Active subduction and collision in Southeast Asia[☆]

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Keywords: Subduction; Collision; Southeast Asia; Taiwan

1. Introduction

This volume contains a collection of 18 papers on ‘Active subduction and collision in Southeast Asia’ presented at the SEASIA International Conference and Fourth Sino-French symposium in Montpellier, France, May 9–12, 1999. Previous Sino-French symposia on Earth Sciences have been held in Taipei (1984 and 1995) and Paris (1988). Proceedings have been published in Angelier et al. (1986), Angelier (1990) and Lallemand and Tsien (1997).

More than one hundred scientists have attended this fourth meeting, about one half coming from abroad (Fig. 1). The previous Sino-French symposia mainly dealt with onland geology. During this meeting, the results of both marine research carried out offshore Taiwan and in the surrounding seas, and onland studies were presented.

Sixty oral presentations and forty posters were presented in ten sessions including (1) SE Asian tectonics and kinematic reconstructions; (2) tectonic processes at the Taiwan–Ryukyu junction area; (3) interaction between tectonics and sedimentation in

orogenic forelands; (4) active tectonics in mountain belts; (5) GPS and kinematics; (6) variations in subduction parameters and their implications; (7) new data in and around the Taiwan arc-continent collision; (8) recent geochemical and geophysical advances on arcs and back-arcs; (9) complex evolution of arcs and back-arcs; and (10) seismicity and tectonics in Taiwan and models of arc-continent collision. The meeting was followed by a four-day field trip in Corsica.

Arc-continent collision(s) usually occur before the main continent–continent collision(s). Ophiolitic rocks providing evidence for the early stages of mountain building are observed in and around the suture zones of most collisional mountain belts. Southeast Asia offers a wide range of both active and ancient convergent domains, where collisions between arcs and continents played an important role. Black stars in Fig. 2 show such active collision zones between the Luzon Arc and the Chinese margin in Taiwan, the Izu-Bonin Arc and Central Japan, the Kurile Arc and Hokkaido, the Halmahera and Sulu Arcs against the Philippine mobile belt, the Timor Arc and the Australian margin, and the Melanesian Arc against New Guinea. The white star marks the area of the collisions between two arc terranes and the Kamtchatka Peninsula during the Early Tertiary and at the end of the Miocene.

Despite its relatively small size, the Taiwan arc-continent collision is probably one of the most actively studied in the world. This interest is raised

[☆] A preface to the special issue of Tectonophysics. Active subduction and collision in Southeast Asia (SEASIA), edited by S. Lallemand, C.-S. Liu, J. Angelier and Y.-B. Tsai.

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Fig. 1. Group photo of the participants of the SEASIA Meeting in front of the Corum Building of Montpellier (France). From back left to front right: Robert Hall, Rinus Wortel, Claude Rangin, Jacques Malod, Stéphane Dominguez, Florent Hinschberger, Philippe Schnurle, Fred Wang, Benoît Deffontaines, Jean-Claude Sibuet, Anne Replumaz, Jonathan Aitchison, Eileen Davis, Kensaku Tamaki, Chao-Shing Lee, Shu-Kun Hsu, Hung-Ming Kao, Siegfried Lallemand, Herman Munsch, Jinder Chow, Martin Block, Chung-Pai Chang, Honn Kao, Frédéric Mouthereau, Tim Byrne, Laurent Jolivet, Hao-Tsu Chu, Olivier Lacombe, Wim Spakman, René Maury, Anne Deschamps, Alexandra Martinez, Dany Hurpin, Edith Hafkenscheid, Heidrun Legelmann, Elena Konstantinovskaya, Francis Wu, Ching-Hui Tsai, Chang Chi-Fong, Xavier Le Pichon, Alexandre Chemenda, Maurice Brunel, Jean-Francois Stéphan, Marc-André Gutscher, Kirk McIntosh, Teh-Quei Lee, Jih-Chuan Tang, Win-Bin Cheng, Jian-Cheng Lee, Jacques Angelier, Shui-Beih Yu, Serge Lallemand, Jean-Paul Cadet, Roland von Huene, Yvonne Font, Mireille Polvé, Jacques Malavieille, Yi-Ben Tsai, Chi-Yue Huang, Char-Shine Liu, Bee-Deh Yuan, Ho-Shing Yu, Chia-Yu Lu, Jyr-Shing Lee, Jiun-Chuan Lin, and Wen-Chen Jou.

because the collision zone is young (a few million years), extremely active, easily accessible and well monitored through geological, geophysical, geodetic and remote sensing approaches.

The main plate boundaries in and around Taiwan are shown in Fig. 3. Major collision occurred in Taiwan because the continental part of the Eurasia (EUR) plate (including the Chinese continental shelf) entered into subduction beneath the Luzon volcanic arc a few millions years ago. A simplified section across the Manila Trench (AA' in Fig. 3) shows a typical oceanic subduction, whereas another section to the north across Taiwan (BB' in Fig. 3) shows a less typical continental subduction beneath an oceanic plate (i.e. the Philippine Sea Plate, PSP).

The September 21, 1999 Mw7.6 Chi-Chi earthquake, which occurred in Central Taiwan, clearly demonstrated

that elastic energy could be released near the deformation front of the orogen with surface displacements up to 10 m both in the horizontal and vertical directions (Ma et al., 1999). Hypocentral and focal determinations of the mainshock and aftershocks (Kao and Chen, 2000) are in agreement with the existence of a seismogenic zone dipping 25 to 30° east beneath the central foothills area as expected from a 'subduction' earthquake (Lallemand, 2000; see BB' on Fig. 3). There exists another active fault: the Longitudinal Valley Fault (LVF) that has long been considered as 'the' plate boundary by many authors. The kinematic role of the LVF as an 'eastern Taiwan plate boundary' is highlighted by the occurrence of continuous creep, with about 3 cm/year shortening. However, the kinematic contribution of the thrust zone at the belt front as a 'western Taiwan plate boundary' is similar in

importance. As a rough preliminary estimate, assuming that the Chi-Chi earthquake represents about 3 m of average shortening and follows a period of about 100 years of compressive stress accumulation, one obtains the same average velocity of 3 cm/year as for the Longitudinal Valley.

Lallemand and Angelier (2000a,b) have thus proposed that the present-day plate boundary in Taiwan is essentially a twin-fault system (Fig. 3) with contrasting mechanical behaviors in the upper crust (creep and periodical large earthquakes), at least for the present.

Fig. 2. Sites of arc-continent collision in the northwest Pacific modified after Lallemand (1999). Black stars represent active arc-continent collision zones. The white star represents past collision.

Fig. 3. Location of major plate boundaries in and around Taiwan. The two schematic sections AA' and BB' are located on the map. This figure is modified from Lallemand and Angelier (2000b) and Lallemand (2000).

The papers in this special issue are arranged on the basis of the investigation area, starting with Southeast Asia including Indonesia, then moving along the Pacific rim from the Kamtchatka to Taiwan.

2. The origin of back-arc basins in Southeast Asia

The first paper by Flower et al. (this issue) presents an extensive review of isotopic data supporting a model in which the openings of the Western Pacific back-arc basins are linked with the extrusion of East Asia in response to the 'hard' collision between India and Eurasia. The link can be obtained by the singularity of the asthenosphere that has contaminated the basement of the Western Pacific arcs, including the Izu-Bonin–Mariana Arc. The next three papers concern the history of subduction, back-arc opening and post-orogenic 'collapse' in the Indonesian region. Hafkenscheid et al. (this issue) have computed seismic velocity models from kinematic reconstructions and compared them to a recent tomographic model. This technique allows them to discuss the validity of

the kinematic reconstructions. Hinschberger et al. (this issue) provide additional constraints based on magnetic anomalies interpretation for the Late Miocene–Early Pliocene back-arc opening of the South Banda Basin that supports recent geochronological studies on dredge samples. Their results confirm the extreme youth of the basin despite its great depth. The paper by Milsom et al. (this issue) aims at demonstrating that gravity variations and ophiolite distribution around the Banda Sea are consistent with extension in the Sulawesi region following, and as a result of Oligo–Miocene collision with an Australian-derived microcontinent.

3. Subduction and collision from the Kamtchatka to the Ryukyus

A set of five papers present detailed studies on various subduction zones of the northwest Pacific rim starting in Kamtchatka (NE Russia). Konstantinovskaya (this issue) proposes a model of arc-continent collision that evolved into a reversal of subduction, based on

detailed field studies in Kamchatka. Gutscher (this issue) has applied a model of interplate coupling and strain partitioning that was developed for the northern Andes (Gutscher et al., 1999), to the ‘flat’ subduction of Nankai (Southwest Japan). The model infers that a new transcurrent shear zone is developing along the northern rim of SW Japan, that should account for the lateral motion of the forearc sliver in complement with the Median Tectonic Line. Hsu et al. (this issue) have performed a magnetic inversion to reveal the distribution and characteristics of the belts and basins in the East China Sea and Okinawa Trough. Their study adds new constraints which confirm that the southern segment contrasts with the middle and northern segments of the Ryukyu subduction zone as previously indicated by the arc volcanism and Okinawa Trough history. Chiao et al. (this issue) have calculated the velocity field for the specific subducting slab geometry in the southern Ryukyu adjacent to the collisional area in Taiwan, based on the rationale that the subduction flow field should be the one that endures the least amount of intraplate deformation. Their kinematic model accounts for the observed slip vectors and lateral compression reported from earthquakes solutions. The paper by Font et al. (this issue) gives new constraints on the geometry of the southern Ryukyu Arc basement near Taiwan based on reflection seismic profiles. They clearly demonstrate that the basement ends sharply along a nearly vertical — about 5 km high-wall, buried beneath the rear of the accretionary wedge. They also show that two rises in the basement may reveal the presence of subducting or underplated oceanic asperities that could represent the northern extension of the Gagua Ridge and scraped-off pieces of the colliding northern Luzon Arc, respectively.

4. Arc-continent collision in Taiwan

The second half of the volume presents nine papers dealing with various aspects of the arc-continent collision in Taiwan. Chemenda et al. (this issue) present an evolutionary model based on new 2D and 3D analog models of arc-continent collision. The exhumation of a subducted continental slice of crust to produce the Central Range, the underthrusting of the Luzon forearc basement beneath the arc and the reversal of

subduction are described as a logical suite of events that occur during oblique arc-continent collision. Kao and Jian (this issue) provide the global seismogenic patterns in Taiwan based on a source parameter inversion of 96 earthquakes recorded by the newly established Broadband Array in Taiwan for Seismology (BATS). They confirm the existence of five seismogenic regions in the southern Ryukyu and northern Luzon forearc areas, near Hualien (northern Coastal Range), within the PSP, and the Okinawa Trough. These new determinations allow the authors to promote the idea that lithospheric collision in Taiwan should be dominated by an ‘arc-continent collision’ in the central and southern part of the island and a ‘slab-continent collision’ in the northern part.

The next four papers are all devoted to the southern part of the LVF which separates the Coastal Range (Eastern Taiwan) from the Central Range. Yu and Kuo (this issue) present a detailed analysis of GPS-derived velocities from repeated measurements between 1992 and 1999 at geodetic sites on both sides of the LVF. About 3 cm/year of convergence are accommodated across that west-vergent high-angle thrust fault. Five creepmeters were installed at two sites across the Chihshang Fault (southern segment of LVF). Lee et al. (this issue) present the results of one year of measurements across five branches of the active fault. They conclude that creep is continuous with a horizontal shortening of 17–20 mm/year accounting for two third of the GPS-derived motion. This suggests that there exist other shortening deformations across the active fault zone. Ground penetrating radar (GPR) and high resolution seismic reflection have been carried out to delineate the subsurface pattern and paleoseismic facies of this active fault. The results are presented by Chow et al. (this issue) enabling the authors to detect a paleoseismic event and the complicated pattern of antithetic subsidiary faults in the near-surface part of the Chihshang Fault. A 3D distinct element model has been applied by Hu et al. (this issue) to determine the behavior of the two active branches of the LVF in the southern part of the Coastal Range where convergence is oblique and strain partition is observed from GPS data. Their models that emphasize the role of the direction of convergence, the

geometry of the faults and their friction coefficient, predict an average displacement rate of 33 mm/year in the direction N318°E that is quite consistent with geodetic measurements.

The last three papers concern the western Taiwan foreland basin that formed during the Early Pliocene as the flexural response of the Eurasian plate to loading of the Taiwan orogen. Yu and Chou (this issue), using an extensive collection of multichannel seismic lines and more than 20 exploration wells offshore and onland, are able to recognize the major nonconformities and to reveal the extent of the foreland basin: 350 × 150 km. Mouthereau et al. (this issue) focussed their work on the southwestern part of the foreland thrust belt providing a detailed structural and tectono-sedimentary analysis that allows them to balance cross-sections. They conclude that 2 levels of decollement are acting simultaneously including a deep one through the basement. One consequence of their restoration is that shortening is surprisingly low and the thickening especially high. Finally, Lacombe et al. (this issue) investigate the presently active mechanisms of tectonic escape in the same area in a context of oblique continental subduction. They demonstrate that the escape propagated from north to south and began during the late Pleistocene in the southwestern part of the island.

5. Conclusions

The variety of contributions in this issue, most of them dealing with Taiwan, confirms the idea that this island and its surroundings are an exceptional natural laboratory for studying active subduction and collision processes as well as mountain building and collapse.

The recent Chi-Chi earthquake has urged the community to draw conclusions from this dramatic event. A first Sino-French Symposium on Natural Hazard Mitigation was held in May 22–25, 2000 in Taipei with scientists and engineers joining together because all are deeply concerned with hazards causing a threat to public safety. It is obvious that future studies in active subductions and orogens will be closely connected with societal problems linked with natural hazards such as earthquakes, tsunamis, pollution or climatic events.

Acknowledgements

The permanent support of the Institut Français à Taipei (IFT) and the National Science Council (NSC) to develop and maintain cooperation in Earth Sciences between France and Taiwan was a source of strong encouragement in international scientific research and is gratefully acknowledged. The Symposium was sponsored by NSC, IFT, the Bureau de Représentation de Taipei à Paris (BRT), the French Ministry of Foreign Affairs (MAE), the Centre National pour la Recherche Scientifique (CNRS), the University of Montpellier 2 (UM2), the Institut des Sciences de la Terre, de l'Eau et de l'Espace de Montpellier (ISTEEM), the Conseil Régional Languedoc-Roussillon, the Conseil Général de l'Hérault and the District de Montpellier. This Symposium was held under the patronage of the Geological Society of France (SGF). The proceedings of the extended abstracts were published in the *Mémoires Géosciences Montpellier* n°14 (1999, 335 pp.). We warmly thank Anne Deschamps for her management of the web site and her help in the organization of Congress, Anne Delplanque who designed the logo, Jacques Malavieille for his organization of the field trip in Corsica, Xavier Le Pichon who gave a keynote address and chaired the Scientific Committee of the Congress. Finally, we are grateful to the numerous referees who evaluated the manuscripts, with special thanks to the editor-in-chief Jean-Pierre Burg who carefully reviewed all the papers that were sent to him.

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