Model for a Passive to Active Continental Margin Transition: Implications for Hydrocarbon Exploration: Reply[1]

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I thank Lash (1983) for his discussion and comments on my continental margin transition paper (Cohen, 1982). Although the two specific regional examples he cites (central and northern Appalachians, southern Banda Sea area) may indeed reflect slight variations to the proposed general model, both examples pertain to tectonic settings wherein the site of initiation of rupture was *not* the continental-oceanic crustal boundary but rather a site farther seaward. The original paper stated quite explicitly that for such tectonic settings, the proposed model was indeed only generally similar. This reply, therefore, is confined to addressing the following salient points: (1) the temporal relationship between normal faulting and flexure (peripheral bulge of Jacobi, 1981), (2) the existence of deeper water-unconformity-deeper water stratal assemblages as a variant to the deeper water-shallower water-deeper water assemblages, as originally proposed (Cohen, 1982), and (3) the role of flexure in the passive to active continental margin transition (with reverse polarity).

ROLE OF NORMAL FAULTS OF DIFFERENT GENERATIONS

Differentiation of the role(s) played by each of several generations of faults in the continental margin's deformation history is difficult. Lash's statement that the peripheral bulge "of the shelf took place before and during subsidence which *may* [my italics] have occurred by normal faulting as the shelf approached the trench" appears to ignore the continental margin's initial extensional history. Hence, if this extension is predominantly via listric normal faults, as proposed in the original model (Cohen, 1982), load-induced flexure (Watts and Talwani, 1974) during basin closure clearly cannot occur prior to the very age of the basin itself.

On the other hand, *later* normal faulting contemporaneous with load-induced flexure during basin closure was proposed in the original model (Cohen, 1982) and appears to receive further support from the examples cited by Lash. Whether this "generation" of normal faults nucleates along preexisting lines of weakness (e.g., older faults, fractures) or establishes new discontinuities is problematic; they do, however, postdate the earlier, basin-forming normal faults.

This aspect of fault rejuvenation is important from another "deeper" point of view. Where the initial extension in a basin is accommodated through the development of listric normal faults (these faults affecting the continental crust and soleing out in some brittle-ductile transition zone at depth), new mineral parageneses formed within the ductile environment along these faults will clearly be syntectonic. Furthermore, radiometric "clocks" within these new mineral parageneses will remain open so long as sufficient heat exists to keep them above their blocking temperatures. Hence it would only be later, postdating movement at depth on these listric normal faults, and hence extension in the basin, that (1) subsidence of isotherms and lithospheric cooling could occur, and (2) the earlier formed mineral parageneses could cool through their respective blocking temperatures.

Significant, then, is the implication that age dates from fault-zone rocks in the economic basement of similar basins will be younger that the age of the actual extension in them. This age difference will be a function of the post-extension rate of isothermal subsidence.

If these listric normal faults were later rejuvenated as reverse faults during basin closure as proposed earlier (Cohen, 1982), the radiometric "clocks" in these new mineral parageneses could be reset during this second tectonothermal episode. If age dating were subsequently done on these remobilized fault-zone rocks in the economic basement, it might be possible to discriminate the later "overprinting age," relating to the compressional event, from an "initial age." However, the initial age would clearly postdate both the basin subsidence (and thus could only be regarded as an upper limit on the age of basin subsidence) as well as the true age of the basement.

DEEPER WATER-UNCONFORMITY-DEEPER WATER STRATAL ASSEMBLAGES

Lash accepts the evidence for deeper water-shallower water-deeper water stratigraphic sequences presented in the original model and, indeed, offers several additional examples in its support. He finds the alternative deeper water-unconformity-deeper water sequence out of the realm of experience stating that "it is difficult to visualize the deep water-unconformity-deep water sequence suggested by Cohen." An example which clearly documents this sequence follows.

In the mid-Cretaceous, a rapidly opening southwest-facing marginal basin formed in the Tethys ocean north-

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east (Pierce et al, 1981) of the then passive Arabian continental margin. The initiation of a southwest-facing zone of closure may be temporally correlated with a major middle Albian regression (Murris, 1980) on the Arabian shelf. The regression was due to uplift and flexure of the Arabian continental margin (Gealy, 1977) at the same time as closure of the Tethys.

These regional tectonic events are reflected in an Albian facies change from earlier shallow-marine carbonates to later alluvial and coastal plain deposits (Murris, 1980). Among the latter is the Wasia Formation, a giant hydrocarbon reservoir in the prolific Burgan oil field in Kuwait.

This flexure caused a major unconformity elsewhere in the region, however. In the Umm Shaif field, offshore United Arab Emirates, for example, rather than the shallow-water-continental deposits found in Saudi Arabia, a major Albian unconformity exists which separates underlying dense, non-pellety, upper Aptian micrites with benthonic foraminifera *Praeglobotruncana (Hedbergella)* and ammonites *Cheloniceras* and *Colombiceras* from overlying, lower Cenomanian deep-water shales containing a globigerinid-lituolid microfauna (Banner and Wood, 1964).

Both stratal sequences described in the original model (Cohen, 1982), the deeper water–shallower water–deeper water and the deeper water–unconformity–deeper water assemblages, are thus quite clearly documented within the geologic record.

FLEXURE AND ITS LANDWARD MIGRATION

Although Lash takes the view that ". . . flexure is the result of extreme horizontal compression. . . " (buckling *sensu stricto*) this restrictive usage is disputed by theoretical and empirical data which show flexure to also result from *vertical* loading (Watts and Talwani, 1974). Furthermore, a recent study modeling continental margin flexure patterns suggests that the half-wavelength of load-induced flexure is of the order of 200 to 600 km (125 to 375 mi) (depending on modeled parameters) for the example of a continent with reverse polarity attached to a descending slab (R. D. Jacobi, personal commun., 1982; Karner and Watts, in press). As pointed out in the original model (Cohen, 1982), the half-wavelength for this setting is anticipated to be much greater than the ~100 km (62 mi) distance associated with oceanic settings. This implies that patterns of uplift, bathymetry, and/or normal faulting may develop far landward from the actual site of the disturbance. It makes perfect sense, then, as Lash observes, for the disconformity on top of the Beekmantown Group to relate to "flexure" but predate nappe emplacement in the central Appalachians. However, as mentioned above, he may be incorrect to generally attribute unconformity and flexure to "extreme horizontal compression" rather than seaward vertical loads.

Finally, further supporting the original model, landward migration of the peripheral bulge is additionally documented by the example of the Albian Arabian shelf, described above. There, in concert with the southwestward migration of the peripheral bulge, the threshold between the shallow carbonate shelf and alluvial/coastal plain deposits also moved (Murris, 1980). Between the mid-Albian and early Cenomanian, this threshold migrated on the order of 250 to 500 km (150 to 300 mi), an average rate approximating 5 to 10 cm/year (2 to 4 in./year). What happened subsequently to the flexure is unclear; it may, as Lash infers for the Appalachian Great Valley, have collapsed as it passed through older, thicker continental lithosphere. That it did migrate landward with time, however, is easily demonstrated.

I thank Lash for the opportunity to further clarify these aspects of the model.

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