Contractional, transcurrent, rotational and extensional tectonics: examples from Northern Taiwan

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Abstract

Contraction, transcurrent faulting, block rotation and even extension are four essential tectonic mechanisms involved in the progressive deformation of arcuate collision belts. The neotectonic evolution of the Taiwan mountain belt is mainly controlled by the oblique convergence between the Eurasian plate and the Philippine Sea plate as well as the corner shape of the plate boundary. Based on field observations and tectonic analysis, and taking geophysical data and experimental modelling into account, we interpret the curved belt of northern Taiwan in terms of contractional deformation (with compression, thrust-sheet stacking, folding and transcurrent faulting) combined with increasing block rotation, bookshelf-type strike-slip faulting and extension. As a consequence, the formation of the extensional Taipei Basin, the division of conjugate strike-slip faulted domains and the variable nature and distribution of paleostresses should not be interpreted in terms of distinct Plio-Quaternary episodes but should reflect a single, albeit complicated, regional pattern of deformation. Our study demonstrates that in Taiwan, contractional, extensional and transcurrent tectonics as well as rotations combine together and interact within a single complex framework. The crescent-shaped mountain belt develops in response to oblique indentation by an asymmetric wedge indenter. The distribution, nature and relative importance of these deformation modes are a function of the shape of the indenter and the average direction of convergence.

1. Introduction

When deformation of the upper crust occurs in a tectonic environment where oblique convergence and indentation tectonics play a major role, three major modes of deformation are common: contraction, transcurrent motion and block rotation (Freund, 1970; Biq, 1972; Fitch, 1972; Hossack, 1979; Garfunkel and Ron, 1985; Nur and Ron, 1987). Contractional deformation results in folding and thrusting which thicken the upper crust undergoing shortening, with development of large compressional belts and foreland basins (Hossack, 1979). Transcurrent deformation results in juxtaposition of previously unrelated sectors while localized compressional ranges and basins develop (Burchfiel and Stewart, 1966; Taira et al., 1983; Sylvester, 1988). Block rotation may produce lateral extrusion and facilitate basin formation (Freund, 1970; Christie-Blick and Biddle, 1985; Garfunkel and Ron, 1985; Burke and Sengör, 1986; Souriot and Brun, 1992).

These major deformation modes may occur together, in variable proportions, during the progressive deformation of a collision mountain belt. In this paper, we describe some characteristics of these three tectonic modes (contraction, transcurrent and block rotation), and show their complementarity and common control on regional structural patterns, based on the example of the northeastern Taiwan collision belt (Fig. 1).

2. Tectonic setting: the Taiwan Mountain Belt

The Taiwan Mountain Belt (Fig. 1) is an active curved collisional mountain belt and thrust wedge (Chai, 1972; Suppe, 1981,1987; Barrier, 1985; Angelier, et al. 1986; Angelier, 1990; Ho, 1986a,1988; Teng, 1990, Lu and Hsü, 1992). It developed as a result of the late Cenozoic oblique convergence between the Philippine Sea plate and the
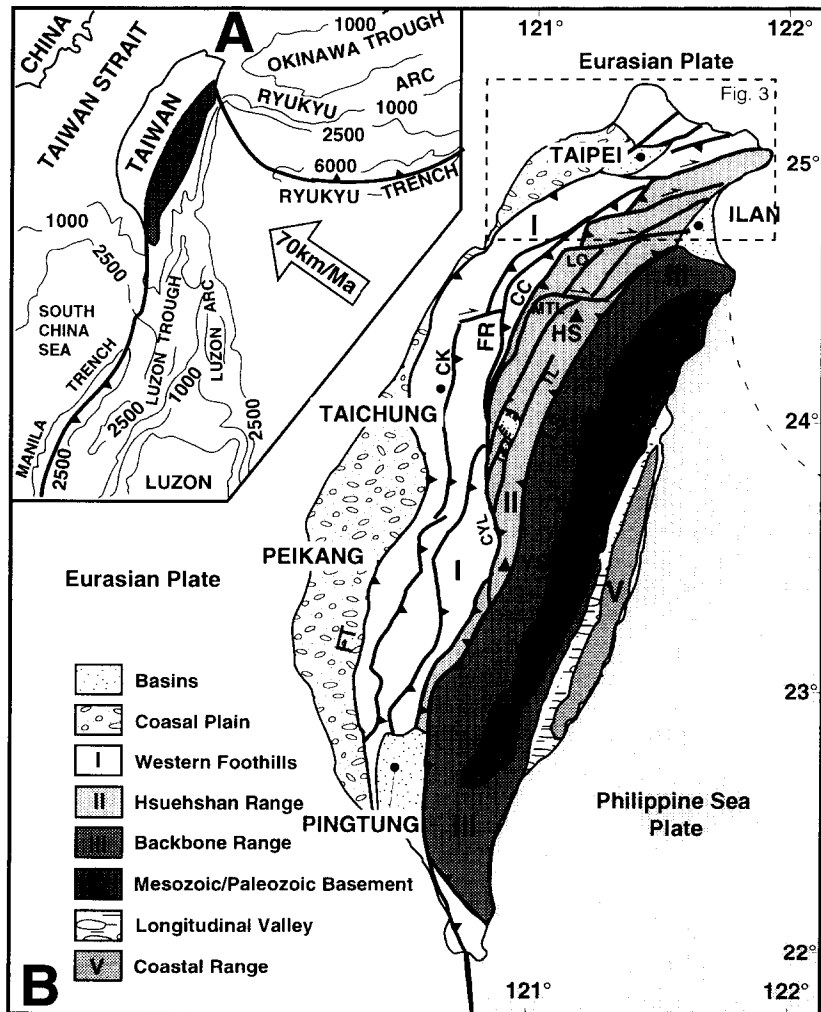

Fig. 1. Geodynamic setting (A) and tectonic map (B) of Taiwan. In (A), isobaths are in meters, and large open arrow shows the direction of convergence (Philippine Sea Plate relative to Eurasia). In (B), main tectonic units are shown following Ho (1986b) and Biq (1989). Major thrust faults are indicated as heavy lines with triangles on the upthrust side. 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 = Yushan.

Eurasian plate. The lithosphere of the Eurasian plate around Taiwan includes the crust of the Chinese continental shelf and margin and the oceanic crust of the South China Sea. It is subducting to the east beneath the Philippine Sea plate, south of Taiwan. The Philippine Sea plate is being subducted beneath the continental part of the Eurasian plate at the Ryukyu Trench, northeast of Taiwan. The initial trend of the Chinese continental margin in the South China Sea averages N60° E; the Luzon arc, which trends approximately N–S and belongs to the Philippine Sea plate, moves towards the Eurasian plate in a N55° W direction (Seno, 1977); the Manila Trench to the south of Taiwan trends N–S to N20° E. This configuration results in oblique subduction and collision (Fig. 1A), with a progressive development of the mountain belt from NE to SW, as suggested by Suppe (1981).

A characteristic feature of the Taiwan Mountain Belt is the major change in the general structural trends between northern Taiwan and central Taiwan (i.e., between 24° N and 25° N, see Fig. 1B). The difference in strikes between these segments of the curved belt ranges from 40° in the outer zones (Western Foothills) to about 90° in the inner ones (the eastern boundary of the Backbone Range), as Fig. 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 (Fig. 1B).

Several tectonic studies have been done in this area. For instance, Tan (1977) first pointed out the existence of major bending in the "Taiwan arc", and interpreted it as a result of subduction. Suppe (1984) interpreted this eastward bending as the result of subduction flipping and opening of the Okinawa Trough. Lue (1989) and Lee et al. (1991), using paleomagnetic data, showed that in northern Taiwan a clockwise rotation of about 20° on average occurred during the Plio-Quaternary, confirming an earlier prediction by Angelier et al. (1986) who inferred such a rotation from their tectonic analyses. In more detail, considering the curvature of about 50° of the Hsüehshan Range, and based on both paleomag-

netic results and the paleostress analyses, Angelier et al. (1990) interpreted part of this curvature (about 20°) as a result of block rotation during the Plio-Pleistocene, and the remaining 30° as inherited from earlier structures and representing the initial shape of the belt at the corner of the collision boundary.

3. Insights from experimental modelling

Recently, Lu and Malavieille (1994) used 3-D sandbox modelling experiments to illustrate the kinematic processes of the Taiwan thrust wedge (Fig. 2). A major consequence of oblique collision with an asymmetrical indenter is the development of an asymmetrical thrust wedge structured with a characteristic distribution of tectonic domains. Deformation within the belt combines shortening, rotations and stretching, which locally results in a partitioning between thrusting, strike-slip faulting and normal faulting. The evidences for oblique indentation and resulting transcurrent and rotation structures are brought by: (1) the crescent-shaped thrust wedge which is strongly controlled by the corner shape of backstop; (2) the presence of particular features induced by strike-slip faulting (e.g., pull-apart and transpression structures); and (3) the occurrence of stretching along the strike of thrust wedge, especially around the indentation point.

Based on results of this experimental modelling, the northeastern segment of the Taiwan belt (Fig. 3; location in Fig. 1B) was interpreted by Lu and Malavieille (1994) as having suffered contractional deformation first (such as shortening and oblique thrust-sheet stacking), associated later with right-lateral transcurrent faulting and normal faulting. These phenomena are related to clockwise block rotation and development of bookshelf-type strike-slip faulting. In the sandbox model, the quantification of progressive deformation was obtained through repeated detailed measurements of displacements (see illustrations and tables in Lu and Malavieille, 1994). The results of these experiments suggested that: (1) most block rotations occurred around the indentation point; (2) most of the vertical displacement
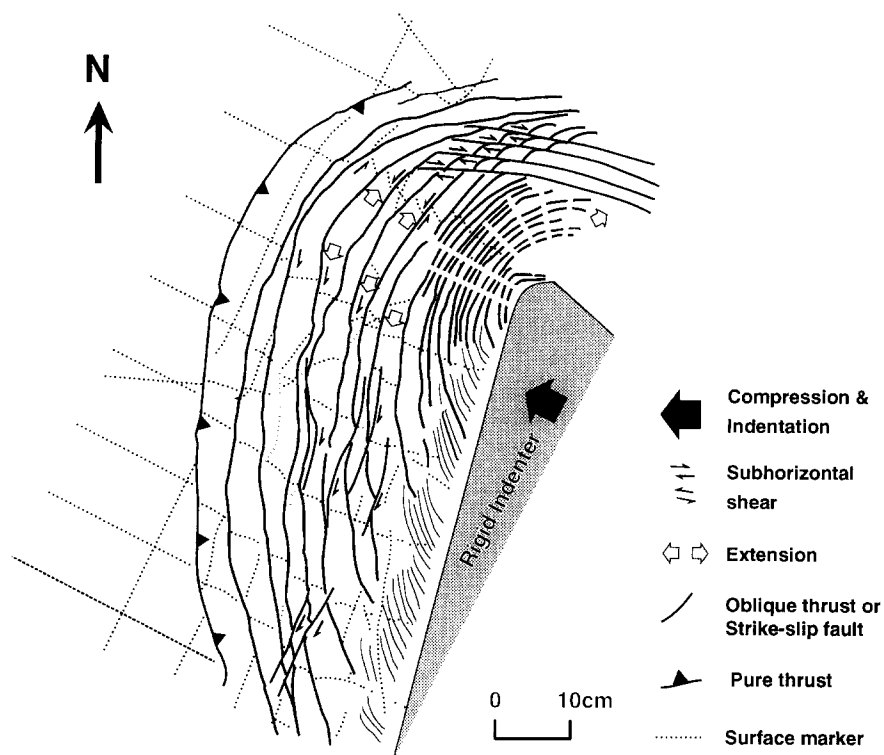
Fig. 2. Vertical view of experimental sandbox model of Taiwan mountain belt (modified after Lu and Malavieille, 1994). Thrust wedge created by oblique indentation of a wedge-shaped backstop. Three different domains were distinguished: (1) to the left of the indenter, oblique thrusts show a left-lateral component of slip, the internal part of the wedge (near the backstop) accommodating left-lateral simple shear deformation by right-lateral bookshelf-type strike-slip faulting; (2) to the right of the indenter, a right-lateral shear zone develops, the internal part of the wedge accommodating right-lateral simple shear deformation by left-lateral bookshelf-type strike-slip faulting; (3) in front of the indenter, significant stretching occurs perpendicular to convergence direction.

of thrust sheets occurred during the early stages of thrust development; and (3) in the whole deformation of northeastern Taiwan, dextral strike-slip movements played a significant role.

In the next sections, the geological structure of northern Taiwan (Fig. 3) is examined in the light of these experimental results, taking into account the results of tectonic analyses in the field.

4. Deformation processes

4.1. Stratigraphy and structures of northern Taiwan

The ENE–WSW-trending segment of northeastern Taiwan is composed of a mosaic of strati-graphic units which belong to the northern Hsüehshan Range, the Western Foothills, the Coastal Plain, and the Pleistocene volcanics (Fig. 3). In the Coastal Plain and Western Foothills, clastic sedimentary formations crop out, with ages ranging from Oligocene to Quaternary. The Hsüehshan Range (Fig. 1B) consists of a passive margin shallow marine sequence that is Eocene to Oligocene in age. Metamorphic grades increase from NW to SE, from unmetamorphosed or slightly metamorphosed rocks in the Coastal Plain area to lower greenschist facies in the inner Hsüehshan Range.

The late Cenozoic structure of northern Taiwan (Fig. 3) is characterized by numerous NE-trending folds and thrust faults, which developed

together but were generally deformed by broadly spaced strike-slip faults and some normal fault systems. There is a slight obliquity between the regional trends of the major thrust units and the fold axes, revealing a poorly marked en échelon arrangement of several folds and thrusts, especially near 121° 40′ E, between Taipei and Keelung. This is consistent with a dextral component of strike-slip. Plio-Quaternary normal faults are present in several basins and depression structures within the compressional mountain chain, such as the Taipei Basin, the Ilan Basin, and the Yenliao Depression together with the Chinkuashih gold-copper field (Fig. 3).

The structural framework of northern Taiwan (Fig. 3) is consistent with morphologic data (Fig.

4) and paleomagnetic information (discussed later). A simple interpretation of a SPOT satellite image shows characteristic drainage patterns related to tectonic structure in northern Taiwan (Fig. 4). The river systems show linear valleys and zigzag pattern and the shaded areas in Fig. 4 correspond to well-defined structural block domains, along the major river systems and the coast. At the regional scale, considering both the geological maps (Ho, 1986b; Huang and Liu, 1988; Huang, 1988) and the SLAR Radar imagery (Mars, 1981), the northern Taiwan belt segment can be divided into two major domains separated by the I-I′ line of Fig. 3. Paleomagnetic results (Lue, 1989) indicate that rotations are present and differ in these main domains, clockwise east
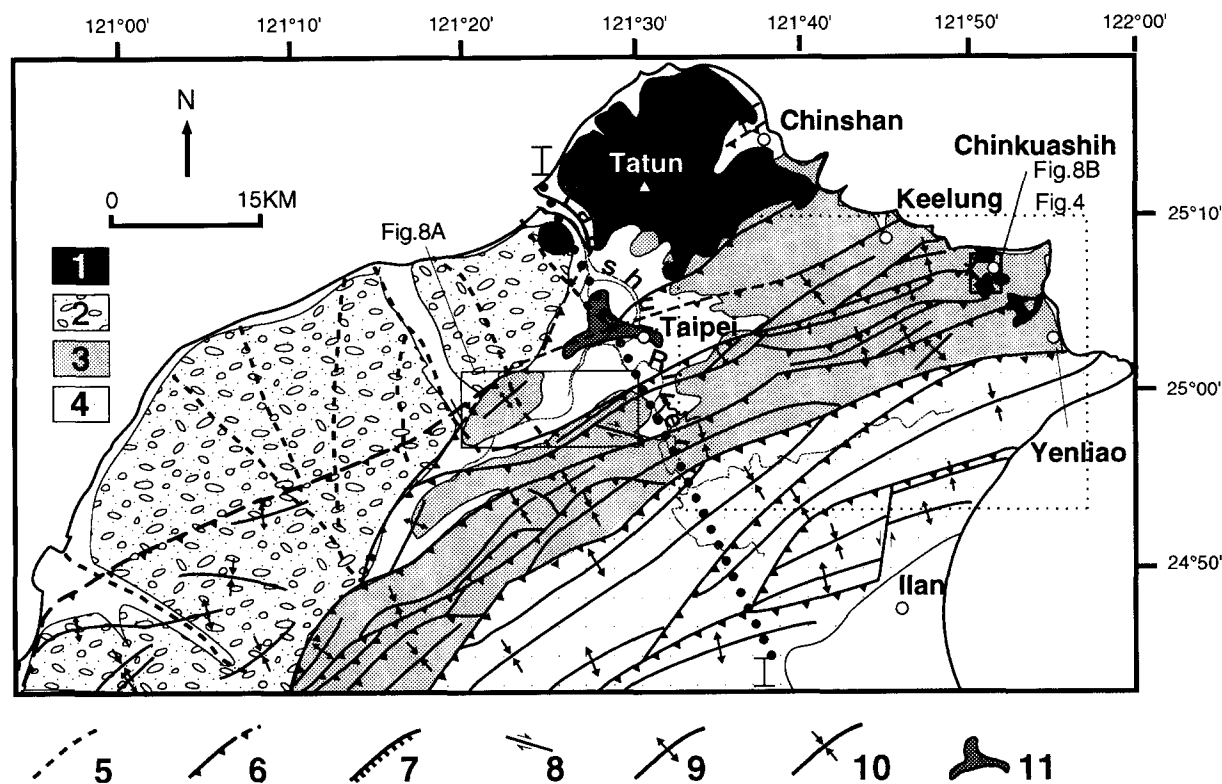

Fig. 3. Location map and general structures interpreted from the geological maps (Ho, 1986a,b) and SLAR (Side Looking Airborne Radar) image of Taiwan (Mars Inc., 1981). Keys: 1 = Pleistocene volcanic rocks; 2 = Pleistocene conglomerate; 3 = Western Foothills; 4 = Hsüehshan Range; 5 = major fracture; 6 = thrust fault; 7 = strike-slip fault; 8 = normal fault; 9 = anticline axis; 10 = syncline axis; 11 = T-shaped Taipei Basin indicated by the 250-m isopach of the Tertiary basement (after Wang Lee et al., 1978 and Consulting Engineers, 1989).

this Tanshui River axis, and anticlockwise west of it. We shall come back to this point.

Major and minor structures observed in the mountain belt segment of northeastern Taiwan (Fig. 3) belong to different types. Reverse, strike-slip and normal faults are present at various scales, while detailed analyses of brittle tectonics were carried out (sites located in Figs. 3 and 4). Four aspects are discussed successively in this section: contractional, transcurrent, rotational and extensional.

4.2. Contractional tectonics

The contractional deformation can be divided into two groups (Hossack, 1979): (1) the 'orogenic contraction' related to thrust faulting, which results in shortening and thickening of the crust;

and (2) the contraction which results in a loss of area in vertical cross-section and may or may not correspond to a real loss of volume in three dimensions. In the last case (volumetric decrease), several physical and chemical processes are involved, such as: (a) compaction during lithification; (b) tectonic compaction resulting in higher rock density; (c) pressure solution. If the volume remains approximately constant while transverse cross-sectional area decreases; and (d) elongation along orogenic strikes is involved, and may correspond to strike-slip faulting in the brittle crust or to ductile processes at greater depths.

Examples of contractional deformation are illustrated in Figs. 5 and 6. At the hectometric scale, an outcrop with nearly vertical Miocene layers in the Keelung area (Fig. 5A) showed reverse fault structures but also apparently nor-
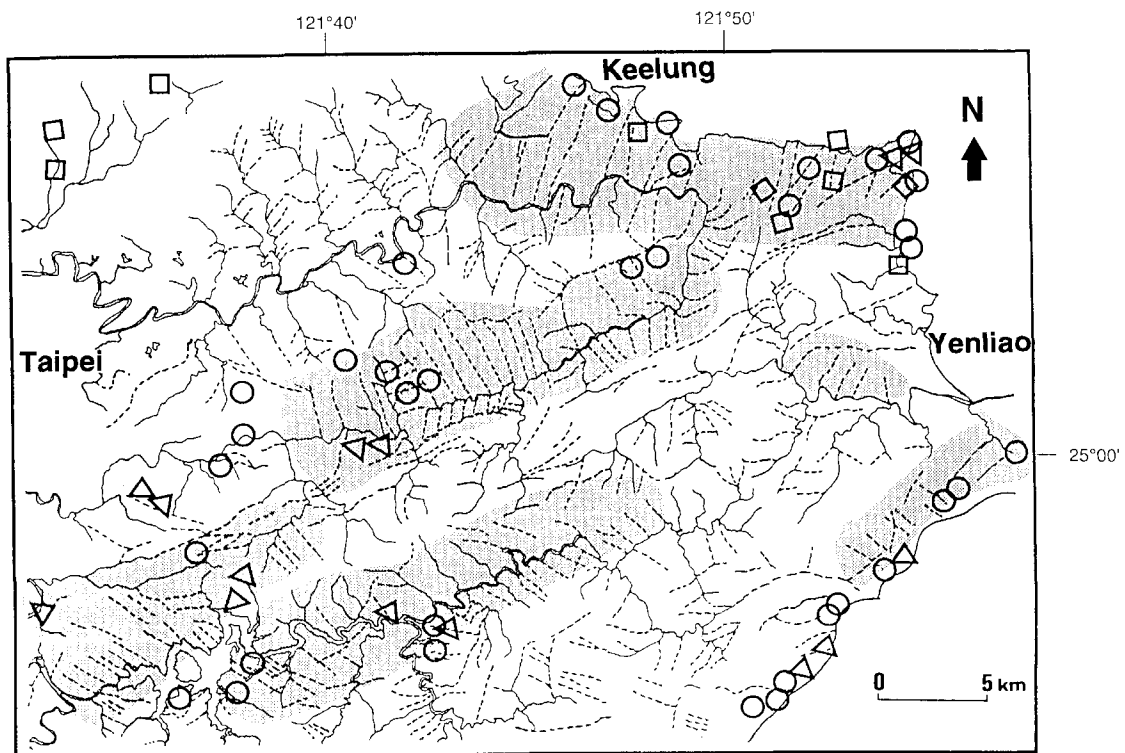

Fig. 4. Drainage and fracture (dashed lines) patterns in northern Taiwan, interpreted from SPOT satellite image. Shaded areas show defined block domains (circles, triangles and squares indicate location of sites of geomagnetic analysis, compressional and extensional tectonic analyses, respectively).
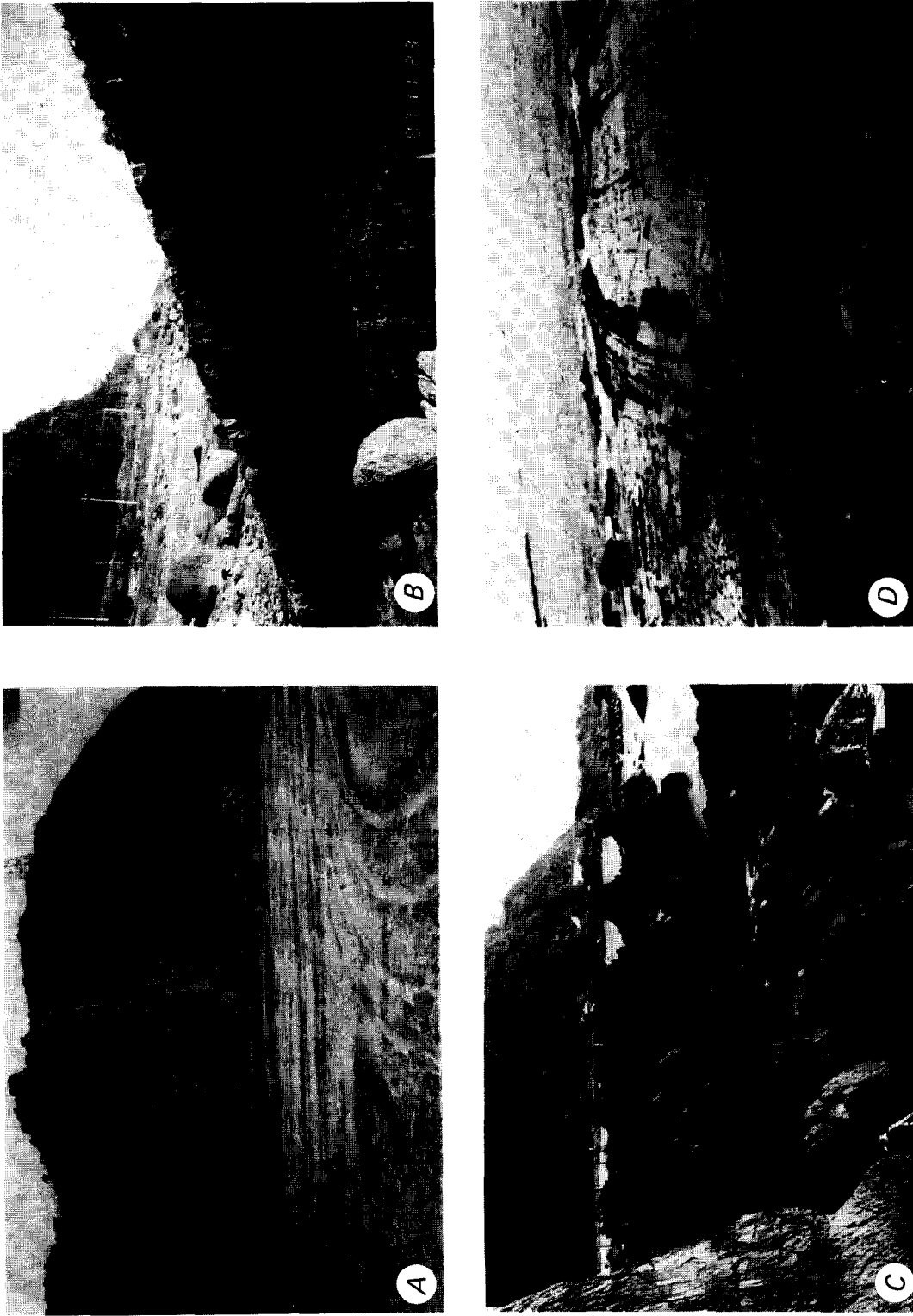
Fig. 5. Contractional deformation in northern Taiwan. (A) Progressive contraction in an outcrop near Keelung (see Fig. 6A). (B) Duplex structure south of Yenliao (see Fig. 6A). (C) Pressure solution cleavage in the argilite unit south of Yenliao. (D) Conjugate strike-slip system south of Yenliao.

mal faults (referred to as 2 and 1 in Fig. 6A, respectively). The latter are clearly crosscut by the thrusts. Tectonic analysis demonstrated that these apparent normal faults were in fact thrust faults which developed prior to tilting of the bedding due to folding, in the same major compressional paleostress field as other thrusts which postdate tilting (Fig. 6A). Progressive contrac-

tional deformation in fold flank thus constricted these sedimentary beds into a complicated faulted mass. At the decametric scale, Figs. 5B and 6B show six minor imbricate thrusts in a sandstone bed, in the upper Oligocene formations north of Ilan; a significant amount of contraction in the lower argillaceous layers (where minor faults are absent) is indicated by the presence of well-devel-
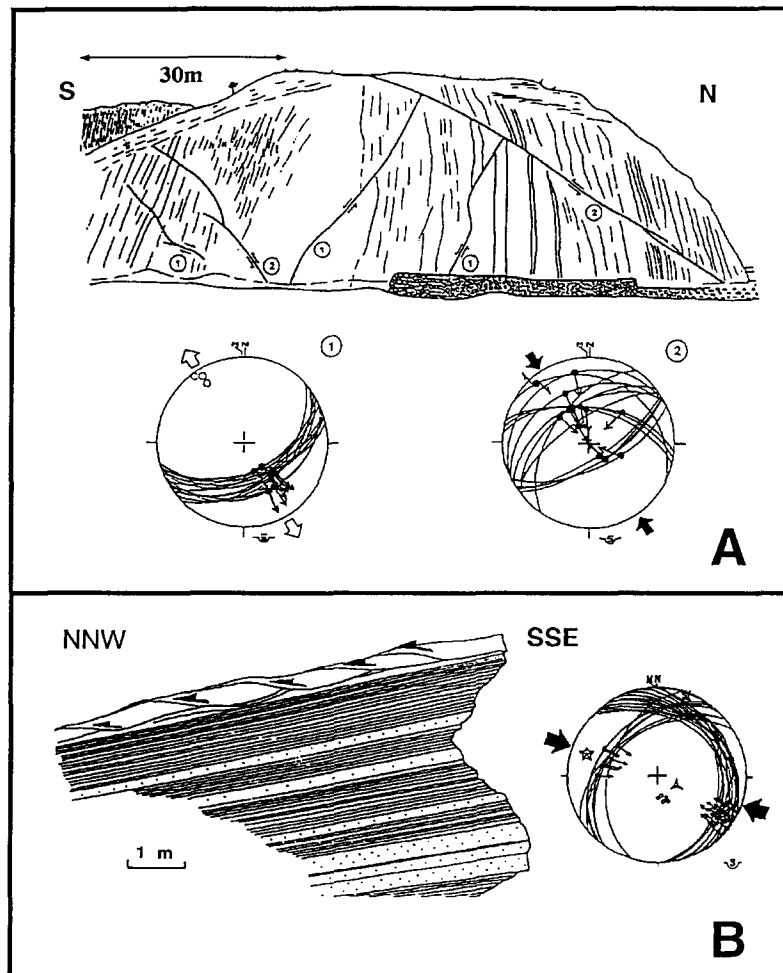

Fig. 6. Contractional deformation in northern Taiwan. (A) Sketch corresponding to Fig. 5A and fault-slip analysis. (B) Sketch corresponding to Fig. 5B and fault-slip analysis. Stereoplots show Schmidt's lower-hemisphere projections of fault planes, with slickenside lineations or as small dots with thin centrifugal arrows (normal slip) and centripetal arrows (reverse slip). Open dots = poles of local bedding. Directions of compression indicated by large black arrows. Principal axes of paleostress reconstructed based on fault-slip data inversion: five-, four- and three-pointed star indicate maximum compressional stress (σ_1), intermediate stress (σ_2), and minimum stress (σ_3), respectively.

oped spaced cleavages, which suggest that pressure solution phenomena played a significant role during contraction (Fig. 5C).

According to Suppe (1980), a retrodeformed cross-section of northern Taiwan showed that the Cenozoic rocks of the Chinese continental margin exposed in northern Taiwan have undergone 160–200 km of horizontal shortening, mostly as the result of thrust imbrication. Considering the additional contractional phenomena which affect the cross-section (i.e., tectonic compaction, pressure solution and elongation parallel to the mountain trend), and despite the difficulties in their evaluation, we estimate that the total horizontal shortening may be as large as 240–300 km, that is, 50% larger than the estimate based on the sole geometrical considerations in cross-section. Such percentages are not surprising according to Hossack (1979). Assuming that the convergence rate remained approximately constant during the orogeny and thus adopting the present value of 70 km/Ma (Seno, 1977), we infer from this simple calculation that the collision may well have started before 4 Ma. Estimates of 3.4–4.3 Ma are thus obtained for the age of the major collision, which followed an earlier stage when the tip of the Luzon arc and the lower Chinese margin came in contact (Angelier, 1990). Such estimates must be considered with caution, taking the extent of assumptions (constant velocity) and uncertainties (amount of shortening) into account.

4.3. Transcurrent tectonics

Strike-slip faulting is common in the area investigated. Figure 5D shows an example of conjugate strike-slip system along the northern coast of Taiwan, south of Yenliao (Fig. 3), where an Oligocene sedimentary unit formation was cut into isolated segments. The pervasive distribution of strike-slip faulting in northern Taiwan has been reported by Ho (1963, 1967). As an example, in fold-and thrust units mapped by Ho (1967) south of Taipei, numerous right-lateral strike-slip faults associated with minor left-lateral ones played a significant role at the kilometric scale (Fig. 7A; location in Fig. 3). In the Chinkuashih area between Keelung and Yenliao (Fig. 7B; lo-

cation in Fig. 3), where detailed geological mapping was done by Wang (1955), most of the E–W-trending faults are right-lateral while N–S ones are left-lateral, so that the development of this strike-slip fault system is related to transverse contraction (NW–SE) and longitudinal elongation (NE–SW) in this segment of the belt. In corresponding cross-sections (Fig. 7B), the apparent fault displacements are either normal or reverse, but the analyses of striae revealed the strike-slip movement. The pattern of gold and copper bearing veins in this area is characterized by a linear or curvilinear principal displacement zone in map view and in profile, with a subvertical fracture zone ranging from braided to upward-diverging within the sedimentary cover (Fig. 7C). All these structures indicate that not only contraction but also transtensional deformation occurred in the Chinkuashih area (in agreement with wrench fault geometry independently discussed by Naylor et al., 1986).

4.4. Rotational and extensional tectonics

The deformation of conjugate strike-slip fault domains leads to complexities. Rotations of fracture bounded block domains may result in lateral extrusion of these blocks and formation of basins and ridges during their progressive rotation and interaction (Ron et al., 1984; Garfunkel and Ron, 1985; Nur and Ron, 1987). Block rotation about vertical axes, which occurred in northern Taiwan (Lee et al., 1991), is an essential result of strike-slip faulting. The rotations of blocks and faults imply that the angular relationship between domains must change as deformation proceeds so that fault geometry vary with time (Nur and Ron, 1987). Detailed transpressional and rotational structures along the northern coast of Taiwan were described in Lu et al. (1994). For instance, an outcrop with sub-horizontal Oligocene sandstone–shale layers south of Yenliao (Fig. 8A) showed straight and curved strike-slip faults. The curved faults are usually crosscut by the straight ones, which are thus considered younger faults. Based on the conjugate character of strike-slip faults patterns, we obtain of about 115° azimuths of major compressional stress for the younger
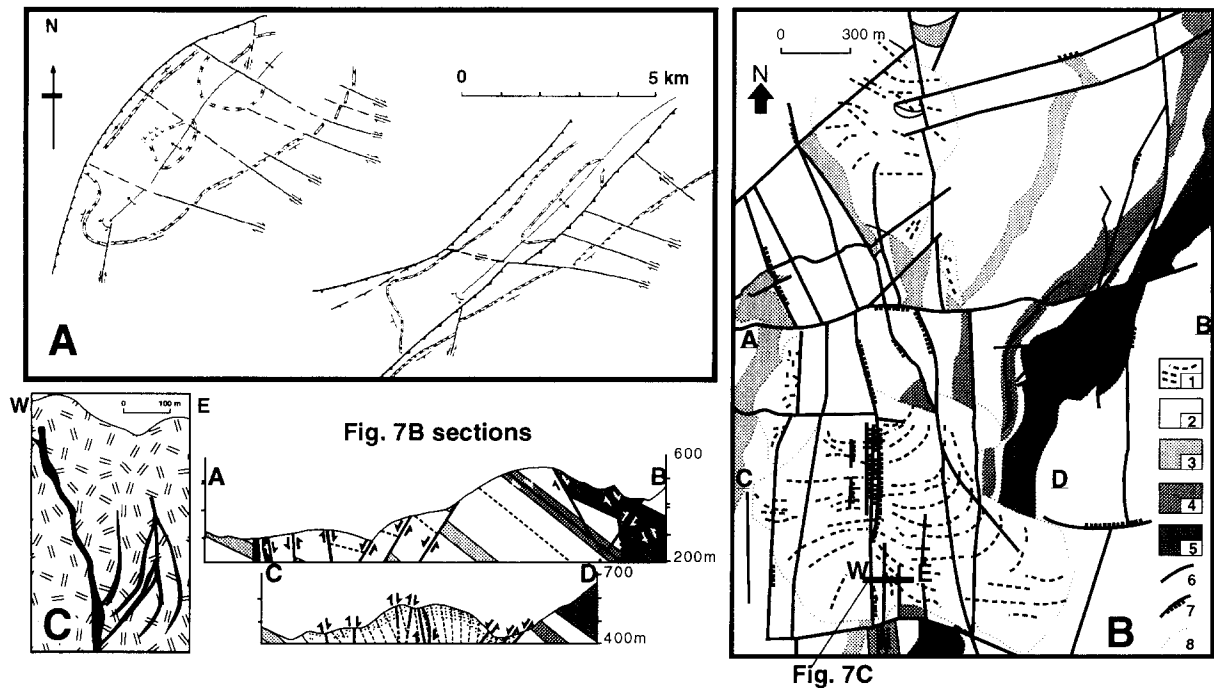
Fig. 7. Transcurrent deformation in northern Taiwan. (A) Two thrust anticlines, south of Taipei (see Fig. 4 for location), cut by E–W-trending (dextral) and N–S-trending (sinistral) strike-slip faults. (B) Structural map of the Chinkuashih gold-copper mine (modified after Wang, 1955): 1 = dacite with flow lines; 3, 4 and 5 = key beds in the Miocene formations with undifferentiated rocks as 2; 6 = strike-slip and thrust fault; 7 = normal fault; 8 = rock formation boundary, most E–W-trending faults are dextral strike-slip and most N–S-trending faults are sinistral strike-slip, in cross-sections, the beds have fault offsets with both normal and reverse separations. (C) Cross-section in dacite body, showing curved shape of the gold-copper-bearing quartz-veins (in black) related to strike-slip.

faults and about 135° for the older ones (sets 2 and 1 in Fig. 8A, respectively). Because all faults probably developed under the same paleostress regime, the southern half of this area probably underwent rotation of about 20° clockwise.

Normal faults are common throughout northern Taiwan, especially in and around the Taipei basin, in the Tatun volcano and Yenliao areas

(locations in Fig. 3). This geographic distribution is shown in the map of extensional trends (Fig. 9B). Some of these normal fault systems affect the Pleistocene formations (see Lee, 1989 and Chu, 1990, for details). Note that our study is restricted to the Plio-Quaternary tectonic history; normal faulting corresponding to the older history of the Chinese margin is not considered

Fig. 8. Field and fault-slip analysis examples of the rotational and extensional tectonics in northern Taiwan. (A) System of rotated strike-slip faults in the Oligocene Aoti Formation (along the coast between Yenliao and Ilan); in the diagrams, D and S are dextral and sinistral strike-slip faults, respectively. (B) System of conjugate normal faults in the Miocene Shihti Formation (Chikuashih area). (C) Normal faults with striated curved fault surface in the Oligocene Wuchishan Formation along the coast at Chinshan (see Fig. 3 for location). Fault-slip analysis: stereoplots are Schmidt's lower-hemisphere projections of fault planes and slickenside lineations are indicated as small dots with thin centrifugal arrows (normal slip) Open dots: poles of the local bedding. Directions of compression and extension are shown by large black arrows (Fig. 8A) and large open arrows (Fig. 8B), respectively.
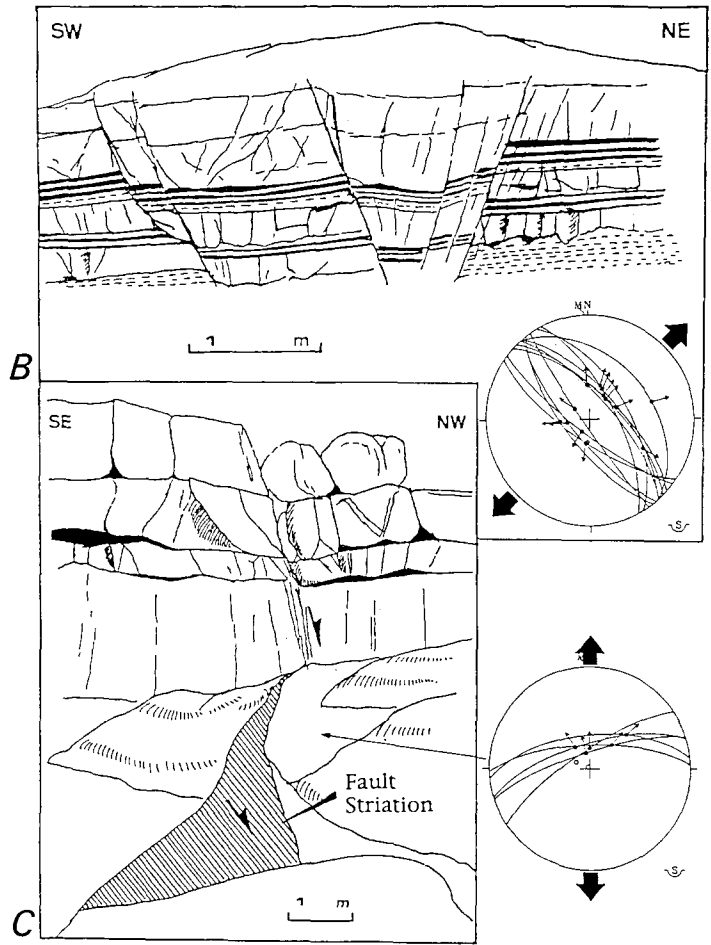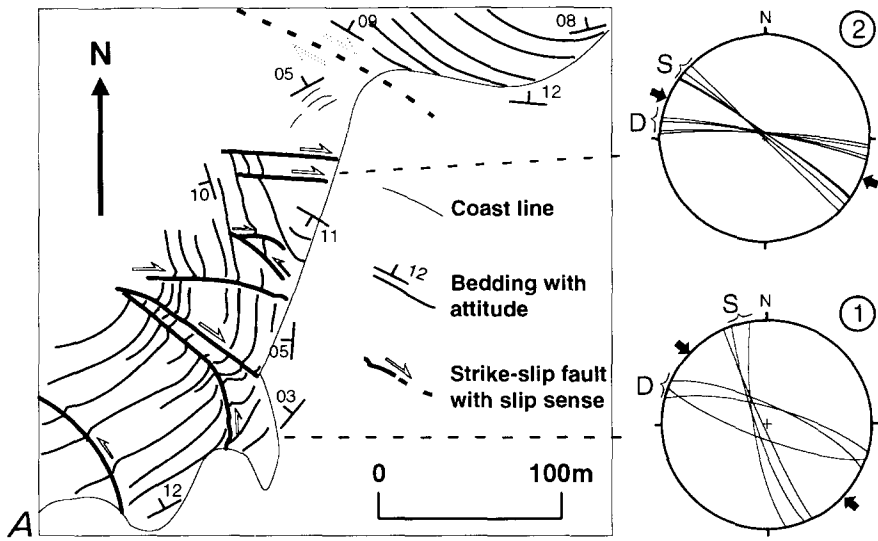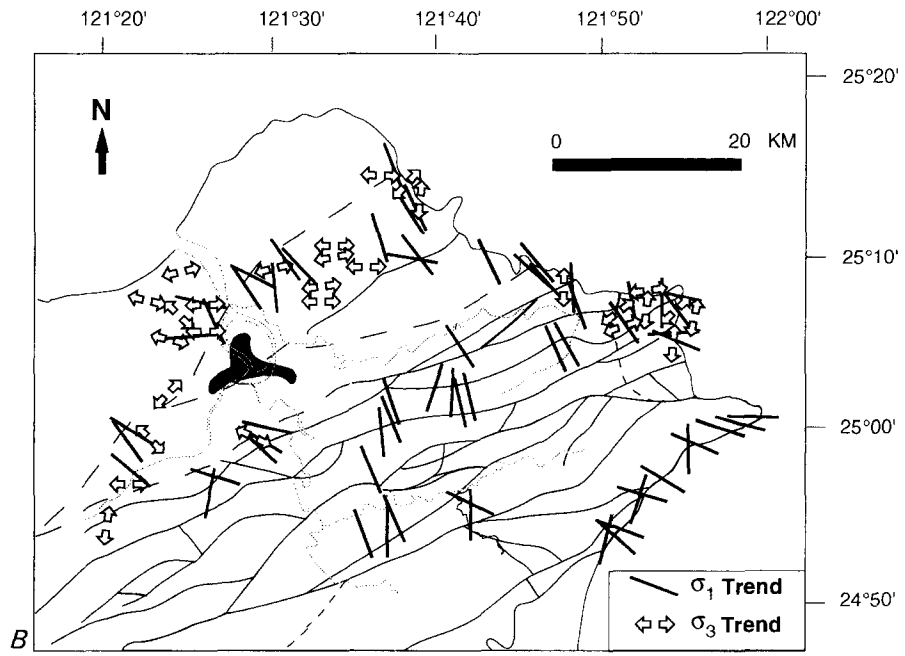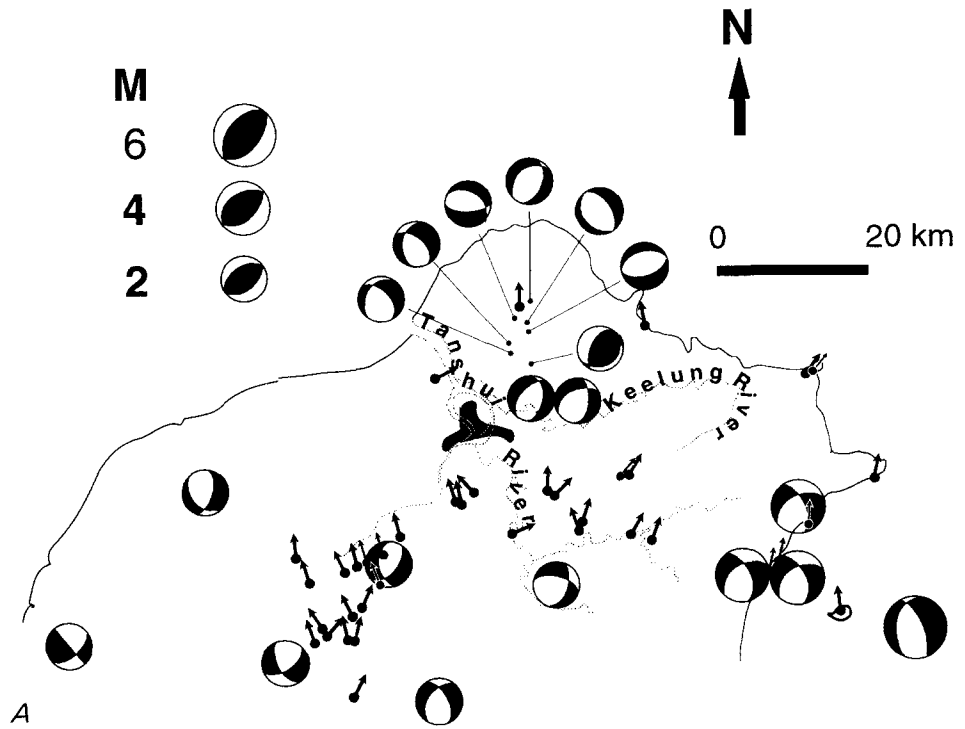
herein. Within the structural framework of the northeastern collision belt of Taiwan, the occurrence of normal faulting may be explained in relation to stretching along the mountain chain, in association with: (1) contraction; (2) transcurrent deformation; and (3) rotations of tectonic units. Selected examples of normal faults are illustrated in Fig. 8B and C. By comparing the outcrop location (Chinkuashih for Fig. 8B, Chinshan for Fig. 8C), the mountain belt trend (Fig. 3) and the examples of brittle tectonic analyses (Fig. 8B and C, see also Fig. 9B), one observes that the major extension trend (σ_3) is subparallel to the mountain chain in Fig. 8B whereas it is oblique in Fig. 8C. This suggests that in cases such as that of Fig. 8B, the extension is related to longitudinal stretching in association with transverse contraction, whereas in cases such as in Fig. 8C, it is related to transcurrent deformation. We infer that extensional trends do not correspond to independent events, but to different deformation modes within a single tectonic regime. The most spectacular example of extension, the Taipei basin, will be discussed later.

5. Tectonic stress and block rotations

5.1. Present-day stress

The distribution of present-day stress provides an important key for understanding the recent deformation in northern Taiwan. Although a compressional stress regime (with reverse and strike-slip faulting) dominates in most of the Taiwan collision area, results of focal mechanism analyses from northern Taiwan (Fig. 9A) indicate that the present state of stress of this part of the island is compatible with strike-slip and extensional regimes (Yeh et al., 1991). In more detail, north of the Keelung River, most fault plane solutions indicate nearly normal fault mechanisms, whereas to the south the strike-slip component increases although a normal component is still present (Fig. 9A).

5.2. Paleostress analyses

The results of the paleostress analyses are summarized in Fig. 9B in terms of trends of the horizontal compressional stress axes (σ_1) corresponding to different compressional structures, including thrusts, strike-slip faults, fracture cleavages, folds and joints (compiled from Lee, 1986,1989; Angelier et al., 1986,1990; Chu, 1990). In the map of Fig. 9B, each bar indicating the local trend of σ_1 results from the analysis of a site where numerous brittle structures have been observed. Even considering the dispersion due to uncertainties of measurements and paleostress determinations, the large variation of these σ_1 trends cannot be simply accounted for by the natural irregularities and stress field inhomogeneity related to a single event affecting a rigid mass. The complexity of compressional stress distribution (Fig. 9B) and of the structural pattern (Figs. 3 and 4) suggests that complex deformation affects in lithologically heterogeneous materials.

Results of paleostress analyses also indicate variable trends of extension related to these normal fault systems in northern Taiwan. Calculated σ_3 trends are shown in Fig. 9B. Note that normal fault concentration occurs principally in the areas where volcanic rocks dominate (around the Tatun Volcano, see Fig. 3) and along the boundaries of major block domains (shown in Fig. 3). This im-

Fig. 9. (A) Geomagnetic data and fault-plane solutions from northern Taiwan. Small dots with arrows describe the declination of magnetic fabrics in the rocks of northeastern Taiwan (after Lue, 1989). Double-couple mechanisms with size as function of magnitude; compressional dihedra are black and extensional ones white (after Yeh et al., 1991). (B) Summary of the results of the paleostress analyses. For extension, each pair of open arrows (local trend of σ_3) corresponds to the analysis of a site with many normal faults. For compression, each bar (local trend of σ_1) corresponds to the analysis of a site with many brittle structures (compiled from Barrier, 1985; Lee, 1986, 1989; Chu, 1990). Compressional structures, including thrusts, strike-slip faults, fracture cleavages, folds and joints. Compiled from Lee (1989) and Chu (1993).

plies some relationship between the presence of volcanic rocks, of normal faults and the block rotations

5.3. Paleomagnetic analyses

Lue (1989) and Lee et al. (1991) demonstrated, based on numerous paleomagnetic analyses in the foreland, that rocks of northeastern Taiwan have been rotated about 20° clockwise on average. This 20° clockwise rotation occurred east of the 'Tanshui River axis' (I-I′ in Fig. 3), whereas to the west the anticlockwise rotations smaller than 10° on average were identified (see details in Fig. 9A). Despite some criticism (Miki et al., 1993), these paleomagnetic results brought evidence that rotations play a significant role in this area. Furthermore, provided that these rotations affected large regions rather than small blocks, these results support the earlier idea that the 40°–60° change in regional strikes in northern Taiwan (Fig. 1B) includes a 20°–30° rotation of blocks and an initial indenter-induced curvature of the belt of 20°–30° (Angelier et al. 1990). Anomalous paleomagnetic declinations (Fig. 9A) may reflect local rotations of relatively small blocks rather than homogeneous rotations of large units; also, within such a pattern of bulk clockwise rotation, some blocks may have rotated anticlockwise to accommodate the space.

5.4. Block rotation vs. stress changes

Based on the principle of superposition of slickensides on fault planes, and in agreement with earlier determinations by Angelier et al. (1986) in all the Foothills of Taiwan, Lee (1989) proposed that the N–S- to NE–SW-trending compression predated the major NW–SE-trending compression in northern Taiwan. Angelier et al. (1990), in their study of the Hsüehshan Range, reconstructed the regional compression into five events, from the oldest to the youngest: (1) approx. N5° E; (2) approx. N70° E; (3) and (5) approx. N110° E; and (4) approx. N150°. Although complex phenomena have probably occurred, such as permutation between principal stresses, local perturbation related to block structure and dis-

continuities, part of these changes probably reflect block rotations occurring in regional stress fields.

Despite the absence of local correlation between paleomagnetic and tectonic analyses, and considering our tectonic interpretation which combines. contraction, transcurrent motion, rotation and extension, we suspect that the paleostress history may in fact be somewhat simpler. We consider that the current plate convergence direction, that is about N130°, may not have changed dramatically since the beginning of the Taiwan orogeny, as suggested by Seno et al. (1987). On the other hand, northeastern Taiwan has suffered bulk clockwise block rotation, with blocks rotating clockwise consistent with the dextral component of regional motion, and some blocks possibly rotating anticlockwise. We suggest that complex local paleostress history can be accounted for by such variable block rotations. For instance, the succession of (1), (4), and (5) may be explained by simple clockwise rotations of 35° and 40° under a single WNW–ESE compressional regime; the succession of (2) and (3) or (5) may correspond to a anticlockwise rotation of 40°. Local observation, such as for Fig. 8A, brings support to such interpretation. Local rotations alone cannot explain the complete succession of paleostress observed, but they certainly result in increasing apparent complexity. In addition, limited changes in plate convergence may interfere and complicate the pattern. Further tectonic and paleomagnetic studies are of course needed in order to distinguish between the different hypotheses (and determine how far the dispersion of vectors in Fig. 9 result from paleomagnetic uncertainties vs. variable block rotations). However, the combination of dominating NW–SE/WNW–ESE compressional stress and rotation related to strike-slip faulting certainly played a role in the progressive development of the cumulative paleostress pattern.

Considering the various tectonic evidences discussed earlier in this paper, we conclude that during the Plio-Quaternary, contraction, transcurrent deformation, rotations and extension in northern Taiwan did not occur as distinct events but concurred to accommodate complex deforma-

tion. Of particular interest is the case of the large Taipei basin.

6. Formation of the Taipei basin

The Taipei basin, a major site of extension has a complex T-shape. The tectonic interpretation of this basin must reconcile this particular shape (Fig. 3), the presence of E–W extension related to normal faulting (Fig. 9), the general context of NNW–SSE compression (Fig. 9) illustrated by the presence of surrounding major fold-and-thrust units (Fig. 3), and the existence of strike-slip faulting and block rotation. We propose that the development of the Taipei basin, mostly extensional, is related to the continuing bending of the

crescent belt. This is supported by the approximate parallelism between the structural trends of the belt and the average trends of extension in this area (Fig. 9B), considering that the same geometrical relationship was observed in the sandbox modelling experiment (Fig. 2).

Figure 9A shows that near Taipei rotations occurred clockwise to the east but anticlockwise to the west, as demonstrated by Lue (1989) and Lee et al. (1991). This distribution of rotations is consistent with the results of experiments (Lu and Malavieille, 1994). These divergent rotations are fairly consistent with local E–W extension, suggesting that the Taipei basin development is similar to that occurring when a series of faulted blocks tends to rotate away from the axis of maximum compression (Garfunkel and Ron,
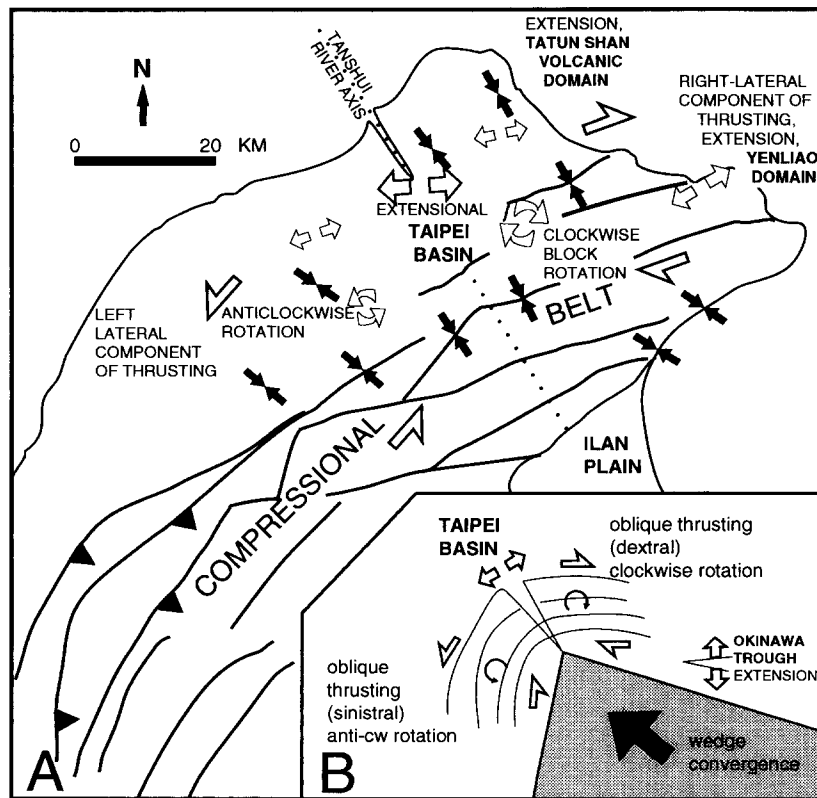

Fig. 10. Model of Plio-Quaternary tectonic deformation in the foreland thrust belt of northern Taiwan, as reconstituted in this paper. Note the existence of three major domains: (1) the eastern domain characterized by oblique-slip thrusts superimposed by major right-lateral strike-slip and bulk clockwise rotation deformation; (2) the central domain characterized by indentation and extensional deformation; (3) the western domain where major left-lateral oblique thrusting superimposed by right-lateral bookshelf-type strike-slip and bulk anticlockwise rotation dominates. (A) Interpretative map. (B) Explanatory sketch.

1985), which may effectively result in the development of a T-shaped basin. The general distribution of the block domains in northern Taiwan, the paleomagnetic data and the tectonic analyses all indicate that two distinct domains, with different systems of conjugate strike-slip faults, are separated by the Tanshui river axis (the I-I' line in Fig. 3) and rotate away from each other.

7. Conclusion

According to the slip line theory applied by geologists to collision with a wedge-shaped indenter (e.g., Tapponnier and Molnar, 1976), the strike-slip faults systems orientations should fall into two groups. The experiments of Lu and Malavieille (1994) illustrated this phenomenon in the case of Taiwan collision. We consider that the two conjugate strike-slip fault domains are the result of an indentation by a wedge-shaped backstop (Fig. 10), in agreement with experimental results (Fig. 2). Our tectonic model of northern Taiwan is summarized in Fig. 10A, the sketch of Fig. 10B illustrates the relationship between the major regional deformation modes, within the framework of oblique collision between the Chinese margin and an asymmetric wedge indenter representing the northwestern corner of the Philippine Sea plate (Fig. 1A). This indentation results not only in contractional tectonics across the belt (black arrows in Fig. 10A), but also in divergent strike-slip components and block rotation, and in local occurrence of extension roughly parallel to the trends of the major units of the belt (open arrows in Fig. 10A). We conclude that extensional structures such as the Taipei Basin developed in response to increasing belt curvature and related block rotations. Although the senses of strike-slip components and rotations are symmetrically distributed on both sides of the Tanshui River axis (Fig. 10A), due to the asymmetry of the collision (Fig. 10B), amounts of dextral strike-slip and clockwise rotation (to the east) are larger than amounts of left lateral strike-slip and anticlockwise rotation (to the southwest) (Fig. 10B).

Contraction, transcurrent faulting, block rotation and even extension are four essential tectonic mechanisms dominating oblique convergence and collision tectonics. It is necessary to take their complementarity into careful account, which was not done before in Taiwan. Our major conclusion is that although significant changes have taken place during the Plio-Quaternary evolution of the Taiwan mountain belt (Fig. 1), most structures of the northeastern crescent-shaped belt (compressional, transcurrent and extensional) developed within a single overall tectonic mechanism (Fig. 10) that rotational tectonics and related space problem made complex.

Acknowledgements

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