PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Musings over Sedimentary Basin Evolution [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1982 **305**, 325-338
doi: 10.1098/rsta.1982.0040

Phil. Trans. R. Soc. Lond. A **305**, 325–338 (1982) [325]
Printed in Great Britain

Musings over sedimentary basin evolution

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Introduction

Field geologists and explorationists are of necessity immersed in numerous very detailed surface and subsurface observations. They are often perplexed by the choice of relatively simple geophysical models that so elegantly explain the origin and evolution of sedimentary basins. Geophysicists, on the other hand, search for a simple theme to explain the origin of sedimentary basins and, much like managers, are often impatient with lengthy detailed geological discourse that often uses fancy jargon to hide the very real difficulty that geologists have in separating important evidence from mere encyclopaedic description.

The following musings address the quality and limitations of geologic and geophysical evidence that may be used to evaluate the relative roles of stress, thermal effects and gravity loading, which have been so lucidly summarized by M. H. P. Bott in the preceding summary. The fine papers presented during this meeting, of course, have led to significant modifications of some of my earlier thoughts. Because these have been previously published elsewhere (Bally & Snelson 1980; Bally 1980), they are summarized here only for the convenience of the reader.

The definition of a sedimentary basin and the need for an ideal information package

It may be useful to define a sedimentary basin as a region that has subsided, that contains sediments in excess of 1 km, and – most important – that is *today still preserved in a more or less coherent form*. Such a definition deliberately excludes former basins whose sedimentary content is now incorporated and deformed in folded belts. The hazards of palinspastic reconstructions of folded belts are great, particularly when little, if any, information is available on the basement configuration that was originally underlying the now allochthonous sequences of folded belts. Therefore, I feel that data from folded belts are so far simply inadequate for a test of any geophysical models that describe basin origin.

The Zagros Basin of Koop (this symposium), the Franklinian Basin of Kerr (this symposium), and some of the Precambrian basins of Bickle & Eriksson (this symposium) are simplified hypothetical reconstructions of folded belts; and therefore – despite their intrinsic interest – they are of little use to test the validity of geophysical models. On the other hand, the stratigraphic evolution of folded belts is important if we are to understand their regional or plate tectonic setting and the temporal interaction of tectonics and sedimentation.

Even in basins that today are still preserved in a more or less coherent fashion we rarely have adequate and complete data. For instance, for many basins in North America we lack crustal refraction and reflexion data. Regional reflexion sections across basins are rarely published. For the basins in the U.S.S.R., we typically lack reflexion seismic data and detailed lithological and

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mechanical log suites. Only for a handful of basins in the world do we have the beginnings of a reasonably complete data bank that is also accessible to academic scientists, e.g. the North Sea, the Alberta Basin, the Paris Basin, the Aquitaine Basin, the northern Bay of Biscay, and parts of the North American Atlantic margin. Therefore, we must endeavour to obtain the most complete data base possible.

Such an 'ideal data base' necessary for the evaluation of geophysical models should include crustal refraction and reflexion profiles, conventional multichannel basinal reflexion profiles, deep stratigraphic tests with complete lithological, palaeontological and geophysical log sets, surface and subsurface maps.

Table 1. Basin classification

1. BASINS LOCATED ON THE RIGID LITHOSPHERE, NOT ASSOCIATED WITH FORMATION OF MEGASUTURES
    - 1.1. related to formation of oceanic crust
        - 1.1.1. *rifts*
        - 1.1.2. *oceanic transform-fault associated basins*
        - 1.1.3. *oceanic abyssal plains*
        - 1.1.4. *Atlantic-type passive margins (shelf, slope and rise) that straddle continental and oceanic crust*
            - 1.1.4.1. overlying earlier rift systems
            - 1.1.4.2. overlying earlier transform systems
            - 1.1.4.3. overlying earlier back-arc basins of (3.2.1.) and (3.2.2.) type
    - 1.2. located on pre-Mesozoic continental lithosphere
        - 1.2.1. *cratonic basins*
            - 1.2.1.1. located on earlier rifted grabens
            - 1.2.1.2. located on former back-arc basins of (3.2.1.) type

2. PERISUTURAL BASINS ON RIGID LITHOSPHERE ASSOCIATED WITH FORMATION OF COMPRESSIONAL MEGASUTURE
    - 2.1. deep sea trench or moat on oceanic crust adjacent to B-subduction margin
    - 2.2. *foredeep and underlying platform sediments*, or moat on continental crust adjacent to A-subduction margin
        - 2.2.1. ramp with buried grabens, but with little or no block faulting
        - 2.2.2. dominated by block faulting
    - 2.3. *Chinese-type basins* associated with distal block faulting related to compressional or megasuture and without associated A-subduction margin

3. EPISUTURAL BASINS LOCATED AND MOSTLY CONTAINED IN COMPRESSIONAL MEGASUTURE
    - 3.1. associated with B-subduction zone
        - 3.1.1. *fore-arc basins*
        - 3.1.2. *circum-Pacific back-arc basins*
            - 3.1.2.1. back-arc basins floored by oceanic crust and associated with B-subduction (marginal sea *sensu stricto*)
            - 3.1.2.2. back-arc basins floored by continental or intermediate crust, associated with B-subduction
    - 3.2. back-arc basins, associated with continental collision and on concave side of A-subduction arc
        - 3.2.1. on continental crust or *Pannonian-type* basins
        - 3.2.2. on transitional and oceanic crust or *W. Mediterranean-type* basins
    - 3.3. basins related to episutural megashear systems
        - 3.3.1. *Great basin-type* basin
        - 3.3.2. *California-type* basins

The variety among sedimentary basins

The variety among sedimentary basins, their tectonic setting and their filling history is overwhelming. It is precisely that variety that has in the past and will in future remain the big challenge for petroleum explorationists. Many authors have proposed various basin classifications and tried to find some order. One such scheme was recently proposed by Bally & Snelson

(1980). Table 1 and figure 1 illustrate the main elements of that classification. These illustrations were the outgrowth of a rather cursory study of the tectonics of the world, illustrated by maps that were displayed in the poster session of this meeting. [Those maps do not appear in this volume.]

Our primary goal was to see whether a classification that was in sympathy with and related to plate tectonics would help to establish simple rules for forecasts of hydrocarbon potential reserves. In this we failed, probably because the distribution of major hydrocarbon source bed intervals is controlled by factors (e.g. biological evolution, palaeoclimatology and regional and global palaeogeography) that often do not sufficiently coincide with the evolution of any given basin type. Nevertheless, the proposed classification provides a guide to and an overview of the

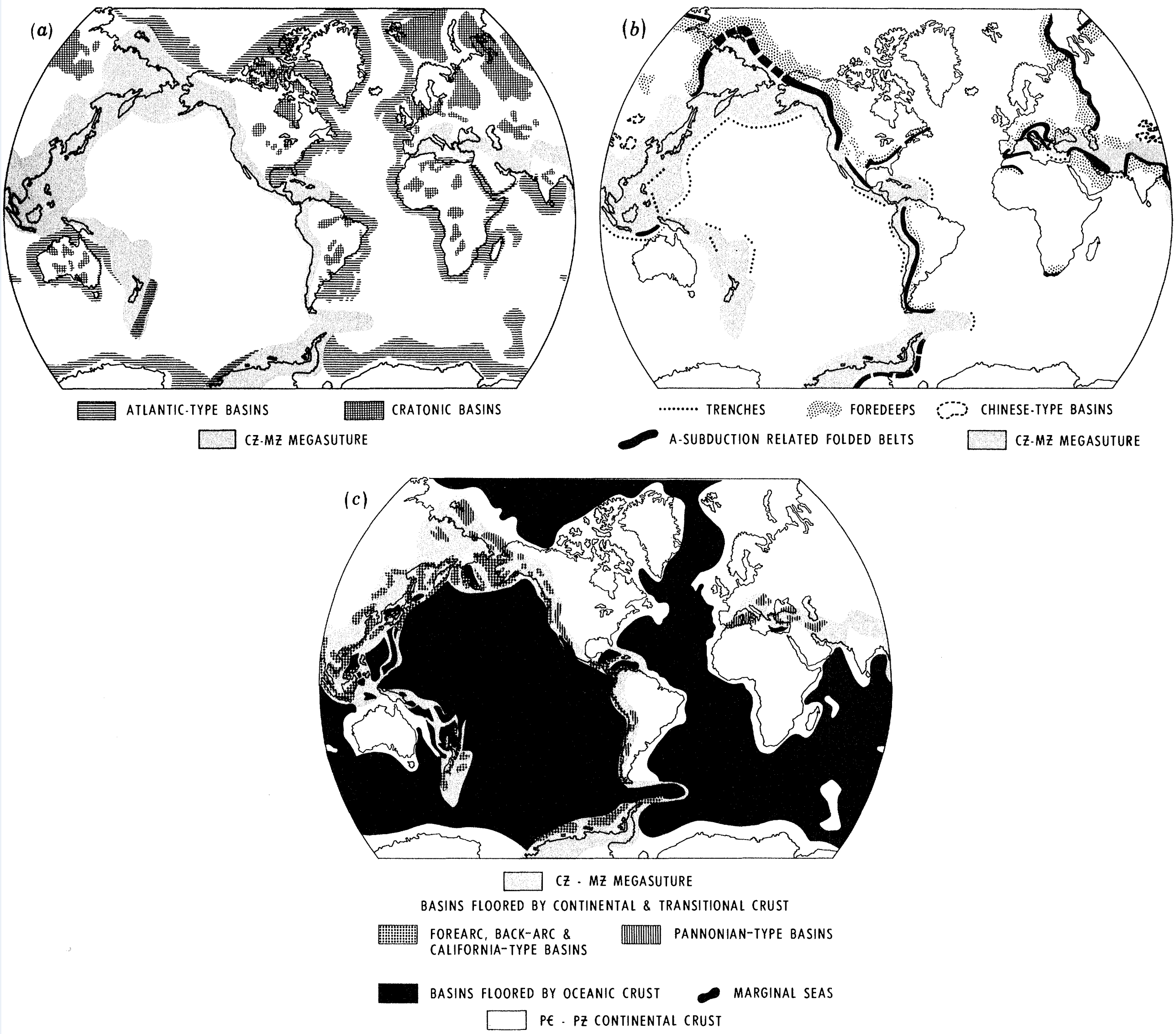

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Figure 1.(*a*) Basins on rigid lithosphere. These are further subidivided on table 1. (*b*) Perisutural basins adjacent to subduction boundaries, but located on rigid lithosphere. These are further subdivided on table 1. (*c*) Episutural basins located on Cainozoic–Mesozoic megasuture. These are further subdivided on Table 1. A small number of preserved Palaeozoic episutural basins (e.g. Gulf of St Lawrence, Sidney Basin) are not shown. (After Bally & Snelson (1980), with permission of the Canadian Society of Petroleum Geologists.)

sedimentary basins of the world. We also hoped that our classification might provide some alternative to outdated geosynclinal concepts and jargon. There again we were not entirely successful, because we could not avoid the introduction of some new descriptive jargon.

Today it is tempting to take an idealized view of basin genesis that would initially ignore some of the more 'spooky' basin-forming mechanisms that have been proposed by our geophysical colleagues, such as those that involve phase changes at the crust mantle boundary and deeper in the Earth, or mechanisms that invoke flow within the crust, or else the flow of melts from continental to oceanic asthenosphere. Such mechanisms may well occur in Nature, but they appear to be 'spooky' because it is so difficult to map them directly or to test them with unambiguous geological and geophysical observations. At best, such concepts will appear to be permissible for a given set of data without excluding other equally permissible alternatives.

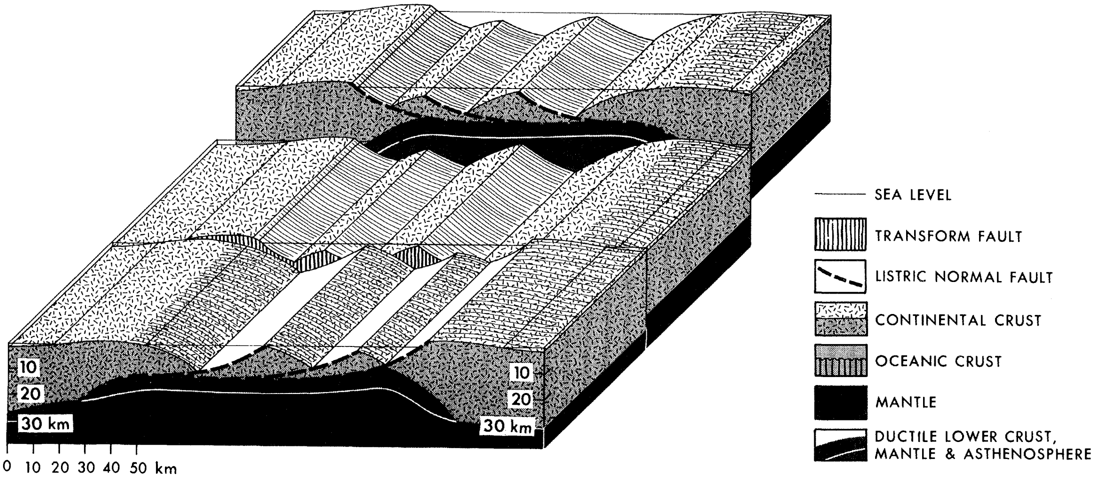

FIGURE 2. Transform zone separating two half-graben segments. This conceptual diagram shows that rift zones, in fact, may be sets of half-graben segments with changing polarity. Each segment would be separated from its neighbour by a complex transform zone. Sediments have been removed from the diagram to show the basement configuration.

A much simplified genetic view of our basin classification is that, with the exception of the perisutural basins and forearc basins, all basins appear to be initiated by a thermal event that is expressed by rifting of the brittle upper crust. Such an all-inclusive statement is naturally wide open to critical exceptions like, for instance, the number of cratonic basins that do not display an obvious rifting event that controls their early evolution.

Nevertheless, let us simply distinguish extensional basins that were initiated by a thermally induced extensional event from basins that are formed in an overall compressional régime with tectonic loading on a basement ramp and with thickening of the lithosphere. In fact, this is the contrast so well summarized by Beaumont *et al.* (this symposium).

In the following I shall dwell briefly on some aspects of crustal stretching and rifting and on matters related to documentation of the tectonic loading model.

Rifting

In the context of this meeting there is no need to recapitulate the historic evolution of various rifting concepts. The stretching model of McKenzie (1978) has triggered a wave of interesting studies (Royden *et al.* 1980; Christie & Sclater 1980; Royden & Keen 1980; Jarvis & McKenzie 1980; Le Pichon *et al.* 1981; Le Pichon & Sibuet 1981). In a nutshell, all these studies suggest that passive margins, some cratonic basins and also some back-arc-type basins may be initiated by lithospheric stretching and an associated thermal event. Subsidence following that event is due to cooling and is amplified by sediment loading. Thus, more stretching and high instantaneous strain rates lead to increased subsidence and less stretching, and low instantaneous strain rates cause less subsidence and in some cases even uplift. If the stretching occurs during a prolonged period that allows the rift system to cool, then ensuing subsidence will be diminished (Jarvis & McKenzie 1980).

The geological and geophysical evidence that is sometimes used to determine amounts of stretching is reasonably convincing but rather fragmentary. For this reason, the studies of Avedik *et al.* (this symposium) appear to be particularly useful in providing a more detailed geophysical data base for the study of the northern Bay of Biscay. The ambiguity of the data is well illustrated by different stretching estimates made by Avedik *et al.* and Le Pichon *et al.* (both this symposium) that are based on different interpretations of the same seismic section.

Very simple geometric considerations suggest that antithetic normal faulting along planar fault surfaces is difficult to achieve without associated folding or uplifting. In all cases the tilted brittle blocks have obvious bottom keels. Such a configuration is implicit in the so-called 'domino' or 'playing-card' models (see Le Pichon *et al.* this symposium). The depth of the keels is a function of the amount of tilting and the width of the rotated blocks. Unfortunately, geophysical data actually showing the existence of these keels on a crustal scale are hard to find. Thus, if the keels do not exist, one must invent some ductile flow process that eliminates them. Needless to say, the planar faults of the 'domino' model are not listric faults.

The listric fault model alleviates some of these problems. It has the obvious advantage that the beds can gradually rotate into the fault plane and that changes in bedding dips are related to changes in the curvature of the fault plane. Listric faults are often grown faults that show a divergence of beds as they dip into the fault plane (i.e. the U.S. Atlantic margin). These growth faults contrast with rotational faults with little growth and infill with more or less horizontal sediment layers (i.e. Bay of Biscay, North Sea). On a crustal scale listric normal faults also have their share of problems. These problems include excessive rotation of pointed, probably unstable, bottom keels or else compensatory faulting in the tops of the tilted fault blocks. Such faulting is commonly observed in Nature.

Reflexion seismic data may be most useful to determine the shape of listric fault planes. In some spectacular cases one can actually see the sole of the listric fault system (Montadert *et al.* 1979*a*, *b*). On other profiles, such as the ones reported from the Basin and Range province, only segments of the system are seen. A review of some of the seismic and surface evidence of a number of examples is given by Bally *et al.* 1981. Based on that summary, it would appear that for the brittle segment of the lithosphere we need better evidence for the actual shape of listric faults based on detailed seismic reflexion sections.

In recent years, after having looked at a number of seismic reflexion profiles from various areas, I have been impressed by the dominant asymmetry of rift systems. Half-grabens and systems of multiple half-grabens are the rule, and reflexion seismic evidence for symmetrical grabens is virtually absent. The main theme always seems to be rotation into a main master-fault system with some subsidiary compensatory faulting. The polarity of the master fault may change within a graben, and two segments of opposing master-fault systems appear to be separated by a transform fault (see figure 2). The transform segments are often complex and difficult to map. In hindsight, it is puzzling why the concept of more or less symmetrical graben systems has dominated the geological literature for decades. Is it possible that the geophysical tools and geological methods that were used to depict the graben configuration were simply too crude to resolve the shallow structure and the question of symmetry?

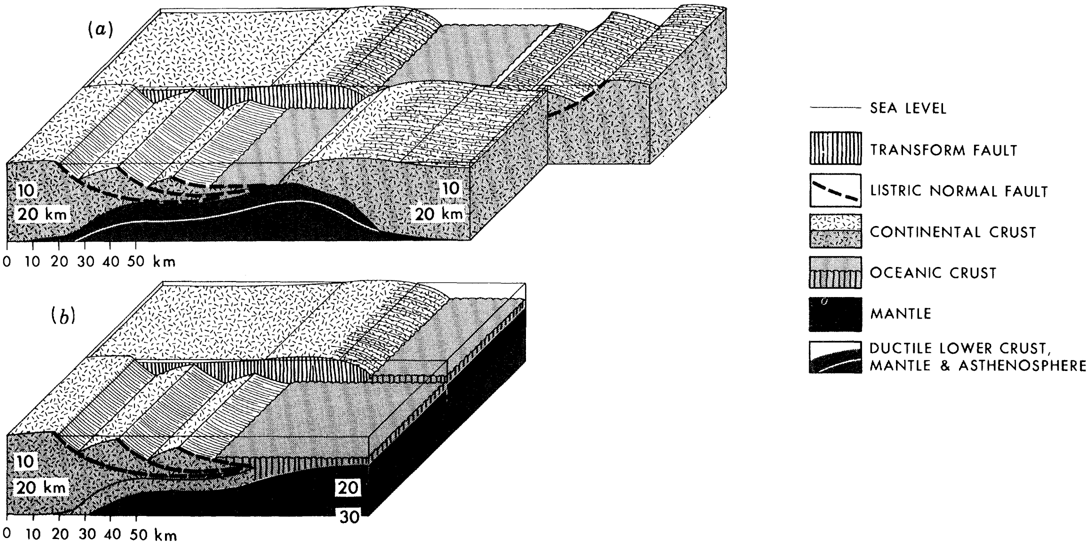

FIGURE 3. The development of a passive margin, with fault blocks rotating toward the ocean. (*a*) Rifting stage; (*b*) spreading (drifting) stage.

The asymmetrical nature of graben systems may be of some consequence in the assessment of changes occurring along Atlantic-type margins and in the comparison of conjugate margins across a spreading ocean. Figures 3 and 4 show the evolution of half-graben systems into passive margins. They suggest that the polarity of the bounding listric fault systems may change, i.e. the listric faults may dip towards the ocean (e.g. Bay of Biscay) or else away from the ocean (e.g. Baltimore Canyon). The same diagrams also suggest that relatively abrupt changes in basement depth (e.g. from Georges Bank to Baltimore Canyon) probably occur across transform fault systems that offset major half-graben systems. Another consequence of the asymmetrical nature of half-graben systems is that the genesis and evolution of conjugate margins across a spreading ocean may differ substantially. All these concepts need more verification.

Bott (this symposium) discusses the global origin of large tensile stresses. On a more restricted regional scale, it may also be important to look into the demonstrability of pre-existing zones of weakness. For instance, listric normal faulting in the Western Cordillera appears to be semi-concordantly superposed on an earlier gently westward dipping listric décollement – thrust fault system. The suggestion there is that listric normal faults prefer to sole out in the basal sole fault system of earlier thrust faults (Price 1981). By analogy, a quick glance at the disposition of the Triassic graben systems of the Appalachians shows a crude parallelism with the strike of the foreland folds. This again strongly suggests that late Triassic listric normal faults merge into the sole of a late Palaeozoic thrust fault system, which, as the COCORP data across the Appalachians suggest (Cook *et al.* 1979; Brewer *et al.* 1981), may underlie much if not all of the Piedmont. The observation that fault blocks of the U.S. Atlantic shelf are rotated towards the continent would in turn suggest that the bounding listric faults are soling into a decoupling system that has an easterly vergence and relates to the Palaeozoic folded belts of Africa.

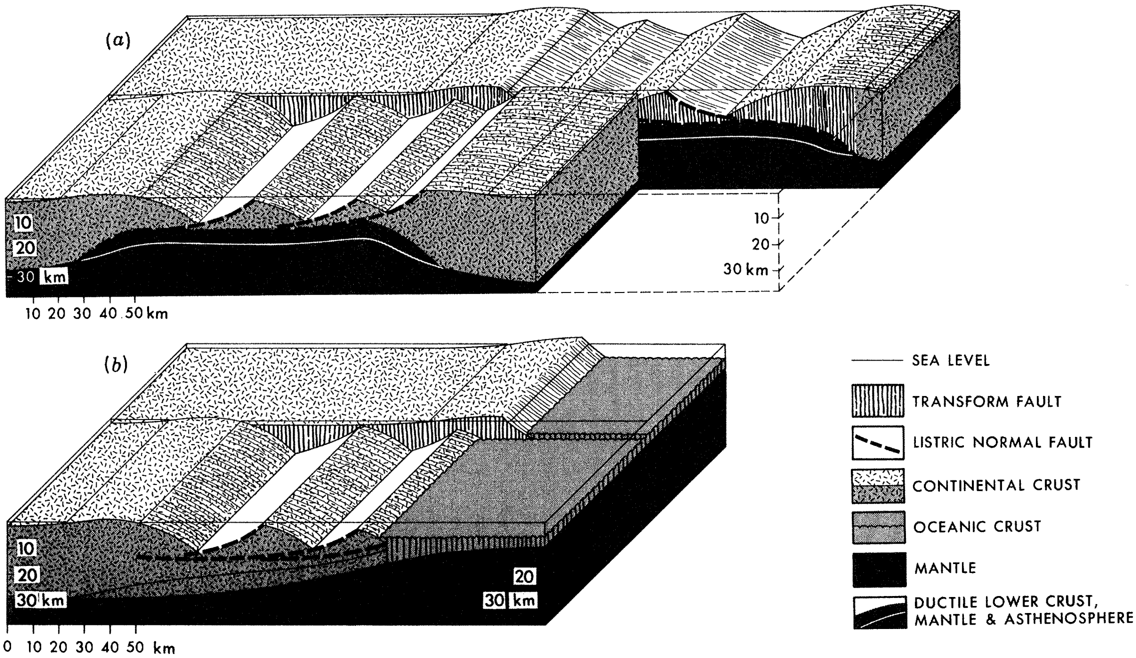

FIGURE 4. The development of a passive margin with listric fault blocks rotating toward continent. (*a*) Rifting stage; (*b*) drifting stage.

In conclusion, the stretching model appears to be a reasonably viable model for the formation of many basins. The evidence documenting planar or else listric fault blocks is far from conclusive, although in my judgement reflexion profiles and mechanical considerations (Hafner 1951) so far favour a low-angle listric fault model. Either way, estimates of stretching based on reflexion seismic data will be limited by the general absence of detailed regional reflexion lines, with key beds in the stretched crust that are calibrated by drilling. In all cases it is important to differentiate growth faults that are associated with one or more sets of updip converging beds from fault systems that show no growth and slow infilling by horizontal beds.

When analysing the subsidence of basins that suggest a thermal extensional origin, it may be wise to isolate the effects of sediment loading, as is done by Watts *et al.* and Beaumont *et al.* (both this symposium) and the effects of demonstrable minimum stretching (Avedik *et al.*) from the effects of stretching permissible but not shown by actual data (Le Pichon *et al.*) as well as the effects of other 'spooky' but possible mechanisms such as thermally induced phase changes (Turcotte) and ductile flow in the lower crust (Bott).

Foredeeps

Earlier it was pointed out that the perisutural basins of our classification are formed in a compressional, i.e. collisional, régime. The Carboniferous Permian basins of the U.S. continental interior (Dewey & Pitman, this symposium), the restored Zagros Basin (Koop), the restored southern part of the Franklinian Basin (Kerr), some of the Carboniferous sedimentary basins of northern Europe (Clarke), and the Western Canada Basin (Porter *et al.* and Beaumont *et al.*) all formed in a collisional régime.

Only for western Canada, Wyoming and some parts of the Appalachians are published reflexion seismic sections available that permit observation of the common ramp that underlies both the foredeep and the adjacent folded belt. The most extensive reflexion seismic data set is from western Canada and, together with surface and subsurface data (Price 1981), forms the base of the structural interpretations of Beaumont *et al.* Unfortunately, most of the published seismic sections in that area are over 20 years old. With advances in modern reflexion seismology, it would be greatly desirable to have high-quality data available for the study of the structural details of the ramp. All in all, the model of Beaumont *et al.* simply and adequately explains the subsidence of a foredeep by the mechanical loading (by thrust sheets) on a thermally old and thick lithosphere.

Beaumont's model is compatible with a general mountain-building concept that involves the subduction of sialic lithosphere, with extensive decoupling of the sedimentary skin in the form of thrust sheets and folds. The inner portion of such folded belts is characterized by the formation and deep burial of basement nappes that leads to regional metamorphism and the formation of gneiss folds. These are subsequently uplifted and eroded. The uplift history of the interior folded belts can now be traced by the study of the different methods of radiometric age dating and fission tracks analysis.

Obviously then, future studies on foredeep subsidence should be supported by high-quality seismic reflexion data and a comparison of the uplift history in the mountains with the sedimentation and subsidence in the adjacent foredeep. In effect, the foredeep stratigraphy directly reflects the subsidence and uplift history of the basement ramp that underlies both the foredeep and the adjacent folded belt.

A number of foredeeps, i.e. the Palaeozoic Arkoma Basin and the St Lawrence lowlands, and parts of the Tertiary Alpine Molasse basin, show considerable normal faulting in the underlying ramp. Much of the normal faulting occurs at about the same time as the thrust faulting. The significance of these normal faults is still obscure, but it is not likely that they are associated with a thermal event or else with significant crustal stretching.

An important variation on the theme of mechanical loading is offered by the development of foreland uplifts and associated basins that involve the basement, i.e. the Colorado–Wyoming Rocky Mountains and some of the Palaeozoic foreland uplifts of Oklahoma and West Texas (Dewey & Pitman, this symposium). Relatively little is known about these uplifts, but the Cocorp line across the Wind River Mountains and reflexion profiles obtained by the oil industry indicate that these foreland blocks are bounded by reverse faults and oblique-slip fault systems (Brewer *et al.* 1979). This in turn suggests a common decoupling level near the crust–mantle boundary. Where basement uplifts are in effect thrust over an adjacent block, basins develop that appear to be explainable by simple loading. More quantitative studies, preferably based on relatively complete data packages, are needed to confirm this suspicion. A better documentation is particularly urgent for the Palaeozoic basins studied by Dewey & Pitman. My recollection of these basins is that seismic reflexion data show little, if any, support for the late Palaeozoic extensional–thermal events postulated by these authors.

What little we know about the basins of interior China (e.g. Tarim and Dzungarian Basins) Bally *et al.* 1980) suggest that they are formed in a compressional, collisional context and that their subsidence is due to loading by reverse faulting and overthrusting of thick sialic sheets on the platforms that underlie these basins (i.e. the Chinese basins of our classification).

The global synchronism of subsidence and uplift episodes

A number of authors, mostly following in the footsteps of Sloss (1972), have made a convincing case for the worldwide correlatibility of major sedimentary sequences that are separated by unconformities. The concept has gained further support by the worldwide study of stratigraphy as displayed on reflexion seismic profiles undertaken by Vail and his colleagues at Exxon (Vail *et al.* 1977). There is little doubt in my mind that in a first approximation, the major sequences are indeed correlatable. I am disturbed, however, that we lack in-depth stratigraphic and palaeontological documentation to support the postulated correlations.

The issue of documentation is of some importance in the context of basin origin and evolution. Vail and his associates interpret their cyclical sequences in terms of eustatic sea level changes. They are convinced that from the reflexion seismic record of subsiding basins, they can extract a signal that – if correlated – is uniquely characteristic of eustatic sea level changes. From looking at subsidence plots such as those published by Keen (1979) and by Watts & Steckler (1979), it would appear that the influence of sea level changes on subsidence is minimal and therefore that most of what we see on reflexion seismic lines is in fact a record of subsidence. Watts (this symposium) makes a good case for the tectonic origin of 'coastal' onlap on which many of Vail's curves are based.

In other words, it appears to a number of authors and myself that the major stratigraphic sequences that we see and correlate in many parts of the world are correlatable tectonically induced subsidence cycles, separated by ubiquitous unconformities. The latter may well in some cases reflect a lowering of the sea level.

A simple glance at a Lower Cretaceous isopach of North America indicates substantial subsidence occurring at the Atlantic margin, in the Gulf of Mexico, in the foredeep of the Western Cordillera, and in the Great Valley of California. We thus see more or less synchronous subsidence that on Atlantic-type margins may be caused by more or less advanced cooling and sediment-loading that is dependent on the opening time of the adjacent ocean, while in the Rocky Mountain foredeep subsidence is dominated by mechanical loading by thrust sheets of a lithospheric ramp; and, finally, in the Great Valley we see subsidence that may either be associated with a fore-arc basin or else by a back-arc basin. The point is that plate tectonics is responsible for different modes of simultaneous subsidence that are dependent on the plate tectonic setting. For the Western Cordillera, this context has been well described by Coney (1979).

If, however, instead of focusing on the sequences themselves, we look at the unconformities separating them, it turns out that they are typically continent-wide, as shown by characteristic subcrop maps that are based on subsurface control. The apparent structural origin of major arches associated with these subcrops remains obscure. It is not likely that they are composites of peripheral bulges associated with sedimentary loads of a number of adjacent basins, because

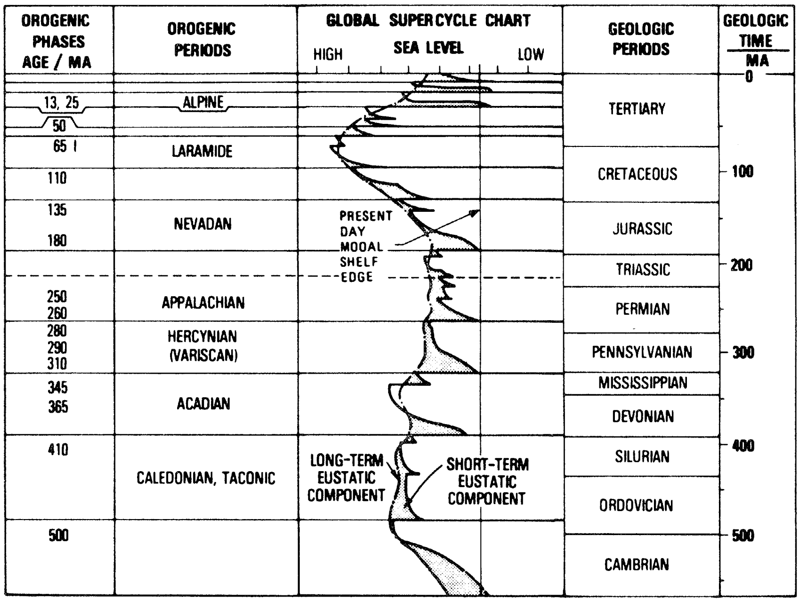

FIGURE 5. Global supercycle chart and correlation with orogenic activity. (From Vail (1977).)

they extend well beyond, and often are discordant with, the outline of single basins. Regional subcrops appear to be preferentially formed at the inception of a major collisional phase, and they often immediately precede the formation of foredeeps (i.e. the pre-middle Devonian subcrop of North America, the pre-Cretaceous subcrop of the Western Interior basins of North America (Bally 1980), and the pre-Eocene subcrop of the Molasse Basin of the Alps). One gains the impression that somehow, with the inception of a major collision, extensive cratonic portions of a continent are being warped or tilted.

Whatever the reason for the extensive supraregional subcrops, we are still confronted with their approximate worldwide correlatability. A major problem becomes evident when we compare a chart by Vail (1977) with one by Schwan (1980) (see figures 5 and 6). With regard to unconformities, the obvious question is: what is an orogenic phase? Schwan (1980), following the Stille tradition, equates the unconformity with an orogenic phase, while Vail (see also Johnson 1971) has his orogenic phases bracketed by major unconformities or, in other words, correlated with his sequences. As expressed elsewhere (Bally 1980), and in support of the Johnson (1971) concept, my own suspicion is that the sequences reflect continuing plate tectonics, while the major unconformities mark the slow-down and ultimately the cessation of one major plate tectonic régime and a plate reorganization into a new plate tectonic régime. However, to demonstrate this point convincingly, one would have to undertake a well documented study of the structural palaeogeographic characteristics that precede the formation of supraregional unconformities. A precise statement of the palaeontological brackets that straddle the unconformity would also be necessary. For the Mesozoic and Cainozoic, similar age brackets would be needed for discordances that separate parallel packages of magnetic stripes, as well as for the inception and cessation of igneous events (see Schwan 1980).

Clearly all of this would entail a major international cooperative effort, and I am planning to explore the feasibility of such an effort.

A few concluding remarks

The papers in this meeting focused only on a limited number of basin types: passive margins, cratonic basins and foredeeps. A quick glance at table 1 will show that a large number of basin types were not discussed, most notably forearc and backarc basins. The latter were discussed in some detail during a 1980 Royal Society Discussion Meeting on extensional tectonics associated with convergent plate boundaries (Vine & Smith (eds) 1981). Furthermore, the basins that are associated mega-shear systems, i.e. the oblique-slip related basins, were discussed in a recently published collection of papers (Ballance & Reading 1980). In oblique-slip systems both compressional and extensional basins may form, and it may be reasonable to presume that either lithospheric stretching or mechanical loading may be responsible for the formation of individual basins. The problem is that we so often lack critical reflexion and refraction data to tell us what the precise basement configuration in oblique-slip related basins is.

PERIODS	EPOCHS	AGE Ma	DISCONTINUITIES OF OCEAN – FLOOR SPREADING IN THE NORTH ATLANTIC	UNCONFORMITIES OF OROGENIC PHASES IN EUROPE AND NORTH AMERICA
TERTIARY	PLIOCENE	5		
	MIOCENE		10 – 9 Ma	STYRIAN
			ca. 17 Ma	STYRIAN
		23		
	OLIGOCENE	36	42 – 38 Ma	ILLYRIAN (1. PYRENEAN)
	EOCENE			
		53,5	53 Ma	LARAMIDE
	PALAEOCENE	65	63 Ma	LARAMIDE
CRETACEOUS	UPPER CRETACEOUS		80 – 75 Ma	SUBHERCYNIAN
		100		
	LOWER CRETACEOUS		115 – 110 Ma	AUSTROALPINE
		136		
JURASSIC	UPPER JURASSIC	148	148 Ma	NEVADAN (1. LATE CIMMERIAN)
		157		

Figure 6. Outline of discontinuities in the course of plate movements in the north Atlantic Ocean and of orogenic events in bordering continents showing time parallels. (After Schwan (1980), with permission of the American Association of Petroleum Geologists.)

A number of the proposed basin-forming mechanisms make assumptions with regard to processes that might occur in the middle and lower crusts. There detailed refraction, wide-angle reflexion, and more conventional reflexion profiles might provide additional information. Another research avenue, which to my knowledge has not yet been adequately explored, involves surface geological studies in basement thrust sheets that bring to the surface the deeper crustal portions of obvious passive margins, e.g. the Eastern Alpine thrust sheet, the Insubric and Ivrea Zones of the Alps, and the main basement sheet of the High Himalayas. Typically the work in these areas is aimed at studying the age and origin of the basement, the effects of orogenic metamorphism, etc. If, however, these basement sheets are the exhumed deeper portions of former passive margins, they should also reveal some of the effects related to the origin of these margins, e.g. stretching in the lower crust and the soles of listric normal fault systems. Of course, the Himalayas would offer a particularly attractive target for such a study, because there the deeper portions of an ancient passive margin to the south at the Yalu–Tsanpo suture can be compared with the deeper portions of the ancient active margin of the Trans-Himalaya to the north (Bally *et al.* 1981).

It looks as if the ability of our geophysical colleagues to invent models is moving much faster that the capacity of geologists and geophysicists to acquire the critical high-quality information to unambiguously support these models. At issue, of course, is the possibility for research institutions to acquire expensive crustal reflexion and refraction profiles and to have access to detailed industry reflexion profiles across sedimentary basins. With research funds becoming scarcer on both sides of the Atlantic, a close dialogue and cooperation with industry becomes increasingly desirable. In this context it will become more important to view sedimentary basins in their totality, including their hydrological and hydrodynamic characteristics, their finite groundwater reserves, the potential and risks of subsurface waste disposal, and, of course, the exploration for additional fossil fuel reserves. A fine recent example of cooperation was the creative interaction of academic geophysicists interested in thermal models for sedimentary basin genesis with geologists and geochemists in industry, who were focusing on maturation studies of hydrocarbon source beds. Analogous cooperation in future could involve geochemists interested in diagenetic problems, hydrologists and geophysicists. The key to successful cooperation is going to be a common subsurface data bank.

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Discussion

R. A. PRICE. In western North America there are a number of places where you can see two different crustal levels in contact, separated by a normal fault with a shallow dip. The metamorphic rocks beneath the fault show evidence of rapid quenching. A wide variety of rocks are found above the fault, from well consolidated rocks to fanglomerates containing detritus from the metamorphic rocks. These structures are probably the flat parts of listric normal faults. Frequently the metamorphic rocks form a dome that rises well above the surrounding basins, which contain the rocks overlying the faults. It is not obvious how to use this geometry to estimate the amount of extension.

A. W. BALLY. Listric normal faults may sole at different levels. For instance, in the Western Cordillera some faults appear to be rooted in the Moho and therefore will offset the basement overlying the Moho. Other faults, however, are rooted at the sediment–basement interface, at the base of the overlying décollement thrust sheets. Price has described some that are involved in mantled gneiss domes. These too appear to be located at an old sediment–basement interface. I am puzzled by these features and wonder particularly why the domes themselves should be uplifted. There is little doubt in my mind that some kind of broad regional uplift affected the Western Cordillera of the U.S. as suggested by Oligocene levels that climb from the Western Plains into the Colorado Mountains, and then descend across the Sierra Nevada into the Great Valley. Thus the whole intervening region has been regionally uplifted and been intersected by a complex system of listric normal faults that are likely to be linked by transform segments. What is needed now is a detailed study of the geomorphology, the geology and the structures as seen on reflexion seismic profiles, because the surface geology of the cross section of Nevada that I showed on my slide is only known in outline.

D. G. ROBERTS. In the Bay of Biscay granites have been dredged from the tops of the listrically faulted blocks. Therefore these faults cannot sole out against the basement sediment interface, but must be rooted in a plane within the crystalline basement. Why should this behaviour occur?

A. W. BALLY. I have no difficulty seeing listric normal faults within the basement. The COCORP line shows that the Appalachian thrusts are all rooted in a large subhorizontal thrust which essentially moves basement over basement. Listric normal faults that merge with older décollement systems of the Appalachian type must be mostly intrabasement faults. I can easily imagine a Precambrian shield having a similar internal structure, with basement structures stacked on top of each other. On a reflexion seismic line all fault planes would be within the basement. Precambrian basement may contain many planes of weakness corresponding to older décollement systems which could provide soles for listric normal fault systems.

M. F. Osmaston. Could the normal faults in the Baltimore Canyon area postdate the continental separation, and have been produced by the thermal upwarping of the margin? They would then have to be downthrown towards the continent to the west.

A. W. Bally. I do not believe that the normal faults in the Baltimore Canyon area postdate the continental separation. I believe that the faulting I see on the Atlantic offshore sections forms part of a 'Triassic' graben system that is well known on land. On land the rifting starts in late Triassic and ceases at the end of the lower Jurassic. In the Grand Banks (offshore Newfoundland) rifting starts at the same time but the cessation is considerably later. Thus different parts of rifted margins have different histories. The influence of an extended period of extension on thermal subsidence has been investigated by Jarvis and McKenzie. If the extension is rapid, the faults are only active for a short period of the time, and sediment layers deposited after the grabens have formed will be horizontal.

Reactivation of such faults will displace younger beds, and new grabens will form over the old ones. Therefore the breakup unconformity may be in some cases at the base of horizontal sediments that fill a graben and reactivation of the extension may result in the formation of other unconformities.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

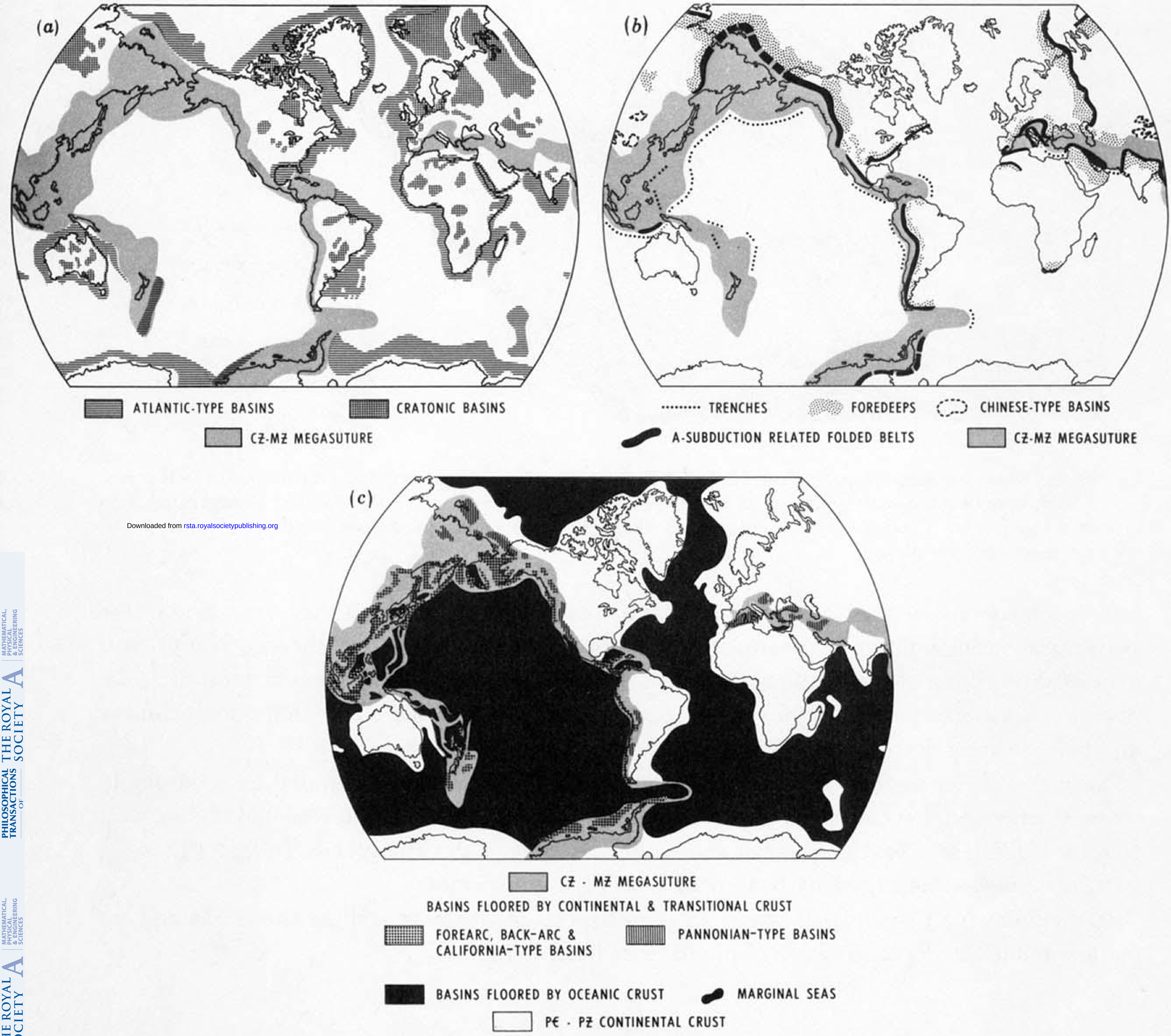

FIGURE 1. (*a*) Basins on rigid lithosphere. These are further subidivided on table 1. (*b*) Perisutural basins adjacent to subduction boundaries, but located on rigid lithosphere. These are further subdivided on table 1. (*c*) Episutural basins located on Cainozoic–Mesozoic megasuture. These are further subdivided on Table 1. A small number of preserved Palaeozoic episutural basins (e.g. Gulf of St Lawrence, Sidney Basin) are not shown. (After Bally & Snelson (1980), with permission of the Canadian Society of Petroleum Geologists.)

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