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Project Targets Mantle Dynamics and Tethyan Hazard Mitigation

More than half of the Earth's population lives within the confines of the Tethyan tectonic collision belt (Figure 1), a high-risk zone that contains at least 20 of the world's "mega-cities." During the 20th century alone, collision-related seismicity and explosive volcanism (Figure 2) caused over a million deaths and catastrophic economic losses in this region.

Destructive volcanism results mostly from the eruption of viscous, volatile-rich magma generated near converging or colliding plate margins, while the most damaging earthquakes are produced by post-collision tectonic thrusting and strike-slip faulting. An exploratory program has been initiated to coordinate research in the Tethyan region, appraise the role of collision-related mantle-dynamics in seismicity and volcanism, and assess their potential significance in mitigating seismic and volcanic hazards across the entire Tethyan belt.

Program Addresses Tethyan Hazards

International Geological Correlation Project (IGCP) 430, cosponsored by the United Nations Education, Science, and Cultural Organization (UNESCO) and the International Union of Geosciences (IUGS), is addressing mantle-lithosphere interactions associated with Tethyan plate collisions. IGCP 430 is coordinating multidisciplinary research in two Tethyan natural laboratories to evaluate the role of collision-related mantle flow fields in determining geologic hazard scenarios.

Vigorous, multidisciplinary research will help us better understand the physical, chemical, and geologic factors that characterize Tethyan hazard scenarios. The project could dramatically improve our ability to develop predictive models by exploiting the use of super-computers, knowledge-based systems, and large-scale physical monitoring, along with conventional seismologic and geologic methods. Input of collision-related criteria from natural lab studies into hazard scenarios will be used to rank regional risk inventories in GIS/map-form, and results will be disseminated through relevant national and international channels.

The project's two natural laboratories are referred to as PANCARDI (the Pannonian basin and Carpathian and Dinaride orogens, in eastern and southeastern Europe) and SEA-WPAC (southeast Asia and western Pacific marginal basins) (Figures 3 and 4). Each is the subject of strongly funded, multidisciplinary studies. By integrating results from these studies and initiating new research, IGCP 430 will assess the implications of mantle dynamic responses to continental plate collisions.

Tethyan Closure

Post-Mesozoic closure of neo-Tethys involved diachronous collision of the African, Arabian, and Indian plates with Eurasia and, more recently, between Australia and Indonesia. While western Tethyan collisions are more or less complete, the Indian and Australian indentors continue their northward motions, producing diverse—and controversial—tectonic responses. Evidence from a number of sources has emerged to support the notion that the plastic asthenosphere is strongly affected during progressive stages of plate convergence.

Typical pre-collision effects, evident in the Mediterranean and parts of the western Pacific, include the subduction of oceanic lithosphere, back-arc basin opening, and volcanic arc rollback. These processes imply variable mantle flow scales between and beneath the converging plate—the paradox of oceanic lithosphere extension in compressive, pre-collision settings—characterizing the first of several continental accretion stages. This unusual pairing of petrologic, thermal, and tectonic factors provides the conditions necessary for the generation of ophiolite assemblages, which are subsequently entrapped in orogenic sutures by the succeeding collision of converging plates.

"Hard" plate collisions have been dynamically connected with two types of lithospheric response. The first type is the escape or extrusion of continental blocks such as Indochina and Anatolia, which is enabled by continent-scale strike-slip faults [e.g., *Molnar and Tapponnier*, 1975] exemplified by the Insubric Line in Europe, the North and East Anatolian faults, and the Altyn Tagh and Ailao Shan-Red River faults in east and southeast Asia. The second response is crustal thickening and shortening, which is accompanied by massive thrust faulting and rapid uplift of features such as the Tibetan plateau [*Houseman et al.*, 1981]. Neither of these models invokes mantle driving forces, however, and both assume that lithosphere motions are independent of the latter.

Collision-related volcanic activity shows a progression from pre-collision calcalkaline to post-collision ultrapotassic and basaltic products, which presumably reflects changes in

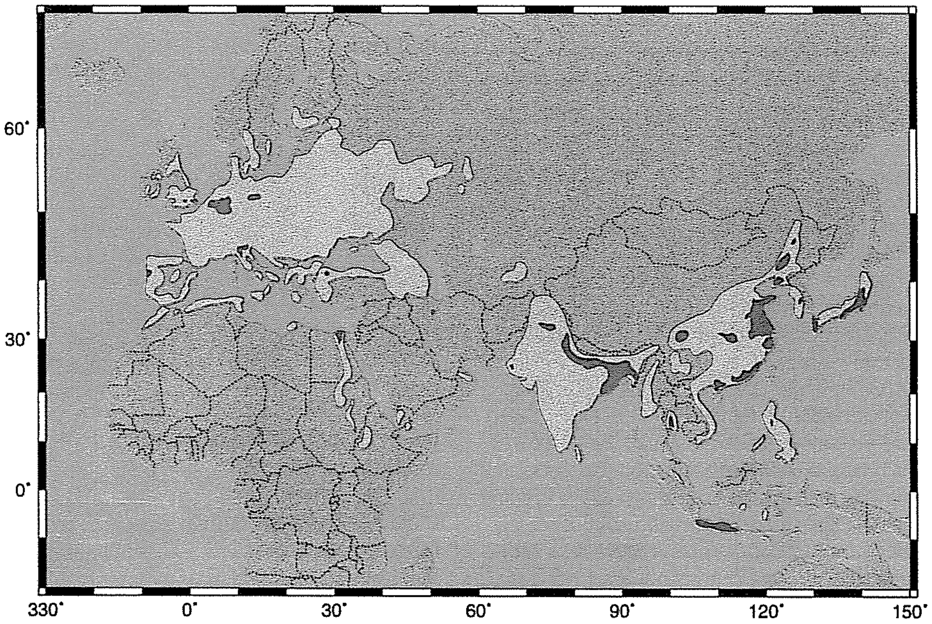

Fig. 1. Population distribution in Eurasia and the southwestern Pacific. Red: > 10,000/km², pink: 10,000-1,000/km², blue: < 1,000/km². The Tethyan tectonic belt extends through Europe, the Mediterranean, and central Asia to the southwestern Pacific and is the premier global example of a colliding plate boundary. (Adapted from Oxford Atlas of the World, 4th Edition, Oxford University Press, 1996, with permission.)

mantle thermal and compositional character, and interactions with the continental crust. Ultra-potassic volcanic activity near extinct or near-extinct subduction zones appears to tap mantle sources that are strongly contaminated by continental crustal material, suggesting the possibility of large-scale mantle overturn associated with slab detachment and orogen collapse [*Molnar and Tapponnier*, 1975].

Ultra-potassic magmatism is invariably followed by dispersed intraplate eruptions of tholeiite and alkali basalt within conjugate pull-apart basins, reflecting the decompression of thermally anomalous mantle in response to lithosphere rifting and shearing. The timing and thermal character of dispersed basalt magmatism, coupled with the possibility that regional mantle isotopic anomalies reflect large-scale contamination caused by discrete indentor events, further supports a role for collision-related mantle perturbations [*Flower et al.*, 1998].

Meanwhile, tomographic and seismic shear-wave splitting studies reveal intriguing corollaries between magmatism, lithosphere kinematics, and upper mantle flow [e.g., *Spakman et al.*, 1993; *Russo and Silver*, 1994; *Flower et al.*, 1998], from which basis we argue that a better understanding of collision-related asthenosphere dynamics should allow for refined characterizations of the associated seismicity and volcanism. Accordingly, IGCP 430 will explore post-collision mantle response models that integrate geophysical data bearing on mantle flow fields, geochemical/geochronologic data for Tethyan ophiolites and magmatic bodies, and numerical analyses of the inferred mantle dynamics.

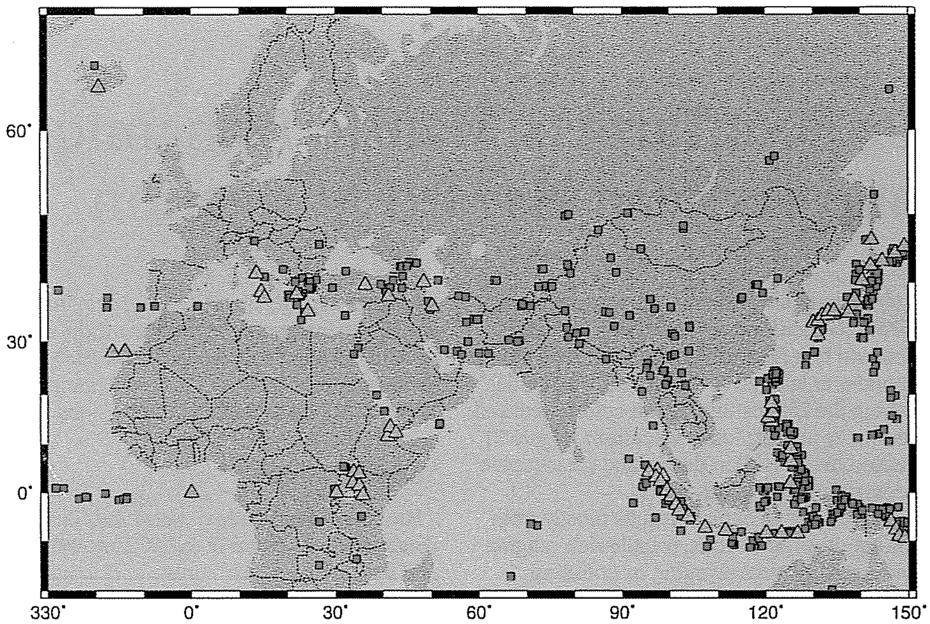

Fig. 2. Catastrophic events in Tethys during the 20th century: (squares) earthquakes of magnitude 6 or greater; (triangles) explosive volcanic eruptions. (Adapted from Oxford Atlas of the World, 4th Edition, Oxford University Press, 1996, with permission.)

Hazard Mitigation in the New Millennium

While our ability to explain earthquake and volcanic activity has greatly advanced, many aspects of hazard mitigation remain enigmatic. Progress is frustratingly slow and controversy abounds, with hazards often characterized by case-by-case investigations rather than deterministic, theory-based interpretations. Assumed "active lithosphere-passive mantle" relationships implicit in conventional collision tectonic models may also bias our understanding of natural hazard causes. Factors linking collision-related mantle flow with earthquake and volcano behavior may include processes such as asthenosphere perturbation associated with the detachment of subducting lithospheric slabs, lateral squeezing or extrusion of the asthenosphere, post-orogenic collapse, mantle delamination and exhumation, and the lateral escape of lithosphere. It is also likely that melting associated with plate convergence or collision is largely decoupled from subducting slabs and triggered by dehydration reactions within the convecting supra-subduction mantle [e.g., *Tatsumi*, 1989].

Regarding seismic risk, we generally view oceanic plate motions and velocities as resulting from density variations within the lithospheric plates themselves, expressed by a combination of slab-pull and ridge-push effects. In contrast, continental plates may be driven by mantle flow acting on deep continental roots, although these forces are less well understood. Since the extent to which plate force-balances control plate velocities (hence, seismic activity), an improved understanding of upper-mantle dynamics seems essential for modeling seismic risk in Tethyan-type collision belts.

Knowledge of collision-related mantle flow fields may also be important if their relationship to slab subduction is other than suggested by traditional slab-entrained flow models. For example, we know that the asthenosphere may flow parallel to subducting trenches, exerting normal stresses on both the slab and overriding plate, which leads to slab detachment and channeling through asthenospheric "windows" [*Russo and Silver*, 1994]. Both increased tectonic shortening and high strain rates associated with slab tearing and detachment in collisional belts are expressed by higher-than-normal seismicity, which further highlights the importance of mantle-dynamic factors. We therefore argue that earthquake hazards could be fruitfully addressed in a broader and more fundamental framework than has hitherto been the case.

The prediction of volcanic eruption patterns faces analogous problems, despite the evidence that precursive volcanic activity is more readily linked to major eruptive events, and that some eruptions are verifiably triggered by earthquakes [*Linde and Sacks*, 1998]. Because the thermal structure of subduction-related mantle wedges may be relatively insensitive to the angle and velocity of subduction [*Furukawa*, 1993], we might expect near-uniform melt products at most, if not all, subduction zones. However, melts are not compositionally uniform and there is still no consensus on the causes of mantle wedge melting. Is lowering of the solidus as a result of introduced H_2O the primary cause of magma formation, or is this process merely a trigger for diapirism or hydraulic fracturing? Also, is the mantle wedge destabilized by the incorporation of delaminated, low-density lithospheric mantle?

Some petrologists [e.g., *Tatsumi*, 1989] believe that magma is produced in this environment by decompression triggered by low-fraction (metasomatic) partial melts, which in turn result from the breakdown of minor, volatile-bearing mineral phases. This view implies that the style and intensity of volcanic eruptions should correlate closely with external dynamic factors such as the progress of a tectonic collision, the age of subducting or subducted lithosphere, and the composition of sediment or fluid introduced by subduction to the convecting mantle.

Slab-derived or lithospheric mantle-derived contamination appears to vary as a function of tectonic setting, as recorded in The Philippines, Japanese, and Indonesian volcanic arcs. The type of contamination determines which minor phases (examples may include phlogopite, amphibole, apatite, and dolomite) are stabilized in the mantle wedge and how their respective stabilities in pressure-temperature space may control metasomatism, gravitational and thermal perturbations, and, ultimately, the magma type produced.

Patterns of volcanism in The Philippines—variably associated with west-dipping, east-dipping, and collision-related subduction—illustrate this particularly well. To the east, non-calderagenic Bicol volcanoes such as Mount Mayon are quite "well-behaved," with frequent eruptions of basaltic andesite, andesite, and rare dacite-tapping CO_2-poor mantle enriched by hydrous (but non-carbonate) ocean-derived sediment. To the west, the calderagenic Bataan volcanoes (including Mount Pinatubo) are highly explosive, erupting acid magmas such as dacite and rhyolite that are frequently CO_2-saturated and have relatively long repose times, and tapping CO_2-rich mantle enriched by hydrous, aluminum-rich, and carbonate sediment. Further southwest, the extremely explosive (phreatomagmatic) Taal caldera complex is dominated by basalts and andesites, tapping mantle that reflects collision-enhanced enrichment in these components.

Thus, if geodynamic setting is the prime determinant of thermal structure and volatile budget within the supra-subduction mantle "wedge," along with the stress field in the overlying lithosphere (constraining magma supply and fractionation paths), there is a clear need to characterize volcanoes and their eruptive products in terms of these parameters. Studies of deep Earth structure focused on volcanic rock chemistry, high-temperature and high-pressure experiments, and numerical modeling provides powerful tools for defining degrees of mantle mixing, fractionation, and flow heterogeneity, thereby enhancing our understanding of collision-related eruptive processes.

Two Natural Labs

The PANCARDI region evolved during Mesozoic-Cenozoic collisions between stable Eurasia and migrating continental fragments such as the African Italo-Dinaric microplate; the region reflects tectonic escape, arc rollback, and eastward-directed collision of the retreating arc (Figure 3). Southward subduction of Eurasia during the Eocene produced a discontinuous volcanic arc beneath Pannonia, followed by rapid extension and basin subsidence in the Miocene and continued underthrusting and calcalkaline volcanism in the northern and northeastern Carpathians. Ultrapotassic magmas appeared in several areas following collisions of the Carpathian arc with the European plate, and the late Miocene cessation of extension was followed by widespread extensional basalts.

The Vrancea bend zone of the southeast Carpathians is confined by strike-slip fractures that are left-lateral to the north and right-lateral to the south (Figure 3). Vrancea is characterized by an unusually narrow, vertical zone of intense seismicity, between 70 km and 180 km in depth, matched by a gap in the volcanic arc. Surface-wave tomography suggests that the asthenosphere beneath the PANCARDI continental crust is well-developed and shallow and may have decoupled lithosphere from the deeper mesosphere during tectonic escape.

Despite several indications that post-collision subduction ceased or decelerated ~10 Ma, vertical extension of the Vrancea slab continues at a rate of ~3.8 cm/yr^{-1}. A tomographic experiment conducted by the universities of Karlsruhe and Bucharest [*Wenzel et al.*, 1998], as part of the EUROPROBE-PANCARDI program, is currently acquiring high-resolution, three-dimensional images of mantle beneath Vrancea, providing detailed velocity information on the subducted slab, possible detached remnants of the latter, and the asthenosphere.

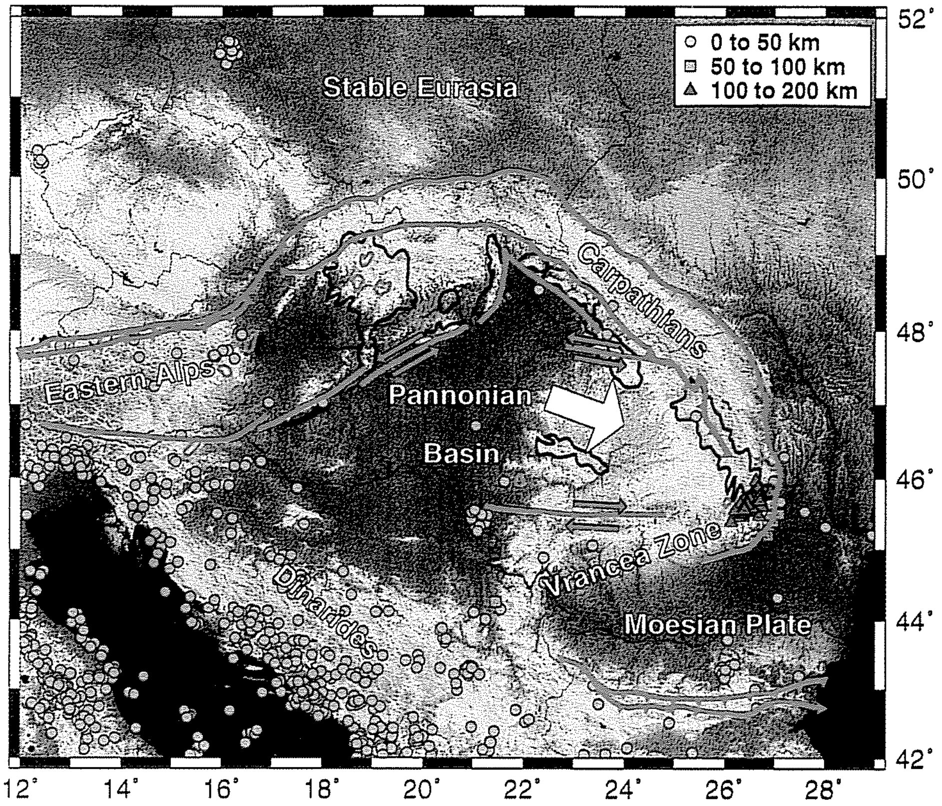

Fig. 3. Tectonic boundaries and major faults of the PANCARDI region. Background: 30-s topography. Seismicity from 1963 to 1997 (more than 30 locating stations) plotted as per symbol key, upper right. Black and red outline areas bound by Neogene and Plio-Pleistocene volcanics. White arrow indicates approximate directions of Pannonian escape.

The SEAWPAC region (Figure 4) is dominated by the Ailao Shan-Red River shear zone that extends from eastern Tibet through Yunnan and Vietnam to the South China Sea, and continues to be the object of several international studies.

Following the ~45 Ma India-Asia collision, the Indochina microplate apparently moved southeastward, accommodated by left-lateral motion on the Ailao Shan-Red River and other regional faults (Figure 4). Syn- and post-collision magmatism in Indochina and southwestern China resembles magmatism in eastern Europe: pre-collision calcalkaline volcanism gives way to post-collision, pre-escape ultrapotassic magmatism and widespread dispersed basalt centers [*Flower et al.*, 1998]. Moreover, seismic activity in western Yunnan, which is squeezed between Namche Barwa and Gongha syntaxes, is notoriously intense. The ages of shear-offset volcanic bodies constrain the timing of left-lateral motion [*Chung et al.*, 1997], suggesting that Indochina began "escaping" well after opening of the South China Sea commenced.

This important observation indicates that the southeastern boundary of Indochina was characterized by surface extension rather than by compression, in turn suggesting that driving of the Indochina microplate is most likely related to subduction rollback southeast of the South China Sea (Figure 4). Thus, driving through tractions along vertical but shallow strike-slip faults such as the Ailao Shan-Red River shear zone is most likely secondary to collision-induced asthenospheric flow exerting shear and normal tractions on the base of the microplate and subducted slab face to the southeast.

As in other parts of the Tethyan belt, collision-induced mobilization of the asthenospheric mantle may have fundamentally affected east and southeast Asia and the western Pacific, with critical environmental implications for China and the densely-populated Japanese, Philippines, and Indonesian archipelagoes. Associated arc rollback, concomitant arc-arc and arc-microcontinent collisions, basin opening, and secondary mantle turnover would thus be major factors determining hazard scenarios.

IGCP 430 Summary Plan

Program plans and research priorities were discussed at the first IGCP 430 workshop, which was held the summer of 2000 in Covasna, Romania (for a summary, see http://www.gg.unibuc.ro/igcp430 on the World Wide Web). Future workshops are planned for October 2001 (Haiphong, Vietnam), May 2002 (Antalya, Turkey), March 2003 (Yunnan, P.R. China), and April 2004 (Manila, The Philippines), with a plenary symposium in May 2005 in Chicago/Evanston, Ill., USA.

IGCP 430 is closely linked with research groups working in Europe, the Mediterranean,

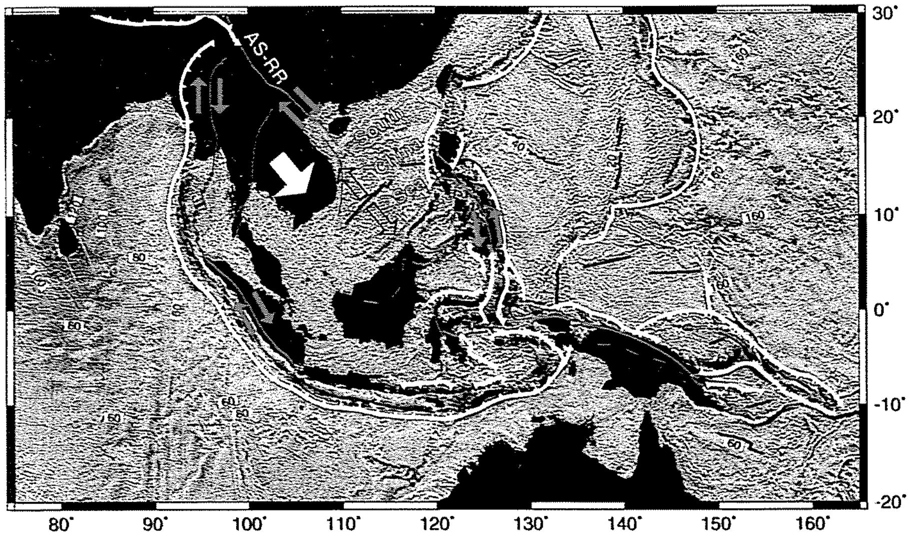

Fig. 4. Tectonic boundaries and major faults of the southeast Asian region. Background: 2-min free-air gravity anomalies. AS-RR: Ailao Shan-Red River fault zone, the primary on-land feature associated with tectonic escape; Indochina escape direction is shown by white arrow. Spreading in the South China Sea is also shown schematically by arrows. Note that tectonic escape is associated with extensional tectonics (South China Sea opening) rather than compressive deformation at the southeastern edge of Indochina.

Asia Minor, the Himalayas, east and southeast Asia, and the western Pacific margins, as well as with colleagues in hazard prediction agencies. Input from the Earth and environmental science community is solicited for participation in working groups and workshops and to promote new research in these problem areas. Further information will be available at the project's Web site.

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Authors

Martin Flower, Ma Zongjin, Victor Mocanu, Ray Russo, Nguyen Trong Yem, Cung Thuong Chi, Nguyen Quoc Cuong, Deng Jinfu, Yildirim Dilek, Corneliu Dinu, Liu Futian, Mian Liu, Nguyen Hoang, Paul Robinson, Mo Xuanxei, Ray Punongbayan, Friedemann Wenzel, Graciano Yumul, and Elisabeth Widom

For more information, contact M. F. J. Flower, Department of Earth and Environmental Sciences, University of Illinois at Chicago (M/C 186), 845 W. Taylor St., Chicago, IL 60607-7059, USA; E-mail: flower@uic.edu; www.tethys.com.

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