Conference report

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Structural style of continental margins: a discussion

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Publication of the results of continuous seismic reflection surveys around the continental margins (Beck & Lehner 1974, Seely *et al.* 1974, Lehner & Ruiter, in press) and discoveries made by drilling in the deep-sea by JOIDES and IPOD (Initial Reports of the Deep Sea Drilling Project) have shown that seismically active continental margins display structures very different from the structures associated with aseismic margins.

Lehner showed that after the initial rifting phase of evolving aseismic margins the main structural features are vertical movements manifested by the development of sedimentary basins at the margin of the new ocean and complementary basins on the craton. Some of these cratonic basins may be associated with aulacogens (Dewey & Burke 1974), others appear to be separated from the continental margin basins by a geanticlinal structure.

The structural style of the present aseismic margins of West Africa, northwest Australia and elsewhere can be summarized as asymmetric in cross section showing a 'steep, mostly faulted landward flank on continental basement and a gentle seaward flank on oceanic basement' (Lehner).

Evidence is available from parts of the Mediterranean region (Smith) and from northern Australia (Carter *et al.* 1976) which shows how within few Ma an aseismic continental margin can become seismically active and be involved in orogenic processes such as major overthrusting.

Recent papers by Fischer (1975) and Bally (1975) have greatly influenced the way we think about the structural style of seismically active continental margins. Fischer's suggestion that oceanic lithosphere has a maximum life of about 170–200 Ma before it sinks back into the asthenosphere points the way for palaeogeographical constraints. Bally's description of the compressional mega-suture in terms of the oceanic margin associated B-zone, and an A-zone marking the cratonic margin of the fold belt, provide a widely applicable palaeogeographical framework with which to approach the objective models Ziegler calls for (below).

Whereas a basic geometry and structural development can be recognized despite the great diversity of local structure and stratigraphy in the aseismic margins (Lehner), the diversity of structure in the seismically active margins obscures any but simplistic interpretations of their geometry and structural development. This wide range of structures was emphasized by Spencer. The origin of the oceanic floor of the back-arc basins, for example, appears to involve at least two very

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different processes, namely, back-arc spreading as revealed by the Scotia arc (Barker) and trapping of the older ocean floor by development of a new trench, exemplified by the Bering Sea (Cooper *et al.* 1976).

The occurrence of ophiolites at seismically active margins is in many cases attributed to overthrusting of ocean floor (Milsom 1973) although Stoneley (1975) argued that this cannot be claimed of some ophiolites. Shearman showed evidence that some ophiolites in SE Iran were part of a sedimentary slump deposit occupying deep erosion channels, from which he argued they could not be thrust sheets as had been claimed. Folk & McBride (1976) proposed a sedimentary origin for serpentinite breccias capping ophiolites in Liguria. It is this kind of detailed study of specific examples that has led Ziegler to suggest (below) that mountain belt ophiolites may have a wide variety of structural setting and mode of emplacement at active margins.

The rising body of evidence that questions the simplistic or Procrustean interpretations of the structure of seismically active continental margins was discussed for the western margin of the Americas. Badham argued that the western margin of northern North America displayed no evidence of rifting during the Phanerozoic; it could be objected, however, that the sequence of volcanic arcs and back-arc basins, which he proposed had occupied the margin at various times during the Phanerozoic, may have involved rifting processes of the back-arc spreading type. Pitcher drew attention to the dominance of vertical tectonics associated with plutonic and volcanic processes within the C-megasuture of the Andes. He emphasized how little tectonic accretion appears to be associated with the B-zone over large parts of the Pacific margin and how little folding and thrusting is present at the complementary A-zone. The structural processes involved in the accommodation of plates at trenches has been discussed by Helwig & Hall (1974) in terms of the uncoupled or underthrusting mode and the coupled or orogenic mode. The rate of sediment supply to trenches also plays a role here. The tectonic style developed at the Andean-Pacific margin where starved trenches are associated with imbrication of the downgoing slab has been discussed by Hussong *et al.* (1975).

Stride's interpretation of the three deformed sedimentary geanticlinal structures in the East Mediterranean draws attention to one kind of possibly anomalous structural style in the Mediterranean, that Ziegler (below) contrasts with the features associated with 'drift' regimes. The Lesser Antilles also reveal departures from the usual pattern of major morpho-tectonic elements of island arc systems, in, for example, the lack of a trench (Westbrook), although, as Milsom remarked, here the structural style is obscured by the sediment pile.

One question raised by this meeting is the degree to which the modern tectonic paradigm may be used to interpret pre-Triassic palaeogeographies (Ziegler). Some of the difficulties associated with interpreting older continental margins were illustrated by McKerrow in his remarks on the Caledonides and by Glennie's discussion of an *ms* copy of a geological map of SE Iran.

An important feature of the seismically active continental margins that remains submerged by ignorance is the origin, structure and mode of development of the 'mobile shelves' that are found in a back-arc position around the northern and western Pacific margins from the E Bering Sea, Sea of Okhotsk, East China Sea to the Sunda Shelf of the South China Sea and Java Sea. These seas have the bathymetric and sedimentary characters of Atlantic-type shelves but available evidence suggests they have developed by very different processes (Burk 1975).

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Summing up on aseismic margins

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Aseismic margins are subdivisible into rifted and offset (sheared) types. Most of the papers presented concentrated on the better known rifted type, but Roberts described DSDP holes SW of Rockall adjacent to both types. Reading outlined formation of pull-apart basins along transform faults relevant to the early shearing phase of offset types, and Blundell noted the importance of basement geology in defining the offset segments of West Africa. Wilson also noted the significance of basement geology to margin tectonics.

The tectonic history of aseismic margins is revealed by the structure and stratigraphy of the thick sediment piles which may exceed 15 km thickness. An early *rift phase* of subsidence lasting about 50 Ma associated with doming (?) and block faulting prior to significant continental separation, occurs beneath some but not all margins, good examples being the Angola–Gabon margin described by Lehner and the NW Australian margin described by Mills. Jenkyns described Toarcian and Upper Oxfordian palaeo-faulting in southern Spain and related this to stages in the opening of the Atlantic. The rift phase may terminate when spreading starts, but there is also evidence that rifting ceases in many regions in the mid-Cretaceous irrespective of the stage of opening (Kent). After the rift phase, the margins have generally undergone *subsidence by flexure* without conspicuous faulting. Roberts showed that DSDP results from Rockall and Biscay indicate that rapid initial subsidence decreases with time in agreement with the oceanic lithosphere cooling profile. However, Wilson showed that there are significant irregularities in space and time in the subsidence rates for west and north Spain, which do not appear to fit conveniently into the simple exponential cooling model. On another tack, Osmaston suggested that ophiolites may be emplaced by gravity gliding from a steep, newly formed ocean ridge.

Salt basins may occur just after the split in regions where new oceanic circulation is restricted such as the NW African and Angola–Gabon margin segments (Lehner), but are absent where more open circulation can occur such as north of Australia (Mills). A spectacular erosional unconformity beneath the west Saharan continental rise was described by Hamilton from DSDP drilling results, emphasizing the importance of contour current activity. These and some other sedimentological features of aseismic margins can thus be related to the structural development of the opening ocean which controls the changing ocean current patterns.

The rift phase may be associated with continental doming and stretching prior to continental splitting. A modified Vening Meinesz wedge subsidence hypothesis applied to the brittle upper continental crust may explain the rifting and block faulting. After the split, gravity loading by sediments can explain the Niger Delta (Lehner) and similar features, but cannot be the primary explanation of most marginal subsidence. Present hypotheses to explain post-split flexural subsidence include: (1) thermal uplift followed by erosion and subsidence on cooling of the lithosphere with time constant of about 50 Ma, (2) subsidence produced by increase in lower crustal density as a result of metamorphism or intrusion caused by a thermal event, (3) continental crustal creep towards the sub-oceanic topmost mantle in response to the tensional stresses in the continental crust near a margin. To test the hypotheses, adequately, we need more detailed and accurate knowledge of subsidence history from the sediments, and also much more information on the deep crustal and upper mantle transitions beneath the margins and associated basins.

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Summing up on seismically active margins W. L. Ziegler

The papers presented during the session on seismically active continental margins have mostly been based on recent observations and original research and therefore are a real contribution to our knowledge of these margins. On the theoretical side the wide divergence in the explanations of observed facts shows how limited still is our understanding of the megatectonic processes. 'Limited' may be a strong word as our knowledge has made enormous progress in the last two decades. On the other hand 'limited' reflects the lack of proof and consensus about the causes.

After the final breakthrough of plate tectonic concepts and a period during which these ideas reigned nearly unchallenged some doubt has clearly resurfaced and the divergence of opinions appears to be on the increase again. The questions that arise are mainly concerned with the applicability of the subduction hypothesis. Other models of tectogenesis such as those involving gravitational instability of the crust and mantle were mentioned. These ideas in part ante-date plate tectonics. To some degree the renewed interest in these 'Neo-Plutonist' theories may be a reaction to the often over-enthusiastic and uncritical application of plate tectonic models to every conceivable geological setting. But perhaps there are other processes at work in some areas.

A review of the distribution of seismicity at plate margins shows that most of the activity takes place either along the constructional plate boundaries, i.e. on mid-ocean ridges, or along the compressional plate boundaries. Attention was focused on the latter.

Compressional margins can occur between any couple of oceanic or continental plates. By definition such plate collisions involve the whole lithosphere. This is where the plates scrape along each other, and where earthquakes occur. The effects of compression along plate boundaries are complex. The classical view is that the oceanic–continental compressional plate couple is mainly a destructional margin along which oceanic plate material is consumed by subduction. In global tectonics this is a required process for those that believe in a nearly steady size of the earth. However, since the plates are irregular bodies, moving about on a globe, compressional phenomena invariably must involve some elements of shear between abutting plates.

Plate collision leads to suturing of the plate margins and their sedimentary cover by imbrication or folding. In this zone it also causes thickening of the crust and changes in the mantle, and is accompanied by igneous and metamorphic processes. All this can be observed today in orogenic belts and in other collision margins as the end result of the process.

Important questions are: how did the collision happen in detail and what processes took place? To understand how these zones evolved we need to direct our attention step by step to palaeogeographic reconstructions. Only in this way can we really establish the sequence of structural events and consequent stratigraphic changes and only on this basis can we eventually deduce the causes and mechanisms. A working hypothesis is an integral part of scientific investigations but on its own it is never proof. It should evolve out of the observations and not be preconceived. We must let the geology tell us what happened, not select what fits a particular theory and subduct the rest, for we all know that the subduction zone is theoretically proof against such critical analysis because it swallows the key evidence!

It is only comparatively recently that the plate tectonic hypothesis became widely acceptable. Since then a huge amount of brilliant research and analytical reasoning has been compiled and published. International programmes such as JOIDES and IPOD have had an enormous impact on the understanding of the earth. On the whole their results have confirmed plate tectonics, particularly the spreading ocean concept and continental drift in the passive margin realms. Few today would doubt the existence of fundamentally different cratonic and oceanic plates nor that these plates have moved and dispersed around the globe, at least since Triassic time. Plate growth by accretion along oceanic spread zones is no longer seriously in doubt. The list of such near certainties is substantial.

The weakest link in the global tectonics theory remains our understanding of the process in seismically active margins. This is partly a function of their inaccessability and intractability to geological and geophysical study. Most involve mountainous terrain or complex island arcs—and associated basins—which are difficult to study. Much of the evidence comes from surface observations, particularly in so called 'A-Subduction' zones where craton-ward overthrusting can be observed. Whereas marine seismic data can be obtained in the island-arc setting, modern multi-channel deep reflection seismic surveying which has proved so successful on passive margins offers little hope to resolve the fundamental structure of the mountain belts of the seismically active margins. There are technical limits to this tool. Nor is there much economic incentive for industry to attempt such surveys or to drill deep wells. Deep sea drilling which has effectively contributed to our understanding of the oceanic spread history has not resolved the problems of the active margin. It is difficult to formulate a proper research programme and to define real 'active margin' objectives which can be tested by this kind of high cost research. The deeper investigation of these active zones still depends greatly on indirect tools like magmatic and metamorphic studies, earthquake analysis, gravity observations and fabric analysis. Large-scale refraction seismic experiments give us some clues to the nature of the deeper crust.

How then can we answer the questions about history and cause? As stated before, palaeogeographic reconstructions remain an effective way but they must take account of the whole gamut of facts and processes and ask what is known with certainty and what is proved. This is the way to isolate problems and to define the areas of concern where basic research is required.

Plate collision manifests itself in many ways. Subduction may be one aspect of it and a reasonably convincing case can be made for it in certain settings. Plate collision also manifests itself in enormous and continuous shear zones in which much of the movement between the plates is dissipated in wrench-dominated tectonic belts. The circum-Pacific seismic belt is the classical example where shear movements occur between continental and oceanic crust. Yet it is also the classical site for the subduction model. Subduction associated with shear phenomena equals California in every textbook. In fact, shear and possibly oceanic spreading is observable but subduction is surmise, albeit, probable!

Invariably the ophiolite question is related to the subduction model. Most ophiolites in mountain belts are interpreted as scraped-up oceanic basement. Yet most Alpine ophiolite zones occur above acidic, clearly continental basement. The contradiction is obvious. Could it be that alternative or additional models are required, such as simple rifts or shear gashes which would allow for the exposure of such material in structural belts?

The other main seismically active craton margin of this globe, the Himalaya–Alpine–Mediterranean belt is for the most part intercratonic. It is characterized by a complex mass of microcontinental fragments and intercalated tectonized sediment troughs which are thought to be the remains of the classical Tethys ocean. The main observable facts in this zone are products of compression and shear. Plate tectonic reconstructions have been tried by many. Complex scenarios have been described, involving spreading of oceans, subduction, plate rotation and other tricks. Despite some serious attempts, subduction is hard to demonstrate in a really convincing way. What can be demonstrated nearly everywhere is rifting before the onset of compression and shear. In places it is then followed by collapse. This applies particularly to the western end of this belt.

The Mediterranean area reveals a type of structural deformation which does not fit the picture of 'normal' compressional plate tectonics. Here one finds very young, post-orogenic collapse basins which lie in the 'collision zone' between Europe and Africa. They are characterized by rifting, volcanism, extreme thinning of the crust and deep and rapid subsidence. Before they collapsed, some of these blocks appear to have shed their sediment load in gigantic olistostromes. Therefore they must have once been lifted up higher than their forelands. To explain these observations 'vertical tectonic' models have gained new adherents. Key elements are 'mantle differentiation', 'buoyancy', or 'asthenolitic tumescene' as Van Bemmelen has called the phenomenon. Does such a process exist? It has a certain appeal. Its theoretical manifestations seem to match many facts. Can we observe it in action and where?

As with subduction we end up again by looking for an answer to processes in the lower crust and mantle, an area about which we know very little and which can only be explored by very indirect means. Testing of hypotheses in this realm is difficult and it is easy to enter the field of enlightened speculation. The geology and geophysics of this area is a field where research is urgent. It should be rewarding. The processes that go on there effect cratonic and oceanic crust alike and provide the link between active and passive margins, between mountain building and basin formation.

One flight of fancy is offered to conclude these observations. In a curious way the structural style and evolution of the Mediterranean basins resembles those of the Palaeozoic basins of northern Europe and the Atlantic suture, whose history is somehow not like that of modern ocean basins. Based on factual observations it looks increasingly probable that some of the plate tectonic phenomena like 'drifting' and the generation of ocean crust by the 'spreading centre' model are post-early Triassic only. No convincing proof of older phases of continental drift of this type has yet been put forward. But ocean basins have formed, filled and were destroyed since the earliest days of the earth. Most seem to have a history of rifting, followed by compression and wrenching, often accompanied by intense igneous and regional metamorphic activity. Could it be that the Mediterranean tectonics are a last example of a much older style of cratonic deformation, whereas the remainder of the world has switched to a new tectonic 'Drift regime' since the advent of Mesozoic time? Both tectonic processes may be valid but one is the primary and the other the secondary, younger process, which has taken over during the ageing of the planet.

Believers in uniformitarian principles may find this hard to accept.

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List of contributions to the discussion

P. Lehner (Introduction to aseismic margins), D. G. Roberts (IPOD recent results —rifting and subsidence on Biscay and Rockall margins), H. C. Jenkyns (Mesozoic continental margins of southern Spain), R. C. L. Wilson (Continental margin basins of Iberia and the Grand Banks), S. J. Mills (Geological evolution of the continental margin of northwest Australia), H. G. Reading (Strike-slip nature of past continental margins), M. H. P. Bott (Summing up on aseismic margins), A. M. Spencer (Introduction to seismically active margins), A. H. Stride (The Calabrian, Hellenic and Cyprus outer ridges of the eastern Mediterranean), D. J. Shearman (Modes of emplacement of ophiolite melanges), J. P. N. Badham (Western continental margin of North America), W. S. Pitcher (Western continental margin of South America), P. F. Barker (Evolution of the Scotia Arc), G. K. Westbrook (Interaction between the Lesser Antilles island arc and the northern continental margin of South America), W. S. McKerrow (Southeast margin of North America during the Lower Palaeozoic), K. W. Glennie (Geology of SE Iran) and W. L. Ziegler (Summing up on seismically active continental margins). Other contributions were made by: D. J. Blundell, N. L. Falcon, N. Hamilton, P. E. Kent, M. D. Max, J. Milsom, M. F. Osmaston, R. C. Selley and A. G. Smith.