Downloaded from specialpapers.gsapubs.org on January 6, 2013

Geological Society of America Special Papers

Role of ophiolites in archipelago model of orogenesis

Kenneth J. Hsü

Geological Society of America Special Papers 2003;373;159-171
doi: 10.1130/0-8137-2373-6.159

Email alerting services	click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article
Subscribe	click www.gsapubs.org/subscriptions/ to subscribe to Geological Society of America Special Papers
Permission request	click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

Geological Society of America

THE
GEOLOGICAL
SOCIETY
OF AMERICA

Geological Society of America
Special paper 373
2003

Role of ophiolites in archipelago model of orogenesis

Kenneth J. Hsü*
Tarim Associates AG, Frohburgstrasse 96, Zurich, Switzerland

ABSTRACT

Ophiolites are mafic and ultramafic rock assemblages occurring in mountain belts, and they are commonly found in mélanges. Their association with deep-sea sediments suggests that they represent fragments of raised ocean floor. This conclusion is supported by marine geological and geophysical investigations.

This paper presents the evolution of my own thinking on the origin of ophiolites. I interpret ophiolites as relics of the ocean floor of backarc basins on the basis of my own investigations in the Alps and in China, as well as of literature surveys. I have concluded that only rarely do ophiolites mark the suture zones of plate-collisions.

Keywords: ophiolite, mélange, backarc basin, archipelago, orogenesis.

INTRODUCTION

The term *ophiolite* is a Greek synonym for the Latin *serpentine* and was introduced by Brongniart in the early nineteenth century; it was borrowed subsequently by Steinmann (1905), and the definition was specified to denote a suite of closely associated basic and ultramafic igneous rocks, including pillow lavas, spilite, diabase, gabbro, pyroxenite, peridotite, dunite, serpentinite, and related rocks. Steinmann recognized their association with deep-sea sediments. Suess (1909) agreed with Steinmann in that the ophiolites represent raised ocean floor. He also noted that they are not uncommonly associated with rocks of exotic origin, and that they occurred only in mountains. The ophiolite concept since has played a significant role in various models of orogenesis. Ophiolites were an indispensable component of eugeosynclinal rocks in the geosynclinal theory of orogenesis. Ophiolitic mélanges are considered as evidence of forearc accretion as a consequence of ocean-continent interaction, or of the suturing of two plates in a continent-continent collision zone.

This paper is a personal narrative of the evolution of my own thinking on the origin of mountains, progressing from the geosynclinal to the plate-tectonic theories, and culminating in the formulation of the archipelago model of orogenesis (Hsü, 1994). I finally came to the conclusion (Hsü, 1995) that ophiolite mélanges are not necessarily defining a plate-boundary. In fact, ophiolites are more commonly found in ancient subduction zone environments where backarc basins collapsed as a consequence of intraplate deformation.

Ophiolites in Eugeosynclines

When I first went to the Ohio State University in 1948, my mentor Ed Spieker asked me what would I like to do for my master's degree. I told him rather naively that I wanted to write a thesis on the origin of mountains. I was only 19 years old, and I knew little geology, but Spieker was very kind. He did not tell me to get lost, instead he told me to read Bucher and Holmes, and to study the German masters, Suess, Kober, Kossmat, Staub, Steinmann, among others. I checked out from the university library Staub's *Der Bewegungsmechanismus der Erde*. Little did I think that I was to be his successor in Eidgenössische Technische Hochschule–Zurich (ETH-Zurich) (Switzerland) some 30 years later.

Staub (1928, p. 209), following Argand (1922), recognized that geosynclines are formed by crustal thinning. If Staub had postulated extension as the cause as Walter Bucher did in 1933, or Rudolf Trümpy in 1960, he might have anticipated the modern theory of seafloor spreading. Instead, he followed Argand (1916)—incorrectly—and thought that geosynclines had evolved as a result of compression. Staub developed an idea that geosynclines had their origin through a mantle-density change in a region where the mantle-convection is descending (p. 255). That idea is somewhat similar to Beloussov's (1962) hypothesis of basification of crust; Staub's arrows showing the crustal and

---

*Kenjhsu@aol.com

Hsü, K.J., 2003, Role of ophiolites in archipelago model of orogenesis, *in* Dilek, Y., and Newcomb, S., eds., Ophiolite concept and the evolution of geological thought: Boulder, Colorado, Geological Society of America Special Paper 373, p. 159–171. For permission to copy, contact editing@geosociety.org. © 2003 Geological Society of America.

mantle displacements are exactly opposite to those predicted by the modern plate-theory. Staub was wrong.

Staub was even more wrong to postulate that ophiolites were emplaced in an embryonic nappe as intrusives into a geosyncline under compression. In fact, the Alpine ophiolites include extrusive pillow lavas at the top, overlain by Middle Jurassic sedimentary rocks in many places. The Alpine ophiolites are thus dated as early Middle Jurassic. Trümpy (1960) voiced a consensus of the Alpine geologists that the Alpine sequences are continuous from Carboniferous to lower Tertiary. The change from Triassic shallow-marine to Jurassic deep-marine sedimentation was considered as an evidence of "leptogeosynclinal subsidence." The misidentification of the ophiolites as intrusives or as lavas in a continuously deposited sequence led Trümpy (1960) and other Alpine geologists to deny the existence of fossil oceanic crust in the Alpine region.

Silicic, intermediate, and mafic volcanic rocks are interbedded with, or intercalated in "geosynclinal" sedimentary rocks. Bubnoff (1937), Stille (1924), and Scheumann (1932), among others, invented the scheme of pre-orogenic, synorogenic, and post-orogenic stages of magmatic activities. The ophiolites were interpreted as pre-orogenic and were considered an indispensable component of eugeosynclines. The temperatures at the base of subsided sialic crust were subsequently raised high enough to produce synorogenic granite magmas. Synorogenic plutonic activities were succeeded by post-orogenic volcanism. The confusion lasted even into the earlier years of the plate-tectonics: Dewey (1969), for example, echoed the sentiments of Staub (1928) when he stated that ophiolites were emplaced through the imbrication of the top of subducting oceanic lithosphere along the inner walls of deep-sea trenches.

Ophiolites as the Crust and Upper Mantle Beneath Ocean Floor

When I first attended an annual meeting of the American Geophysical Union in 1955, I saw George Wollard's cross-section depicting the thickness of the earth crust under North America. The thickness was calculated on the basis of Airy's theory of isostasy, and the results were verified in a large part by seismic surveys. The crustal cross-section made obvious that geosynclines were simply regions underlain by thin crust. I had my first publication, *Isostasy and a theory for the origin of geosynclines* (Hsü, 1958) three years later. Miogeosynclines were continental margins where subsidence was balanced by sedimentation; eugeosynclines were simply regions underlain by oceanic crust.

I took a second step forward when I recognized Franciscan mélanges as a model for eugeosynclinal sedimentation and underthrusting tectonics (Hsü, 1971). Steinmann and Suess were right: The ophiolites are simply fragments of crust and upper mantle under ocean floors, and they are tectonically mixed with, but not intruded into, the so-called eugeosynclinal sediments. The postulate found verification by the deep-sea drilling in the eastern Atlantic. At Deep Sea Drilling Project (DSDP) Hole 120, drilling penetrated pelagic sediments on top of an ophiolitic basement. The Steinmann's trinity of radiolarian chert, pillow lava, and gabbro-serpentinite was found on modern seafloor (Hsü and Ryan, 1971).

The studies of the Troodos ophiolite have given us a "standard model" of the layered structure of oceanic crust (Moores, 1982), and this model has since been supported by observations elsewhere on land, and by drilling the in situ oceanic crust (i.e., DSDP/Ocean Drilling Program Hole 504B in Costa Rica Rift; Dilek, 1998).

The Spilite Problem

Near the turn of the last century, Harker (1896) and Becke (1903) popularized the terms "Pacific Suite" and "Atlantic Suite" for saturated and undersaturated (with respect to silica) basalts. Later, Dewey and Flatt (1911) noted the high soda content of pillow lavas associated with eugeosynclinal sediments, and they proposed a "spilitic suite" as a third major type of basalt. A controversy was born—is spilite a primary extrusive rock or an albitized basalt?

When Kennedy and Anderson reviewed the basalt problem in 1938, the geographical designations *Pacific* and *Atlantic* had proved misleading. Substitute terms *alkaline* and *calc-alkaline* were proposed. The latter is known by the now-popular name of "tholeiitic magma-type." The authors related the genesis of those two magma types to tectonisms: alkali basalts were found in stable ocean basins, whereas tholeiitic basalts and their derivatives were considered as volcanic products in orogenic belts. They found no place for spilite in their scheme; spilite was not a primary extrusive rock.

Kennedy and Anderson related the genesis of tholeiites to granitic crust, but Tilley (1950) corrected that mistake. Tholeiitic basalts are very common on the ocean floor. They have been dredged up from the ocean floor long before the start of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) Deep-Sea Drilling Project (Kuno, 1962). We now know that the mid-ocean ridge basalts (MORB) at active ocean-ridges are tholeiitic in composition, whereas alkali basalts are common on top of seamounts and guyots.

Spilites occur in the mountains and on ocean floor. They are basalts altered by albitization of feldspar. There are disputes as to whether spilites occurring in the mountains are albitized MORB basalts, or whether they are the alteration products of other kinds of extrusive rocks.

Miyashiro (1973) presented geochemical evidence that the Troodos ophiolite was the crust and mantle of a backarc basin. Could the chemistry of the Alpine spilites be related to their origin as a soda-rich basalt originated in a backarc basin? The studies of actualistic ocean basalts have yielded no satisfactory answer. James Hawkins (this volume, Chapter 14) believed, for example, that the ophiolite-tectonics could not be deciphered on the basis of geochemistry. We need independent lines of evidence to reconstruct the history of ophiolite emplacement.

One, Two, or More Oceans

As mentioned earlier, Steinmann and Suess voiced a consensus at the beginning of the twentieth century that alpine ophiolites were raised ocean floors. After much confusion during the next half century, the classic interpretation was accepted by all participants of the First Penrose Conference in Monterey, California (Dickinson, 1970). The conventional model of plate tectonics assumes the origin of mountains as a consequence of continental collision after the intervening ocean has been consumed. Because ophiolites are assumed to represent the remnants of fossil ocean floor, ophiolitic mélanges should mark suture zones; however, geological data are not always easily explained by such a simplistic model because more than one zone of ophiolites are present in numerous orogenic belts. Was there one, or were there two or more, oceans between the continents before their collisions?

The problem is not acute in the Western Alps. Paleogeographically, the Alpine ophiolites are mainly those of the Piedmont terrane in the South Penninic realm. Ultramafic rocks are also present in the Adula Nappe and other North Penninic units. Not much effort has been made to explain these two belts of ophiolites, except to assume a "geanticlinal," a *Zwischengebirge*, or a relic island-arc between the North and South Penninic Oceans.

The problem in the Dinarides (former Yugoslavia) and the Hellenides (Greece) is more controversial, and the debates are continuing. Steeply dipping ophiolites are present in the Vardar Zone, and a Vardar ocean is postulated between the Russian Platform and an eastern European passive margin, which was covered by shallow marine sequences of the Dinarides and Hellenides. Overthrust, apparently from east or northeast, onto the carbonate-platform deposits are ophiolite nappes. Do those ophiolites constitute rootless nappes derived from the floor of a small ocean in an archipelago of islands and basins? Or, are the ophiolites the klippen of a giant ophiolite-nappe from the Vardar Zone?

The same issue has divided the students of Anatolian geology. Are the Anatolian (northern Turkey) and the Antalya (southern Turkey) ophiolite mélanges the remnants of two different oceans, or are the Antalya nappes derived from the root zone of the Anatolian ophiolites farther to the north?

For two decades, I subscribed to the one-ocean postulation. Occam's razor favors a simpler solution, and one ocean represents a simpler mode than two or more oceans. I had to change my mind, however, when I went to northern Tibet in 1995.

The collision of Cathaysia (Mesozoic Cathaysia) and Tibet (Gondwanaland) brought two Jurassic limestones in a close juxtaposition north of Amdo on the Golmud-Lhasa Road. To the north is the Jurassic shallow limestone of the Qiangtang foreland basin of Cathaysia. To the south is the Jurassic pelagic limestone, occurring as exotic blocks in the Amdo Mélange. Aside from the Jurassic, other slabs include Lower Cretaceous pelagic limestone, radiolarian chert, as well as mafic and ultramafic rocks. The ophiolites are 75–80 m.y. old. The matrix of the mélange is made of Jurassic/Cretaceous hemipelagic and flysch sediments. The Amdo Mélange represents the accretionary complex dipping southward under a magmatic arc of Gondwanaland. The mélange crops out within the Nujiang/Bangong Zone, which marks a site of plate-collision. The contrast between the two Jurassic limestones of these two terranes is so obvious that our expedition group easily identified the spot when they drove from Cathaysia to Gondwanaland (Hsü and Chen, 1999, p.84).

There was the one ocean, but ophiolites dated at 85 to 95 Ma occur as exotic blocks in a Jurassic flysch matrix near Dongjiao, some 200 km south in Tibet. Adopting the single ocean hypothesis, the British expedition considered the Dongjiao ophiolites as the erosional remnant of a huge nappe from the root zone of the Bangong/Nujiang suture (Dewey et al., 1988), even though there is no evidence to support this audacious postulation. To the contrary, it is unlikely that the northward vergence of the Bangong/Nujiang collision could have propelled a giant ophiolite nappe nearly 200 km south (in the opposite direction).

The Dongjiao Mélange has a very limited extent. If the ophiolites are not a klippe of a large nappe, they could not be the floor of an intercontinental ocean either. The issue is no longer whether there were one or two oceans, but rather whether the Dongjiao ophiolites are fragments of a fossil oceanic crust that had evolved in a local deep-sea basin, such as a backarc basin.

Ophiolites as an Indicator of Backarc Collapsing

I first visited the Indonesian Archipelago in 1973, when I was appointed an External Examiner by the University of Malaysia. Instead of a cash-honorarium, I requested that I be taken on a field trip to see the local geology. Neville Haile knew of my interests in ophiolitic mélanges, so he arranged that I be taken to Sarawak.

The Lupa Valley Mélange of Sarawak consists of ophiolites, Mesozoic radiolarian cherts, and exotic blocks of Eocene coralline limestone. Haile and I drove from Kuching to Sibu, traversing the geological formations formed in the Oligocene/Miocene foreland basin. The ophiolite mélange extends from Lupar Valley near the western end of Sarawak, along the border region of Sarawak and Kalimantan, to Sabah, where massive ultramafic rocks are exposed. Although we could not ascertain the eastern and western continuations outside of the Island of Borneo, we did know of the ophiolite occurrences on the Islands of Anambas in South China Sea. Those might be correlative to the ophiolites of Thailand and Burma at one end and to those of the Philippines at the other end.

Assuming that ophiolite mélanges mark suture zones of inter-continent collisions, I had to postulate a paleo-Indian Ocean between South China and Sibumasu, which was assumed to have been split off from Gondwanaland. The Lupa Valley Mélange was thus considered a segment of that Southeast Asian (Donanya) suture zone. I did not think in 1973 that the mélange could represent the collapse of a local backarc basin.

My appointment in 1986 to the Tectonics Panel of JOIDES Ocean-Drilling Project broadened my horizon. I became a promoter of drilling South China Basin, and I got to know Ian Dalziel.

Marine geophysicists of the Kwangtung Regional Bureau of the Ministry of Geology in the People's Republic of China showed me their paleomagnetic and seismic results. They had submitted a proposal for drilling the continental margin and the abyssal basin of South China Sea, and I was asked to lobby for their cause.

The South China Sea is a backarc basin, floored by oceanic crust. The seafloor spreading, dated by seafloor magnetic lineation, continued during the time interval from the mid-Oligocene to mid-Miocene. Since then, the oceanic lithosphere of the eastern half of the basin has been subducted at the Philippine Trench, under the Philippine Islands. The initiation of the consumption of this basin floor via subduction was a manifestation of the collapse of the backarc basin.

Ian Dalziel was then the chairman of the JOIDES Tectonics Panel. He informed me that he had interpreted the process of backarc subduction as a "collapse of backarc basin" on the basis of his studies of the southern Andes Mountains (Dalziel, 1981). In this interpretation, the consumption of the backarc-basin ocean floor eventually leads to an arc-arc or an arc-continent collision. In the southern Andes, the eastern margin of the Pacific Ocean once had a frontal arc reminiscent of the Western Pacific. The backarc spreading started during the Jurassic, when extensive normal faulting and volcanism took place in the region behind that island arc, while the Pacific Plate was thrust under South America. Backarc basins, floored by oceanic crust, came into existence between this west-facing frontal arc and the South American continent. These basins thus had a tectonic framework similar to that of South China Sea. The Andean backarc basins were eliminated by arc-continent collisions. The suture zones of local collisions are marked by ophiolitic mélanges in the Andes. The ophiolites are present in a zone of penetrative deformation and metamorphism. East of the suture zones is the east-vergent foreland thrust belt of the Sub-Andean Foothills. Farther east are the foreland basins. In such an orogenic belt formed by backarc collapsing, the Patagonian batholith is the "motor," the ophiolite mélange and the mobilized basement are the "overridden," and the foreland thrust-belt and foreland basins are the "escape" structures in the model for Alpine Orogenesis formulated much earlier by F.E. Suess (1937).

Was There an Ocean?

I was among those who welcomed a delegation sent by China to the International Geological Congress in Sydney in 1976, and I was invited to visit China in 1977; so I made my return to the land of my birth 29 years after I had left for graduate school education in the United States.

I studied geology as an undergraduate student in China. Chinese geologists used the term North and South China Platforms, but the sedimentary formations on those platforms are not flat-lying like those on the North American platforms (or cratons). We took field trips to the vicinities of Chungking and Nanjing. We saw, and later mapped, anticlines and synclines. To contrast their tectonic style to the undeformed sedimentary rocks in North America, Chinese geologists chose the term "unstable platforms," or *diwa* (geodepressions).

I was given a geological atlas of China when I was a consultant for the Chinese government in 1979. Opening up the Hunan Sheet of the atlas volume, I was impressed by the tectonic style of the province. The structures are typical of foreland fold- and thrust-belt, analogous to those in the Appalachian Valley and Ridge province. There are also flysch formations and ophiolites. Without actually having a chance to do any fieldwork, I published at the request of Huang Jiqing, the Grand Old Man of Chinese geology, an essay speculating on a thin-skinned plate-tectonic model for collision type orogenesis (Hsü, 1981). Later I was invited by Sun Shu, Director of the Geological Institute, Chinese Academy of Sciences, to start a program to re-interpret the geology of China on the basis of the plate-tectonics theory. I spent the next 20 years doing that, with the help of Sun and his colleagues and students. We started out with an outrageous hypothesis and wrote *Huanan Alps, Not South China Platform* (Hsü, et al., 1987), and the final product was the new *Geological Atlas of China* (Hsü and Chen, 1999).

When I first started in 1983, I thought that the task would be easy. We expected to find an ophiolitic mélange marking the suture zones of plate-collisions, between the rigid-basement thrusts of the overriding continent and the foreland-deformed belts of the underthrust continent. We started in Qinling, the well-known mountain range between North and South China, and the model seemed to be applicable. Phyllites and schists constitute the matrix of an ophiolite-bearing mélange, traditionally considered as a Precambrian basement. The mélange is present in an east-west trending belt between the Archaean rigid basement to the north and the foreland folds to the south. The age of metamorphic rocks in the Qinling Mountains ranges from 500 Ma to 200 Ma. This scatter did not surprise us, because metamorphism should have taken place during subduction and collision in a time interval of a few hundred million years (Hsü et al. 1987).

The Qinling Mélange, we thought, was the remnant of an ocean separating North China from South China. Thus, crust of this ocean basin should be now represented by the Qilian and Kunlun Ophiolites in the west, and by Dabie and Jiaonan Ophiolites in the east. Our campaign thus seemed to have begun triumphantly, and we expected a quick ordering of the plates and plate-collisions by mapping and dating of ophiolites in China.

We faced a difficulty with our simplistic interpretation. Ophiolitic mélanges (Coaliangyi and Zhiyang Celtides; Fig. 1) are present in a terrane south of the foreland-deformed belts. We were thus encountering again the old dilemma of one versus two ocean basins. Choosing the ultra-nappist solution, we considered the southern ophiolites as the klippe remnants of a giant ophiolite nappe derived from a root-zone to the north (Hsü et al., 1987). It was not a very satisfactory interpretation.

Our simplistic interpretations became even less credulous when we began in 1985 to apply the collision model to interpret the geology of South China. We had to postulate the existence of two oceans in order to end up with two suture zones. (Hsü and Chen, 1999). Furthermore, the two inferred "ocean basins" separating the continental areas seemed to have a very limited geographical extent.

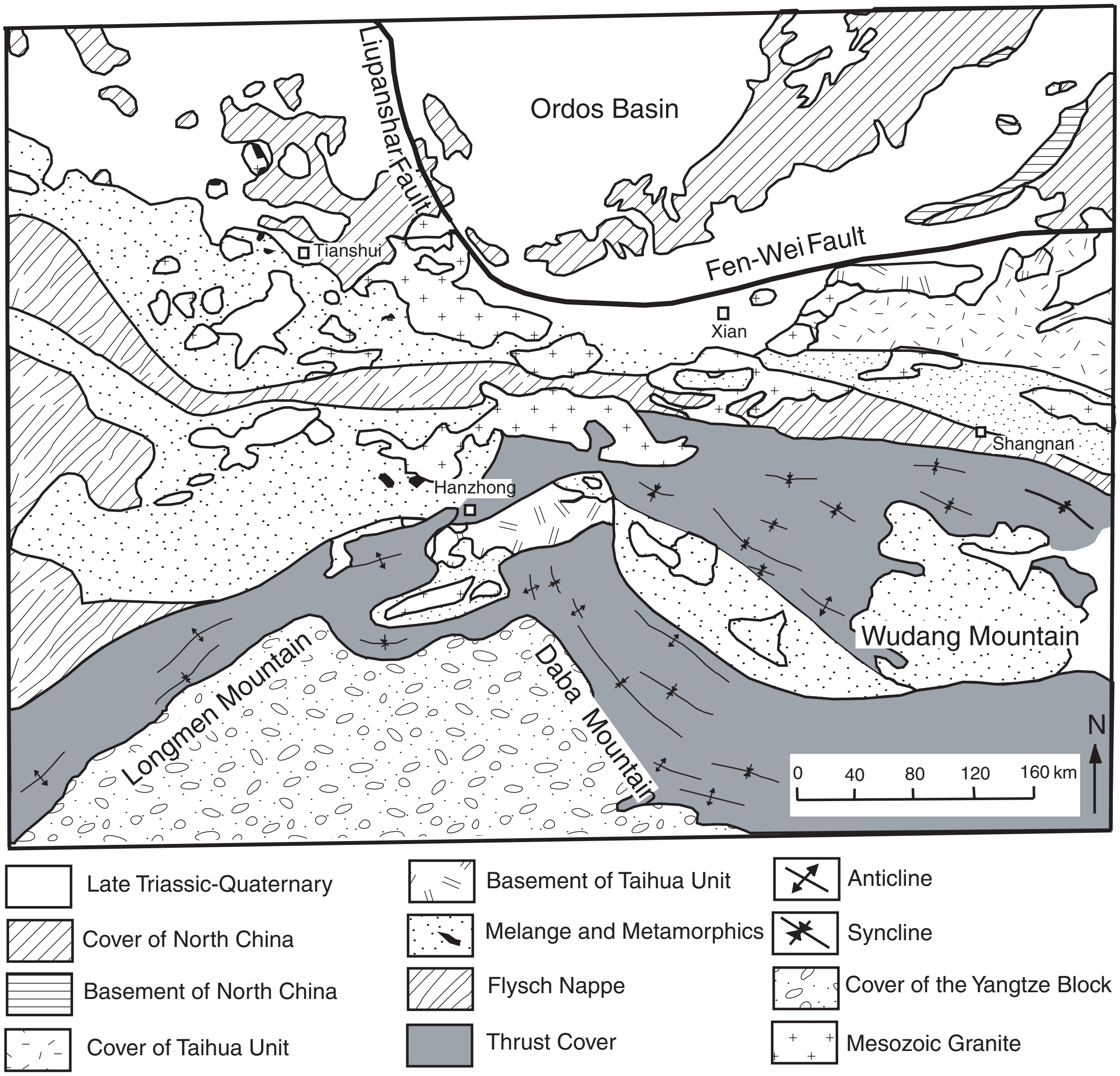

Figure 1. Tectonic facies units in Qinling Mountains, China (after Hsü and Chen, 1999).

The problem was compounded when we went to Inner Mongolia in 1988. We expected to find one suture zone between China and Siberia, as Li et al. (1982) had postulated. We found instead two belts of discontinuous outcrops of ophiolites (Ondorsom and Hegenshan Mélanges) in Inner Mongolia (Hsü et al., 1991). Şengör et al. (1993) postulated that the Hegenshan Mélange is a forearc-accretion complex on the trench wall of a subduction zone within an ocean basin separating China from Siberia (Unit C in Fig. 2). This interpretation was not consistent with our field observations: we had to suggest instead that the South Mongolia Mélange (Unit E in Fig. 2) represents the last remnant of the great Altaid Ocean (Hsü and Chen, 1999). What was the paleogeographic position of Hegenshan then?

The puzzle of multiple ophiolite belts is well known to Chinese geologists. One solution was to adhere to the simple "one ocean model," to resolve the problem through an assumption of the repeated opening (by seafloor spreading) and closing (by continental collision) of a differently positioned single ocean between the two continents. The *hypothesis of polycyclic deformations* advanced by Huang Jiqing contended, for example, that North and South Asia were pulled apart and pushed together again and again like the playing of a manual harmonium (Huang and Chen, 1987). He thus converted a spatial problem into a temporal problem: there was always only one ocean between the two continents, but the location of that ocean was different at different times. Huang and Chen (1987) applied this hypothesis to interpret the geology of Tianshan.

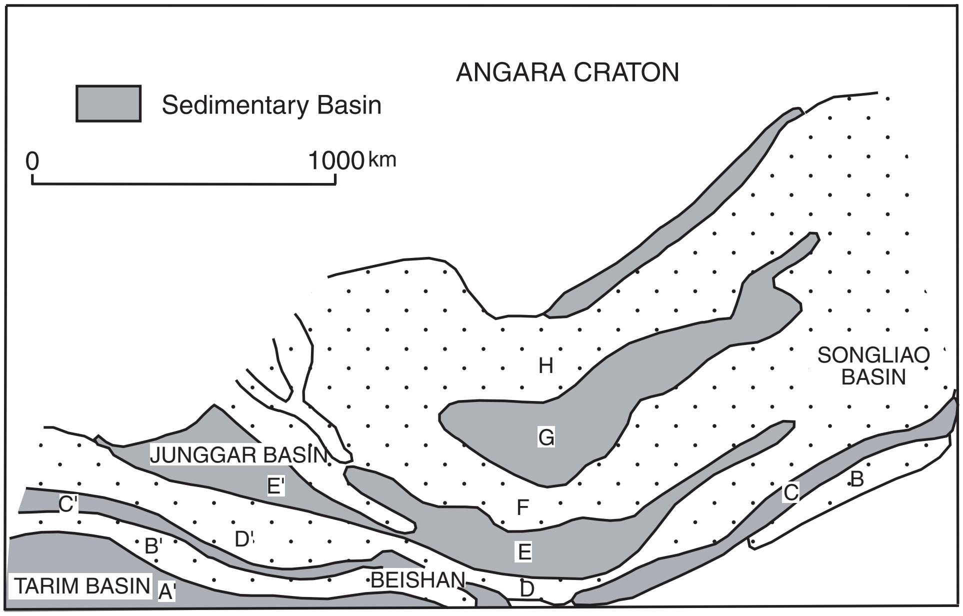

Figure 2. The tectonic facies distribution of Mongolia and the adjacent regions (after Hsü and Chen, 1999). A′—Tarim Basin; B—Sonidzuogi Rhaetide; B′—Kelpin/Kuruktag Rhaetide; C—Hegenshan Celtide; C′—South Tianshan Celtide; D—Uliasta Rhaetide; D′—Middle Tianshan Rhaetide; E—South Mongolia Celtide; E′—Junggar Basin; F—Southern Tuva Rhaeitde; G—Khanghai Celtide; H—Northern Tuva Rhaeitide.

In the company of my Chinese colleagues, I went on five expeditions across Tianshan and found that we could disprove Huang's hypothesis. Tianshan was not a "geosyncline" or an ocean between Junggar and Tarim Cratons. Tianshan was an island-arc complex between the Altaid Ocean and the Tarim Backarc-Basin. The Northern Tianshan Mélange was a forearc-accretion complex beneath a north-facing trench wall (Hsü et al., 1994). But there is still the Southern Tianshan Mélange (Fig. 3). Those ophiolites have a limited distribution and could not represent a great ocean basin. Comparing the geology of Tianshan to that of the Marianas, we came to the conclusion that there were several rows of backarc basins in Xinjiang. Between the Middle Tianshan Arc and the Kelpin Remnant Arc was a backarc basin (Fig. 3). The collapse of that backarc-basin and the subsequent arc-arc collision led to the genesis of the Southern Tianshan Mélange (Hsü et al., 1994).

"Holes in Cratons"

The sedimentary basins of the world can be grouped into three mutually exclusive and all-inclusive categories: (1) basins formed by crustal compression; (2) basins formed by crustal extension related to lithospheric stretching; and, (3) basins formed by crustal extension related to lateral movement of crustal blocks. I introduced this generic classification during an oral presentation in Xining (China) in 1985, and claimed that all basins could find their place in a pigeonhole of such a scheme. It was a rude awakening, however, when a young geologist of the Qinghai Provincial Geological Survey challenged my authority; he asked me to find a place for the Qaidam Basin of Qinghai in this classification.

Qaidam is situated near the northern edge of the Tibetan Plateau and has been considered as an "intermontane basin." The designation is literally correct, because the basin is bounded by the Kunlun Mountains to the south and by the Altun and Qilian Mountains to the north (Fig. 4). Whereas thick Neogene formations are present in pull-apart troughs along strike-slip faults, the older sediments of Qaidam were deposited in a basin underlain by thin crust.

The mountains surrounding Qaidam are not orographic features like those in the western United States, where the relief has resulted largely from normal faulting. The Qilian Mountains are underlain by deformed belts. Prior to orogenic deformations, the East Kunlun Mountains were an island arc, the Paleozoic frontal arc of the North China Plate. The Altun and Qilian Mountains were remnant arcs. Qaidam thus is not an intermontane basin as the term is commonly understood. The basin reminded me of the "holes in the ground" in the Russian Platform, such as the Caspian Sea and the Black Sea. I suspected then and my suspicion is now confirmed that very thick sediments in the so-called cratonic basins are deposited in backarc basins that became landlocked and were filled up (Hsü, 1988; Aplonov, et al., 1992).

Replying to the impertinent young man, I shot back and claimed that Qaidam was *a basin formed by crustal extension related to lithospheric stretching*. It started out as a Paleozoic backarc basin north of the East Kunlun Arc, and the stretching of the crust was caused by convection currents beneath the backarc region induced by the subduction of Prototethys under the frontal arc (Hsü and Chen, 1999, p. 62).

A similar basin between Kunlun and Tianshan is Tarim, with a size and shape comparable to the Sea of Japan. The deepest Tarim depressions are underlain by oceanic crust, the existence of which is manifested by seafloor lineations (Hsü, 1988). The Kunlun Mountains south of Tarim represent the western continuation of the East Kunlun Arc. The Southwest Tarim Depression was a

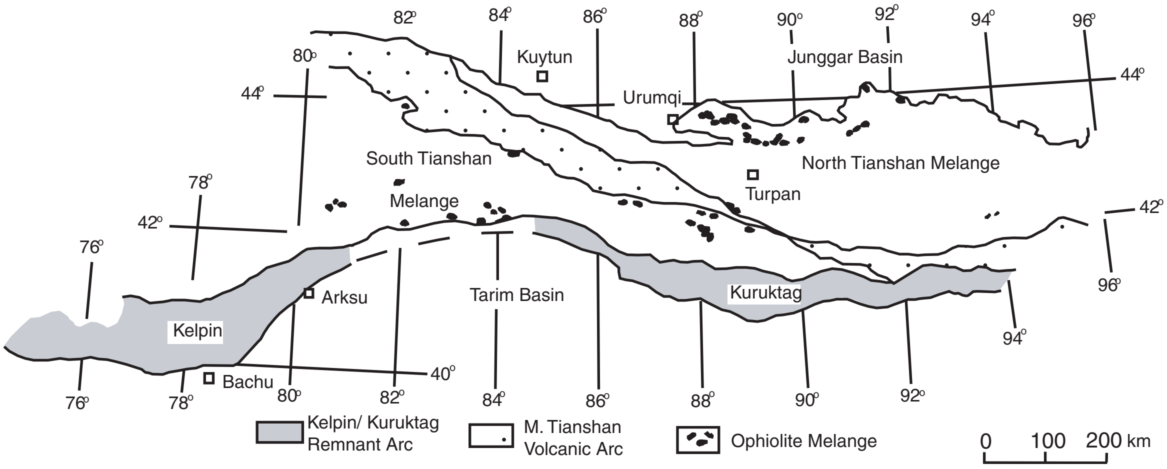

Figure 3. Tectonic facies units in Tianshan, China (after Yao and Hsü, 1994).

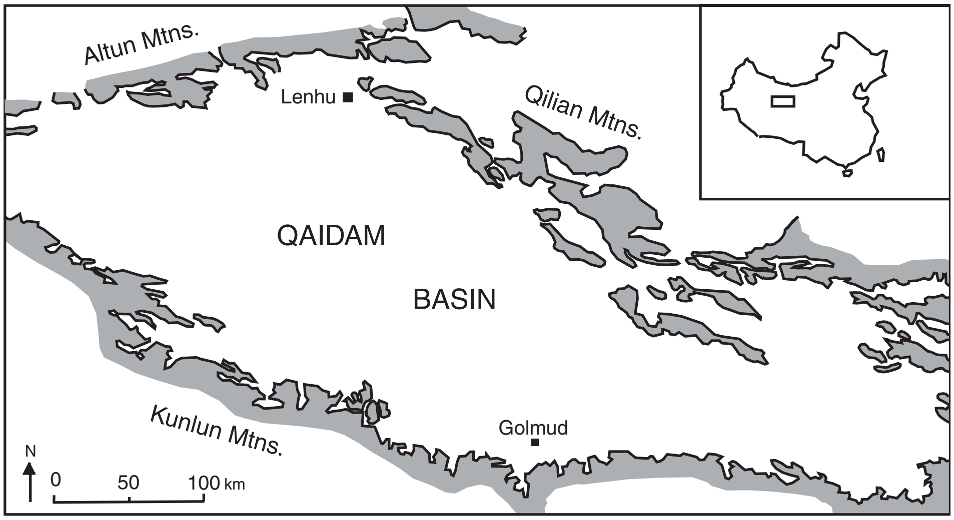

Figure 4. Qaidam Basin—a relic backarc basin surrounded by mountains, China (after Hsü, 1988).

backarc basin, and Northeast Tarim a relic backarc basin, and the two were separated by a remnant arc that is now the Central Tarim Ridge. The actualistic analogue for the Tarim backarc depressions and the Kunlun volcanic arc system can be found in the Philippine Sea region, where the Mariana Arc, Pala-Vela Basin, Kyushu-Palau Ridge, and West Philippine Basin can be considered as the modern analogues of the Kunlun volcanic arc, SW Tarim backarc basin, Central Tarim Ridge remnant arc, and the Northwest Tarim relic backarc basin, respectively (Fig. 5A, B).

The distribution of the frontal arcs, the relic arcs, and former backarc basins of Northwest China describes the paleogeography of an archipelago terrane. Not all former backarc basins have collapsed completely to form ophiolitic mélanges. The oceanic crust within Tarim and Qaidam, for example, has not been subducted completely, and the ocean floor subsided isostatically under the sedimentary load, resulting in the formation of those "holes in the craton."

Archipelago Model of Orogenesis

The first theory of the origin of mountains, the geosynclinal theory of James Hall, assumed crustal shortening of a cooling earth. The discovery of radioactive generation of heat permitted an alternative assumption of convection currents in Earth's mantle as a driving force for moving crust laterally. Wegener's theory of mountain building by collision of drifting continents was then modified into the modern plate-tectonics theory of continental collision. In classic theories, large-scale mountain building is

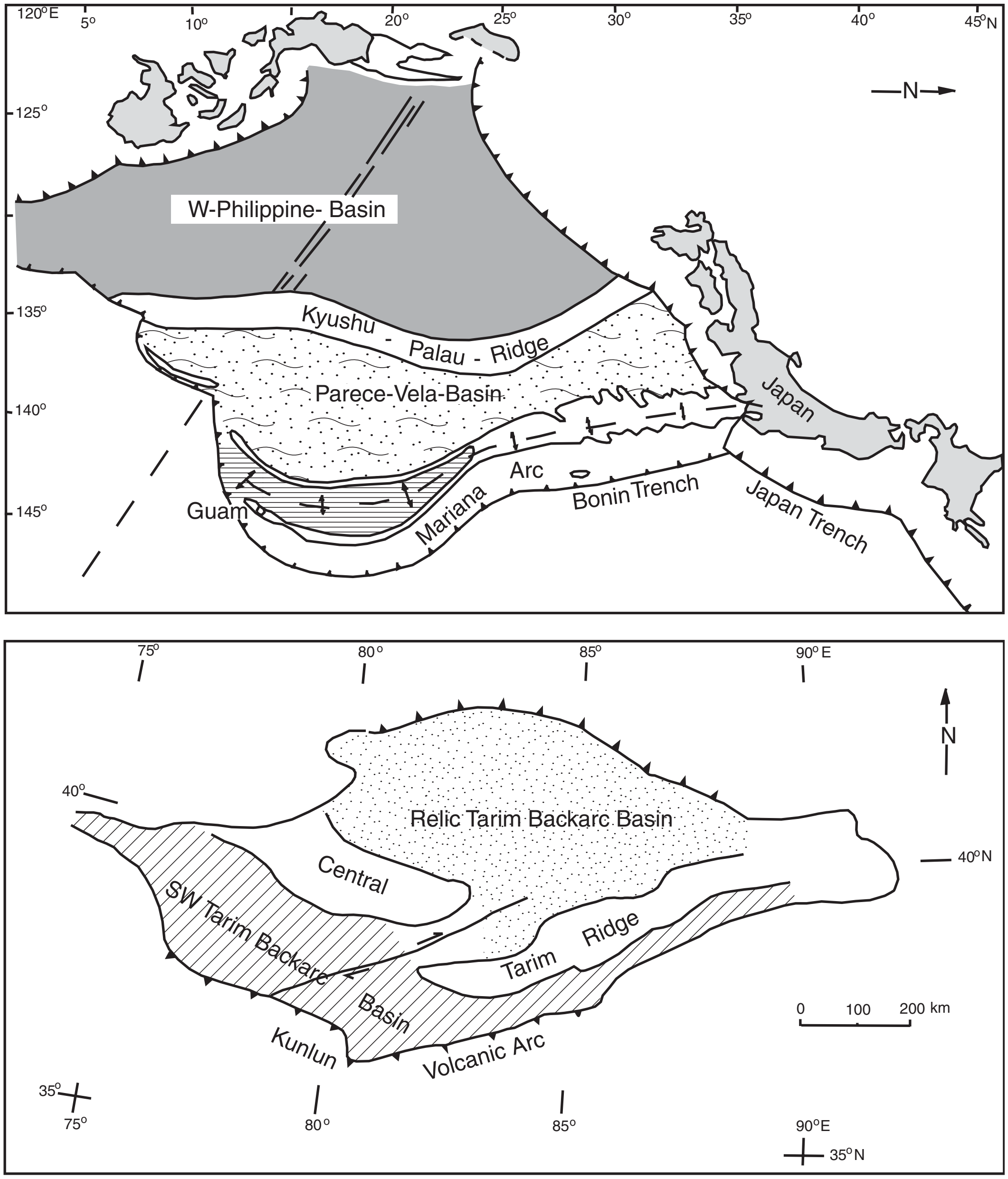

Figure 5. A: Backarc depressions of the Philippine Sea. B: Relic backarc depressions of Tarim, China. (after Hsü, 1988).

assumed to have occurred along a linear trend, although there has been controversy as to whether orogenesis is episodic and globally synchronous. As the plate tectonics theory has become the ruling paradigm, orogenic deformations are believed to have been continuous, and three types of orogenic systems have been recognized: (1) the California type, dominated by strike-slip faults; (2) the Andean type, dominated by the subduction of an oceanic lithosphere under a continental plate; and (3) the Alpine type, dominated by plate collision after the consumption of an intervening ocean basin.

When I started my project to produce a geologic atlas of China in 1983, I adopted the collision model to interpret what I considered the Alpine Type mountains in China. My experience in the Swiss Alps gave me a head start. I used Alpine terms Helvetic, Penninic, and Austroalpine to communicate with the young Chinese colleagues. I came eventually to the realization, however, that the Alpine terms are used not only to designate tectonic, but also paleogeographic units. The Helvetic and Austroalpine sedimentary sequences, mainly shallow marine, were "miogeosynclinal," laid down on European and North African margins (respectively). The Penninic were the sediments and ocean floor within the Tethyan Ocean.

The Alpine model, first proposed by Edward Suess and then refined by his son, F. Suess (1937), is a model of continental collision. Africa and Europe collided after the intervening ocean (Tethys) had been compressed together to form the Penninic Alps. The bounding continents have had different roles during this collisional orogeny. The Austroalpine nappes are thrust above the Penninic nappes, which in turn have overridden the Helvetic nappes.

Suess Junior pointed out that the three vital elements in orogenesis are: the motor, the overridden, and the escaped. Phrased in terms of the mechanics of collision between continental plates, the *motor* is represented by the overriding continental crust, and the *overridden* by the basement of underthrust continental crust and by a part of the consumed oceanic crust, whereas the *escaped* consists mainly of the sedimentary cover of the underthrust continental crust. In the Alps, the Austroalpine nappes are the motor, the Penninic the overridden, and the Helvetic the escaped.

After the adoption of the plate tectonics theory, the Alpine orogeny has been interpreted by two models of subduction: the B-type (honoring Benioff) subduction of the Tethys leading to the collision of Europe with Africa, and the A-type (honoring Amstutz) subduction of Europe beneath Africa. Substituting the Alpine paleogeographic terms by those denoting tectonic style of deformation, I proposed the names rhaetide, celtide, and alamanide to designate the three tectonic facies of the deformed rocks (Fig. 6): (1) the rhaetide facies, consisting mainly of the basement rocks of a continent crust, overthrusting onto (2) the celtide facies, consisting mainly of ophiolitic mélanges and mobilized and underthrust crust, overthrusting onto (3) the alamanide facies, consisting of thin-skinned deformation of décollement overthrusts, flysch, and molasse deposits.

The rhaetide and alamanide rocks could be the basement and the sedimentary cover of a continental margin, or of an island arc (active or remnant). The celtide rocks include those of deep-sea deposits and ocean crust.

The Helvetic and the Austroalpine sequences were the deposits of the European and African continental margins, respectively. They occupied different paleogeographic locations, but both the Helvetic and Austroalpine sedimentary sequences have been deformed to form structures of the alamanide facies. The Helvetic nappes are those of a foreland thrust belt, and the Austroalpine sedimentary rocks (e.g., the Lower Austroalpine nappes) have been deformed by décollement between underthrusting (Err-Bernina) and overthrusting (Silvretta) Austroalpine basement-nappes.

The simple single ocean model of continental collision has always been a problem, because of the presence of deformed shallow marine sequences in the Penninic realm that are represented by the Briançonnais and Schams nappes. Sandwiched between the ophiolites of the North Penninic (Valais) and South Penninic (Piedmont) nappes, those alamanide-facies rocks were supposed to have been the sedimentary cover of islands or a chain of islands in the Tethyan Ocean. Those were then detached from the underlying granitic basement and thrust northward during the Tertiary deformation. Such an oversimplified explanation has created, however, a paradox because the Schams sequences have a southerly vergence, indicating that they have been overthrust from north to south, not from south to north.

The solution of the so-called Schams paradox turns out to be very simple, after it is discovered that the Schams sequences were deformed during the Cretaceous (Hsü, 1994). The shallow marine sedimentary rocks of Schams were the sedimentary cover of a remnant arc, and the seafloor deepened to the north to form a backarc basin, alias "Valais Geosyncline." That basin was separated from a South Helvetic Flysch basin by the Habkern volcanic arc. The ocean floor of this Valais backarc basin was subducted under the Habkern arc. A Cretaceous/Paleocene

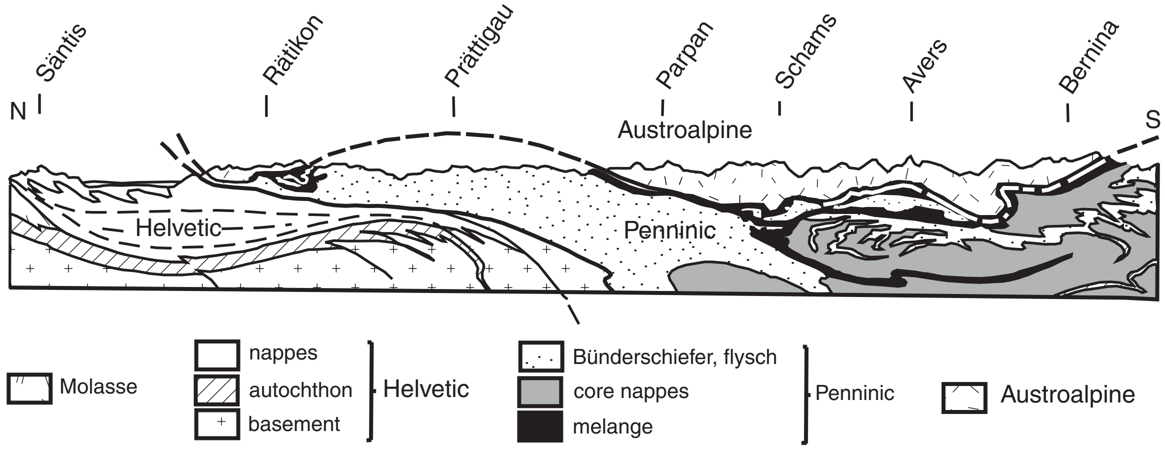

Figure 6. Tectonic facies units in the Alps, Switzerland (after Hsü, 1995). Tectonic units of the Alps, Helvetic, Penninic, and Austroalpine are designated by their paleogeographic framework. Those units have a tectonic style typical of the Alamanide, Celtide, and Rhaetide tectonic facies, respectively.

Gurnigel Flysch was deposited in a trench setting south of the arc (Fig. 7). In the back-arc basin north of the arc, the Schlieren Flysch deposits were laid down (Hsü and Schlanger, 1971). The arc volcanism of the Cretaceous subduction is evidenced by the volcanic debris in the Gurnigel and Schlieren Flysch.

The forearc basement of Habkern Arc has been metamorphosed to form the metamorphic rocks of the Adula Nappe, which is considered lower Penninic in the classic Alpine literature. Through the dating of Alpine metamorphic rocks, this Cretaceous belt of forearc metamorphism has been traced to the French Alps, to Corsica, to offshore Sardinia, and to Calabria. The north-dipping Benioff zone of the Cretaceous subduction in Switzerland has been detected by the seismic crustal studies (Frei et al., 1989).

The continental margin (Helvetic) of Europe could not have been a plate boundary, nor could the axis of the Tethyan seafloor spreading have been the southern plate margin. The northern ocean margin of Africa must have been subducted under an active margin. The European Plate margin (Cretan and Calabrian Arcs) has indeed been an island-arc margin since the middle Miocene. The topography and the magnetic anomalies indicate that the older active margin is now buried under the sediments of the Mediterranean Ridge (Hsü, 1994). Interpreted within such a paleogeographic framework, the Alpine Tethys included one or more backarc basins (Penninic, or Valais and Piedmont) beyond the European passive continental margin (Helvetic). In this configuration of an archipelago, Italy was not a passive margin on a North African promontory, but a remnant arc of carbonate sedimentation.

Adopting the archipelago model of orogenesis, I proposed that the Alpine structures were first formed as a consequence of a backarc basin collapse during the Cretaceous-early Tertiary, when the North Penninic (Valais) backarc basin was subducted down a north-dipping Benioff Zone under the Habkern Arc. Meanwhile, the South Penninic (Piedmont) floor was consumed down a south-dipping subduction zone under the Austroalpine (Italy) remnant arc. The collapse of the South Penninic basin caused a continent-arc collision between Europe and Italy. The recognition of southern Europe as a Mesozoic and Cenozoic archipelago behind an active margin of island arcs refutes the classic concept that the Alps owed their origin to the collision of two passive continental margins.

The pre-middle Miocene European plate-margin extended eastward from the Mediterranean Ridge to Florence Rise and Cyprus (Fig. 8). The ocean floor of the African Plate has been subducting beneath that arc, and the last remnant of the Tethyan Ocean between Europe and Africa is the Levantine Sea. The Permian age of the eastern Mediterranean ocean floor is indicated by a negatively magnetized quiet zone, and by the Permian and younger passive margin sequences in Levantine and Egypt. The forearc trench sediments are now covered by the sediments of Herodotus Abyssal Plain. A tectonic mélange is present under Cyprus, and ophiolitic rocks have been dredged up from the steep escarpment south of the island. A north-dipping, pre-middle Miocene subduction zone has been detected by seismic tomographic images. The European plate margin did not shift to its present position along the Cretan Arc until the late Miocene.

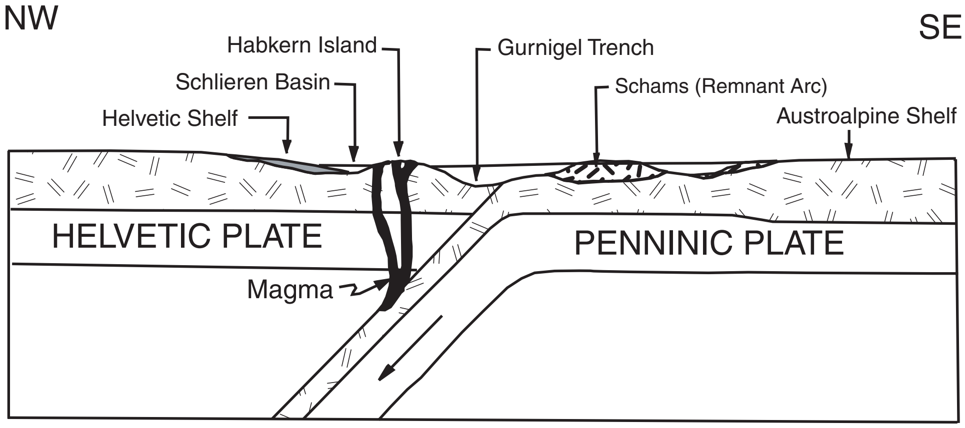

Figure 7. Plate tectonic model of Flysch deformation (after Hsü and Schlanger, 1971). The Late Cretaceous/Paleocene paleogeography of flysch sedimentation suggested to Hsü and Schlanger the presence of a magmatic arc on the southern margin of Europe. This arc was a south-facing feature bounded by a north-dipping subduction zone, which consumed the Northern Penninic backarc basin floor. The presence of volcanic debris in the flysch indicates arc volcanism during its formation. Regional tectonic considerations suggest that the Habkern arc was not the frontal arc of the European plate. The Cretaceous island arc margin of the plate had lain far to the south, and is now buried under the Mediterranean Ridge.

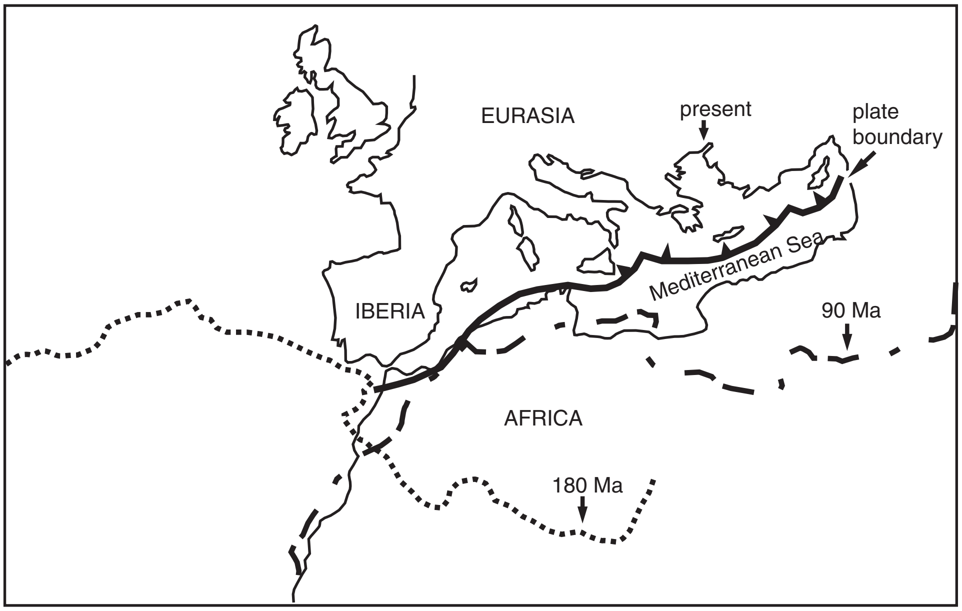

Figure 8. Plate tectonic evolution of the Alpine Mediterranean region. The southern margin of the European plate is a magmatic arc, now buried under the Mediterranean Ridge. On the basis of the data provided by magnetic lineations of the Atlantic Ocean, the African plate was found to have first moved eastward from 180 to 90 Ma, and to have rotated counterclockwise since then. Subduction of the lithospheric plate under the Paleotethys during the Mesozoic caused the change from an Andean type to an island-arc type of European margin. Subduction of the plate caused the consumption of the Paleotethys. The ocean basin south of the Mediterranean is the last remnant of the once vast Paleotethys ocean.

Franciscan Mélanges in Archipelago Model of Orogenesis

I obtained this new understanding of the Alps only after I had found that the numerous ophiolite belts of China are not suture zones of continental collisions; they are the collapsed ocean floors and sediments of former backarc basins. My tenure at ETH-Zurich was coming to an end. The model of archipelago orogenesis was formulated, but I had little chance to discuss its applications with colleagues before and after my retirement. The idea was to fade into oblivion, when the editor of this volume Yildirim Dilek asked me to contribute this article and urged me to expound my new hypothesis.

Having been encouraged to speculate, I returned to contemplate again the Franciscan-Knoxville paradox of the California Coast Ranges. I used to consider the Franciscan ophiolites as fragments of subducted crust and mantle under the Pacific Ocean. I felt uneasy with that interpretation because no remnants of the Cenozoic Pacific ocean floor have ever been found in the Franciscan. Even though all of the Mesozoic and much of the Cenozoic Pacific ocean floor east of the East Pacific Rise have been subducted under western North America, all datable Franciscan rocks are Jurassic and Cretaceous in age. There were many other problems that puzzled me when I left California for Europe: What is the structural relation of the Cretaceous broken formations to the ophiolite mélanges in the Franciscan? What is the relation of the Coastal Franciscan to the Coast Range Batholith? What is the relation of the Batholith to the Diablo Range and the Northern Franciscan? What is the relation of those mélanges to the Great Valley Sequence? What is the relation of the Franciscan/Great Valley to the Sierra Nevada Mountains?

I thought of western North America again when I wrote the chapter on Global Tectonic Facies in my introduction to tectonic facies concept (Hsü, 1995). Paleogeographic reconstructions leave little doubt that the ancient passive margin of the North American Continent could be defined by the deformed Paleozoic and Mesozoic sequences in the Foreland Thrust Belt of the Western Interior and in the Rocky Mountain region. The margin of the North American Plate was a magmatic arc active in the Sierra Nevada region during the Triassic and Jurassic, but was shifted to a position west of the Coast Range Franciscan in the late Mesozoic and Cenozoic. Considering the Continental Borderland offshore southern California as a submerged archipelago, the past magmatic margin is now buried. The topographic expression of the forearc margin should thus be the Patton Escarpment bounding the Borderland.

Adopting archipelago model of orogenesis, I propose to interpret the greenschists and ophiolites in the Mojave Desert and in the Sierra Nevada as the relics of collapsed Mesozoic backarc basins; those basins were located behind an active arc rooted in the plutonic rocks of the Sierra Nevada. The arc ceased to be active in the Cretaceous, when the active plate-margin was shifted westward. The eroded western slope of the Sierra Nevada Mountains became the site of a passive continental margin, on which the Great Valley Sequence was laid down. Farther to the west, the seafloor deepened and a basin underlain by oceanic crust evolved as a backarc basin behind an inland arc, the root of which is composed of the Coast Range Batholiths. The Cretaceous sedimentary rocks that exist in the basin are now present as exotic blocks or broken formations in the Franciscan Mélange. The island arc west of that basin was capped by the Cretaceous Calera Limestone and the associated volcanics.

In such a scheme, the Great Valley Sequence, representing the sediments of the foreland-basin, constitutes an Alamanide facies. The mélanges of the Northern Franciscan and the Diablo Range are the Celtides, which are bounded now by the San Andreas Fault of Cenozoic origin. Prior to the faulting, the Franciscan should have been separated by thrust faults from the Coast Range Batholith and its northern extension on the west side of the San Andreas Fault. The Cretaceous arc volcanism, related to this backarc subduction, was rooted in the Coast Range Batholith. The batholith should thus have been a Rhaetide in the archipelago model of orogenesis. In such an interpretation, the Franciscan/Great Valley deformation is analogous to that in the Southern Andes, where a back-arc basin floor has been subducted down a west-dipping Benioff Zone under the Andean Batholith.

The Southern Franciscan sediments of the California Coast Range were laid down in a more distant offshore backarc basin. The Jurassic Point Sal Ophiolite represents a relic of the ocean floor of that basin. Other ophiolitic rocks are present as exotic blocks in the Franciscan Mélange, which constitutes a celtide. Since no extensive shallow marine sediments were laid down in a narrow strip of the remnant arc, a foreland thrust belt does not exist. The Upper Cretaceous molasse of the Gabilan Range are the foreland-basin alamanide. Such a configuration of alamanide-celtide in the Southern Coast Ranges suggests that the offshore Channel Islands and the Transverse Ranges should have been the Rhaetide, under which the Southern Franciscan was subducted.

Are There Ophiolites at Suture Zones of Plate Collisions?

Ophiolites are not uncommon in active plate margins. Tertiary ophiolites, for example, are present along the Washington coast, where the Pacific Ocean floor is subducted under North America; they should represent a small remnant of the subducted Pacific Ocean floor. A late Mesozoic ophiolitic mélange has been sampled by dredging of the escarpment of the Mariana Trench; that ophiolite was also a remnant of the Pacific Ocean floor.

Are ophiolites common in suture zones? A few years ago, I made a survey of global tectonic facies, including those in the Alps, Appalachians, Scandinavian and British Caledonides, China, and North and South Americas, and I found that the ophiolites occurring in the mélanges within these orogenic belts were all made of the ocean floor of former backarc basins.

One notable exception could be the Zhanbo Ophiolites, commonly considered as a suture mélange developed during the collision of Tibet and India. After nine expeditions to the Tibetan Plateau, I presented my reason in *The Geologic Atlas of China* (Hsü and Chen 1999) as to why that suture zone cannot be represented by the Zhanbo ophiolites. According to the archipelago model, the former plate margin of Tibet is underlain by the metamorphic rocks of the Central Gneiss Zone on the southern slope of the Himalayas. The Zhanbo rocks constituted the ocean floor and deep-sea sediments of two backarc basins behind the Himalayan arc, which has been and is the southern boundary of the Eurasian Plate. The rocks formed by forearc accretion were metamorphosed subsequently to form the Central Gneiss Zone. After the collision of India with Eurasia, the rigid basement of the Frontal Arc Rhaetide and the Central Gneiss Celtide rose to become the Himalayan Mountains. The two collapsed backarc basins have left relics in the two ophiolite zones along the Zhanbo River Valley. The alamanides are the foreland thrust belt and the Siwalik Foreland Basin at the foot of that great mountain range (Hsü and Chen, 1999). The line of demarcation between the Eurasian and Indian plate lies buried under the Cenozoic foreland basin deposits of the Himalayas.

The Himalayan arc extends westward to the Karakorum. On an expedition to the Karakorum in 1999, we drove across a belt of mafic and ultramafic rocks (celtide) between the plutonic complex of the Karakorum (rhaetide) and the foreland fold belt of the Salt Range (alamanide). Those metamorphosed ophiolites could represent the crustal and upper mantle rocks of the Neotethyan Ocean, which separated Cathaysia from India. Farther to the west is the Bagh Celtide in the Muslim Bagh district of Pakistan, where the mélange consists of exotic blocks of ophiolites, radiolarites, and limestones in a shale matrix (Koima et al., 1994). These Neotethyan rocks crop out in the suture zone, because they have been spared from getting subducted to great depths (Hsü and Chen, 1999, p. 91).

In conclusion, I might say that I have learned a lesson after 20 years of fieldwork in China. I now think that ophiolites mostly represent the crustal and upper mantle rocks beneath the floor of former backarc basins; ophiolites are rarely present at suture zones where plates collide.

CONCLUSION

Famous Last Words

When I retired from ETH-Zurich in 1994, I planned not to do any more geology, so as to leave the field to the young people. I did not keep my promise, and the coda, like the one in Beethoven's symphonies, never ends. I thought I had sung my swan song when I completed the Geologic Atlas of China, but Yildirim Dilek urged me to make this contribution. Having given up my library and subscriptions upon my retirement, I have not been current for almost a decade. I do hope that my readers excuse me if I have not included a citation of their new discoveries or their new insights. In writing this article I summarized some personal experiences, but I could not claim to have presented any new idea. I have attempted to raise some new questions about the origin of ophiolites in association with the evolution of orogenic belts, and I do hope that new progress will be made when my hypotheses are put to test.

REFERENCES CITED

Aplonov, S., Hsü, K.J., and Ustritsky, V., 1992, Relic back-arc basins of Eurasia and their hydrocarbon potentials: The Island Arc, v. 1, p. 71–77.

Argand, E., 1916, Sur l'Arc des Alpes Occidentales: Eclogae Geologicae Helvetiae, v. 14, p. 145–191.

Argand, E., 1922, La Tectonique de l'Asie: Compte Rendu, Congrès Géologique International, 13th, Bruxelles, p. 171–372.

Becke, F., 1903, Die Eruptivgesteine der böhmischen Mittelgebirge und der amerikanischen Anden: Tschermaks Mineralogische und Petrographische Mitteilungen , v. 22, p. 209 ff.

Beloussov, V.V., 1962, Basic Problems in Geosciences: New York, McGraw-Hill, 820 p.

Bucher, W., 1933, The Deformation of the Earth's Crust: Princeton, Princeton University Press, 518 p.

Dalziel, I., 1981, Back-arc extension in the southern Andes: A review and critical appraisal: Philosophical Transactions of the Royal Society of London, ser. A, v. 300, p. 319–335.

Dewey, H., and Flett, J.S., 1911, On some British pillow-lavas and the rocks associated with them: Geological Magazine, Decade 5, v. 8, p. 202–209, 241–248.

Dewey, J., 1969, Evolution of the Appalachian/Calledonian Orogen: Nature, v. 222, p. 124–129.

Dewey, J., Shackleton, R.M., Chang, C., and Sun, Y., 1988, The tectonic evolution of the Tibetan Plateau: Philosophical Transactions of the Royal Society of London, ser. A, v. 327, p. 379–413.

Dickinson, W.R., 1970, Second Penrose Conference: The New Global Tectonics: Geotimes, v. 15, p. 18–22.

Dilek, Y., 1998, Structure and tectonics of intermediate-spread oceanic crust drilled at DSDP/ODP Sites 504B-896A, Costa Rica Rift: *in* Cramp, A., McLeod, C.J., Lee, S.V., and Jones, E.J.W., eds., Geological Evolution of Ocean Basins: Results from the Ocean Drilling Program: London, Geological Society of London Special Publication 131, p. 179–197.

Frei, W., Heitzmann, P., Lehner, P., and Vlasek, P., 1989, Die drei Alpentraversen von NFP 20: Bull. Verein Schweizersche Petroleum Geology und Inginier, v. 55, p. 13–43.

Harker, A. 1896, The Natural History of Igneous Rocks. I: Their geographical and chronological distribution: Science Progress, v. 6.

Hsü, K.J., 1958, Isostasy and a theory for the origin of geosynclines: American Journal of Science, v. 256. p. 305–327.

Hsü, K.J., 1971, Fransciscan mélanges as a model for eugeosynclinal sedimentation and underthrusting tectonics: Journal of Geophysical Research, v. 76, p. 1162–1170.

Hsü, K.J., 1981, Thin-skinned plate-tectonics model for collision type orogenesis: Scientia Sinica, v. 24, p. 100–110.

Hsü, K.J., 1988, Relic backarc basins: *in* Kleispehn, K.L., and Paola, C., eds., New Perspectives in Basin Analysis: New York, Springer Verlag, p. 246–263.

Hsü, K.J., 1994, The Geology of Switzerland: Princeton, Princeton University Press, 250 p.

Hsü, K.J., 1995, Tectonic facies in an archipelago model of intra-plate orogenesis: GSA Today, v. 4, p. 289–290.

Hsü, K.J., and Chen H., 1999, Geologic Atlas of China: Amsterdam, Elsevier, 262 p.

Hsü, K.J., and Ryan, W.B.F., 1971, Implications concerning ocean-floor genesis and destruction from deep-sea drilling in the Mediterranean Sea and eastern Atlantic Ocean: Proceedings, of the International Union of Geodesy and Geophysics, General Assembly, 15th: Moscow, sec. 1, p. 44.

Hsü, K.J., and Schlanger, S.O., 1971, Ultrahelvetic Flysch sedimentation and deformation related to plate tectonics: Geological Society of America Bulletin, v. 82, p. 1207–1218.

Hsü, K.J., Wang Qingchen, Li, J., Zhou, D., and Sun S., 1987, Tectonic evolution of the Qinling Mountains: Eclogae Geologicae Helvetiae, v. 80, p. 735–752.

Hsü, K.J., Wang Qingchen, Li, J., and Hao, J., 1991, Geologic evolution of the Neimonides: Eclogae Geologicae Helvetiae, v. 85, p. 213–225.

Hsü, K.J., Yao Y., Hao, J., Li, J., and Wang, Q., 1994, Origin of Chinese Tianshan by arc-arc collisions: Eclogae Geologicae Helvetiae, v. 87, p. 265.292.

Huang Jiqing and Chen, B., 1987, The Evolution of the Tethys in China and Adjacent regions: Beijing, Geological Publishing House, 109 p.

Kennedy, W.Q., and Anderson, E.M., 1938, Crustal layers and the origin of magmas: Bulletin Volcànologique, ser. II, v. 3, p. 24–82.

Kojima, S., Naka, T., Kimura, K., Mengel, J.M., Siddiqui, M.R.H., and Bakht, M.S., 1994, Mesozoic radiolarians from the Bagh Complex in the Muslim Bagh area, Pakistan; their significance in reconstructing the geologic history of ophiolites along the Neo-Tethys suture zone: Bulletin of the Geological Survey of Japan, v. 45, p. 63–97.

Kuno, H., 1962, Frequency distribution of rock types in oceanic, orogenic and cratogenic volcanic associations, *in* MacDonald, G.A., and Kuno, H., eds., The Crust of the Pacific Basin: Washington, D.C., American Geophysical Union Monograph Series 6, p. 135–139.

Li, C.Y., Wang, C., Liu, X.I., and Tang, Y.Q., 1982, Tectonic map of Asia: Beijing, Geological Publishing House.

Miyashiro, A., 1973, The Troodos Complex was probably formed in an island arc: Earth and Planetary Science Letters, v. 25, p. 217–222.

Moores, E.M., 1982, Origin and emplacement of ophiolites: Reviews of Geophysics, Space Physics, v. 20, p. 735–760.

Scheumann, K.H., 1932, Über die petrogenetische Abteilung des roten Erzgebirgsgneisses: Mineralogische und Petrographische Mitteilungen, v. 42, p. 423–426.

Şengör, A.M.C., Natal'in, B.A., and Burtman, V.S., 1993, Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia: Nature, v. 364, p. 299–304.

Staub, R., 1928, Der Bewegungsmechanisms der Erde: Berlin, Borntraeger, 270 p.

Steinmann, G., 1905, Die geologische Bedeutung der Tiefseeabsätze und der ophiolitischen Massengesteine: Bericht naturforschenden Gesellschaft: Freiburg, v. 16, p. 44–65.

Stille, H, 1924, Grundfragen der vergleichenden Tektonik: Berlin, Borntraeger, 413 p.

Suess, E., 1909, Das Antlitz der Erde: Leipzig, Freytag, v. 3, 789 p.

Suess, F., 1937, Baustein zur einer Snhese Tektogenese: Fortschritt Geologie u. Paläontologie, v. 13, p. 1–86.

Tilley, C.E., 1950, Some aspects of magmatic evolution: Quarterly Journal of the Geological Society of London, v. 106, p. 37–61.

Trümpy, R., 1960, Paleotectonic evolution of the central and western Alps: Geological Society of America Bulletin, v. 71, p. 843–908.

von Bubnoff, S., 1937, Gebirgesgrund und Grundgebirge: Naturwissenschaften, v. 25, p. 577–588, p. 593–598.

Yao, Y., and Hsü, K.J., 1994, Origin of Kuenen Mountains by arc-arc and arc-continent collisions: The Island Arc, v. 3, p. 75–89.

Manuscript Accepted by the Society May 2, 2003

Printed in the USA