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INSIDE

Tectonic Facies in an Archipelago Model of Intra-Plate Orogenesis

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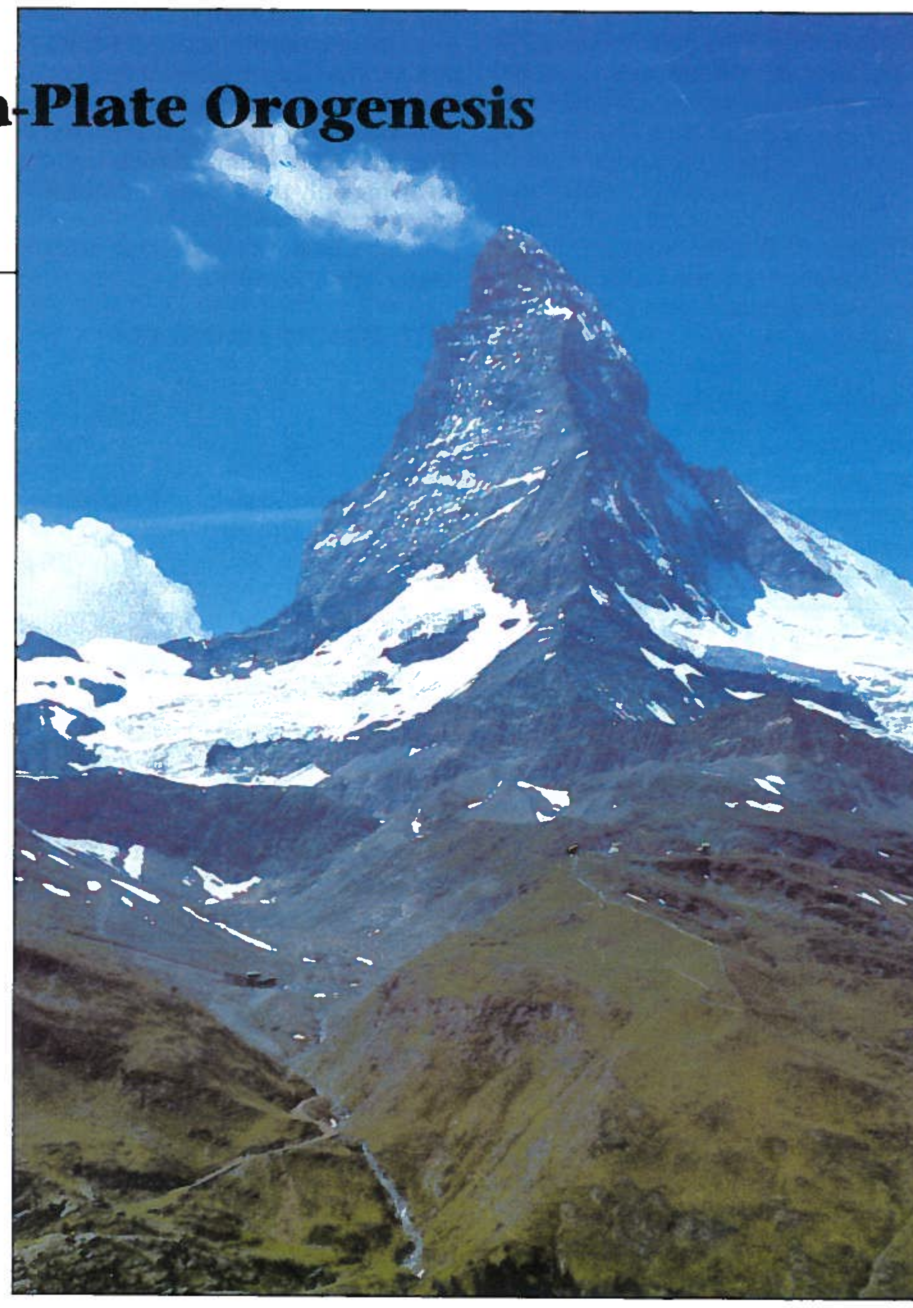

The Matterhorn. The Austroalpine Dent Blanche nappe (upper part) is a fragment of the Apulian plate thrust northward over the Penninic rocks (lower part), which are from the ocean basin that separated the European continent from the Apulian continent in Mesozoic time. Photo by Ueli Briegel, ETH, Zurich.

ABSTRACT

The Alpine units Austides, Pennides, and Helvetides are applicable to designate the basement and cover thrusts of the overriding and underthrust plates in mountains formed by plate collision. These units are not useful in mapping orogenic systems formed by intraplate deformation in back-arc regions. The three tectonic facies of the archipelago model of orogenesis are characterized by their styles of (1) rigid-basement thrusts, (2) mobilized basement-and-cover deformation, and (3) thin-skinned-cover deformation.

INTRODUCTION

The revolutionary new idea of the plate tectonics theory is the postulate of large horizontal displacement of continents and oceans, and a new geological interpretation is the concept of melange, which has been held up as the field evidence of ocean subduction. The theory has retained, however, the classic notion that the precursors of mountains are mobile belts; they were called *geosynclines,* but are now called *active margins*. Terranes outside the mobile belts were once called *cratons;* they are now called *plates*. Mountains were thought to have been formed when cratons were pressed together, by compression or by continental drift, and we now postulate plate displacement and plate collisions. What was a miogeosyncline is now known as a passive margin, and a eugeosyncline is an ophiolite melange. We still think in terms of orogenic phases; flysch continues to be synorogenic and molasse, postorogenic, whereas igneous activities can be pre-, syn-, or postorogenic.

In my efforts during the past 15 years to apply the two-plate model to the geology of China, I have run into difficulties. There are too many melange belts, too many suture zones, and too many plates. The puzzles were resolved after I adopted an actualistic analogue of intraplate deformation in the back-arc region of the southwest Pacific. This experience led me to reexamine the Alpine, and this article is a narrative of my awakening.

TEMPORAL EVOLUTION OF MOUNTAINS

The genesis of mountains, like that of living organisms, has been studied on the basis of comparative anatomy. The approach is to identify the few basic elements in the *Bauplan* (blueprint) for all different individuals. There are the two major kinds of mountains on the surface of Earth: the Tethyan and the circum-Pacific. They seem to be distinctly different, but the geology of Switzerland shows that the Cretaceous Alps underwent the circum-Pacific stage of orogenesis before the postcollisional deformation during the Tertiary Tethyan stage (Hsü and Briegel, 1991). Mountains made by ocean-continent interactions are the precursors of collisional mountains after the intervening ocean is consumed.

The continuous growth of mountains suggests a comparison of their anatomy to living organisms. "Higher" animals are born essentially as they will be. Plants differ from animals in that they undergo fundamental changes during their growth. The seed of a redwood is not only greatly different in size from a fully grown tree, the process of seed germination is quite different from that of a photosynthetic plant. Comparison of the anatomy of mountains to that of animals may have served to perpetuate the classical prejudice that the structures in a mountain chain were formed mainly during its "birthday" (i.e., the paroxysmal phase of an orogeny). Mountains were, however, not made in an orogenic phase. Mountains evolving steadily from the circum-Pacific stage to the Tethyan stage is a process comparable to the growth of a plant, with all its gradual changes from seed germination to full blossom (Hsü, 1989).

THE ALPINE *BAUPLAN* AND TECTONIC UNITS OF STRUCTURAL SUPERPOSITION

The *Bauplan* concept of comparative anatomy is derived from an analysis of architectures. If we overlook the decorative superficiality, the essential elements are the same: buildings have a foundation, floor, walls, ceiling, and roof. There should be windows and doors for most, and chimneys for some. Buildings do not sprout spontaneously from the ground; there is an orderly process of construction. Knowing the indispensability of the vital parts, we could conclude, on the basis of broken tiles in a ruin, where a house once stood. Likewise for a plant, traces of a crown imply the presence of a tree with its stem and root.

The two vital organs in the *Bauplan* of geosynclinal theories were oldland and geosyncline. Mountains were formed when an oldland was thrust on top of a geosyncline (Grabau, 1924; Bucher, 1933). The process is now called *intraplate collision,* or post-collisional deformation. Oldlands such as Appalachia may or may not have survived the earth science revolution, whereas geosynclines are disguised under pseudonyms such as unstable platforms, intracratonic basins, and quasigeosynclines.

The three vital organs in the *Bauplan* of the plate tectonic theories are (1) the motor *(erzeugende Scholle),* (2) the overridden *(überfahrene Zone),* and (3) the escaped *(unbelastete Zone).* Phrased in terms of a two-continents–one-ocean model, the motor is the overriding plate in a continental collision, the overridden are the underthrust and subducted elements, whereas the escaped did escape because

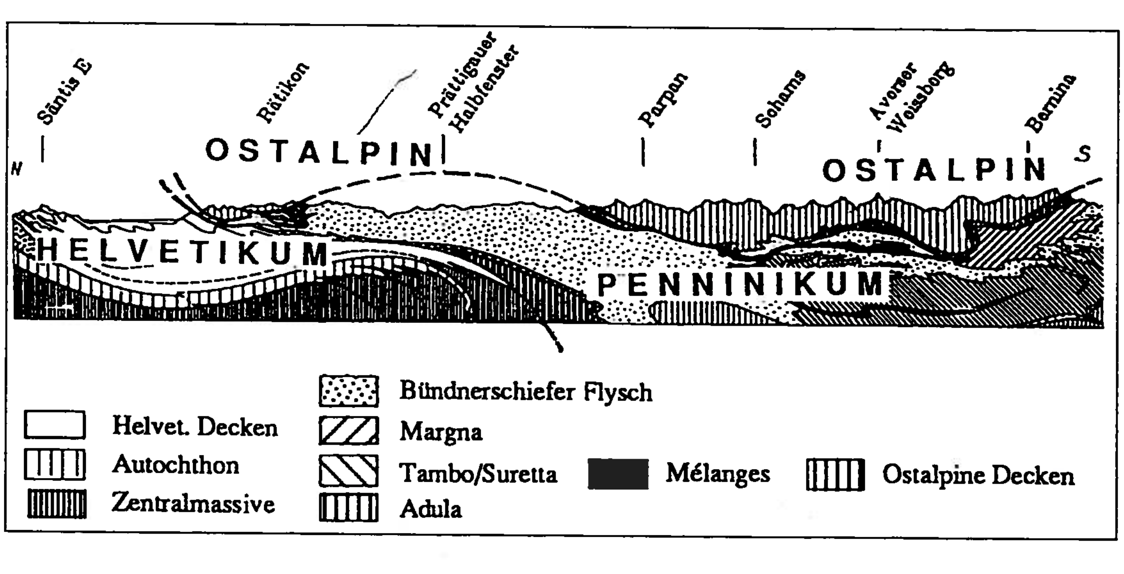

Figure 1. Tectonic units of the Alps; a schematic north-south cross section across eastern Switzerland (after Hsü and Briegel, 1991).

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it had been pushed to the foreland by the motor (Suess, 1937; Trümpy, 1960; Şengör and Okurogullari, 1991). This trinity was first recognized in the Alps (Fig. 1). The Austrides (Ostalpin) of rigid-basement nappes are the motor. The Pennides (Penninikum), including ophiolite mélanges, mobilized-basement nappes, *Bündnerschiefer*, and *schistes lustrés* are the overrun elements, and they are characterized by ductile deformation under metamorphic conditions. The escaped elements are the Helvetic, Prealpine, and Flysch nappes, collectively known as the Helvetikum. The style of thin-skinned tectonics, involving only the folding and thrusting of the sedimentary cover, is the dominant mode of the Helvetic deformation (Hsü, 1994).

THE BANXI PROBLEM

The Swiss tectonicists E. Argand and R. Staub described the Alpine orogenesis in terms of a collision between European and African continents; we now use the word *plates* as a substitute for *continents*. The Alpine collision took place during the late Eocene (Trümpy, 1973). The Tethys was once considered a narrow trough, but it is now viewed as a wide expanse of ocean. The paradigm of two-continent (now two-plate) collision has served for more than a century as the ruling theory of the Alpine tectonics. The trinity of Austrides-Pennides-Helvetides (Ostalpin-Penninikum-Helvetikum) was the foundation of the classic theory, and the trinity is held up as verification of plate tectonics.

Armed with this simplistic trinity, I went to work in China. Six tectonic units are recognized, from north to south, in the deformed terranes in south China (Fig. 2): (1) the Yangtze deformed belt, folded Sinian to Mesozoic strata; (2) Proterozoic granite and Banxi melange; (3) the Huanan deformed belt, folded Sinian to Mesozoic strata; (4) Huanan flysch, mainly lower Paleozoic; (5) Huanan metamorphics, Paleozoic and/or Mesozoic metamorphism; and (6) Huanan Precambrian basement and Phanerozoic intrusives.

Applying the Alpine model of two-plate collision, I suggested that the Yangtze and Huanan (units 1 and 3) are the Helvetides; the Banxi melange, the Huanan flysch, and the Huanan metamorphics (unit 2 melange, units 4 and 5) are the Pennides; and the Precambrian rocks (unit 2 granite and unit 6) are the Austrides of the Huanan Alps (Hsü et al., 1990). They should constitute the trinity of the escaped, overrun, and motor elements of the collisional type of mountains. The two-plate interpretation requires that the Banxi be klippes overthrust on top of the Helvetides (Fig. 2) and that they be metamorphosed and deformed during the Mesozoic. Field work and subsurface and seismic data have indicated that the Banxi melange is indeed overthrust above the Yangtze carbonate terrane (Chen et al., 1993). On the other hand, field evidence also indicates that the Huanan sequence (unit 3) is not thrust under Banxi; it overlies Banxi unconformably. The Banxi ophiolites and eclogites have been dated radiometrically at 850–950 Ma (Zhou et al., 1992), suggesting that the Banxi melange was an accretionary wedge formed by subduction prior to the Mesozoic collision. This melange is at least in part Precambrian and was a part of a rigid basement long before its Mesozoic thrusting above the Yangtze foreland. My predictions based on a simplistic Alpine model were contradicted.

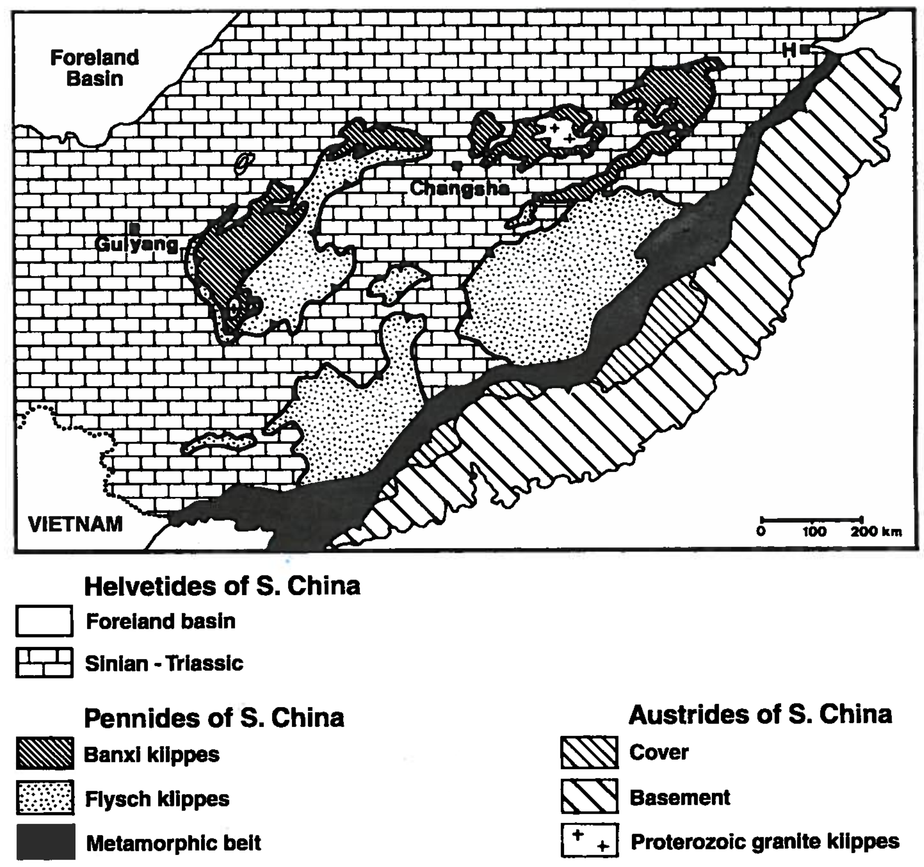

Figure 2. A two-plate model for the tectonics of south China. The hypothesis that the Banxi rocks are klippes of Mesozoic mélanges has been falsified by observations that the Banxi is the Precambrian basement of an island arc overlain by a Paleozoic sedimentary cover.

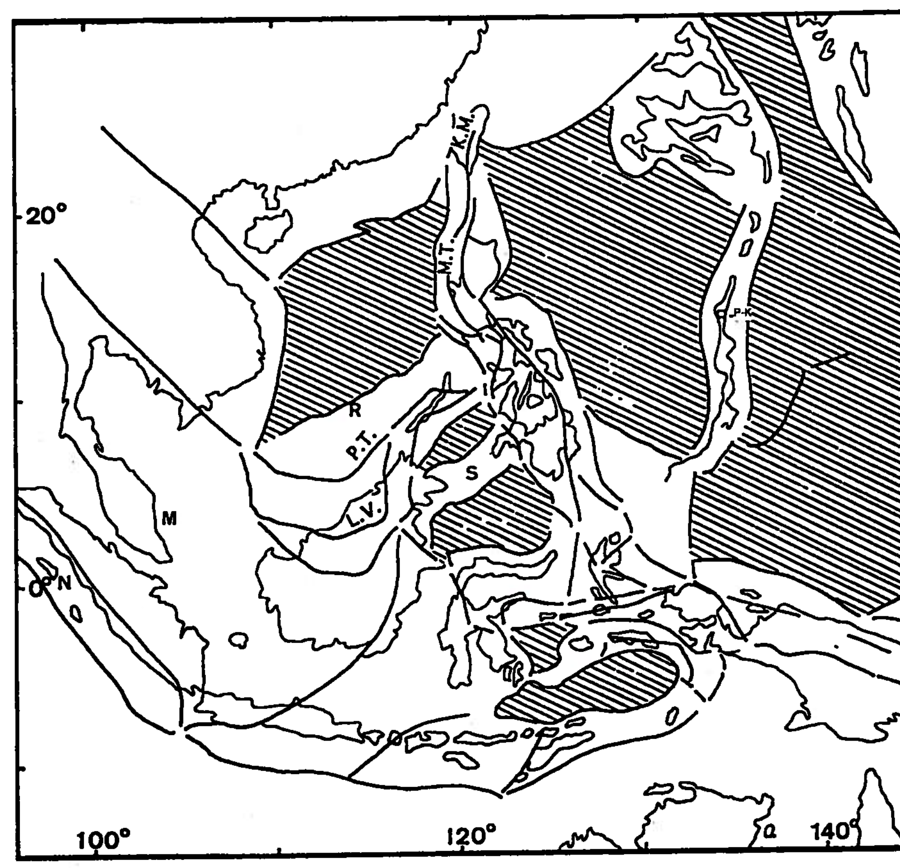

Figure 3. Back-arc basins and sutures in Southeast Asia. M.T.—Manila Trench, K.M.—Kenting melange, L.V.—Lupar Valley melange, P.T.—Palawan Trough, S—Sulu Ridge, R—Reed Bark, M—Malay Peninsula.

WEST PACIFIC MODEL OF OROGENESIS AND DEFINITION OF TECTONIC FACIES

While serving on the JOIDES Tectonics Panel in the late 1980s, Ian Dalziel introduced me to the concept of the back-arc basin collapse. He pointed out that there is more to Andean geology than that portrayed by the hypothesis of the subduction of the Pacific plate. The eastern margin of South America, like that of the southwest Pacific, was once fringed by island arcs and back-arc basins. The structures of the southern Andes are demonstrably formed by the elimination of the basins by arc-arc collisions (Dalziel, 1981), and the actualistic analogue is to be found in southeast Asia.

The southern continental margin of Asia is not the plate margin. Considering back-arc basin intra-plate features, I place the plate boundary of Asia south of the Banda-Sunda arc of Indonesia and east of the Mariana arc of the west Pacific (Fig. 3). Between the frontal arcs and the mainland are numerous remnant arcs and basins. Some of the basins are still active centers of seafloor spreading, such as the Mariana Basin behind the Mariana arc. Some are no longer active, such as the West Philippine Basin and the Malaysian Basin. Some are actively being pressed together, such as the Celebes Basin, the Sulu Basin, and the South China Sea. The lithosphere of the South China Basin, for example, is thrust under the Manila Trench, and the northern tip of the basin is eliminated by the collision of mainland Asia with the Philippine arc along the Kenting melange zone of the Taiwan Central Range. Some back-arc basins have already been completely eliminated by back-arc basin collapse. The back-arc basin between what was once an active

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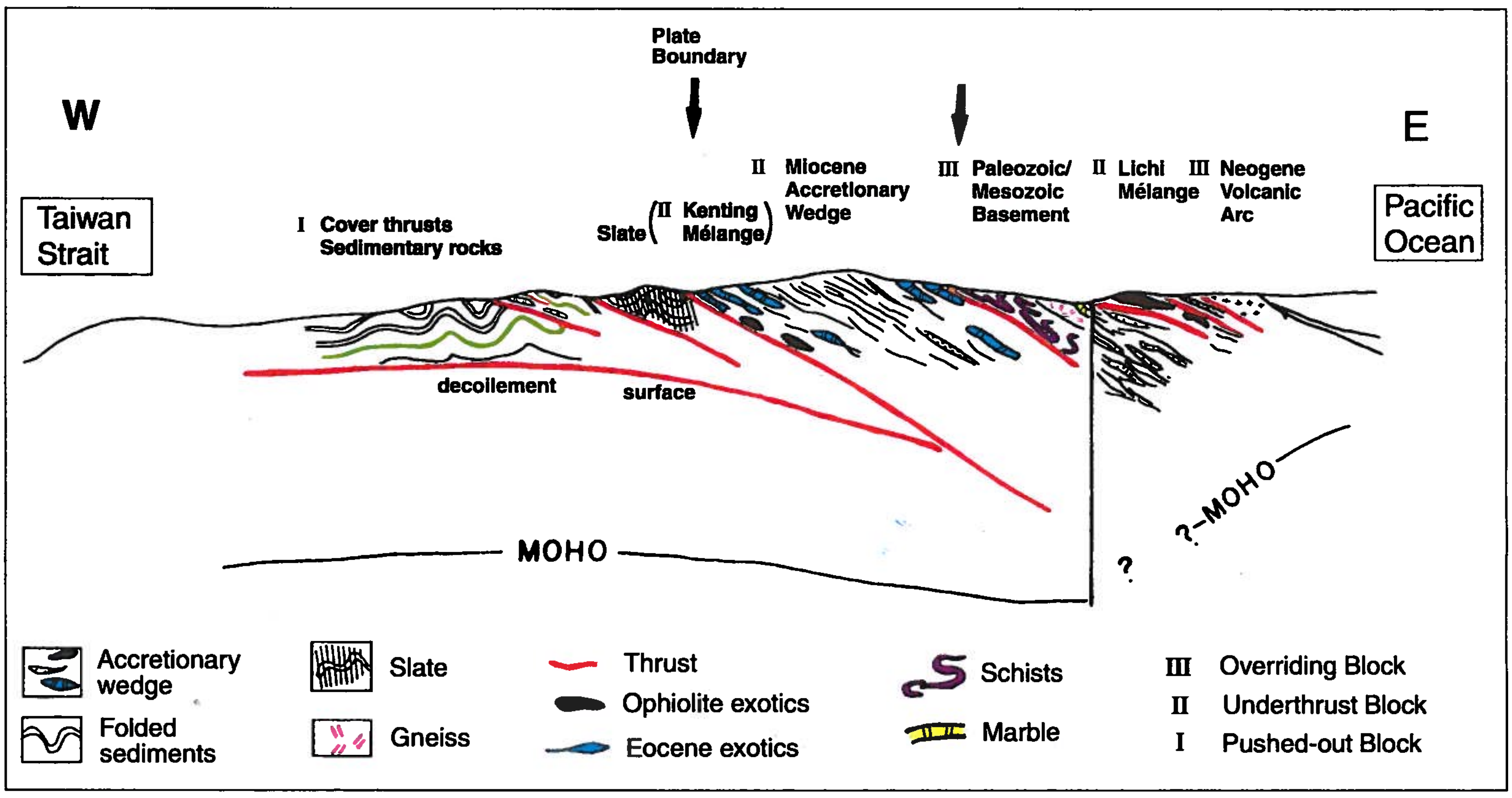

Figure 4. Tectonic units of Taiwan; a west-east schematic cross section across the island.

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volcanic arc in southern Borneo and a remnant nonvolcanic arc in Sarawak was, for example, a Cretaceous and Paleogene basin, and the basin was consumed by an arc-arc collision in the late Eocene marked by the suture of the Lupar Valley melange. The Palawan Trough is another collapsed back-arc basin.

Between back-arc basins are the remnant arcs, such as the Palau-Kyushu Ridge between the West Philippine and Parece Vela Basins, the Sulu Ridge between the Sulu and Celebes basins, and the Reed Bank between the South China Basin and the Palawan Trough. The sedimentary sequences on top of subsiding remnant arcs are similar to those on passive margins.

The terms Austrides, Pennides, and Helvetides are useful indicators of structural superposition within the framework of a two-plate model. The trinity of terms is almost useless where there has been more than one collision; the Austride sedimentary cover of an overriding element of one arc-arc collision may be the Helvetide or the escaped of the next. Another flaw of the nomenclature lies in the supposition that the style of deformation of each unit has a one-to-one correspondence to its tectonic superposition. The Helvetides in the foreland deformed belt of the Alps are the escaped structures, and the Austrides are the overriding structures. However, Austrides, such as the nappes of the North Limestone Alps, are characterized by décollement tectonics like the Helvetides; only the thin-skinned sedimentary cover, not its basement, is involved in the deformation. The same kind of deformation is thus manifested by units in different structural positions, the escaped and the motor.

I was thus compelled to select a different set of criteria for tectonic classification. Tectonic facies are definable by their style of deformation, and the styles reflect grossly different pressure-temperature conditions of deformation, as do the mineral assemblages that characterize metamorphic facies. I propose that units characterized by thin-skinned deformation, be they Helvetides, Pennides, or Austrides, be called *alemanides*; the name is chosen because this tectonic style is typical of regions inhabited mainly by German-speaking Swiss, or descendents of the Alemann people. Units characterized by ductile deformation under various metamorphic conditions, such as *schistes lustrés* and ophiolite melanges, are called *celtides*; the name is chosen because this deformation style is typical of the Pennine Alps of western Switzerland, where the French-speaking Swiss had a Celtic heritage. The Pennides are not the only celtides in the Alps; those Austrides that have been underthrust (i.e., overrun) and metamorphosed are also celtides. Units characterized by rigid-basement thrusting are called *rhaetides*; the name is chosen because these nappes are present mainly in southeastern Switzerland, where the inhabitants claim a Rhaetic ancestry. The rhaetides are commonly motor structures or Austrides, but autochthonous or parautochthonous massifs are also rhaetides. The tectonic facies alemanide, celtide, and rhaetide are thus units descriptive of a style of deformation, and they can be used to describe tectonic units that are formed by any combination of continent-continent, arc-continent, or arc-arc collisions, regardless of their tectonic superposition. In areas of repeated deformation, rocks formed by an earlier ductile deformation (celtides) may have later been deformed by rigid-basement thrusting; they are the rhaetides of the second generation of deformation.

WEST PACIFIC MODEL FOR THE GEOLOGY OF CHINA

In analyzing the Tertiary geology of Taiwan, the western foreland fold belt is easily recognized as the alemanide, the Kenting and Lichi melanges as the celtide, and the Paleozoic-Mesozoic basement rocks as the rhaetide of a Neogene deformation (Lu and Hsü, 1992); the three tectonic facies are also, respectively, the escaped, the overrun, and the motoring structures. The Neogene rhaetide basement (unit III of Fig. 4) consists, however, of metamorphic rocks, including a Cretaceous ophiolite melange, which was a Mesozoic celtide, formed during a Cretaceous collision between Eurasia and a Gondwanaland fragment (Hsü et al., 1990). This metamorphic terrane was split off from Eurasia during the early Tertiary, when it was the basement of an island arc. It was then deformed by rigid-basement thrusting during the collision of the arc and Eurasia, so that the melange (a Mesozoic celtide) in unit III became a part of the Neogene rhaetide.

The Taiwan example illustrates that the functional unity of the same object may have changed with time. Our failure to recognize that an earlier celtide has become the rhaetide of a later deformation was the stumbling block in our interpretation of the geology of South China. We had to abandon our assumption of a Mesozoic age for the Banxi deformation; the ocean lithosphere that was subducted to form the Banxi accretionary wedge is Precambrian.

The Banxi is not a group of formations; the melange consists of rocks of different origins separated by shear surfaces. The three main components of the Banxi are (1) ophiolites and high-pressure metamorphic rocks, (2) calc-alkaline volcanics, and (3) flysch (Xu et al., 1993). The Banxi was a celtide during the Precambrian, but those rocks were the rigid basement of a Paleozoic remnant arc separated from the Yangtze passive margin by a deep-sea basin. This back-arc basin collapsed during the early Mesozoic when the Banxi rocks were overthrust as rhaetides above the Yangtze alemanides. The melanges in the Nanpanjiang region include sediments on the ocean crust of a back-arc basin between the Yangtze and Banxi arcs, and they became a celtide when the two arcs collided (Fig. 5).

A trinity of Paleozoic alemanides, celtides, and rhaetides is recognizable south of the Banxi belt. They include (1) the thin-skinned deformation of the lower Paleozoic sedimentary cover of the Banxi arc, (2) the accretionary wedge of the lower Paleozoic flysch and metamorphics under the Huanan arc, and (3) the Precambrian basement of the Huanan arc and its lower Paleozoic sedimentary cover. The three units of alemanide, celtide, and rhaetide were formed prior to and during the mid-Paleozoic suturing of the Banxi and Huanan arcs, and they are now buried under a neo-autochthonous sedimentary cover.

A WEST PACIFIC MODEL FOR THE ORIGIN OF THE ALPS

Argand postulated in 1911 that the Tethyan mountains owed their origin to the collision of Europe and Africa and supposed that the Mediterranean

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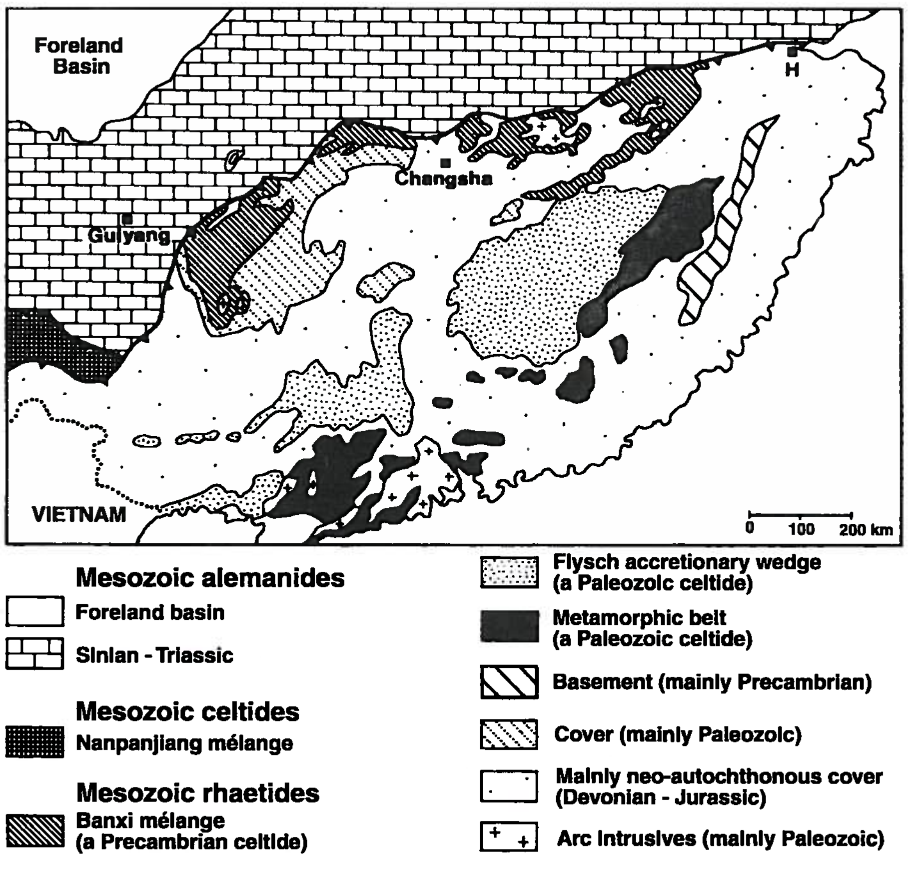

Figure 5. An archipelago model as the working hypothesis to interpret the tectonics of South China.

Tectonic *continued*

basins did not come into existence until after the Eocene Alpine collision. Placing the north boundary of the African plate along the Tethyan suture, Italy and the Balkans are now considered a North African promontory and the Mediterranean basins, holes in the African plate. The relative position of Europe and Africa has been determined on the basis of interpreting the magnetic lineations under the Atlantic seafloor. The displacement was largely left-lateral from 180 to 90 Ma, and there has been a counterclockwise rotation since then (Dewey et al., 1973; see also Fig. 6). A two-plate scheme has not been an adequate model to interpret European geology, and the existence of numerous microcontinents between Europe and Africa has been assumed.

The key to understanding the geology of the Alps is perhaps a belated recognition that the southeastern European margin was an Andean type of magmatic arc in Permian time. This northern margin of the Paleotethys ocean was changed during the Mesozoic into an island-arc type of active margin. There should thus have been an outer volcanic arc between the European continent and the open ocean near the western terminus of the Panthalassa.

The existence of a pre–middle Miocene arc-trench system, buried under the Mediterranean Ridge, is suggested by geophysical evidence (Hsü, 1994). Apparently the southern active margin of Europe extended westward, and the plate boundary between Europe and Africa was a transform margin. This transform fault is now buried under the shelf sediments of the western Mediterranean or under the Numidian flysch of North Africa.

The orogenesis of Southeast Asia, except that of Timor, was not caused by the collision of Asia and Australia; the two continents have not collided yet except in Timor. Likewise, the origin of the Tethyan mountains cannot have been related to a collision of the European and African continents, because the collision has not yet taken place. The active margin of eastern Europe (south of Crete) is still separated from the passive margin of Africa by the Levantine Sea, and the passive margin of continental Europe (north of the Balearic and Tyrrhenian back-arc basins) is still separated from the transform margin of Africa by the western Mediterranean. Buried under the Tertiary sediments of the Mediterranean Ridge is the outer magmatic arc of the European plate, equivalent to the Mariana-Sunda-Banda arcs of Asia. The Mesozoic and Tertiary Paleotethys and Neotethys were marginal seas, and the Tethyan deformation can only have resulted from arc-continent or arc-arc collisions within the European plate, north of its island-arc margin. The Alpine deformation is a manifestation of the collapse of the Piedmont back-arc basin. Other Tethyan mountains, such as the Pyrenees, Austrian Alps, Apennines, Carpathians, Dinarides, Hellenides, Taurides, and Troodos, have likewise been formed by back-arc basin collapse. Small areas underlain by ocean crust in southern Europe, such as the Caspian Sea, Black Sea, Antalya Basin, Rhodos Basin, and Ionian Basin, are relict-back-arc basins; they owed their origin to back-arc seafloor spreading during the Mesozoic, and they have not yet been completely eliminated by arc-arc collisions.

SUMMARY

Structural geologists have always known that lithospheric plates are not rigid. The geology of the west Pacific is an excellent demonstration that the zone of orogenic strain is not limited to a plate margin. Intraplate deformation causes the orogenesis that eliminates back-arc basins, thereby causing arc-continent or arc-arc collisions. Whereas I recognize the many accretionary complexes in the geological record of Asia, I cannot subscribe to the hypothesis of Şengör and Okurogullari (1991), that continents have grown mainly by forearc accretions. Şengör and I visited eastern Tibet recently to examine the Paleotethyan suture zone between Eurasia and Gondwanaland. We encountered evidence of numerous Precambrian or Paleozoic terranes in the great pile of the Triassic accretionary complex on the southwest fringe of Eurasia. The existence of several remnant arcs with Precambrian-Paleozoic basement was sufficient to convince Şengör of the role of back-arc accretion in the Phanerozoic growth of Asia.

I express my wonder that the precursors of mountains are not mobile *belts*. Mountain chains are linear features, but tectonically active back-arc regions, such as the southwest Pacific today, may originally have been wider than they are long. The collapse of numerous back-arc basins explains the fact that ophiolite sutures rarely occur singly.

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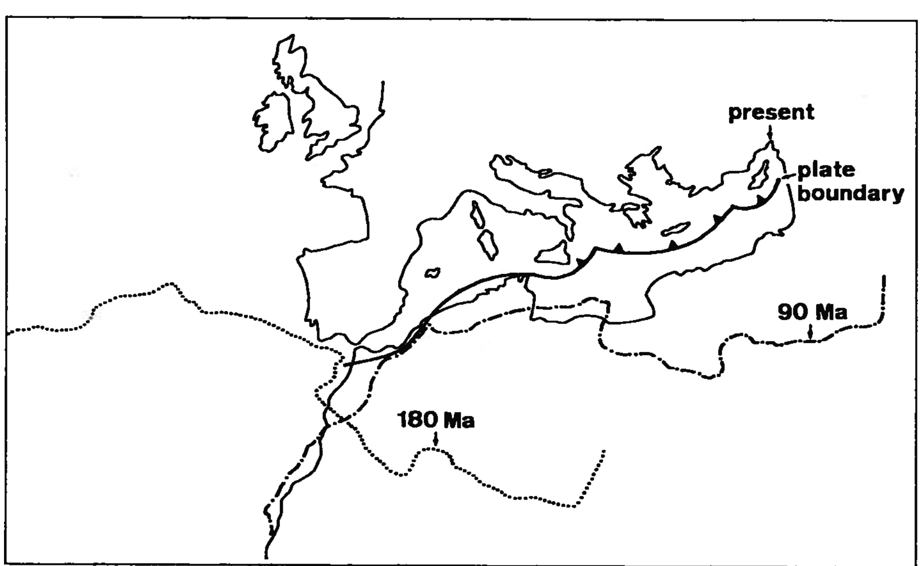

Figure 6. Displacement of the African plate relative to Europe during the past 180 Ma.

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