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PERTURBED MANTLE: A UNIFYING CHARACTERISTIC OF PLATE BOUNDARIES

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ABSTRACT

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Ocean-spreading ridge-, basin-and-range-, graben-, young-alpine-, island-arc-, and intra-continental-geosynclinal types of terrestrial crust are indicative of 'unstable' lithosphere. Whether undergoing tensional or compressional tectogenesis, these areas have certain geological and geophysical characteristics in common. Observations and measurements include anomalously high heat flow (>1.8 HFU), shallow intermediate P-wave velocities (7.2-7.8 km/s), low Q (i.e. a high attenuation factor), attenuated S-wave velocities (<4.5 km/s), and high electrical conductivity. Most 'unstable' areas are also marked by shallow seismicity and outpourings of basaltic volcanics which testify to shallow mantle sources. The data suggest welts of raised mantle as a common denominator under all types of 'unstable' crust. Therefore, seismicity, which presently defines the plate boundaries in plate tectonic theory is only a conspicuous effect of a deeper and more fundamental global phenomenon. I propose that the concept of plate boundaries be redefined on the basis of the wider range of geological and geophysical characteristics indicative of sublithospheric perturbations.

INTRODUCTION

The recognition of subcrustal disturbances as the fundamental cause of most tectogenesis on the surface of the earth must be a cornerstone of any viable geotectonic hypothesis. The occurrence of such subsurface perturbations, for instance, is basic to the undation theory (e.g. VAN BEMMELEN, 1972, 1978) the father of which we honour in this issue. In this paper, however, I discuss subcrustal peculiarities within the paradigm of the 'new global tectonics' as the combined theories of continental drift, sea-floor spreading, and plate tectonics are sometimes called.

It is not particularly surprising that with the rapid ascendence of the 'new global tectonics' many important facets of the paradigm remain poorly defined. The definition of plate boundaries is one such facet. Plate boundaries as presently recognized are of three types:

(1) constructive plate boundaries, where oceanic crust is formed at mid-ocean ridges;
(2) destructive plate boundaries, where crust returns to the mantle;
(3) transform faults, where the plates jostle and slide against each other.

At the present time, plate boundaries are defined on the basis of seismicity (LE PICHON ET AL., 1973, p. 3). The reliance on seismicity, however, presents insuperable problems and contradictions:

(1) plate boundaries, although obvious in general outline, are arbitrary in detail. What degree of frequency, density and intensity of seismicity constitutes a plate boundary?
(2) Seismicity at a plate boundary may be suppressed by superimposed loads on the crust such as ice sheets (e.g. the Antarctic ice sheet) or thick and loosely consolidated sediment accumulations (e.g. the West Siberian Lowland).
(3) Seismicity can obviously only be an effect of stress in the lithosphere so that the use of seismicity as the basis for outlining plates begs the question of cause.
(4) Earthquakes and other seismic phenomena are ephemeral events. When seismicity can no longer be monitored the geologist and geophysicist is left almost entirely without means with which to trace plate boundaries into the geologic past.

Thus, in order to unravel some of the conundrums presented by the presently restricted definition of plate boundaries on the basis of seismicity, I propose to examine the con-

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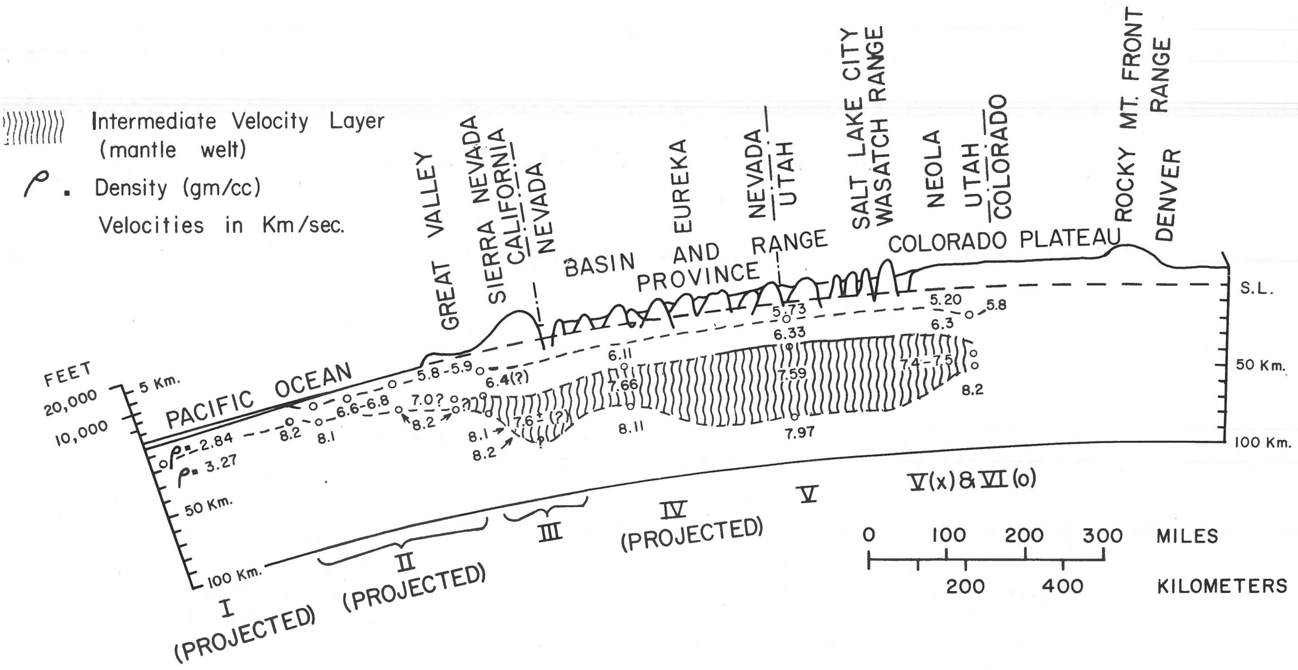

Fig. 1

A composite of projected cross-sections across the western United States illustrating the mantle welt (vertical wavy lines) under the Basin-and-Range Province. The mantle welt is distinguishable by the intermediate seismic velocities of between 7.2-7.8 km/s. At the surface, the anomalous mantle is expressed as basin-and-range type 'unstable' crust (after Cook, 1962).

cept and understanding of plate boundaries in terms of 'unstable' crust and anomalous mantle.

'UNSTABLE' VERSUS 'STABLE' CRUST

About 10 to 20% of the earth's lithosphere situated above the Moho is presently undergoing intense tectogenesis as the result of tensional- and/or compressional forces. Such 'unstable' crust is expressed at the surface in crustal accretion, subduction, orogeny, taphrogeny and intrusion. 'Unstable' crust is distributed in long linear belts surrounding cratonic (shield and mid-continent) and thalasso-cratonic (ocean basin) types of 'stable' crust (WILSON, 1968) which, by definition, are not presently subject to deformation except perhaps for epeirogenesis.

In terms more specific than 'crust undergoing tectogenesis', 'unstable' crust, despite its apparent heterogeneity, can be classified on the basis of common geophysical and geological characteristics. The groupings of 'unstable' and 'stable' crust then approach the classification of BRUNE (1969) who, mainly on the basis of seismic-wave-dispersion characteristics, identified the following 'unstable' crustal types (see Table I):

(1) ocean-spreading ridges;
(2) basin-and-range and continental graben provinces;
(3) back-arc basins;
(4) young alpine, i.e. young fold belts.

The classification advocated in this paper is similar but based on both a wider spectrum of geophysical and geological phenomena and on the broader aspects of crustal and subcrustal deformation. Specifically, I modify BRUNE's (1969) classification to include horst-block mountain trends in the alpine category so that 'alpine' is used here generically for all presently tectonically-active mountain belts. Furthermore, I add a fifth category: the active intra-cratonic geosyncline, which encompasses those crustal depressions which form prior to inversion (uplift), rifting, and eventual separation of continental crust.

The additional category of active intra-cratonic geosynclines is justified by the evidence for subcrustal deformation by plastic flow which forms the geosyncline in the first place. This subcrustal deformation is, therefore, the logical and necessary preliminary to the more-evolved 'unstable' states (VAN DER LINDEN, 1977).

The category of 'unstable' crust includes all the constructive and destructive plate boundaries of plate-tectonic theory, but does not only coincide with presently recognized plate boundaries. For instance the types of 'unstable' crust include young folded or block-faulted mountain belts (e.g. the Tienshan-Sayan belt) and certain intracontinental geosynclines (e.g. West Siberian Lowland) not generally accepted as plate boundaries, but also exclude the boundaries of the transform type (WILSON, 1965). Where the last apparently dislocate or terminate constructive or destructive plate boundaries (e.g. the San Andreas fault), crustal and sub-

Table I
Tectonic classification of the earth's surface 1)

Crustal Type	Tectonic Characteristic	Crustal Thickness or Depth to Mantle Welt	Pn (km/s)	Heat Flow H.F.U.	Bouger Anomaly (mgal)	Other Geologic and Geophysical Features
Continental Crust Overlying Perturbed Mantle						
Basin-and range and graben	very unstable	25	7.2-7.8	1.7-2.5	-200 to -250	Recent normal faulting, volcanism, and intrusion, electrical anomalies, high mean elevation
Young alpine	very unstable	10	7.4	0.7->2.0	-200 to -300	Includes fold and horst block mountains; rapid recent uplift, relatively recent intrusion; high mean elevation
Island-arc	very unstable	5+	7.2-7.8	0.7-4.0	-50 to +100	Includes back arc and marginal basins, back arc volcano-tectonic rift zones; high volcanism, intense folding and faulting
Active Geosyncline (intra-continental) infracratonic ensialic	unstable	>30	?	?	negative	Active crustal sag and subsidence; thick sediment acumulation, extensively fractured basement
Oceanic Crust Overlying Perturbed Mantle						
Ocean ridge	very unstable	5	7.2-7.8	1.0-8.0	+200-to +250	Active basaltic volcanism, little sediment
Continental Crust Overlying Stable Mantle						
Shield	very stable	35	8.3	0.7-0.9	-10 to -30	Little or no sediment, exposed batholitic rocks of Pre-cambrian age. Moderate thicknesses of Post-Pre-cambrian sediments
Mid-Continent	stable	38	8.2	0.8-1.2	-10 to -40	
Oceanic Crust Overlying Stable Mantle						
Ocean 2) Basin	very stable	11	8.1-8.2	1.3	+250 to +350	Very thin sediments overlying basalts, linear magnetic anomalies, no thick Palaeozoic sediments

1) modified from Brune (1969)
2) thalassocraton of R. W. Fairbridge (1955)

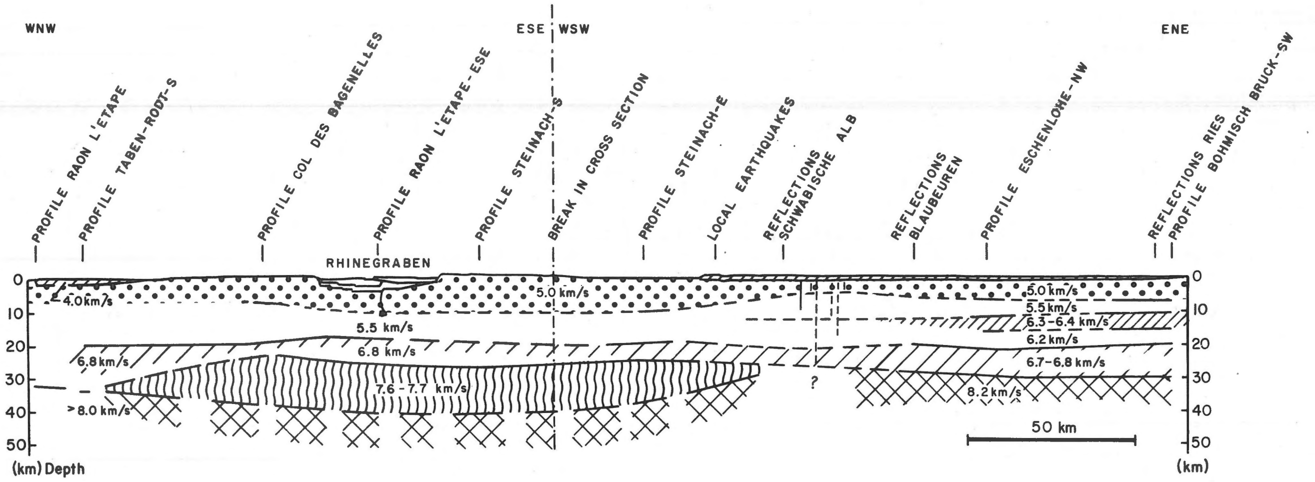

Fig. 2
Profile and section through the Southern part of the Rhine Graben. The mantle welt (velocity 7.6-7.7 km/s) is 250-300 km across. Its lower boundary at 40 km is not confirmed (after Mueller et al., 1973, Fig. 6).

crustal peculiarities often demonstrate that, in fact, the boundaries continue under the guise of a different type of 'unstable' crust. A brief description of each type of 'unstable' crust and a sampling of associated subcrustal peculiarities will set the stage for a summary of the peculiarities which unify 'unstable' crustal types.

TYPES OF 'UNSTABLE' CRUST AND RELATED MANTLE PECULIARITIES

Graben and basin-and-range type (Figs. 1, 2, 3)

Belts of rifts, grabens, normal faults and basin-and-range morphology, indicate that the crust is under strong tensional stress. Therefore, brittle deformation, pulling apart, and collapse are the outstanding surficial characteristics of the basin-and-range and continental-graben types of 'unstable' crust.

Differences in detail, such as width and scale of magmatic activity, do exist, but the rifted and basin-and-range crustal types are so similar in character and origin that they may be presumed to be related stages of crustal response. Typical areas include the East African Rift, the Baikal Rift, the Rhine-Rhone Graben, the North American Basin-and-Range Province, and the Great Artesian Basin of eastern Australia.

Heat flow in grabens and basin-and-range areas is usually above 1.8 HFU and, therefore, considerably above the global mean of 1.5 HFU. Seismic-refraction studies indicate P-wave velocities between 7.2-7.8 km/s which are lower than the 8.0-8.2 km/s velocities usually associated with the Moho in areas of 'stable' crust. Electrical studies of the crust and upper mantle in the Rhine Graben (LOSECKE, 1970; SCHEELKE, 1974), in the Baikal Rift (ARTEMJEV & ARTYUSHKOV, 1971), and in the Basin-and-Range Province (KELLER, 1971), indicate a subcrustal zone of high electrical conductivity. The topography and belts of shallow seismicity emphasize the linearity of taphrogenic areas. Flood basalts, volcanism, and the intrusion of alkaline basalts confirm raised isotherms.

Under the Basin-and-Range Province of the western United States, the geographic distribution of high heat flow, basaltic intrusives, and the extent of intermediate P-wave velocities (HERRIN, 1969) coincide with reduced crustal thickness; less than 30 km in the Basin-and-Range Province contrasts with 50 km and more in surrounding 'stable' areas (PAKISER & ZIETZ, 1965). The basaltic nature of the intruded and extruded rocks, and the thinner crust suggest shallow upper mantle.

In the Rhine Graben, by plotting observed against theoretical Rayleigh waves, SEIDL ET AL. (1970) demonstrated the presence of a shallow intermediate-velocity layer. BRUNE's (1969) observations indicate this fact to apply generally to basin-and-range type 'unstable' crust.

Under the East African Rift Valley, the suspected presence of anomalous mantle material is based on seismic and gravity observations by KAHN & MANSFIELD (1971). They calculated upper mantle densities of 3.15 g/cm^3 under the rift contrasting with 3.4 g/cm^3 from tectonically less active areas. LONG & BACKHOUSE (1976), likewise, showed that anomalous mantle extends under the African Rift System. The geothermal activity in the rift may indicate high heat flow (TOBIN ET AL., 1969).

The Baikal Rift System, situated in eastern Siberia, also exhibits geophysical peculiarities typical of graben-type 'unstable' crust (ARTEMJEV & ARTYUSHKOV, 1971). These peculiarities include refraction velocities of 7.1-7.5 km/s just under the Moho discontinuity, a zone of tensional shallow earthquakes, and a sharp gravity minimum. Furthermore, the heat flow mean is about twice the world's average, high electrical conductivity indicates a shallow anomalous layer, and the magnetic field displays a banded character parallel to the rift valleys. Striking petrological and chemical similarities between the trachybasalts of the Baikal region and mid-ocean ridges suggest a common mode of genesis.

To summarize, the data from areas of graben and basin-and-range types of 'unstable' crust strongly indicate related subcrustal peculiarities. Details require greater scrutiny and discussion but the existence of material apparently in the form of perturbed mantle argues for a cause-and-effect relationship between such material and taphrogeny.

Ocean-spreading ridge type of 'unstable' crust (Fig. 4)

Ocean-spreading ridges are tectonically very active submarine mountain chains situated on long continuous cracks in the earth's crust through which mantle-derived tholeiitic basalts semicontinuously intrude to form new oceanic crust. This type of 'unstable' crust is uplifted, highly fractured, and cut by deep axial rift valleys at the crest of slow-spreading ridges, or crested by extensive horst blocks when associated with higher spreading rates (e.g. CANN, 1968). The spreading ridges are marked by a narrow zone of shallow earthquake epicenters (BARAZANGI & DORMAN, 1969), indicative of relatively deep-seated tensional processes, as well as by high heat flow from 2 HFU to as high as 8 HFU reflecting raised mantle isotherms (SOLOMON, 1973). Intermediate P-wave and S-wave velocities of 7.2-7.8 and 4.2-4.4 km/s, respectively, are generally recorded at a depth of less than 10 km (DRAKE & NAFE, 1968; KEEN & TRAMONTINI, 1970; ORCUTT ET AL., 1975). The presence of shallow mantle is also inferred from low-Q zones (SOLOMON, 1973) and the distribution of fundamental-mode Love and Rayleigh dispersion curves (BRUNE, 1969).

Although Bouguer gravity values measured over ocean-spreading ridges tend to be high (see Table I), they are lower than the values over 'stable' oceanic crust. Thus, the absence of a gravity high suggests low densities which, when interpreted together with the other geophysical observations, are thought to reflect extensive partial melting at depth at temperatures in excess of the anhydrous solidus of mantle material.

Back-arc basins (Fig. 5)

Back-arc basins are areas of 'unstable' crust situated between the frontal and remnant arcs of island-arc complexes. The basins are of intermediate to normal oceanic depth and are usually underlain by highly fractured oceanic crust. They relate to both tensional (back-arc spreading) and compressional (subduction) environments. Crustal extension similar to sea-floor spreading is thought to be the mechanism responsible for the opening of these basins (KARIG, 1971). Models of anomalous mantle under back-arc basins in the form of 'peridotic' or 'thermal diapirs' or as 'a wedge of upwelling mantle' have been elaborated by OXBURGH & TURCOTTE (1970) and KARIG (1971), respectively.

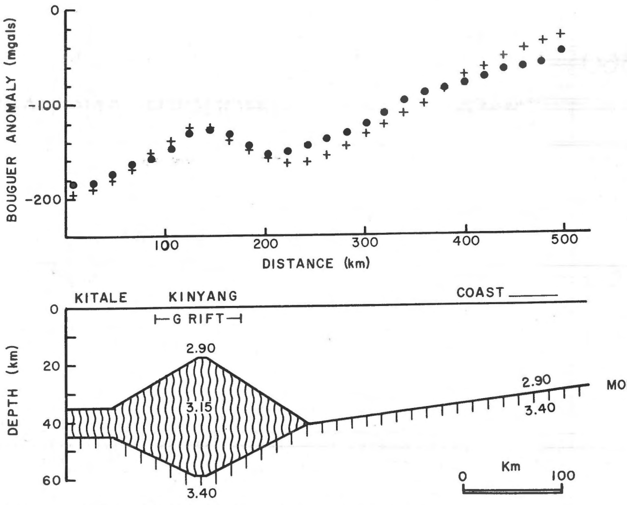

Fig. 3
West-east Bouguer gravity profile across the Gregory Rift of East Africa with a model of an underlying mantle welt. The mantle welt is more then 200 km across. Numbers represent specific gravities (after Kahn & Mansfield, 1971).
● Observed
+ Calculated

Presently-active inter-arc basins with high heat flow in the western Pacific include the Bonin basin, the Mariana trough, the New Hebrides zone, and the Lau-Havre basin (KARIG, 1971). Other marginal basins with high heat flow, but which appear to be tectonically inactive, include the Sea of Japan, the Sea of Okhotsk, the Parece Vela basin and, provisionally, the Celebes and Sulu Seas (KARIG, 1971).

In the back-arc areas with thermal anomalies, seismic-refraction intermediate velocities of 7.2-7.8 km/s are common (e.g. SHOR ET AL., 1971; MARAUCHI ET AL., 1968; FUROMOTO ET AL., 1970; DU BOIS ET AL., 1973). A summary study by BARAZANGI ET AL. (1975) confirms that zones of high compressional-wave attenuation and inefficient high-frequency shear-wave propagation are characteristic of the upper mantle behind island arcs.

Ordinarily, a large positive free-air gravity anomaly should occur over back-arc basins when oceanic crust is positioned at shallower-than-normal-for-its-age oceanic depths. The absence of such an anomaly requires compensation by low-density, probably high-temperature lower crust or upper mantle.

Linear magnetic anomalies, which in some cases correlate with the magnetic time scale (WATTS ET AL., 1977; TAYLOR, 1975; WEISSEL, 1977), and attest to the generation of new sea floor, have been found in many back-arc basins.

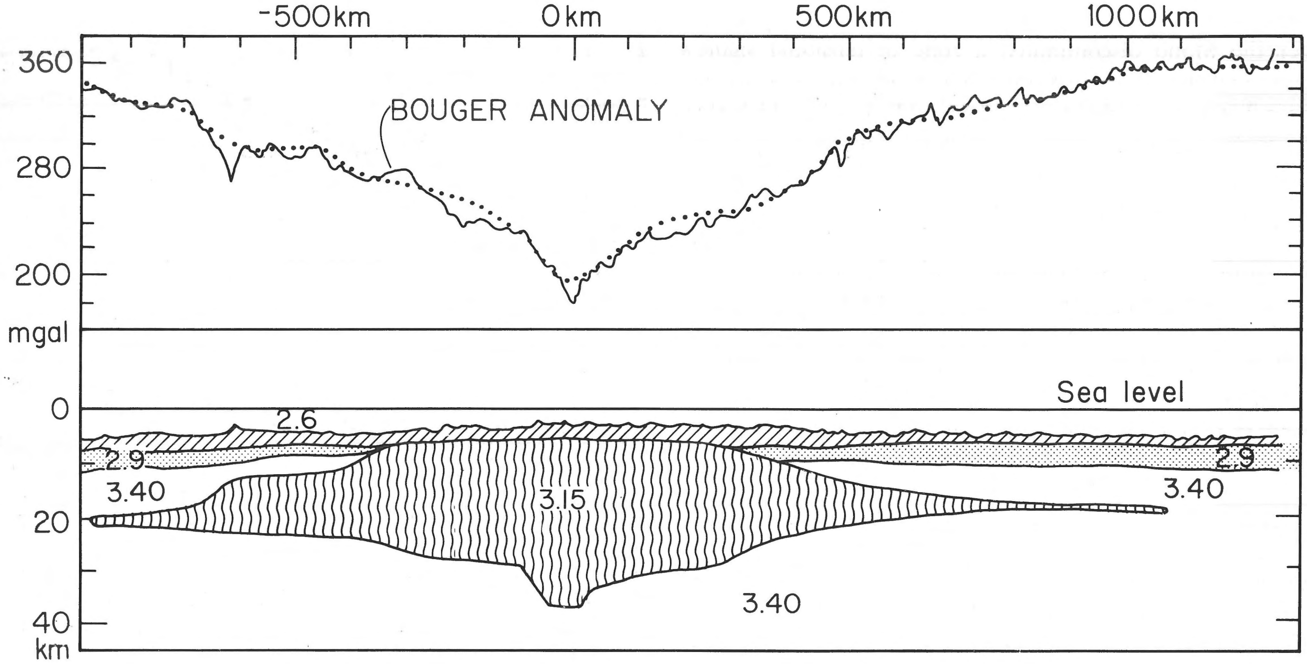

Fig. 4
Three possible configurations of the anomalous mantle under the north mid-Atlantic Ridge constrained by the observed gravity anomaly and in accord with seismic-refraction results. In case I, the density of anomalous mantle is assumed to be uniform; in case II, the density of the mantle welt is assumed to increase downward; in case III, the anomalous mantle is assumed to be lighter near the axis of the ridge (after Talwani et al., 1965; Wyllie, 1971, p. 145).

To summarize, high heat flow, intermediate refraction velocities, shallow (and deep, when subduction associated) earthquake hypocenters, linear magnetic anomalies, and mantle-derived tholeiitic basalts are associated with the back-arc-basin type of 'unstable' crust suggesting shallow perturbed mantle.

Intracontinental geosynclines

The type of geosyncline included in the classification of 'unstable' crust is the active sag of continental crust which occurs prior to rifting and crustal separation. For clarity, these geosynclines are called intracontinental or proto-seas so that they may be distinguished from back-arc basins, continental-margin crustal depressions and other intra-continental negative areas.

The reconstruction of the presently separating Gulf of California indicates the former existence of a proto-Gulf of California (MOORE, 1973), similar in scale to the intracontinental geosynclines discussed here. Seismic reflection profiles, structural interpretations, and depths associated with forams in dredged sediments, suggested to MOORE (1973) that 'the central part of the early gulf which existed prior to the time of the most recent plate separation was locally at least 1000 m and probably as much as 2.5 km deep'.

Another example is the pre-rifting history of the Red Sea-Afar-Gulf of Aden-Ethiopian Rift areas (MOHR, 1975). Extensive Mesozoic downwarping along the axes of these rifts resulted in the accumulation of intracontinental geosynclinal sediments in a proto-Gulf of Aden, a proto-Afar, a proto-Red Sea trough, and in a depression antecedent to rifting in the northern part of the Ethiopian Rift (MOHR, 1975).

In eastern Greenland there is, likewise, evidence that prior to crustal separation, 'a fluctuating shelf sea persisted throughout the Mesozoic. The basement under the shelf (sea) gradually was broken into a complex pattern of tilted fault blocks' (HALLER, 1969). In the terminology used here, this shelf sea, which anticipated the opening of the Norwegian Sea, is the proto-sea or intracontinental geosyncline which appears to precede crustal inversion and break-up.

It seems reasonable that certain presentday intracontinental geosynclines are the early surficial manifestations of the large-scale sub-crustal tensional strain and plastic flow associated with rising isotherms. The West and North Siberian Lowlands, which meridionally traverse the Eurasian continent just east of the Ural Mountains illustrate the dimensions, the deep sediment accumulation, and the geological history, to be such a geosyncline post-Palaeozoic sediment thicknesses in the lowlands vary from 3 km to 10 km and more. Accumulation continues and is irrefutable evidence for slow and episodic net subsidence.

Basement in the West Siberian Lowland is characterized

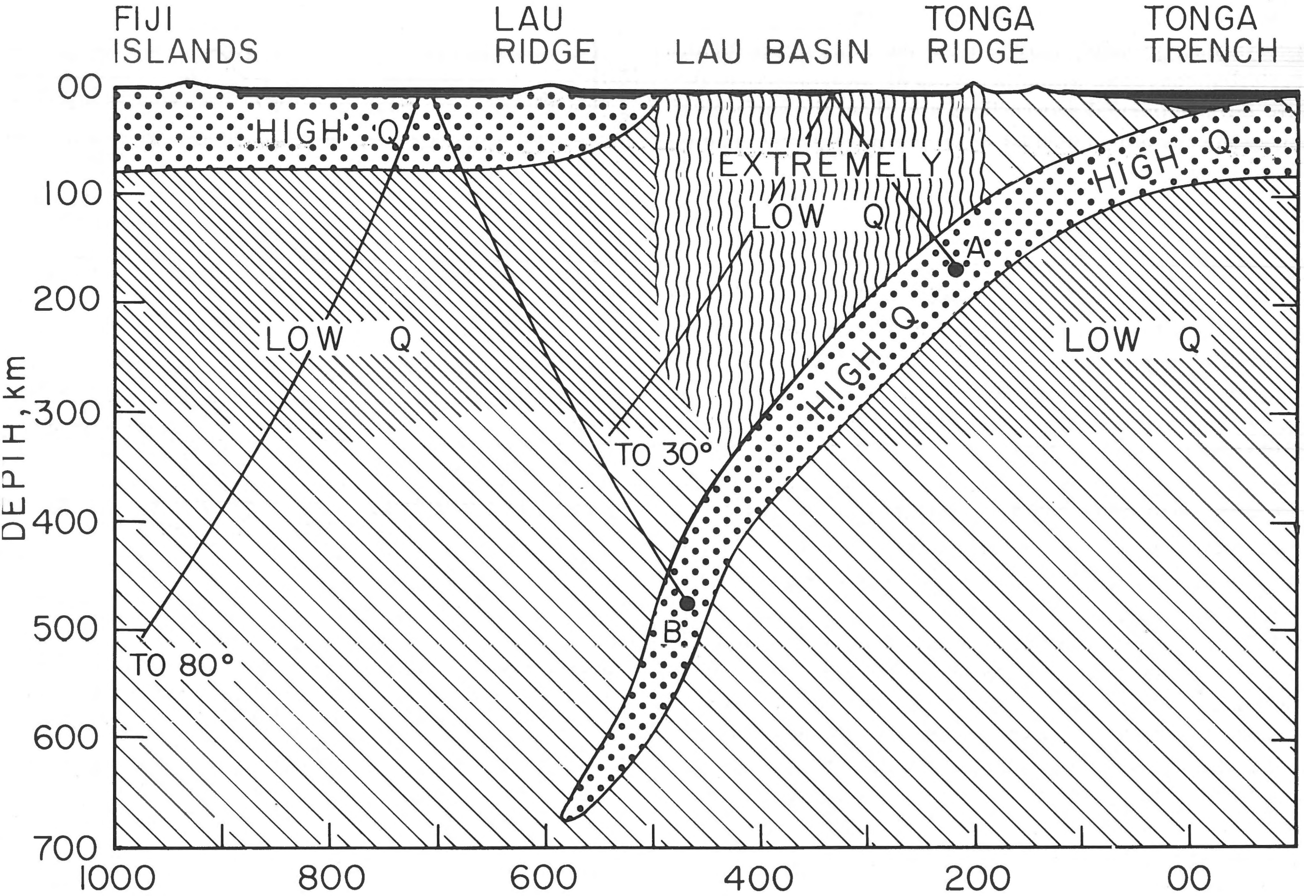

Fig. 5
Schematic profile and section perpendicular to the Tonga Island Arc showing lithospheric plates (dotted) and the high- and low-attenuation zones. The 'extremely' low-Q zone, associated with high heat flow, is best explained by partial melting and can be considered evidence for the position of the mantle welt beneath the actively spreading Lau Basin. Two representative ray paths originate from seismic events A and B (after Barazangi et al., 1975).

by north-south oriented, subparallel systems of normal faults which have uplifted and downdropped basement blocks by as much as 1000 m (DICKEY, 1972). This crustal fracturing has been active into Quaternary time in the Ural Mountains (NALIVKIN, 1960, p. 41) and, presumably, in the West Siberian Lowland to judge by the continuing downwarping (NALIVKIN, 1973, p. 302) and monoclinal folding of overlying sediments (SHATZKI & BOGDANOFF, 1959). Earthquakes have been recorded on the western edge of the Lowland (KIRILLOVA & PETRUSHEVSKIY, 1972).

HAMILTON (1970) indicated that the West Siberian Lowland has been undergoing subsidence and 'post-Paleozoic tensional thinning of the crust' as evidenced by the fanning-out and 'divergence across the West Siberian Lowland of the magnetic anomaly belt continuous from the southern Ural Mountain geosyncline'. The linear anomalies, themselves, may have resulted from horizontal strain and intrusion. Underlying crystalline fold belts are now about 8 km thinner than similar crust under the flanking shield areas (see also the relief map of the Moho for the U.S.S.R. by KOSMINSKAYA ET AL., 1969). A preliminary heat-flow map by STEGNA (1972) updating an earlier map by MAKARENKO ET AL. (1968) indicates a geothermal high throughout the Lowland.

Other examples of active intracontinental geosynclines are the Verkhoyansk Trough and the Vilyui Syneclise (geosyncline) which lie to the north of, and in line with, the Baikal Rift. These depressions, which are believed to be underlain by faulted and thinned crust (HEEZEN & EWING, 1961) are filled with 7 to 8 km of sediments (SHATZKI & BOGDANOFF, 1959). Tectonization of these intracontinental geosynclinal areas of 'unstable' crust would link the active Arctic Nansen spreading ridge to the north with the intense rifting of the Baikal Rift System to the south and southwest.

To summarize, intracontinental geosynclines are seen as sites of regional stress and strain largely relieved by subcrustal plastic flow. The participation of sublithospheric heat suggests a continuum between the intracontinental geosyncline, taphrogeny and crustal separation. By analogy, therefore, the source of heat and tensional stress under intracontinental geosynclines probably derives from the same upper mantle perturbations found with other types of 'unstable' crust. Active intracontinental geosynclines are, then, the surface expression of continental crust underlain by perturbed mantle *in statu nascendi.*

Young alpine belts (Fig. 6)

Sediment-filled troughs such as back-arc basins, continental margins, narrow ocean basins, and deep linear intracontinental crustal depressions are subject to deformation. Belts of young alpine-type 'unstable' crust include collision and obduction zones following the models of DEWEY & BIRD (1971) and COLEMAN (1971), as well as belts subjected to vertical uplift under compressive stress, following the BELOUSSOV (1962) model. In any of these cases, the folded and/or horst-uplifted mountain belts are the strain resultant of both horizontally-compressional and vertical stress in the crust.

Gravity measurements over folded mountain belts indicate a mass deficiency which suggested a less-dense sialic 'root' projecting deeply into the underlying mantle. Recent geophysical studies, however, have indicated subcrustal peculiarities similar to those associated with other types of 'unstable' crust. Characteristically, the evidence comes from high heat flow, intermediate-velocity P-waves, and often from the presence of mafic intrusives and ophiolites.

A striking correlation between heat flow and age of folding is apparent: younger folding is associated with higher heat flow, whereas progressively older and more stable crust is associated with lower heat flow (POLYAK & SMIRNOV, 1968). This correlation helps to distinguish active alpine belts from inactive alpine belts which have cooled sufficiently to become part of the 'stable' craton.

Long-range seismic refraction experiments under the western Alps indicate a 7.4 km/s P-wave velocity under the Ivrea Zone (BOTT, 1971, p. 58). Other young orogenic systems including the eastern Alps, the northern and southern Apennines, the Crimea and the Kura Depression adjacent to the Greater Caucasus range have been probed by deep seismic-refraction waves and exhibit similar crustal and subcrustal peculiarities (GIESE & PAVLENKOVA, 1976).

Low fundamental-mode Rayleigh-wave group velocities are lower for alpine-type 'unstable' crust than for any other crustal type. Thus, the interpretation of the geophysical data supports partially molten crust and/or mantle as discussed by HAENEL (1974). Underlying similarities between young alpine belts and ocean-spreading ridges suggest related subcrustal underpinnings (MAXWELL, 1968).

Horst-block mountain trends are included in the classification of alpine-type 'unstable' crust. In Asia, the more than 4000 km long, tectonically very active Tienshan-Sayan Belt consists of linear, uplifted block mountains and depressions (NALIVKIN, 1960; BESSONOVA ET AL., 1960) outlined by intense and shallow (less than 70 km deep) earthquake activity (MOLNAR ET AL., 1973; BESSONOVA ET AL., 1960). This is the 'Pamir-Baykal' seismic belt of GUTENBERG & RICHTER (1954) and LANG & SUN (1966), and reflects the impressive present-day vertical movements and displacements measurable in terms of several kilometres since the Pliocene (BELOUSSOV, 1962, p. 213). Minor basaltic intrusives date tectonic activity still earlier into the Tertiary (BESSONOVA ET AL., 1960).

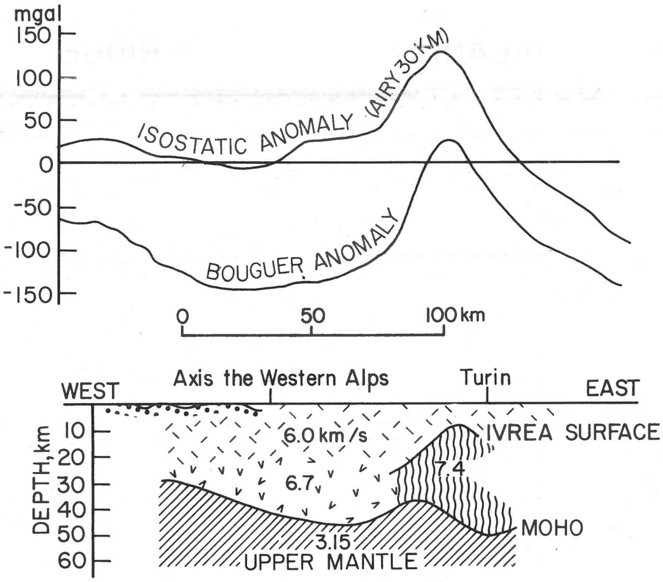

Fig. 6
Crustal structure, Bouguer and isostatic anomalies across the western Alps. Numbers are seismic velocities. The 7.4 km/s seismic velocity under the Ivrea Zone is associated with high heat flow and suggests partially molten crust and/or mantle as discussed by Haenel (1974) (reproduced from Bott, 1971, p. 58).

Evidence for subcrustal peculiarities under the Tienshan-Sayan belt is not readily available or of dubious quality (RODRIGUEZ, 1969). Therefore, without more seismic measurements and confirmation from heat-flow measurements, the supposition of an underlying perturbed mantle still rests on insufficient data. However, I include horst-block mountain trends in the classification of 'unstable' crust by virtue of their high seismicity and obvious tectonic instability, which, by analogy, should result from perturbed mantle.

MEASUREMENTS AND OBSERVATIONS COMMON TO 'UNSTABLE' CRUST

The review of 'unstable' crustal areas has consistently shown the presence of subcrustal peculiarities. In this section, the geological and geophysical peculiarities and parameters used to define them are summarized. In every case, a past or present link between 'unstable' crust and shallow anomalous mantle, i.e. a mantle welt (used in the sense of raised asthenosphere rather than the raised crust of, for instance, BUCHER, 1933), is indicated.

(1) *Heat flow:* the primary cause of crustal stresses is thermal in origin. High heat flow, i.e. more than 1.8 to 2.0 HFU (VON HERZEN & LEE, 1969), probably indicates partially molten mantle, i.e. raised asthenosphere, under 'unstable' crust. Surface heat flow plotted against the heat productivity of crustal rocks strongly indicates that the major source of the heat is subcrustal (BIRCH, 1955; ROY ET AL., 1968).

(2) *Intermediate P-wave velocities:* deep seismic refraction experiments in areas of 'unstable' crust indicate a shallower-than-normal, intermediate velocity (7.2-7.8 km/s) zone which might confirm the presence of partially-molten upper mantle. The 7.2-7.8 km/s P-wave velocities under 'unstable' crust contrast with the velocities greater than 8.0 km/s usually associated with the upper mantle under 'stable' crust.

(3) *P-wave attenuation:* lateral variations in the upper mantle, such as the proposed mantle welts, can be located by the distribution of travel-time anomalies (HALES, 1972). In general, upper-mantle P-wave arrivals are late (by 0.2 to 0.8 seconds) in areas of young orogenic activity, and early (by 0.0 to -0.5 seconds) in shield and stable craton areas.

(4) *Low S-wave velocities:* shear wave velocities (S) in the upper mantle beneath 'unstable' crust are anomalously low. Whereas subcrustal S-wave velocities under 'stable' crust usually range above 4.6 km/s, they average less than 4.5 km/s beneath 'unstable' crust (BRUNE, 1969; MOLNAR & OLIVER, 1969).

(5) *Seismic surface waves:* the study of seismic surface waves, i.e. plotting phase and group velocities of Rayleigh and Love dispersion waves, allowed BRUNE (1969) to classify the earth's crust into the 'unstable' and 'stable' categories. The behaviour of such waves requires a shallow intermediate velocity channel under areas of 'unstable' crust (BRUNE, 1969).

(6) *Gravity:* ideally, Bouguer gravity anomaly profiles over areas of 'unstable' crust are negative relative to the surrounding 'stable' crust (Table I). This evidence is suggestive of partially molten, low-density upper mantle which, however, always requires confirmation by other geophysical data.

(7) *Intermediate density:* plotting of mantle P-wave velocities versus densities on the NAFE-DRAKE (1963) curve, indicates that upper mantle under areas of 'unstable' crust has a density of about 3.1 g/cm^3. This contrasts with 'normal' mantle densities of about 3.4 g/cm^3 and coincides with expected densities of partially-molten mantle material.

(8) *Low quality factor (Q):* attenuation of seismic waves is usually represented by Q, the Quality Factor (e.g. BARAZANGI ET AL., 1975). The low Q in areas of 'unstable' crust suggests asthenosphere reaching close to the earth's surface.

(9) *Relatively thin crust:* in most places the crust overlying the proposed mantle welts is thin relative to flanking areas.

(10) *Shallow asthenosphere:* the average depth to the low-velocity layer (asthenosphere) is about 50 km under 'stable' oceanic crust and 175 km under 'stable' continental crust. In contrast, the depths typical of mantle welts (raised asthenosphere) under the various types of 'unstable' crust are considerably shallower:

basin-and-range	25 to 40 km	(ZIETZ, 1969)
grabens	25 to 45 km	(ANSORGE ET AL., 1970)
ocean-spreading ridges	5 to 30 km	(EWING & EWING, 1959)
back-arc basins	5 to more than 20 km	(COOK, 1962, p. 318; KARIG, 1971)
young alpine belts	10 km and deeper	(BOTT, 1971, p. 58)
active intra-continental geosynclines	more than 30 km.	

(11) *Shallow earthquakes:* 'unstable' crust, with the exception of geosynclines, is generally defined by shallow earthquakes. The hypocentres are shallow, presumably because higher isotherms have raised the transition zone between seismic brittle deformation and aseismic plastic deformation.

(12) *Microseismicity:* measurements in continental rifts (TOBIN ET AL., 1969) and ocean-spreading centers (FRANCIS & PORTER, 1972, 1973) indicate an abnormally high degree of microseismicity. Apparently, elevated microseismicity is characteristic over perturbed mantle precisely where the overlying crust is under maximum stress.

(13) *Petrology and geochemical association:* the chemistry and petrology of the copious intrusions and extrusions of alkaline and tholeiitic basaltic volcanics in areas of 'unstable' crust suggest partial fractionation of raised and partially molten asthenosphere (e.g. GREEN & RINGWOOD, 1967). Associated degassing affects the geochemistry of overlying rocks (WAKITA ET AL., 1978).

(14) *Electrical soundings:* the electrical conductivity of rocks increases by about two orders of magnitude at 920 °C. (AKIMOTO & FUJISAWA, 1965). A compilation of data (KELLER, 1971) indicates that electrical conductivity is at its maximum in areas of mobile, i.e. 'unstable' crust. Thus, electrical conductivity has been shown to increase over spreading ridges (VACQUIER, 1972), the basin-and-Range Province (PORATH, 1971), the Rhine Graben (LOSECKE, 1970; SCHEELKE, 1974),

and the Baikal Rift (GORNOSTAIEVE ET AL., 1970).

(15) *Linearity:* the plot of earthquake epicenters associated with 'unstable' crust shows linear continuity for long distances. This undoubtedly reflects an important characteristic of the underlying mantle.

(16) *Crustal accretion and magnetic anomalies:* magnetic anomalies suggest present or former raised asthenosphere over which oceanic crust formed or continental crust stretched and attenuated.

(17) *Transverse offsets and transform faults:* transverse offsets, i.e. transform or transcurrent faults, are characteristic of 'unstable' crust. They are most obvious on ocean-spreading ridges and common in graben and basin-and-range trends (ILLIES, 1974), back-arc basins (CARR ET AL., 1973), and related volcano-tectonic rift zones such as the Kamchatka-Kuril (GORYATCHEV, 1962).

DISCUSSION

When the crust and mantle are seen in perspective as parts of a dynamic planetary body, the relative insignificance of crustal thickness suggests that crustal features are secondary to a more-fundamental and global mantle process. Thus, despite the different types of 'unstable' crust, the repeated association of similar geological and geophysical peculiarities indicates one common unifying characteristic: 'unstable' crustal types are the surficial expression of long welts of perturbed mantle. Conversely, 'unstable' crust is underlain by perturbed mantle. This relationship is logical considering that overlying crust is structurally weakened by rising isotherms, partial melting, phase changes and tectogenesis.

Constructive and destructive plate boundaries illustrate diverse 'unstable' crustal types with similar tectonic underpinning directly related to perturbed mantle. Seismic belts are then only one symptom, albeit a most noticeable one, of perturbed mantle. The recognition of the 'unstable' crust/perturbed mantle couple as a global phenomenon refines the understanding of plate boundaries. The increase of geological and geophysical parameters which becomes available to define present, as well as palaeo-plate boundaries once seismicity ceases is one of many immediate advantages.

In the 'new global tectonics' compressional mountain chains result from the collision of continental blocks at the site of subduction zones (DEWEY & BIRD, 1970). Such collisions infer a sequential evolution of the crust (from subduction to obduction and orogeny) over one and the same zone of subcrustal perturbation. This last is a raised zone of subcrustal weakness-a stress guide- for the various types and styles of tectogenesis expressed in 'unstable' crust. This zone becomes the logical locus for horizontal (i.e.sea-floor spreading and subduction), as well as vertical (i.e. compressional diastrophism and horst uplift) tectonism. The intracratonic-geosynclinal-, the graben-, the basin-and-range-, and the ocean-spreading types of 'unstable' crust also appear to relate, in order, to a sequential change of a growing and developing mantle welt. Thus, just as 'unstable' crust undergoes a developmental cycle, it is probable that the underlying mantle, likewise, undergoes a developmental cycle, in which case each phase of tectonism along plate boundaries becomes dependent on a complex interrelationship between the crust and an actively expanding or contracting welt of perturbed mantle. This interrelationship should eventually serve as the basis for a deterministic geotectonic cycle complementing the theory of plate tectonics.

Recognition of the 'unstable'-crust/mantle welt/plate-boundary association implies that vertical and horizontal tectonics are different aspects of the same phenomenon. The occurrence of either tectonic style is then determined primarily by the regional crustal stress at the time of tectogenesis. Therefore, concepts of vertical diastrophism (important in classical geology) and horizontal motion (basic to modern geology and plate tectonic theory) become largely compatible.

A redefinition of plate boundaries on the basis of subcrustal peculiarities also suggests that the proposed mantle welts, as long, continuous subcrustal features, are perhaps subject to a global, geometrically-symmetrical distribution. The resulting pattern would be expressed by all the different types and stages of 'unstable' crust. The spatial and temporal complexity of the components of such a pattern involving 'unstable' crust may explain why such a geometric pattern is not, as yet, obviously discernable. If found, however, such a pattern would confirm the as-yet-unsupported supposition that continental drift and plate tectonics are the manifestations of a non-random planetary process. Thus, when considered as a global phenomenon, the concept of mantle welts and their relation to 'unstable' crust and plate boundaries may offer a key to a unifying hypothesis of tectogenesis and mantle circulation.

CONCLUSIONS

(1) The different types of 'unstable' crust display dissimilar surface expressions, but exhibit the same or similar subcrustal peculiarities.

(2) The similarity of the geophysical and geological peculiarities under the different types of 'unstable' crust and the on-strike continuity of the peculiarities independent of the type of overlying 'unstable' crust suggests that the subcrustal peculiarities result from an identical cause and process.

(3) The subcrustal peculiarities are best interpreted as evidence for partially molten mantle. The reason for the mantle's partially molten state and its anomalously shallow position under belts of 'unstable' crust is not known, although some form of cellular convection is suspected.

(4) All presently accepted accreting and consuming plate boundaries fall within belts of 'unstable' crust underlain by subcrustal peculiarities, i.e. perturbed mantle.

(5) Whereas the present definition of plate boundaries is based almost exclusively on seismicity, it is suggested that in view of the similarity of many other crustal and subcrustal occurrences (and not only seismicity), the definition of plate boundaries be extended to include all areas of 'unstable' crust underlain by perturbed mantle.

REFERENCES

Akimoto, S. & H. Fujisawa 1965 Demonstration of electrical conductivity jump produced by the olivine-spinel transition – J. Geophys. Res. 70: 443-449.

Ansorge, J., D. Emter, K. Fuchs, J. P. Lauer, St. Muller & E. Peterschmidt 1970 Structure of the crust and upper mantle in the rift system around the Rhinegraben. In: J. H. Illies & St. Muller (eds.): Graben problems – Int. upper mantle project sci. rept. 27: 190-197; E. Schweizerbart'sche Verlagsbuchhandlung (Stuttgart).

Artemjev, M. & Y. Artyushkov 1971 Structure and isostasy of the Baikal Rift and the mechanism of rifting – J. Geophys. Res. 76: p. 1197-1211.

Barazangi, M. & J. Dorman 1969 World seismicity maps compiled from ESSA coast and geodetic survey epicenter data, 1961-1967 – Seismol. Soc. Amer. Bull. 59: 369-380.

Barazangi, M., W. Pennington & B. Isacks 1975 Global study of seismic wave attenuation in the upper mantle behind island arcs using P-waves – J. Geophys. Res. 80: 1079-1092.

Beloussov, V. V. 1962 Basic problems in geotectonics (translater: P. T. Broneer) – McGraw Hill Book Co. (New York): 809 pp.

Bessonova, E. N., O. D. Gotsadze et al. 1960 Investigations of the mechanism of earthquakes. In: Soviet Research in Geophysics 4 (English translation: Amer. Geophys. Union, Consultants Bureau (New York).

Birch, F. 1955 Physics of the crust. In: The crust of the earth – Geol. Soc. Amer. Spec. Paper 62: 101-118.

Bott, M. H. P. 1971 The interior of the earth – St. Martin Press Inc.: 316 pp.

Brune, J. N. 1969 Surface waves and crustal structure. In: P. J. Hart (ed.): The earth's crust and upper mantle – Amer. Geophys. Union, Geophys. Monographs 13: 230-242.

Bucher, W. H. 1933 The deformation of the earth's crust – Hafner Publishing Co. (New York) (reissue 1968): 518 pp.

Cann, J. R. 1968 Geological processes at mid-ocean ridge crests – Geophys. J. Roy. Astron. Soc. 15: 331-341.

Carr, M. J., R. E. Stoiber & C. L. Drake 1973 Discontinuities in the deep seismic zones under the Japanese arcs – Geol. Soc. Amer. Bull. 84: 2917-2930.

Coleman, R. G. 1971 Plate tectonic emplacement of upper mantle peridotites along continental edges – J. Geophys. Res. 76: 1212-1222.

Dewey, J. F. & J. M. Bird 1970 Mountain belts and the new global tectonics – J. Geophys. Res. 75: 2625-2647.

—— 1971 Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland – J. Geophys. Res. 76: 3179-3206.

Dickey, P. A. 1972 Geology of oil fields of West Siberian Lowland – Amer. Assoc. Petrol. Geol. Bull. 56: 454-471.

Drake, C. H. & J. E. Nafe 1968 The transition from ocean to continent from seismic refraction data. In: The crust and upper mantle of the Pacific Area – Amer. Geophys. Union Monograph 12: 174-186.

DuBois, J., G. Pascal, M. Barazangi et al. 1972 Travel times of seismic waves between the New Hebrides and Fiji Islands; a zone of low velocity beneath the Fiji Plateau – J. Geophys. Res. 78: 3431-3436.

Ewing, J. & M. Ewing 1959 Seismic refraction measurements in the Atlantic Ocean basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge and the Norwegian Sea – Geol. Soc. Amer. Bull. 70: 291-318.

Fairbridge, R. W. 1955 Some bathymetric and geotectonic features of the eastern part of the Indian Ocean – Deep-Sea Res. 2: 161-171.

Francis, T. J. G. & I. T. Porter 1972 A microearthquake survey of the Mid-Atlantic Ridge – Nature 240: 547-549.

—— 1973 Median valley seismology: the Mid-Atlantic Ridge near 45 °N – Geophys. J. Royal Astron. Soc. 34: 279-311.

Furumoto, A. S., D. M. Hussong, J. F. Campbell, G. H. Sutton, A. Malahoff, J. C. Rose & G. P. Woollard 1970 Crustal and upper mantle structure of the Solomon Islands as revealed by seismic refraction survey of Nov.-Dec. 1966 – Pacific Sci. 24: 315-332.

Giese, P. & N. I. Pavlenkova 1976 Some particularities of crustal structure in young orogenic systems – Geol. Rundschau 65: 1109-1125.

Gornostaieve, V. P., V. I. Michailovskiy & V. J. Pospelov 1970 Deep magnetotelluric soundings on the south of the Siberian Platform and in the Baikal Rift Zone (in Russian) – Geol. Geofiz. 4: 111-118.

Goryatchev, A. V. 1962 On the relationship between geotectonic and geophysical phenomena of the Kuril-Kamchatka folding zone at the junction zone of the Asiatic continent with the Pacific ocean. In: G. A. MacDonald & H. Kuno (eds.): The crust of the Pacific basin – A. G. U. Mono. 6: 41-49.

Green, D. H. & A. E. Ringwood 1967 The genesis of basaltic magmas – Contrib. Mineral. Petrol. 15: 103-190.

Gutenberg, B. & C. F. Richter 1954 Seismicity of the earth and associated phenomena (2nd ed.) – Princeton Univ. Press: 310 pp.

Haenel, R. 1974 Heat flow measurements in Northern Italy and heat flow maps of Europe – J. Geophys. Zeitschr. Geophys. 40: 367-380.

Hales, A. L. 1972 The travel times of P seismic waves and their relevance to the upper mantle velocity distributions – Tectonophysics 13: 447-482.

Haller, J. 1969 Tectonics and neotectonics in East Greenland. In: Marshall Kay (ed.): Review bearing on the drift concept in North Atlantic geology and continental drift – A. A. P. G. Memoir 12: 852-858.

Hamilton, W. 1970 The Uralides and the motion of the Russian and Siberian platforms – Geol. Soc. Amer. Bull. 81: 2553-2576.

Heezen, B. & M. Ewing 1961 The Mid-Oceanic Ridge and its extension through the Arctic basin. In: G. O. Roasch (ed.): Geology of the Arctic I – Univ. Toronto, Ontario: 622-642.

Herrin, E. 1969 Regional variations of P-wave velocities in the upper mantle beneath North America. In: P. J. Hart (ed.): The earth's crust and upper mantle – Amer. Geophys. Union, Geophys. Monogr. 13: 242-246.

Illies, J. H. 1974 Taphrogenesis and plate tectonics. In: J. H. Illies & K. Fuchs (eds.): Approaches to taphrogenesis, Inter Union Comm. Geodyn. Sci. Rept. 8 – E. Schweizerbart'sche Verlagsbuchhandlung: 433-458.

Karig, D. E. 1971 Origin and development of marginal basins in the Western Pacific – J. Geophys. Res. 76: 2542-2561.

Keen, C. & C. Tramontini 1970 A seismic refraction survey on the Mid-Atlantic Ridge – Geophys. J. Roy. Astron. Soc. 20: 473-491.

Keller, G. V. 1971 Electrical studies of the crust and upper mantle. In: J. G. Heacock (ed.): The structure and physical properties of the earth's crust – Amer. Geophys. Union Geophys. Monogr. 14: 107-121.

Khan, M. A. & J. Mansfield 1971 Gravity measurements in the Gregory Rift – Nature Phys. Sci. 229: 72-75.

Kirillova, I. V. & B. A. Petrushevskiy 1972 Transverse tectonic zonation in folded belts and continental drift – Int. Geol. Review (A. G. I.) 14: 866-879.

Kominskaya, I. P., N. A. Belyaevsky & I. S. Volvosky 1969 Explosion seismology in the U.S.S.R. In: P. J. Hart (ed.): The earth's crust and upper mantle – Amer. Geophys. Union Geophys. Monogr. 13: 195-208.

Lang, W. P. & R. J. Sun 1966 Atlas of Asia and Eastern Europe to support detection of underground nuclear testing III – Seismicity, U.S.G.S.

Le Pichon, X., J. Francheteau & J. Bonnin 1973 Plate tectonics – Devel. Geotectonics 6, Elsevier Sci. Publ. Co.: 300 pp.

Long, R. E. & R. W. Backhouse 1976 Structure of the Western flank of the Gregory Rift (Kenya) Part II – Geophys. J. Roy. Astron. Soc. 44: 676-688.

Losecke, W. 1970 Ergbnisse magnetotellurischer Messungen bei Speyer. In: Graben problems – Int. upper mantle proj. Sci. Rpt. 27: 242-244.

Makarenko, F. A., B. G. Polak & J. B. Smirnov 1968 Geothermal field on the U.S.S.R. Territory – 13th Int. Geol. Congr. 5: 67-73.

Maxwell, J. C. 1968 Continental drift and a dynamic earth – Amer. Scientist 56: 35-51.

Mohr, P. A. 1975 Structural setting and evolution of Afar. In: Afar Depression of Ethiopia – Inter-Union Comm. Geodyn. Sci. Rept. 14: 27-37.

Molnar, P., T. J. Fitch & F. T. Wu 1973 Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia – Earth Planet. Sci. Lett. 19: 101-112.

Molnar, P. & J. Oliver 1969 Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere – J. Geophys. Res. 74: 2648-2682.

Moore, D. G. 1973 Plate edge deformation and crustal growth, Gulf of California structural province – Geol. Soc. Amer. Bull. 84: 1883-1906.

Mueller, S., E. Peterschmitt, K. Fuchs, D. Emter & J. Ansorge 1973 Crustal structure of the Rhinegraben area – Tectonophysics 20: 381-391.

Murauchi, S., N. Den, S. Asano et al. 1968 Crustal structure of the Philippine Sea – J. Geophys. Res. 73: 3143-3171.

Nafe, J. E. & C. L. Drake 1963 Physical properties of marine sediments. In: M. N. Hill (ed.): The Sea 3 – Interscience Publ.: 794-815.

Nalivkin, D. V. 1960 The geology of the U.S.S.R.: A short outline with geologic map – Pergamon Press (New York): 170 pp.

——1973 Geology of the U.S.S.R. – Oliver and Boyd (Edinburgh): 855 pp.

Orcutt, J., B. Kennett, L. Dorman & W. Prothero 1975 A low velocity zone underlying a fast-spreading rise crest – Nature 256: 475-476.

Oxburgh, E. R. & D. L. Turcotte 1970 Thermal structure of island arcs – Geol. Soc. Amer. Bull. 82: 1665-1688.

Pakiser, L. C. & I. Zietz 1965 Transcontinental crustal and upper mantle structure – Review Geophys. 3: 505-520.

Polyak, B. G. & Y. B. Smirnov 1968 Relation between terrestrial heat flow and the tectonics of continents – Geotectonics 4: 205-213 (Am. Geophys. Union; Translated from Acad. Sci. U.S.S.R.).

Porath, H. 1971 Magnetic variation anomalies and seismic low velocity zone in the Western United States – J. Geophys. Res. 76: 2643-2648.

Rodriquez, R. G. 1969 Atlas of Asia and Eastern Europe to support detection of underground nuclear testing, V: Crust mantle conditions – U.S. Geol. Survey.

Roy, R. F., D. D. Blackwell & F. Birch 1968 Heat generation of plutonic rocks and continental heat flow provinces – Earth Planet Sci. Lett. 5: 1-12.

Scheelke, I. 1974 Models for the resistivity distribution from magneto-telluric soundings. In: Approaches to taphrogenesis – Inter-Union Comm. Geodyn. Sci. Rept. 8: 362-365.

Shatzki, N. S. & A. A. Bogdanoff 1959 Explanatory notes on the tectonic map of the USSR and adjoining countries – Int. Geol. Review (AGI) 1: 1-49.

Shor Jr., G. G., H. K. Kirk & H. W. Menard 1971 Crustal structure of the Melanesian area – J. Geophys. Res. 76: 2562-2586.

Solomon, C. 1973 Shear wave attenuation and melting beneath the Mid-Atlantic Ridge – J. Geophys. Res. 78: 6044-6059.

Stegna, L. 1972 Geothermal map of Eastern Europe – Geothermics 1 (4): 140 pp. + map.

Talwani, M., X. Le Pichon & M. Ewing 1965 Crustal structure of the Mid Ocean ridges 2 – J. Geophys. Res. 70: 341-352.

Taylor, B. 1975 The tectonics of the Bismarck Sea region – Unpubl. B. Sci. Thesis Univ. Sydney, Australia.

Tobin, D. G., P. L. Ward & C. L. Drake 1969 Microearthquakes in the rift valley of Kenya – Geol. Soc. Amer. Bull. 80: 2043-2046.

Vacquier, V. 1972 Geomagnetism in marine geology – Elsevier Oceanogr. Series 6: 185 pp.

Van Bemmelen, R. W. 1972 Geodynamic models, an evaluation and a synthesis – Devel. Geotectonics 2, Elsevier Publ. Co.: 267 pp.

Van Bemmelen, R. W. 1978 The present formulation of the undation theory – Zeitschr. geol. Wiss. Berlin 6: 523-540.

Van der Linden, W. J. M. 1977 How much continent under the ocean? – Marine geophys. Res. 3: 209-224.

Von Herzen, R. P. & W. H. K. Lee 1969 Heat flow in oceanic regions. In: P. J. Hart, (ed.): The earth's crust and upper mantle – Am. Geophys. Union Geophys. Monogr. 13.

Wakita, H., N. Fujii, S. Matsuo, K. Notsu, K. Nagao & N. Takaokz 1968 'Helium spots': caused by a diapiric magma from the upper mantle – Science 200: 430-431.

Watts, A. B., J. K. Weissel & R. L. Larson 1977 Sea floor spreading in marginal basins of the Western Pacific – Tectonophysics 37: 167-181.

Weissel, J. K. 1977 Evolution of the Lau Basin by the growth of small plates in island arcs, deep sea trenches and back-arc basins – Maurice Ewing Series 1: 429-436.

Wilson, J. T. 1965 A new class of faults and their bearing on continental drift – Nature 207: 343-347.

——1968 Static or mobile earth: the current scientific revolution – Proc. Amer. Phil Soc. 112: 309-320.

Wyllie, P. J. 1971 The dynamic earth – John Wiley & Sons Inc.: 416 pp.

Zietz, I. 1969 Aeromagnetic investigation of the earth's crust in the United States. In: P. J. Hart (ed.): The earth's crust and upper mantle – A. G. U. Geophys. Monogr. 13: 404-415.