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Impact of Basement High on the Structure and Kinematics of the Western Taiwan Thrust Wedge: Insights From Sandbox Models

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ABSTRACT

Experimental modeling allows description of the development and kinematics of structures in mountain belts formed during oblique convergence. In the collision geometry of the Taiwan mountain belt, the Chinese continental margin is oriented about N60°E, whereas the N16°E Philippine Sea plate backstop is moving toward the Eurasian plate in a N55°W direction. In addition to this oblique convergence mechanism, most of the foreland structures are strongly influenced by the shape of the backstop and structural highs. Sandbox experiments have been conducted to simulate the neotectonics of western Taiwan. The kinematics of deformation comprises a combination of compression and rotation, which results in a local partitioning between thrusting and strike-slip movements. The results of specific analog models demonstrated that: (1) most of the tableland structures in the western Taiwan, such as the Tatu, Pakua, Chungchou and Chia-Yi tablelands can be interpreted as a hinge part of drag anticline formed by fault-propagating fold process; (2) most of the basin and plain structures in the western Taiwan, such as Taichung and Chianan basins, can be interpreted as a part of piggy back basins; (3) the frontal thrust may have the first appearance of rupture in front of and between the Peikang high and the Kuanyin high; (4) NW trending link faults may be developing within the transfer zones; and (5) an escape structure formed to the south of the Peikang high can be correlated with bathymetric map and models.

(Key words: Neotectonics, Western Taiwan, Sandbox)

1. INTRODUCTION

In the last decade, research into thrust belts (e.g. Suppe, 1980; Malavieille *et al.*, 1984; Laubscher, 1985; Mattauer and Collot, 1986; Ricou and Siddans, 1986; Lacassin, 1987), experimental work (e. g. Davis *et al.*, 1983; Stockmal, 1983; Malavieille, 1984; Mulugeta, 1988;

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Colletta *et al.*, 1991; Liu and Dixon, 1991; Lui *et al.*, 1991), and discussions on 3-D kinematics of continental convergence and collision (Fitch, 1972; Chapple, 1978; Mattauer and Collot, 1986; Tapponnier *et al.*, 1986; Peltzer and Tapponnier, 1988) have provided a clearer scenario and insight into both the geometry and associated mechanism of the thrust wedges, and collision tectonics.

The Taiwan mountain belt is an active curved thrust wedge (Figure 1) and represents an ideal tectonic setting to examine the process of active faulting in relation to oblique convergence, indentation and rotation tectonics because (1) the recent kinematics of plate movement around Taiwan is well known; (2) deformation is relatively simple as the Taiwan island is isolated from mainland China; and (3) the existing geodynamic understanding of the Taiwan thrust wedge is advanced.

This paper is an attempt to use 3-D sandbox modeling to better understand the kinematics of the western Taiwan thrust wedge and to interpret the structures produced by oblique convergence, indentation and rotation tectonics.

2. PREVIOUS WORK

The Island of Taiwan is situated on the corner-shaped convergent boundary between the Eurasian plate and the Philippine Sea plate, resulted from the flipping of the subduction zone from the N-dipping Ryukyu Trench to the E-dipping Manila Trench. This results in the oblique convergence and indentation tectonics setting. In the collision geometry of the Taiwan mountain belt, the Chinese continental margin is oriented about N60°E, whereas the N16°E Philippine Sea plate backstop is moving toward the Eurasian plate in a N55°W direction (Lu *et al.*, 1997 and references there in).

Deformation and metamorphism of the Taiwan thrust wedge have been well studied, and different models are presently advocated (Suppe, 1980; Davis *et al.*, 1983; Suppe, 1983; Barr and Dahlen, 1989; Dahlen and Barr, 1989). However all these models are constrained by frontal and normal convergence. Finite element methods have been conducted in order to reconstruct the paleostress fields (Huchon *et al.*, 1986; Lee, 1986; Hu *et al.*, 1996; Jeng *et al.*, 1996; Hu *et al.*, 1997) and to account for the observed transcurrent movement (Biq, 1972; Fitch, 1972; Bowin *et al.*, 1978). However, these methods are limited to two dimensions and cannot easily take into account for the large displacements occurring on the long and narrow shear zones.

Lu and Malavieille (1994) used 3-D sandbox modeling experiments (Figure 2A) to illustrate the kinematic processes of the Taiwan thrust wedge development during oblique indentation. The major result obtained from this model is the development of an asymmetrical thrust wedge with different tectonic domains. The kinematics of deformation comprises a combination of compression, rotation and extension, which results in a local partitioning between thrusting and wrenching. This experimental model shows that the faults or shear zones went through a rotation centered at the indentation point of the backstop and induced a series of transcurrent and bookshelf faulting.

However, this simple preliminary work cannot account several features of western Taiwan.

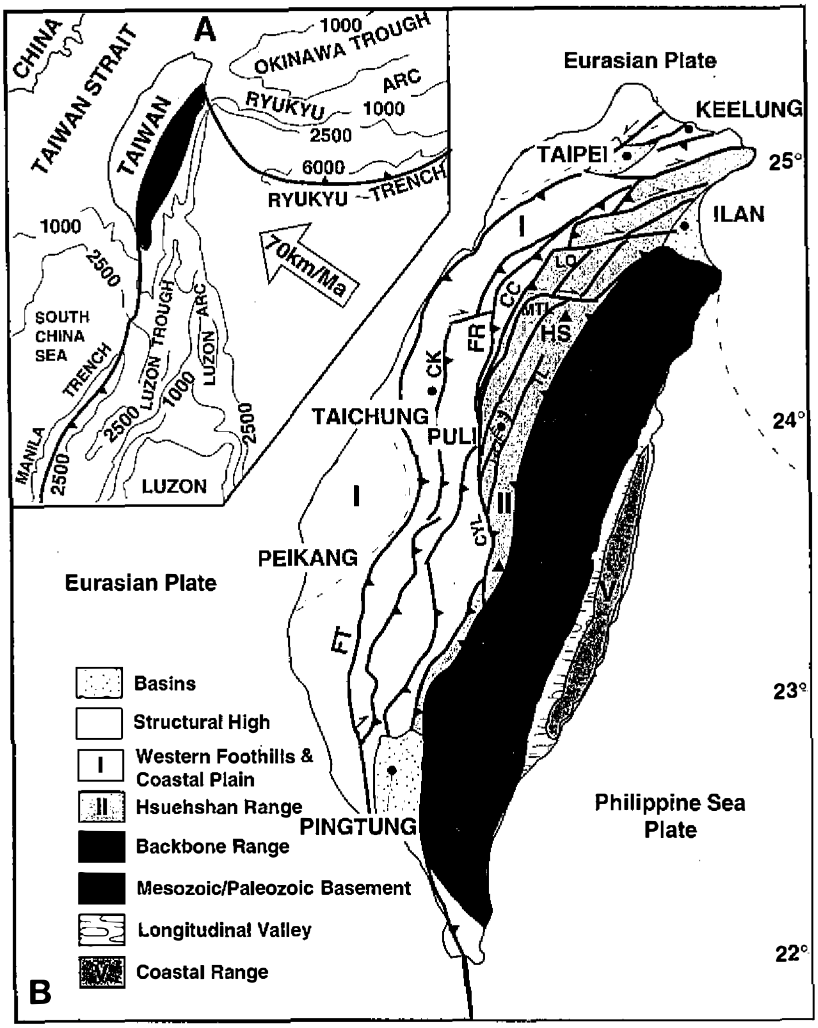


Fig. 1. A. General tectonic map of Taiwan (upper left corner): Isobaths in meters, large open arrow showing direction of convergence (Philippine Sea plate relative to Eurasia). B. Main tectonic units. (Compiled from Ho, 1986b; Biq, 1989). Major thrust faults as heavy lines with triangles on the up-thrust side. Small arrows indicate the sense of strike-slip movement. Map of basement highs are modified from (Chang, 1971; Chou, 1973; Lee *et al.*, 1973; Meng, 1971; Meng and Chou, 1962; Tang, 1964; Wang, 1965; Wang, 1967). CC: Chiuchih Fault, CK: Chukou Fault, CYL: Chenyulanchi Fault, FR: Frontal Range Thrust (Chishan-Chinkuashih line), FT: Foothill Thrust (Kaohsiung-Tanshui line), LO: Loshan Fault, LS: Plate Boundary Fault (Hungchun-Ilan line), MTL: Matalanchi Fault, TL: Tili Fault; YS: Y¸shan, HS: Hsuehshan.

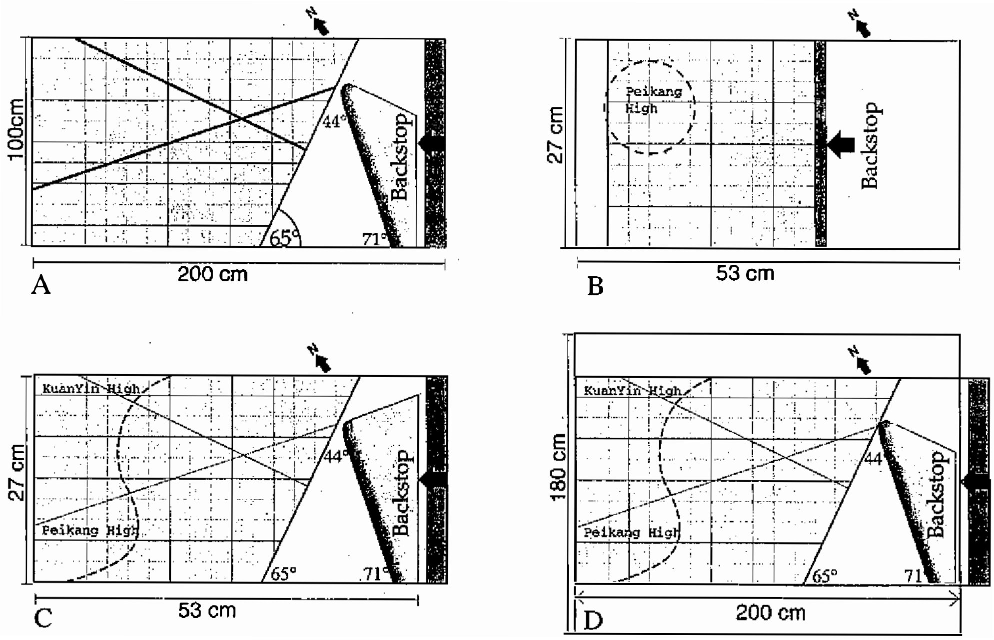


Fig. 2. Experimental boundary conditions of models: A. Oblique convergence and collision model (Lu and Malavieille, 1994), backstop dip =30, low basal friction and free borders. Thickness of sand cake = 1.5 cm. B. Diameter of basement high = 12 cm, low basal friction, thickness of sand cake = 1.5 cm to right end and decrease to 0 at left end. C. Backstop dip =15, low basal friction thickness of sand cake = 1.1 cm. D. backstop dip =15, low basal friction and free borders, thickness of sand cake = 1.5 cm.

For example: (1) the sigmoidal shape of the mountain front; (2) the Taiwan thrust wedge is much thinner to the south; and (3) the thrust spacing is smaller in the Western Foothills and relatively large in the Hsuehshan Range. These structural features were well illustrated by Biq (1989) and are shown on the geological map of Taiwan. We consider the major discrepancies between the actual situation and this work to be the result of ignoring the existence of basement structure to the west.

To better describe and understand the complex structures that may have resulted from the effect of basement structure, we used the same experimental modeling approach as Lu and Malavieille (1994) with emphasis on the important boundary conditions in the basement morphology.

3. TECTONIC SETTING: THE TAIWAN MOUNTAIN BELT

The Taiwan Mountain Belt (Figure 1B) is an active curved collision belt and thrust wedge

(Chai, 1972; Suppe, 1981 and 1987; Barrier, 1985; Angelier, 1986; Ho, 1986 and 1988; Lu and Hsu, 1992), which developed as a result of the late Cenozoic oblique convergence between the Philippine Sea plate and the Eurasian plate (Figure 1A). A characteristic feature of the Taiwan Mountain Belt is the S shape virgations of the general structural trends (Lu, 1994): (1) Northern Taiwan (i.e., to the north of 24.5°N, see Figure 1B). The difference in strikes between these segments of the curved belt ranges from 40° in the outer zones (Western Foothills, unit I in Figure 1B) to about 90° in the inner ones (the eastern boundary of the Backbone Range - unit III), as Figure 1B shows. On average, the mountain ranges of Taiwan trend NNE-SSW (azimuth 020) south of 24.5°E, whereas they trend ENE-WSW (azimuth 070) in northeastern Taiwan, near 25°N -121.5°E, which represents an average difference of 50 in strike (Figure 1B). (2) Central Taiwan (between 23.7°N and 24.5°N). The mountain ranges of the Taiwan foreland trend NNE-SSW (azimuth 020) south of 24.5°E, whereas they trend NW-SE (azimuth 330) to the south of Taichung. Azimuth 350 , on average, along the contact of Hsuehshan Range (unit II) and Western Foothills, and nearly N-S along the contact of the Backbone Range and the Hsuehshan Range). (3) In southern Taiwan (to the south of 23.7°N) a complicated transfer zone occurs (to be discussed later). (a) Along the contact of the Western Foothills and the Coastal Plain, the mountain ranges trend NE-SW north of 23.5°N, azimuth 030 on average, whereas they trend N-S south of 23.5°N. (b) Along the contact of the Hsuehshan Range and the Western Foothills the mountain ranges trend NNW-SSE north of 23.5°N, azimuth 345 on average, whereas they trend NE-SW, azimuth 030 on average, south of 23.5°N. (c) Along the contact of Backbone Range and Hsuehshan Range the mountain ranges trend NNE-SSW north of 23.5°N, azimuth 345 on average, whereas they trend N-S, azimuth 005 on average, south of 23°N.

The stratigraphy of the Coastal Plain and the Western Foothills is known as a passive margin shallow marine clastic sequence of the Oligocene-Miocene-Quaternary age. The strata are fossilferrous and little metamorphosed, and they have been deformed by folding and faulting. However, their stratal continuity has not been severely disrupted. The stratigraphy is divided naturally into two sequences by a regional lower Oligocene unconformity (Huang, 1982). The units near the unconformity function widely as the basal décollement in the Western Foothills fold-and-thrust belt (Suppe, 1987). They are succeeded by a Pliocene and Pleistocene a four-kilometer thick molassic sequence of foreland basin sediments, derived from the eastern mountain chains. No clastic sediment was found encroaching from the east before 3 Ma (NN15) (Huang, 1976). The Backbone Range Slate Belt (unit III) is interpreted as a part of the Miocene accretionary wedge. The boundary between the Backbone Range and the Hsuehshan Range (unit II) is considered as the boundary between the Philippine Sea plate and the Eurasian plate (Lu and Hsu, 1992). According to these interpretations, the western boundary of the Paleozoic/ Mesozoic basement is regarded as the crystalline leading edge of the overriding plate and the Backbone Range Slate Belt is inferred to represent the remnants of a Miocene accretionary wedge. The contact between the Paleozoic/Mesozoic basement and the Backbone Range is marked by a mylonitic fault zone associated with a series of thrust and ductile shear structures in the Backbone Range Slate Belt. The boundary between the Hsuehshan

Range and the Backbone Range on the Central Cross Island Highway is presently mapped as a major west-dipping back thrust (the Lishan fault), based on up dip stretching lineations and reverse movement sense as indicated by asymmetric pressure shadows in the slate units (Clark *et al.*, 1993). Actually this fault separates the active part of the Taiwan Mountain Belt from the older metamorphic domain structured earlier than the current collision. Our study is mainly concerned with the post-collision deformations to the west of the Lishan fault, in the foreland thrust belt. Therefore the Mesozoic/ Paleozoic metamorphic tectonic units situated east of this boundary fault may be regarded as a relatively rigid backstop during the active foreland wedge building.

4. EXPERIMENTAL SET-UP

The principle of our apparatus is similar to that used by Davis *et al.* (1983), except that our device is large enough to simulate oblique convergence boundary conditions. Sand constitutes a good analog to the brittle Mohr-Coulomb behavior during the superficial deformation of sedimentary materials (Hubbert, 1951; Horsfield, 1977; Byerlee, 1978; Krantz, 1991). In our study we used dry cohesionless quartz sand. It exhibits a Navier-Coulomb rheology and has a friction angle of about 30, similar to many sedimentary rocks. This sand has a density of 1.6 g/ cm^3 and a fairly homogeneous grain size, mostly ranging from 150 μm to 300 μm based on sieve analysis. Liquid dye was used to mark the sand layers without altering its mechanical properties.

In addition to those used in the to Lu and Malavieille (1994) experiments, three additional kinds of boundary conditions (Figure 2 A) were built by laying horizontal layers of colored sand onto a plastic plate (Figure 2 B-D). A rigid mobile backstop pushes the sand over the basement plate and generates a Coulomb thrust wedge. The amount of shortening is large enough to reach the critical taper of the wedge, to which a shortening of 20 cm is required. A sufficient width, greater than 30 cm, minimizes the influence of boundary effect on the variation of lateral deformation to be investigated. In experiments C and D, the 3D basement shapes were built mainly on the basis of aeromagnetic profiles (Bosum *et al.*, 1970) and other published profiles (Tang, 1964; Chiu, 1973; Chou and Yang, 1986). A grid of colored lines was lain on the models allowing observation of the kinematics of surface deformation. The experiments were video recorded and photographed at small shortening intervals. After deformation, the models were impregnated with water and cut along directions perpendicular, parallel and oblique to the backstop in order to reconstruct the 3-D geometry of structures.

5. EXPERIMENT RESULTS

A detailed description of the experiment for the genesis and the evolution of the thrust wedge has been given in Lu and Malavieille (1994). This paper focused on the impact of the basement highs on structures observed in thrust wedges and then compared with the structures described in Taiwan. Western Taiwan is essentially studied and discussed, since the previous model (Figure 2A) did not involve these under-lain basement highs.

The experimental results are described as follows:

5.1 Experiment B

We began to modify the previous model (Figure 2A) by using a dome-shaped glass to represent the Peikang High (Figure 2B). A thrust wedge built up at the beginning of the collision. At 15 cm of shortening, the wedge was constructed by ~2 cm-spaced imbricate thrusts. As the thrust front approached the basement high, the propagation of the thrust front was retarded in front of the basement high (see Lallemand *et al.*, 1994). Nevertheless, the thrust fronts advanced more to the south of the basement high upon subsequent shortening. As a result, a curvature of the thrust front in association with an escape structure in the southwestern part of model was yielded (Figure 3A).

5.2 Experiment C

This experiment series (Figure 2C) comprises triplicate experiments with the same testing conditions, to determine the reproductivity of the experiment. The results of each experiment are consistent with one another. A curved thrust wedge built up at the beginning of the collision. At 15 cm of shortening, the wedge was constructed by ~1 cm-spaced imbricate thrusts (Figure 4A). While approaching the basement high underneath the sand layer, the thrust front ad-

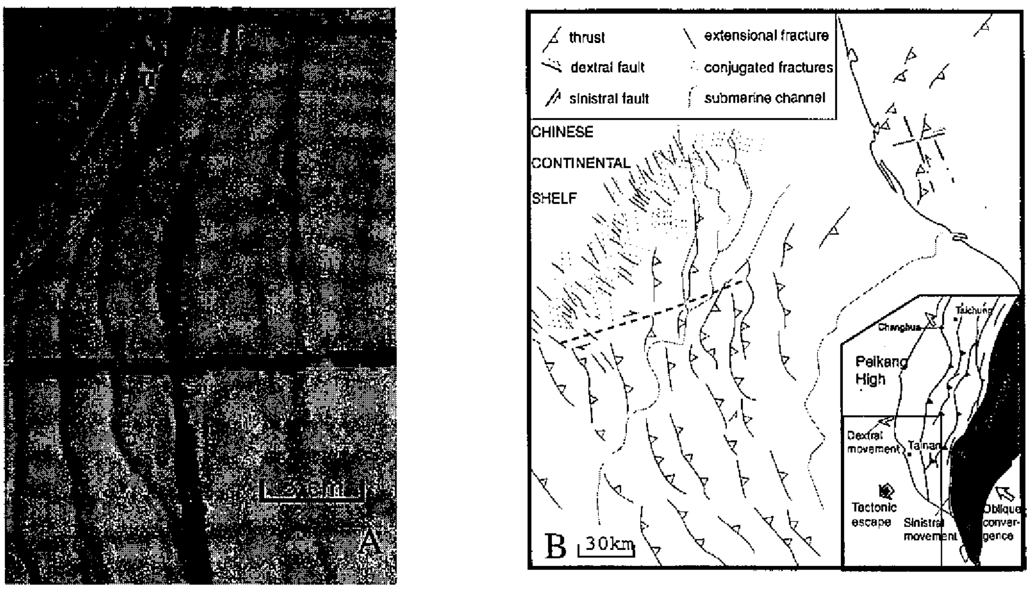


Fig. 3. A. Experimental result of experiment B (Figure 2 B) shows tectonic escape to south of basement high. B. Structural sketch map of southwestern Taiwan based on bathymetric map of ACT cruise (Lallemand *et al.*, 1996).

vanced more in the region around the Peikang high and the Kuanyin high. The sudden appearance of a thrust segment occurs in this area during the subsequent compression (marked as F. A.T.S., first appearance of thrust segment, in Figure 4A). Subsequently this segment was further elongated along the strike, while the segment, which developed last, was elongated in the south. A northwest oriented link fault was then (after 25 cm of shortening) developed between these two thrusts (Figure 5A).

5.3 Experiment D

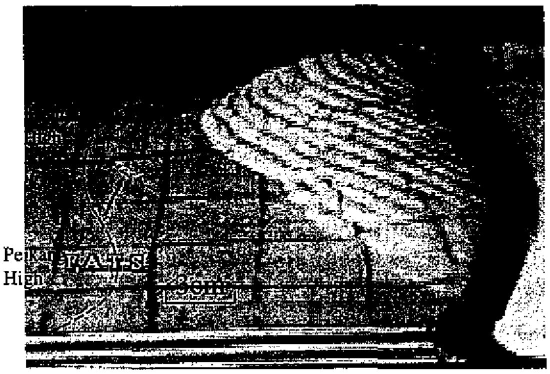
This experiment series (Figure 2D) comprises triplicate experiments with the same testing conditions. Because experiment C was not large enough to accommodate the whole mountain range in western Taiwan, we then continued with a larger sandbox, 1.8m X 2m in size, to verify whether the neotectonics of the northern and the southern part of the western Taiwan deformation belt can be simulated.

Figure 7 shows the evolution stages of the thrust wedge. The results indicate that the beginning stages were similar to those in experiment C, i.e. curved thrust wedge, with the first appearance of a thrust segment in front of and between the two basement highs and link faults. In contrast to the previous experiment, the final stages formed an asymmetrical mountain belt with a narrower southern end and a sharp elevation change. (Figure 7)

6. APPLICATION TO REGIONAL GEOLOGY OF WESTERN TAIWAN

6.1 Escape Tectonics in the Southwestern Region Offshore From Taiwan

The Peikang high is beneath the middle part of western Taiwan and the adjacent Taiwan Strait. The drilling data and the leading edge of the foothills thrust front sketch out the semicircular shape of this structural high (Figure 1). The earthquakes with epicenters in the inner part of this thrust-rimmed semicircle are apparently fewer than those with epicenters both in the peripheral zone and the areas immediately on the other side of the boundary thrust. This significant map-pattern shows clearly that the pre-Tertiary Peikang high underlies the coastal plain and is distinguished by its steadfastness in a mobile belt. Such a crustal mass of great rigidity is very likely to play an important part in determining the superficial strain pattern high above. The Chinese continental margin is oriented in a N55°E direction in this sector, and thus a large transfer zone is associated with the increasing sediment thickness to the south, during the plate convergence (Figure 3B). The thrusts and folds along the deformation front change their trend continuously into a curve form convex to the WSW (Figure 3B). This demonstrates a large dextral transfer zone around the shelf-slope break of the SE China continental margin, the structure to the south being dragged to the SW. This indicates that the thrust to the SW migrates faster than those around the Peikang basement high. As a result, the sediments in southwest Taiwan are now escaping to the SW. Along the shelf-slope break three sets of systematic fractures are evident: two of them are conjugated fractures, the third one is parallel to the convergent direction and bisects the direction of the previous fracture sets. Sandbox models have been performed to demonstrate the kinematics of this escaping tectonics in this paper.



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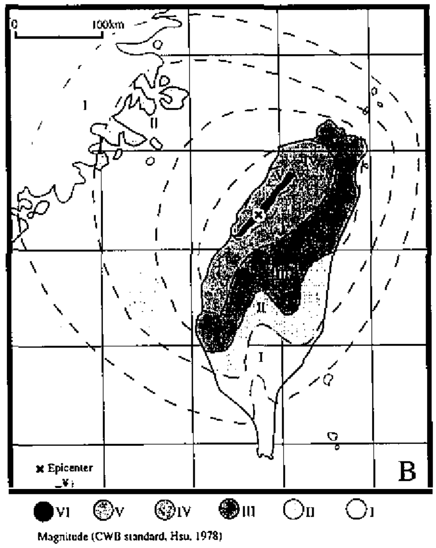
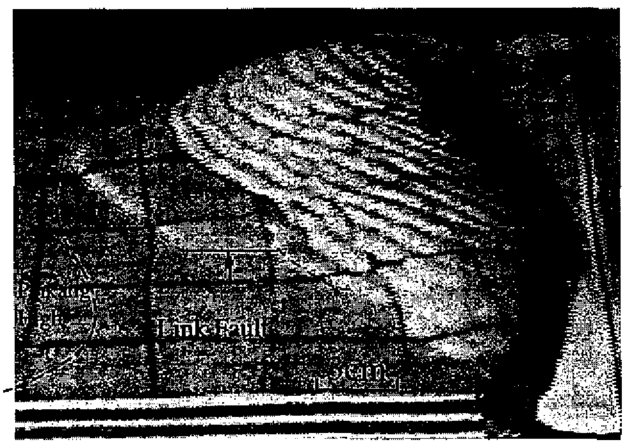


Fig. 4. A. Experimental result of experiment C (Figure 2 C) shows first appearance of thrust segment (F.A.T.S.) in front of and between the two basement highs. B. Magnitude contour of 1935 earthquake around Taiwan (after, Hsu, 1978).



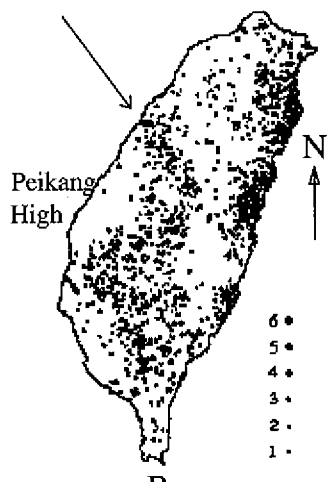


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Fig. 5. A. Experimental result of experiment C (Figure 2 C) shows development of northwest-directed link faults between two thrusts. B. Distribution of earthquakes in Taiwan based on data of the year 1992 (Shin and Chang, 1992). Arrowhead line indicated the possible trace of link fault zone.

The southern boundary of the Peikang high is underneath the shelf-slope transition of the Chinese continental margin. To the south of the Peikang high, there is a large transtension zone (Yang *et al.*, 1991; Biq, 1992; Yang *et al.*, 1994). Earthquake focal mechanisms indicate some extension events and geomagnetic data show a diachronic clockwise rotation in this area (Yeh, 1991; Horng, 1991). This suggests that a dextral shear zone bound the southern edge of the Peikang high. As the conjugate part, the boundary between the Western Foothills and the eastern backstop (Backbone Range) is a sinistral shear zone (Figure 3B; Biq, 1989). The shift in velocity of GPS stations (Yu *et al.*, 1997) of the southwestern Backbone Range to the E-W direction instead of the general NW convergent direction also suggests that there might be left lateral movement along this boundary. In the Kaohsiung- Pingtung coastal area, the station velocities are even directed toward the southwest. These arguments suggest that the area between the two shear zones mentioned above is escaping toward the SW (Lu, 1994).

6.2. The Potential of Earthquake in Western Taiwan

Friction of faults is often unstable, and slip occurs rapidly as a rupture dynamically propagates over the fault surface. These sudden motions generate seismic waves and this is the mechanism of the most common and important type of earthquake (Scholz, 1990). The geologist G. K. Gilbert (1884) first clearly made connection between earthquakes and dynamic faulting and its relationship to tectonic processes. He had seen the immediate aftereffects of earthquakes and had remarked on the fresh-appearing scarps that so often front the mountain ranges. He concluded that repeated ruptures along these faults produced the elevation of the mountain.

The energy released from the suddenly occurring thrust movement and the link fault deformation can be reasonably assume to provides the source of the major local earthquake in this area, namely, the first appearance of thrust segment in front of and between the Peikang high and the Kuanyin high. Coincidentally, a major earthquake occurred in 1935 located in this specific area. Figure 4B shows the magnitude contour of the 1935 earthquake around Taiwan (Hsu, 1978), in which the largest magnitude contour (black area in Figure 4B) coincides with the first appearance of the thrust segment. The development of the northwest-directed link faults can be correlated with the transform fault or transfer fault described in other papers (Biq, 1976; Biq, 1992; Deffontaines *et al.*, 1997). In this paper we emphasize the significance of the forming mechanism of these transfer faults. Because these faults remain active during the thrust front migration, they might cumulate the strain energy, discontinuously release the energy through local earthquakes and consequently give rise to earthquake concentration zones. Figure 5B shows the distribution of earthquakes in Taiwan based on the events recorded in the year 1992 (Shin and Chang, 1992), in which the NW-directed earthquake concentration zones are well-illustrated (arrows).

6.3 Impact of Basement High on the Morphotectonic Units of Western Taiwan-insight From Analog Models

Interpretation of natural tectonic situations with the help of model experiments must be done with caution. Sand box experiments focus mainly on brittle to brittle-ductile structures in the thrust wedge, to the exclusion of equally important ductile deformation. The influence of anisotropic layering on the deformation of sediments is also not accounted for. However, if one merely looks at geometric and kinematic aspects of the coulomb wedges, analogies between figure 1B and figure 7E warrants attention.

In kinematics, basin and tableland topography in association with the 3-D morphologic map of western Taiwan can be interpreted as piggy back basins and anticlinal terraces. For instance, Figure 6A shows the morphology to be similar and can be interpreted as the Taichung Basin, the Tatu Terrace and the Pakua Terrace (Figure 6B). Figure 6C shows the vertical section in association with interpretations (Figure 6B) within the model.

The 3-D topography of the deformed model was replicated by pouring silicon over the model to form a mold, casting with plaster, and finally digitizing and processing using a computer (Figure 8A), The digitized data were than used to generate 3D oblique views with different shading which help with structural interpretation. For example, in Fig 8A the light source is from the N30°E direction and the large NS trending structure units are well defined. As shown in Figure 8B, this topography exhibits the following features: (1) the major structure units of part of the Hsuehshan Range and the Western Foothills are consistent with the actual geological units; (2) most of the basins in western Taiwan can be interpreted as piggy back basins formed during fault-propagating folding; (3) the thrust and backthrust have intensively developed in the eastern part; (4) wide-spaced thrusts and strike-slip faults have developed in the middle part; and (5) narrower spaced thrusts have developed in the Western Foothills.

7. CONCLUSIONS

The results of these analog models suggest that: (1) the geometrical similarity of the structure of the model and the regional structures suggests that the same mechanism can be apply to the actual tectonic setting as we performed in the analogic models; (2) the structural units of the foreland thrust wedge and the tectonic style are strongly influenced by the shape of the backstop and the geometry of basement highs; (3) the kinematics of deformation comprises a combination of compression and rotation, which together result in a local partitioning between thrusting, transcurrent and strike-slip faulting; (4) the contraction against structural highs is the main cause for the curvature of the thrust front and escape tectonics of western Taiwan; (5) in fault kinematics, the first appearance of thrust segments, and the NW link transcurrent faults between these segments, might be correlated with the earthquake distribution in western Taiwan.

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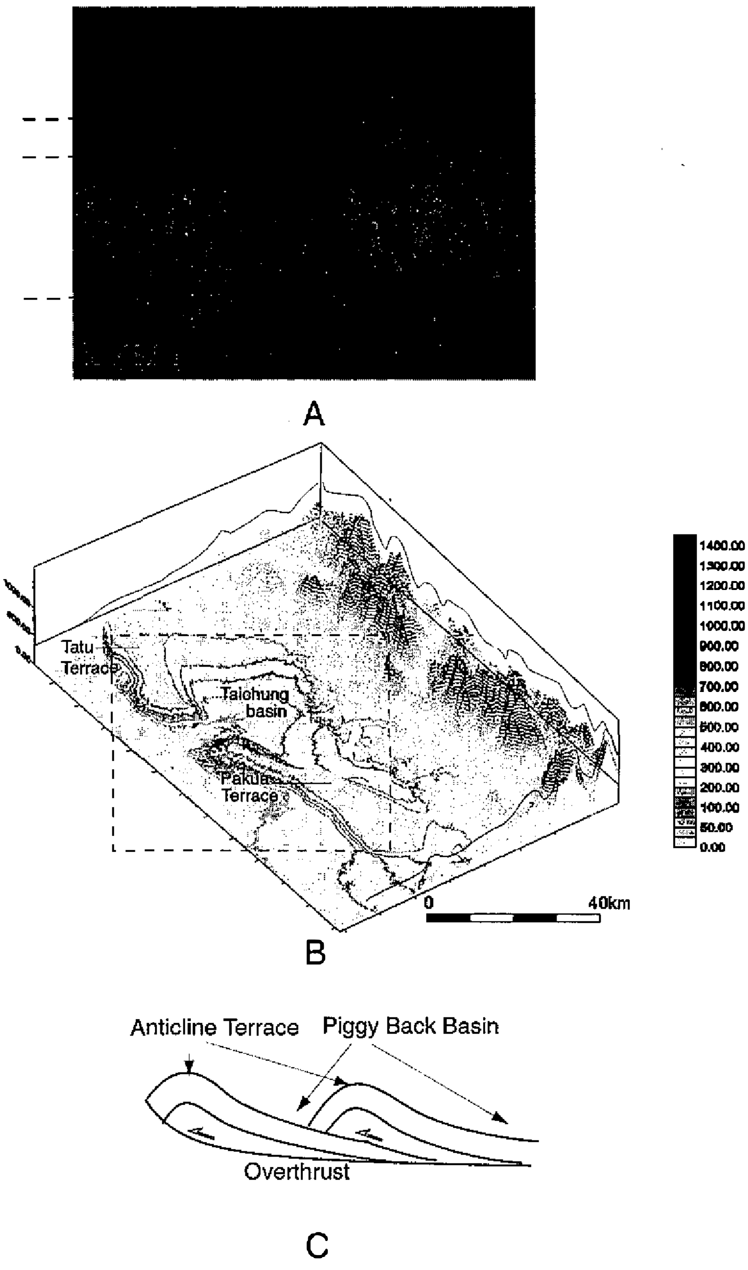


Fig. 6. A. Experimental result of experiment C (Figure 2 C) demonstrates the similarity of morphology in areas indicated by arrows with inset of B. B 3D morphology of Taichung Basin, Tatu Terrace and the Pakua Terrace from DTM (digital terrain model) data. C. Schematic sketch of the vertical sections

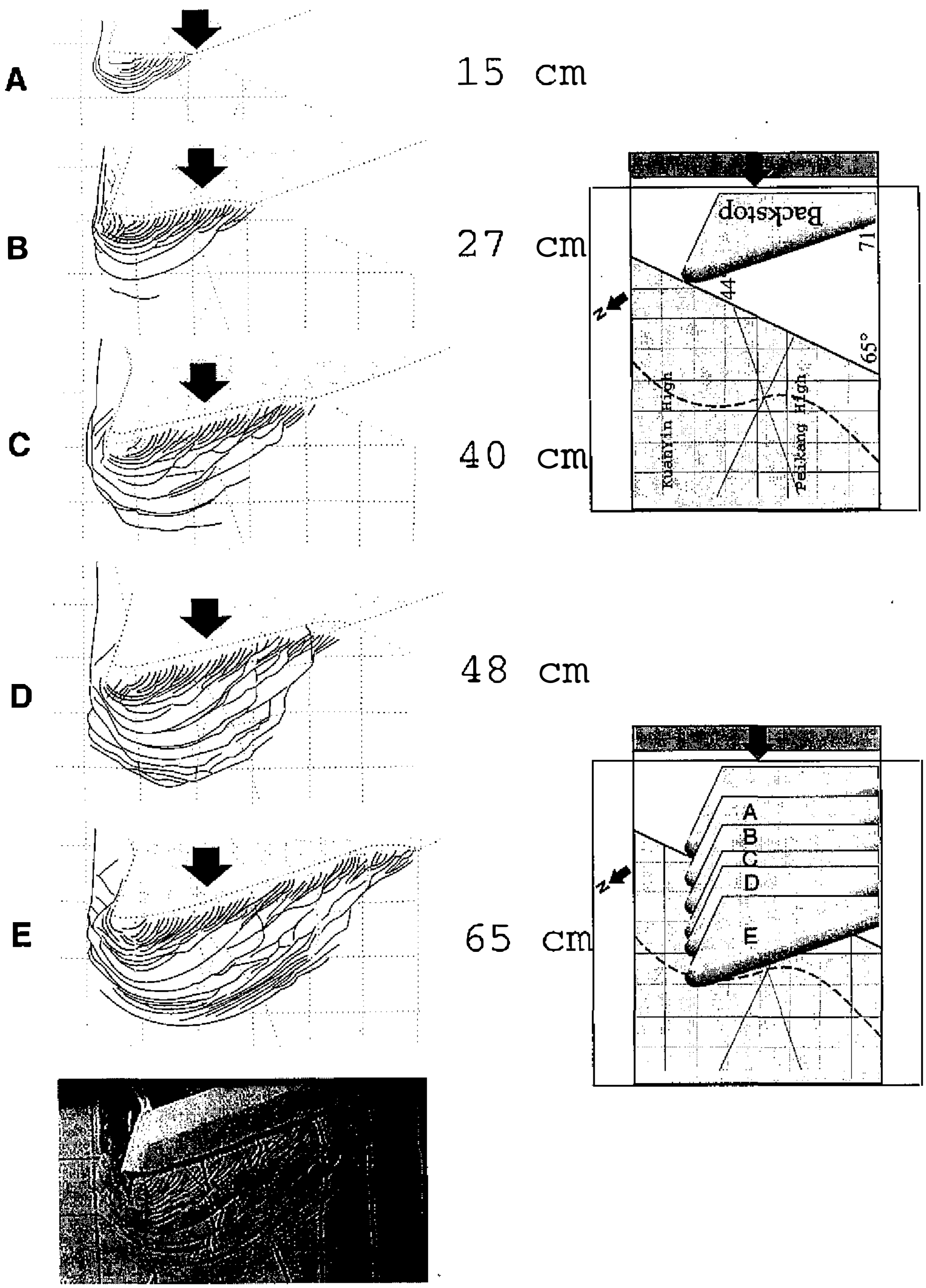
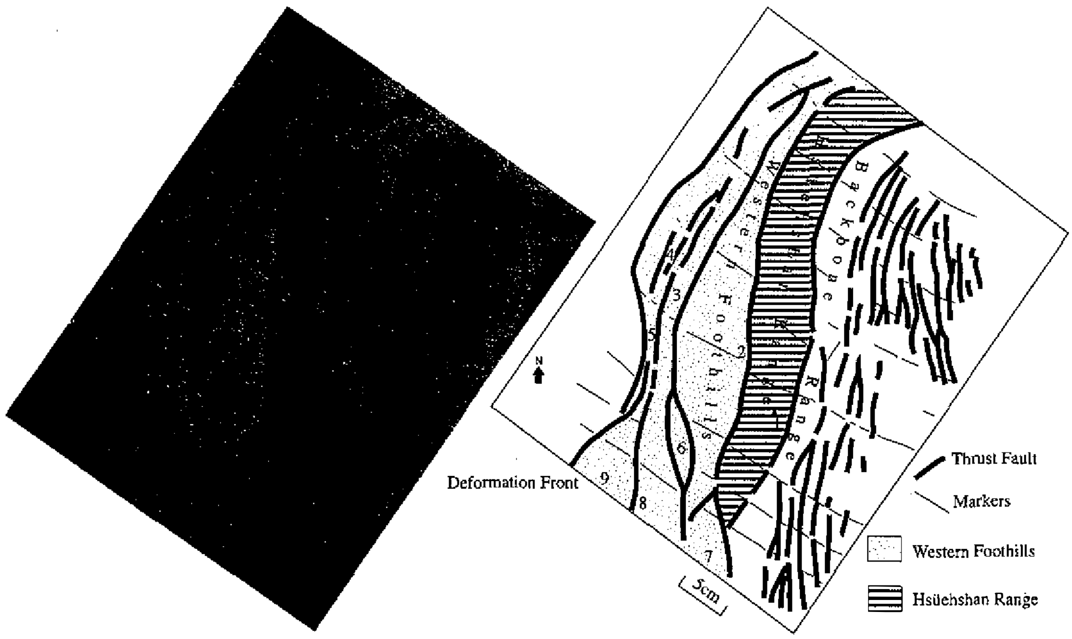


Fig. 7. Evolution stages of experimental result of experiment D number 2 (Figure 2 D)



A B

Fig. 8. A. 3-D shaded morphology process by computerized digital data after plaster mode. B. Morphology of plaster mode of experiment C (Figure 2 C), compared with 3D topography of Taiwan. Keys: 1. Yushan; 2. Puli Basin; 3. Taichung Basin; 4. Tatu Terrace; 5. Pakua Terrace; 6. Tsengwen Basin; 7. Pingtung Plain; 8.Chungchou Terrace; 9. Chianan Plain.

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