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Detachment faulting and the evolution of passive continental margins

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ABSTRACT

Major detachment faults play a key role in the lithospheric extension process in the Basin and Range province and may also be important in other continental extension terranes. Such detachment faulting leads to an inherent asymmetry of extensional structure and of uplift/subsidence patterns. Detachment models developed for the formation of metamorphic core complexes can also be applied to the formation of passive continental margins. We therefore suggest the existence of *upper-plate* and *lower-plate* passive margins. These give rise to a complementary asymmetry of opposing margins after continental breakup. Transfer faults offset marginal features and allow margins to switch from upper-plate to lower-plate characteristics along strike.

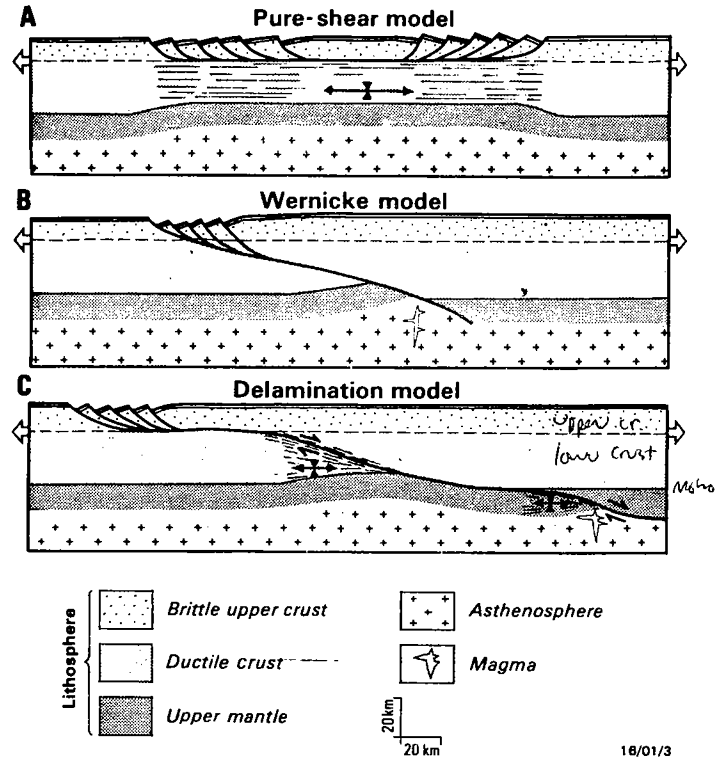

Figure 1. Three models for continental extension.

INTRODUCTION

There is widespread acceptance of the lithospheric stretching model proposed by McKenzie (1978) to explain the crustal thinning, rifting, and subsidence that predate and accompany continental breakup and lead to the development of passive continental margins. Evidence for such stretching comes from (a) crustal thinning and ~~(b)~~ normal fault geometries that require large extensions (Bally, 1981; Le Pichon and Sibuet, 1981). Geophysical modeling of this phenomenon has been based entirely on symmetrical, pure-shear extension models (McKenzie, 1978; Sclater and Christie, 1980; Le Pichon and Sibuet, 1981). Such models, with variations induced by depth-dependent strain (Keen et al., 1982) or depth-dependent rheology (Vierbuchen et al., 1982), allow prediction of the crustal thickness, subsidence histories, and gravity profiles of extended terranes.

Symmetric extension models, however, do not predict the wide variation in gross continental margin architecture, crustal thinning, and continental uplift reported, for example, by Kinsman (1975) or Falvey and Mutter (1981). Features such as marginal plateaus, outer highs, detached continental ribbons, and submerged continental fragments remain largely unexplained, although sophisticated multilayer modeling (Keen et al., ~~1982; Vierbuchen et al., 1982) addresses some of these~~ questions (e.g., ~~the origin of outer highs; Schuepbach and Vail, 1980)~~. More important, there is a notable absence of symmetrical rift structures in reflection seismic profiles (as pointed out by Bally, 1981, 1982), and opposing margins do not generally exhibit identical structures. We conclude, therefore, that symmetrical extension models have limited applicability. Structural asymmetry may be a general feature of passive margin development.

Structural asymmetry on a range of scales is a feature of many of the models recently proposed for continental extension in the Basin and Range province of the western United States. These models are based on detachment faults and/or shallow-dipping crustal shear zones (Wernicke, 1981, 1985; Wernicke and Burchfiel, 1982; Davis, 1983). In this paper we explore the consequences of continental separation as the result of the operation of such shallow-dipping detachment faults, and we describe the architecture of passive margins that would result from these inherently asymmetric models for continental extension.

DETACHMENT MODELS FOR CONTINENTAL EXTENSION

Several authors have recognized similarity of passive margin structures to those recognized in the Basin and Range province. However, there is an important element of Basin and Range–style tectonics that has not been recognized on passive margins: detachment faults associated with the formation of metamorphic core complexes and/or (mylonitic) detachment terranes (Crittenden et al., 1980). Metamorphic core complexes, or mylonitic detachment terranes, consist of a largely brittle upper plate overlying ductilely deformed igneous and metamorphic rocks. The upper plate is truncated at its base by low-angle faults of large areal ex-

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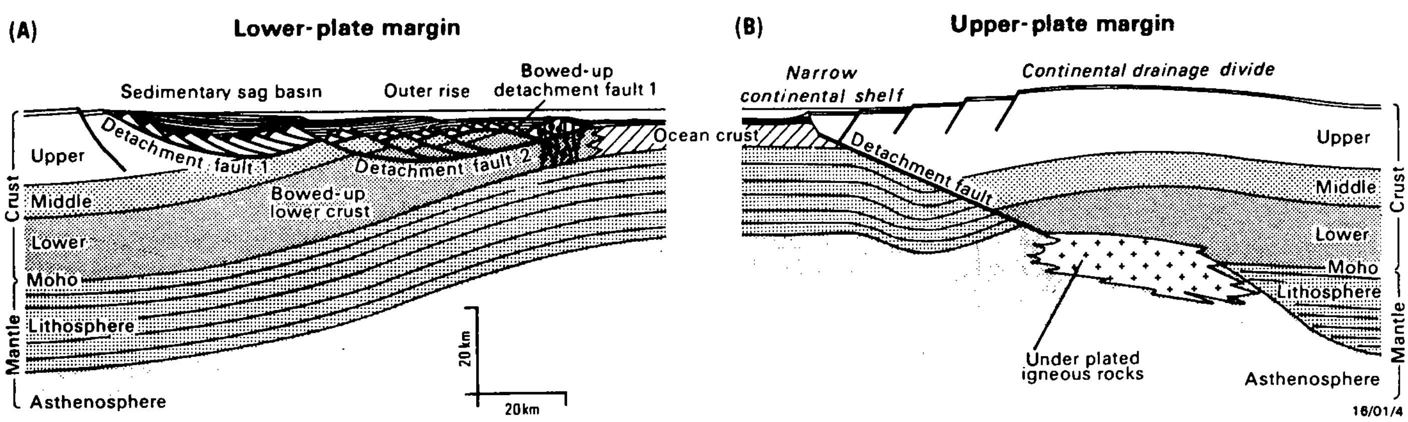

Figure 2. Detachment-fault model of passive continental margins with lower-plate or upper-plate characteristics. Lower-plate margin (left) has complex structure; tilt blocks are remnants from upper plate, above bowed-up detachment faults. Multiple detachment has led to two generations of tilt blocks in diagram shown. Upper-plate margin (right) is relatively unstructured. Uplift of adjacent continent is caused by underplating of igneous rocks. Opposing passive margin pairs exhibit marked but complementary asymmetry.

tent which appear to be normal-slip *detachment* faults on which substantial relative displacements have occurred (e.g., Reynolds and Spencer, 1985). The upper plate has been extended 100%–400% (see Davis et al., 1980; Miller et al., 1983) as the result of movements on listric normal faults and/or dominolike rotations of fault blocks bounded by initially high-angle normal faults (see Wernicke and Burchfiel, 1982; Jackson and McKenzie, 1983). As it is dragged to the surface, the lower plate is subject to intense ductile deformation in intracrustal zones of noncoaxial laminar flow (Lister and Davis, 1983). The lower-plate rocks record a history of rapid uplift while, enigmatically, sedimentation may continue on the upper plate.

There is still some argument about the exact role detachment faults play in the continental extension process. Symmetric pure-shear models assume that the detachment fault represents the brittle-ductile transition (e.g., Miller et al., 1983). The brittle upper crust, typified by rotated tilt blocks, is shown extended over a more uniformly stretched ductile lower crust (Fig. 1A). There is increasing support, however, for models based on shallow-dipping movement zones (Wernicke, 1981, 1985; Davis, 1983; Davis et al., 1986). Wernicke suggested that detachment faults represent low-angle normal faults that cut through the entire lithosphere (Fig. 1B). An alternative separation geometry (Fig. 1C) would involve delamination of the lithosphere, the detachment zone running horizontally below the brittle-ductile transition, steepening, and then again running horizontally at the crust-mantle boundary. We are aware that detachment faults may be merely upper crustal manifestations of major ductile shear zones at depth (Davis et al., 1986) and that the concept of a single lithospheric dislocation may be a gross oversimplification. However, limited space prevents us from developing these concepts further without considerable elaboration. Therefore, in this paper we confine dis~~cussion to detachment faults that penetrate the entire lithosphere~~.

DETACHMENT MODELS FOR THE EVOLUTION OF PASSIVE MARGINS

Asymmetric detachment models imply that continental extension will result in highly asymmetric structure on all scales as the middle to lower crust is dragged out from underneath the fracturing and extending upper crust. The asymmetry of the extended terrane becomes increasingly obvious as continental extension continues. Ongoing extension will eventually lead to continental breakup and to the formation of an ocean basin. The resultant passive margins will, in consequence, also display a marked but complementary asymmetry. On the crustal or lithospheric scale, the asymmetry of the margin is determined by whether the underlying master detachment fault originally dipped toward the ocean or away from it. In consequence, we predict that there will be two broad classes of passive margins. *Upper-plate margins* comprise rocks originally above the detachment fault. *Lower-plate margins* comprise the deeper crystalline rocks of the lower plate, commonly overlain by highly faulted remnants of the upper plate (Fig. 2). Upper-plate and lower-plate margins will differ primarily in their rift-stage structure and in their uplift/subsidence characteristics. Secondary controls on their character arise from variation in the location of the ocean-continent boundary, complex detachment-fault geometries, and displacement of master detachment faults on transfer faults.

The basement of a lower-plate margin is generally highly structured and has the rotational normal faults, tilt blocks, and half-graben typical of the so-called rift phase of passive margin development (Fig. 2, left). The structure of an upper-plate margin is relatively simple by comparison (Fig. 2, right). Normal faulting on upper-plate margins is generally only weakly rotational.

During detachment faulting the lower plate must warp upward as the load formerly exerted by the upper plate is removed, and a broad arch or culmination will develop. The final form of this culmination is the result of several factors, including the initial geometry of the detachment-fault system (Spencer, 1984) and the effects of multiple generations of detachment faults (Fig. 2). Isostatic stresses acting on the relatively undisrupted upper-plate margin lead to different effects. The detachment system attains its deepest structural levels on the continent side of an upper-plate passive margin where the detachment system passes into the upper mantle. Extension causes horizontal translation of relatively cool and dense lithosphere toward the developing ocean basin, thus exposing the base of the crust to warmer, and hence relatively less dense, rising asthenosphere. The result will be uplift of the continental land surface adjacent to the upper-plate margin. Seaward of the uplifted area, the gravitational response will be reversed because here movement on the detachment results in substitution of mantle for lower crustal material. The upper-plate margin is therefore subjected to an isostatically derived torque. The uplifted area will pass seaward into a sequence of normal faults that drop the land surface abruptly toward sea level. This marginal flexure of the upper-plate margin may be accentuated by sediment loading on the leading edge of the upper plate.

not shown in Fig 2

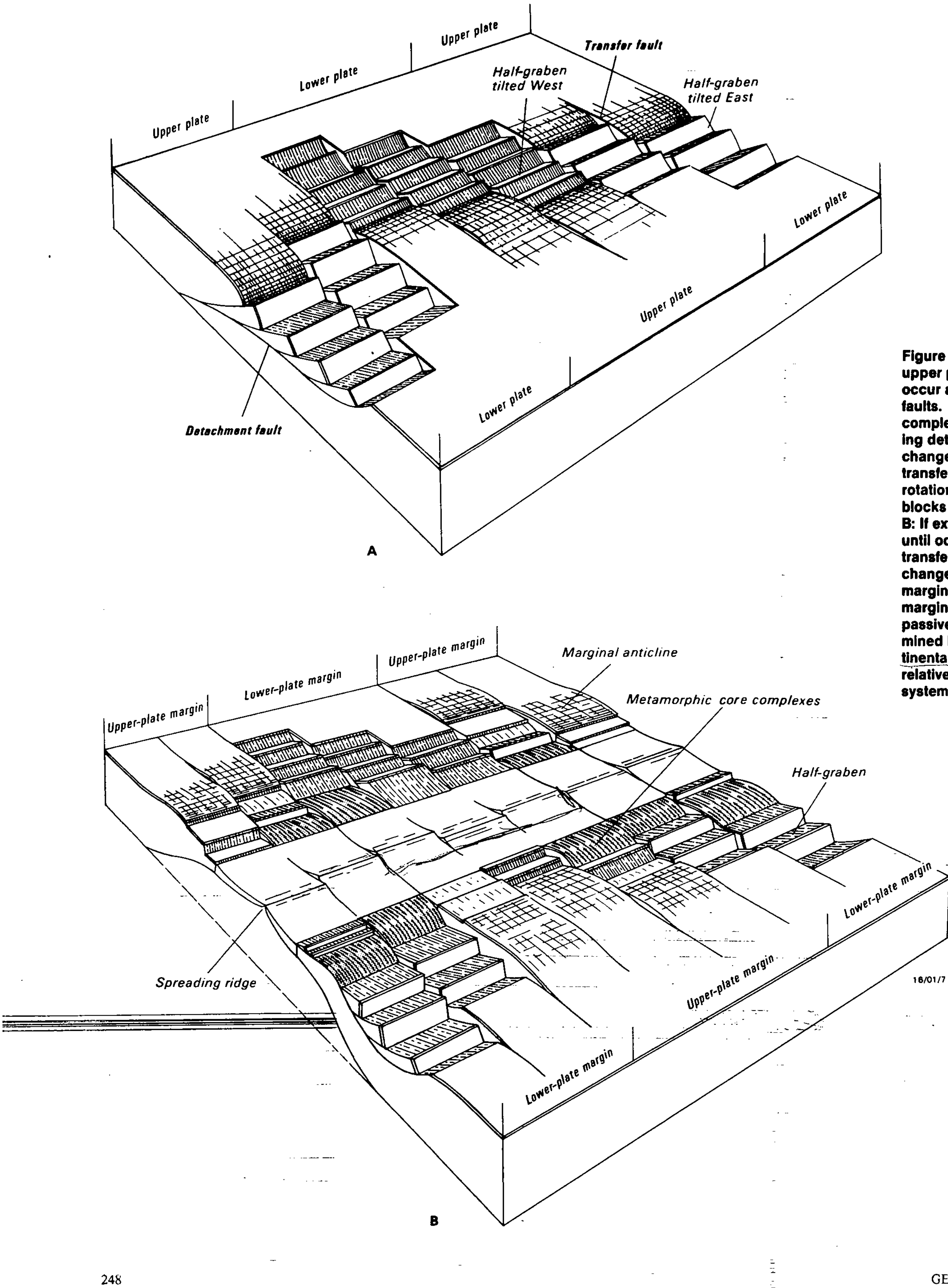

Figure 3. Changes from upper plate to lower plate occur across transfer faults. A: Half-graben complex. When underlying detachment faults change dip across transfer faults, sense of rotation of overlying tilt blocks also changes. B: If extension continues until ocean basin forms, transfer faults mark changes from *upper-plate* margins to *lower-plate* margins. Architecture of passive margin is determined by where final continental separation began relative to detachment system.

where is 'lower plate culmination'

In the basic model, depicted in Figure 2, continental breakup is predicted within or close to the culmination in the bowed-up lower plate because that is where the crust is thinnest. This explains one of the more enigmatic features of passive margin development. As noted by Winterer and Bosellini (1981) and Falvey and Mutter (1981), the locus of final continental breakup frequently does not coincide with the rift basins but occurs in the oceanward basement blocks. The rift basins represent the extended part of the upper plate, whereas the oceanward basement blocks represent deeper levels of the crust exposed in the lower-plate culmination where the crust is thinnest. Breakup near this central culmination separates the margins into dominantly upper-plate and lower-plate types. Breakup significantly to either side of this location will produce margin pairs with upper-plate and lower-plate structures on a single margin (Fig. 3).

If breakup occurs seaward of the lower-plate culmination (as shown in Fig. 2), the lower-plate margin will be typified by rift basins defined by half-graben, inboard of an external basement high. The lower-plate culmination could well be the reason for the existence of the *outer highs* that are commonly recognized in passive margins (see Schuepbach and Vail, 1980; Symonds et al., 1984). The outer high is directly analogous to a metamorphic core complex. If erosion of this culmination occurs during the uplift phase, the upper-plate remnants will be lost, and the metamorphic basement will be exposed. If the basement culmination is not eroded, strongly rotated tilt blocks, remnants of the upper plate, will overlie the metamorphic basement.

What is this?

The uplift-subsidence pattern predicted for lower-plate margins can explain the uplift and denudation of outer highs while rapid deposition occurs in adjacent rift-basin troughs. This is difficult to explain on the basis of conventional models (Falvey and Mutter, 1981). Rift basins defined by half-graben complexes form major sediment traps toward the continent side of the culmination defined by the bowed-up lower plate (Fig. 2, left). The outer culmination will slowly subside after the extension phase as the thermal anomaly caused by extension relaxes. Subsidence will be greatest where the thermal anomaly was strongest, and sediment thicknesses above the culmination will obscure the original structure.

ROLE OF TRANSFER FAULTS

Major normal faults in extensional terranes commonly terminate at orthogonal strike-slip faults or shear zones, which perform a function similar to that of oceanic transform faults (Bally, 1981). These faults have become known as transfer faults (Gibbs, 1984). As shown in Figure 3A, the transfer faults divide the extending terrane into segments. Detachment faults in individual segments may terminate at major transfer faults, in which case the detachment fault may be stepped, or even reverse dip. Other (minor) transfer faults may be confined to the upper plate, affecting only the tilt-block geometry.

Where the detachment fault changes dip direction across one or more transfer faults, the passive margin will change along its length from an upper-plate to a lower-plate margin (Fig. 3B) and will exhibit rectilinear variations in its architecture. Occasionally such variation can be discerned in the bathymetry—e.g., in the Exmouth Plateau area of the northwest Australian margin. We emphasize that transfer faults are a general feature of extended terranes; therefore, they should be expected to occur commonly in passive continental margins. Transfer faults result because both high- and low-angle normal faults nucleate at different places along strike, and mismatches between different fault blocks must be accommodated. Transfer faults are also important in accommodating oblique extension.

Significant variation in margin architecture along strike is therefore a natural consequence of the detachment-fault model, since changes along strike at the rift stage (Fig. 3A) are subsequently reflected geometry of the sag phase of the passive margin (Fig. 3B). Transfer faults may pass laterally into oceanic transform faults, but this is not necessarily the case.

examples?

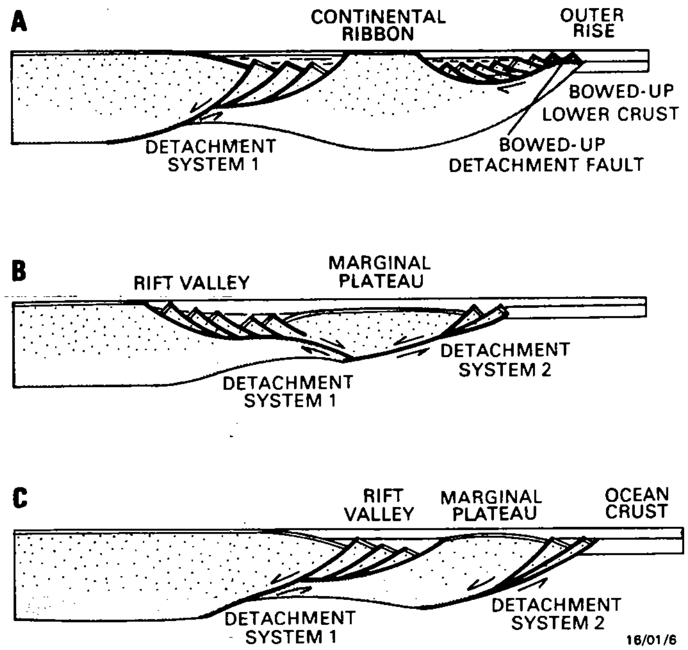

Figure 4. More than one detachment system may be involved in continental extension. Paired detachment systems lead to formation of marginal plateaus, internal rift valleys, or isolated ribbons of continental crust.

ORIGIN OF MARGINAL PLATEAUS AND RIBBON CONTINENTS

Continental separation accomplished by more than one detachment system allows explanation of other aspects of continental margin architecture. Davis and Hardy (1981) described "crustal megaboudins" bounded by (oppositely dipping) shallow-dipping movement zones. If extension continued, a relatively unthinned ribbon continent would result (Fig. 4A), bounded by either ocean crust or an inland rift system.

Another phenomenon results when one shallow-dipping movement zone is cut by another movement zone with the opposite dip (Fig. 4B). One movement zone deactivates, and operation of the transecting movement zone results in removal of the lower part of the crust beneath relatively undeformed parts of the upper plate. Instead of a high-standing region, a low plateau develops (Fig. 4B). Alternatively, two movement zones may develop with the same dip direction, separated by a relatively undeformed region. This event also gives rise to a low plateau (Fig. 4C). If the strike length of these relatively undeformed, high-standing regions is limited by transfer faults, relatively equidimensional highs like many marginal plateaus may develop. Where their strike length is greater, elongate highs (ribbon continents) are formed. Other potential complexities in low-angle extensional fault systems have been described by Gibbs (1984); these also have implications for continental margin architecture when applied on the scale of major detachment faults.

aren't plateaus made of oceanic crust?

COMPLEMENTARY ASYMMETRY OF OPPOSING PASSIVE MARGINS

The major prediction of the detachment-fault model is that opposing margins should exhibit complementary asymmetry. The upper-plate margin is relatively devoid of structure (Fig. 2, right) and may be uplifted if simple underplating models apply. In contrast, the upper parts of a lower-plate margin are highly structured. The basement to the postextension sag basin on a lower-plate margin (Fig. 2, left) should consist of highly faulted and extended upper-plate remnants overlying the detachment fault and hence will be characterized by highly tilted fault blocks adjacent to half-graben filled with synrift sediments. These rocks are overlain by the gently dipping strata deposited during the postextension, subsidence, or sag phase of margin development. This complementary asymmetry of opposing margins will be easiest to recognize if the margins have straightforward upper-plate or lower-plate characteristics and if relatively precise prebreakup reconstruction can be achieved.

RECOGNITION OF DETACHMENT FAULTS IN PASSIVE MARGINS

We suggest that detachment faulting is an integral part of the continental extension process; therefore, detachment faults are to be expected beneath passive continental margins. Detachment faults, and mylonites in deeper shear zones, may be significant seismic reflectors either because of velocity contrast between upper and lower plates or because of the seismic anisotropy of the mylonites (Fountain et al., 1984). Vaguely defined subhorizontal reflectors have been recognized below highly faulted sequences from several margins (see Fig. 4 of Montadert et al., 1979; Le Pichon and Sibuet, 1981).

Lower-plate passive margins are characterized by rift basins lying inboard of external basement highs. This outer rise represents the culmination formed by the bowed-up lower crust and is therefore the location where the detachment fault is closest to the surface. The dip of the normal faults separating tilt blocks will decrease and may approach horizontal or even reverse dip in the most extended and bowed-up regions above the culmination. Such extreme rotations on the normal faults will give rise to steep dips in the synrift sediments; therefore, these structures will be difficult to resolve on conventionally processed seismic data. An important test of the detachment-fault model would be to mount a drilling program into basement rocks in outer highs and to demonstrate the presence of deeper level sediments and/or metamorphic rocks.

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FORUM

Comment and Reply on "Detachment faulting and the evolution of passive continental margins"

COMMENT

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Lister et al. (1986) have provided a concise and thoughtful discussion of the possible roles played by low-angle detachment faults in the break-up histories of passive continental margins. They developed a model of asymmetric crustal extension that helps explain or predict such diverse features as outboard marginal highs, isolated margin-parallel rift valleys and abrupt along-strike changes in margin uplift-subsidence histories. Although Lister et al. clearly stated that a one-to-one correspondence between cross faults (transfer faults) in the continental rift stage and transform faults in the oceanic spreading stage does not exist, their discussion and particularly their Figure 3 imply that oceanic structural geometry is inherited directly from the earlier rift geometry. I believe that this is a critical, and perhaps generally invalid, assumption, one that conceals a very intriguing problem in our understanding of the geology of the continental rifting process.

Asymmetry in continental rifts, although inadequately considered in many theoretical treatments, has been nearly universally suggested by both geological and geophysical field observations (e.g., Gregory, 1921; Evison, 1959). Industry reflection seismic profiling has confirmed that this is the case (Bally, 1982) and has shown that the sense of asymmetry periodically reverses along the length of most rifts, as was first recognized in the Gulf of Suez (Moustafa, 1976). Several authors have interpreted these relationships in terms of shallow level listric and planar normal faults that sole out into subrift detachment zones (Wernicke, 1981; Bally, 1982; Gibbs, 1983, 1984). Seismic stratigraphic data suggest that in many rifts symmetrically opposed detachment systems are coevally active during the earliest phases of rifting. The mechanical inefficiency of symmetrical detachments repeatedly offsetting each other at depth would then eventually lead to one system locking and the progressive evolution of an asymmetric half-graben form. Reversals in this asymmetry along a rift axis have been related to the manner in which the competing, opposed detachments propagate laterally (Bosworth, 1985a).

Lister et al. (1986) identified two forms of cross-structures in their rift model: (1) major strike-slip faults perpendicular to the rift trend that cut the detachment faults, producing a step in the detachment and in some cases allowing a reversal in dip of the detachment, and (2) minor strike-slip faults perpendicular to the rift trend that are restricted to the upper plate. Both of these cross-structures are referred to as "transfer faults" after Gibbs (1984). This transfer fault geometry produces the ~~abrupt along-strike changes in margin geology predicted~~ by the Lister et al. model and provides a logical template for the location of oceanic transform faults. It is my experience, however, that these two types of transfer faults are seldom oriented in an orthogonal position relative to rift-trend faults, nor are they parallel to the regional extension direction.

Minor transfer faults are difficult to map seismically because (1) they generally result in limited vertical offset of seismic horizons and (2) seismic data are acquired with a prejudice toward recognizing faults that parallel some regional "strike" orientation. After extensive mapping in the North Sea rifts, Gibbs has stated that the transfer faults there are most likely *oblique* structures, greatly confounding precise section balancing efforts (Gibbs, 1985). Similarly, in the Gulf of Suez and rifts of Sudan, transfer faults are seldom perpendicular to half-graben main bounding faults and rarely pass more than halfway across the rift, unlike the cross-structures depicted in Lister et al.'s (1986) Figure 3. Major transfer faults separating half-grabens with opposing detachment asymmetries have been referred to in the petroleum industry as "accommodation zones" (S. J. Derksen, 1984, personal commun.). Accommodation zones are areas of exceptional structural complexity, dominated by oblique wrench-style tectonism. The interaction between adjacent detachment systems is generally distributed over a broad zone, crossing the rift trend at an oblique angle.

An example of the relationships between transfer faults, accommodation zones, and rift trend structures from the Gregory Rift is shown in Figure 1. Proprietary data from the North Sea and Gulf of Suez, where crustal extension has been greater, can be interpreted in a similar structural style. The Bass Basin in southeastern Australia (Etheridge et al., 1984) has been interpreted in the fashion of Lister et al.'s model, but I would suggest that the same seismic data could be interpreted in the style

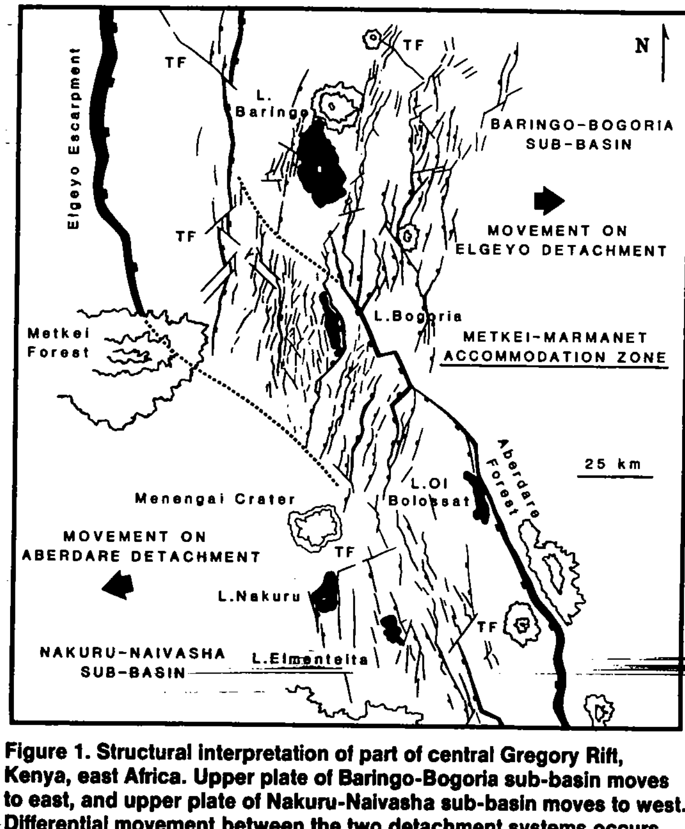

Figure 1. Structural interpretation of part of central Gregory Rift, Kenya, east Africa. Upper plate of Baringo-Bogoria sub-basin moves to east, and upper plate of Nakuru-Naivasha sub-basin moves to west. Differential movement between the two detachment systems occurs across Metkei-Marmanet "accommodation zone," an area of oblique wrenching manifested at surface by broad zone of complex faulting (area between dotted lines). Transfer faults (TF) are geometrically analogous structures on smaller scale that are probably confined to upper plate. Both accommodation zones and transfer faults are, in general, oblique to rift trend.

of Figure 1, which is based on surface expressions of faulting. The flip-flopping detachment model first recognized by Bally (1982), and now refined by Lister et al. (1986), appears to account for many of the geologic and geophysical features of rifted continental margins. The transition from continental-style structure to the oceanic ridge–transform fault system must occur someplace in a margin transect and sometime in a margin history, but at what place and at what time?

REPLY

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Bosworth raises several issues that must be dealt with in any model of continental extension involving detachment faulting, particularly concerning the role of associated strike-slip or transfer faulting. We agree with Bosworth's concept of asymmetric rift development and of reversals in asymmetry along the strike of a rift zone. His paper on this topic (Bosworth, 1985a), which came to our attention after submission of our paper (Lister et al., 1986), represents an important development in the study of continental rifting. We respond here to the two main points Bosworth raises in his Comment.

1. Are transfer faults generally orthogonal to the rift-trend normal faults, and are they parallel to the regional extension direction? Bosworth presents evidence from the East African Rift System (Fig. 1 in Bosworth's Comment) and refers to other rift systems in that region and in the North Sea (Gibbs, 1984, 1985) to argue that transfer faults are commonly, if not generally, oblique to the rift trend and to the regional extension direction. In contrast, we clearly implied that transfer faults on the scale of both individual normal faults within the basin and the major bounding detachment faults are orthogonal to the normal faults and contain the extension direction.

Our conclusion was based on two main lines of evidence. First, there is the geometric requirement that the movement direction on the normal fault must lie in the plane of the transfer fault, at least at moderate to large extensions, unless substantial internal deformation of the fault blocks takes place. As Bosworth (1985b) has pointed out, there is unlikely to be significant penetrative deformation of the fault blocks at these high crustal levels. This requirement alone does not mean that the normal and transfer faults must be perpendicular. However, where the normal (and detachment) faults are essentially dip-slip, steeply dipping transfer faults must be perpendicular to them and will therefore contain the extension direction. Where the normal faults are oblique slip, near-vertical transfer faults will also be parallel to the movement direction, but the normal and transfer faults will not be perpendicular, which may be the situation in the North Sea (Gibbs, 1984, 1985).

We emphasize that it is important to distinguish between the fault displacement vector, the extension direction within a single transfer fault-bound compartment, and the mean extension direction of the basin-wide strain field. Even the horizontal components of these three directions need not be parallel. Bosworth states that the transfer faults are seldom *parallel to the regional extension direction.* We maintain that the requirement of compatibility between adjacent fault blocks does require that vertical transfer faults are parallel to the movement direction and to the local extension direction. The average regional extension direction will depend upon whether there is a consistent sense of offset on the transfer faults (see Fig. 1 here and discussion below of the Bass Basin). Certainly, if both normal and transfer structures are oblique slip faults (i.e., nonvertical transfer faults), the movement direction will not be parallel to the strike of the transfer faults, and the relationship between the various indicators of extension direction will be complex.

Second, one of us (Etheridge) has carried out detailed mapping of the normal/transfer fault array from seismic data in the Bass and Gippsland basins, southeastern Australia (Etheridge et al., 1984, 1985). These basins are failed rifts formed during the early stages of the separation of Australia and Antarctica. Bosworth states that the Bass Strait basins were "interpreted in the fashion of Lister et al.'s model," implying that the mapping was not carried out objectively. However, the availability of closely spaced networks of modern multichannel seismic reflection data enabled fairly precise mapping of both normal and transfer fault trends. In both basins, the transfer faults are indeed close to vertical and perpendicular to the normal faults, and many of them can be traced across the whole basin (Fig. 1 here). However, we point out that in both the Bass and Gippsland basins, the transfer faults give rise to a systematic sense of offset of the normal fault array, giving rise to an oblique extension component for the basin as a whole. This basinwide extension direction is not parallel to the transfer faults, although the local movement direction within each fault compartment is. The transfer faults were mapped directly both from strike lines and from discontinuities in the trend of major normal faults (see also Williamson et al., 1985). Bosworth is correct in pointing out the difficulty of recognizing transfer faults in seismic data; however, Etheridge et al. (1985) illustrated several examples from strike lines in the Bass Strait basins. Along the Gippsland Basin southern margin, in particular, a seismic grid with a 1-km line spacing of both dip and strike lines enabled precise mapping of the trends of both fault sets. Preliminary mapping of rift structures from more widely

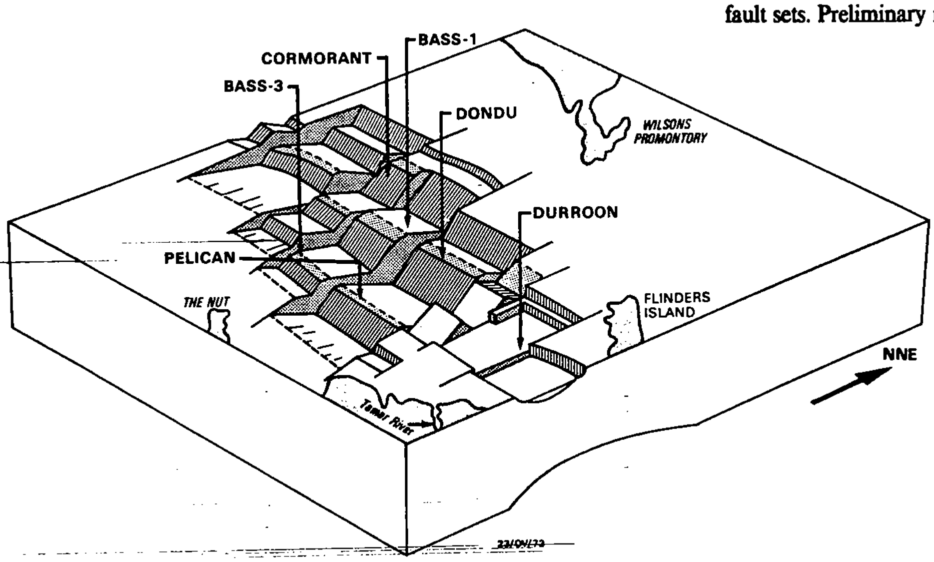

Figure 1. Perspective view of Early Cretaceous structure of Bass Basin, southeastern Australia, showing consistent right-lateral offset across major transfer faults (after Etheridge et al., 1984, 1985).

spaced data elsewhere around the Australian margin tends to confirm the commonly near-orthogonal relation between normal and transfer faults.

We ascribe the apparent inconsistency between these observations and the data provided by Bosworth (Comment, Fig. 1) from the East African Rift to the very low extensional strain in that area. At extensions of a few percent, distributed faulting throughout the rock mass can accommodate the along-strike variations in normal fault geometry, and the geometric requirements for compatibility between fault motions need not be strictly obeyed. At larger extensions, we maintain that the broad accommodation zones that connect oppositely dipping detachments will become increasingly dominated by a few transfer faults that will commonly, if not generally, be orthogonal to the normal faults, unless the movement direction on the normal faults is significantly oblique. We also point out that the part of the East African Rift illustrated by Bosworth contains complexities that we did not attempt to incorporate in our simplified model. For example, in this part of the Gregory Rift, the normal and detachment faults change strike through about 20°, which alone necessitates a complex accommodation zone. Some of the faults labeled as transfer faults in Bosworth's Figure 1 do not appear to satisfy the geometric requirements outlined above, and they may be strike slip faults that accomplish some of the small penetrative strain demanded by the normal fault geometry shown.

2. Is the oceanic transform fault geometry inherited directly from the continental transfer fault geometry? Although we clearly stated that there is no one-to-one correspondence between transfer faults developed in the continental extension stage and transform faults in the subsequent oceanic spreading stage, Bosworth is correct in pointing out that our Figure 3 (Lister et al., 1986) implied otherwise. We agree that our Figure 3 probably overstated the degree of correspondence between the continental and oceanic structures, and that such a correspondence certainly cannot be assumed. However, it should also be pointed out that there are almost no suitable data available in the public domain that bear on this question, and that there is certainly some degree of correspondence between the gross continental extensional structures and oceanic transform geometry at certain passive margins. For example, the gross structure of marginal plateaus such as the Exmouth Plateau off northwestern Australia seems to be controlled, at least in part, by continental transfer faults that can be traced oceanward into typical transform faults. We expect the major transfer faults that accommodate large displacements or along-strike switches in asymmetry of master detachment faults to be the most likely to propagate into oceanic transform faults. This is because the location of the intrusions that initiate sea-floor spreading is likely to be controlled to some extent by the geometry of the immediately overlying detachment fault, since it will exert an important control on the thinning of the underlying lower crust and lithospheric mantle.

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Comment and Reply on "Sedimentology, stratigraphy, and extinctions during the Cretaceous-Paleogene transition at Bug Creek, Montana"

COMMENT

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Various articles have recently appeared that purport to give the most accurate assessment of the stratigraphy and sedimentology of the Bug Creek Anthills (BCA) area, Montana (Smit and van der Kaars, 1984; Sloan et al., 1986; Fastovsky and Dott, 1986), yet they all differ in their conclusions. The article by Fastovsky and Dott (1986) is the most thoroughly documented and the most convincing. Their assessment that it is not possible to establish a Cretaceous or Paleocene age for the BCA on the basis of sedimentologic argumentation appears to be well reasoned. The conclusion of these authors, however, that the BCA fauna "cannot be used to support either gradual or catastrophic hypotheses," does not follow from their work for two reasons.

First, Fastovsky and Dott discussed a single site and fauna, the BCA. Clearly, a single site cannot be used by itself to assess whether a pattern of change is gradual or not. The assessment of gradual (or stepwise) extinctions originally discussed by Sloan and Van Valen (1965; Van Valen and Sloan, 1965) utilized five faunal levels that span the Cretaceous-Tertiary boundary. These levels, from oldest to youngest, are the following: sites with undisputed typical latest Cretaceous faunas; the Bug Creek sequence of three faunas that might in part be coeval with some typical latest Cretaceous faunas (oldest to youngest)—BCA, Bug Creek West, and Harbicht Hill; and the early Paleocene Purgatory Hill site. This sequence has been supplemented considerably by other sites in eastern Montana that have been discussed at length elsewhere (Archibald, 1981, 1982, 1986; Archibald and Clemens, 1984).

Second, if the geochronologic age of the BCA were known with more certainty, one could assess more fully the relationship between biologic change (originations and extinctions) and environmental change