

Active Deformation and Paleostress Analysis in the Pakua Anticline Area of Western Taiwan

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ABSTRACT

The active Quaternary deformation of the Pakua anticline area in the foreland belt of western Taiwan has been examined based on field investigation as well as paleostress analysis. The strata exposed in the Pakua area are composed of Quaternary molasse sediments of conglomerate and sand or sandstone (Toukoshan Formation). The seismic reflection profiles show that the main structure of this area is characterized by frontal thrust (the Changhua Fault) and the associated anticline fold (the Pakua anticline). Three principal deformation structures at outcrop scale have been recognized: (1) compressional fracture of pebbles, (2) strike-slip fault, and (3) normal fault. It indicates that the Pakua anticline area has experienced a complex history of tectonics including different stress regimes of contraction, strike-slip and extension. The study of paleostress shows: (1) compression in a WNW direction as deduced from both the fracturing of pebbles and strike-slip faults; and (2) the occurrence of E-W and N-S extension accommodated by normal faulting, especially in the northern part of the Pakua anticline area. The WNW compression, being perpendicular to the trend of the frontal thrust and the regional major folds, represents the regional compressional stress direction in the foreland of Taiwan. The normal faulting in this fold-and-thrust belt suggests that the importance of the force of uplift/gravitation resulted from the release of the frontal thrusting and/or the transtensional stress regime of possible regional transfer faults.

(Key words: Deformation, Fault, Pakua, Quaternary, Paleostress, Taiwan)

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1. INTRODUCTION

The Pakua area, an anticline composed of Quaternary terrestrial sediments, is located besides the thrust front of the Foreland Belt in western Taiwan, near the city of Taichung (Figure 1). The Pakua anticline is bounded by the Changhua Fault (frontal thrust) to the west, and by the piggyback Quaternary basin around Taichung, to the east. The Pakua anticline describes a sinuous path trending from NNW in the north to N-S in the south. It is about 30 km long and 5 - 10 km wide.

The Toukoshan Formation, a Quaternary molasse deposit, constitutes the principal rock composition of the Pakua anticline (Figure 2). Two lithological units have been recognized in the Toukoshan Formation: (1) Hsiangshan Facies, which is composed of sand or sandstone with intercalated conglomerate, forms the lower Toukoshan Formation (Chang, 1955; Sun, 1965; Chang, 1971; Chou, 1971), and is about 0.5-1.8 Ma old (Chi and Huang, 1981: nannofossil study in the Miaoli area); and (2) Houyenshan Facies, which consists of conglomerate with thin sand layers, makes the upper Toukoshan Formation, and is about 0.5-0.9 Ma old (Chi and Huang, 1981: nannofossil study in the Miaoli area; Liew, 1985 and 1988: pollen analysis in Taichung area). The study of sedimentology and stratigraphy shows that between these two facies there exists a transition zone which is several hundred meters thick (Chang, 1971), and is less than 0.9 Ma old (Chi and Huang, 1981). There are also the lateritic and terrace deposits which overlay the Toukoshan Formation, especially on the ridge portion and the two flanks of the Pakua anticline (Figure 2).

On the one hand, the Pakua anticline represents the young molasse deposits with rapid sedimentation during the uplifting of the Taiwan mountain in the Quaternary. On the other hand, it also indicates that an even younger tectonic deformation exists, which affects these Quaternary sediments. The Pakua area thus gives a good opportunity to study both the active tectonics in the foreland belt of western Taiwan, during the arc-continent collision (Philippine Sea plate and Eurasian continental plate), and the relationship between sedimentation and tectonics which are generally interrelated in western Taiwan (Ho, 1986; Reed *et al.*, 1992; Delcaillau *et al.*, 1993; Lee, 1994).

This paper aims to reveal the characteristics of neotectonics and its associated deformation structures in the Pakua anticline area. The study is based on field investigation, seismic reflection profiles on a regional scale, and paleostress analysis. A model of a major transfer fault zone is proposed to explain the extensional/transensional stress regime of the northern part of the Pakua anticline.

2. GENERAL GEOLOGICAL STRUCTURE

Western Taiwan is characterized by a thrust-and-fold zone. Figure 1b shows the general geological structures of the foothills in this region. We find that within the Plio-Pleistocene terrain there are three major thrusts which are commonly accompanied by gentle anticlinal folds on the hanging walls (Figure 1b).

Figure 3 illustrates the evolution of the thrust fronts in the foothills and the relationship between erosion, sedimentation and tectonics. By the early Pleistocene (about 2 Ma), the first phase of the Toukoshan Formation (Hsiangshan Facies) was deposited (Chi and Huang, 1981)

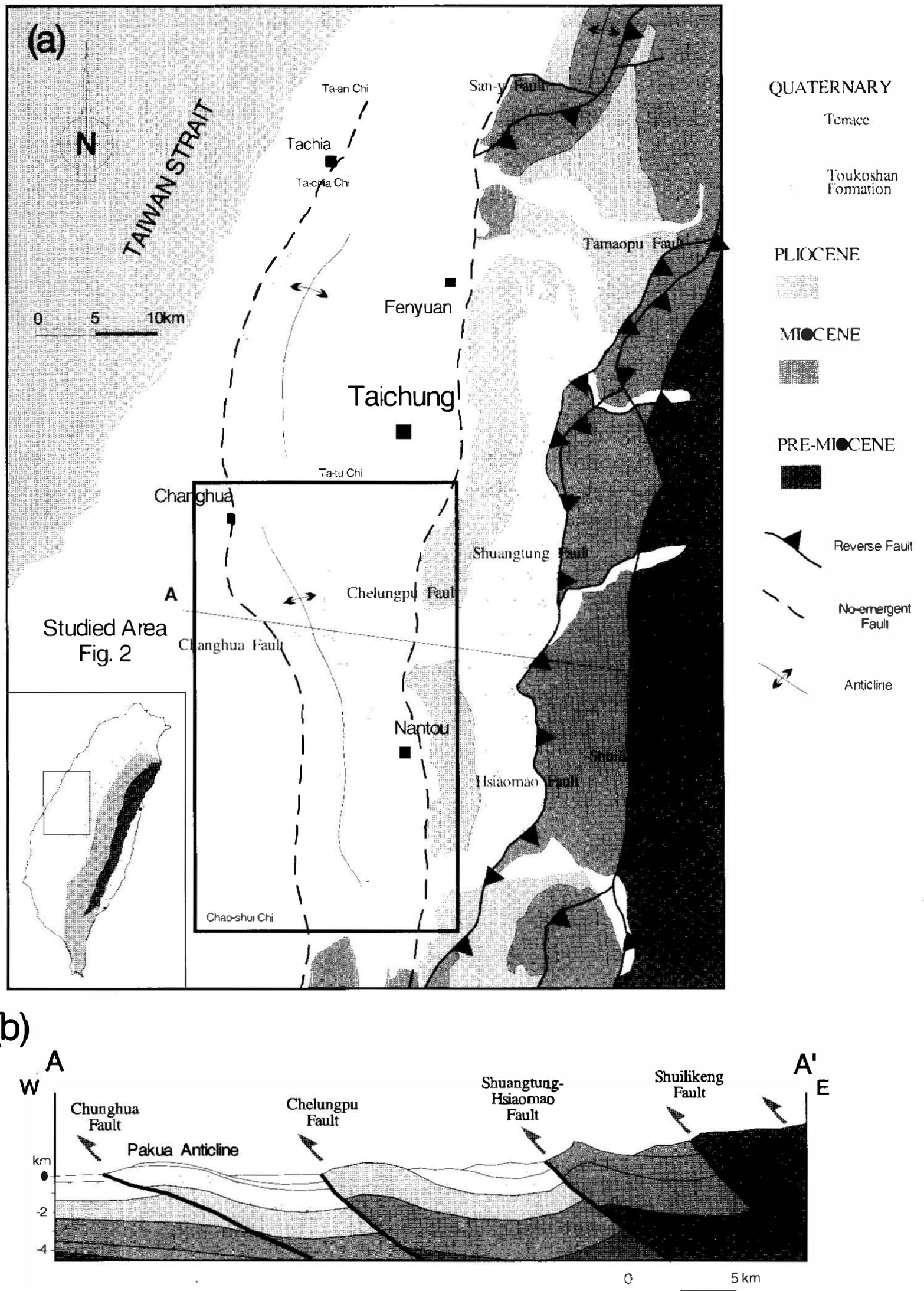


Fig. 1. (a) General geological map of western Taiwan near Taichung area (modified after CPC, 1971, scale 1:200 000). (b) Geological cross-section of the western foothills in Taichung area. The Pakua anticline (in the far west) shows the structural characteristics of thrust-and-fold in this area.

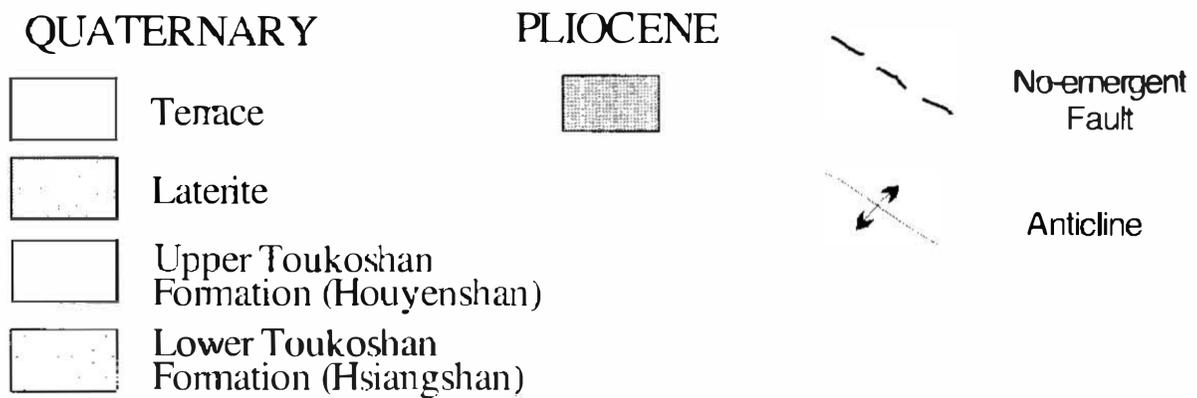
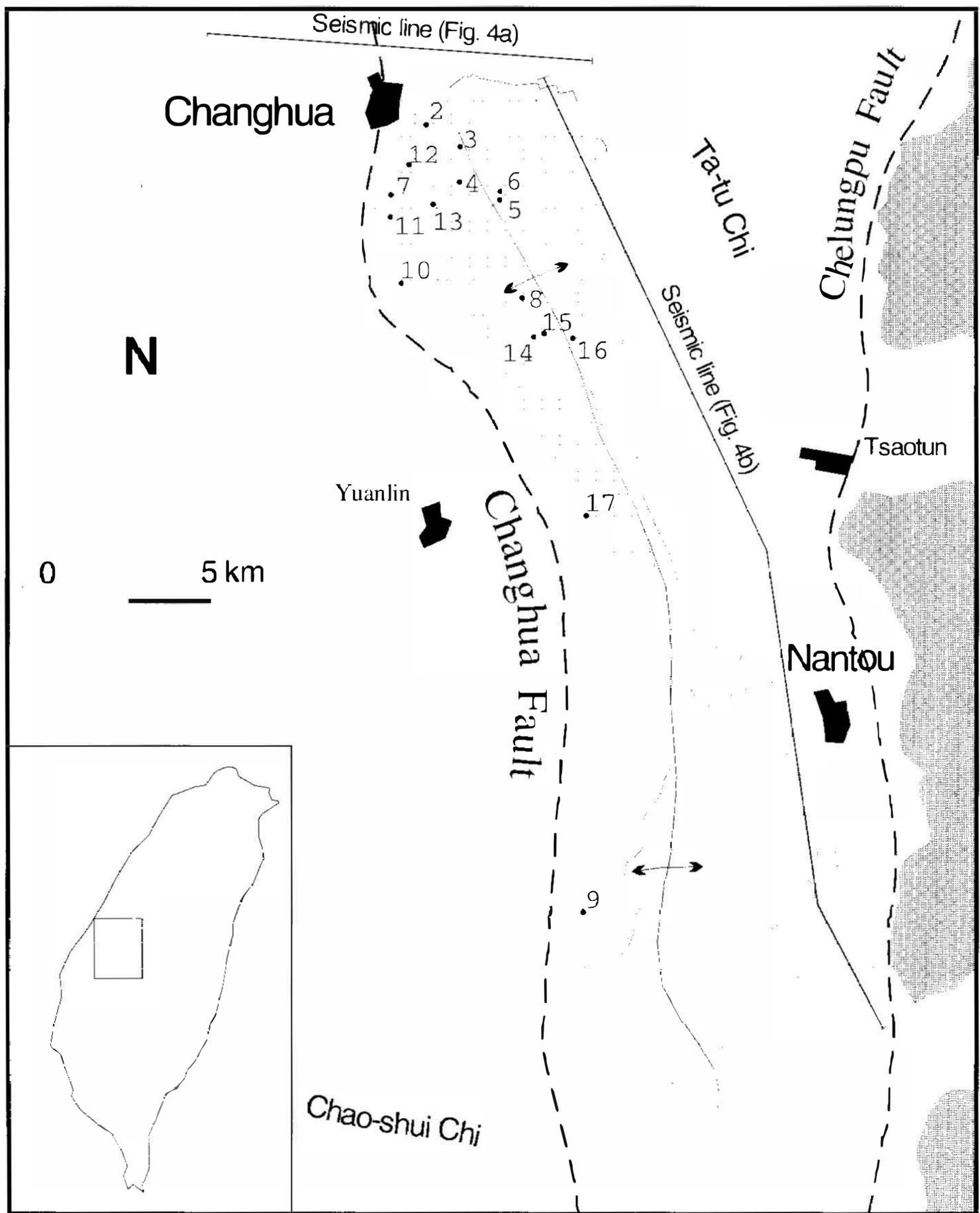


Fig. 2. Geological map of the Pakua anticline area. The numbers show the outcrop sites. The seismic lines represent the locations of seismic profiles in Fig. 4.

to the west of the thrust front because of the westward thrusting of the Shuilikeng Fault, which was associated with the rapid uplifting of the Central Range to the east (Figure 3a). During this time, the uplifted Central Range would be a good candidate to provide the sediment source of the terrestrial Toukoshan Formation. As the westward frontal thrust migrated to the Shuangtung-Hsiaomao Fault (Figure 3b) by the Middle Pleistocene, the second phase of the Toukoshan Formation (Huoyenshan Facies) occurred (about 1 Ma, Chi and Huang, 1981; Liew, 1985). The frontal thrusts continued to move to the west, producing the Chelungpu Fault, and then the Changhua Fault (Figure 3c) which deformed the upper Toukoshan Formation (0.5-0.9 Ma in age), implying that the Changhua frontal thrusting is probably younger than 0.5 Ma. The Pakua Anticline tectonically neighbors the eastern side of the present frontal thrust (the Changhua Fault).

The E-W trending seismic profile on a regional scale (Figure 4a) reveals the major structure of a low angle thrust fault (the Changhua Fault) and associated gentle folds, especially in the hanging wall (the Pakua anticline). However, the N-S trending seismic profiles show that the major normal faults are also present within the Plio-Pleistocene sediments (Figure 4b) in the Pakua anticline. These major faults (Figure 4b), having a steeply inclining fault surface and apparently occurring down to a depth of 2-3 km, may have some strike-slip component contributing to the total fault movement. On a regional scale, it shows there is a complex tectonic history in the frontal thrust of the Pakua anticline area: both compressional and extensional stress regimes occurred during the late Quaternary. In the next section, we will examine the structures of deformation on an outcrop scale to illustrate the tectonic characteristics in this young deformation zone.

3. TECTONIC ANALYSIS

Field investigation, particularly for the tectonic analysis, is carried out in the Pakua anticline area. Three main kinds of structures on an outcrop scale represent the characteristics of deformation in the Pakua anticline: normal fault (Figure 5), compressional fracture of pebbles (Figure 6), and strike-slip fault. The locations and site numbers of the outcrops have been summarized in Figure 2.

3.1 General Features

3.1.1 Normal fault

The normal fault is a frequently occurring structure in the studied area, especially in the layers of sand and sandstone with less conglomerate, which are particularly present in the northern part of the Pakua anticline. Substantial normal faults have been observed at different scales. The offsets of normal faults vary from a few centimeters to several meters. This implies that most of the normal faults probably related to superficial or local deformation rather than to major earthquakes or deformation on a lithosphere scale. Several kinds of fault geometry can be found. Examples of these are listric faults, with fault surfaces dipping in only one direction, and conjugate faults which have two sets of fault surface dipping face to face (Figure 5).

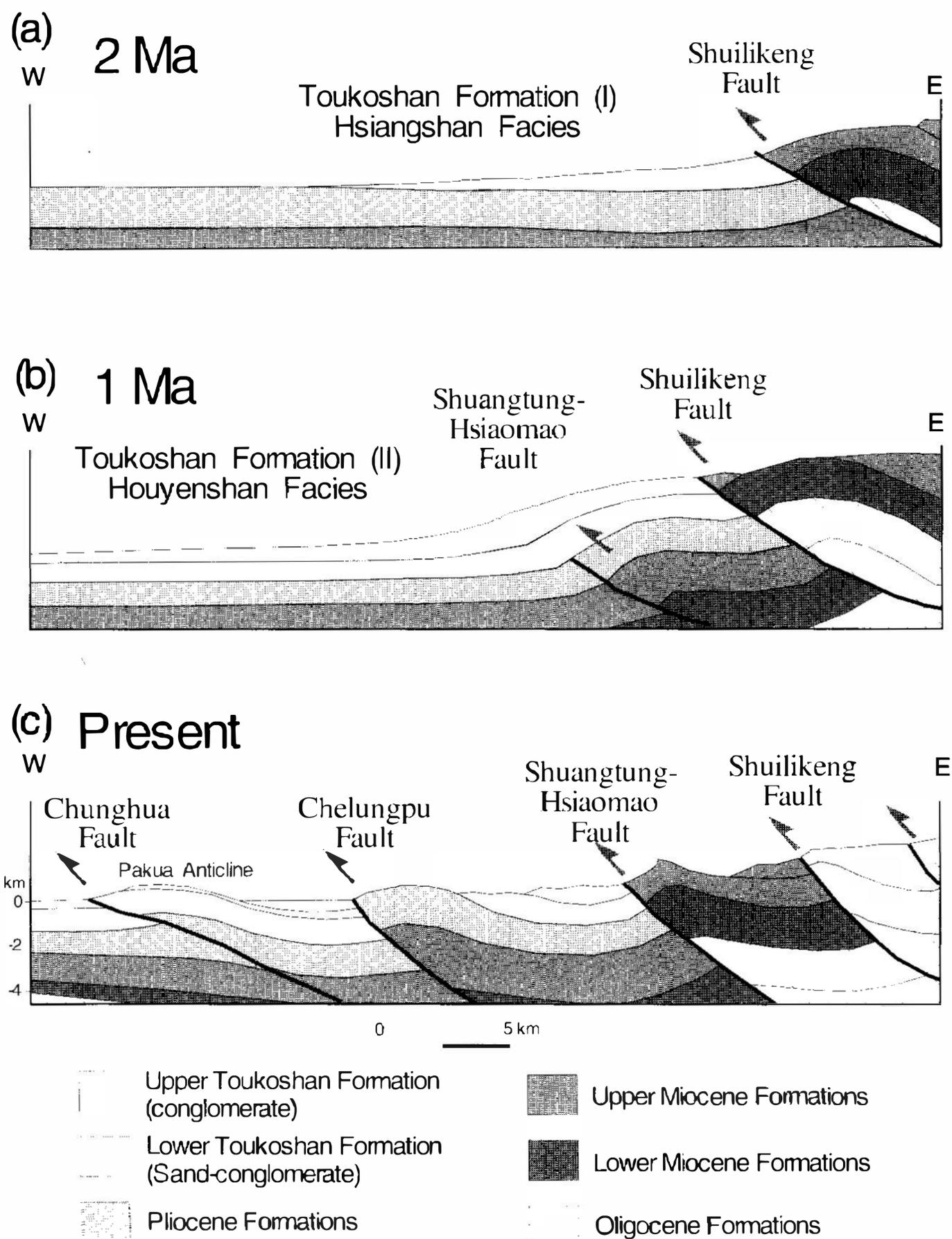


Fig. 3. Evolution of thrust front and the relation between erosion, sedimentation and tectonics in western Taiwan. (a) Erosion of the Central Range (Hsuehshan Range) and sedimentation of the lower phase of the Toukoshan Formation, accompanied by thrusting of the Shuilikeng Fault (Chuchih Fault). The beginning of sedimentation of the Hsiangshan Facies is approximately 2 Ma (Chi and Huang, 1981). (b) Erosion of the Central Range and sedimentation of the upper phase of the Toukoshan Formation, accompanied by thrusting of the Shangtung-Hsiaomao Fault. The boundary between the Hsiangshan Facies and the Houyengshan Facies is approximately 1 Ma old (detailed discussion see text). (c) Thrusting of the Chelungpu Fault and subsequent folding of the Pakua anticline with associated thrusting of the Changhua Fault.

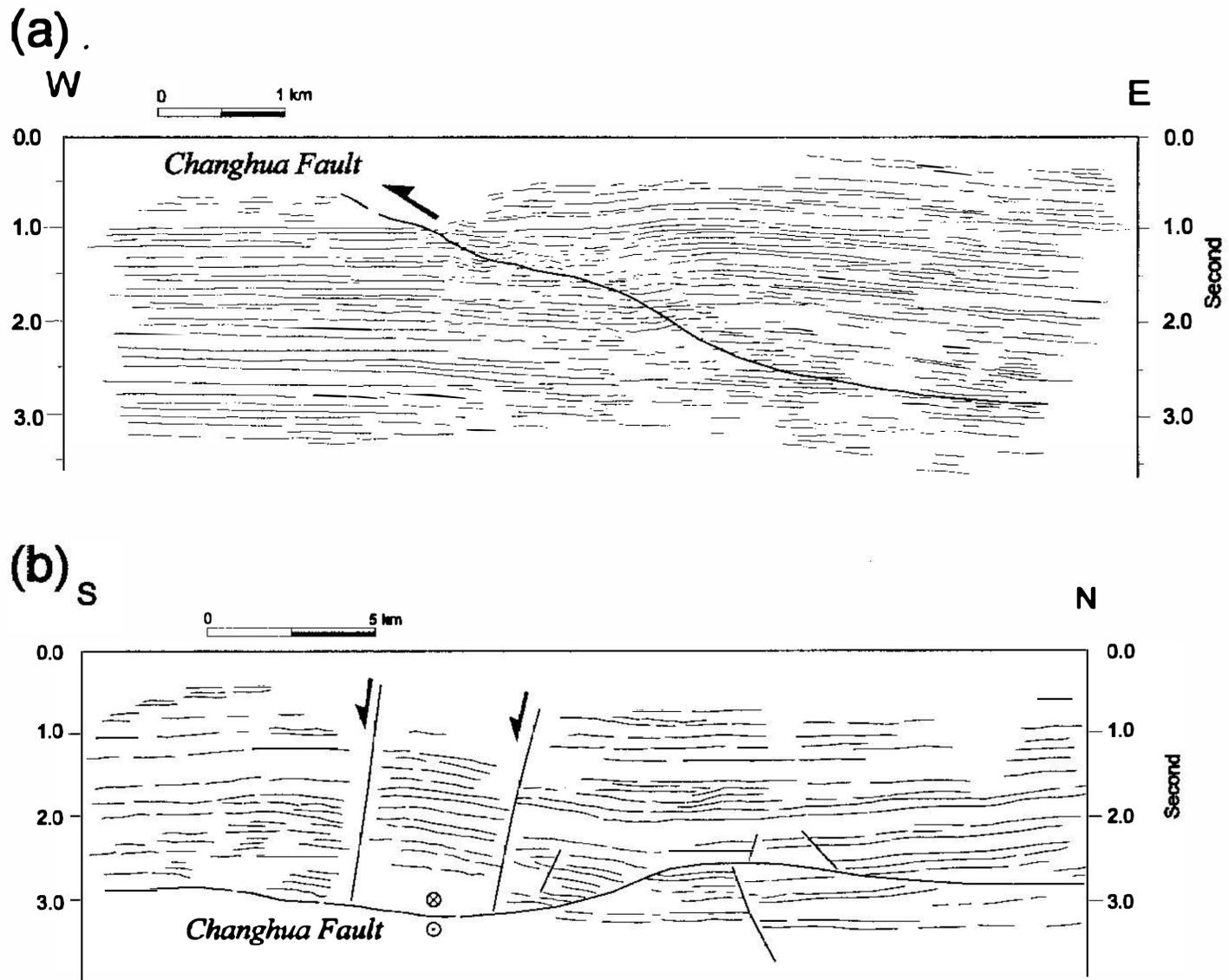


Fig. 4. Interpretation of seismic profiles in the northern Pakua anticline. (a) E-W trending seismic profile shows the frontal thrust structure (the Changhua Fault) and the associated anticlinal fold (the Pakua anticline). (b) N-S trending seismic profile presents the probable E-W trending normal faults developed within the Quaternary sediments. Location: see Fig. 2.

Synsedimentary normal faults have been observed in the field. Sometimes it is not easy to distinguish them from post-sedimentation normal faults because similar features are exhibited by Quaternary sediments which are not well-consolidated. Both faultings are very young and occurred within a short period. Lacking detailed dating data, it is difficult to determine the exact age of the post-sedimentation normal faulting. In fact, these two kinds of normal faults both occurred during the past 1 Ma, and on a geological time scale, are not far apart. The normal faulting strongly indicates that this area has suffered the vertical force since the sedimentation of the Toukoshan Formation. The characteristics of the correlated relationship between sedimentation and tectonics reveal a remarkable feature in the thrust front of the foreland region. We will discuss this in more detail in a later section.

Numerous measurements of fault geometry and striated-slip data have been done in order to illustrate the extensional stress regime in this area. Figure 7 shows the distribution of the extensional stress in the Pakua anticline area. The horizontal extensional directions are determined by the calculated reduced tensor (for those having fault-slip data, solid arrows in Figure 7) and by the perpendicular direction of average fault trends (for those without fault-slip data, open arrows in Figure 7). The extensional directions show there are two major trends, one being a N-S and the other in an E-W direction.

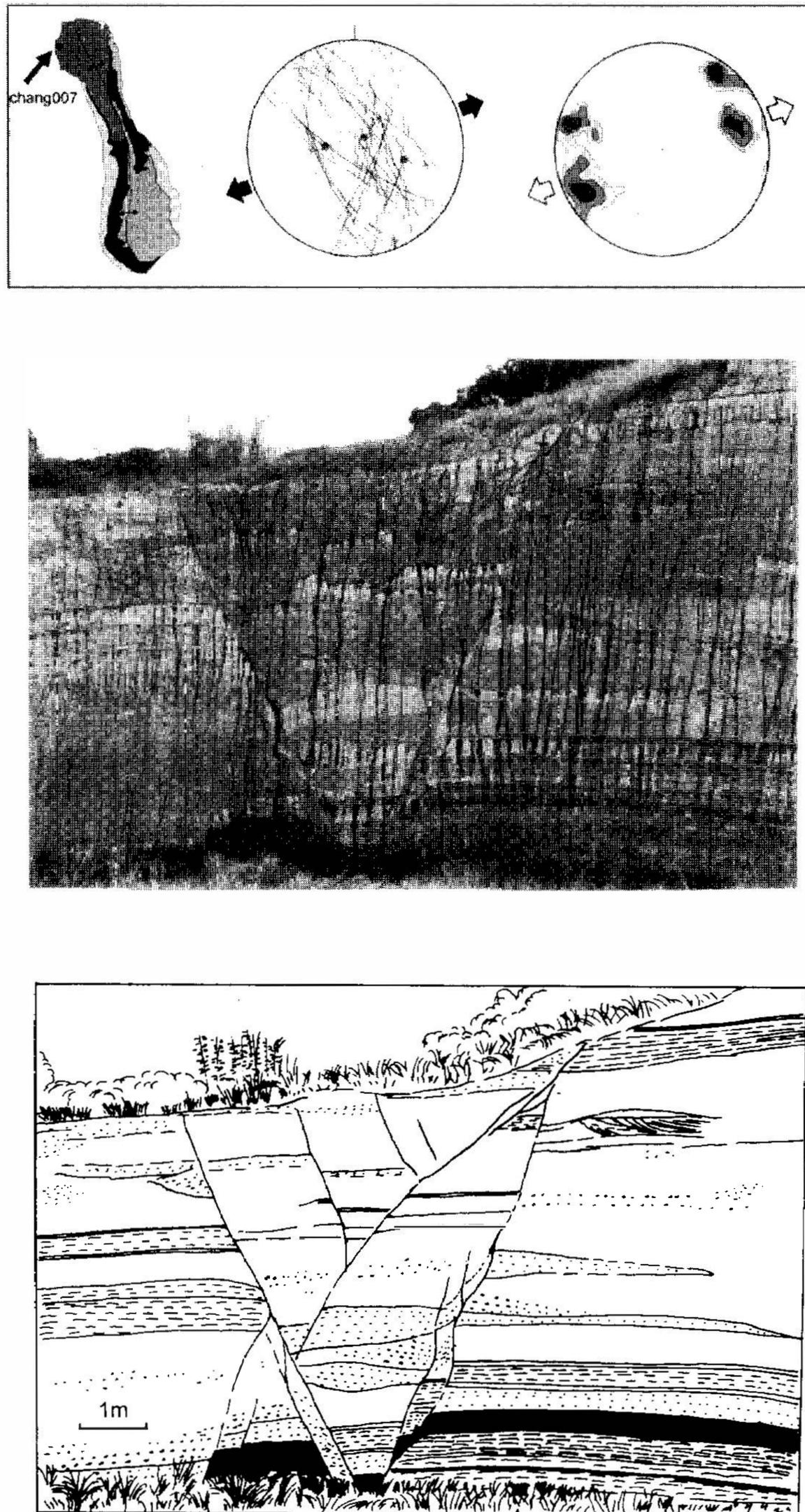


Fig. 5. Example of conjugate normal faults in the northern Pakua anticline area. Diagrams: Schmidt, projection, lower hemisphere (great circles: fault planes; points with arrows: fault striations with slip directions).

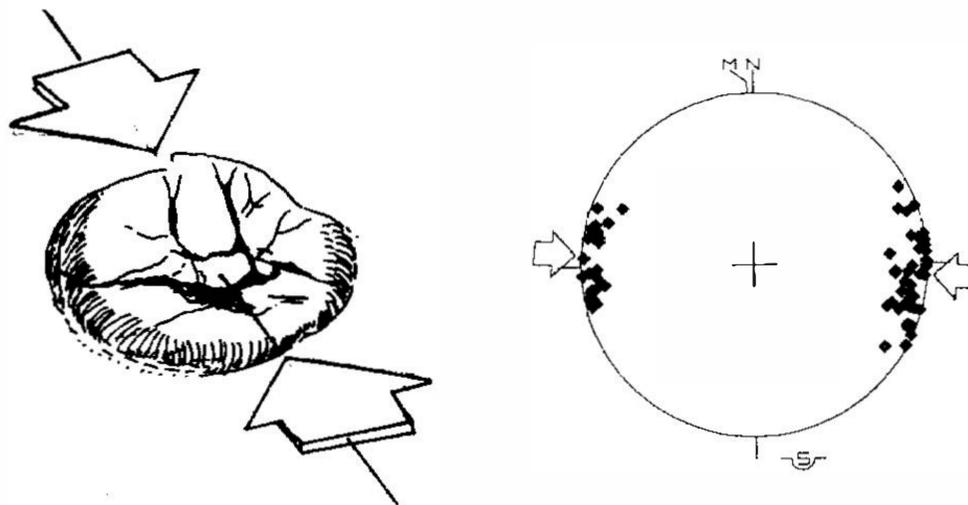


Fig. 6. Example of impact fractures of pebbles in the Toukoshan Formation. The axes of the center of the impact fracture are measured as the axes of the principal compressional stress σ_1 . Diagrams: Schmidt, projection, lower hemisphere.

3.1.2 Compressional fracture of pebble

The compressional fracture of pebbles (Figure 6) is an onmi-present deformation structure which existed in the conglomerate formation in the studied area. This deformation structure has been documented (Lee, 1989; Chu, 1990; Lee, J. C., 1994; Lee, J. F., 1994) in the Quaternary conglomerate formations occurring western Taiwan. The prevailing fractures of pebble in the Houyenshan Facies (conglomerate layer) of the Toukoshan Formation imply that it suffered a compressional stress, and that the confining pressure caused the closely-packed and clast support pebbles within the conglomerate layers to collide with each other, thereby introducing star-like cracking fractures (Figure 6). Lee, J. C. (1994) reported that in the adjacent area (north-east Fenyuan) close to the San-yi Fault (northern extension of the Chelungpu Fault), this fracturing of pebble may have been widespread along a thrust fault zone where the tectonic stress had been concentrated. Through measuring the center axes of this star-like fracture structure in a given site (Figure 6), statistically we can find the regional compressional direction (Figure 8) which is represented by the average trend of the center axes in a site.

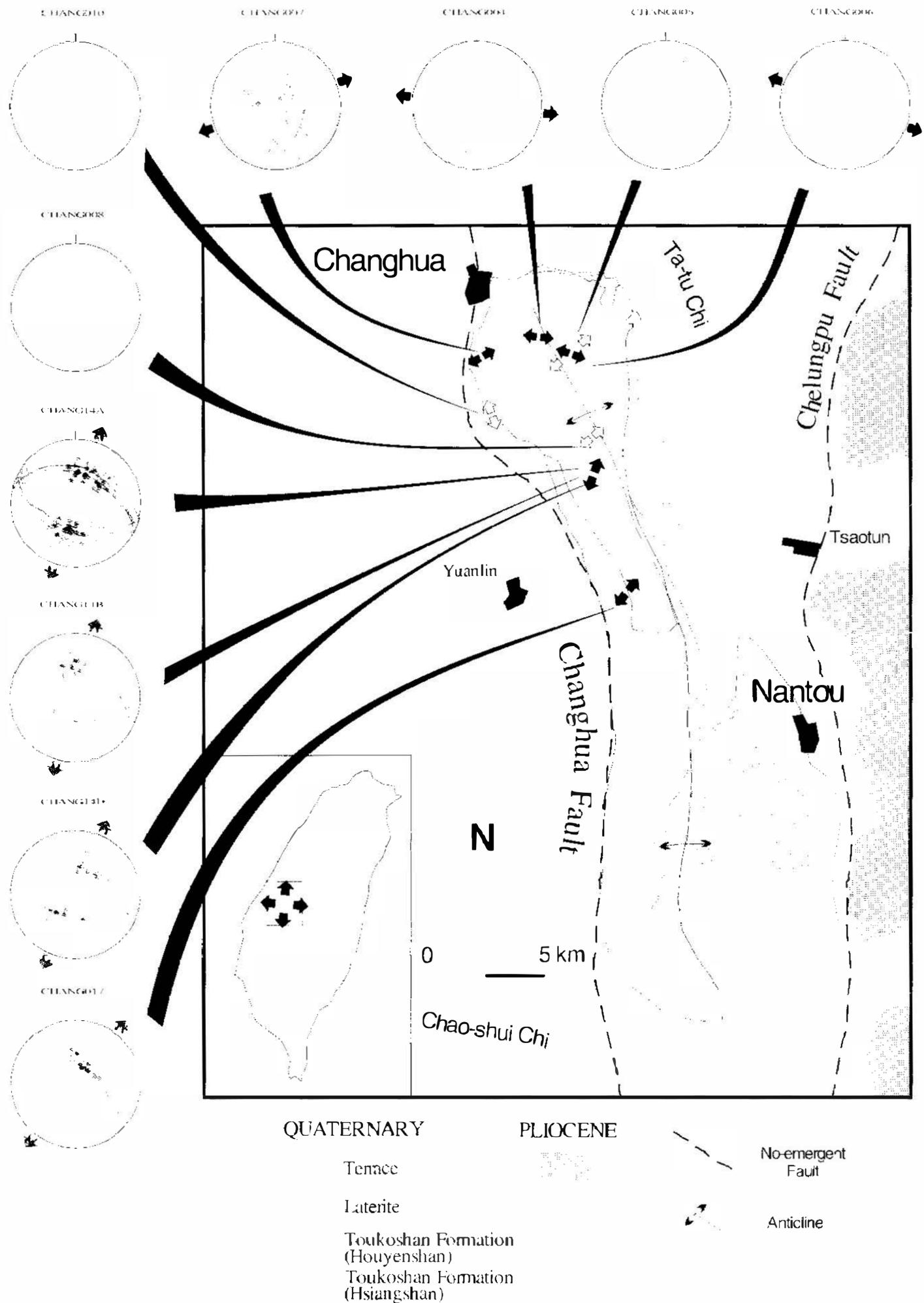


Fig. 7. Distribution of normal faults and their tectonic analysis in the northern Pakua anticline. Heavy arrows show the extensional directions of paleostress determination for each site. Solid arrows are determined by the stress tensor analysis of fault-slip data, while open arrows are determined by the orientation of the fault planes only. Diagrams: Schmidt, projection, lower hemisphere (great circles: fault planes; points with arrows: fault striations with slip directions). For detailed results of local determinations, see Table 1.

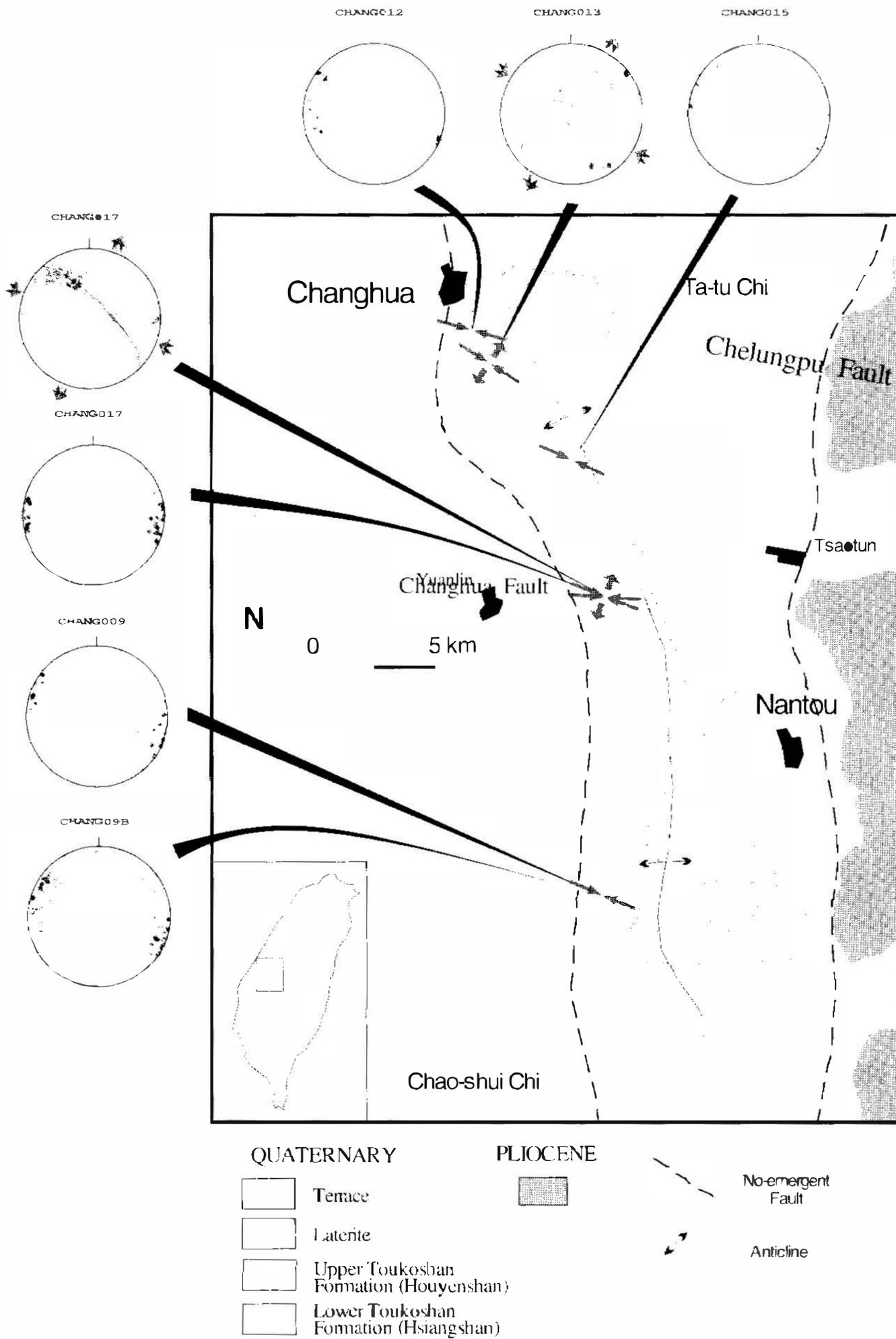


Fig. 8. Distribution of compressional directions determined from impact fractures in the Pakua anticline area. Heavy lines represent the directions of maximum principal stress (σ_1). For detailed results of local determinations, see Table 1.

Table 1. Results of paleostress analysis in the Pakua anticline area. Directions and dips of the principal stress axes in degrees. (: ratio of principal stress $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$). St: structures: F, faults; J, joints; A, fractured pebbles.

No	Site	Stratigraphy	Lat.(N)	Long.(E)	σ_1	σ_2	σ_3	Φ	St			
2	CHANG002	"	24°04'25"	120°33'20"					J			
3	CHANG003	"	24°04'00"	120°33'55"					J			
4	CHANG004	"	24°03'25"	120°34'05"			277	-	F			
5	CHANG005	"	24°03'05"	120°34'55"			229	-	F			
6	CHANG006	"	24°05'05"	120°34'55"			110	-	F			
7	CHANG007	"	24°03'10"	120°32'30"			250	-	F			
9	CHANG09A	"	23°51'30"	120°36'50"	112	2			A			
	CHANG09B	"	"	"	293	2			A			
12	CHANG012	"	24°03'42"	120°32'48"	286	11			A			
13	CHANG013	"	24°03'06"	120°33'42"	302	9	78	78	211	8	.83	F
14	CHANG14A	"	24°00'48"	120°35'06"	111	88	289	2	19	0	.36	F
	CHANG14B	"	"	"	298	77	105	12	196	3	.43	F
	CHANG14D	"	"	"	332	86	113	4	203	3	.47	F
15	CHANG015	"	24°00'48"	120°35'06"	114	6						A
17	CHANG017	"	23°58'12"	120°36'06"	94	2						A
	"	"	"	"	291	4	160	84	21	5	.76	F
	"	"	"	"	282	82	129	7	39	4	.55	F

3.1.3 Strike-slip fault

The strike-slip fault has also been found in the sand and conglomerate interbed layers of the Toukoshan Formation. Strike-slip faults observed in the field usually occurred along the joint sets. The fault traces generally do not extend for a long distance. The calculated stress tensors (Figure 8) indicate that the compressional direction (WNW) is generally in agreement with the compressional trend obtained from the fractures of pebbles (Figure 8).

3.2 Results of Paleostress Analysis

Figure 7 represents the results of the extensional paleostress analysis for the normal faults in the Pakua anticline area. In Figure 8, the major compressional direction (WNW) summarizes the paleostress analysis for both the compressional fractures of pebbles and the strike-slip faults.

The results of compressional stress analysis (Figure 8) show that they are consistent with the direction of transportation of the frontal thrust (the Changhua Fault) and can also correspond to the motion vector of plate convergence between the Philippine Sea plate and Eurasia, while the results of the extensional stress analysis (Figure 7) show the irregularity of extension directions in the northern Pakua anticline. It indicates that during the Quaternary period since the sedimentation of the Toukoshan Formation through the folding and uplifting of the Pakua anticline, the extensional stress regime continued to affect the area. Therefore, the active deformation of the Pakua anticline area is, in fact, characterized by the complex deformation of extension and compression tectonic regimes.

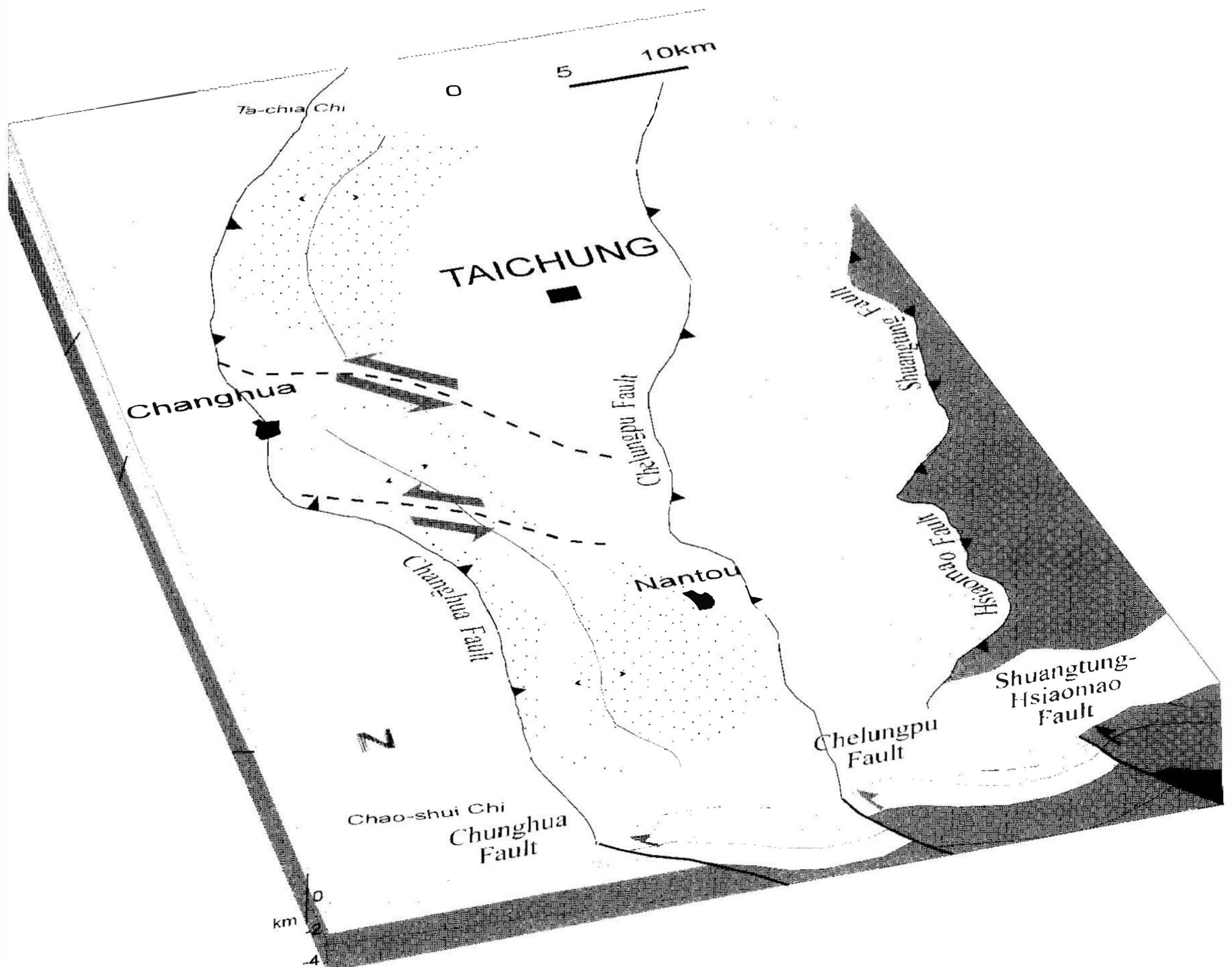


Fig. 9. Proposed model of the transfer fault zone between the Tatu anticline to the north and the Pakua anticline to the south. The left-lateral transfer fault might produce local extension in the northern Pakua anticline where numerous normal faults occurred.

4. DISCUSSION

The widespread distribution of normal faults, particularly in the northern Pakua anticline may result from two different origins: (1) synsedimentation normal faulting developed during the period of rapid sedimentation of the Toukoshan Formation; and (2) post-sedimentation normal faulting which occurred after the area had suffered from regional extensional tectonic stress, and which especially affected the northern Pakua anticline. However, it was not possible to easily distinguish these two kinds of faults in the Pakua anticline area. It seems that the normal faulting was continuous throughout the sedimentation, folding and uplifting which resulted from westward thrusting in the western foreland of Taiwan.

In order to provide an explanation for the normal faulting in the northern Pakua anticline, which could be related to the regional transtensional stress regime (Figure 9), a model of transfer faults zone was then proposed. These NW trending transfer zones are probably either between the Tatu anticline and the Pakua anticline, or cross through the northern Pakua anticline (Figure 9). These probably represent linear structures which can also be recognized from several remote sensing data (Deffontaines *et al.*, 1994), and would result in local extension near the frontal thrusts as in the northern Pakua anticline. To test this model however, more detailed studies are indispensable.

Possible mechanisms for the normal faulting involve a continuation of the deformation of the Changhua Fault, causing the adjacent upthrusting Pakua anticline to pass through a compressional stress regime to an extensional stress regime. The activation of the westward upthrusting Changhua Fault has the concomitant Pakua anticline not only migrating westward in the horizontal direction but also moving upward in the vertical direction. Uplift force and gravitational instability, as deduced from the uplifting Pakua anticline, will certainly favor the development of normal faults.

5. TECTONIC EVOLUTION OF THE PAKUA ANTICLINE

Based upon the above study, we can establish the tectonic evolution of the Pakua anticline area.

Rapid sedimentation with synsedimentary normal faulting. During the early Quaternary, about 1.8 Ma ago (Chi and Huang, 1981), rapid uplift of the Central Range and westward thrust faults provoked the immense sedimentation of the Toukoshan Formation in the foothills within a shallow water environment (Hu, 1977), including the Pakua area. This dynamic rapid sedimentation also results in synsedimentary normal faults, especially in the lower Toukoshan Formation (Hsiangshan Facies), because of the gravitational instability of the non-consolidated sediments.

Frontal thrusting and extensional-compressional deformation. During or soon after sedimentation of the Toukoshan Formation (<0.9 Ma), the frontal thrusts developed westward and were in their present position (the Changhua Fault) by the late Quaternary. During this period, the Pakua area suffered from compressional stress to form an anticline structure on a regional scale, and other compressional deformation structures on an outcrop scale (e.g. compressional fractures of pebbles in the conglomerate layer and strike-slip faults at some sites). At the same time, the uplift of the Pakua anticline, located on the hanging wall of the Changhua frontal thrust, caused the maximum principal stress to be in the vertical direction and that is one of the probable reasons for normal faulting in the surface of the crust. The thrusting, the anticlinal folding, and the microstructures of pebble fracturing and strike-slip faults, however, probably occurred in the same period.

Normal faulting in the northern part of the Pakua anticline. Although there is no well-defined chronological relationship between the major tectonic stress regime of compressional deformation structures and the extensional normal faulting, we should note that normal faulting also plays an important role in terms of tectonics because of its structural scale and widespread distribution. The normal faulting in the northern Pakua anticline could be interpreted as being related to either the strong uplift of the northern Pakua anticline, as deduced from the

development of thrust faulting and folding, or from the local extension resulting from a transfer fault zone situated in the northern Pakua anticline.

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