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ACTIVE CONTINENTAL GROWTH UNDER TRANSPRESSIONAL TECTONICS - EXAMPLE FROM SOUTHEASTERN TAIWAN

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ABSTRACT

Based on structural analysis and regional kinematics data from GPS measurements, we propose a tectonic evolution model for the active continental growth in southeastern Taiwan. We found that the deformation structures in the Miocene deposits of the southeastern Central Range exhibit characteristics of early-stage orogenic processes. These brittle-ductile deformation features indicate complex tectonic processes involved, including underthrusting, exhumation, and left-lateral transpressional movements. It seems evident that the observed deformation structures in the southeastern Central Range occurred before the arc-continental collision, because the Luzon arc, which is located about 100 km east of the Taiwan island, has not yet to be collided with the southeastern Central Range. In an E-W transect across the southern Central Range, regional foliation orientations generally display a fan-shaped pattern with dips to the mountain core on both sides. In addition, kilometer-scale overturned structures were mapped at the eastern flank of the southern Central Range. This overall upward flower structure is consistent with an early-proposed exhumation model, which explains the presence of higher-grade rocks along the central axis of the mountain belt. Because of the rapid uplifting and erosion rates in Taiwan, it is suggested that many early orogenic structures, such as those observed in the southeastern Taiwan, were either obliterated or eroded away in the older mountain belt in the north. Based on previously published GPS data, we estimated the southward propagation rate of the accretion of the Luzon arc along the Longitudinal Valley, to be 7.9 cm/yr. In general, the kinematics

data suggest left-lateral transpressional tectonic movement is currently important process in the southeastern Taiwan. And under such tectonic movement, we highlight the contribution of the Luzon arc accretion to the continental growth of East Asia.

Key words: active tectonics, continental growth, transpression, southeastern Taiwan, underthrusting, exhumation

INTRODUCTION

The Taiwan mountain belt is one of the youngest mountain belts on the Earth's surface. It is a result of the oblique convergence between the Eurasian plate and the Philippine Sea plate (Biq, 1971; Biq, 1972; Chai, 1972; Ho, 1975, 1986; Suppe, 1981) (Fig.1). The present convergent velocity between these two plates is 8.2cm/yr in N54°W direction according to the recent GPS measurement (Yu *et al.*, 1997). The geometric configuration of this oblique convergence is revealed by the trends of the different geologic units. For instance, the Luzon arc (belonging to the Philippine Sea plate) trends N10°W, whereas the Central Range including the Hsuehshan Range, the Backbone Range, and the Paleo/ Mesozoic Basement trends N16°E (Figure 1B with an oblique angle about 26° against the Luzon arc). The deformation partitions of the Luzon arc against the Central Range can be decomposed into 7.7 cm/yr shortening and 2.7 cm/yr left-lateral strike slip (Fig. 1C). This plate convergence results in the oblique accretion of the Luzon arc thus produces the continental growth of East Asia, which can be regarded as a result of northward movement of the Luzon arc obliquely attaching to the continental margin of East Asia. The oblique convergence also results in a southward propagation of mountain building in Taiwan (Suppe, 1981). The initial deformation stages of the mountain evolution of Taiwan were therefore better preserved in the southern part of the mountain range. Furthermore, the accretion of landmass at the southern end of the Coastal Range of the Luzon arc in combination with the oblique convergent tectonics and indentation of the forearc basement represent a left-lateral right step transpressional environment in the southeastern Central Range (Lu *et al.*, 2001). In this paper, we aim at characterizing the deformation structures of the continental growth of East Asia in this specific transpressional tectonism environment.

The rocks of southeastern Taiwan of the study area consist of thick series of Miocene accretionary wedge deposits. They are mainly composed of dark gray argillites, phyllites, and flysch deposit with occasional interbeds of gray compact sandstone and disseminated marly nodules (Hu *et al.*, 1981). They were metamorphosed under the prehnite-pumpellyite facies to lower greenschist facies conditions (Chen *et al.*, 1983) and are characterized by the intense layer parallel shearing with or without slaty cleavage (Pelletier and Hu, 1984). As the Luzon arc is located some 100 km east of the study area, we argue that the rocks in the southeastern Taiwan have not yet undergone the arc-continental collision processes, as have the central and northern parts of the Central Range of Taiwan. As a consequence, southeastern Taiwan provides a good opportunity to examine the geologic features in the initial stage of the ongoing mountain belt. In this paper, we not only describe the deformational structures in southeastern Taiwan but also integrate the regional kinematics data from GPS measurements, in attempt to better understand the kinematics evolution of the Taiwan mountain belt.

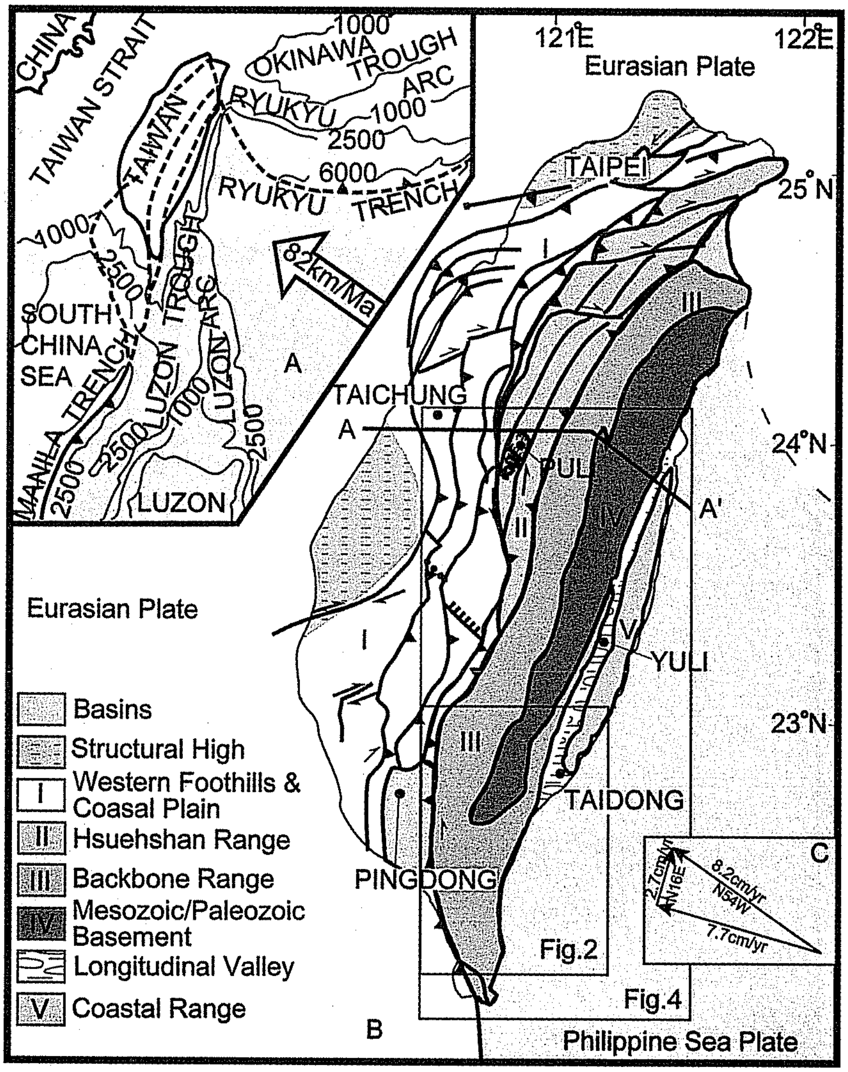

Figure 1. A. Geodynamic map of Taiwan mountain belt. B. Geological setting and location map of study area. C. Deformation partitioning of compression/left-lateral shearing against the Central Range.

GEOLOGICAL STRUCTURES IN SOUTHEASTERN TAIWAN

Topographic features

Taking a glance at the topographic map of southeastern Taiwan (Fig. 2A), one can get impressed immediately by the regular en-echelon pattern of rivers and ridges. At least four parallel E-W trending rivers and ridges align from north to south in southeastern Taiwan. It appears a slight counter-clockwise rotation in the westernmost of these rivers-and-ridges (Figs. 2A,B). This pattern is more evident in the perspective view (Fig. 2C). We interpret that this particular topography is largely dictated by the regional structures. For instance, the E-W trending river-and-ridge basically corresponds to regional E-W trending folds and thrust. However, along the coastline on the east flank of the southern Central Range, the deformation structure is characterized by a NNE-trending zone of left-lateral strike-slip faults (Fig. 2B). This regional feature of complicated topographic structures has been suggested as a result of transpressional tectonics (Fig. 2D) (Lu *et al.*, 2001).

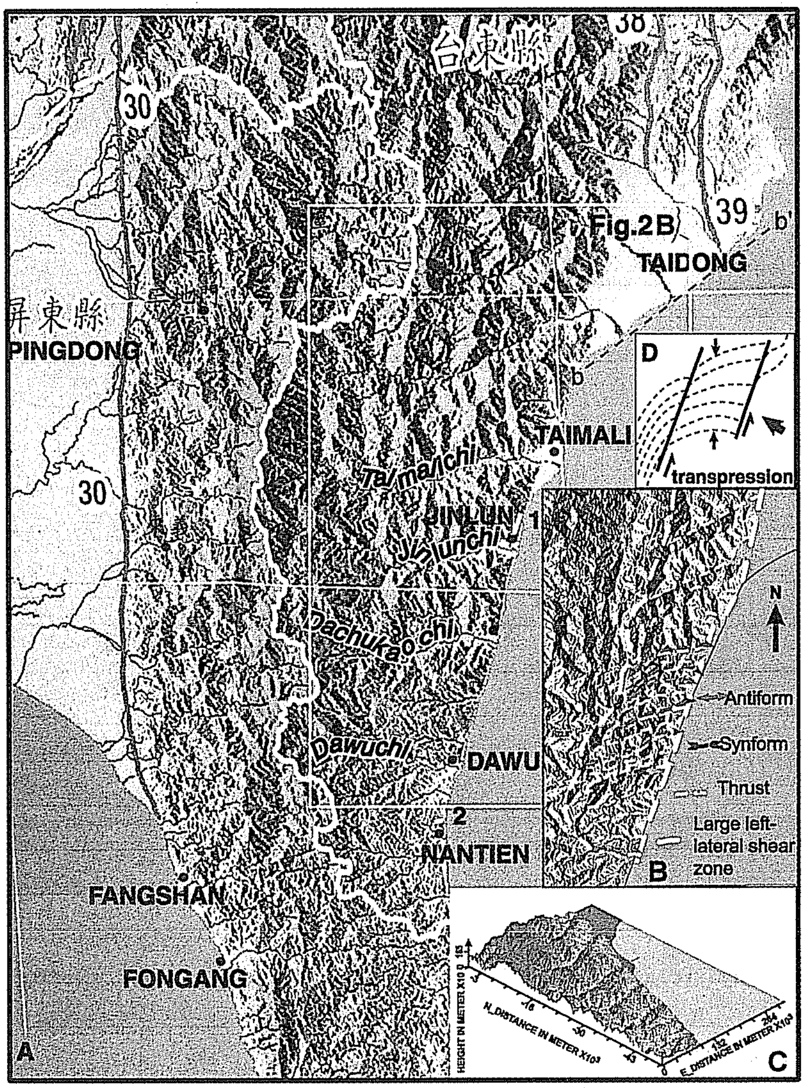

Figure 2. (A) Topographic map shows the study area and the well-aligned en-echelon structure pattern in the southeastern part of the Central Range. (B) Regional structures (C) Perspective view of (B). and (D) simplified interpretation of transpressional setting. Numbers: (1) Jinlun section, (2) Nantien section. Numbers in circle are active faults: (30) Chaochou Fault, (38) Luyeh Fault, (39) Southern Longitudinal Valley Fault.

Underthrust structures

We can recognize several deformation structures with characteristics of underthrusting in the study area. The underthrust deformation structures are observed mainly in metamorphic rocks, which are characterized by ductile deformation of basement and their sedimentary cover (Hsü, 1994). These units had been brought down to the subduction zone and metamorphosed during the mountain building processes. In the study area, the underthrust deformation structures represented by the metamorphosed W-vergent ductile shear structures (Fig. 3) and they have been observed to occur penetrative within the Central Range. West-vergent asymmetrical isoclinal and tight folds in association with σ or δ type sheared quartz veins are quite common. This west-vergent shearing correspond to the major deformation process in the southern Central Range in the study area. The stretching lineation related to this deformation stage is characterized by west-vergent quartz fibers and west-vergent drag fold or thrust (Lu *et al.*, 2001).

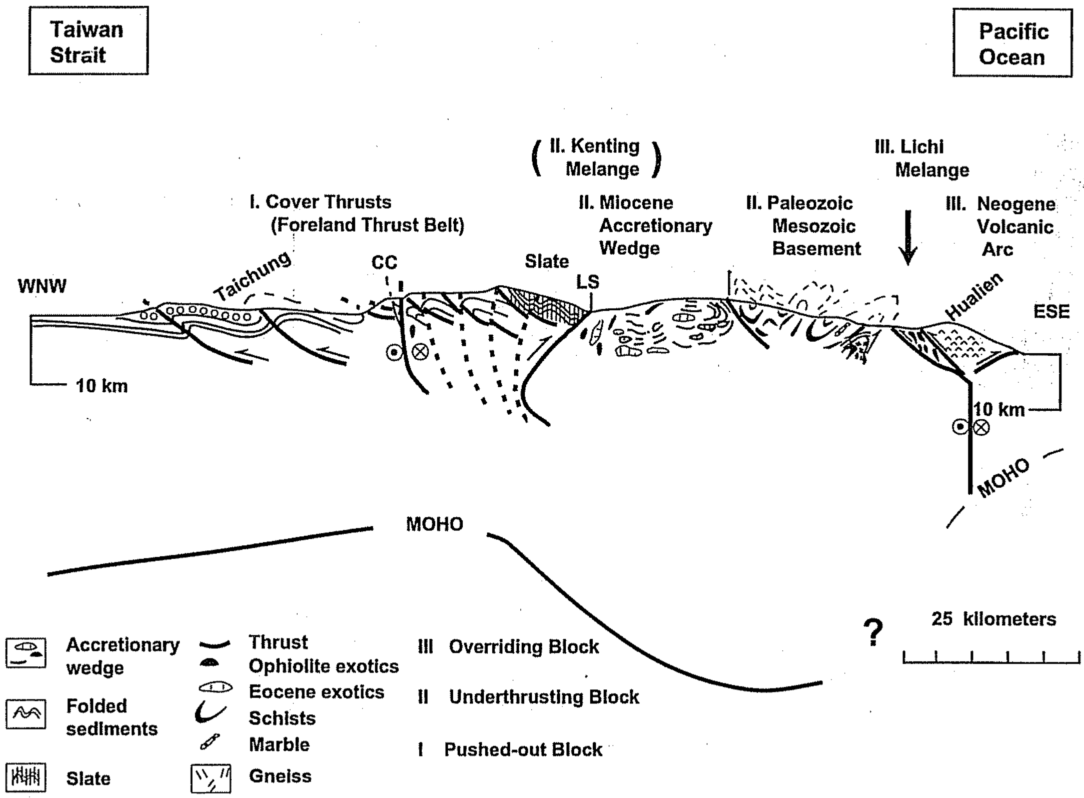

Figure 3. General structural section of Taiwan. (Section A-A' in Fig. 1. Modified after, Biq, 1985, Lu and Hsü, 1992, and Hsü, 1994). The underthrusting block consists mainly of metamorphic rocks, characterized by ductile deformation of basement and their sedimentary cover.

Exhumation structures

We interpret the surface exposure of the underthrusted structure as a result of exhumation process in the Central Range. This process was accompanied by the upward flower structure with regional overturning of stratigraphic units on the west and east sides of the Central Range (Yui and Chu, 2000). It is revealed by the E- to SE-vergent shear structures, which generally distributed along the eastern flank of the Central Range (Lu *et al.*, 2001). The ductility of these structures decrease from the north to the south. The geodetic uplift rate of the southern part of the Central Range is about 1cm/yr according to the GPS measurement (Yu and Kuo, 2000). Therefore, the superficial east-vergent nappes structures were gradually obliterated by erosion during the oblique convergence. We will discuss this argument in the later sections.

Left-lateral shearing and transpression

The accretion of landmass creates a clockwise bend with NE trending folds (e.g. b-b' bend in Figure 2) at the southern end of the Coastal Range. This bend is almost perpendicular to the plate convergence direction (N54°W). The regional oblique convergent tectonics against the Central Range has a compression/ left-lateral ratio about 3:1 (Fig. 1C). This specific combination performs a left-lateral right step transpressional environment in the southeastern Central Range (Fig. 2D). Finite elements numerical models not only support these arguments but also indicate the transpressive structures will progressively disappear toward the north (Lu *et al.*, in preparation).

The N-S trending left-lateral shearing and transpression structures are most predominant along the eastern boarder of the southern Central Range. They overprinted the previous structures by left-lateral faulting and by densely distributed fracture cleavage (Lu *et al.*, 2001). The regional NNE trending foliations were deformed into NE or ENE trending. The transpression deformation in association with left-lateral shearing resulted in mesoscale folding and thrusting (Fig. 2D). The wavelength of folds ranges from 20-200m. (Lu *et al.* 2001).

KINEMATICS OF DEFORMATION STRUCTURES

Microstructural analyses were carried out in the study area. We characterize the ductile structures and determine the kinematics of cleavage formation. Detailed descriptions of the micro-structural analyses have been presented elsewhere by Lu *et al.* (2001). Hereafter we only discuss some important results from the structural analyses.

Stretching lineations defined by phyllosilicates lie approximately parallel to the axes of regional folds with varying trends from northeast to east. Geometries of strain shadows indicate that (a) extension directions changed from along-strike toward down-dip during the deformation processes and (b) top-to-the southwest or west shearing occurred in the direction of along-strike. Regional-scale overturned sedimentary strata and the top-to-the southwest shearing suggest rocks on the southeastern Central Range have experienced a left-lateral movement in the early stage and then have extruded upward and flipped upside down in the late stage.

The early stage of left-lateral shearing has also been observed elsewhere in the eastern flank of the Central Range (Fisher, 1999). The late stage of large-scale overturn tectonism is in accord with the exhumation mechanism of the Central Range suggested by geochemical study (Yui and Chu, 2000).

INSIGHTS OF ACCRETION TECTONICS FROM GPS DATA

In order to understand the actual accretion of the Luzon Arc to the Asian continent, we re-analyzed the published GPS data (Yu *et al.*, 1997) by considering the Lanyu Island as a fixed point on the Philippine Sea plate. The relative movement between Asian continental margin and the Philippine Sea plate can be re-evaluated from the other point of view (Fig. 4). Because the stations far from the fixed point reflect cumulated relative movements in between that point and the fixed point, so that the change of vectors are less visible for the areas far from the fix points. As a result, the movement vectors in the eastern side of the Central Range and the Coastal Range are more visible while the Lanyu Island is considered as a fixed point.

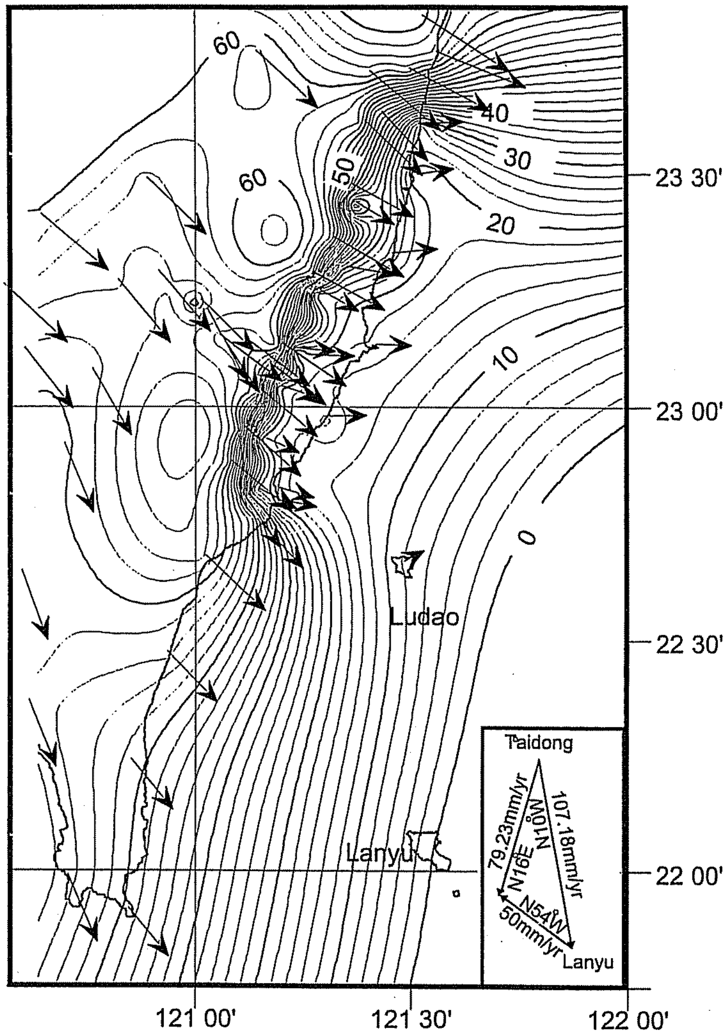

Figure 4. GPS velocity field of Taiwan recalculated in consideration of the Lanyu Island as a fix point on the Philippine Sea plate. Contours show the mean GPS velocity values and the arrows showing the displacement direction of each GPS station. The lengths of arrows are proportion to the velocity values.

Taking the Lanyu Island as the fix point, we calculated the GPS velocity field contouring and shading as illustrated in Figure 4, by using GMT tools (Wessel and Smith, 1998). The accreted part of the Coastal Range and the Ludao Island is moving toward ENE with respect to the Lanyu Island. The Luzon arc moves laterally and the moving vectors are oblique to the plate motion N309 E. So that there absorbs more deformation in the Luzon arc than in the Central Range. This may indicate that the Luzon arc is relatively weaker in comparison with the eastern side of the Central Range. This also implies that the processes of the Taiwan Mountain building might have more complicated mechanisms than a simple mechanism of the collision of the Luzon arc with the Asian continent.

The eastern side of the Central Range is moving to the SE relative to the Lanyu Island. The 50mm/yr contour line fit well with the western boundary of the Longitudinal Valley. This indicates that the accretion velocity of the Coastal Range is about 50mm/yr. We thus use 50mm/yr as the average velocity and the direction vector of Penghu to Lanyu (126°or N54°W) as the accretion direction. The western boundary of the Longitudinal Valley orients in N16°E and the Luzon arc is trending N10°W. Under this configuration, the accretion of the Coastal Range to the Central Range along Western boundary of the Longitudinal Valley is about 79. 2mm/yr.

TECTONIC EVOLUTION

Based on the above arguments, the tectonic history of southeastern Taiwan might be summarized as follows (Figure 5, Malavieille *et al.* 2001):

During the Cenozoic oblique convergence between the Philippine Sea plate and Eurasian plate, deformation occurred both in the continental margin of East Asia and the northwestern corner of the Philippine Sea plate. From the point of view at the plate-scale, this tectonism corresponds to an offscraped slice of the upper crust in the basement of the continental margin (Fig 5a). A set of conjugate thrusts develops within the arc lithosphere. Collision-related deformation migrates toward the south. Continuing subduction of the continental margin involves the growth of a large sedimentary wedge by W-vergent stacking of thick sedimentary sequences of the passive margin. West-vergent thrusting and folding as well as left-lateral shearing were the dominant deformation mechanisms in this early stage of mountain building. Subsequently, in the core of the growing wedge, subducted metamorphic rocks of the Central Range are progressively exhumed up to the surface level, forming a positive flower structure (Figs. 5 B, C). It resulted in the back-tilted, SE- to E-vergent, and "overturned" structures in the eastern flank of the Central Range (Fig. 5B). The original left-lateral sheared stretching lineations were turned into right-lateral movement in local areas, particularly in the southeastern Central Range (Fisher, 1999; Fisher *et al.*, 2001). Whereas, in the north and middle part of metamorphic core, the deep structure that had been keeping the same shear sense as before were exposed (Fig. 5C). The accreted block of arc materials gives southeastern Central Range a particular structural kinematics of left-lateral, right step transpressional environment. This situation is magnified progressively to the south.

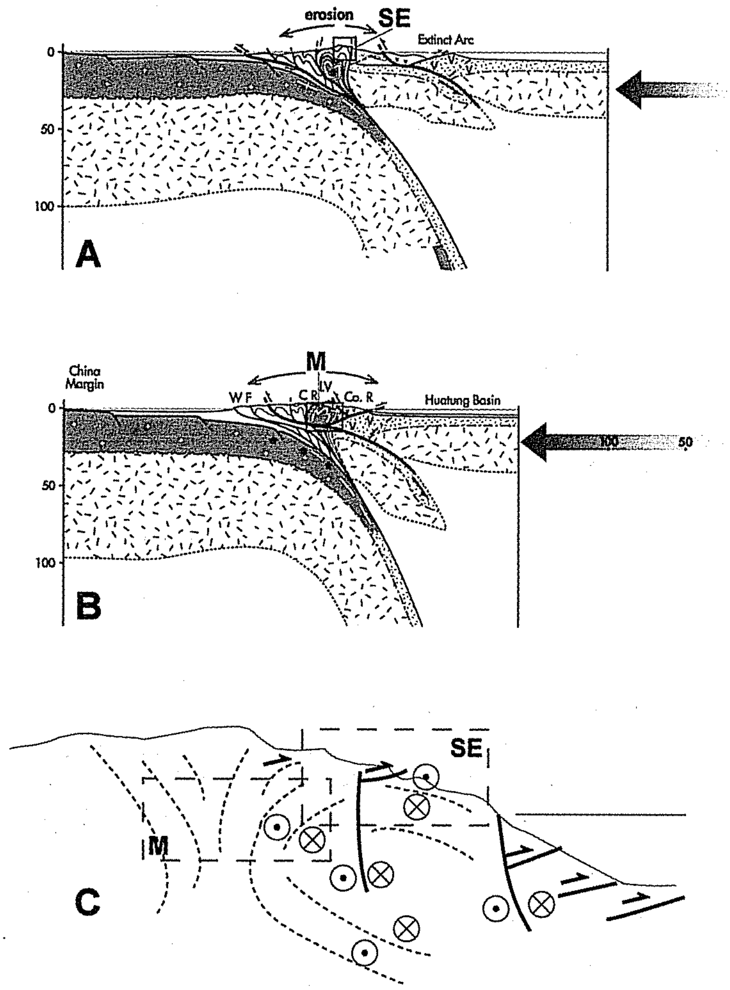

Figure 5. A, B: Tectonics history of the study area (After Malavieille et al. 2001). C. Structural interpretation of shear senses in southeastern Taiwan (SE) and middle Taiwan (M). Note that the original left-lateral sheared stretching lineations were turned into right-lateral movement in local areas, particularly in the southeastern Central Range.

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