain the discrepancies between the plate tectonic convection model and the tomographic image of the Earth's interior structure (e.g. Condie, 2001) through the transfer of the convection model into the inner zones of the Earth. However, the assumption of the two-layered convection model does not explain surface discrepancies, and the one-layer (all mantle) convection model cannot be reconciled with the existence of distinct seismic discontinuities occurring at a depth of 650–660 km (Condie, *op. cit.*).

The causes of expansion have been sought for over 100 years now. Two main research trends can be observed: searches for external (cosmic) causes; and terrestrial causes associated with the inner structure of the planet. The first concepts to explain the expansion process involved outgassing (Hixon, 1920) or radioactive heating of the Earth's interior (Lindemann, 1927; Bogolepov, 1930); since the 1930s the expansion idea has been based on a concept of the change in the gravitational constant of the Universe (Dirac, 1937, 1938). Since that time, many papers have been published by physicists and astronomers (e.g.: Brans, Dicke, 1961; Wilson, 1960; Ivanenko, Sagitov, 1961; Holmes, 1965; Jordan, 1966) postulating that the expansion of the Earth and other planets was caused by a decrease in the gravitational constant of the Universe. However, the calculations of followers of this concept indicated the very limited extent of such expansion. In the extreme case, Halm (1935) estimated that the Earth's radius has increased by approximately

1,000 km since the beginning of the geological evolution of the Earth. Most often, the values were considerably lower (e.g. Brans, Dicke, 1961 — 200 km during 4 Ga). Such results are contradictory with the observed rate of Mesozoic and Cenozoic oceanic lithosphere accretion. Therefore, as stressed by Białas, Klimek and Skarżyński (1976), other factors are needed to explain the rate of expansion.

The causes resulting from processes that occur inside the planet have usually been related to phase alterations within the Earth's core. Mouritsen (1976) considered that the inner core of the Earth can be composed of completely ionized atoms of star-core densities. Gradual phase alterations into atomic matter are associated with a considerable increase in volume. This process results in the expansion of the Earth group planets (not only the Earth alone). Similar views on the causes of expansion were postulated by Gorai (1984), who analysed the effects of phase alterations between the metallic phase of chemical elements (the loss of some electrons under very high pressure) and the normal oxide-silicate phase. He also assumed a pulsatory character of expansion, based on data which indicate the periodic nature of orogenic and tectonothermal processes. Pfeufer (1981, 1983, 1992) is also a follower of the theory of phase alterations; his are related to the Earth's rotation and the tidal influence of the Moon. In general, concepts related to cosmogonic changes of the G and phase alterations within the core/mantle system are sufficient to explain the causes of the slow and continuous expansion of the Earth (Hora, 1983; Weijermars, 1986), but they are insufficient to explain the expansion manifested by the Mesozoic and Cenozoic spreading of oceanic lithosphere.

An analysis of the increase in the Earth's radius indicates that this is a permanent process defined by an exponential function (Carey, 1976; Owen, 1983; Koziar, 1991a; Cwojdziński, 1991a; Maxlow, 2001). The expansion of the Earth must be accompanied by a continuous increase in its mass (Tassos, 1983b; Ivankin, 1990; Koziar, Ciechanowicz, 1993; Ciechanowicz, Koziar, 1994; Davidson, 1994; Maxlow, 2001). In the opposite case, the Earth's gravity (assuming constant Earth volume) would have been too high in the geological past to allow biological life-forms to exist. The evolution of expansion indicates the possibility of a gradual increase in the mass of the Earth as it expanded, since the surface gravity and angular momentum have changed insignificantly. The calculation of the principle physical parameters of the expansion process enabled Ciechanowicz and Koziar (1994) to postulate that the creation of matter in the Earth's interior is associated with the capturing of so-called dark matter by the iron-nickel core of the planet.

The idea of dark matter composed of weakly interacting massive particles (WIMP) has been broadly discussed by physicists (e.g.: Gould, 1987, 1988) for 10 years. Work on this idea is in progress. However, it seems that this is a promising research trend which can put forward cosmological theories in the close future.

Cosmological causes are also referred to by Tryon (1983) and Carey (1976, 1983b, 1988, 1996). The latter author refers to the idea of the so-called "null-Universe" theory, which implies a continuous creation of matter. Many modern physicists consider that such a process is possible. The quantizaized instability of space, which appears in time and space, may be the "creator" of the matter.

To summarize, the expansion process has not been explained by physics so far. However, the expansion parameters, obtained with the use of various independent research methods (the ocean floor spreading rate, satellite geodesy and palaeomagnetic studies), indicate that a process of creation of barionic matter which enables an increase in the planet's volume and mass goes on in the Earth's core. Carey (1976) puts the question: "What causes the Earth to expand?" And replies: "My first answer is I do not know. Empirically I am satisfied that the Earth is expanding".

Geoscientists are now faced with a historic chance, just like at the turn of the 19th century, when the geological data which indicated long duration of geological processes made physicists question the previous views on the origin of solar energy and the search for another theory. As a result, the process of nuclear and thermonuclear reactions was discovered at that time. Also today, geological data on expansion of the Earth and on the extent and character of this process can serve as an indicator for physicists that there are also unknown physical processes in nature. The first steps on this road have been taken (Koziar, Ciechanowicz, 1993).

PRESENT-DAY KNOWLEDGE ON THE EXPANDING EARTH THEORY

Research workers which have been concerned with the expansion of the Earth during the last 30 years form a small group of scientists from different countries and scientific centres. As geotectonics was becoming increasingly dominated by the plate tectonics theory and followers of this theory were taking various posts in committees and editorial boards of major periodicals, the possibilities of publishing papers which did not correspond with the dominant Dogma were reduced (cf. Carey, 1976, 1988). This is one of the fundamental reasons why expansionist papers have most frequently been published in minor domestic or regional periodicals. This is also the reason why there is nearly a complete lack of information on the expansion process among the world's geological community.

Since the turn of the 1950s, i.e. the moment when the modern version of the expansion theory was ultimately shaped, two main research areas have developed: on slow and on fast expansion. Followers of the former search for different "intermediate" or "mixed" hypotheses which prove the occurrence of expansion on a smaller scale, compared with expansion which results from simple interpretation of the evolution of modern oceans (e.g.: Gorai, 1984; Owen, 1983; Weijermars, 1986). They also sometimes make attempts to create hypotheses connecting the expansion of the Earth with lithospheric plate tectonics (e.g.: Barnett, 1969; Shields, 1990). Followers of the latter concept claim that all the modern oceans formed due to Mesozoic–Cenozoic expansion, and thus they assume that "oceanization" is a single process of the Earth's evolution, and calculate the resultant fast and exponential increase in the Earth's radius (e.g.: Carey 1976, 1983b, c, 1988, 1994, 1996; Koziar, 1980, 1985, 1991a, 1994; Vogel, 1983, 1990, 1994; Cwojdziński, 1991a; Chudinov, 1998; Maxlow, 1995, 2001).

In the late 1970s, the first complex expansion ideas were created. However, those were based on different premises. Mouritsen (1976) presented a hypothesis of crater fracturing tectonics which formed on the Earth (and the Moon) due to expansion. Gorai (1984) analysed the pre-geological, protoplanetary stage of the evolution of the Earth and compared its inner structure with the Moon's structure, coming to the conclusion that the original andesitic continental crust, which had formed a massive continental block before the Mesozoic–Cenozoic break-up, covered approximately 60% of the pra-Earth surface. The rest was represented by a basaltic pra-ocean. Gorai (1984) calculated the original Earth's radius at about 4,900 km; thus, the rate of expansion was obviously considerably lower than that resulting directly from the Mesozoic–Cenozoic expansion of the oceans. An interesting eclectic idea, involving the concept of the lateral drift of tectonic plates relative to their deep basement on the expanding Earth, was created by Shields (1990).

Of fundamental significance for the expanding Earth theory and for arguments in favour of this theory were several international symposia devoted to these problems. The first symposium was held in 1981 in Sydney. Its aftermath was a volume entitled *The Expanding Earth. A Symposium* (Carey, 1983d). That year, another conference devoted to problems of expansion and the pulsatory evolution of the Earth was organized in Moscow by Milanovskiy (1984). Both these conferences enabled an open discussion between expansionists and followers of the plate tectonics theory, and contributed to the integration of the environment of expansionists, and to the creation of closer contacts between them. Not much later, Chudinov (1985) presented an original eduction theory. The eduction hypothesis principles, along with detailed characteristics of Benioff seismic zones, were later published by Chudinov (1998) in English. Coming from data on the structure and age of the oceanic crust along active continental margins, he created an idea of the outflowing of mantle matter from beneath the edge of continents in the places where the plate tectonics theory assumes the occurrence of subduction zones. Therefore, according to that author, the expansion of the Earth is recently manifested by the accretion of new oceanic crust (lithosphere) not only in ocean-floor spreading zones but also in eduction zones. The eduction hypothesis is a good explaination for a range of geological and geophysical features of active continental margins, in particular in those zones where the rejuvenation of the oceanic crust has been proved to occur: towards a deep marine trench in the northern Japanese Islands–Kurils, along the Aleutes and the Sunda Trench (Geological Map of the World, 1990; Chudinov, 1985, 1998).

In 1990, a two-volume report entitled *Critical aspects of the plate tectonics* (Barto-Kyriakidis, 1990) was published. It includes several tens of papers presenting critical opinions on individual aspects of plate tectonics (e.g.: Krayushkin, Shapiro and Ganelin, Kiskyras, Medina Martinez). There are also papers showing alternative theories, including the expansion theory (Neiman, Vogel, Scalera, Ivankin, Strutinski). Although this work is characterized by a great thematic variability, it provides a broad review of the weak points and discrepancies in plate tectonic interpretations, allowing the conclusion to be drawn that modern geotectonics, dominated by the plate tectonic Paradigm, is in stagnation.

As the aftermath of the participation of expansionists in the international conference on new frontiers of physics in Olympia, Greece, in 1993 (Cwojdziński, 1994), a series of papers was published in the volume *Frontiers of fundamental physics* (Barone, Selleri, 1994).

The theory of the expanding Earth is being developed today in several scientific centres throughout the world, mainly by individual geologists or geophysicists. The fact that this theory is not commonly accepted or even discussed, despite significant geological arguments, results not from some inherent flaw in the theory, but from the psychology of the establishment. Actually, there is no discussion between expansionists and plate tectonicians today. It is obvious that this situation does not positively influence the development of geology as a science (Cwojdziński, 2001).

In conclusion, it should be said that the modern theory of the expanding Earth very logically links geological and geophysical data from the continents and ocean floors. According to the Okham's razor principle, this theory does not rely on assumptions but draws direct conclusions from observations. Most of the modern geodynamic processes indicate that rapid expansion of the Earth is a real process. The expansion process is obviously best visible on oceanic structures, but the continental lithosphere has also been shaped by the expansion of the Earth's interior, and is now subject to a continuous remodelling by this process. The continental lithosphere has been permanently affected by two processes: (1) the isotropic extension of its basement (Koziar, 1994); and (2) the constrained change in the Earth's curvature. Both of these factors greatly affect the evolution of the Earth.

THE CHANGE IN CURVATURE OF THE CONTINENTAL LITHOSPHERE — THE GEOLOGICAL CONSEQUENCES

THEORETICAL BASIS OF THE PROCESS

The smaller the diameter of the Earth, the larger the surface curvature. As the planet expands, the curvature must decrease. The amount of change in the curvature of the expanding Earth depends primarily on the rate of expansion. The simplest way to estimate it is a method employed by Hilgenberg (1933) and Vogel (1983, 1990, 1994), which relies on the fitting of all the modern continents on a sphere of smaller diameter so that all of the Mesozoic and Cenozoic oceanic structures are closed, and the subsequent calculation of the radius of the obtained terrella. This method yields the following results: R (for 180 Ma) = 3,509 to 3,830 km, i.e. 55 (Vogel *op. cit.*) and 60% (Hilgenberg, 1933) of the present-day Earth's radius, respec-

tively. However, this method is based on the assumption that the continental lithosphere had not been subjected to extension before the oceans formed or at the same time. Meanwhile, mantle diapirism and its crustal equivalents (granitogneiss domes), Proterozoic greenschist belts, rifting zones, and Palaeo-, Meso- and Cenozoic aulacogens, as well as intracratonic basins on Precambrian platforms, ophiolitic complexes and trap extrusions indicate that extension on continents occurred as long ago as the early Precambrian. These show that expansion of the Earth is much older than the oceanic spreading that has lasted for 180 Ma. The answer to the question how the expansion of the Earth proceeded — by a uniform increase in the Earth's size through geological time (Egyed, 1960), as a pulsatory process (Kremp, 1990, 1992), or as a process defined by an exponential function in time — can be found by analysing the values of the ages of ocean floors, confirmed by the results of different independent methods (including drilling data concerning sedimentary rocks and the so-called second layer of the oceanic crust). The isochrones of the world's ocean floor allow the oceanic area that formed through a specified time period to be calculated (Fig. 38). These, in turn, enable the calculation of the radius for a sphere of a given area. The obtained curves of the increase in Earth's radius are defined by an exponential function in geological time (Koziar, 1980; Cwojdziński, 1991a; Ciechanowicz, Koziar, 1994) (Fig. 44). Obviously, the main problem relates to estimates of the rate of this increase during the pre-oceanic period. It partly results from the shape of the curve obtained for Mesozoic and Cenozoic times, and its image if drawn back to the Palaeozoic. Undoubtedly, this curve flattens out, suggesting an increasingly slower increase in the planet's size back in time. Blinov (1983) mathematically calculated the Earth's dimensions for particu-

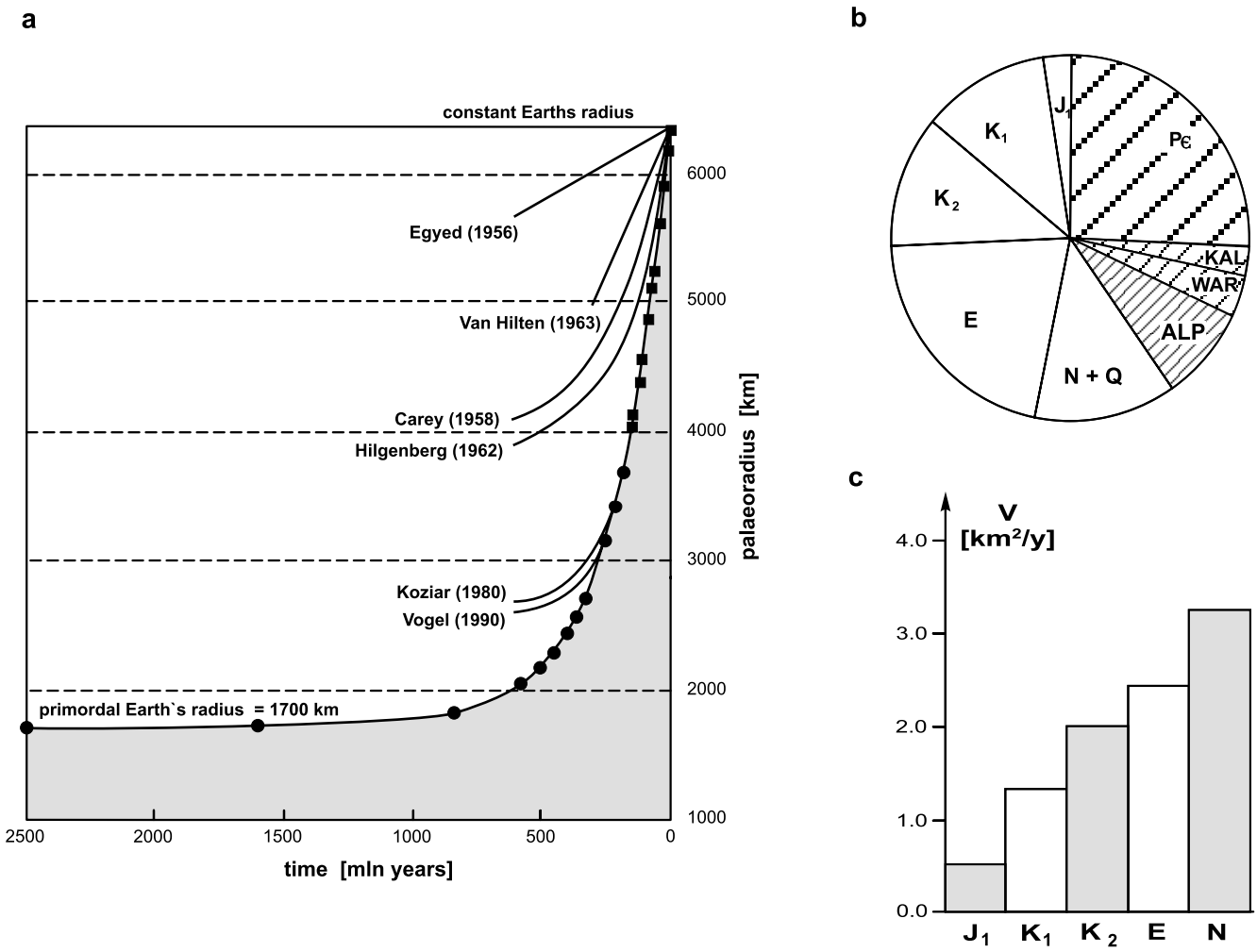

Fig. 44. A graphic illustration of the expansion of the Earth

a — a graph of the exponential increase in the area and radius of an expanding Earth after Maxlow (2001, courtesy of the author); apart from a graph of changes in the Earth's radius from the Archean until recent, there are also graphs of changes in the Phanerozoic palaeoradius postulated by other authors; **b** — a circle diagram illustrating the quantitative contribution of oceanic and continental crust of different ages; **c** — a histogram of the increase in the Earth's surface area from the late Jurassic until recent; **continental crust**: P — Precambrian crust, KAL — Caledonian-deformed crust, WAR — Variscan-deformed crust, ALP — Alpine-deformed crust; **oceanic crust**: J_3 — late Jurassic, K_1 — early Cretaceous, K_3 — late Cretaceous, E — Palaeogene, N+Q — Neogene and Quaternary

lar periods, starting from parameters characteristic of this curve, and gave the following values for the Earth's radius:

Precambrian (600 Ma) — 2296 km; Cambrian (550 Ma) — 2551 km; Ordovician (463 Ma) — 2933 km; Silurian (415 Ma) — 3189 km; Devonian (375 Ma) — 3380 km; Carboniferous (313 Ma) — 3763 km; Permian (255 Ma) — 4145 km; Triassic (205 Ma) — 4528 km; Jurassic (158 Ma) — 4911 km; Cretaceous (99 Ma) — 5357 km; Tertiary (51 Ma) — 5867 km.

Estimates of the Palaeozoic and Precambrian Earth's dimensions can also be based on a method of the gradual removal of continental spreading areas, in order to better match the various fragments of the continental lithosphere.

Following this method, individual scientists came to the following results: for 600 Ma, R = 2850 km (Koziar, 1980); or R = 2,800 km (44% of the present-day radius) (Vogel, 1990); for 1700 Ma, R = 2,500 km (40% of the present-day radius); and for 2700 Ma R = 2,345 km (36.85% of the present-day radius) (Kremp, 1990). Maxlow (2001) recently reconstructed the expansion process back in time to Archean–Palaeoproterozoic times and obtained values of the Earth's palaeoradius during individual periods of the geological past (Tab. 1). The original radius R = 1700 km corresponds to the Earth covered exclusively by Archean–Palaeoproterozoic cratonic crystalline continental basement. However, Maxlow (2001) did not take into account that part of the old Precambrian continental lithosphere, included in younger Proterozoic and Phanerozoic orogenic zones, underwent processes of tectonothermal rejuvenation. Therefore, these data on the original Earth's radius represent extreme values. According to me, the exponential character of the increase in oceanic area during Mesozoic and Cenozoic times, and the nature of late Precambrian and Palaeozoic geological processes indicate that the expansion of the planet commenced during the late Precambrian, with a slow phase of expansion that continued throughout the entire Palaeozoic. The original Earth's size was probably about 2,500–2,800 km, including areas of extending continental lithosphere on continental margins and also within the continents.

The above facts show that the results of estimates differ insignificantly, in particular for Phanerozoic palaeoradii. Different views are put forward by followers of slower expansion. Hilgenberg (1962, 1973) calculated the Earth's palaeoradius on the basis of palaeomagnetic data and obtained lower results of R = 4,018 km for the late Precambrian. However, he did not take into consideration data on the rate of oceanic spreading. According to Gorai (1984), the original Precambrian Earth's radius was 4,900 km (77% of the present-day radius), i.e. as much as the present-day radius of the outer Earth's core. Owen (1983) claimed that the original Earth's radius was 5,102 km (80% of the present-day radius). However, each of these authors made an incorrect assumption inconsistent with the present-day knowledge on oceanic floors.

An increase in the Earth's radius obviously implies a decrease in the Earth's curvature. The magnitude of this phenomenon is illustrated in a two-dimensional cross-section (Fig. 45), beginning with a palaeoradius which accounts for 63% of

Table 1

Values of the Earth`s palaeoradius after Maxlow (2001)

Maxlow`s model number	Geological age (era and period)	Age (Ma)	Paleoradius of the Earth (km)
1	Archean to Mesoproterozoic	1600	1703
2	mid Neoproterozoic	850	1799
3	late Neoproterozoic	700	1895
4	late Neoproterozoic	600	2007
5	Cambrian	565	2060
6	mid Ordovician	455	2293
7	mid Silurian	420	2395
8	early Devonian	380	2533
9	late Devonian	360	2612
10	early Carboniferous	320	2794
11	early Permian	260	3136
12	Triassic	245	3237
13	Isochron M34 – early Jurassic	205	3543
14	Isochron M29 – late Jurassic	160	3960
15	Isochron M17 – early Cretaceous	144	4130
16	Isochron M0 – mid Cretaceous	118	4435
17	Isochron C34 – late Cretaceous	84	4891
18	Isochron C29 – Palaeocene	66	5162
19	Isochron C25 – Eocene	59	5274
20	Isochron C15 – Oligocene	37	5649
21	Isochron C6B – Miocene	23	5908
22	Isochron C3A – Pliocene	6	6245
23	Isochron C0 – recent	0	6370
24	future	+5	6478

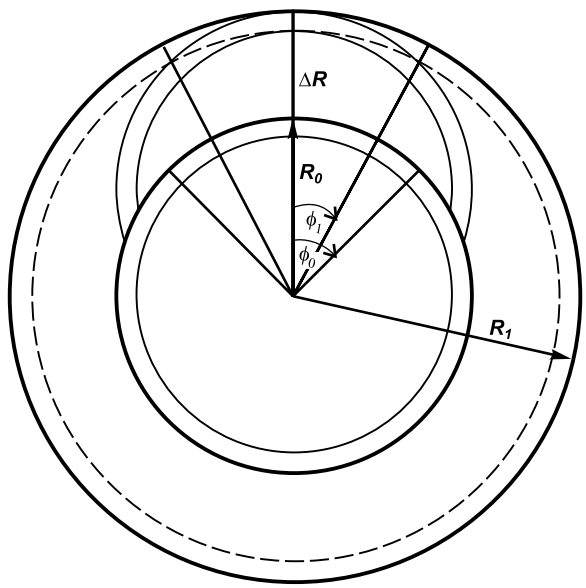

Fig. 45. A graphic illustration of changes in the Earth's curvature during expansion, starting with an original radius = 63% of the present-day radius and ending with the recent size

R1 — present-day Earth's radius, R0 — late Jurassic radius = 63 % R1, ΔR — increase in radius length over 180 My, ϕ_0 and ϕ_1 — angles showing the change in curvature of an expanding Earth; these angles correspond to arc distances on surface of a globe of diameters R0 and R1

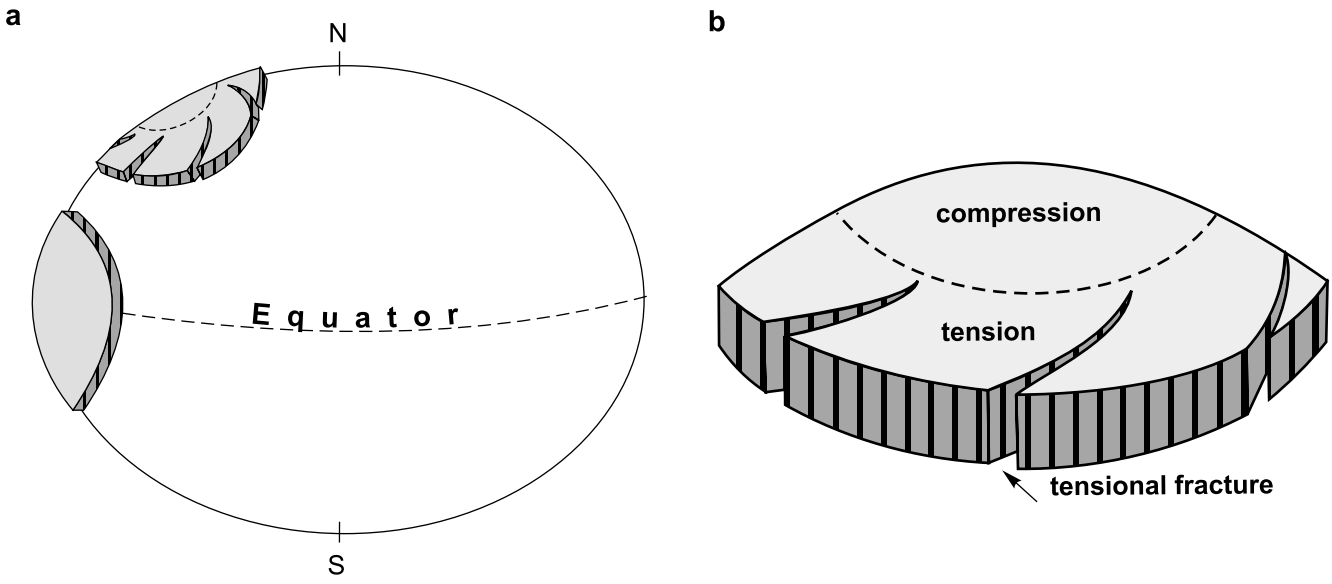

Fig. 46. A scheme of flattening deformations, after Turcotte and Oxburgh (1973; supplemented)

a — the explanation of membrane deformations on a non-expanding Earth; **b** — a block diagram illustrating the distribution of different types of deformation within a plate undergoing a flattening process

the present-day radius. Regardless of how great the original Earth's size is assumed to have been, changes in the surface curvature play an important role and must significantly affect the evolution of lithosphere and, therefore, produce a range of structures within it, which are genetically related to this process. Obviously, this process is the longest and most intense in the continental lithosphere, due to its rheologic properties and thickness. However, the process also occurs in the lithosphere of the modern oceans.

A gradual decrease in the Earth's surface curvature as the radius increases induces various stresses in the lithosphere. These stresses are responsible for tectonic deformations in the upper mantle and the Earth's crust. They are mostly represented by the so-called intraplate deformations, very poorly examined by the plate tectonics theory, and commonly genetically related to mantle plumes and hot spots. The plate tectonic equivalent of these flattening deformations is the theory of membrane tectonics developed by Turcotte and Oxburgh (1973, 1976). The idea of membrane tectonics was applied to calculate stresses within a elastic lithospheric plate whose geographic coordinates change due to a drift on an ellipsoidal globe. Turcotte and Oxburgh (1973) introduced the term "non-spherical plate tectonics" and noted that many intraplate deformations do not correspond to those interpreted to occur along the so-called active (subduction and collisional deformations) and passive (riftogenic deformations) plate margins. Having related them with the above-mentioned process, those authors derived equations based on the so-called Novozilov membrane theory. These equations define the stress pattern within an oval, elastic and spherical plate, subjected to a flattening. Weijermars (1986) developed and applied these equations to an expanding planet. A graphic scheme (Fig. 46) explains how membrane stresses are formed within an oval plate due to the increase in the Earth's radius. Turcotte (1974) proposed mathematical equations to calculate membrane stresses in two perpendicular directions, i.e. the radial membrane stress and the tangential membrane stress when the modulus of elasticity is known. Weijermars (1986) transformed these equations, applied them to the case of radial expansion, and calculated the values of membrane stresses for fragments of the continental crust subjected to straightening according to expansion models of Owen (1983), where Rt = 0.8 Rw, and of Carey (1976), where Rt = 0.63 Rw (Rt = 4,000 km). For both of these cases, the possible range of stress values varies between 1,000 and 10,000 MPa, i.e. the stress significantly exceeds the strength of the rigid upper parts of the lithosphere (continental crust), estimated at 500 to 800 MPa (Goetze, Evans, 1979). Further transformations of these equations permitted the determination of the minimum diameter of the crustal fragments which remain unfractured due to the expansion of the planet. The values for the models of Owen and Carey are 80 and 52 km, respectively. The calculations are correct if an assumption is made that the entire continental crust is brittlely deformed; in this situation, the expansion of the planet's interior should lead to the homogenous dispersion of continental lithospheric fragments on the surface of a radially expanding Earth. In fact, expansion is asymmetric (Carey, 1976). Wejiermars (1986) also analysed the behaviour of the deformed water-saturated quartzites (representing the continental crust) under different temperatures and stress increase rates, as well as the resulting character of those deformations under slow and fast expansion. These analyses show that the continental crust is brittlely deformed down to a depth corresponding to a temperature of approximately 300°C, but at deeper depths, it is ductilely deformed. The boundary between brittle and ductile deformation depends on the thermal conditions and the petrographic composition of the crust, i.e. on its rheologic properties. The upper mantle, at least to a depth of considerable plasticization of the rock mass where

thermal processes and flow deformations become dominant, is also subject to flattening deformations. The expansion of the Earth must give rise to both brittle and ductile deformations. Turcotte and Oxburgh (1973) claim that tension fractures, with radial compression in their centres (Fig. 46), must appear at the margins of oval plates subject to a decreasing curvature. In the vertical section of a flattening crust, compression should also be a dominant factor in its upper portion, at least to the point of exceeding the internal strength of the continental crust, when its fragments move apart through the processes of rifting and ocean-floor spreading. In the lower continental crust, the dominant deformation tends to be extensional.

The ductile extension of the lower continental crust must accommodate a considerable increase in Earth's surface, although not so much as that assumed by Weijermars (*op. cit.*) — i.e. the increase by 60% in Carey's model, since part of the processes of adjustment to a smaller curvature also occurred at deeper lithospheric levels, in the upper mantle. Having analysed lithospheric stresses, Weijermars (1986) came to the conclusion that without inner deformations of the continental crust (the lithosphere) on the expanding Earth, the continents would have lost contact with the mantle basement. Simultaneously, the existence of "cool and rigid" mantle roots beneath the continental masses (Woodhouse, Dziewonski, 1984; Dziewonski, Woodhouse, 1987 and others) indicates that, despite the process of flattening of the globe's outer zones, the continents have not lost the contact with the deeper basement (Fig. 30). If this is so, it means that the entire continents are subject to heterogenous deformations which must also affect their shapes as expansion accelerates.

An analysis of the theoretical consequences of the Earth's expansion shows that one of these is huge stresses within the lithosphere, resulting from lithospheric flattening due to the "swelling" of the Earth's interior. These various stresses are responsible for the extensional, compressional and shear deformations at different crustal and upper mantle levels.

THE EFFECT OF THE DECREASING CURVATURE OF AN EXPANDING EARTH ON GEOLOGICAL PROCESSES — THE DEVELOPMENT OF VIEWS

The change in the surface curvature of an expanding Earth and its effect on geological processes has been poorly recognized. Followers of the expansion theory have shown little interest in this problem. Most of them have searched for the cause of tectogenesis and orogeny in diapiric processes and so-called vertical tectonics. Indeed, diapiric and secondary (in relation to vertical movements) orogens and gravity deformations on diapir slopes are perfectly documented (e.g. De Jong, Scholten, 1973), and can be excellently applied in the expansion theory (Carey, 1976; Koziar, Jamrozik, 1985; Jamrozik, Koziar, 1986; Ollier, 1990; Ahmad, 1990, Saxena, Gupta, 1990 and others). According tothe present author, there are many tectonic processes genetically related to the process of lithospheric flattening on an expanding Earth. The effect of a decrease in the Earth's curvature on tectonic processes can be studied from the point of view of the above-discussed modellings of the Earth's expansion; as the radius of Earth's models decreased, their authors were forced to assume increasing rotations and deformations along continental margins to obtain a gradual closure of the modern oceans and to distribute the continents logically.

Hilgenberg (1933) proposed an idea of the effect of a decrease in the Earth's curvature on tectonic processes within the Earth's crust. He considered this process (Fig. 47a) to be the major one causing the formation of fold mountains. In his model, fold-and-thrust deformations occur within the upper crust of "flattened" continents, whereas the lower crust is the zone where extension is dominant and the magnitude of extensional stresses increases downwards. According to Hilgenberg (1933), this extension results in the formation of huge fractures which are penetrated by mantle material. As the flattening process continues, these fractures can transect the entire crust, giving rise to basins, ridges and rift zones. Hilgenberg obviously considered the entire Earth's crust to have been a brittlely deformable rigid layer.

The relaxation of the lithospheric curvature of an expanding Earth was analysed by Rickard (1969), who made attempts to join the theory of the formation of geosynclines and geosynclinal orogens with the process of change in the Earth's surface curvature. He considered the continental crust to represent a geozone deformed brittlely as a whole, and rejected the earlier suggestions of Van Hilten (1963) and Creer (1965) that the adjustment of continents to a new Earth's curvature is a continuous process that proceeds through plastic flow and fracturing. As the curvature of the expanding Earth decreases, continental plate fragments keep their former curvature for a certain time and form, according to Rickard (1969), domal structures along margins in which down-buckles of the basement develop to form geosyncline-like basins rapidly filled with deposits derived from uplifted continental margins (Fig. 47b). In this model, the origin of geosynclinal troughs is associated with the radial expansion of the Earth's interior. Low velocity zones, favouring the development of mantle diapirism and rifting, form in the centre of the domal elevation. The simultaneously expanding mantle tends to balance the curvature; the horizontal shear stresses which accompany this process are responsible for both the formation of seismic zones along continental plate margins and the compressional stresses that appear during the final stage of orogeny. In Rickard's model (1969), the basic hypothesis of vertical tectonics and gravitational deformations on orogenic diapir slopes is augmented with an idea of lateral push by the continental crust due to its decreasing curvature. These processes result in a gradual adjustment of the continental plate to a new, smaller curvature of the Earth.

Veselov and Dolitskaya (1984) studied the effect of curvature changes of a "swelling" globe on geological processes. Those authors concluded that this effect was particularly intense during the Precambrian, when crustal elements were highly mobile. A breakup of the original crust into blocks which often retained their former curvature and formed domal structures, conditioned the intensity of sedimentary and volcanic processes in zones located between these blocks. The adjustment of the blocks to the new curvature generated compressional stresses causing the zones situated between them to be

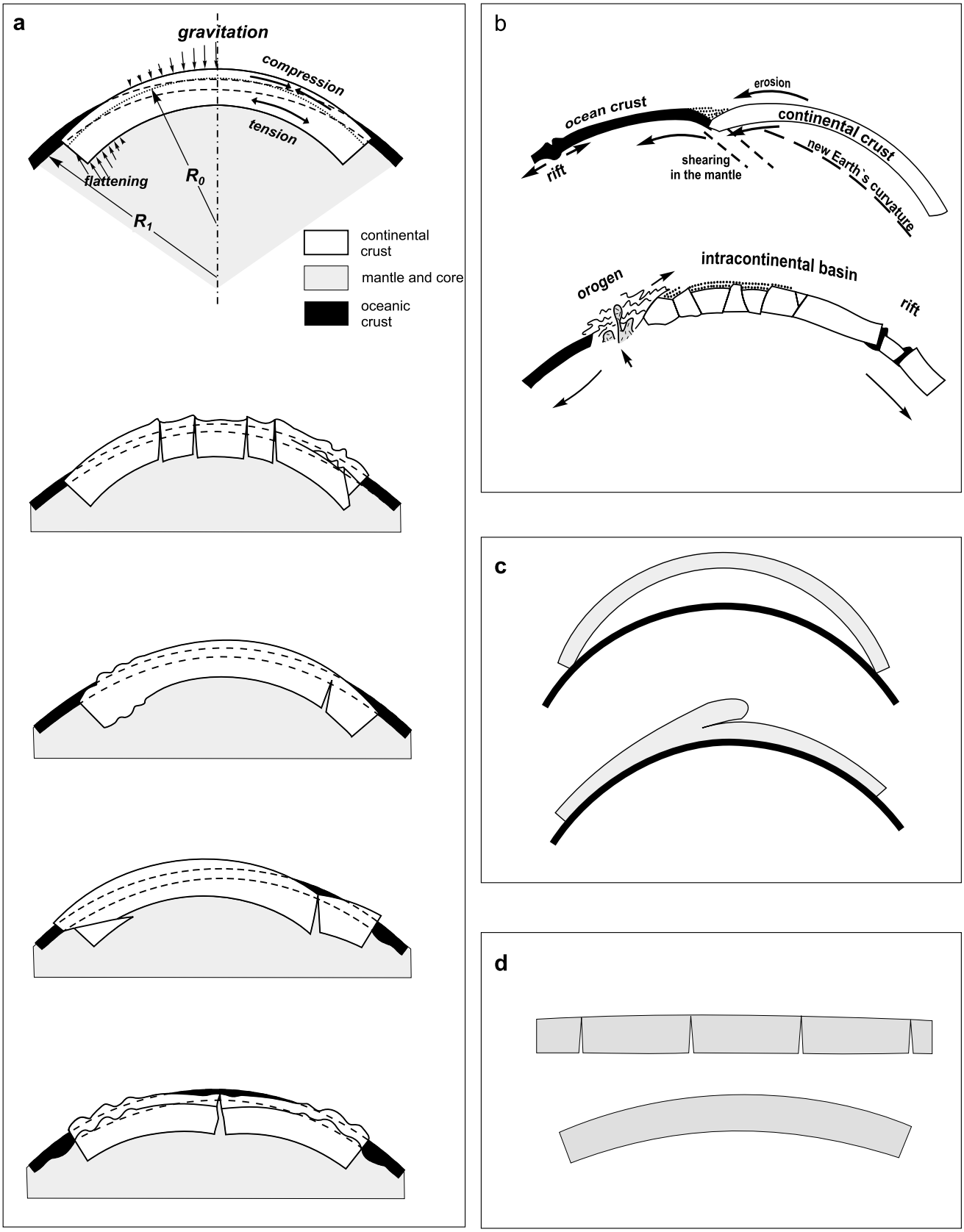

Fig. 47. The effect of the curvature changes of the expanding Earth on tectonic processes within the continental lithosphere

a — after Hilgenberg (1933): this drawing shows the distribution of stresses resulting from the gravity-induced flattening process; compressional stresses dominate in the upper crust, extensional processes in the lower crust; the other drawings show crustal deformations resulting from the decreasing curvature of an expanding Earth; **b** — after Rickard (1969): the formation of a geosyncline and its transformation into an orogen at the margin of a flattened continental plate; **c** — after Jordan (1971): the formation of a "pinch" orogen; **d** — after Carey (1983c): the formation of a basin and swell pattern due to a gradual, gravitational adjustment to a new, smaller curvature

folded. As expansion continued and the lithospheric thickness increased, tectonic processes were limited to narrow mobile zones of rift systems, oceanic trench/island arc/marginal basins systems, etc.

A similar model of the deformation of rigid continental plates was postulated by Jordan (1955, 1971), who, referring to a graph scheme of Matchinski (1953, *vide* Jordan, 1971), claimed that the decrease in surface curvature might result in the formation of fold mountains (Fig. 47c). Jordan (1971) also applied the term "pinch folding", which was earlier introduced by Haber (1965). Dooley (1973, 1983), however, opposed Jordan's views. He estimated that the vertical adjustment of continental plates (which remained their former, greater curvature) to a new curvature should result, during the last 200 My, both in subsidence that would amount to tens or even hundreds of kilometres in the central parts of old Precambrian platforms, and in the formation of considerable positive gravity anomalies visible in the recent image. Considering the example of Australia, he stated that there is a lack of evidence for such a huge process of adjustment to a smaller Earth's curvature.

The Rickard–Jordan concept, in particular the assumption of permanent continental plate deformations and mid-craton elevations, was also criticized by Carey (1976, 1983c). According to Carey (1976, 1983c), the rapid compensation of isostatic heterogeneities of the asthenosphere prevents the formation of superelevations such as those assumed by Rickard (1969). However, megatumores can be formed at those parts of the continental plates which are subject to bending due to the change in Earth's curvature. Carey (1983c) also rejected Dooley's (1983) arguments. Referring to data on the relaxation of tectonic stresses within the subcrustal upper mantle, he claimed that the maximum time of adjustment to a new curvature does not exceed 100,000 years, i.e. it is so short that it cannot result in the deformations analysed by Dooley (1983). According to Carey (*op. cit.*), a decrease in the Earth's curvature which is not accompanied by an increase in the area of the flattening element does not cause residual doming, which, moreover, cannot form due to gravity constraints. The features which are related to a change in curvature are represented on the Earth's surface by large polygonal structures — basins and swells (Fig. 47d). The radial expansion of the Earth is primarily manifested by the occurrence of 8 first-order global polygons on the Earth's surface, which are delineated by the oceanic rift system (Carey, 1976). Each of these polygons contains a continental core in its centre. These polygons have increased their areas since the Palaeozoic. This is an additional argument for the expansion process. The first-order polygons cover the entire Earth's mantle. Each of these polygons includes a number of shallower second-order polygonal structures, up to several hundreds of kilometres in diameter, as well as third-order polygons, tens of kilometres in diameter, etc. Carey (1976, 1983c) is of the opinion that the hierarchal pattern of polygons, with its dense grid of fractures transecting all of the geological structures, is a result of flattening deformations accompanied by a permanent radial extension of both the continental and oceanic lithospheric basement. Thus, Carey (1976) rejected the possibility of compressional stresses related to lithospheric flattening.

A similar adjustment process was assumed by Mouritsen (1976) in his idea of crater tectonics. This adjustment relies on the gradual formation of "crater" structures — oval in cross-section — which are a surface response to the development of a system of oblique fractures, so-called "fracture splay", inside the Earth. The density of these fractures increases in the outer geospheres, and on the surface of the outermost one the fractures form overlapping oval structures of different diameters represented by island arcs, arched mountain belts, arched continental margins, etc. According to the depth to which these fractures penetrate the planet, these arcs represent either shallow structures of small sizes (up to 350 km) or deep structures that reach the mantle/core boundary and significantly influence the present-day image of the continental plates and oceans. In this hypothesis, the gradual development of fault structures allows the outer geospheres to be adjusted to a smaller curvature, and on the other hand, it controls geological processes such as riftogenesis, mantle diapirism and orogeny.

A horizontal adjustment to the smaller curvature is also manifested by the rotations of continental blocks and their fragments (cf. Carey, 1976). Such rotations are evidenced by palaeomagnetic investigations. However, contrary to the plate tectonics theory, which explains such movements as the result of displacements of continental lithosphere fragments (terranes) upon the astenospheric basement, the expansion theory considers these movements to be an effect of spherical force to adjust to a greater curvature of the expanding sphere. This process was termed by Van Hilten (1963) the "orange peel" effect (Fig. 48), and it is responsible for the formation of sphenochasms — triangular breakups of continental plates being "filled" with newly formed oceanic lithosphere (Carey, 1958, 1976). The origin of rapid torsions of foldbelts (oroclines), which are often contemporary with deformation processes, is associated with sphenochasms. These torsions form during the opening of sphenochasms and the rotation of continental fragments (Carey, 1958, 1976; Rickard, 1969). The major sphenochasms that control the course of foldbelts are the Bay of Biscay, the Tyrrhenian and Ligurian seas, the North Atlantic, the Indian Ocean and the Tassman Sea. Structures genetically related to sphenochasms are also represented by great regional shear zones, commonly transecting entire continents. Shear processes have been particularly well explored since the 1980s, and are now considered to be one of the most frequent types of deformations of the Earth's crust. Compressional folds (Strutinski, 1990, 1994), pull-apart basins and a range of complex tectonic structures (Carey, 1976, 1996) are associated with great shear (torsion) zones. Shear zones are also a sign of the adjustment of the lithosphere to a new Earth's curvature. Regional analyses of the evolution of orogens on an expanding Earth indicate a great role of deformations which result from the flattening of the continental lithosphere. Such an analysis for the Mediterranean Alpides was performed by Koziar and Muszyński (1980), Chudinov (1980, 1985), and for Central Asia — by Crawford (1983). The asymmetric expansion of the Earth relies on the very rapid growth of a new lithosphere in the Southern Hemisphere, resulting in a seeming shortening and the bringing of continents located in the Northern Hemisphere closer to each other, and also in the develop-

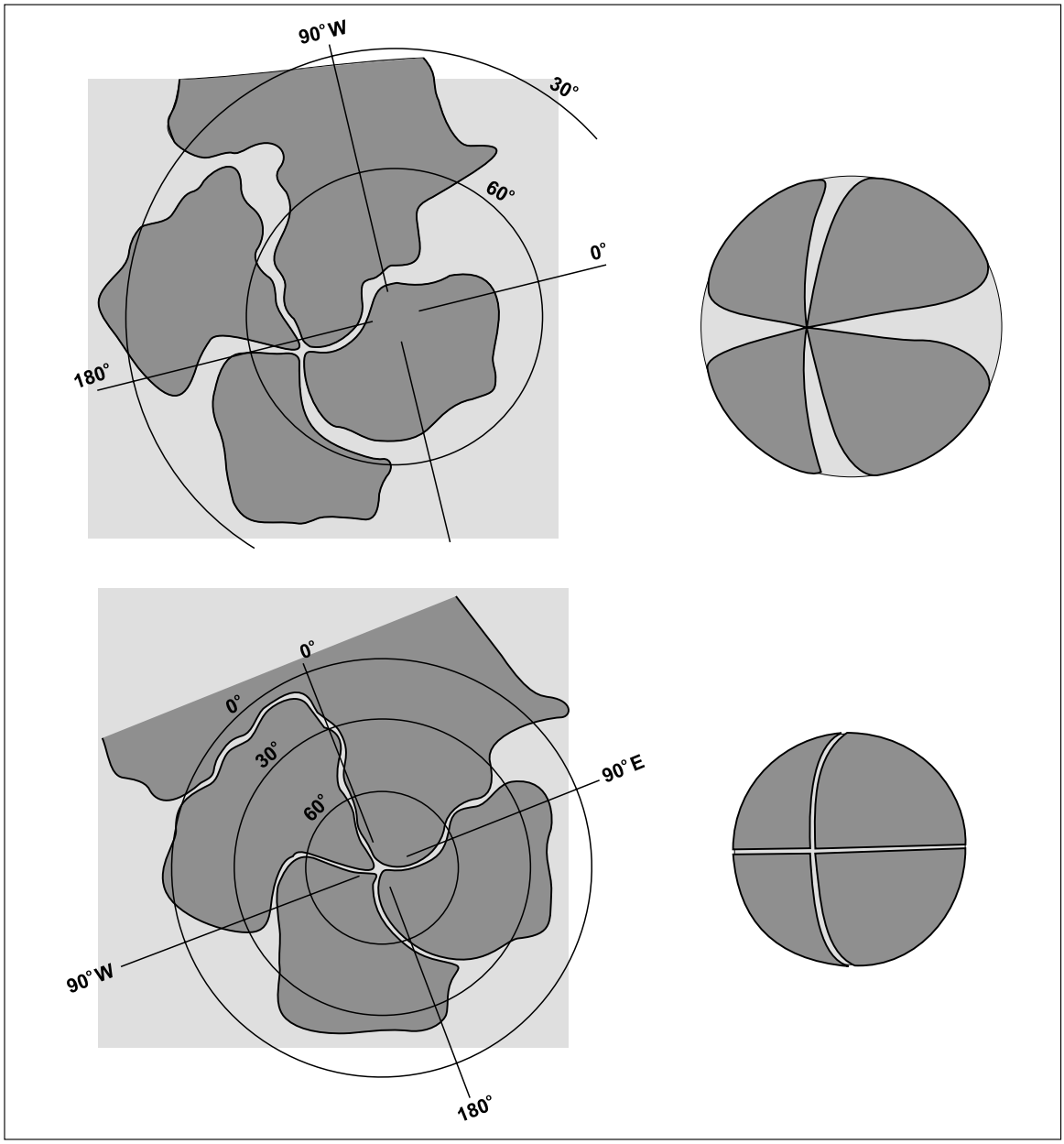

Fig. 48. A scheme explaining the "orange peel" effect, exemplified by the Gondwanian continents and interpreted by Koziar (1991b; simplified)

ment of huge global shear zones that controlled the evolution of Alpine orogens. This process is represented by the sinistral rotation of Europe, relative to Africa, which is confirmed by palaeomagnetic investigations (cf. Koziar, Muszyński, 1980), and results in offset rotations of smaller lithospheric blocks, giving rise to fold deformations and the opening of pull-apart basins underlain either by oceanic crust (e.g. the Tyrrhenian and Ligurian basins) or by thinned continental crust (e.g. the Pannonian, Egean and Po basins). The mosaic structure of Central Asia (Crawford, *op. cit.*) has also been shaped out by a system of major fracture zones and a varied gravity subsidence rate of blocks that resulted in a flattening of this largest continental plate due to the rapid spreading of the Indian Ocean.

Owen (1976, 1983) and Scalera (1988, 1990b) also analysed the effect of curvature changes on the shape of the continents, using various cartographic projections and computer software. Owen's reconstructions (1976, 1983) were made for the Earth's radius = 80% of the present-day radius, and they show that the matching of present-day continents on an Earth of smaller size eliminates the gaps and overlaps that appear on reconstructions that ignore changes in the Earth's radius. Simul-

taneously, flattening deformations are manifested by the extension of continental margins and their breakup into small lithospheric blocks, as evidenced from these reconstructions. These structures are represented, for example, by the extensional structure of southernmost South America, the complex structure of the Sunda Archipelago and the area of Middle America.

Considerable distortions in the shapes of the continents are necessary to close Pangea on an Earth's radius = 3,500 km, the value assumed by Scalera (1988) for the Archean. If such distortions are not assumed, false and unreal gaps between the continents appear. But if we take into consideration great shear deformations and the rotation of microcontinents, we can obtain excellent reconstructions which additionally correspond to the terrane idea recently developed by plate tectonicians (cf. Howell, 1993). It should be added that Scalera (1988) does not take into account inner continental deformations.

Scalera's Pangea model (1990a) is consistent with data on the directions and distances to the Earth's palaeopoles during the Palaeozoic. He also considered the origin of propagating volcanic zones on oceanic floors, and concluded (Scalera, 1991) that the zones are the result of the fracturing of the oceanic lithosphere, caused by the process of adjustment to a smaller Earth's curvature. Chudinov (1976) estimated the compressional stresses which are genetically related to lithospheric flattening. The expansion of a planet's interior results in the fragmentation of the outer geosphere (crust). Due to the effect of gravity, the crustal fragments adjust to a new curvature and the process gives rise, according to Chudinov (1976), to elastic deformations and subsequently, to the formation of horizontal compressional stresses. According to Hilgenberg's model, the estimates of these stresses, performed for a Baltic Shield-sized spherical fragment of the continental crust which was subject to a change in curvature during the last 40 My (change in the Earth's radius from 6,100 km to 6,360 km, assumed modulus of resilience = 1 Mbar), would give a value of 900 kg/cm^2. The real horizontal compressional stresses, measured in the upper crust, range from 600 to 800 kg/cm^2. The similarity of these values speaks in favour of the idea that the flattening process exerts an effect on tectonic processes.

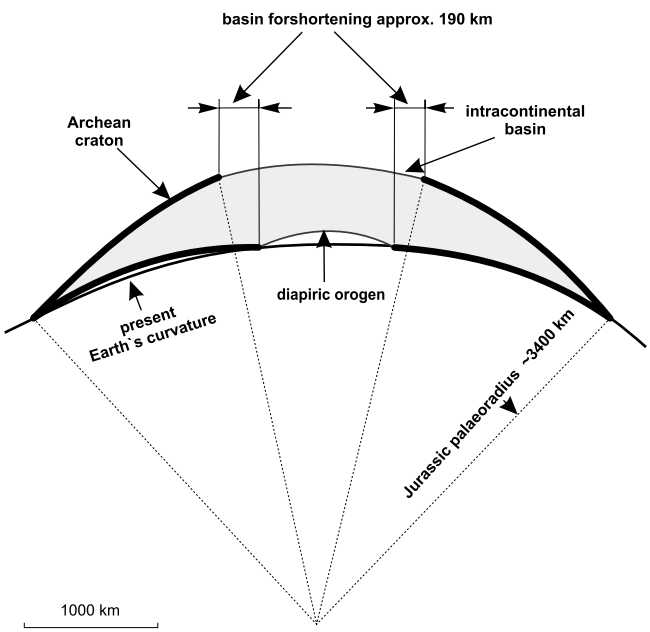

Fig. 49. A scheme of the tectonic processes caused by a flattening of the inner zones of the Earth, interpretation by Maxlow (1995) for a Jurassic palaeoradius of 3400 km, simplified

Change in the curvature of the Earth's outer geosphere was also discussed by Maxlow (1995). He considered the theoretical behaviour of cratons, sedimentary basins and orogens on the surface of an expanding globe (Fig. 49). For an average Archean craton, approximately 1000 km in diameter and tectonically stable during expansion, the uplift of the central point of the craton (connected with the change in curvature for an Earth' radius = 53% to the present-day radius, and the recent curvature level) is 17.5 km. This value corresponds to the commonly acceptable amount of erosion of these cratons during isostatic uplift. Maxlow (1995) also calculated the amount of marginal extension of a craton during the levelling of the crust curvature to be 8.3 km, i.e. approximately 2.6 m per 1 km for the assumed craton diameter. The mobile areas of intracratonic sedimentary basins located between rigid cratonic elements are subject to a considerable shortening due to the adjustment process. The calculated value of the shortening of lithospheric continental elements with diameter of 1/3 of the Jurassic radius (3,400 km) is 190 km. This value is large enough to explain the horizontal shortening of most orogens. Therefore, according to Maxlow (1995), the process of continental lithosphere adjustment also plays an important role in the orogenic process, generating compressional and translational stresses.

The present author (Cwojdziński, 1991a, b) has also come to similar conclusions; that the asymmetric expansion of the Earth gave rise to a seeming "assemblage" of continental plates on the Northern Hemisphere. He favoured their mutual interactions resulting from the adjustment process to a new, smaller curvature of the planet. He had an opportunity to present his own model (Fig. 50) illustrating this process during the conference devoted to the 30th anniversary of the Department of Physical Geology of the Wrocław University in 1992. This model was made of a glue-covered ball bladder, manually blanketed with a gypsum-sand mixture, 0.7–1 cm thick. The glue imitated gravity, whereas the gypsum-sand mixture represented the continental lithosphere. Obviously, the mixture was of variable thickness due to handcovering. The expansion process was modelled by slowly inflating the ball. Although the sphere swelled radially, the rigid gypsum-sand mixture began to crack along classical triple junctions on one of the hemispheres (probably due to the heterogeneity of the cover or its

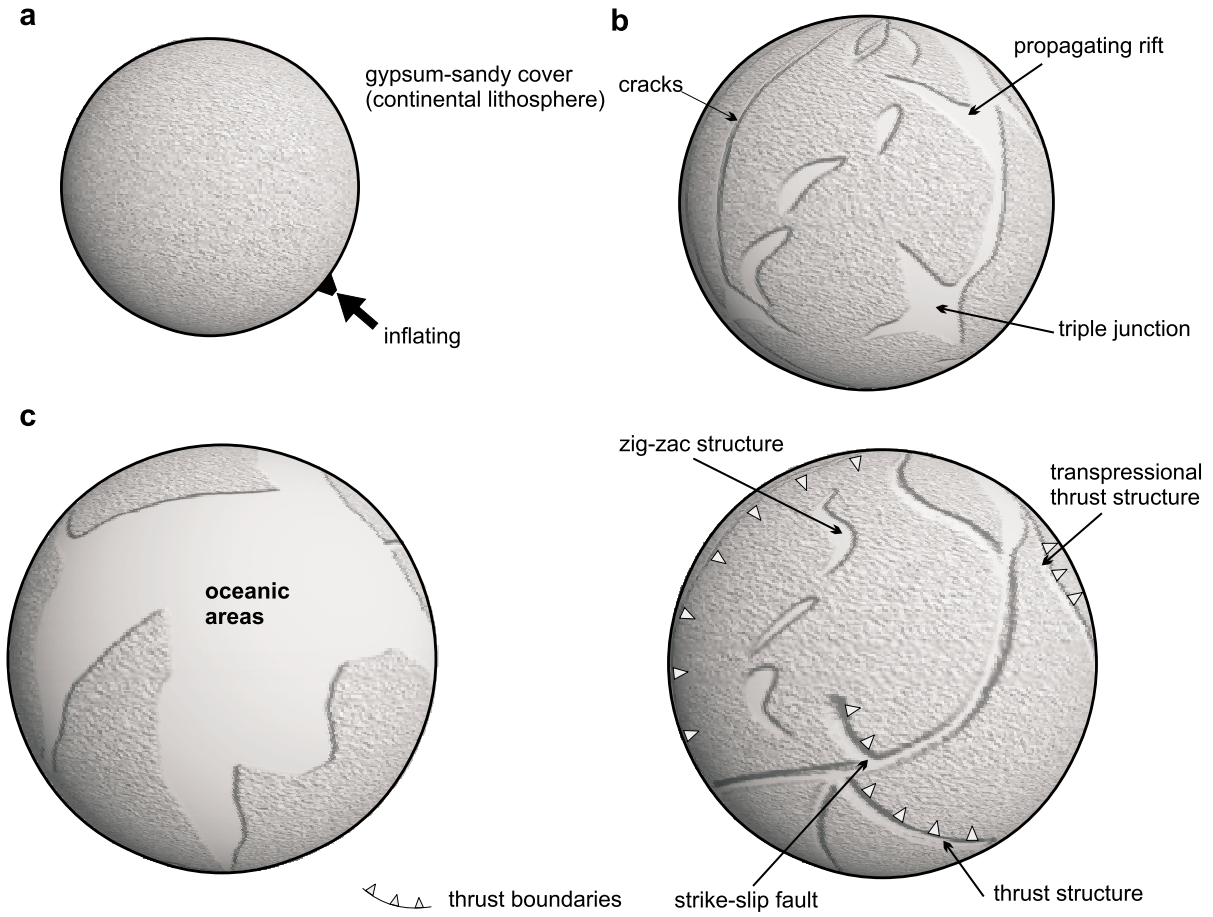

Fig. 50. The expanding Earth model after Cwojdziński (drawn from nature)

a — before inflation, **b** — the first phase of inflation, **c** — the second phase of inflation: a view of the two hemispheres

smaller thickness) to form propagating rift structures. A grey ball bladder basement, representing new oceanic crust, appeared from under the gypsum-sand mixture. As expansion continued, the cracks became longer and the "oceanic" areas larger. This process was accompanied by clear signs of compression and transpression on the opposite hemisphere of the model. Zig-zag fracture zones, along which horizontal or oblique thrust-type displacements occurred, appeared in that area. This process was of a global character on the model (Fig. 50). Obviously, the experimental conditions, rigidity and brittleness of the cover, as well as the difficulties in modelling the gravitational process, only permitted the demonstration of the early phase of the evolution of the oceans. Nevertheless, the results were impressive. The expansion of the Earth can and must result in the occurrence of typical compressional and strike-slip structures, genetically related to the process of adjustment of the continental lithosphere to a new, smaller curvature of the Earth. The entire continental lithosphere (and, to a lesser extent, the younger oceanic lithosphere) is obviously subject to stresses induced by these processes. Therefore, in the outer geosphere, the stresses must give rise to the formation of tectonic structures developed in the same manner in all the types of the continental lithosphere. Such structures are detectable by reflection seismic investigations. The only factor affecting its character and geometry are the rheological properties of the continental crust and the upper mantle of the continental lithosphere.

THE TECTONIC STRUCTURE OF THE CONTINENTAL LITHOSPHERE AS A RESULT OF A CONSTRAINED DECREASE IN LITHOSPHERIC CURVATURE

The process of continental lithospheric flattening can give rise to the formation of characteristic tensional, compressional and strike-slip tectonic structures, clearly visible in reflection seismic profiles. In the upper crust, the first phase of flattening is manifested as the formation of compressional crustal structures described in plate tectonics as flake structures (Oxburgh, 1972) or tectonic wedges (Price, 1986), and also as crustal delamination processes (Bird, 1979) (Fig. 51). As expansion accelerates, compressional structures are replaced by extensional structures in some areas (Fig. 52). The subsequent geological evolution may proceed both towards further extension until the crust breaks, or, in the case of the consolidation of the area, towards another compressional phase which can result from the adjustment of the rigid upper

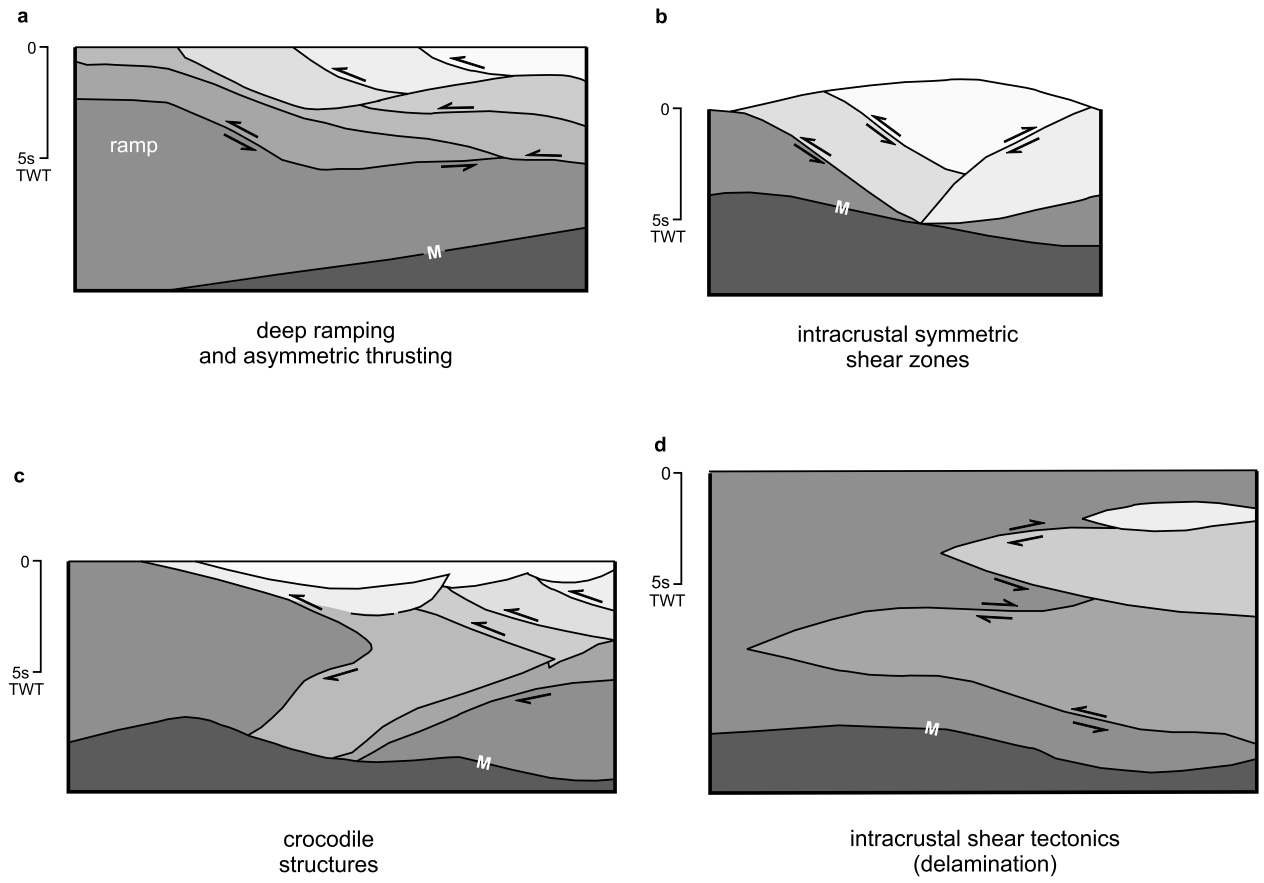

Fig. 51. Examples of crustal compressional structures due to the flattening of the continental crust

crust to a new, smaller curvature of the Earth (tectonic inversion). Flattening structures correspond to the ones which are described by plate tectonic theory as resulting from so-called membrane tectonics. These deformations are caused by changes in the curvature of lithospheric plates. The authors of the term "membrane tectonics" (Turcotte, Oxburgh, 1973, 1976) relate this deformation to the drift of a plate across an ellipsoidal (geoidal) globe. On an expanding Earth, it becomes one of the major mechanisms explaining the seismic structure of the continental lithosphere. Flattening tectonics also explains numerous strike-slip, transpressional and transtensional structures, palaeomagnetically determined lateral rotations of blocks, the formation of oroclines and foldbelts, etc., commonly described in recent literature (e.g. Dadlez, Jaroszewski; 1994; Foster, Beaumont, 1989; Park, 1988).

The flattening process logically explains the geometry of these structures, their mutual spatial relationships and their depth extent. In the light of the proposed geological interpretation, the seismic structures of the continental lithosphere ob-

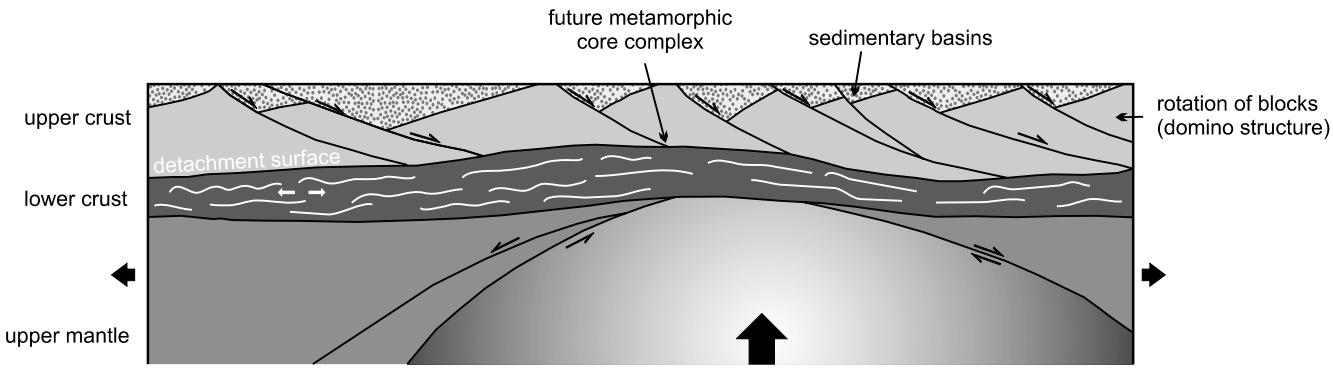

Fig. 52. A scheme of a typical extensional structures forming within extended continental crust. The process can lead to the creation of metamorphic core complexes and the exhumation of lower crustal rocks

served in reflection seismic profiles reflect different states of tectonic stresses (Fig. 37). The upper crust is subject to brittle deformation concentrated in narrow fault and thrust zones. Rigid deformations of the upper crust are in sharp contrast with the ductile deformations observed in its lower part. Planetary and regional intracrustal detachments occur at the lower/upper crust boundary and crust/subcrustal mantle boundary. Extensional stresses are transferred from the upper mantle towards the crust. Upper crustal brittle deformation is independent of the more homogenous deformation of the lower crust. This phenomenon is what we can expect to be the result of the Earth's expansion.

The present author is of the opinion that the seismic structure of the continental crust, observed in reflection seismic sections, distinctly shows that the tectonic stresses responsible for its formation were induced by the expansion of the Earth and the decreasing curvature of its outer surface. The proposed mechanism of deformation explains many of the features of tectonic crustal structures which cannot be well explained by the plate tectonic theory (e.g. Turcotte, 1983).

THE FLATTENING PROCESS IN THE GEOLOGICAL HISTORY OF THE EARTH — A SUMMARY AND CONCLUSIONS

The interpretation of the seismic structures of the continental lithosphere, suggested in this paper, is based on the model of an expanding Earth, and logically explains their geometry and origin, taking into account recent views of geologists and geophysicists on the nature of reflection seismic images. The flattening process of the Earth's outer zones is an extremely complicated tectonic process (Fig. 53). On the one hand, its intensity grows through time as the rate of increase of the Earth's radius accelerates. During the Precambrian, a slow increase in the Earth's radius (Maxlow, 2001) could not result in much change in the Earth's curvature. Therefore, the flattening process was of little geotectonic significance. This process manifested itself for the first time during the Palaeozoic. The fast phase of Mesozoic–Cenozoic expansion meant that the adjustment to a new, smaller Earth's curvature became a huge, global geotectonic process. This expansion phase is responsible for the multilayer structure of the continental lithosphere, layered stress distribution and common signs of membrane tectonics across the continents.

The flattening process primarily affects the continental lithosphere, but it also influences the Mesozoic and Cenozoic oceanic lithosphere. Seismic images of the inner structure of the oceanic crust from the western North Atlantic, far from the fracture zones of the mid-ocean ridge, indicate that the structure is similar to that observed in the continental crust. The only difference is the thickness of individual crustal layers (White *et al*., 1990). Horizontal reflections corresponding to the laminated lower crust of the continents occur at depths of 6–8 km. The seismic structures observed in profiles parallel and perpendicular to the axis of the mid-ocean ridge show much similarity. Therefore, there is no preferred structural orientation.

The flattening deformation of the continental crust is a complex and multi-phase process. However, it does not occur as a single tectogenic factor. The thermal activity of the planet's interior is a major process giving rise to tectonic deformations on an expanding Earth. It is manifested by mantle diapirism and vertical tectogenesis, with gravity tectonics as a secondary process. The flattening process is responsible for the occurrence of the worldwide system of *in situ* stresses (e.g. Zoback, 1992; Townend, Zoback, 2000) in the upper crust, as well as for a wide range of transpressional and transtensional strike-slip deformations associated with the rotation of crustal blocks.

The phases of flattening processes and the corresponding structures of the upper and lower crust are shown in Table 2.

Table 2

Phases of flattening processes and corresponding structures of the upper and lower crust

Phase	Process	Upper crustal structures	Lower crustal structures
I	flattening of continental lithosphere: upper crustal shortening, lower crustal stretching	thrust stacking, tectonic wedges, flake tectonics, detachments	extensional lenticular structures, simple shear zones
II	transfer of tensional stresses to the upper crust, crustal thinning	gravitational faults superimposed on older structures normal listric faults basement blocks rotations - domino structures metamorphic core complexes	laminated seismic structure induced by extensional ductile pure shear
III	riftogenesis, crustal thinning	normal faulting listric faults tectonic grabens and half-grabens	laminated seismic structure, magmatic intrusions
IV	mantle diapirism	orogenic domes gravity deformation wave	intrusions metamorphic stratification
V	adjustment of consolidated crust to new surface curvature	shortening structures detachments strike-slip faults	laminated seismic structure

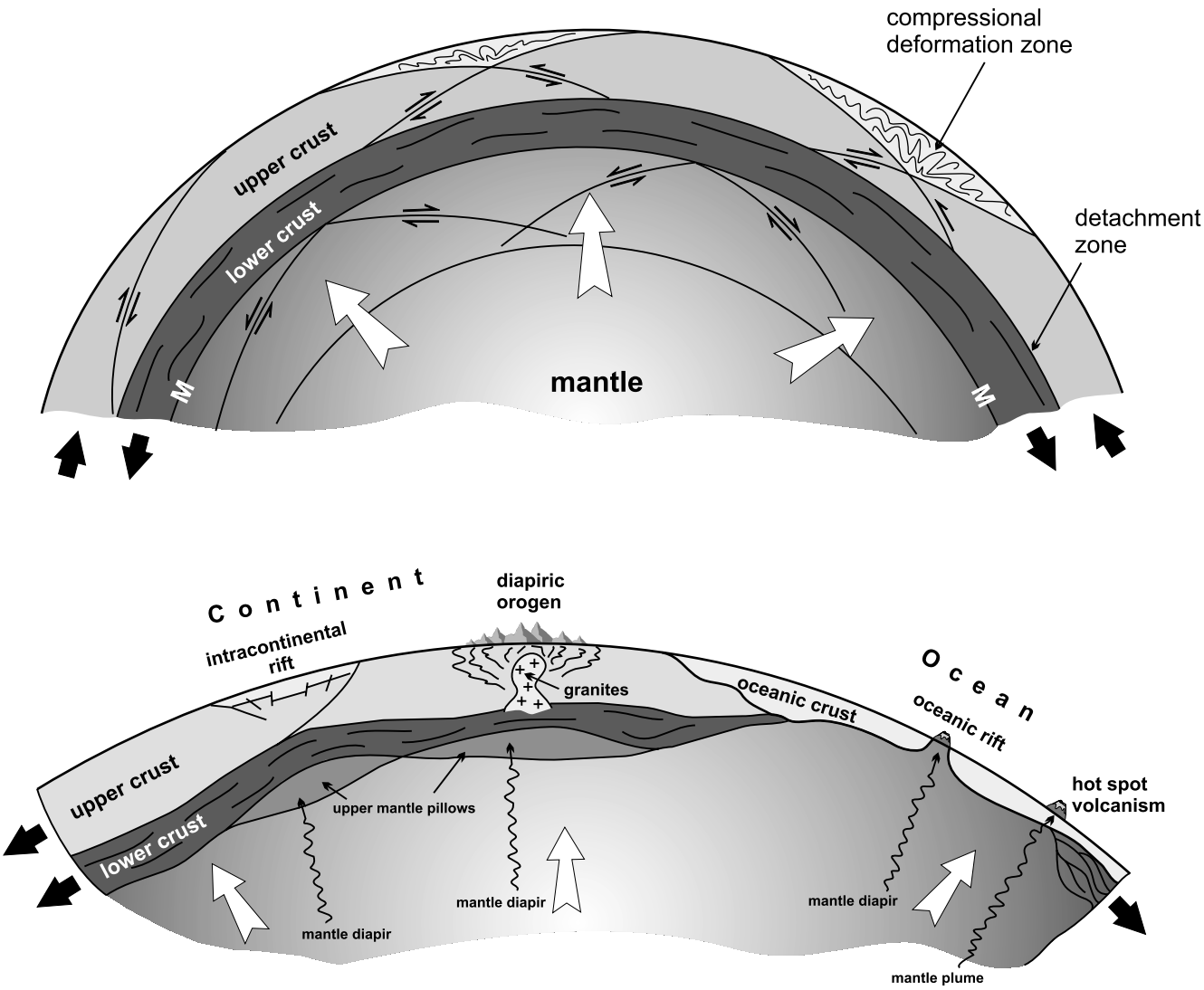

Fig. 53. A scheme of tectonic processes induced by the expansion of the Earth's interior and associated with the decreasing curvature of its surface

a — the first phase of the flattening process — the flattening of the continental lithosphere: upper crustal shortening, stretching of the lower crust and subcrustal mantle due to the expansion of the planet's interior ;(white arrows) the upper mantle transmits stress upwards, the lower crust acts as a wide detachment zone; **b** — the next phase of flattening: the transfer of tensional stresses to the upper crust, mantle diapirism, crustal thinning, rifting, diapiric orogeny

This is an idealization of the discussed process. In fact, the adjustment of the continental lithosphere, in particular of the crust, to a permanently decreasing curvature of the Earth's surface is a continuous process. Recent *in situ* stresses in upper crustal rocks have not only been commonly observed on continents, but also in the rocks composing the oceanic crust, even close to the mid-ocean ridges (Bott, Kusznir, 1984). It indicates that the flattening process also affects the young oceanic lithosphere, and is a global process *sensu stricto*.

Conclusions:

1. The seismic structure of the continental lithosphere, as observed in many reflection seismic profiles, reflects the process of a gradual decrease in the spherical curvature of the surface of the Earth and its outer zones during the expansion of the Earth's interior.

2. The seismic images correspond to structures which are a response to the adjustment process to a new, smaller curvature of the Earth's surface. These are the so-called flattening structures, differently developed at various deformational levels of the lithosphere.

3. The age of flattening structures is difficult to identify. In general, these are young structures representing the Mesozoic and Cenozoic stages of the Earth's evolution. Locally, the upper crust shows evident older structures which are superimposed by structures of younger deformation phases related to the flattening process. The occurrence of such structures shows that the expansion of the Earth also took place before the Mesozoic–Cenozoic breakup of Pangea.

4. The depth extent of flattening deformations depends on the composition of the crust, its thickness and the thermal con-

ditions which reigned within the crust and upper mantle during the deformation process.

5. A 3-D image of the adjustment structures shows that they are represented by strike-slip faults, shear zones, rotations of blocks and pull-apart basins.

6. *In situ* compressional stresses, commonly observed in rocks from the topmost fraction of the upper crust, are genetically related to the flattening process.

7. Adjustment structures, similar to those observed on the continents, also occur within the oceanic lithosphere. Deep discontinuities, giving rise to volcanic ranges on oceanic floors, can also be of this origin.

This paper is based on the expanding Earth theory. This theory enables a logical explanation of a range of seemingly contradictory observations. It permits a return) to the "classical" geology of continents and appears to be a bridge between mobilistic and stabilistic ideas. Facts such as the palaeogeographic nearness of the Pangea continents, the Mesozoic–Cenozoic breakup of Pangea, and the deep rooting of the continents in the Earth's mantle have become understood. Also, as data on the one-way geochemical evolution of our planet become obvious, so does an image of the present-day geotectonic setting, which if analysed in detail, shows plenty of discrepancies with the plate tectonic model. Neither palaeomagnetic data nor satellite geodesy data contradict the expanding Earth theory (Cwojdziński, 2001, Koziar, 2002).

For most geologists, one of the major arguments against the expansion theory is the lack of explanation of phenomena such as compression and orogeny. This accusation is a misunderstanding. The presented idea of the tectonic effect of the flattening process of the outer zones on the expanding Earth provides arguments in favour of a compressional and shear deformation mechanism in the lithosphere. This idea finds support in the results of reflection seismic investigations. The process of continental crustal flattening is powerful enough to explain the occurrence of compressional stresses responsible for fold-and-thrust deformations, and crustal and strike-slip tectonics. However, the substantial orogenic mechanisms on an expanding Earth are mantle diapirism (Carey, 1976), and gravity tectonics (De Jong, Scholten, 1973) as a secondary process. Both these co-operating processes are responsible for all of the tectonic deformations induced by thermal activity of the Earth's interior.

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