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Drift tectonics – the fundamental rhythm of crustal drift and deformation

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With 19 figures and 3 tables

Zusammenfassung

Mehrjährige Untersuchungen der Deformationsgeschichte der Alpen und ihres europäischen Vorlands führten zur Entwicklung neuer Modelle für den Antrieb der Kontinentaldrift und zum Problem der intraplate tectonics. Es konnte nachgewiesen werden, daß ein weltweiter Bewegungsrhythmus der Kontinentaldrift existiert, der sich durch gesetzmäßige Deformation von Lithosphärenstrukturen in den Phasen der Epirogenese auswirkt. Dieser Nachweis wurde durch die Entwicklung einer neuen Methode zur vergleichenden Analyse paläomagnetischer und tektonischer Daten ermöglicht.

Durch den Entwurf einer neuen Kartenprojektion gelang es erstmals, alle wesentlichen geologischen und geophysikalischen Daten in einer übersichtlichen Abbildung auf ihre Beziehung zur Driftrichtung hin zu untersuchen. Dies führte zur Identifizierung der Driftfelder als größte Bewegungseinheit der Lithosphäre. Ihre Geometrie regelt ein konvergierendes Fließen der Lithosphäre und damit die Richtung der Plattenbewegungen. Zugleich beeinflussen die Driftfelder über die Temperaturverteilung im oberen Mantel den Verlauf asthenosphärischer Gegenströmungen, deren interne Strömungsmuster zur Entwicklung von Aufströmen (plumes) und zu epirogenetischen Aufdomungen führen.

So bietet die Entdeckung der drifttektonischen Gesetzmäßigkeiten über eine Synthese horizontal- und vertikaltektonischer Hypothesen hinaus ein vielversprechendes Bezugssystem zum Verständnis der tektonisch-magmatischen Zyklen des Proterozoikums.

Abstract

Several years of research on deformational history of the Alps and their Central European foreland led to the development of new models for the driving mechanism of continental drift and intraplate tectonics. It was found that a global rhythm of continental drift exists, which causes the phases of epeirogeny by regular deformation of lithospheric structures. This approach was made possible by the development of a new method of comparing and analysing paleomagnetic and tectonic data.

A new map projection provided for the first time the order necessary to analyze on a global scale the relations between the direction of drift and all essential geological and geophysical data. This led to the identification of drift fields as the largest lithospheric structural units. Their geometry controls a narrowing lithospheric flow and thus the direction of plate movements. By redistributing upper mantle isotherms, the drift fields simultaneously control the course of asthenospheric counterflows, whose internal flow patterns can trigger asthenospheric upwellings and epeirogenic uplifts.

Thus, besides providing a synthesis of horizontal- and vertical-tectonic hypotheses, the discovery of drift tectonic rules offers a promising framework for the understanding of the Proterozoic tectonomagmatic cycles.

Résumé

Des recherches de plusieurs années sur l'histoire déformative des Alpes et de leur avant-pays européen, permettent de développer un nouveau modèle qui répond aux problèmes de la tectonique intra-plaque et du moteur de la dérive continentale. On montre l'existence, à l'échelle mondiale, d'un rythme dans le mouvement de dérive, qui se traduit par une déformation ordonnée des structures lithosphériques aux cours des phases de l'épirogenèse. Cette conclusion résulte de l'emploi d'une méthode nouvelle d'analyse comparée des données paléomagnétiques et tectoniques.

Grâce à une nouvelle projection cartographique, on a pu, pour la première fois, mettre toutes les données géologiques et géophysiques actuelles en relation avec la direction de dérive, ce qui a conduit à identifier les champs de dérive comme les unités structurales majeures de la lithosphère. Leur géometrie définit un écoulement convergent de la lithosphère et, partant, la direction des mouvements des plaques. En raison de la distribution de la température dans le manteau, les champs de dérive définissent en même temps la position de contrecourants asthénosphériques, dont la disposition interne conduit au développement de »plumes« et de bombements épirogéniques.

La découverte du caractère ordonné de la dérive permet une synthèse des hypothèses »verticalistes« et »horizontalistes« en tectonique et, de ce fait, une meilleure compréhension des cycles tectono-magmatiques du Protérozoïque.

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Краткое содержание

Многолетние исследования деформации Альп и их предгорья помогли создать модель, дополняещую в частности гипотезу тектоники плит и материкового дрейфа. Попытались установить существование определенного ритма в передвижении дрейфующих материков в глобальном масштабе, проявляющееся в закономерной деформации структур литосферы во время эпирогенеза. Наличие такого ритма удалось установить с помощью нового метода сравнения данных палеомагматизма и тектоники. В новой проэкции представили на карте все геологические и геофизические данные, что дало возможность представить их взаимодействия и связи с направлением дрейфа плит. Удалось идентифицировать дрейфующие поля, как гигантские структурные единицы литосферы. Их геометрия регулирует конвергирующие течения литосферы и связанные с ними направления движения плит. Дрейфующие поля регулируют как распределение температуры в мантии, так и направление течений астеносферы, которые образуют куполовидные структурные формы.

Таким образом можно установить определенные закономерности при дрейфе плит, и это разрешает сравнить, как вертикальные, так и горизонтальные перемещения их, а также объяснить появление определенных тектономагматических циклов в протерозое.

Introduction

By the discovery of the phenomenon of sea-floor spreading the final step towards the mobilistic theory of plate tectonics was made. It was recognized that lithospheric plates instead of continental platforms were the large mechanical units which move with respect to one another. Their margins are defined by earthquake-zones, whose sense of relative movement could be derived from the orientation of compression and tension (McKenzie & Parker, 1967; Isacks et al., 1968).

Plate tectonics offered two fundamental innovations: firstly the lithospheric plates were the basic kinematic elements which made a realistic model of relative continental movement possible; secondly, the pull of the heavy down-going slab represented a plausible driving force for those plates whose frontal margins sink back into the mantle at the Benioff zones (Elsasser, 1968, McKenzie, 1970b). Fig. 1 summarizes the successful kinematic aspects of plate tectonics. The lithosphere consists of a number of plates drifting on a partially molten asthenosphere, which move relative to one another. Rift zones, which widen into oceans, form when the plates move apart; when they approach one another, one plate is subducted beneath the other; shear movements between the plates occur in transform faults. The continents are passive loads on the conveyor-belt of oceanic plates.

Whereas seismic and, to a certain extent, geochemical data correlate well with plate kinematics, it has been increasingly recognized that the dynamic aspects of the model do not show this clear correlation (e.g. Karig et al., 1978, Grohmann, 1981, Hsü, 1982:2, Kennett, 1982:170, 387). This is understandable since these dynamic aspects – the concepts of pushing mantle upwellings and pushing plates – are almost exclusively horizontal- or vertical-tectonic models which have been taken over from pre-plate tectonic times and adapted to fit the »new global tectonics«.

Problems of Epeirogeny in Central Europe

Epeirogenic uplift and subsidence of the Earths crust are much less spectacular than the dramatic changes seen in »active« tectonic zones. In particular since research has been concentrated on the investigation of plate margins, epeirogeny has been regarded as a secondary phenomenon. In contrast to this view, the author's systematic investigations of the history of continental drift and deformation have resulted in the surprising realisation that a most important key to understanding geodynamics is to be found in the supposedly »tectonically dead« plate interiors.

Absolute vertical crustal movements in the geological past can best be determined in regions which were frequently inundated by sea, because the coastline provides a reference level parallel to the geoid; even slight vertical movements cause considerable shifts of the coastline as a result of the neglebile slope of the continental surface.

The best conditions for such research are found in Europe, where a long history of geological and geophysical research has resulted in a wealth of data. This enabled the author to compile in 1978 an atlas of 24 maps, depicting European paleogeography, volcanism and intra-plate tectonics of the last 230 Ma* along with a collection of essential geophysical data. The comparison of consecutive maps of this series allowed the identification of systematic trends in the crustal movements.

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* Ma = Million years

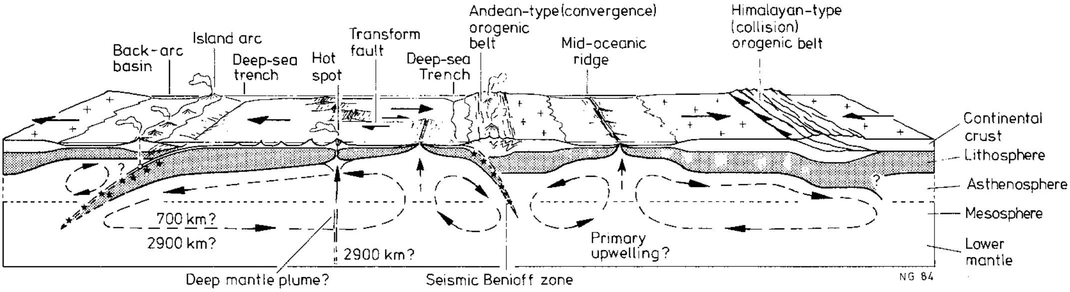

Fig. 1. The well-known two-dimensional model of plate kinematics and some hypothetical roller-shaped convection cells.

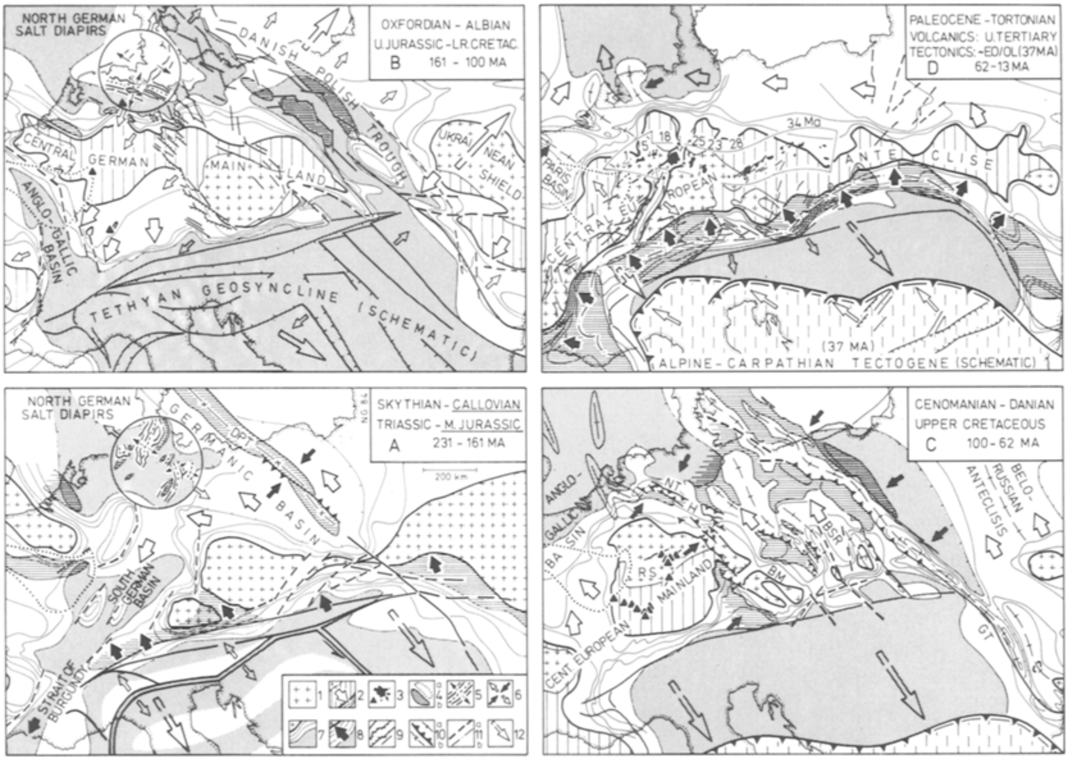

Fig. 2. Drift tectonic development of Central Europe. Symbols are as follows: 1. Areas never covered by sea; 2. Direction of counterdrift regression; 3. Volcanic activity; 4a. Thick lithospheric basin (GROHMANN, 1981:201); 4b. Zones of subsidence; 5. Salt stock families, migration of salt; 6. Compression and dilatation; 7. Frequency of coverage by sea, reflecting average depth relations. Shaded areas: deepest basins; 8. Direction of counterdrift transgression; 9. Block-faulted zones; 10a. Thrusts and anticlines; 10b. synclines; 11a. Topographic hinge zones, lineaments; 11b. Future front of Alpine deformation; 12. Direction of continental drift. Since the Oligocene closing of the Tethyan geosyncline Europe drifts towards NE. Consequently, Upper Tertiary volcanic activity (After DUNCAN et al., 1972) shifts along the Central European Anteclise and along the Upper Rhine Graben (Fig. 3M) in counterdrift direction towards W-SW. BM, Bohemian Massif; BSR, Bohem.-Silesian Rise; GT, Greenschist Treshold; H, Harz Mts.; NT, Lr. Saxonian Tectogene; RS, Rhenish shield.

The most important result of this investigation was the recognition of three short episodes of rapid change in epeirogenic relief in Europe: At the Dogger/Malm, Lower/Upper Cretaceous and Cretaceous/Tertiary boundaries. For each of the four epochs with distinctly slower change of the relief, the maps of sea-distribution have been superimposed and thus a composite map of the frequency of inundation by sea was developed. Because this frequency of coverage by sea indicates the average depth between those regions which have always been land and those which have always been sea during the respective epochs, these maps also represent average bathymetry of the contemporary shelf. These four maps, supplemented by additional information (see following discussion), form the basis of Fig. 2.

First of all, the obvious division of epeirogenic history into four phases with basically different relief demonstrated that epeirogeny is more than just a random warping of a floating crust: it reveals important information about upper mantle dynamics. It was, however, hitherto impossible to reconcile vertical tectonic or horizontal tectonic interpretations entirely with observed geological data.

A vertical tectonic model, attributing the doming of the Rhenish shield to the rise of a hot mantle diapir, was proposed by CLOOS (1939) and more recently by WERNER et al., (1982). This model was also fully supported by the present author (1981:228) until a closer examination demonstrated, that it cannot satisfactorily explain the fact that the uplift occurred in discontinous »jumps« rather than continously as might be expected from doming over a rising mantle diapir. Moreover, neither epeirogenic uplift nor volcanism exhibits the expected radial spreading from the centres of uplift (Fig. 2). Thus, the diapiric model is basically correct, but the nature of diapiric rise of light asthenospheric material is influenced by factors which were yet to be determined.

Nor can these factors be satisfactorily explained by the published horizontal tectonic models which draw conclusions about relative plate motions on the basis of intraplate deformation. The age of the ocean floor (BERGER & SEIBOLD, cit. in BISCHOFF, 1984:66) showes that Africa steadily moved SE-wards relative to Laurasia (N-America + Eurasia) from 180 til 80 Ma. In this movement no discontinuity at the Dogger/Malm (Fig. 2A/B) and Lower/Upper Cretaceous (Fig. 2B/C) boundaries, which might explain extensive changes in relief and – as demonstrated below – in the tension field of Europe, can be detected.

Similarly the classic plate tectonic explanation of the Upper Cretaceous-Lower Tertiary epoch of SW-NE compression in Europe (DEWEY et al., 1973; SCHÄFER, 1978; FRISCH, 1981), a change from divergence to convergence of Africa with Europe in SW-NE direction, is contradicted by sea-floor spreading data: The opening of the Labrador sea (80–40 Ma, BISCHOFF, 1984:66) increased the N-S component of the divergence between Africa and Europe during this time. Further, the opening of the N-Atlantic at 60 Ma between Greenland and Scandinavia supposedly pressed Europe (NW-SE) against Africa, resulting in »considerable compression in the Alps« (FRISCH, 1981:402). However instead of the postulated NW-SE compression there was a period of NW-SE dilatation, resulting in the Eocene formation of the Upper Rhine graben (ILLIES, 1975). NW-SE compression in central Europe occurred much later, starting in the Oligocene according to ILLIES (1974:6) and SCHÄFER (1978:42) or 35–30 Ma ago according to this work (Fig. 3, H–L), when convergence of Europe with Africa was terminated by the final collision.

These examples, to mention but a few (see also GROHMANN, 1981), demonstrated that neither the kinematic phases of seafloor spreading, nor the proposed plate-tectonic models give a consistent explanation of Central Europe's epeirogenic phases. They emphasized the necessity of collecting more data and investigating independently the deformational history of the plates' margins, the phases of sea-floor spreading and of continental drift and then, unbiased by prevailing theories, to compare the results in search of still unknown connections.

Phases of Continental Drift, Based on Paleomagnetic Data

Since, on the basis of the remanent magnetization of rocks, geophysicists construct polar wander paths for the different continents, it is sometimes questioned, whether these »polar wander paths« indicate a true continental drift relative to the geographic and magnetic poles, or whether they represent only polar wandering relative to stable continents (e.g. SALOP, 1983:398). Up to now two arguments have proved a real continental drift: OPDYKE & RUNCORN (1959) and later eg. MCELHINNY (1973:254) demonstrated that the Paleozoic polar wander paths, which were identical as long as Laurasia was still one unit, separated after the break-up of N-Amerika and Eurasia by E-W directed relative movement of the two continents. That N-S movements are also registered by the polar wander path, was shown by the fact that paleomagnetic latitudes unequivocally correspond to the paleoclimatic belts, which are, as shown first by KÖPPEN & WEGENER (WEGENER, 1929:142; MAAK, 1969:73; SEYFERT & SIRKIN, 1973) derived from geological data.

To describe the details of continental drift, however, paleomagnetics offered – apart from timing of microcontinent rotation – until now no sufficient framework. The main cause for this is the scarcity of measurements: Since magnetic poles wander around geographic poles during very short geological time spans over an average distance of approximately 10° (DOELL & COX, 1972:279), a natural scatter of magnetic pole positions exists, from which the geographic pole position can only be derived as a calculated mean. As long as only relatively few measurements were available for these calculations, polar wander paths were based at best on three, but often only on one of these main pole positions per geological formation (MCELHINNY, 1973). A sufficient amount of data to register details of the polar wander path by this method was available only for N-America (IRVING, 1977). In most cases, however, discontinuities of the polar wander path, which are important for the discussion of continental drift, have been smoothed mathematically by the method of mean calculation.

Therefore, in 1981, the author developed a new method of graphic and mathemathical analysis of paleomagnetic data. In this procedure longitude and latitude of the paleopoles, calculated from remanent magnetization of the samples, are plotted separately against the age of magnetization (e. g. Fig. 3A for African data). This type of plot reveals the periods of continously increasing or decreasing latitude/longitude, indicating the times of changes in the trends and bridging smaler data-gaps. If the plots show a small scatter and a parallel course of maximum and minimum values, this indicates that the data have not been disturbed by tectonics or remagnetization. This method allows a useful classification of the data into age divisions, for which mean values now can be calculated. Through these mean values, parallel to the maximum and minimum curves, two mean curves can be constructed which more accurately represent the variations of geographical longitude and latitude. On a map (Fig. 3F) both mean curves can be combined to derive a polar wander path, which avoids a smoothing of important discontinuities as much as possible.

Using this method, the author analyzed all available paleomagnetic data (Tab. 1) for the continents of Africa, Eurasia and India. The original data in the variation diagrams of pole positions in time and the newly derived polar wander paths are shown in Fig. 3A–F. A comparison with IRVING'S polar wander path of N-America (1977, Tab. 1) corroborates the reliability of the method, since the polar wander path of N-America fits the new Eurasian path, if the two continents are rejoined (Fig. 3E).

Principle phases of divergence and convergence between the continents may be obtained with a crude accuracy similar to that found in conventional representations (e.g. KLOOTWIJK, 1976:893) by using just the latitude- time diagrams (Fig. 3C). In the polar wander paths, however (Fig. 3E-F9), the discontinuities separating these phases are represented by very sharp »hairpins«, whose dates caused some surprise: In spite of the relatively large scatter of the original data, they are identical for all continents with maximum deviations of only ± 10 Ma: 30–35, 80–90, 130–150, 190–200 and 260 Ma.

This implied that continental drift is subject to a global rhythm, which does not fit the classical geological formations. Longer phases of continous drift of all continents, lasting about 60 Ma, have been interrupted by relatively short episodes of a common re-orientation.

Drift and Deformation in Hercynian Time

Following the above project, the author developed several map series of continental drift in the Mediterranean region as well as on a global scale. On the base of these maps, a systematic comparison between the paleomagnetic phases of absolute continental drift with the phases of relative continental drift – derived from the age of oceanic basement – and the deformation of the plate margins and in the plate interiors was possible.

It turned out that the motion-phases of the polar wander paths are the long-sought for keys to comprehension of plate deformation. This discovery was made in the Alpine-Carpathian region, but the understanding of the relationships where was hindered for a long time by the superimposition of different processes. Therefore, in order to explain these newfound relationships, Laurasia's Hercynian drift is here used as an example.

The above-mentioned rotation of N-America away from Eurasia, which opened the N-Atlantic (Fig. 3E), is an example of relative continen-

TABLE 1

Fig.3A-D,Construction of polar wander paths, sources of data (paleomagnetic measurements):

Fig.3A, Africa

1 Hussain et al. (1980)
2 Phillips& Forsyth (1972)
3 Africa, McElhinny (1973)
4 Arabia, McElhinny (1973)

Fig.3B, Eurasia

1 Measurements from W-Europa, Russian Platform, Siberia, China, Korea, McElhinny (1973)
2 Europe, Duncan et al. (1972)
3 N-Bavaria, Pohl& Soffel (1977)
4 S-Germany, Heller (1977)
5 Pfalz, Dachroth (1977)

Mean values from McElhinny (1973):
6 W-Europe
7 Russian Platform
8 Siberian Platform
9 China

Fig.3C, India

Data from Klootwijk (1979):
1 Indian shield (Tab6, Tab9)
2 DSDP cores (Tab9)

Fig3D, Eurasia

* Tibet,Molnar& Chen (1978)

Fig.3D,Polar wander path of Eurasia after Fig.3B

Fig.3E,Polar wander path of N-America after Irving (1977,Tab1)

Fig.3F,Polar wander path of Africa after Fig.3A

Fig.3F,Polar wander path of India after Fig.3C

TABLE 2

	Fig.3I,New parallel coastlines	Age	Reference
	NW-SE Tension:		
1	Upper Rhine Rift	M.Oligocene	1:165
2	Cimbria Isl.	Lr.Lias	2:430
3	Anglo-Gallic Basin	Lr.Lias	2:430
4	Irish Sea	Lr.Lias	2:430
5	Strait of Burgundy	Up.Buntsandstein	2:418
6	Hunsrück-Rothaar Isl.	Up.Buntsandstein	2:418

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6	Hunsrück-Rothaar Isl.	Up.Buntsandstein	2:418
7	Hessian Strait	Up.Permian	3:403
8	Centr.Europe: NE-striking basins	Lr.Permian	3:400
	NE-SW Tension:		
9	Innersudetic Basin	Cenomanian	2:445
10	Cret. Bay of E Bavaria	Cenomanian	2:445
11	Lr.Saxony Basin: bays	Valanginian	2:442
12	English Wealden Basin	Valanginian	2:442
13	Danish-Polish Trough	Portlandian	2:433
14	Lr.Saxony Basin: bays	Portlandian	2:433
15	English Salinar Basin	M.Keuper	2:418
16	Pyrenean Geosyncline	Up.Buntsandstein	2:418
17	Germanic Basin	Up.Permian	3:403
18	Centr.Europe: SE-striking basins	Lr.Permian	3:400
19	Centr.Europe: Hercynian tectogenesis	Up.Carbonifer. to Stephanian	4:389

	Fig.3K, Strike of tectonic structures	Age	Reference
	NW-SE Tension:		
1	Eger Graben, sedimentation	since M.Oligocene	5:191,193
2	Lr.Rhine, Rentdorfer Blatt,thrusting;	Turonian to Lr.Oligocene	6:29,81
3	Dan.-Polish Trough, folding after Up.Cretaceous subsidence	Maestrichtian/Danian	7:177; 5:163,238-40
4	Lr.Saxonian Tectogene, folding	Campanian	8
5	Roer Valley, reverse faults	Coniacian-Campanian	9:5,7
6	Schonen, thrusting	Coniacian	5:18
7	Bornholm, synsedimentary folding	Turonian-Santonian	5:15
8a	Lr.Rhine, Krudenberg Sprung,thrusting;	Turonian-Santonian	6:27
8b	Bavaria,Bodenwöhr Basin,syncline	Turonian-Santonian	5:198,336
9	Innersudetic Basin, folding	Cenomanian-Coniacian	5:147f
10	Roer Valley, uplift, erosion	Dogger	9:5-7
11	"Rhenish" rifts in the Pompeckj ridge;	Lias-Lr.Malm	5:211
12	N-German salt diapirs,marginal basins;	Lias-Dogger	5:224;10:264;11:424
13	Dan.-Polish Trough, syncline	Lias	12; 5:388
14a	Bornholm, Dan.-Pol.Trough, subsidence;	Rhaeth.-Lias	5:15,19
14b	Schonen, synsedimentary thrusting	Rhaeth.-Lias	5:19
15	Offenburg Basin, subsidence	Rotliegend-Buntsandstein	13
16	Bavaria,Bodenwöhr Basin,sedimentation;	Permotriassic-Dogger	5:352

	NE-SW Tension:		
17	Centr.Europe today´s stress field (seism.focal solut.; in-situ meas.)		14
18	Donaurandspalte,normal fault	Up.Miocene	5:198
19	Eger Basin, NW-striking fractures	since Lr.Miocene	5:191
20	Bohemian Massif,NW-str. grabens	Mio.-Pliocene	15
21	Roer Valley , rifting	Mio.-Pliocene	9:5,148
22	Lr.Rhine,Rentdorf,Hüxen norm.faults	since M/Up.Oligocene	6:49,70
23	Bohemian Cret.,"Hercynian" fractures	since Cenomanian	5:203
24	Innersudetic Basin, sedimentation	Cenomanian	5:147
25	N-German salt diapirs,marginal basins;	Malm-Cretaceous	10,264;11:429
26	Bavaria,Bodenwöhr Bas.,uplift,erosion;	Malm-Cenomanian	5:195,352
27	Lr.Saxonian Tectogene,synsed.fractur.;	Malm-Lr.Cretaceous	8
28	NW-German Basin: WNW-strike	Portlandian	5:278
29	Beskydy Parageosyncline(W-Carpath.)	Portlandian	16
30	Centr.Germany,SE-str. grabens	Malm	1:135
31	Salt diapir marg.bas.,Deister,Hils	Oxfordian	1:141
32	Bornholm,uplift,NE-str.Anticline	post Liassic- pre Lr.Cretaceous	5:15
33	N-German salt diapir marg.basins	Keuper	10:264;11:429
34	Lr.Rhine Rifts	Keuper	6:16
35	Schonen, fractures	preLiassic	5:18
36	Lr.Rhine,Rentdorf normal fault	Zechstein-Scythian	6:74,79,81
37	Saar-Nahe Syncline, folding	Lr./Up.Rotliegend	5:104,105
38	Black Forest,Baden Syncl.,ENE-str.	Lr./Up.Rotlg.,"Saalian"	5:170
	Hercynian Tectogene,Centr.Europe		
39	"Asturian phase"	290Ma,Westfal./Stephanian	5:40,46
40	"Sudetian phase"	325Ma,Lr./Up.Carboniferous	5:46

Fig.3L,Strike of dated volcanic dykes		Age	Reference
	"Rhenish"(NNE-)strike: NW-SE Tension		
1	Grabenstätten	± 15 Ma	18
2	Hinterhauenstein (rhenish)	35 Ma	18
3	Urbeis (EW)	58,4 ± 2.3 Ma	19
4	Neckarbischofsheim (rhenish)	55-65 Ma	18
5	Mosbach (rhenish)	55-65 Ma	18
6	Le Valtin (NNE)	64.5 ± 5.5 Ma	17
7	Hirzberg (rhenish)	68.6 ± 2.3 Ma	17
8	Attental (rhenish)	81	17
	"Hercynian" (WNW-)strike: NE-SW Tension		
9	Hegau (hercynian)	7-14 Ma	17,18
10	Lehen n. Freiburg (NNW)	13.4 ± 0.9 Ma	19
	"Hercynian" (WNW-)strike: NE-SW Tension		
9	Hegau (hercynian)	7-14 Ma	17,18
10	Lehen n. Freiburg (NNW)	13.4 ± 0.9 Ma	19
11	Lausitz volcanics (NW trend)	28.0 ± 0.6 Ma	21
12	Tannenbach (NW)	28.1 ± 2.8	19
13	Langental (WNW)	30.7 ± 5.7 Ma	19
14	Tannengrund (hercynian)	60.1 ± 2.0 Ma	19
15	Uhlberg II (hercynian)	83.1 ± 2.1 Ma	19
16	Schlauderberghof (hercynian)	88.2 ± 2.8 Ma	17
17	Drei Ähren (NW)	99.8 ± 7.6 Ma	19
18	Uhlberg I (hercynian)	116.8 ± 2.5 Ma	19
19	Pfahl (Quartz dyke, NW)	230	20
20	Saarland volcanics (mostly hercyn.)	Rotliegend	5:105
21	Col de Pêternit (NS)	296 ± 7 Ma	17

Fig.3M, Frequency of dated volcanic rocks	
Upper Rhine Graben, Southern part	17
Upper Rhine Graben, Northern part	22

References are as follows: Fig.3G,Van Eysinga (1975) Time Scale, Amsterdam, Elsevier; Fig.3H, Fig3D; Reference numbers, Fig3I-M: 1, Schmidt (1972); 2, Müller (1970); 3, Kölbel (1970); 4, Gothan& Daber (1979); 5, Dorn-Lotze (1971); 6, Ahmed (1980); 7, Pozaryski& Pozaryska (1960); 8, Stadler& Teichmüller (1971); 9, DeSitter (1956); 10, Sannemann (1968); 11, Rutten (1969); 12, Pozarysky& Brochwicz-Lewinski (1978); 13, Boigk& Schöneich (1970); 14, Ahorner (1978) and Greiner (1975); 15, Geol.Map of Czechoslovakia 1:500 000, Geol.Surv.Czech.; 16, Hanzlikova& Roth (1965); 17, Baranyi et al.(1976); 18, Illies(1974) after Lippolt, Mäussnest; 19, Baranyi (1976); 20, P.Horn (1984), pers.comm.; 21, Todt& Lippolt (1975); 22, Lippolt et al.(1975).

TABLE 3

Fig.9, Measurements of stress-orientation, references:

Ahorner(1978), Das& Filson(1975), Fairhead& Stuart(1982),Fitch(1972), Furlong(1979), Golenetsky& Misharina(1978), Haimson(1976), Hashizume(1977), Ichikawa(1969), Isacks et al. (1968), Jones et al.(1980), Johnson& Molnar(1972), LePichon et al.(1973), McKenzie(1972), Nikolayev(1977), Nowroozi(1971), Ranally&Chandler(1975), Ritsema(1970), Roman(1973), Sbar& Sykes(1973), Sykes&Sbar(1973), Tapponier& Molnar(1977), Udintsev(1971),Weissel(1980)

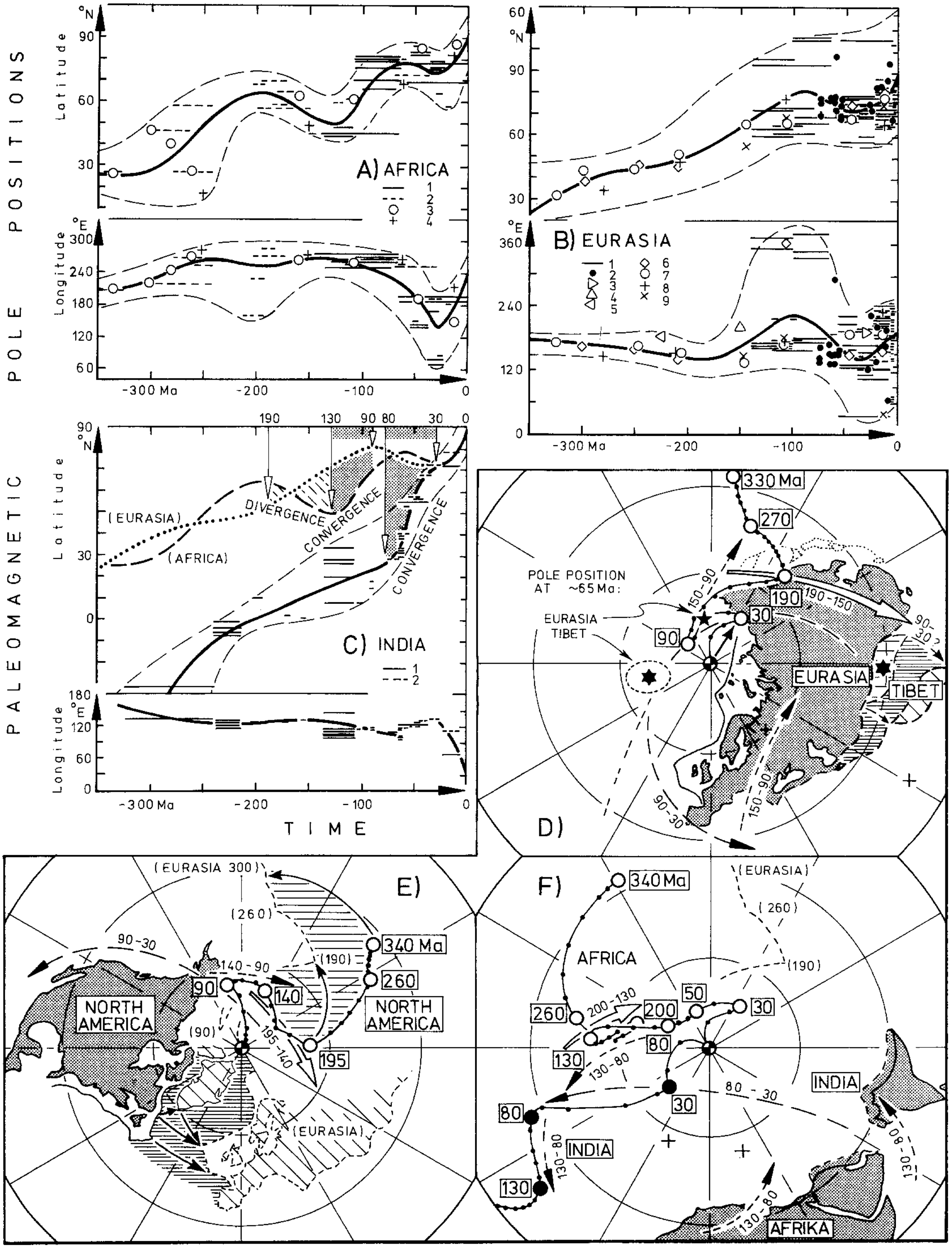


Fig. 3. A-B-C Latitude-age and longitude-age relationships of paleomagnetic measurements for Africa, Eurasia and India. Main periods of convergence and divergence are indicated by comparison of the derived mean latitude curves (Fig. 3C). D-E-F Polar wander paths, derived from a combination of the mean curves of A-B-C. Arrows indicate corresponding absolute drift direction. For references see Tab. 1.

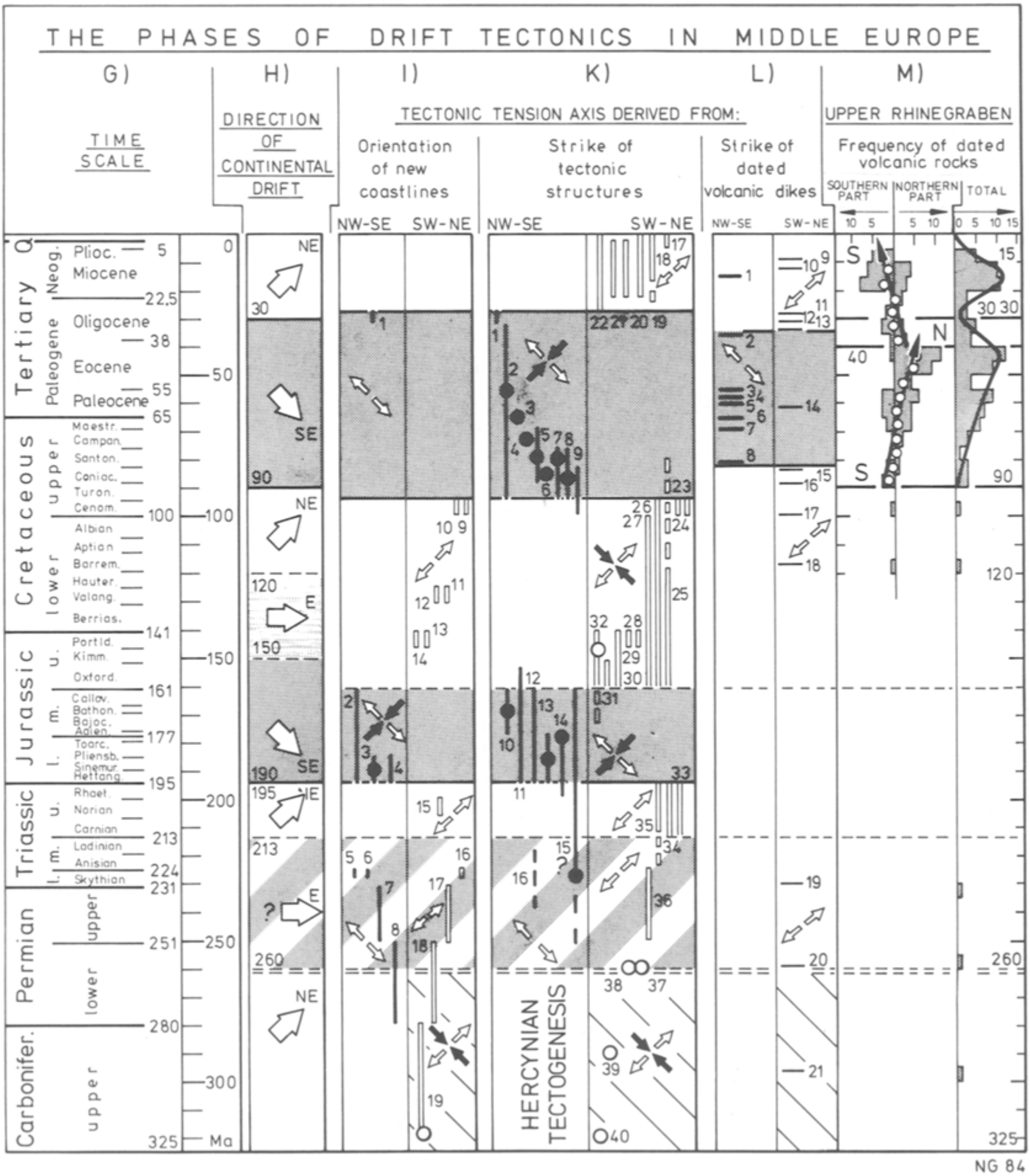


Fig. 3. G-M Phases of drift direction (H) are reflected in phases of intraplate-deformation (I-L). Frequency of volcanic rocks (M) along the Upper Rhinegraben displays a shift in counterdrift direction. For references see Tab. 2.

tal drift. If the continents are rejoined as in Fig. 4A, it can be demonstrated that from Laurasia's re-united polar wander path the direction of absolute continental drift can also be derived.

Since every plate motion on Earth's surface represents a rotation around a rotation pole, that rotation which transports the final point of a polar wander path (in this case the 190 Ma Position) exactly along the path to its starting point (here the 330 Ma pole-position) represents the absolute direction of continental drift. Therefore, in Hercynian time, the rotation pole should have been located in the N-Pacific so that Laurasia's drift between 330 and 190 Ma could have moved Asia's coast 3000 km toward the geographic pole. Paleoclimatic evidence is provided by the distribution of reefs (BEDERKE & WUNDERLICH, 1968:13) in Carboniferous and Triassic-Jurassic times, which are arranged parallel to the respective paleomagnetic equators, proving northbound continental drift.

Geometrically, the position of the rotation pole is defined unequivocally: Firstly, it is located on the great circle, which lies within the plane of symmetry between the starting- and the final points of the polar wander path. Secondly, the distance of the rotation pole from the polar wander path is defined by the condition that the polar wander path coincides with one of the small circles around the rotation pole. The second condition is less well fulfilled, due to the scatter of data.

When a sufficient number of measurements is available the rotation pole can be satisfactorily determined.

Fig. 4 demonstrates that the most important structures of Hercynian lithospheric deformation are clearly related to the absolute direction of drift: The most important compressional structure, the Hercynian »super foldbelt«, was formed parallel to the drift along the SE-border of Laurasia, whereas the most important rift system, precursor of the break-up of Laurasia, was oriented transverse to the drift (Fig. 4B, 4C). Therefore, the Pangean lithosphere was subjected to a transversal compression and a longitudinal extension.

Almost contemporaneously with this deformation, the megacontinent Gondwana collided with Laurasia, succeeded by a number of smaller continental terranes, e.g. Sino-Korea, Yangtse and Tibet (JONES et al., 1982). Paleomagnetic data and the geometric conditions (Fig. 4B) show that in Hercynian time compression of the plate margins contemporaneous with this convergence, was connected with lateral-type convergence of the continents. Frontal convergence, however, usually thought to result in foreland compression (Fig. 1), is contemporaneous with foreland dilatation, as demonstrated later.

Drift Tectonics in Central Europe

This clear relationship between drift and tension-field in Hercynian times was still unknown in 1981, when the author began a closer investigation of the relationship between the deformational history of Central Europe and the tensional history of the Austroalpine Altkristallin (Field measurements: GROHMANN, 1979; TROLL & GROHMANN, 1981; GROHMANN & TROLL, 1983). The research showed that the European foreland as well as the Alpine mountain chain was subjected alternately to NE-SW and NW-SE compression. In addition to the two last phases of foreland compression, described e.g. by ILLIES (1975) and SCHÄFER (1978), several other phases were documented.

This change in the direction of horizontal compression can be demonstrated most clearly by the orientation of vertical volcanic *dykes* (Fig. 3L): Nearly all dykes which are younger than approx. 35 Ma strike ± NW-SE. This corresponds to the present orientation of horizontal compression (NW-SE) and dilatation (SW-NE) (AHORNER, 1978), which has thus prevailed since the Oligocene. In the previous phase (approx. 85–35 Ma), almost all dykes formed ± perpendicular to the younger ones. Thus, some 35 Ma ago, the tension field rotated through approx. 90°. Basaltic dykes which are older than 85 Ma show the same orientation as the Neogene dykes.

The same division into phases of tension-orientation was found in the orientation of tectonic structures, such as normal faults, reverse- and thrust faults and folds (dated using field relationships of and fossils in the sediments) (Fig. 3K). These structures enabled the division of the time before 160 Ma into tension-phases. A similar pattern resulted from the orientation of long parallel coastlines, which are newly formed during epeirogenic movements (Fig. 3I). Often, they reflect a regional crustal stretching.

This development of a model of European tension history marked a deciding step: It was now obvious that the best-defined events of continent-wide re-organization of the tension field coincided with the sharpest »hairpins« of the polar wander paths.

Moreover, the reconstruction of the kinematics of continental drift on the basis of the sea-floor spreading data, revealed that even in Alpine time orientation of drift and deformation have been directly connected:

1.) 190 Ma ago, the period of Hercynian drift was succeeded by a clockwise rotation of the supercontinent Pangea (white arrows in Fig. 3, D–F), as indicated by the polar wander paths of the northern and the southern continents (ANDERSON & SCHWYZER, 1977) (Fig. 5A). Europe moved SE-wards (Fig. 2A, 12) and was obviously dilated too in this direction. This is to be deduced from the strike of N-Germany's linear salt-diapirs (»Salzmauern«, SANNEMANN, 1968) subparallel to the Alpine geosyncline: Both

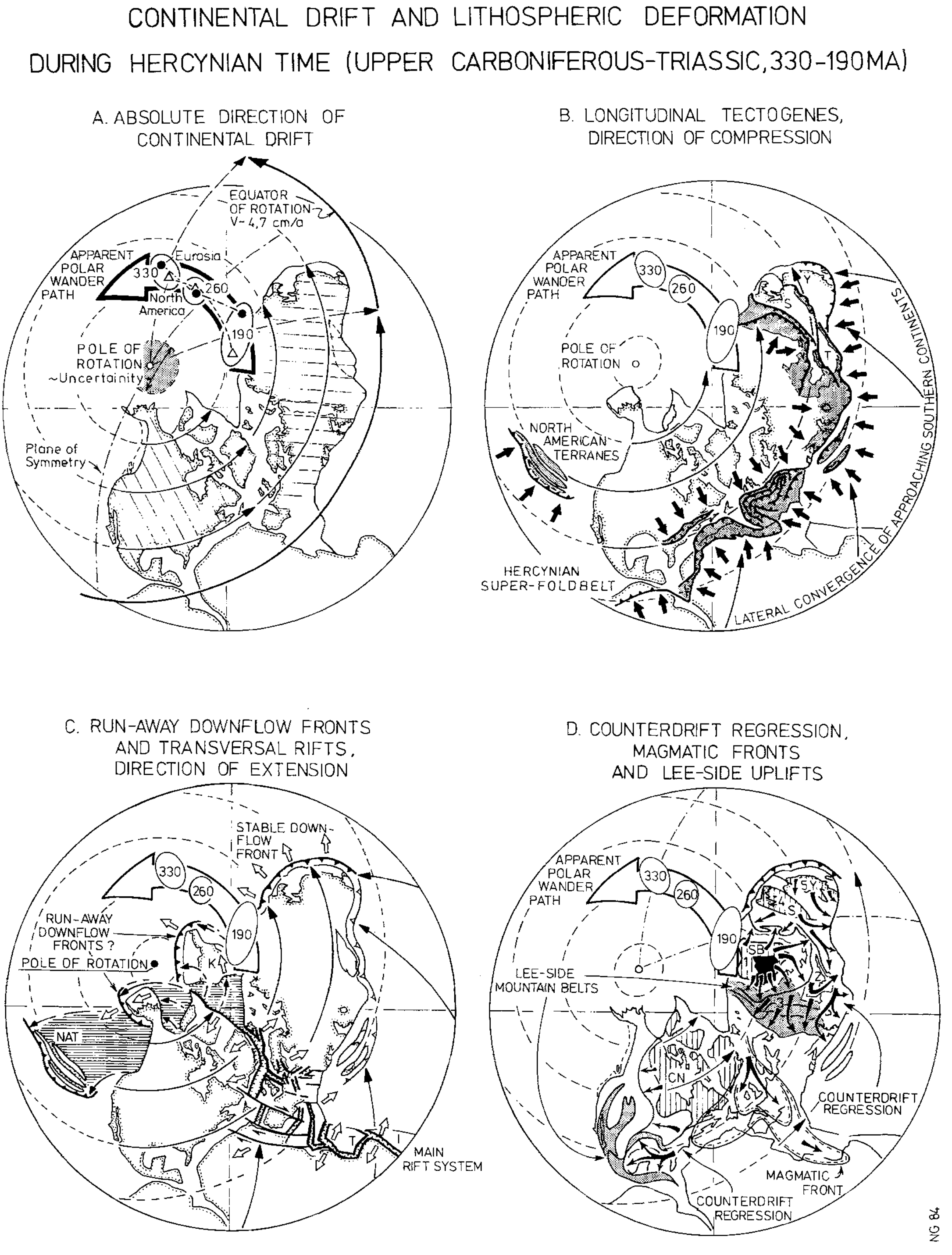


Fig. 4. Relationship between drift and deformation during the Hercynian formation of the Pangean supercontinent. CN, Canadian shield; K, Kolyma; NAT, N-American terranes; S, Sino-Korea; SB, Siberia; T, Tarim; Y, Yangtse.

structures are dominated by NE-striking normal faults. A similar direction of extension may, as explained later, be responsible for the transgression of the Hessian-Burgundian strait, transgressing from NE to SW over the Hercynian mountainland. The Germanic basin, which is perpendicular to these lithospheric extension zones, is a broad compressional structure with thick Liassic sediments (POZARYSKY & BROCHWICZ-LEVINSKI, 1978: 544) on the thick lithosphere of the Danish-Polish trough.

2.) During the Upper Jurassic-Lower Cretaceous phase (Fig. 2B) the tectonic-epeirogenic situation was totally different, in that SE-striking structures dominated. In N-Germany only a few linear salt diapirs followed the older NE-direction, in spite of the fact that they did rise by an independent diapiric process (TRUSHEIM, 1960; SANNEMANN, 1968; RUTTEN, 1969). The majority were formed parallel to a SE-striking mother-saltstock. This strike, indicating a continent-wide dilatation in SW-NE direction (Fig. 3 I–L), dominated the coastlines of the Ukrainean shield, faults in the Danish-Polish trough, the Beskydy parageosyncline HANZLIKOVA & ROTH, 1965) and the Donaurandspalte along the SE- respective SW-margins of the Bohemian massif, the Anglo-Gallic basin as well as new faults in the Carpathian geosyncline during this phase. According to the polar wander curves of N-America and Eurasia (Fig. 3D, E), this change in the direction of extension from NW-SE to SW-NE corresponded to a change of drift-direction from a SE-wards drift during Lower Jurassic (190–150 Ma) to a NE-wards drift during the Lower Cretaceous (150–90 Ma). The continous change of drift-direction between 150 and 120 Ma, suggested by Fig. 3H, is caused mainly by a scarcity of data for this time (Fig. 3B). This change was probably quite abrupt, however, since the Dogger/Malm boundary separates two phases of tension-orientation in Europe and Asia. Regardless of the duration of this change over, it became clear that during the two drift phases from Lower Jurassic to Lower Cretaceous the direction of horizontal extension corresponds also to the direction of continental motion.

3.) The polar wander curves of Eurasia and N-America exhibit at 90 Ma a sharp turn of nearly 180° and a pronounced curvature in the following time. This implies that the rotation poles of both continents were close to the polar wander curves: N-America moved, rotating counterclockwise, towards the Gulf of Mexico (Fig. 3E). Only 8 Ma later, Greenland-Eurasia broke away from N-America whereupon Baffin-Bay opened (BERGER & SEIBOLT, 1982, cit. in BISCHOFF, 1984:66) and Europe, still rotating counterclockwise, moved towards the SE (Fig. 3D).

This phase of European SE-wards drift continued into the Oligocene. Coinciding with the re-convergence of Europe with the Alpine-Carpathian pile of nappes formed in the meantime, the phase exhibited not only tension parallel to the drift (Fig. 3H–L) but also a strong compression perpendicular to the drift. At the beginning, compression prevailed: numerous systems of tear faults, which had opened during the foregoing phase, were converted into reverse faults and thrusts. The Lower Saxonian tectogene (Teutoburger Wald, STADLER & TEICHMÜLLER, 1971, the N-margin of the Harz Mts. and the Lausitz thrust are well-known examples. The Upper Cretaceous sediments have been folded here, as in the Bodenwöhr basin W of the Bohemian massif and in the Danish-Polish trough.

As Central Europe approached the Alpine tectogene, volcanism in the foreland increased, forming dykes parallel to the Alpine margin (Fig. 3L). While the orientation of tension remained constant, the component of extension obviously increased and resulted in tear-faults in the Molasse basin (KING, 1977:1683) as well as in the rifting of the Upper Rhine graben during the Lower Tertiaty (Fig. 2D). Folding of the foreland due to a dominating compression was confined to a distinct minimum-distance from the tectogene and occurred for example in the Pays de Bray anticline (N-France) and in the Wealden dome (S-England) (ZIEGLER, 1978:618).

4. Overthrusting of the Helvetic zone and the beginning Alpine uplift (GWINNER, 1971:122, 166f) indicate the Oligocene collision between the Alps and Europe. It is evident that volcanism of the foreland was not increased by this collision; on the contrary, it decreased, reaching its next maximum only in Middle Miocene (Fig. 3M). The orientation of today's tension field (GREINER, 1975, AHORNER, 1978) came into existence for the first time in the Oligocene (±35–30 Ma), contemporary with the change to the Neogene drift direction.

Therefore, nearly the whole Upper Paleozoic in Europe exhibits a division into phases of tension and drift direction, which are oriented alternately SW-NE or NW-SE. Only the time span between 270 and 213 Ma, when both directions are observed simultaneously, does not fit the simple scheme. According to the strike of Permian coastlines and sedimentary basins (KÖLBEL, 1970:400, 403), this could well be an interference of two conjugated shears (hk0-faults), whereby the North Sea and Oslo grabens, as N-S striking bisectors, suggest N-S compression and E-W dilatation. This means a rotation of Central Europe's tension field through approx. 30–35° after the close of Hercynian tectogenesis. Although details of Permian tectonics are still under discussion, two processes, whose consequences may superimpose, are likely to explain this phase:

1.) Large-area shear movements between N-America, Europe and Africa (ZIEGLER, 1984:56), which resulted in somewhat differing drift directions since the 260 Ma discontinuity of the polar wander curves (Fig. 4A).

2.) A wide front of volcanic activity which advanced during the Permotriassic from the N over W-Europe and Turkey to Sinai (Fig. 4D).

To summarize the geologically provable relations between drift and deformation in Central Europe, it became evident that epeirogeny is to a major part a kind of horizontal lithospheric deformation which reflects the phases of the drift. Up to now, this has been suspected, but not verified. Contrary to the hitherto existing opinion (e. g. NAIRN, 1975), a continent is not shortened but stretched in the direction of its movement. Since it was found that this phenomenon follows a general rule, even where it is not explained by plate tectonic models, it may be suitably termed drift tectonics.

Drift Tectonic Crustal Extension: the Break-Up of Gondwanaland

Since the early sixties, when interest was focussed on ocean exploration, the crustal structures Rhine graben, Red Sea, Atlantic Ocean have usually been regarded as the subsequent steps of a development over hot rising mantle upwellings (OROWAN, 1965, DIETZ & HOLDEN, 1970, DEWEY & BURKE, 1974, BISCHOFF, 1983). Contrary to these very simplified models of successive development of an ocean, data about the actual phases of volcanism and epeirogeny in Africa revealed again clear relations to the rhythm of continental drift. Because of space limitations this paper will deal only with those drift tectonic phases which resulted in the break-up of Gondwanaland:

At the beginning of the 200–130Ma phase (Fig. 3F) slow uplifts, accompanied by the vast Karroo-volcanism (210–154Ma; MAAK, 1969:98), caused the development of the African Gondwana erosional surface (HOLMES, 1965:62f.; WALTERS & LINTON, 1973:152). Thus presumably a hot upwelling existed in the upper mantle, but it cannot be regarded as the main cause of the continent's disintegration, since the break-up started much earlier and at a distance of 6000 km from the volcanic centre, between Arabia and India (Fig. 5A): Already in the Upper Permian a marine strait transgressed from this area to Madagascar. During the Jurassic two propagating rifts advanced to the volcanic centre. This opening of the early Indian Ocean was accompanied by crustal subsidence and transgression over Arabia and Ethiopia (TERMIER & TERMIER, 1960; BELTRANI & PYRE, 1973:170).

Fig. 5 outlines the situation at 134 Ma (Anomaly m 16 time, considerably modified after NORTON & SCLATER, 1979:944, 946): India, Seychelles Bank and Madagascar had already shifted S-wards along large dextral shear zones. Overlaps in predrift-reconstructions (e. g. NORTON & SCLATER, 1979:956) suggest a deformation of the Antarctic Peninsula along dextral shear zones, too. Subparallel shears separated the Agulhas plateau from Africa. They form one of two conjugated shears, which mark the orientation of the Karroo-dykes (CLIFFORD & GASS, 1970:323).

In an acute angle to this the second Karroo-direction strikes E-wards. Since both shear directions outline, even further to the N, volcanic dykes (CLEVERLY, 1979) and crustal blocks such as N-Madagascar, it is possible to construct a shear net of the tensional relations in Jurassic times (Fig. 5B).

This drift tectonic phase was finished, when rifting and crustal subsidence (MASCLE & PHILLIPS, 1972; REYMENT, 1969) had propagated around S-Africa to initiate the separation of S-America and Africa. During this opening of the S-Atlantic (FÖRSTER, 1978), Africa-India rotated counterclockwise and separated from S-America-Antarctica (Fig. 3F). The now inactive rifts along E-Africa together with simultaneous uplift leading to the formation of the Gondwana erosional surface (HOLMES, 1965:602f.; WALTERS & LINTON, 1973:152), as well as a new orientation of the post-Karroo dykes (Fig. 5) (REEVES, 1978), indicate the formation of a new tensional regime.

From the Jurassic shear net the pertinent tension field can be derived whose orientation is defined by the relative motions along the shear zones as well as by the acute angles in the shear net. As a cause of the compressional trajectories which diverge from the tips of Antarctica and S-America towards the N (black arrows in Fig. 5B), one could postulate a parallel flow in the asthenosphere. The opening of the Indian Ocean, however, is not explained by this flow, since it propagated in the reverse direction from N to S.

Instead, this example, too, reveals an extensive coincidence of the curved extensional trajectories and the direction of absolute drift. The orientation of extension is obviously also the main factor of small-block rotation (Ceylon, Spain, and, perhaps, W-Burma): here, instead of a continous rift, large systems of »feather joints« developed; the newly formed blocks between the joints remained attached to the diverging continents at two diagonally opposite points and thus rotated contemporaneously with the beginning sea-floor spreading (Fig. 5A, B). A well-known example of this process is the Danakil-Alps (Afar-triangle, BARBERI & VARET, 1977), where the tensional rotation is proven by paleomagnetic data (BUREK, 1973).

Drift Tectonic Compression: the »Epiplatform Orogenesis« of Asia

In 1965, when Russian geologists constructed the Tectonic Map of Eurasia (1:5 000 000) on the basis of all available data, they also faced the difficulty of fitting the geological development into a standard scheme. It turned out that the onset of the Caledonian, the Hercynian and the Alpine tectonic megacycles in Asia did not coincide with the European tectonic development. Characteristic stages of the

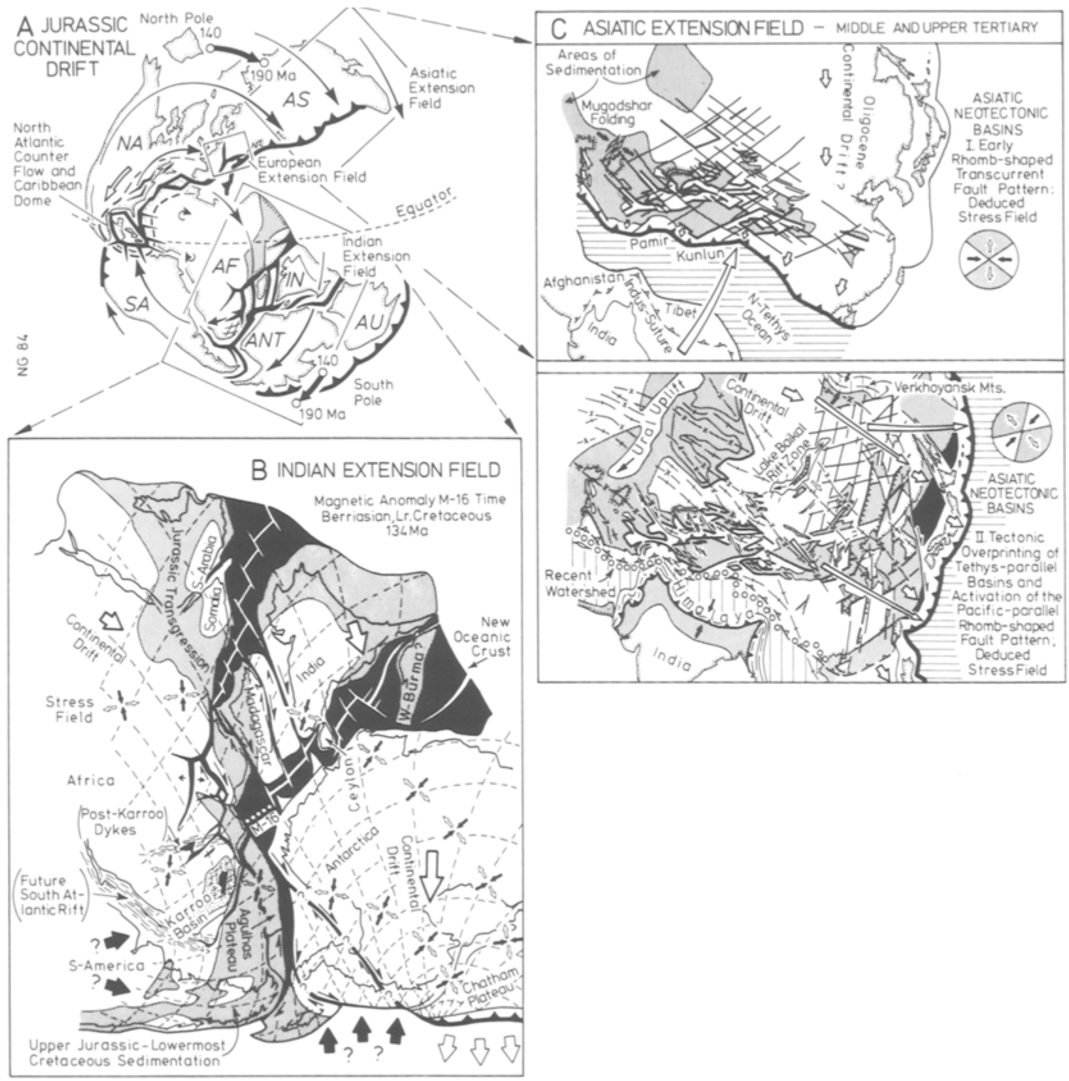


Fig. 5. A. Rotation of Pangea in Lower Jurassic times. B. Propagating rifts and corresponding shear-net during the Jurassic break-up of Gondwanaland. C. The last two stages of lithospheric deformation in the Asian extension field. The Middle Tertiary direction of drift repeats the Jurassic direction.

development revealed a shift of up to 100 Ma in the individual areas (CHAIN, 1968:67 f). Thus JANSCHIN concluded that »many modern tectonic theories would have been formulated differently, if the exploration of tectonics and crustal development had started not in Europe, but at the coast of the Pacific Ocean (1968:57).

It became clear that large areas of the crust could be classified neither as platforms with terminated folding nor as true geosynclines: In these »paraplatforms« graben-like basins, filled with up to 7000m of sediments, volcanics and granitoids repeatedly came into existence. Locally these »Epicaledonic«, »Epihercynian« and »Neotectonic« basins have been affected by metallogeny and folding. Besides JANSCHIN (1968:53), BELOUSSOV (1980:197) presents numerous examples for the fact that Asia's tectonic development does not fit into STILLE's cycle of orogeny:

1.) After the end of the Hercynian geosynclinal stage no mountain building succeeded on the Scythian and the Western Siberian platforms (1980:151).

2.) Between the end of the geosynclinal stage in the Middle Cretaceous and the Neogene uplift of the Werkhoyansk Mountains, there was a pause of 80 Ma (1980:152).

3.) Orogeny without a true geosynclinal development occurred in the Mongolia-Okhotsk zone in Early Mesozoic time (1980:154).

4.) Uplift after a Mesozoic-Paleogene platform regime has happened since the End of the Oligocene in the Tien Shan-Central Asia (1980:152, 154).

For these fundamental problems even the plate tectonic re-interpretation of the geosynclinal cycle by the »Wilson cycle« (DEWEY & BURKE, 1974) of the break-up and later convergence and collision of continents (DIETZ, 1972) gives no sufficient explanation.

The Neogene deformation of Asia, for example, on the basis of the compressional trajectories diverging N-wards from the Himalayan area is regarded as a consequence of the collision of India and Asia in Miocene times (MOLNAR & TAPPONIER, 1975). Contrary to this view, geological investigation of the Baikal graben showed that the development of this graben started much earlier, in Eocene times, and rifting propagated locally, not from the Himalayan area. Therefore LOGATCHEV & FLORENSOV, (1978:7) rejected the model of development of the Baikal area by horizontal transmission of pressure from the Himalayas.

Further, the Alpine foldbelts of Central Asia (JANSCHIN et al., 1968, Tectonic map) are superimposed on older foldbelts just as the Hercynian on the Caledonian folds in the Altai-Sayan area (BELOUSSOV, 1980:190). Often the younger folds disappear in the middle of older structures and the strike of the older folds remains visible in the interference with younger folds. A very similar tectonic situation in the Proterozoic mobile belts of Africa led KRÖNER (1977:173, 203) to refuse large relative plate movements as an explanation of the younger folds.

Therefore, VAN BEMMELEN (1975), BELOUSSOV (1980:304), the author (GROHMANN, 1981:277), ARTYUSHKOV (1982, pers. comm.) and KRÖNER (1982:28) developed vertical tectonic models to explain such intracontinental orogeny by hot mantle diapirism. Synchronous tectonic motions, however, occurring over a distance of thousands of kilometres, are not explainable by these models.

After the discovery of the drift tectonic phases in Europe and Africa, naturally the question arose wether this enigmatic synchronism is related to the change of the absolute drift direction. A revision of the data about the tectono-sedimentary cycles (»structural stages«) of Central Asia, published by JANSCHIN et al. (1968) and BELOUSSOV (1980), confirmed this hypothesis: apart from the still unclear movements at 224 and 65 Ma, most dates in Asia, too, (± 325, 213, 200-195, 160, ± 100 and ± 30 Ma) reflect the drift tectonic phases.

Because of the limitation in space, this paper can only demonstrate the youngest development. Similar to the period 150 to 90 Ma ago, Eurasia has been moving since 30 Ma parallel to the Hindukush-Himalaya belt towards the Pacific (Fig. 3D). The orientation of a continent-wide lithospheric deformation, which repeats the Upper Cretaceous-Lower Tertiary development of the foreland of the Alps (Fig. 2 C-D) on a larger scale, is unequivocally related to the drift-direction. Along the leading edge of the continent extension parallel and compression perpendicular to the drift (Fig. 7A) resulted in the development of a rhomb-shaped block pattern. In China these faults slashed the curst (HILLS, 1983:675), forming ridges of up to 2000 m height which determine the pattern of Plio-Pleistocene sedimentation (Fig. 5C II).

Behind this extension field, on the W-Siberian platform, N-S directed compression resulted in the development of drift-parallel epeirogenic synclines and anticlines (Fig. 5C II, after BELOUSSOV, 1980:24). Further S-wards, between Tienshan and Tibet, the Neogene »epiplatform orogenesis« (BELOUSSOV, 1980:154) represents a gigantic exaggeration of this intraplate-deformation: large crustal blocks have been broken from a platform already peneplained by erosion, and pushed up to 5000 m, whereas adjoining basins have been depressed down to 4000 m (SAWARENSKI & KIRNOS, 1960:69). According to an isostatic map of the Soviet territory (ARTEMYEV, 1973) the uplifts are marked by positive, the synclines and depressions by negative isostatic anomalies.

These structures, however, are not explainable by a one-stage development. Contrary to the Pacific coast, where the orientation of the acute angle in the rhomb-shaped fault pattern is compatible with the recent N-S compression, the orientation of rhomb-shaped blocks of Central Asia suggests N-S dilatation (Fig. 5C I). The activation of these faults began indeed during a drift period, when extension was N-S directed. After the N-S compression of the preceding 190–150 Ma drift period, a continous sedimentary structural stage with fault block tectonics (NALIVKIN, 1973:548, 554) and a last marine ingression into the Tarim basin (SCHAFFER, 1941:764–771) coincided with the Upper Cretaceous-Lower Tertiary phase of drift.

The simultaneous counterclockwise rotation of Laurasia formed the drift tectonic background of this N-S dilatation, whereby Eurasia separated from

N-America, and a complete island arc broke away from Eurasia's lee-side: this may be concluded from the paleomagnetic poles of Central Iran (SOFFEL, 1978, pers. comm.) and Tibet (MOLNAR & CHEN, 1978; COURTILLOT, 1983, pers. comm.), which are nearly identical and indicate a S-ward shift of 2000 km relative to Eurasia between Upper Cretaceous and Lower Tertiary (Fig. 3 D). The simultaneous rapid N-ward drift of India (Fig. 3 C, F) was therefore terminated in the Eocene not by a collision with Asia itself, but by a collision in 10°N latitude (Paleomagnetic measurements in Ladakh, KLOOTWIJK et al., 1979) with this island arc.

The N-Tethys Ocean, which had opened during that time between the N-Afghanistan-Kuenlun zone of Eurasia and the island arc, must have closed again during Oligocene times. The folding of the Mugodjars (S-Ural, NALIVKIN, 1973:358) indicated continuing E-W compression along Eurasia's S-margin (Fig. 5C I) during this convergence. Traces of the End-Oligocene final collision are deformed Upper Cretaceous-Lower Tertiary sediments in the Kuenlun (GATTINGER, 1961:141) and Karakoram (SCHNEIDER, 1957:438, 464), the course of the recent watershed (Fig. 5C II) and a zone of intermediate earthquakes (SAWARENSKI & KIRNOS, 1960:63) along the Gorband-Pjanshir suture.

This development was followed by the Neogene phase of drift (Fig. 3) and the new direction of transversal compression, which pushed the block mountains of central Asia to their present height. Thus, according to the data available, the deformational history of Central Asia is a clear reflection of the drift phases since Upper Jurassic times. On the other hand, the previous popular one-stage concept of a simple N-S compression between India and Asia explains neither the observed correlation between the direction of drift and extension, nor the continuation of the recent trans-Himalayan tension field into Europe and N-America.

Drift Tectonic Structures: Regional Temperature Anomalies of the Lithosphere

The examples above demonstrated how the history of intraplate deformation reflects the history of drift. In the meantime, intensive comparison with geophysical data revealed that the lithospheric structure has a strong influence on this regular epeirogenic behaviour. This was first indicated by the fact that an isostatic equilibrium between crust and mantle does not exist everywhere. According to AIRY (1855) topographic height should always reflect the thickness of the crust. Increasing knowledge of the seismic crustal structure has shown, however, that there are remarkable differences in topographic height up to 8 km at the same crustal thickness (GROHMANN, 1981:193). Since seismic measurements in Central Asiaś block mountains (RYABOY & SHCHUKIN, 1975, VINNIK & LUKK, 1975) revealed high-lying, leight asthenospheric material beneath uplifts, e. g. Tienshan Mts., and a thick, dense lithosphere beneath depressions, e. g. the Tarim Basin, it has become clear that lithospheric thickness and consequently upper mantle temperature also influence topographic height.

Therefore, the author computed an improved three-layer isostatic model (crust, lithosphere, asthenosphere) of the area treated in his paleogeographic atlas of Central Europe, deducing by the reverse procedure lithospheric thickness from the difference between the real topographic height and the ideal topographic height calculated on the basis of crustal thickness.

In spite of the somewhat simplified model, the lithospheric thickness thus computed displayed a good correlation with the seismically measured lithospheric thickness, the heat flow, the pattern of volcanism and the recent epeirogenic history. It was, therefore, interpreted by the author as a proof of shallow convection: a diapiric mass exchange between a sinking, soft lower lithosphere and a rising, hotter and less dence asthenosphere (GROHMANN, 1981:201, 224, 263).

Whereas this model of varying lithospheric thickness gained additional confirmation from new seismic data (SOURIAU, 1981, PANZA et al., 1982), closer investigation of epeirogeny indicated that long-periodic shallow convectional movements are modified by short- periodic drift tectonic dynamics. This, in turn, can be understood as the reaction of two basic models of linear lithospheric anomalies to the changing tension field.

A well-known example of a thin lithospheric anomaly is the history of the Upper Rhine graben (Fig. 6C). As long as drift and dilatation was directed E to SE (260–210 Ma), a hot basin was formed by regional stretching of the Hercynian mountain belt and transgressed by the sea (Fig. 2A). Calculations showed that regional stretching of crust and lithosphere, without the formation of grabens, results in topographic subsidence, even when the influx of asthenospheric material under the thinned lithosphere maintains isostatic conditions (GROHMANN, 1981:193).

During the Dogger/Malmian re-orientation of the drift, paleogeography also changed very quickly. The former basin became the axis of a topographic uplift striking NNE (Fig. 2B). Because of the onset of volcanism along this axis and the strike of the dykes perpendicular to it (Fig. 3L), there is no doubt that the thin lithospheric anomaly was transformed into a giant fold by the re-orientation of compression. Obviously, lithosphere was hereby pushed onto the flanks of the asthenospheric rise, until the weight of the newly formed hot uplift had balanced lateral compression.

In the following phase, a renewed SE-direction extension, faulting was concentrated along the hot axis, due to gravitational spreading (JACOBY, 1970; ARTYUSHKOV, 1973) of the hot uplift. After the formation of parallel dykes (Fig. 3L), rifting started in Upper Eocene times at the sector of the S-Rhinegraben closest to the subduction front of the Alps, extending during the Oligocene in both directions, towards the Rhone graben as well as N-wards along the Rhine graben (Fig. 2D). It was therefore triggered by extensional forces, and not by plate tectonic compression, as suggested by ILLIES (1974, 1975).

The last re-orientation of tension, at the beginning of the Neogene drift phase, converted the zone into a hot uplift again, forming today's topographic relief. At rates of uplift of several 100 m since Pliocene times in the Black Forest, Odin's Forest and Hunsrück (DORN-LOTZE, 1971:175, 112, 47), the time-span since Middle Miocene is sufficient to explain the whole uplift of these low mountains.

Therefore, the epeirogeny of the Upper Rhine area can be described by the model of a thin lithospheric anomaly under changing tensional conditions. This is confirmed by the fact that the Lower Rhine graben, striking nearly perpendicular to the Upper Rhine graben, shows exactly the reverse epeirogenic behavior: Uplift during Upper Cretaceous-Lower Tertiary and subsidence since Middle Oligocene times (DORN-LOTZE, 1971:271; ILLIES, 1974:5, 10). Moreover, the drift tectonic history of Gondwana and Asia followed the same rules. Linear thin lithospheric anomalies reflected in their epeirogenic history the drift tectonic phases, forming alternately transversal basins or longitudinal swells.

Structures such as the Danish-Polish trough or the Paris Basin displayed a completely different behaviour. In spite of an extraordinary thickness of 30–55 km, the crust in these zones is subsiding, and not rising. According to the isostatic model of Central Europe (GROHMANN, 1981:201), this can be caused by an extraordinary lithospheric thickness (Signature 4a in Fig. 2A). Subsequently, it turned out that this anomalous subsidence increased when the zones were oriented as longitudinal basins, e. g. in Liassic times (Fig. 2A; RUTTEN, 1969:425; POZARYSKI & BROCHWICZ-LEWINSKI, 1978).

This behaviour, too, can be explained. The general tendency of thick lithosphere to sink into the asthenosphere (GROHMANN, 1981:267; HOUSEMAN et al.,1981) is increased in such periods by transversal compression (Fig. 6D). In periods of extension, however, the tendency of lithospheric subsidence is balanced by the tendency of asthenospheric uplift. Hence, the anomaly remains relatively stable, whereas extensional tectonics shift to the adjacent thinner lithosphere (Fig. 6E, Fig. 2B).

These basic models may be complicated by shear movements, if the supra-regional tension field is not orthogonally but obliquely oriented to the anomalies.

A broad linear zone with thin crust and positive Bouguer anomaly (STRAHLER, 1971:434; WOOLARD, 1972:474) exists along the Mississippi Valley. Slight modern uplift in this region, a remarkable seismic activity (JOHNSTON, 1982) and an already positive isostatic anomaly (WOOLLARD, 1972:476) probably indicates the contemporaneous conversion of this Eocene basin into a hot longitudinal uplift.

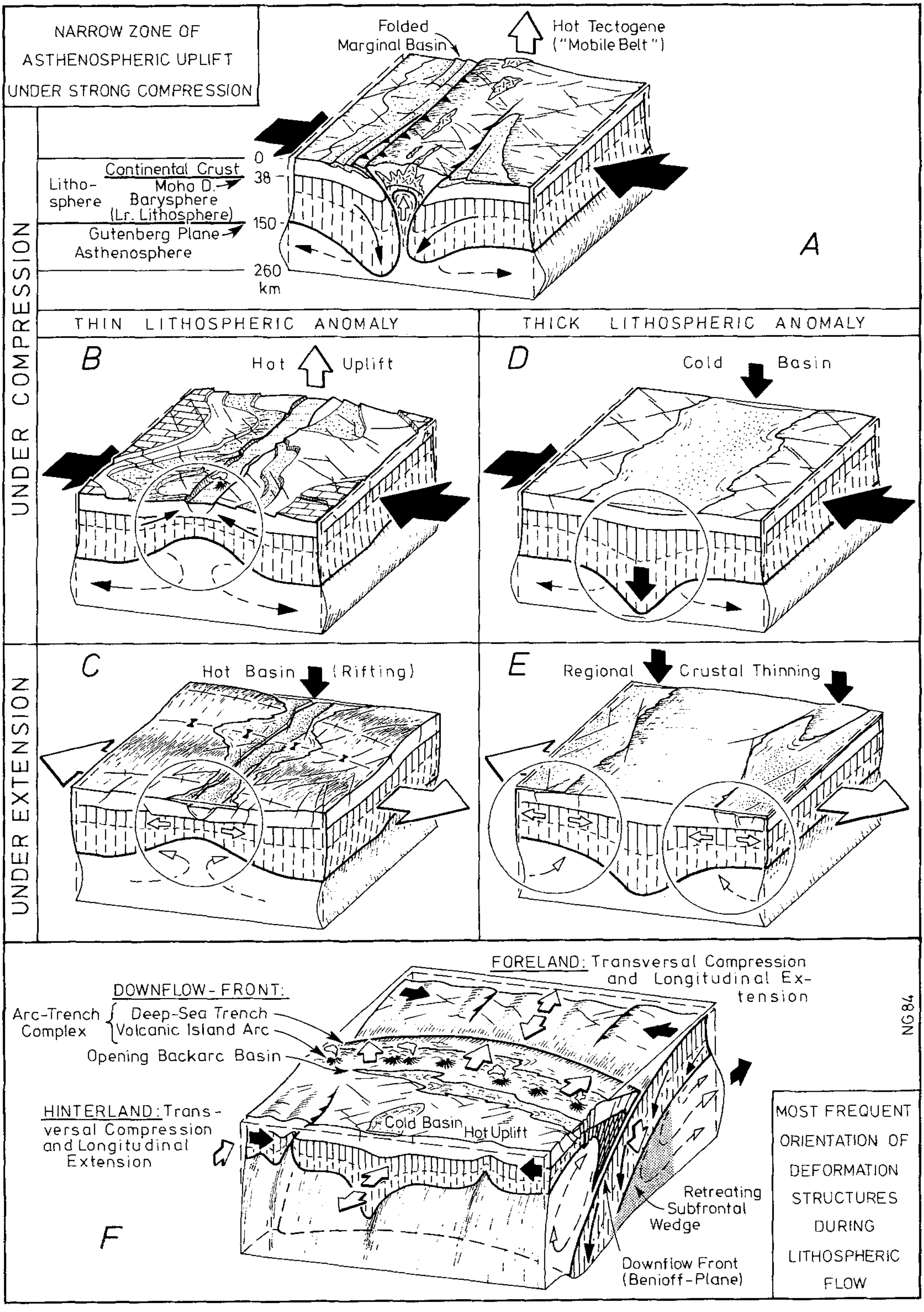
The Cretaceous »inversion« of former graben structures in Europe (Fig. 2B/2C) (RUTTEN, 1969:423, 426) and the »epiplatform orogenesis« in Asia (Fig. 5C I/C II) are comparable processes. Archean greenstone belts and Proterozoic mobile belts are likely to be Precambrian counterparts to these Phanerozoic hot tectogenes. The specific geometry of a hot tectogene with one or two marginal basins (Fig. 6A) may depend upon the original geometry of the lithospheric basis, locally perhaps also upon preceding heating by asthenospheric diapirs. As the extreme form of this intraplate-deformation, a shallow overthrusting of two crustal plates, the so-called »A-subduction« (BEHR, 1978; WEBER, 1978) in the Hercynian mountains, seems also to be caused by drift tectonic transversal compression (Fig. 4B).

Thus, there is increasing evidence that drift tectonic deformation can be understood as a consequent reaction of anomalies of temperature, strength and thickness of the lithosphere to the tension field, resulting in vertical motions and isostatic anomalies.

Contemporaty Drift Tectonics on Oceanic Plates

To investigate the still open question of the origin of the tension field, the author projected all available data about today's stress and strain in the lithosphere onto a globe, constructing a net of tension trajectories and comparing it with the new polar wander paths. A key to a new understanding of lithospheric deformation was found in data obtained from oceanic areas. Whereas in early studies undistorted flat layers of oceanic sediments seemed to confirm the rigidity of the plates (DEWEY, 1972:59), there is now increasing evidence of a specific deformation of oceanic lithosphere.

MENARD (1973) could show that deviations from the normal depth-age correlation form a regular pat-


NARROW ZONE OF
ASTHENOSPHERIC UPLIFT
UNDER STRONG COMPRESSION
Folded Marginal Basin
Hot Tectogene ("Mobile Belt")
Litho-sphere
Continental Crust
Moho D.
Barysphere (Lr. Lithosphere)
Gutenberg Plane
Asthenosphere
0
38
150
260
km
A
UNDER COMPRESSION
THIN LITHOSPHERIC ANOMALY
THICK LITHOSPHERIC ANOMALY
B
Hot Uplift
D
Cold Basin
UNDER EXTENSION
C
Hot Basin (Rifting)
E
Regional Crustal Thinning
FORELAND: Transversal Compression and Longitudinal Extension
DOWNFLOW-FRONT:
Arc-Trench Complex
Deep-Sea Trench
Volcanic Island Arc
Opening Backarc Basin
HINTERLAND: Transversal Compression and Longitudinal Extension
Cold Basin
Hot Uplift
Retreating Subfrontal Wedge
Downflow Front (Benioff-Plane)
F
NG 84
MOST FREQUENT ORIENTATION OF DEFORMATION STRUCTURES DURING LITHOSPHERIC FLOW

tern of undulation on the Pacific ocean-floor. Bathymetric and seismic measurements in the Indian Ocean revealed the existence of similar undulations connected with numerous thrust faults. Since HAXBY computed a continous map of all oceanic depth- and gravity anomalies on the basis of altitude measurements from the SEASAT satellite (FIFIELD, 1984:46; OLSON, 1983:38), it has become clear that these undulations are part of a global pattern.

Whereas this pattern was interpreted by MARSH & MARSH (1976) and MCKENZIE (1983) as a consequence of small-scale mantle convection, on the Indian plate clear relations to the compressional structures and the tension field, derived from seismic focal solutions, speak in favour of an origin in horizontal compression (ETTREIM & EWING, 1972; WEISSEL et al., 1980).

Measurements of two other deformational structures, the horizontal stylolithes and the upper mantle's seismic anisotropy, give further confirmation of the compressional hypothesis and reveal a connection to Europe's drift tectonics. One set of the well-known horizontal stylolithes of the Jurassic limestones in Europe reflects the youngest NW-SE compression (e.g. PLESSMANN, 1972; SCHÄFER, 1978). Similarly, the maximum P-wave velocity in the upper mantle beneath Germany parallels the Upper Rhine graben and is interpreted as a parallel arrangement of olivine crystals, forming a kind of lithospheric schistosity due to NW-SE compression (FUCHS, 1975). Both prove a continent-wide shortening of Europe's lithosphere perpendicular to the Neogene drift direction. The same is indicated in the Pacific, where maximum P-wave velocity (FUCHS, 1975) as well as MENARD's and HAXBY's ocean-floor undulations also parallel the Neogene drift direction.

Moreover, the data show that in the lower lithosphere, during the drift, a deformation by flow occurs. This can also be expected on the basis of upper mantle viscosity (VETTER & MEISSNER, 1977) and from the fact that seismically active fracturing is always confined to the upper part of the lithosphere (KATSUMATA & SYKES, 1969; GROHMANN, 1981:225). Since the elastic »rigid plates« of the theory form only $^1/_3$ to $^1/_2$ of the lithosphere's thickness, the author proposed the term »barysphere« (greek: barys = heavy) for the more ductile lower lithosphere which tends to sink into the asthenosphere (GROHMANN, 1981:227).

Analysis of the drift tectonic relations on the globe now revealed that global baryspheric flow is very probably the cause of the enigmatic longitudinal extension and transversal compression. As can be seen from Fig. 7A, the Indian plate, reaching from India to Australia, is not a linear feature because it is curved around the Sunda subduction zone. Since subduction pulls approximately seven times harder than a mid-ocean ridge can push (HARPER, 1975), this geometry forces the baryspheric flow from the ridge towards the Sunda arc to be be centripetal, but not parallel as in the classic two-dimensional plate model (Fig. 1). This centripetal, narrowing flow of the barysphere necessarily shows transversal contraction, longitudinal extension and acceleration of the flow velocity. Because of the very different rheological properties of the lithospheric layers, this should result in the development of a flow texture of the baryspheric olivines and in internal compression on the more elastic upper lithosphere, which may, in turn, react by the development of broad folding and some faulting (Cross section in Fig. 7B).

The development of a similar radial fault pattern due to centripetal, narrowing flow was also found on the planet Mercury, where the whole lithosphere did flow towards a gigantic impact basin (FLEITOUT & THOMAS, 1982). Experimentally, NICKEL (1967:73) produced a similar flow pattern in high viscous glucose flowing within a rectangular container towards a central outlet. On the Indian plate, the transversal convergence connected with this movement was proven by analysis of sea-floor spreading data to amount to 1 cm/yr between India and Australia (MINSTER & JORDAN, 1978).

The contemporaneous tension field, which is symmetrical to the plate's geometry (Fig. 7A), resembles the conditions in a stone arch, where concentric gravitational movement is converted by the elasticity of the wedge-shaped stones into a compressional field parallel to the arch. In both cases dilatation parallel to the movement is the primary, compression perpendicular to the movement the secondary force.

Surprisingly, this tension field continues over the mid-oceanic ridges. Here, increasing evidence indicates strong compression parallel to the ridges. In the Atlantic Ocean, for example, the real transform-fault pattern is not developed parallel to the small circles around the plate's rotation pole (Fig. 8A), as one would expect from idealized transform-fault kinematics (Fig. 8B). If we rotate the African and American plates back to their relative position some 15 Ma ago, omitting the sea-

◀ Fig. 6. Responses of lithospheric anomalies to changes of the tension field.

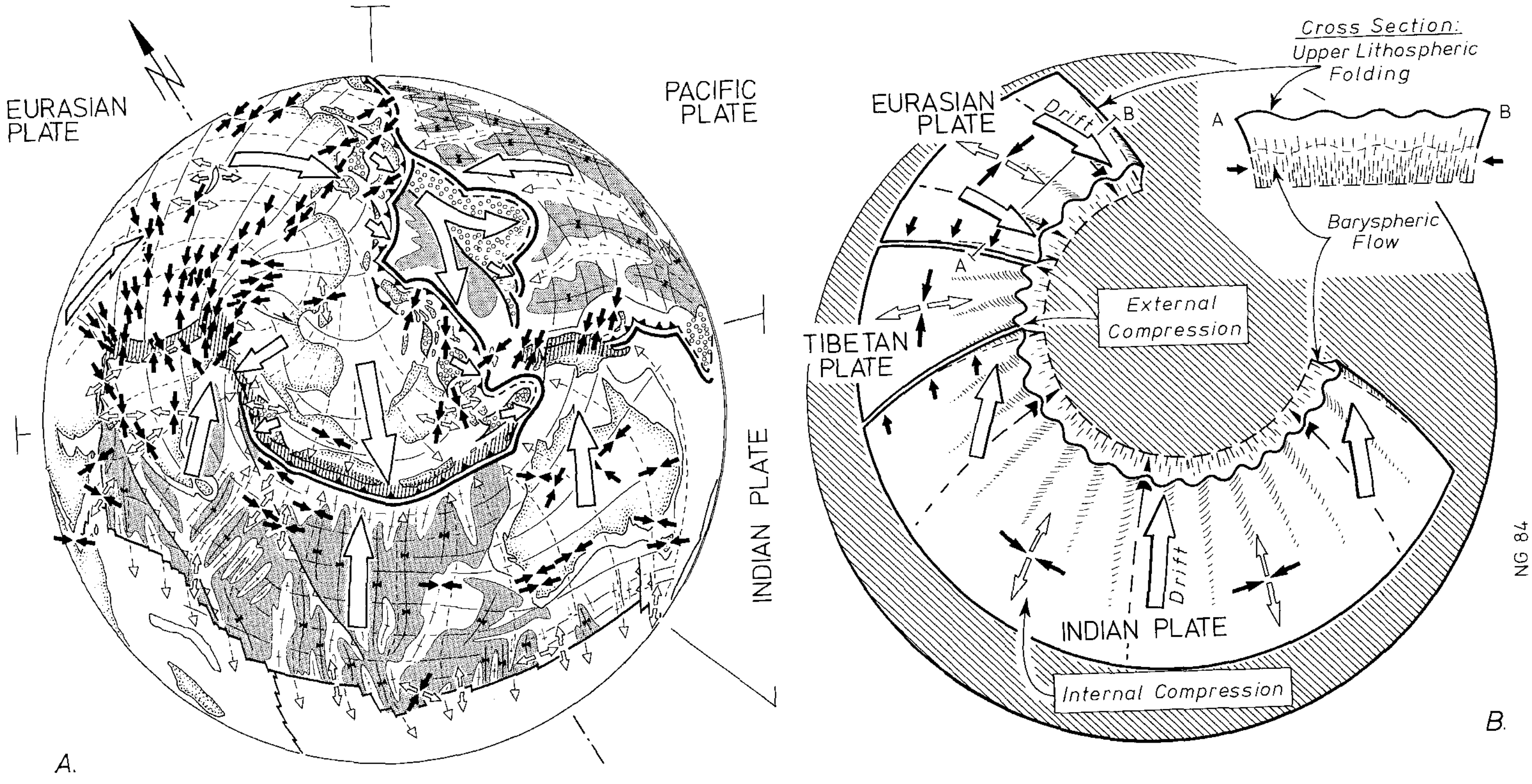


Fig. 7. A. Mapped stress-field of today's plate constellation around SE-Asia (Same ornamentation as in Fig. 9). B. Schematic diagram showing the effect of different viscosities of the Upper and the Lower Lithosphere on plates in centripetal motion: While this motion may result in viscous flow of the hotter and less viscous baryspheric (lower lithospheric) material, in the cooler and more rigid Upper Lithosphere it may result in visco-elastic folding by internal compression. Since the upper layers of these plates cannot flow in the manner of the Barysphere, their movement is resolved in sub-parallel rather than convergent motion.

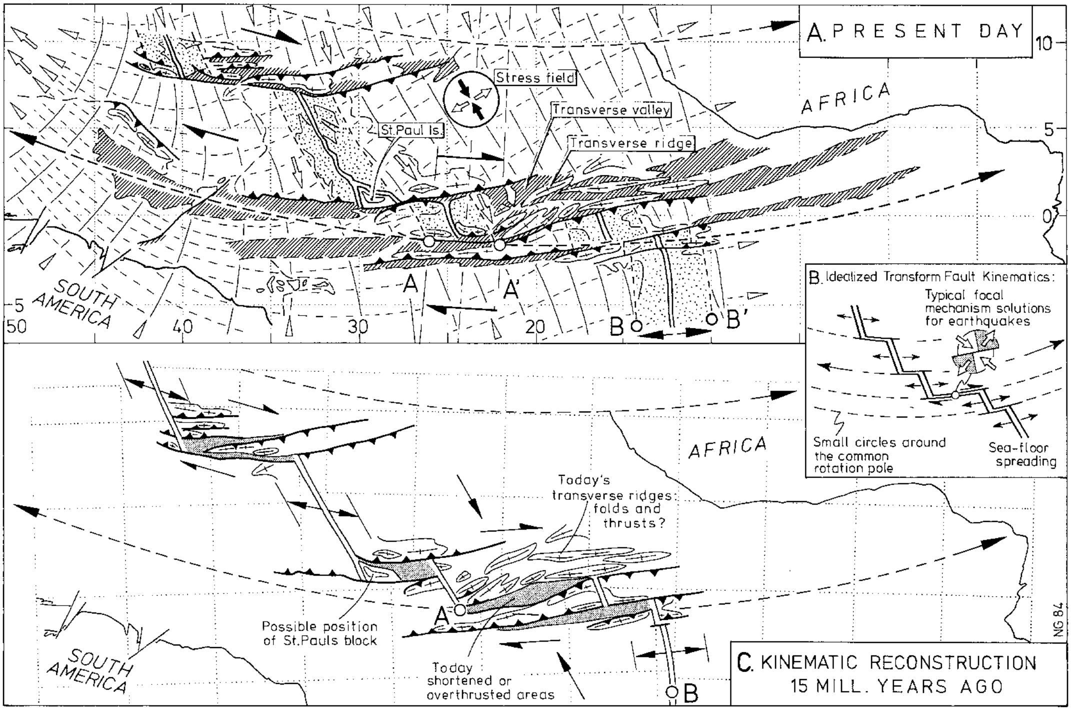


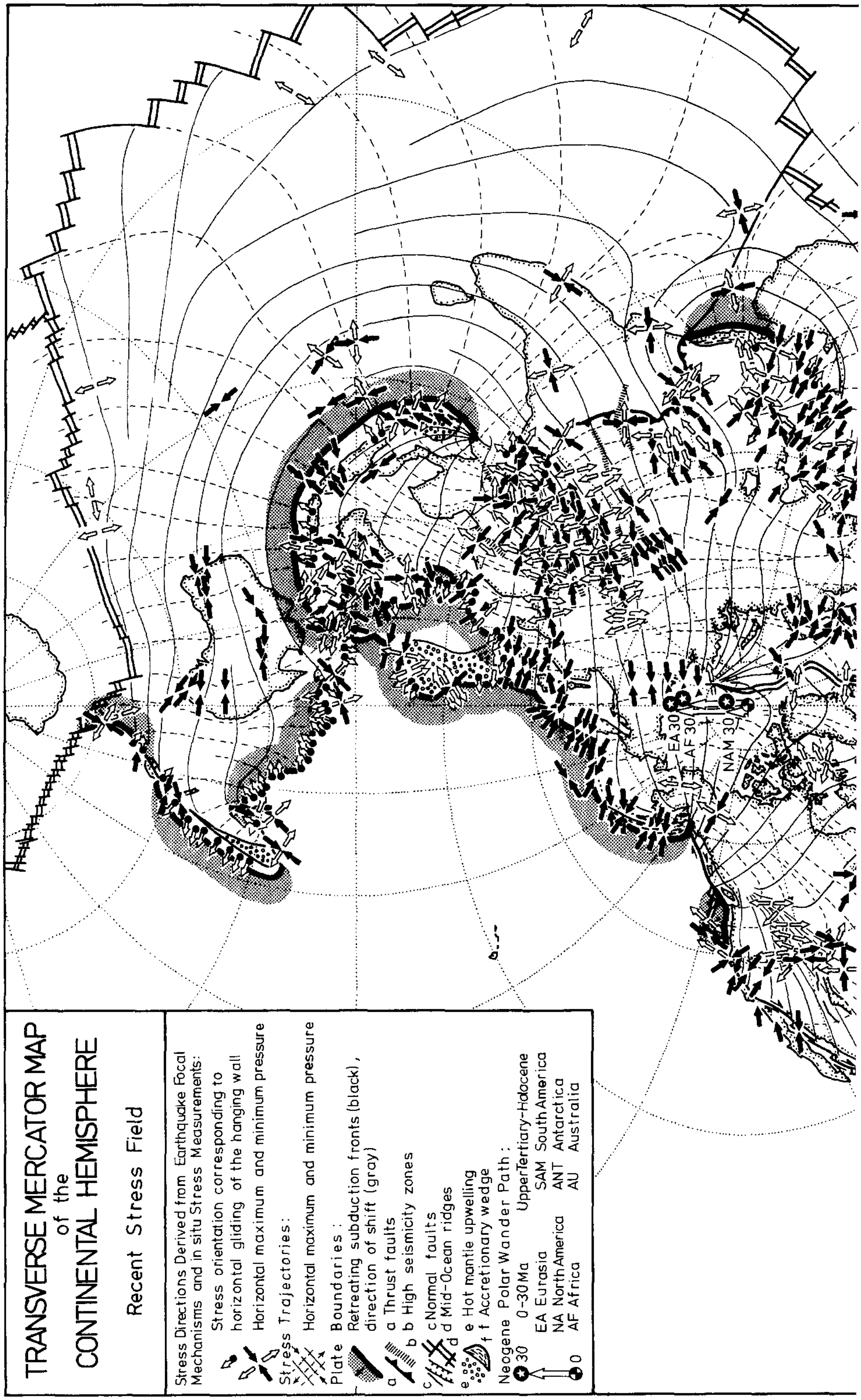
Fig. 8. A. Recent topography of fracture zones in the Mid-Atlantic ridge (Data from HEEZEN & THARP, 1965, BONATTI & CRANE, 1984). B-C. Omiting the ocean-floor, formed during the last 15 Ma (stippled areas in Fig. 8A), a former relative position of South America and Africa can be reconstructed (C). Gaps, appearing in this reconstruction (shaded areas) indicate considerable crustal shortening parallel to the ocean ridge. This causes deviations from the ideal transform-fault kinematics (Fig. 8B after SYKES, 1967).

floor formed in the following time, this reconstruction displays gaps parallel to the transform faults (Fig. 8C). These gaps indicate a remarkable degree of younger crustal shortening parallel to the ridge and contemporaneous with sea-floor spreading. A resulting formation of folds and thrusts could explain the observed topographic »transverse valleys« and »transverse ridges« as well as the thrusting of ocean floor in these fracture zones up to sea level (BONATTI & CRANE, 1984). The reflection of these deformations in the gravity field (MARSH & MARSH, 1976:676f.) is similar to the isostatic anomalies of the continental lithospheric folds.

Ocean-Driven Plate Tectonics?

Since equatorial maps usually used to demonstrate global geophysical or geological features do not allow a clear projection of the Neogene polar wander curves, the presentation of the Neogene drift tectonics was a difficult problem. It was solved by the use of a transverse Mercator map whose projection cylinder is tangent to the great circle representing the Neogene drift direction of N-America, Eurasia and Africa (Fig. 9) according to the new polar wander paths (Fig. 3 D–F). As the vertical axis of the map, this tangent connects equatorial areas running over the poles. The map's conformal properties allowing the rectangular construction of the tension field more than compensate for the disadvantageous lateral exaggeration.

If one compares the Neogene tension field (Fig. 9) to the deformation in the Indian plate, cf above and Fig. 10, it is clearly visible, how compressional trajectories run parallel to the Sunda arc as well as to the Mid-Indian ocean ridge. They continue over the Himalayan and Verkhoyansk mountain belts to Alaska and Japan. The Baikal graben and China's rhomb-shaped crustal blocks strike parallel to this compression, the epeirogenic lithospheric folds of the W-Siberian plate perpendicular to it (Fig. 5, Fig. 10). They also follow according to the polar wander


TRANSVERSE MERCATOR MAP
of the
CONTINENTAL HEMISPHERE
Recent Stress Field
Stress Directions Derived from Earthquake Focal Mechanisms and in situ Stress Measurements:
Stress orientation corresponding to horizontal gliding of the hanging wall
Horizontal maximum and minimum pressure
Stress Trajectories:
Horizontal maximum and minimum pressure
Plate Boundaries:
Retreating subduction fronts (black), direction of shift (gray)
a Thrust faults
b High seismicity zones
c Normal faults
d Mid-Ocean ridges
e Hot mantle upwelling
f Accretionary wedge
Neogene Polar Wander Path:
30
0-30 Ma Upper Tertiary-Holocene
0
EA Eurasia
NA North America
AF Africa
SAM South America
ANT Antarctica
AU Australia
EA 30
AF 30
NAM 30

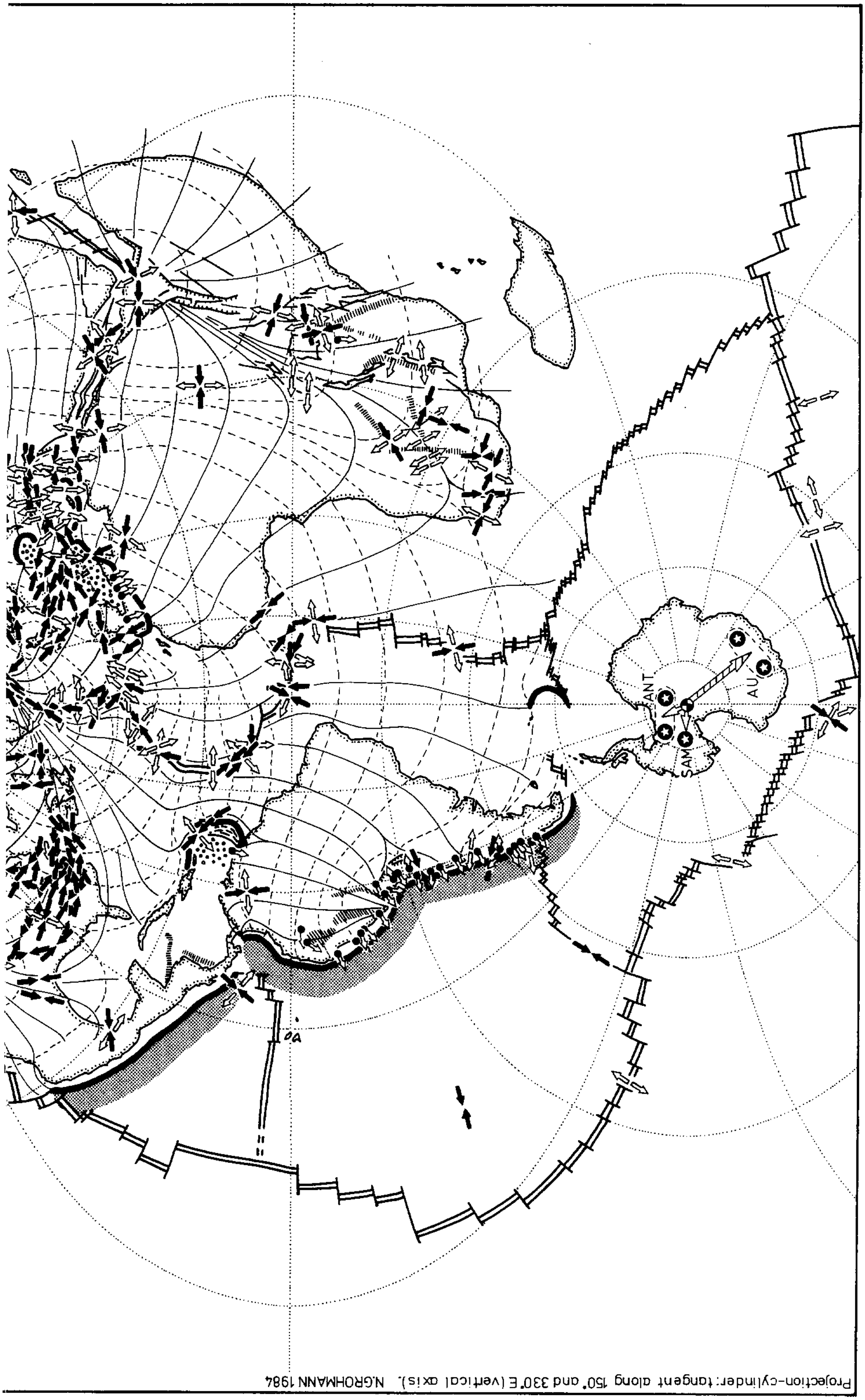
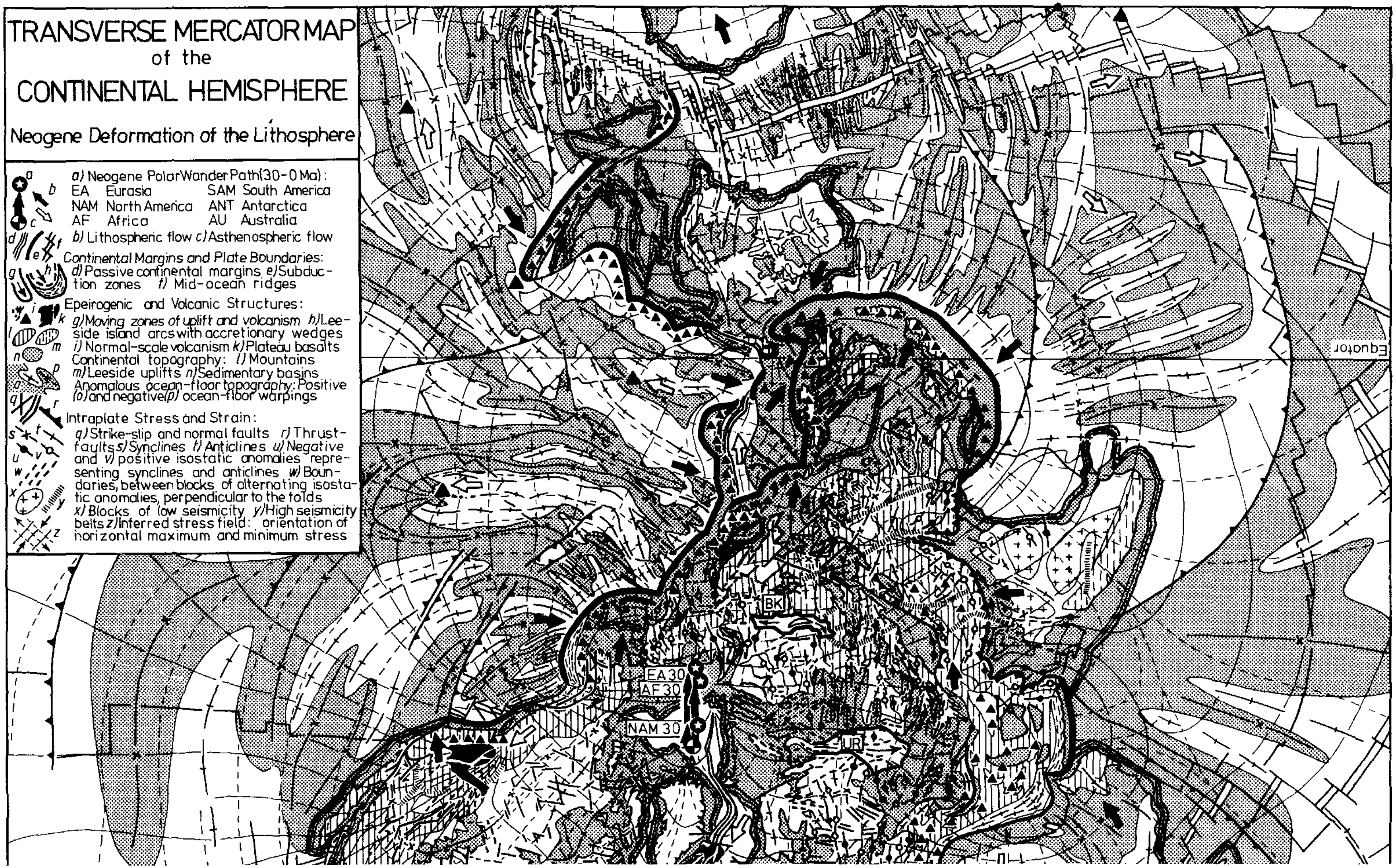


Fig. 9. Transverse Mercator map of today's horizontal stress field as derived from seismic fault-plane solutions and in-situ stress measurements. For references see Tab. 3.


TRANSVERSE MERCATOR MAP
of the
CONTINENTAL HEMISPHERE
Neogene Deformation of the Lithosphere
a) Neogene Polar Wander Path (30-0 Ma):
EA Eurasia SAM South America
NAM North America ANT Antarctica
AF Africa AU Australia
b) Lithospheric flow c) Asthenospheric flow
Continental Margins and Plate Boundaries:
d) Passive continental margins e) Subduction zones f) Mid-ocean ridges
Epeirogenic and Volcanic Structures:
g) Moving zones of uplift and volcanism h) Leeside island arcs with accretionary wedges
i) Normal-scale volcanism k) Plateau basalts
Continental topography: l) Mountains
m) Leeside uplifts n) Sedimentary basins
Anomalous ocean-floor topography: Positive (o) and negative (p) ocean-floor warpings
Intraplate Stress and Strain:
q) Strike-slip and normal faults r) Thrust-faults s) Synclines t) Anticlines u) Negative and v) positive isostatic anomalies representing synclines and anticlines w) Boundaries, between blocks of alternating isostatic anomalies, perpendicular to the folds
x) Blocks of low seismicity y) High seismicity belts z) Inferred stress field: orientation of horizontal maximum and minimum stress
a
b
c
d
e
f
g
h
i
k
l
m
n
o
p
q
r
s
t
u
v
w
x
y
z
Equator
BK
EA 30
AF 30
NAM 30
UR

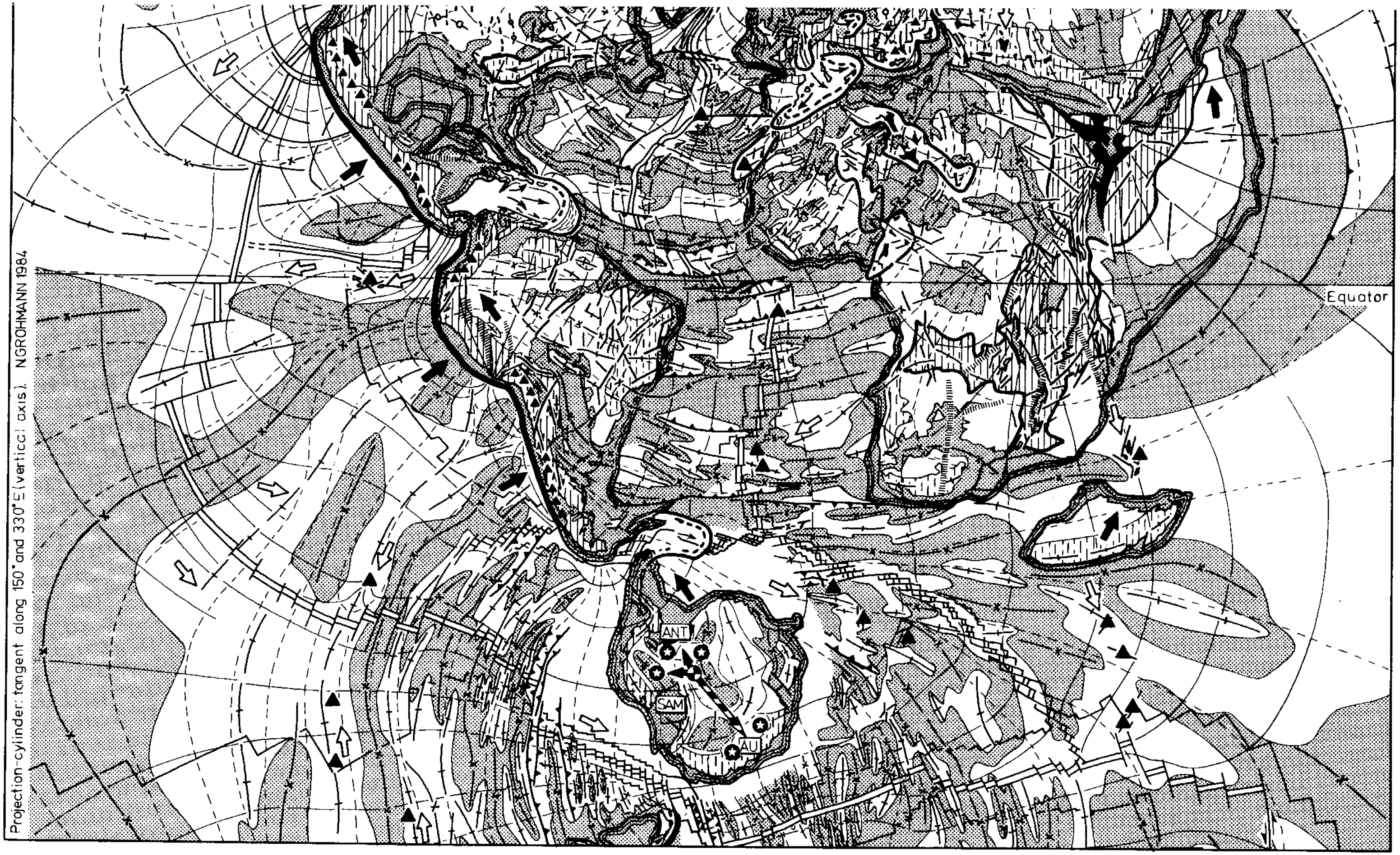


Fig. 10. Transverse Mercator map of today's lithospheric deformation. On the continents: highlands (vertical hatching), lowlands (white), and areas of sedimentation (gray) are shown. Positive (white) and negative (gray) ocean-floor residual depths after Haxby, from Olson, 1983. Since the pattern of these topographic and isostatic anomalies corresponds with the stress field (Fig. 9), it may represent overall internal compression the moving plates. BK, Lake Baikal; UR, Ural Mts. Same projection grid as in Fig. 9.

paths, the rule of longitudinal extension and transversal compression.

The same is true in the rest of Asia, Europe and in Africa outside the East African rift and N-America outside the Rocky Mts. NW-Africa's epeirogenic warpings (Fig. 10) continue on a curve into the ocean-floor undulations of the Atlantic (Fig. 8, Fig. 10). They parallel, according to measurements of the tension field (Fig. 9), the minimum horizontal compression. Similar curves are described by these trajectories between Spain and Iceland and, in the S, around the Ethiopian Highland.

In the eastern United States, they cross at right angles an arch of compressional trajectories (SBAR & SYKES, 1973). Between this arch and Alaska, a continuity of the tension field is indicated by conjugated shear zones, which are reflected in the pattern of isostatic anomalies as well as in the straight course of large rivers. Similar fault zones in Brazil (Fig. 10) allow a hypothetical connection between the tension field of the Atlantic and the field of the Andes (Fig. 9).

In the oceans, the tension-field orientation can be derived from thrust- and strike-slip faulting along transform faults and from the undulations of the ocean-floor, which most probably represent lithospheric folds. Apart from focal solutions of two earthquakes in the Nazca plate (Fig. 9), all available tension determinations confirm this working hypothesis. Once this clear representation of the Neogene direction of drift and deformation was worked out, it could be compared to modern theories of global tectonics.

According to this analysis, the classical model of plate kinematics (ISACKS et al., 1968:5857; ELSASSER, 1968), which regards down-going slabs as the main driving mechanism, was confirmed for all oceanic plates as well as the African plate (HARPER, 1975:471). This model, however, fails to explain the drift of all other continental plates, which lie behind a subduction zone (shaded areas in Fig. 11A).

Similarly, the hypothesis of pushing upwelling mantle currents was disproved by the investigation. According to most authors, a westward drift of the American continents, resulting in the folding of the Cordilleras at the leading edge (Fig. 11 B, (1); e.g. WEGENER, 1929; UYEDA & KANAMORI, 1979), may be explained by some hot mantle upwelling beneath rift zones (Fig. 11, (9), (2); e.g. OROWAN, 1965:292; FRISCH, 1981:402; DEWEY & BURKE, 1974; BONATTI & CRANE, 1984; SCLATER & TAPSCOTT, 1984). Contrary to this view, the polar wander curves unequivocally indicate a continental drift parallel to the compressed fold belts (also in Upper Cretaceous/Lower Tertiary, »Laramide« times) and the orientation of the tension field contradicts the idea of push from the ridges.

The question still remained: could the continental hemisphere be driven by some kind of collisional pressure (FORSYTH & UYEDA, 1975:164)? The assumed direction of the Pacific's motion parallel to the Hawaiian chain (WILSON, 1963, MCKENZIE & PARKER, 1967) around the Pacific rotation pole (PRP in Fig. 11B) as well as the drift direction of the Indian plate (HAGER & O'CONNELL, 1978) around the Indian rotation pole (IRP) agree well with the Neogene paleomagnetic poles (P and IN in Fig. 11B) of both plates. Also, the relative motion of the gigantic shear zone extending from the Gulf of California to China, which opens asymmetric back-arc basins (Fig. 11B, (4) (BENIOFF, 1957), as well as the relative motion in Central Asia's block mosaic behind the Himalayas (Fig. 11B, (6)) (ROMAN, 1973; MOLNAR & TAPPONIER, 1975; TAPPONIER & MOLNAR, 1977) are in agreement with this hypothesis.

As a wedge-shaped continent between the »jaws« of these two plates, however, Eurasia should react similarly to the small wedgeshaped Turkish plate described by MCKENZIE (1970a) (Fig. 5B, (5)): it should be squeezed out in the direction of the big white arrow in Fig. 11B. This, however, is clearly refuted by the polar wander curves of the continental hemisphere (Fig. 9, Fig. 10).

Thus, when the global pattern of data is taken into account, it turns out that the well-known plate tectonic models do not explain the drift of the continental hemisphere.

Drift Fields and Upper Mantle Convection

This apparently conflicting data remained bewildering for quite a long time until comparison of the global tension field (Fig. 9, Fig. 10) with plate kinematics on the drift map (Fig. 11A) marked a decisive step towards understanding plate dynamics. From this comparison it became clear that two types of tension fields, those with extensional trajectories and those with compressional trajectories parallel to the drift, form a regular global pattern (Fig. 12).

This pattern revealed the division of the earth's surface into large drift fields which provide the mechanism for the conversion of upper mantle temperatures (POLLACK & CHAPMAN, 1977:74) into the direction of lithospheric motion. The drift fields are generally surrounded on three sides by hot asthenospheric uplifts, from which a narrowing *lithospheric* flow leads towards a low-topographic subduction zone on the fourth side (Fig. 14A). Hence, these fields represent a three-dimensional version of the two-dimensional model (JACOBY, 1970, 1978a; GROHMANN, 1981:38) that explains the drift of plates by gravitational gliding of wedge-shaped lithospheric elements down the slope of the asthenosphere's surface (Fig. 14B).

The interior of a drift field is governed by an extensional field with converging extensional trajectories parallel to the flow, which is a common phenomenon in cases where material flows out of an enclosed area due to its own weight (Fig. 12C): e.g. in the accumulation zone of glaciers (KÖRNER, 1963:59f.) as well as in the flow of glucose out of a rectangular container in NICKEL's experiment (1967:59–61).

The opposite of these extensional fields, compressional fields with curved extensional trajectories perpendicular to the flow, commonly exist in cases where deformable material is pushed against the resistance of lateral borders (Fig. 12B): e.g. in the compressional zone at the front of glaciers (KÖRNER, 1963) as well as in plutonic bodies. Since in the lithospheric compressional fields that define the borders of the drift fields along the great rift zones, the divergence of the compressional trajectories indicates an asthenospheric flow opposite to the drift (Fig. 12A, Fig. 14), they will be treated later in detail.

Finally, lateral compressional fields, which exist where plates converge laterally because their rigid upper layers cannot fit in the narrowing barysphenic flow, turned out to be secondary phenomena. This type is represented by the Himalayan field (Fig. 13 A5), where the Tibetan plate suffers external compression (Fig. 7). Similar conditions exist in the N-Zagros field (Fig. 13A) and in the Andes (Fig. 12A), both of which have been hitherto regarded as typical examples of a head-on collision (Fig. 11B), but which actually lie at the lateral margins of drifting continents.

At the leading edge of a drift field, the return of the highly viscous lithospheric material must take place in the form of linear subduction zones. Three types of drift fields can be distinguished according to their dip-direction. Among these, only the Pacific type (Fig. 14A) was hitherto known, but it was considered to be the general model of a plate's motion. This type is represented by the Pacific, the Sunda, and the African fields, whose lithosphere, pulled by a subduction zone along the leading edge, is gliding down U-shaped asthenospheric uplifts (Fig. 13A).

The more complicated American type of drift field is represented by the South American field. It consists of several plates which glide centripetally down the East Pacific, the Mid-Indian, and the Mid-Atlantic riges towards the Central American-Andean subduction zone, beneath which cold mantle material flows aside (Fig. 13).

Since Laurasian-type drift fields are located at the leading edge of continents, their flow-geometry provides a solution to the problem of expansion of the continental hemisphere (ELSASSER, 1971; GROHMANN, 1981:67; BISCHOFF, 1984). In 1971 ELSASSER already suspected the existence of some kind of suction force which pulled the continents towards the trenches. Most authors, however, agreed with FORSYTH's and UYEDA's opinion, that »suction . . . appears to be incompatible with the notion that a trench is a colliding boundary across which plates are pushing each other«, (1975:170). The breaking away of island arcs from the continental margin since the beginning of Neogene times, e.g. Japan (Fig. 11B) (MINATO, 1972), was therefore suspected to have happened along a continent's trailing edge (WEGENER, 1929:201, UYEDA & KANAMORI, 1979).

Contrary to this view, intra-plate deformation and polar wander curves speak in favour of a parallel flow of the N-American and Eurasian drift fields like gigantic glaciers down the asthenospheric upwellings of the Basin-and-Range, the Mid-Atlantic, and the Mediterranean zones towards the Indian and Pacific Oceans (Fig. 13). Moreover, the leading chain of island arcs is running away from the mainland, forming the Neogene back-arc basins.

An answer to the question of why this type of a subduction zone obviously follows a retreating deep-sea trench with compression confined to the narrow arc-trench complex (Fig. 12A, Fig. 6F), whereas other subduction zones, e.g. the Hercynian S-margin of Laurasia (Fig. 4B) are embedded into a regional compressional field, was found by the author (1981:74) in the subduction zone's geometry of flow.

If cold oceanic lithosphere sinks beneath a continent, this means a simultaneous transport of mass, leaving a mass deficiency near the oceanic ridges as well as a mass surplus on the continental side. Hence, this subduction zone forms a downflow front, which cannot remain stable under these circumstances (Fig. 15). From the high-pressure area beneath the front's cold masses, material will flow towards the oceanic ridges, forming a retreating subfrontal wedge, which allows a sinking and oceanward shift of the downflow front. As a very likely explanation of ELSASSER's suction force, this wandering

A. NEOGENE PLATE KINEMATICS

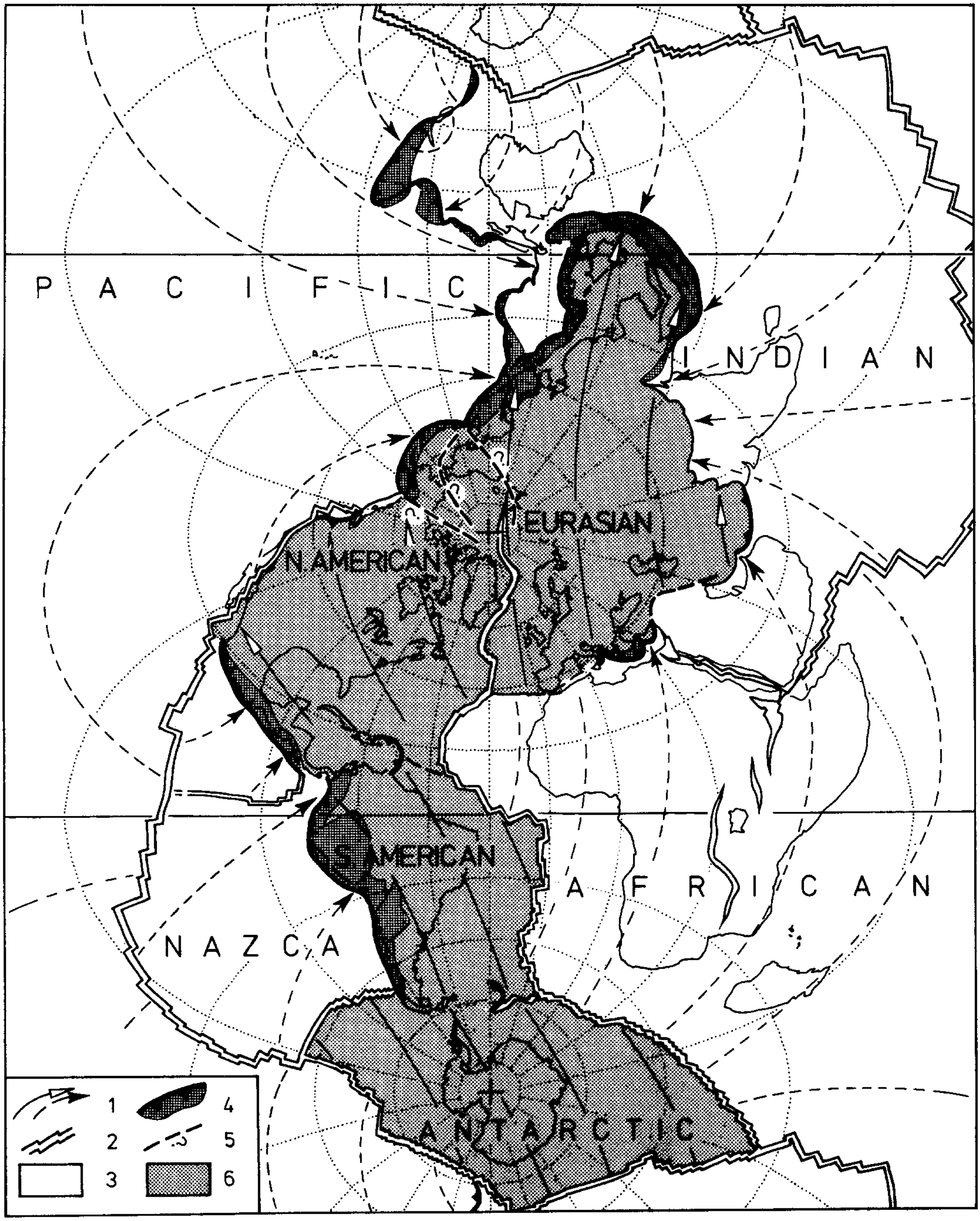
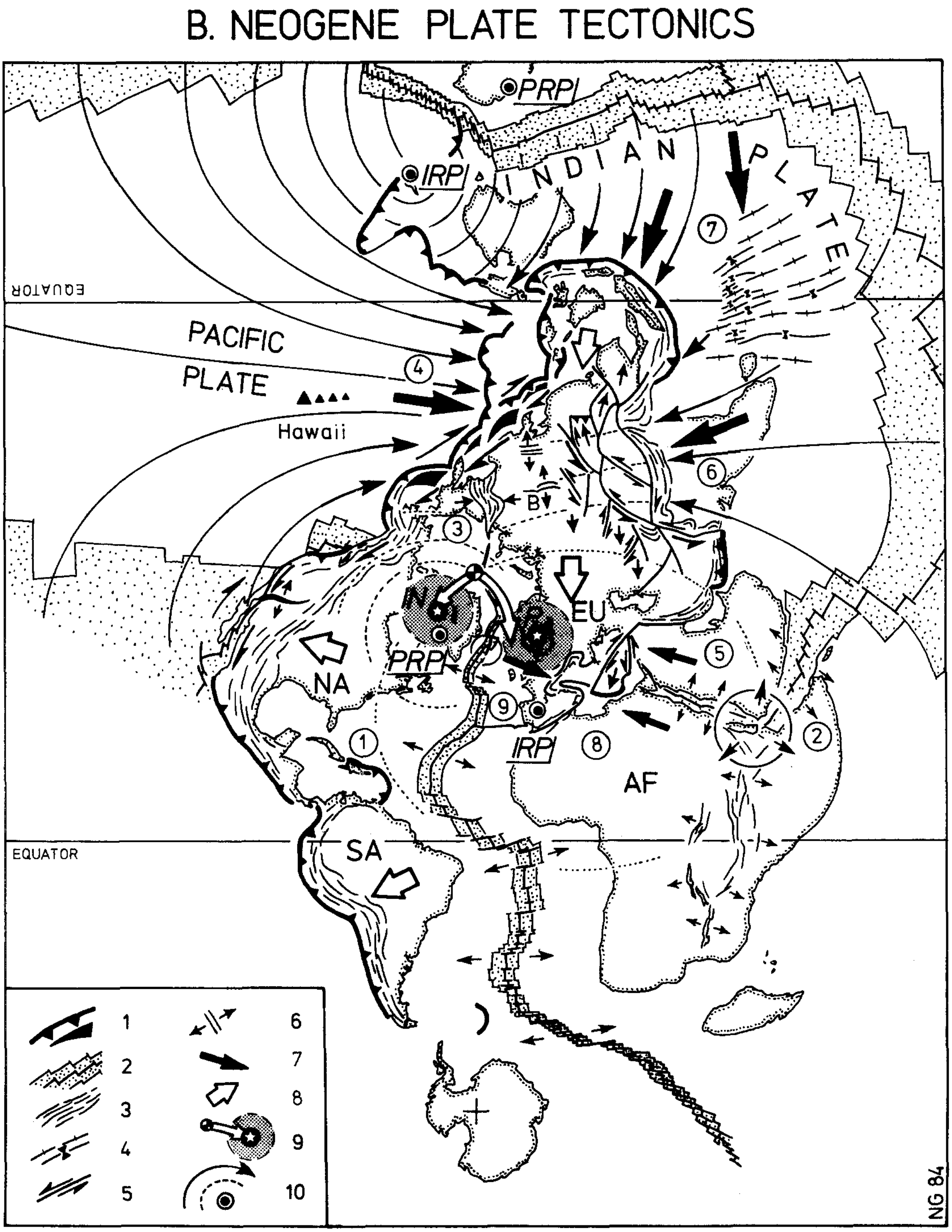


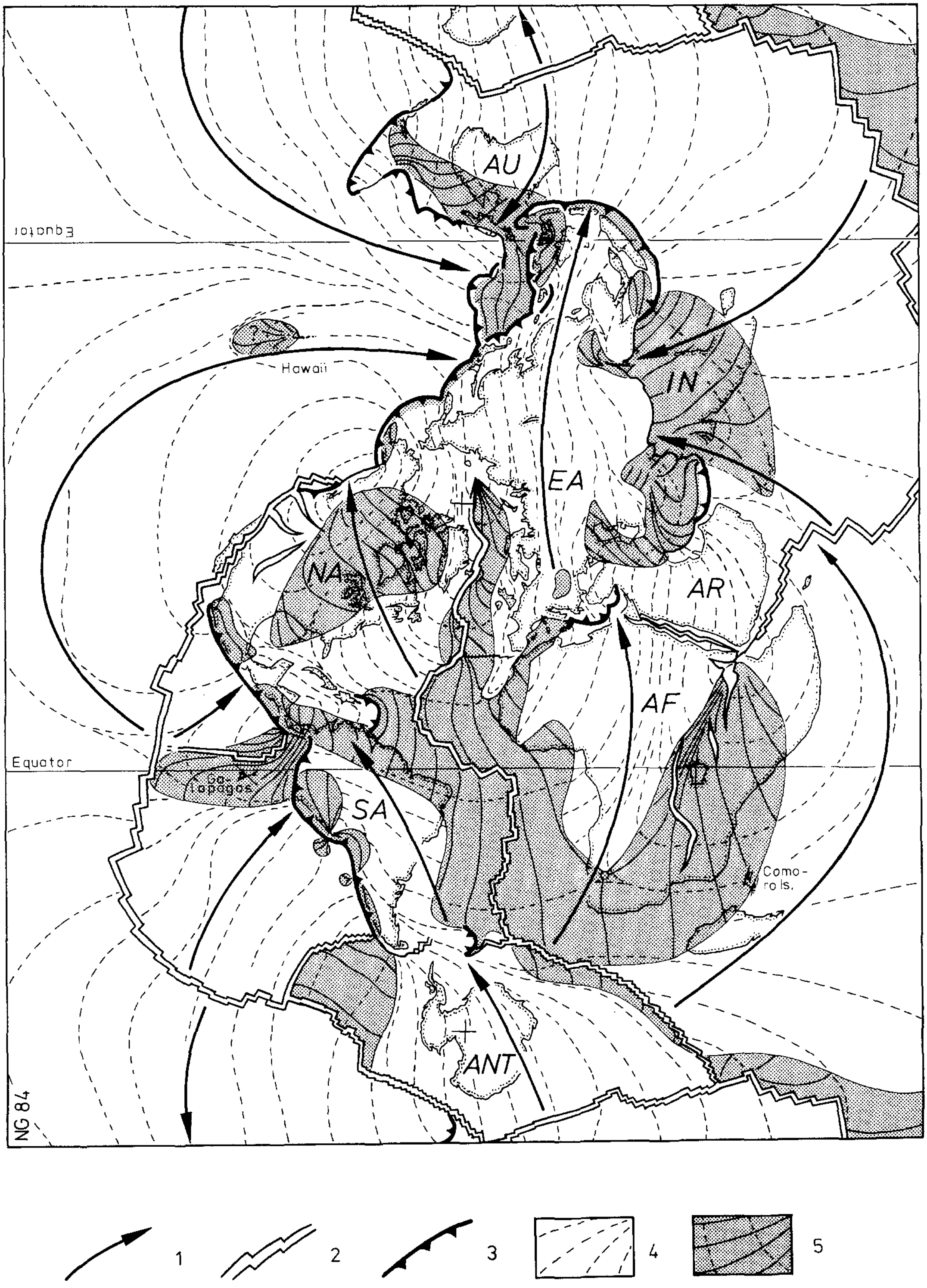
Fig. 11A. On the drift-oriented map it becomes clear that the pull of down-going slabs provides a driving mechanism for oceanic plates and, perhaps, for Africa, but not for Eurasia, America and Antarctica. 1. Drift direction; 2. Mid-oceanic ridges; 3. Plates, driven by slab-pull; 4. Benioff zones; 5. Suspected plate margins; 6. Plates, not driven by slab-pull.

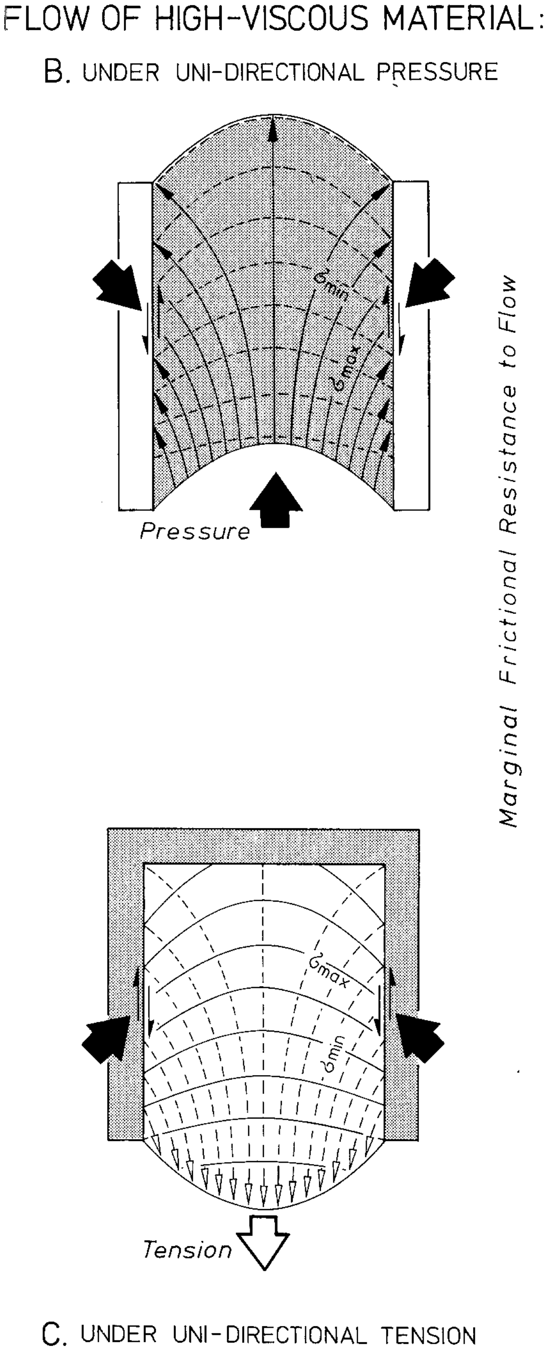
Fig. 11B. The classic plate tectonic models on the drift-oriented map: (1) W-drift of America (WEGENER, 1929; TÖKSÖZ, 1984); (2) Afar-dome (CLOOS, 1929); (3) Suspected folding of the Werkhoyansk Mts. (WILSON, 1963); (4) Pacific megashear



(BENIOFF, 1957); (5) Squeezing of the Turkish platelet (MCKENZIE, 1970a); (6) Himalaya-collision (MOLNAR & TAPPONIER, 1975); (7) Ridge push S of India (ETTREIM & EWING, 1972); (8) Africa pushes against Europe (DEWEY et al., 1973); (9) N-Atlantic ridge push against Africa (FRISCH, 1981); for discussion see text. Signatures: 1. Island arcs; 2. Mid-oceanic ridges; 3. Fold belts; 4. Folds; 5. Shear zones; 6. Rifts; 7. Direction of compression; 8. Resulting movement; 9. Polar wander paths (M. Tertiary poles: IN, India from Fig. 3F.; P. Pacific after VACQUIER, 1972:91); 10. Poles of rotation.

A. RECENT PLATE KINEMATICS AND STRESS-FIELD





downflow front allows, in turn, the mass surplus of the continental hemisphere to spread oceanwards.

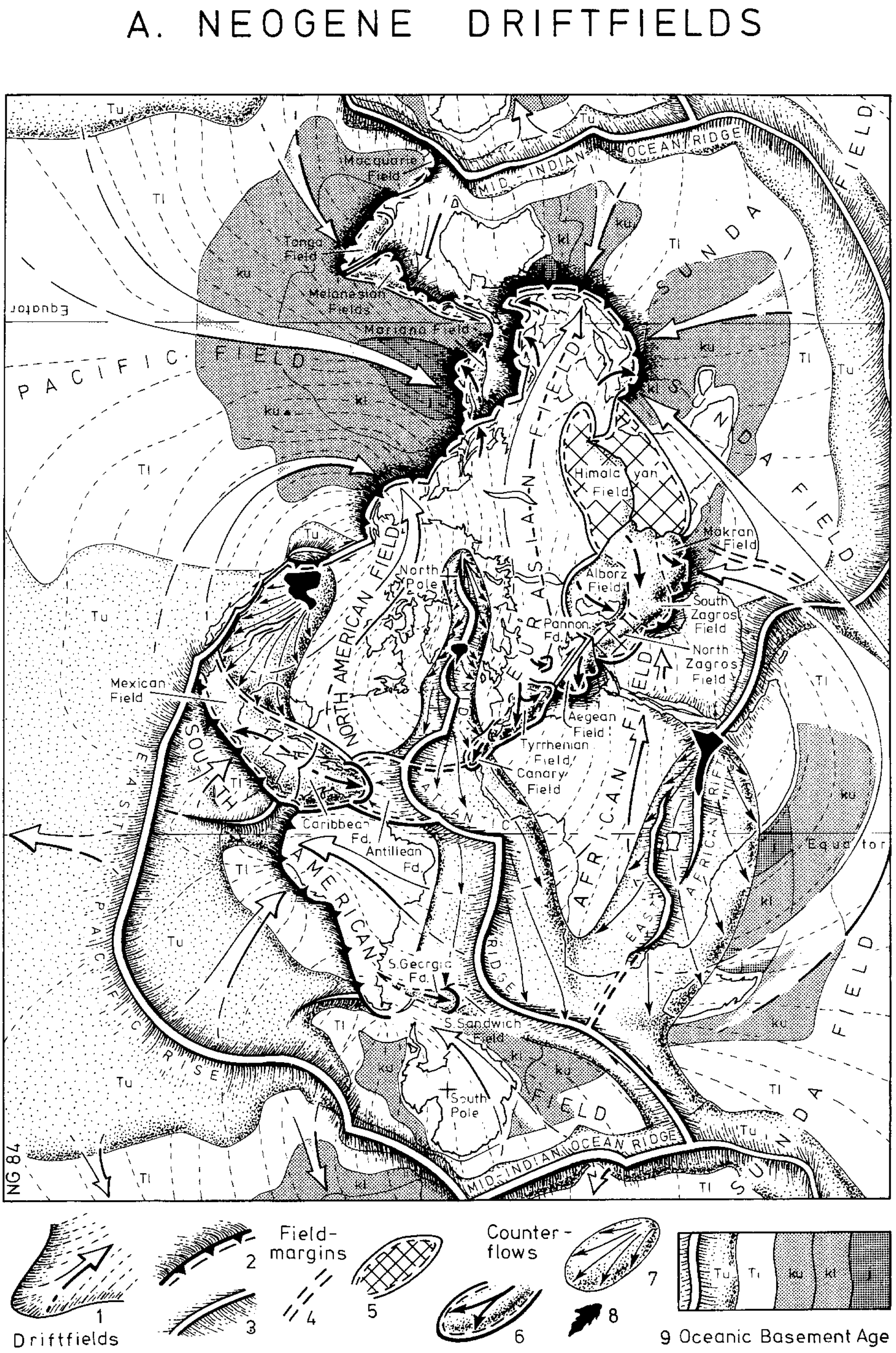
Contrary to this, the second possible pattern of flow forms a stable downflow front because the subducted material returns directly to the mid-ocean ridge without a mass exchange between the continental and the oceanic side (Fig. 15).

The mechanism of wandering downflow fronts also provides an answer to the question of how deep convection currents extend into the mantle: 2900 or only 700 km (Fig. 1) (e.g. HAGER & O'CONNELL, 1978; WYLLIE, 1975; KENNETT, 1982, MCKENZIE, 1983; CHRISTENSEN, 1983)? Since the different, but related velocities of continental and oceanic plates are determined by the mass circulation around a wandering downflow front, it was possible to calculate the vertical extension of this convection from the plates' thicknesses and velocities; this was found to be not greater than 700 km (Fig. 15) (GROHMANN, 1981:83).

This model is confirmed by conventional seismic observations of the geometry and deformation of the Benioff zones (BARAZANGI & DORMAN, 1969; RITSEMA, 1970; STAUDER, 1973) as well as by the new results of seismic tomography, which derives a three-dimensional model of the upper mantle temperatures from a great number of superimposed seismic waves (NAKANISHI & ANDERSON, 1984; ANDERSON & DZIEWONSKI, 1984). It was possible to trace the cold downflows horizontally 2000 to 9000 km behind the W-Pacific-Sunda and the Andean fronts (ANDERSON & DZIEWONSKI, 1984:65). For the first time, the cold subfrontal wedges became visible, too. They extend, as the second branch of the downgoing matter, from the Andean front some 1000 km, from the W-Pacific-Sunda front, however, some 5000 km beneath the adjoining oceans. Because length and temperature of the subfrontal wedges precisely reflect the difference in age structure and temperature of the oceanic plates high above (Fig. 13A), mean upper mantle temperature in the W-Pacific-Indian zone is lower than in the SE-Pacific zone (Fig. 13B).

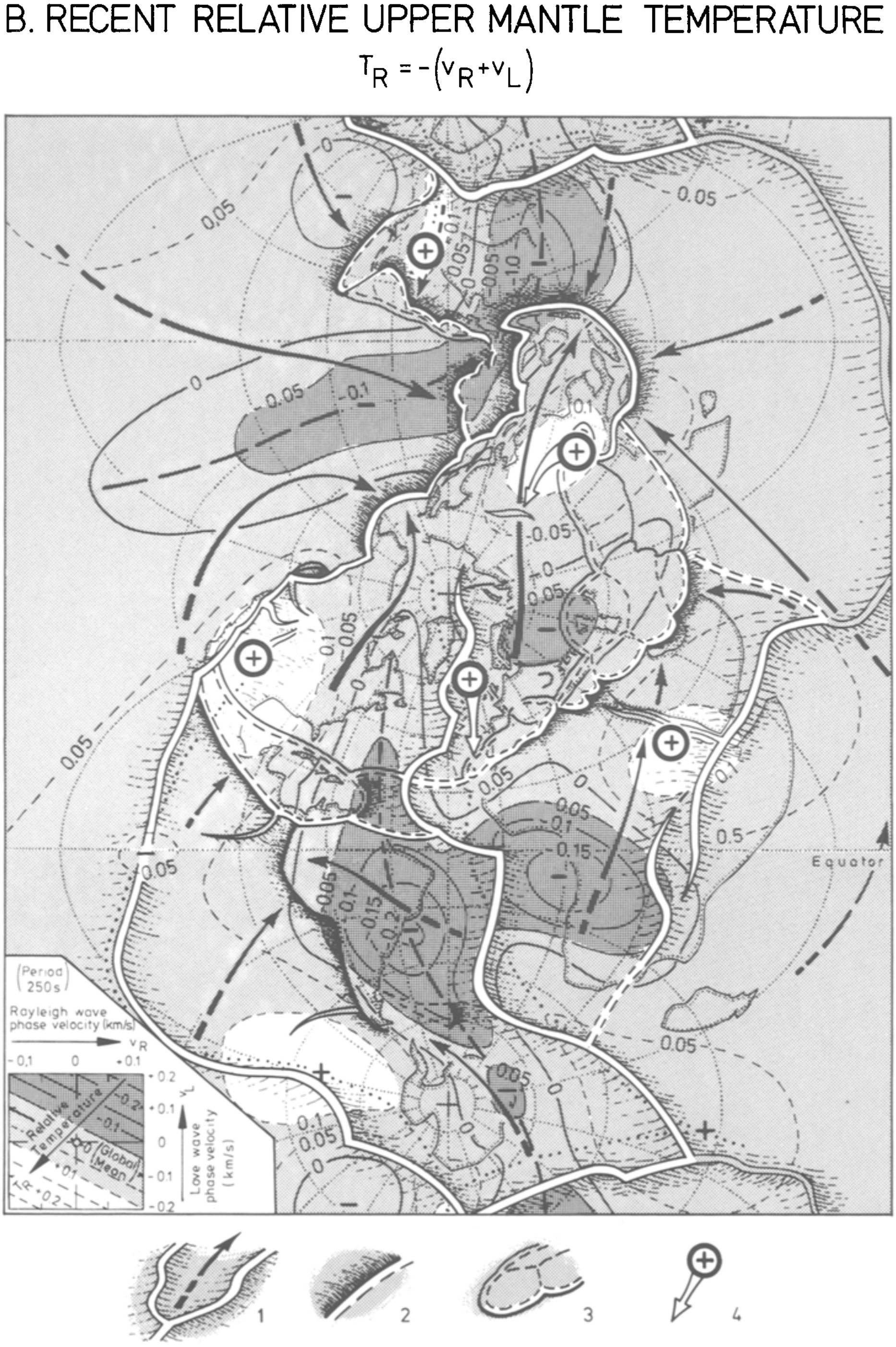
Hence, there are two effects which explain why the continental hemisphere as a whole does not glide towards the American front, but follows the W-Pacific-Sunda front. It flows towards that ocean whose topo-

Fig. 12. Plate kinematics and stress field: In the most areas lithosphere moves (1) parallel to the tensional trajectories (4) resembling a glacier-like flow under tension (12C). Lithospheric movement parallel to compressional trajectories (5) occurs only in the vicinity of mid-oceanic ridges and continental rifts (2) and of some subduction zones (3). Here, the divergence of compressional trajectories, which generally parallels a flow under pressure (12B), suggests the existence of a counterdrift-directed sublithospheric flow.



A. NEOGENE DRIFTFIELDS

Fig. 13a. Present worldwide pattern of drift fields. 1. Lithospheric flow of the drift fields parallel to tensional trajectories; Well defined field margins: 2. Subduction zones; 3. Global rifts; 4. Less well defined field margins; 5. Lateral compressional fields; 6. Counterflow heads; 7. Counterflows parallel to compressional trajectories; 8. Neogene plateau basalts; 9. Oceanic basement age: J, Jurassic; Kl, Ku, Lower-Upper Cretaceous; Tl, Paleogene; Tu, Neogene.



B. RECENT RELATIVE UPPER MANTLE TEMPERATURE

$T_R = -(v_R + v_L)$

Fig. 13b. Present upper mantle temperature, derived by superimposion of anomalies of the phase velocity of Rayleigh waves and Love waves (250s period, data from NAKANISHI & ANDERSON, 1984). 1. Drift fields; 2. Subduction zones; 3. Small lateral compressional fields and counterflow heads; 4. The only hot subvertical channels reaching down 600 km, direction of inclined rise of hot matter.

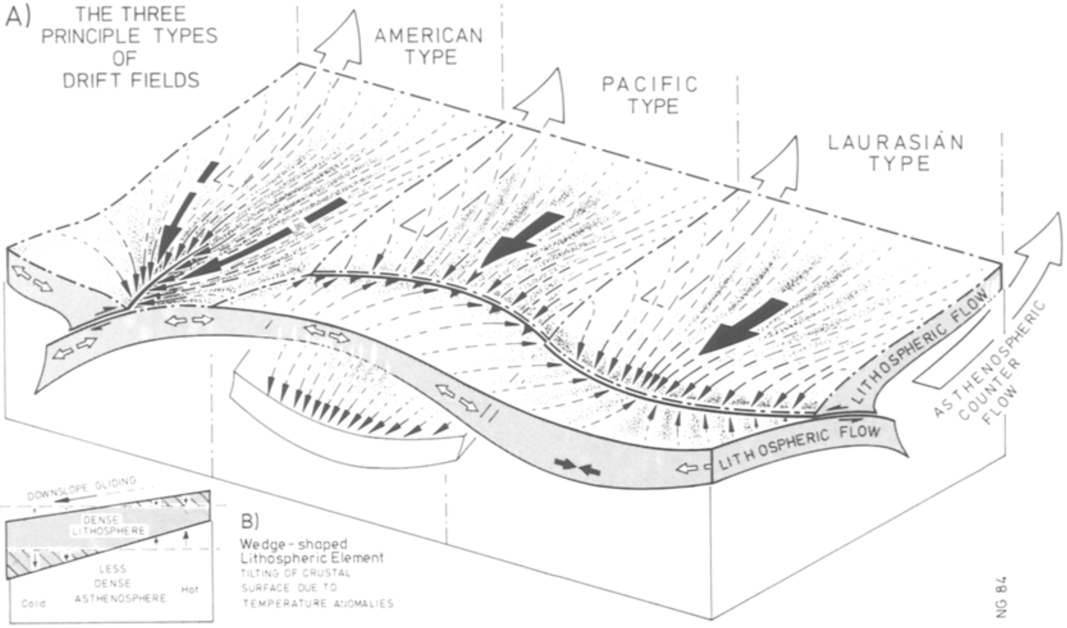


Fig. 14. Stereogram demonstrating the three possible types of drift fields.

graphy is lowest because of the upper mantle's low mean-temperature and at whose margin frontal mass transport is more effective because of the thicker downflowing lithosphere.

Counterflows, Magmatism and Vertical Tectonics

Temperature-depth curves (geotherms) derived from the pyroxene composition of mantle-xenoliths (MACGREGOR & BASU, 1974; KORNPROBST, 1984) form two groups: »hot geotherms« from xenoliths of alkali basalts and »normal geotherms« from xenoliths of continental kimberlite eruptions. Contrary to the former assumption of a peridotitic hot dry mantle (e.g. POLLACK & CHAPMAN, 1977:60), the much lower temperatures indicated by pyroxene thermometry speak, together with other geophysical, mineralogical and geochemical evidence (GROHMANN, 1981:60), in favour of a wet upper

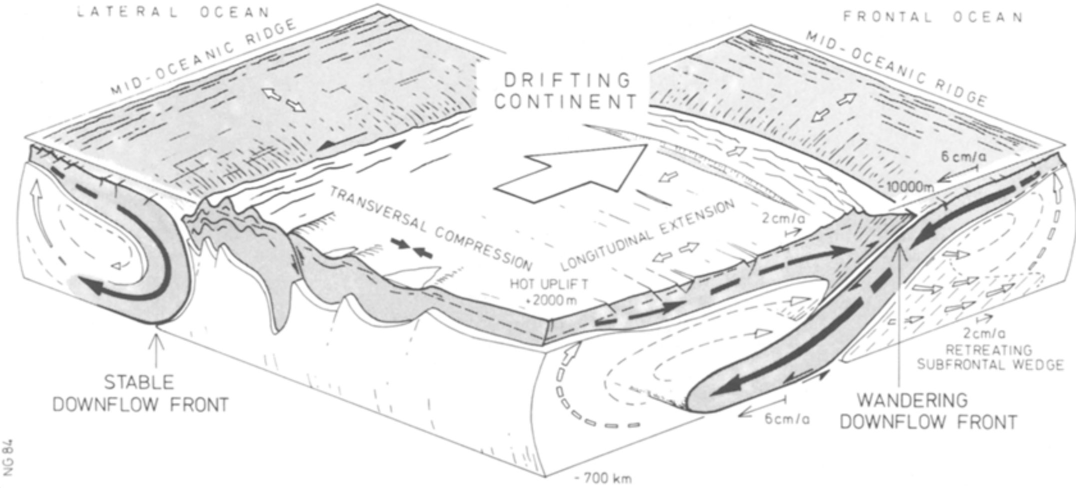


Fig. 15. Model to illustrate the relations between the two possible geometries of downflow fronts and the internal deformation of a drifting continent.

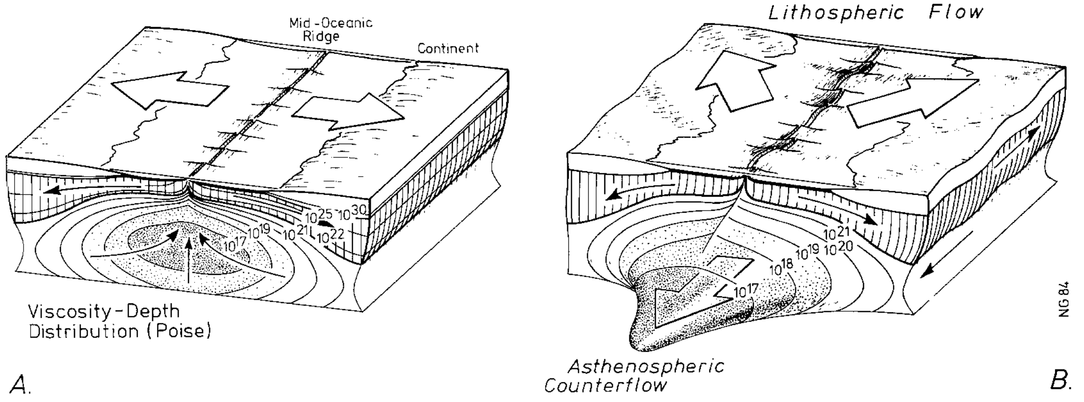


Fig. 16A. Asthenospheric viscosity distribution (After VETTER & MEISSNER, 1977) in the previous two-dimensional model of seafloor spreading.

Fig. 16B. The three-dimensional interaction of lithospheric flow and asthenospheric counterflow should exhibit a concentration of the counterflows in the low-viscosity channels beneath the rift zones.

mantle model consisting mainly of peridotite and eclogite (GROHMANN, 1981:142; ZINDLER et al., 1984).

A model of the complicated structure of the oceanic lithosphere – represented in Fig. 17 by temperature-depth as well as age-depth diagrams – can only be outlined here. In the fresh lithosphere of the mid-oceanic ridges the geotherms run across the hot geotherm field and their intersection with the solidus of wet eclogite (ESW), which obviously determines lithospheric thickness, occurs at less than 55 km depth. With increasing age and cooling, this intersection shifts towards deeper levels, resulting in a maximum lithospheric thickness of ± 130 km under the oceans (LEEDS, 1975) and ± 300 km under continents (SACKS & OKADA, 1973; JORDAN, 1979). Since the solidus of wet eclogite or basalt exhibits the same negative slope as that of wet granite (STERN et al., 1975), asthenospheric melt, rising from the base of the lithosphere, will solidify at about point B in Fig. 17 at the Intersection with the solidus.

This property of the model seems to be very important for the rheological behaviour of the lithosphere. It means that lithosphere can be stretched to a considerable degree (Fig. 6C) without any magma reaching the surface

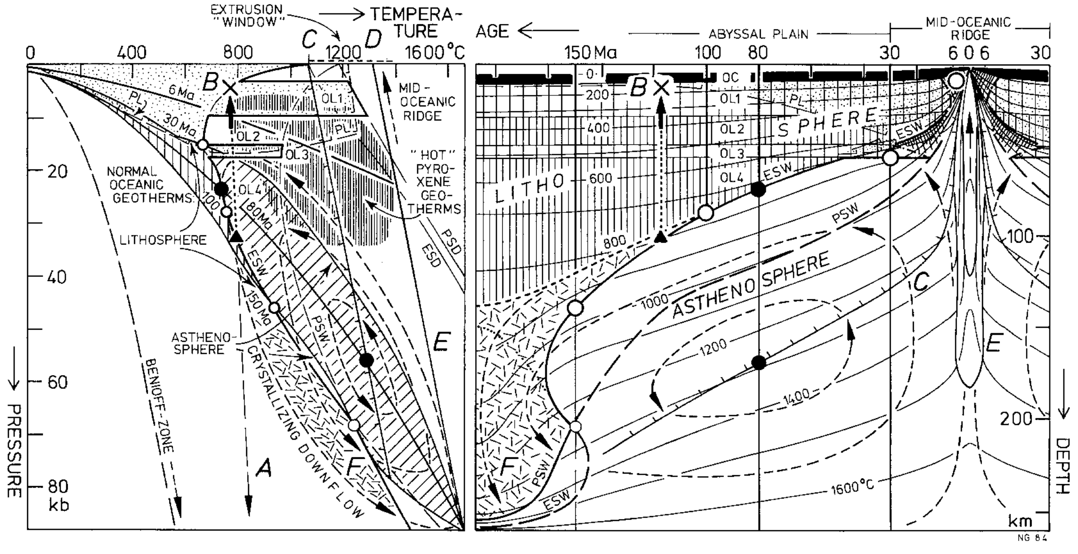


Fig. 17. Temperature-depth and age-depth relations of a model of oceanic lithosphere. For details see text.

and this may explain why, according to new observations (DETRICK et al., 1982; FRANCHETEAU, 1983:81f.), the midocean ridges exhibit a surprisingly low volcanic activity. Even in the quickly spreading Pacific, there are no large magma chambers, instead volcanism is concentrated in narrow zones between the transform faults, whereas plastically flowing peridotitic rocks (serpentinites) form the ocean floor locally near the transform faults. The fact that separation of plates by melt is incomplete may explain why the Sunda tensionfield (Fig. 13) can pull a part of the African plate over the Indian ridge.

As already mentioned, the compressional fields diverging in counterdrift direction (Fig. 12A, B) indicate the existence of asthenospheric counterflows beneath the great rift zones. From flow computations (JACOBY, 1978b) it can be concluded that a major part of the return flow from subduction zones to the ocean ridges should be concentrated in the asthenosphere and when one takes into account the upper mantle's viscosity structure (Fig. 16A), this flow may, in fact, occur as river-like counterflows concentrated beneath the thin lithospheric zones (Fig. 16B).

On the basis of the tension fields alone, vertical mantle up-welling may be expected at the origin of the counterflow fields (Fig. 12A, Fig. 13A). This is fully confirmed by the results of seismic tomography. The Columbia River (N-America, FURLONG, 1979), Iceland, Ethiopia, and E-Himalaya areas belong to the few points on Earth where counterflow centres of hot material reach down vertically to 600 km (Fig. 13B:4). At these points there is a remarkable coincidence of reduced lithospheric thickness (MOLNAR & OLIVER, 1969) and – except in the recent Himalaya uplift (SHIH et al., 1979) – of Neogene plateau basalts and of counter-drift-directed propagating rifting. Even beneath the asthenosphere, at 200–400 km depth, the anisotropy of Rayleigh waves (ANDERSON & DZIEWONSKI, 1984:71) proves by its astonishing parallelism to the plate drift the direction of the return flow as well as the polar wander curves.

From the temperature-depth diagram (Fig. 17) it can now be concluded that in thermodynamically unstable counterflows which pass across lithospheric thickness-anomalies local turbulence may trigger the rise of large asthenospheric diapirs. If, for example, an asthenospheric volume whose undisturbed geotherm may resemble average conditions beneath an 80 Ma old lithosphere develops a rollerlike rotation, its isotherms become distorted. In such intra-asthenospheric downflows isotherms may be depressed beneath the solidus, thus resulting in thikkening of the lithosphere by crystallization, whereas in corresponding upwellings an increasing amount of partial melting should intensify diapiric uplift. Comparable flow patterns provide an explanation for a specific class of counterdrift-directed epeirogenic phenomena:

1.) Irreversible frontal subsidence at the leading edge of the drifting European continent (Fig. 2A, D; signature 8) seems to reflect lithosperic thickening due to crystallization of a frontal undertow (Fig. 18 B–C).

2.) On the contrary, a regular counterdrift regression as well as a counterdrift advance of magmatic fronts (counterflow heads) can be observed during Hercynian and Alpine times (Fig. 4D; Fig. 2, signature 2,3; Fig. 3M, Fig. 10 G, H). Both phenomena are likely to reflect the development of lee-side upwellings (Fig. 18 B–C) which transport matter from the ground to the surface of the asthenosphere, hot enough to cause volcanism (E–D in Fig. 17). Since it has been found that the position of Hawaii also is not stable, but moving towards the East Pacific Rise (KENNETT, 1982:164), it is likely that doming of the ocean floor around the Hawaiian chain (Fig. 11B, Fig. 10) may not reflect a stable »hot spot«, but, instead, a counterflow head. These upwellings may be similar to the upper mantle structure beneath Europe, where lithospheric thickness is reflected by the surface heat flow (Fig. 19). Hot matter beneath the European »hot spots«, however, cannot be traced vertically, since they are underlaid by dense cold material (PANZA et al., 1984). Instead, hot diapiric structures rise regularly in counterdrift direction, intruding locally between crust and mantle.

3.) Evidently, a chain of lee-side island arcs exists along the lee side of Eurasia and the Americas (Fig. 13A, sign. 6; Fig. 13B, sign. 3). Since, in Eurasia, they started their latest phases of development simultaneously with the onset of Neogene drift, they are very likely to represent the most intensive type of lee-side upwellings at a continent-ocean margin. This type is characterized by tremendous vertical uplift, gliding nappes and finally, after the decoupling of continental from oceanic crust, by the development of a new Benioff zone.

Well-known examples are the Aegean (Fig. 18 D–F) (BÖGER, 1983) and the Tyrrhenian Sea (Fig. 19) (VAN BEMMELEN, 1975; BOCCALETTI & GUAZZONE, 1975), probably also the Ladakh island arc (Fig. 3D), which separated from Eurasia's lee side.

4.) Finally, a combination of frontal undertow and lee-side uplift results in continental rolling (Fig. 18C), as seen e.g. in India, Arabia and Madagascar (Fig. 10).

Thus, it seems that a precondition for volcanism outside frontal island arcs are lee-side upwellings which may act as counterflow centres, counterflow heads or lee-side island arcs. Many, perhaps all of them, begin their deve-

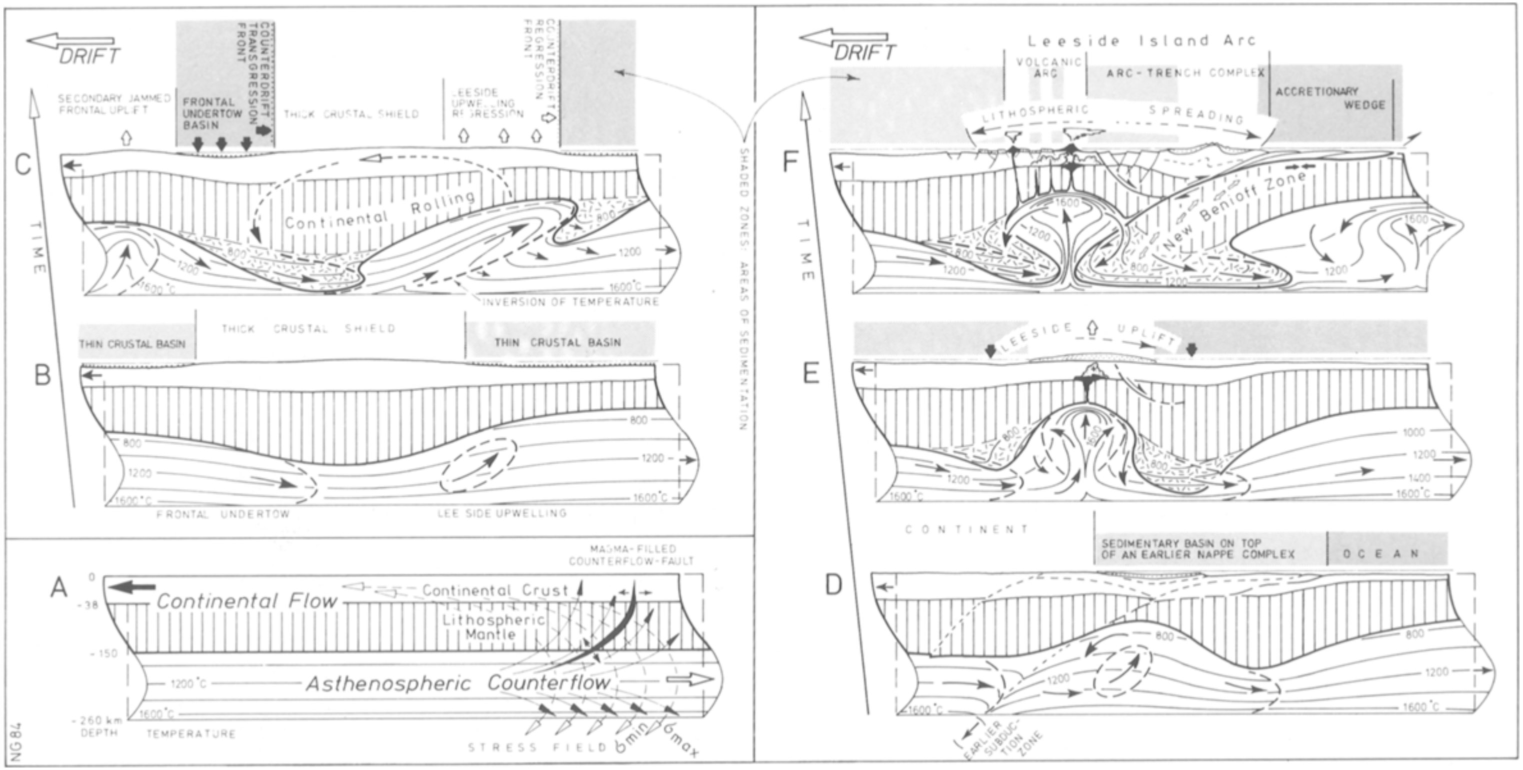


Fig. 18. Schematic models of counterflow activity: B-C Drift of a thick lithospheric shield may cause continental rolling due to crystallization of frontal undertow and partial melting in a lee-side upwelling. D-F Lee-side upwelling at a passive continental margin may result in the development of an »active« continental margin due to the initiation of a lee-side uplift with gliding nappes, lithospheric spreading and, finally, the formation of a new Benioff zone. This model resembles the Neogene crustal development of the Aegean arc (Surface geology after BÖGER, 1983; recent stress distribution in the Benioff zone after HORVATH & BERCKHEMER, 1982).

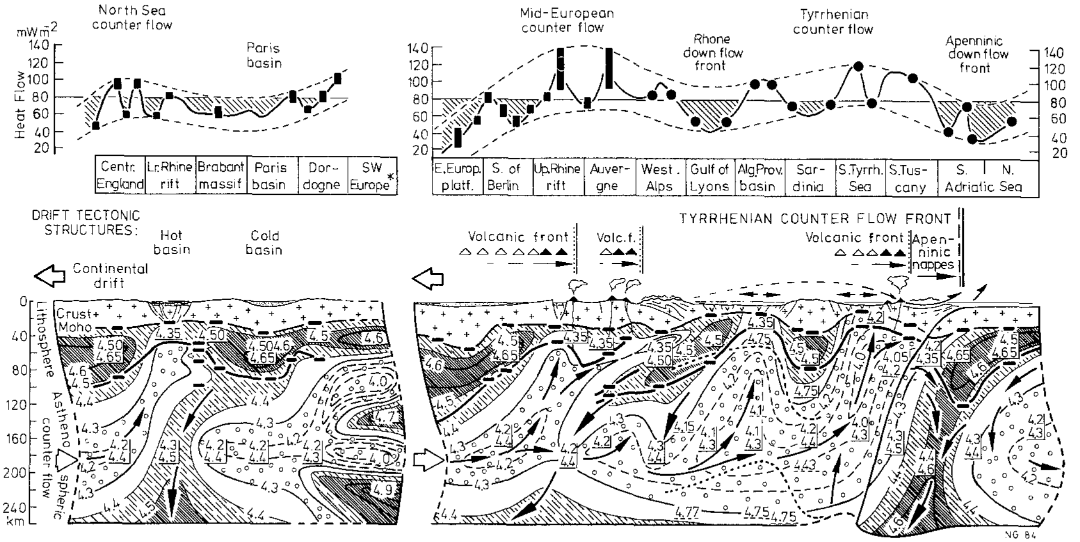


Fig. 19. Synthetic cross section through Central and Southern Europe: vertical distribution of S-wave velocities and surface heat-flow (Data mainly after PANZA et al., 1984). Short-wavelength heat-flow anomalies reflect lithospheric thickness, long-wavelength anomalies asthenospheric upwellings. Rise of hot matter occurs not vertically, but in inclined counter-drift-diapirs, very similar to the models of Fig. 18.

lopment as a local, increasingly turbulent eddy behind a thick lithospheric obstacle. Whereas mass deficiency is indicated in most mid-oceanic ridges and the Baikal rift zone by negative isostatic (ARTEM'YEV, 1973) and free-air gravity anomalies, these upwellings are characterized by positive free-air anomalies (GAPOSHKIN, 1974).

Conclusions

The most important results of the investigations could only be outlined in this paper. They led to a re-evaluation and – to some extent – to a synthesis of previous horizontal and vertical tectonic models.

After the development of new methods of projection, it was found that a fundamental rhythm in the drift of the continents is precisely reflected in regular lithospheric deformations. The main mechanism of this drift tectonic deformation is obviously a visco-elastic, glacier-like flow of the hot barysphere (lower lithosphere) down the inclined slopes of the asthenospheric surface (Gutenberg discontinuity). A second mechanism, the development of diapiric turbulence in asthenospheric counterflows concentrated in thin lithospheric channels, seems to be responsible for the observed counterdrift advance of epeirogenic and volcanic fronts.

Generally, the history of lithospheric tension fields reflects the interaction of lithospheric flow, asthenospheric counterflow and wandering downflow fronts. Counterflow- and downflow-front activity define the borders, lithospheric flow the interiors of drift fields, the largest units of the earth's surface. Their geometry and not that of single plates, determines the direction of continental drift. The deformation of the drift fields closely resembles the deformation of the Ross Ice Shelf, Antarctica (ZUMBERGE, 1960:60), where narrowing ice flow results in the development of a regular pattern of longitudinal folds and transversal crevasses. Thus, a classification of drift tectonic structures, e.g. hot longitudinal uplifts and tectogenes, cold longitudinal basins; as well as cold frontal undertow basins, hot transverse rifts and rhomb-shaped extension fields, is possible. Similar to the plates themselves, these features reflect the effect of the drift tectonic stress fields on the thermal and rigidity structure of the lithosphere.

Seismic anisotropy of the lithosphere, intraplate seismicity, horizontal stylolithes, volcanic dykes, linear salt diapirs and the pattern of sedimentation can also be correlated to this stress field. Thus, drift tectonics provide an explanation for isostatic anomalies, epeirogeny and – at least in part – orogeny.

It became clear that the usual classification of lithospheric structures is not sufficient: we must discern between hot extensional and cold compressional basins; between hot thin lithospheric shields and cold thick crustal shields; between frontal island arcs with mass deficiency and lee-side island arcs with mass surplus, intense vertical uplift and gliding nappe tectonics. Moreover, there is increasing evidence that the enigmatic Precambrian mobile belt dynamics also fit in the framework of drift tectonic correlations.

Generally, lithospheric dynamics can be expressed in four drift tectonic rules:

1.) Due to baryspheric flow the major part of the drifting lithosphere is subjected to longitudinal extension and transversal compression.

2.) Only in thin lithospheric zones, where asthenospheric counterflow is able to deform the crust, are the compressional trajectories arranged parallel to the drift but diverging in counterdrift direction.

3.) Thick crustal shields tend to submerge along their leading edges and to emerge at their lee-sides (»continental rolling«).

4.) Fronts of epeirogenic uplift and magmatic activity advance in counter drift direction.

Acknowledgements

This paper summarizes geodynamic aspects of research programs carried out during the last eight years in the Alps and in the Proterozoic of South Africa. Some aspects of this summary have already been reported at the annual assemly of the Geologische Vereinigung in Berchtesgarden (1983) and Mainz (1984) (drift tectonic phases) as well as at a meeting of German and Russian scientists in Moscow (1982) and at the XVIII general assembly of the IUGG in Hamburg (1983) (downflow fronts).

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