Model Simulation of Mid-Cretaceous Ocean Circulation

E. J. Barron and W. H. Peterson used parameters of global atmospheric circulation models, global paleogeographic reconstructions, and assessments of paleoceanographic boundary conditions to simulate surface circulation patterns in the mid-Cretaceous Tethys Ocean (*1*). Their numerical model suggests the dominance of clockwise gyres between North and South America and between Eurasia and Africa that result in a primary eastward-directed, low-velocity current flow along the mid-Cretaceous Eurasian, northern Tethys margin.

This conclusion appears to be at odds with sedimentologic and paleontologic field evidence (*2, 3*) obtained from the Helvetic tectonic unit that is exposed in the northern Alps and represents the former northern Tethys margin in southern Europe. Cretaceous, Helvetic sediments document the presence and physical imprint of an uniform and erosive, westbound, current system that contoured the southern European border and persisted throughout Aptian to early Cenomanian times (*2, 3*).

A conspicuous zonation of sediments aligned parallel to the shelf break is preserved and consists of a proximal inner-shelf zone of moderate-to-low sediment accumulation rates, in which glauconitic sands dominate; a distal inner-shelf zone of ultralow sediment accumulation rates, where strongly condensed phosphatic beds formed; a zone along the break between the inner and outer shelf, where redeposited, inner-shelf–derived sediments accumulated in channel and fan systems; and an outer-shelf zone of hemipelagic and turbiditic sedimentation. This zonation or parts of it are traceable throughout the Helvetic Alps; beyond the Helvetic zone, it extends from southeastern Spain along the northern Tethys margin to the western Carpathians (*3*). The zonation is interpreted as the "fingerprint" of the Tethyan current system, the zone of strongly condensed phosphatic beds having been formed within the erosive zone along the current axis. Prominent proximal-distal shifts in the locations of the zones are considered to reflect relative sea-level changes.

The unidirectional westward flow of this current system is indicated by the presence of uniform, unidirectional crossbedding in the glauconite sands (*3*); by the shape of glauconitic sandbodies along the boundary of the two inner-shelf zones, wedging out to the east and thickening and broadening to the west (*2*); and by the occurrence of a single, angular, exotic gneiss cobble (*2*). The cobble is of Precambrian age (^{87}Rb-^{86}Sr dating: 827.7 ± 17 million years ago) and is therefore older than plutonic rocks of the Alpine realm. The closest in situ occurrence of rocks similar in composition and age is in the eastern part of the Bohemian Massif, near Brno, Czechoslovakia. The cobble appears to be a dropstone that may have been transported in the roots of a tree drifting along with the westbound current system.

The assumption of Barron and Peterson that "limited biogeographic data may not tightly constrain surface circulation patterns" can be contrasted with new results of an extensive analysis of the paleobiogeographic distribution of mid-Cretaceous ammonoids in the Helvetic area which suggests that important east-west–directed migrations occurred during most of the Aptian and Albian times (*2*).

We interpret the mid-Cretaceous current system along the northern Tethys margin as an uniform and powerful westbound surface current that persistently eroded and winnowed the inner-shelf margin during the Aptian and early Cenomanian times. This interpretation supports the models of Luyendyk *et al.* (*4*). and Seidov (*5*) and contradicts that of Barron and Peterson. One main cause of this apparent contradiction may lie in Barron's choice of paleogeographic reconstructions (*6*), a choice that is pivotal to the modeling of oceanic circulation patterns. The mid-Cretaceous paleogeography of the Tethyan (future Alpine) realm is still controversial (*7*) and that of southeastern Asia is largely unknown; yet both areas are crucial to the reconstruction of Tethyan current circulation patterns (*1*, figures 1 and 2). This does not curtail the value of computer simulations; on the contrary, they force sediment geologists and paleontologists to reassess and compare their field results and interpretations.

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Response: K. B. Föllmi interprets the zonation of a strongly condensed phosphatic zone, unidirectional crossbedding of glauconitic sands, and glauconitic sand body shape as the fingerprint of a powerful inner-shelf Tethyan current system that probably extended over much of the European segment of the Tethyan margin. Such a current system would be very unusual. Strong boundary currents that extend over great distances, with sinuous (or at least changing) continental outlines, tend not to be inner-shelf currents. Rather, such currents typically impinge on the shelf or are deflected as a function of morphologic features.

The occurrence of phosphates is also relevant to the debate. Phosphates are frequently linked to high productivity and upwelling (*1, 2*). The westward flow through Tethys described by Föllmi would not be conducive to the formation of upwelling deposits. However, a prediction of wind-induced upwelling from the atmospheric model used in our simulation suggests that the northern margin of Tethys was a region particularly conducive to upwelling (*3*). Observations on a global basis indicate a very high correspondence of upwelling deposits with model predictions. More specifically, Blueford (*4*) has suggested that the distribution of siliceous deposits, another upwelling indicator, is inconsistent with a westward-flowing circumequatorial current. A plausible interpretation of the phosphates, and the oxygen minimum zone (*5*) described by Föllmi, is high productivity related to wind-induced upwelling.

The evidence of offshore transport in a westerly direction and the nature of the glauconitic sand bodies are indicators of flow direction of the Tethys current. We do not argue with the evidence for the direction of flow indicated by the sedimentologic data, but instead, offer a mechanism different from a westward-flowing inner-shelf boundary current. Föllmi draws an analogy with the sand bodies of similar deposits of Cretaceous age in the western interior seaway of North America (*5*). Erickson and Slingerland (*6*) have provided evidence that these sand bodies are the product of winter storms. Winter storm models generated by the atmospheric simulation of Cretaceous climate, indicate that the winds at the lee of such storms produce shelf currents along the margin sufficient to erode sediments and to produce the shape and direction of the observed sand bodies. An analysis of Cretaceous winter storm tracks (*7*) suggests that the northern margin of Tethys may well have been part of the axis of Northern Hemisphere winter storms in the Cretaceous. Such storms could have produced offshore or westerly flow direction of shelf sedimentation.

Föllmi also cites detailed study of the paleobiogeography of the Helvetic unit as evidence of westward organism migrations. Our simulation allowed both eastward and westward migration. In addition, the evidence from paleobiogeography is entirely unconvincing. Without regional, time-dependent reconstructions, any interpretation must be considered local or nonunique.

Finally, Föllmi suggests that the primary reason our simulations differ lies in the choice of geography. A lack of understanding of the details of geography should certainly play a role in any interpretation—based on models or observations—of current structure. However, since we recognized geography as a major limitation in our paper, we subsequently tested the role of geographic configuration by considering different bathymetries and high- and low-sea level cases for the mid-Cretaceous. We found no reason to alter our conclusions. The difference between our results and those of Luyendyk *et al.* (*8*) is likely due to the fact that they assumed that the position of the westerly and easterly winds would be shifted poleward during warm climates. Such an assumption places the Tethys Ocean entirely within easterly winds. In fact, there is no physical basis for this interpretation of the winds (*9*) during warm geologic climates.

In summary, Föllmi detailed studies offer much to the understanding of Cretaceous climate. However, care must be taken to ensure that all possible interpretations of ocean circulation models are considered. Key to the debate are comprehensive space-time reconstructions (*10*) based on combinations of detailed studies such as those provided by Föllmi.

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