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Modeling of Stress-deformation Relationships in a Collision Belt: Taiwan

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ABSTRACT

This paper presents a review of strain-stress relationships in the active Taiwan collision at different scales based on numerical modeling. As the digital computer has become an important research tool due to its capability of performing numerical simulations of real tectonic processes, a mass of accurate and comprehensive database is required to assure the meaningfulness and accuracy of simulation results. The aim of this study is to refine the general interpretation of the relationships between active deformation and geological structures. Through an evaluation of the presence and role of mechanical decoupling along major faults, distinctive attention will be devoted to the role of geological discontinuities. Such decoupling plays an important role in the distribution of regional and local stress and velocity patterns. In this paper, the relationship between the complexity of modeling and the data within the range of data uncertainties is also discussed in order to determine the level of complexity at which a model can be built, validated and considered significant. The construction of numerical simulation depends on the scale of the model and on the data available as constraints within that scale. The study of the Taiwan collision case provides an illustration of the relationships between kinematics, structure and/or strain fields in a curved belt. It is claimed that although 2-D numerical modeling provides valuable results, validation through 3-D modeling experiments is indispensable in accounting for the oblique dips of major boundaries.

(Key words: Numerical simulations, Mechanical decoupling, Geological discontinuities, Stress and velocity fields)

1. INTRODUCTION

Taiwan is on the site of the present-day arc-continent collision between the Luzon arc of the Philippine Sea plate and the Chinese continental margin (Figure 1). Due to arc-continent

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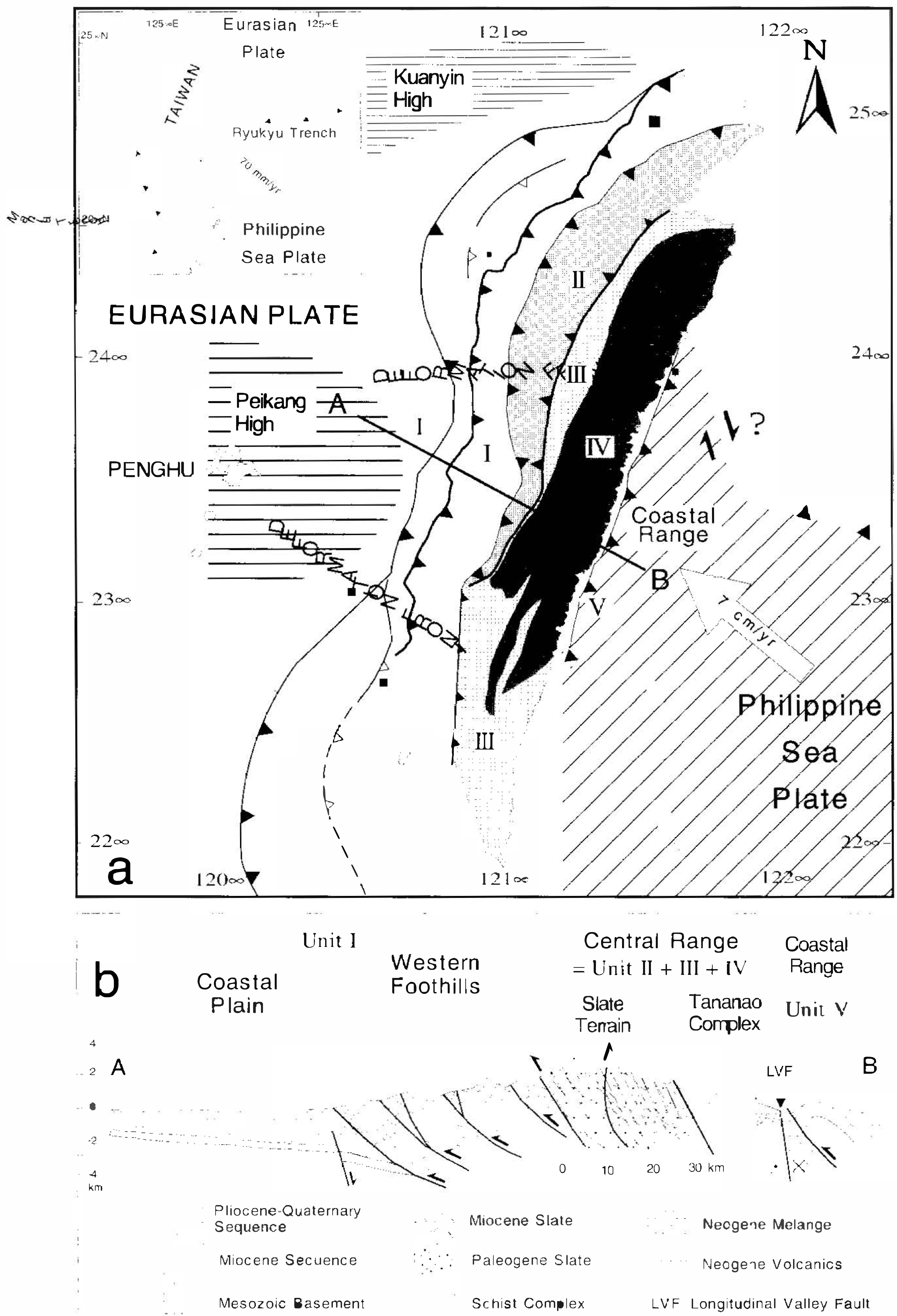

Fig. 1. (a) Tectonic framework and main structural units in Taiwan (geodynamic setting in the upper-left corner): major thrust faults with triangles on the upthrust side (L.V., Longitudinal Valley); I, Western Foothills and Coastal Plain; II, Hueshan Range; III, Backbone Range; IV, Mesozoic/Paleozoic Basement; and V, Coastal Range. (b) Schematic cross-section of Taiwan. (AB, see location in Fig. 1a) after Teng (1990).

collision occurring about 5 Ma ago in Taiwan (for details, see Suppe, 1984 and Ho, 1986), mountain building occurred and compressional tectonism prevailed. Since extensive paleostress analyses have been conducted throughout the island during the last 10 years, the regional distribution and the evolution of such tectonic paleostresses are now rather well known (Barrier, 1985 and 1986; Barrier and Angelier, 1986; Angelier *et al.*, 1986 and 1990; Lee, 1986; Chu, 1990; Lacombe *et al.*, 1993; Rocher *et al.*, 1996). These local paleostress determinations enable researchers to not only describe local mechanisms, but also understand of regional tectonics at the scale of the plates. The regional knowledge obtained of the Late Cenozoic paleostress field has, thus, provided strong constraints in the geodynamic interpretation of the Taiwan collision belt. However, despite its importance in tectonics and geodynamic studies the consistency between the deformation at the regional scale and the reconstructed paleostress patterns has generally remained poorly analyzed. To assess the consistency between paleostress and deformation, it is necessary to carry out numerical modeling of strain-stress relationships, in order to quantitatively analyze the compatibility between kinematic boundary conditions, geological structures and paleostress patterns. This modeling may involve a variety of techniques, which depend on the actual types of deformation. Tectonic processes which affect a geologically homogeneous area produce regular trends in stress and strain at the regional scale, which means that the use of a mathematical model seems quite appropriate; however, any such assumption of continuity is invalid where major 'weak' fault zones (that is, fault zones with little mechanical coupling) are present. When a rock mass containing a structural discontinuity is deformed in a way that relative motion occurs across the discontinuity, the displacement and stress fields are significantly modified. As a result, the knowledge of these 'perturbed' fields must be considered when analyzing the discontinuous active structure and regional deformation. According, the investigation of perturbations in stress and deformation fields in the presence of major mechanical discontinuities becomes an important aspect in the modeling work discussed in this paper.

The general structure of Taiwan has been described in numerous papers (e.g., Suppe, 1984; Ho, 1986). In this paper, the focus is on the reconstruction of the stress and deformation fields because they provide constraints in modeling. Although the general link between the compression in Taiwan and the plate convergence is obvious (Figure 2a), the quantitative relationships in terms of displacement and deformation trends are difficult to recognize due to the complex shape of the plate boundary and the obliquity of relative motion. In 1986, based on the available structural and tectonic knowledge of the Taiwan area, and taking into account other independent information on the kinematics of the Philippine Sea plate relative to Eurasia (Seno, 1977; Minster and Jordan, 1979; Ranken *et al.*, 1984; Huchon, 1986). Huchon et al. (1986) proposed the first viscous 2-D finite-element model including different rheologies and a discussion of the role of variable boundary conditions. That study aimed at simulating a rigid body, the Luzon arc, which indented into a rigid-plastic material, the Chinese continental margin (Figure 2b). Meanwhile, Lee (1986) proposed a 2D finite-element model of plane strain with the joint element in order to partially simulate the effects of mechanical decoupling along the active Longitudinal Valley Fault, the Lishan Fault and the Okinawa trough. In short, both of these models successfully produced the fan-shaped compressional stress patterns radiating from the collision zone, illustrating that the trends of stress trajectories were sensitive to the direction of the collision. At about the same time, Viallon *et al.* (1986) proposed a 2-D finite-element model with an elasto-plastic behavior, and showed that the opening of the

Okinawa basin behind the Ryukyu trench could be well explained by a retreating trench model with lateral anchoring caused by the collision in Taiwan. They highlighted the role of a suction force at the edge of the overriding plate due to the subduction of the oceanic lithosphere of the Philippine Sea plate. More recently, Song (1993) proposed a 2-D finite-element model to investigate the effect of left-lateral strike-slip along the Longitudinal Valley Fault under oblique convergence. In this model, different types of lateral strike-slip motion were implanted along the convergence boundary by incorporating some split nodes with assumed left strike-slip values to simulate discontinuous motions across slip fault plane. Subsequently, Lu and Malavieille (1994) laid out an experimental sandbox modeling which allows for a description of the development and kinematics of structures in mountain belt formed during oblique convergence (Figure 2c). However, it is not yet clear whether the old metamorphic tectonic units which form the core of the Taiwan Mountain Belt are strong enough to be considered capable of serving as a backstop. For the purpose of understanding the stress distribution in and around Taiwan, Cheng *et al.* (1995) employed a 3-D elastic finite-element model. Even more recently, in an attempt to explain the relationships between the stress distribution and the convergent kinematics during the Plio-Pleistocene in the whole subduction and collision zones in and around Taiwan, Hu *et al.* (1996a) presented a 2-D plane stress elastic and elasto-plastic finite-element model (Figure 2d) for both the Taiwan orogen and the neighboring arc-and-trench systems.

Both Huchon *et al* (1986) and Hu *et al.* (1996a) calculated stress trajectories in the Taiwan region with the finite-element methods and compared them to the available tectonic information. In their models, the slip component along the Longitudinal Valley Fault (LVF) was by definition ignored, such that despite the valuable information that was generally provided, their models failed to represent the actual stress-strain situation in the vicinity of the major tectonic boundary where left-lateral strike-slip motion has been involved.

Two important concerns in modeling which apply to the analyses of geodynamic problems deal with (1) the level of detail which can be obtained in realistic conditions using the techniques adopted and the data available, and (2) the need for the full consideration of geological discontinuities, which are known to play a major role in tectonics even if they have been poorly accounted for through a modeling of continuous media. It is now possible, however, to go further in the modeling of the collision zones, first because of the more sophisticated techniques available, such as distinct-element modeling, and second because of the availability of a large mass of new data, including a more comprehensive description of paleostress and a new reconstruction of the present-day deformation field based on GPS studies.

This being the case, we have consequently chosen Taiwan as a case example for this study since it provides an optimal opportunity for understanding the behavior of a collision zone with active shortening and strong mechanical coupling between subduction zones and major fault zones where mechanical decoupling occurs.

2. INFLUENCE OF MECHANICAL DECOUPLING

The mechanical behavior of a rock mass is often strongly influenced by discontinuities. Recent advancements in discontinuum modeling have indeed made it very tempting to try to incorporate a broader depth of detail of the geological structure into the model. This however,

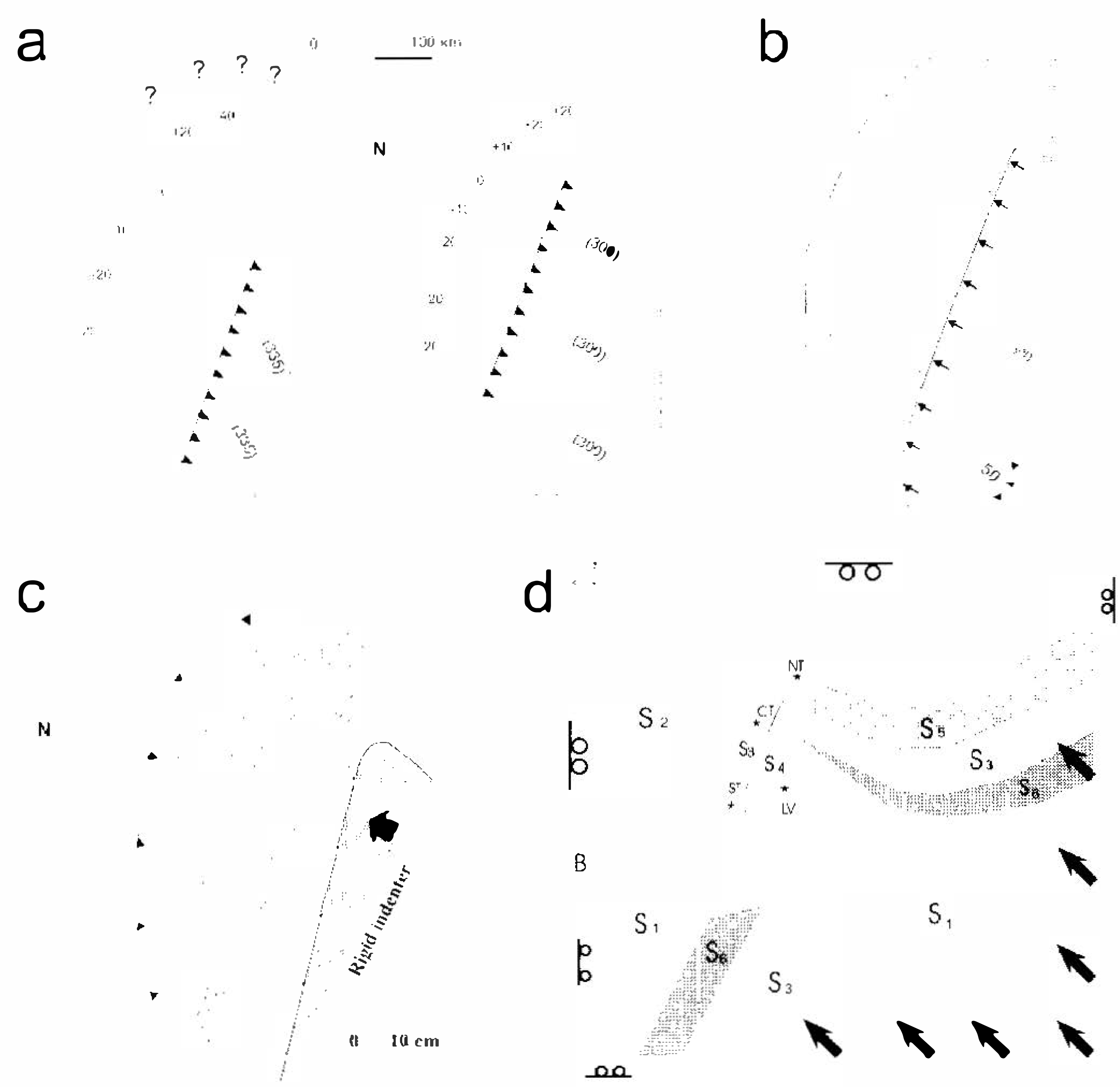

Fig. 2. Different models of Taiwan collision. (a) Stress trajectories and plate convergence, for two events of Taiwan collision (Plio-Pleistocene on the left, Pleistocene-Holocene on the right), after Angelier *et al.* (1986). Philippine Sea plate is represented by hatched lines. Eurasia is white. Convergence boundary of eastern Taiwan with triangles on the upper side. Large arrows: relative motion Philippine Sea-Eurasia (azimuths indicated). Trajectories of s1 with average deviations relative to the direction of plate convergence, in degrees (+, clockwise; -, counterclockwise). Dashed lines present distribution of s1 paleostress in northernmost Taiwan due to clockwise rotation (with question marks because in 1986 no paleomagnetic results were available). (b) Stress trajectories based on a 2-D finite-element viscous model (after Huchon *et al.*, 1986). Continuous lines, maximum compressive stress trajectories; large open arrows, directions of motion of the indenter (azimuth indicated); small solid arrows in lower-left corners, angle between extreme stress trajectories. (c) Experimental sandbox model of the Taiwan mountain belt (after Lu and Malavieille, 1994): thrust wedge created by oblique indentation of a wedge-shaped backstop. (d) Geometry and boundary conditions of the finite-element elasto-plastic model of Taiwan collision (after Hu *et al.*, 1996a). For geographic coordinates, see the coast of Taiwan shown as thin dotted line. S1, S2, S3, S4, S5 and S6 are subdomains with different rheologies (decreasing Young's modulus). Boundary conditions: open triangle for fixed corner; open circles with bar, roller in one direction; no symbol, free segments; large black arrows, common direction of displacement based on plate kinematics.

leads to a basic dilemma if the purpose of the model to be of practical interest to structural geologists (Figure 3). In light of determining the level of complexity at which a model can be built, validated and considered significant, Figure 3 shows the relationship between the level of complexity of modeling and the range of uncertainties in the data (Figure 3). The point in question is whether the model should include as much geological detail as possible, or whether it should primarily aim for a simplified analysis. As for the first premise, it must be noted that it is futile to expect to obtain sufficient geological data describing the medium in every detail, that the computer hardware requirements for such a modeling rapidly exceed those capacities typically available (the shaded zone in Figure 3), and that, most importantly, a significant control by relevant data becomes less effective as a greater source of complexity is added, because many different models can explain the same data. Concerning the second premise, the perceived difficulty is that the problem may appear oversimplified: how can one be certain that none of the critical structures have been omitted from the analysis? The most realistic solution to the dilemma, therefore, consists of building as simple a model as possible which fits the data available; this is then enhanced and refined through a process of gradually increasing its complexity until a good fit is obtained within the range of data uncertainties (Figure 3).

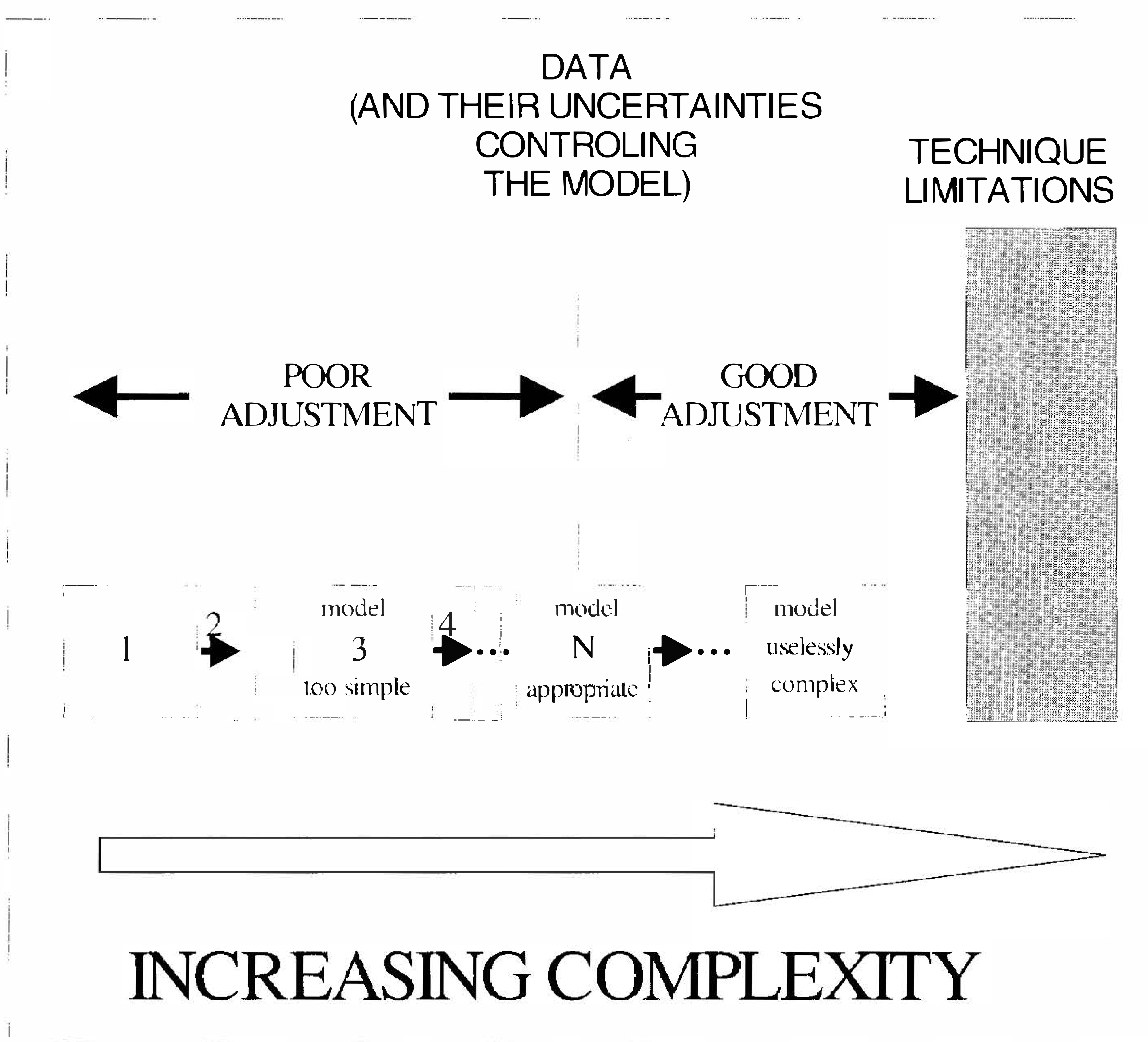

Fig. 3. Modeling dilemma in the relationships between data adjustment and complexity of the model. Model 3 is insufficient detail. Model N is appropriate. Useless model is excessive detail.

Hu *et al.* (1996b) carried out two numerical modelings for the detailed investigation of the stress and velocity fields in the collision belt and foreland around the basement high (Peikang High). The finite-element model (Figure 4a) successfully explains the general shape of the regional stress fields in terms of compressional trends but fails to account for deviations near major thrust zones and for the occurrence of extension on both sides of the Peikang High. In contrast, the effect of the presence of discontinuities is well accounted for through the use of the distinct-element method (Figure 4b) by which a much better fit is obtained; nevertheless, numerous local deviations of the stress and velocity fields still cannot be analyzed at the scale considered.

Distinct-element model (Figure 4b) shows significant stress deviations near the major regional discontinuities (the Longitudinal Valley Fault and the two major thrusts of the western belt, see Figure 1) relative to the dominant NW-SE compressional stress pattern and these cannot be neglected in the geodynamic modeling of the Taiwan mountain belt. The deviations explaining nearly E-W compressional stress trends are effectively observed. These results reveal that the presence of large discontinuities plays an important role in the distribution of local stress patterns. The heterogeneous distribution of the stress fields may be attributed to the complex pattern of the folded-faulted blocks of southwestern Taiwan; these could not be taken into consideration at the scale of the present modeling. The variable location of the active faults through time has made the resulting paleostress pattern even more complex and explain the high variability in compressional trends.

In contrast to Figure 4a, Figure 4b shows the extensional stress on both the northern and southern sides of the Peikang High, trending approximately parallel to the major discontinuities. These results are generally consistent with the presence of normal faulting south of the Peikang High (Yang *et al.*, 1991). Analyses of earthquakes focal mechanisms have also revealed some NE-SW trends of s3 axes near the Kaoshiung area, and nearly E-W ones in the southern part of Taiwan (Yeh *et al.*, 1991; Kao and Wu, 1996). Significant southwestward escaping probably occurs in this area. Based on the distinct-element method with plane strain conditions, the NE-SW extensional stress trends may be attributed to such a tectonic process.

To Sum up, 2-D experiments involving accurate comparisons between finite-element and distinct-element modeling demonstrate that in a similar context of accuracy and data control, the method that accounts for the presence of discontinuities, namely, the distinct-element method, certainly provides much better results in terms of both the distribution of compressional trends and the occurrence of extensional trends on both sides of the Peikang High. At the scale considered, it seems difficult to go further in terms of model complexity (Figure 3) owing to the limited knowledge of the distribution of weakness zones smaller than those shown in Figure 4, and in consideration of the possible control by the data on the actual stress fields.

3. FROM 2-D TO 3-D

A 2-D approximation normally represents a reasonable simplification for the 3-D geodynamic problems, although it involves a drastic simplification (including such shortcomings as the neglect of the rheological stratification, deep structure of the lithosphere, dips of major structure among many others). With regard to the convergent boundary in Taiwan, the situation is essentially 3-D due to the fact that the major discontinuities are not vertical. The

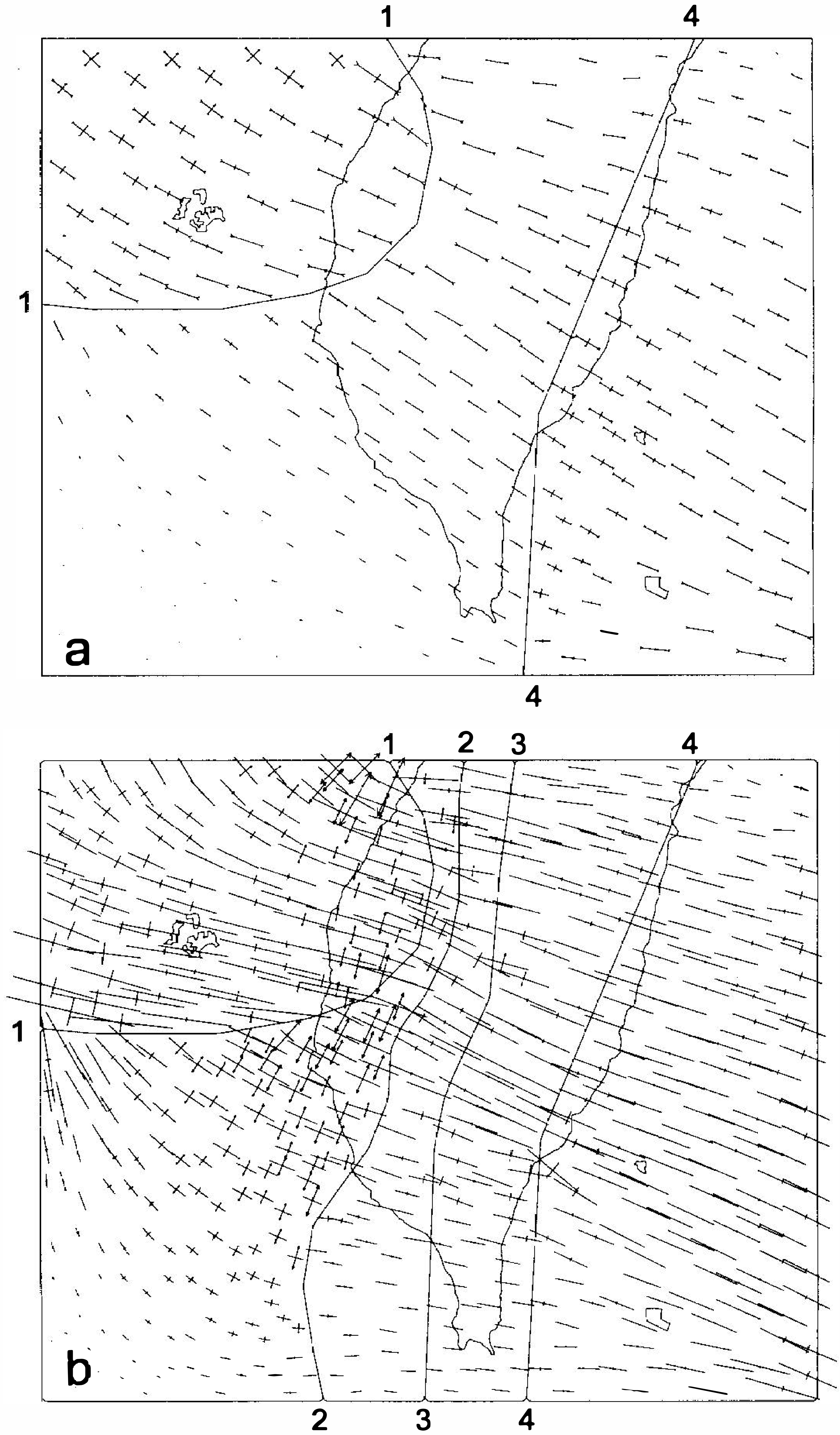

Fig. 4. 2-D finite-element and distinct-element models of collision in southern Taiwan, in terms of stress distributions (after Hu *et al.*, 1996b). (a) Computed stress distribution, finite-element model. Continuous lines 1 and 4: rheological boundaries. Pairs of convergent arrowheads: maximum compressive stress. (b) Computed stress distribution, distinct-element model. Continuous lines: 1 and 4, rheological boundaries; 2, 3 and 4, mechanical discontinuities. Bars: maximum compressive stress. Pairs of divergent arrowheads, indicate extensional stress.

major boundary, the active Longitudinal Valley Fault, is a thrust with a minor left-lateral component; with a dip angle of about 55° (Tsai *et al.*, 1977), there is a large thrust component (Hsu, 1976; Barrier and Angelier, 1986). To elucidate the influence of this dipping surface (in 2-D modeling, the plane is implicitly considered vertical), the 3-D approach is compulsory when modeling the plate convergence in Taiwan. Such modeling may not only reveal new insights in terms of stress-strain relationships, but may also lead to a clarification of the significance and limitations of the earlier 2-D modeling. In order to evaluate the effects of the obliquity of discontinuity, several experiments were carried out, involving comparisons between 3-D distinct-element modeling (Figures 5 and 6a, b) and 2-D ones (Figure 6c, d). In both, the boundary conditions were otherwise similar.

In order to best represent the mechanical behavior of different regions (Figure 5), the model used in this comparison is a 3-D distinct-element model which includes two subdomains with different material properties. This configuration is chosen on the basis of the regional structural framework of the area under investigation (Figure 5a). The 3-D models used for the first-order approximation are of course largely simplified in comparison with actual patterns. The geometry of the model is represented by a rectangle which covers a rectangular area. As for the parameters of the boundary conditions, velocities are used here instead of forces because the latter are difficult to estimate, while the velocity of plate movement between the Philippine Sea plate and the Eurasian plate is well known (Seno *et al.*, 1993). Figure 6 shows the stress and velocity fields of the 2-D model of the collision zone (Figures 6a, b) and of the 3-D corresponding models (Figures 6c, d). Despite the large difference in structure due to the

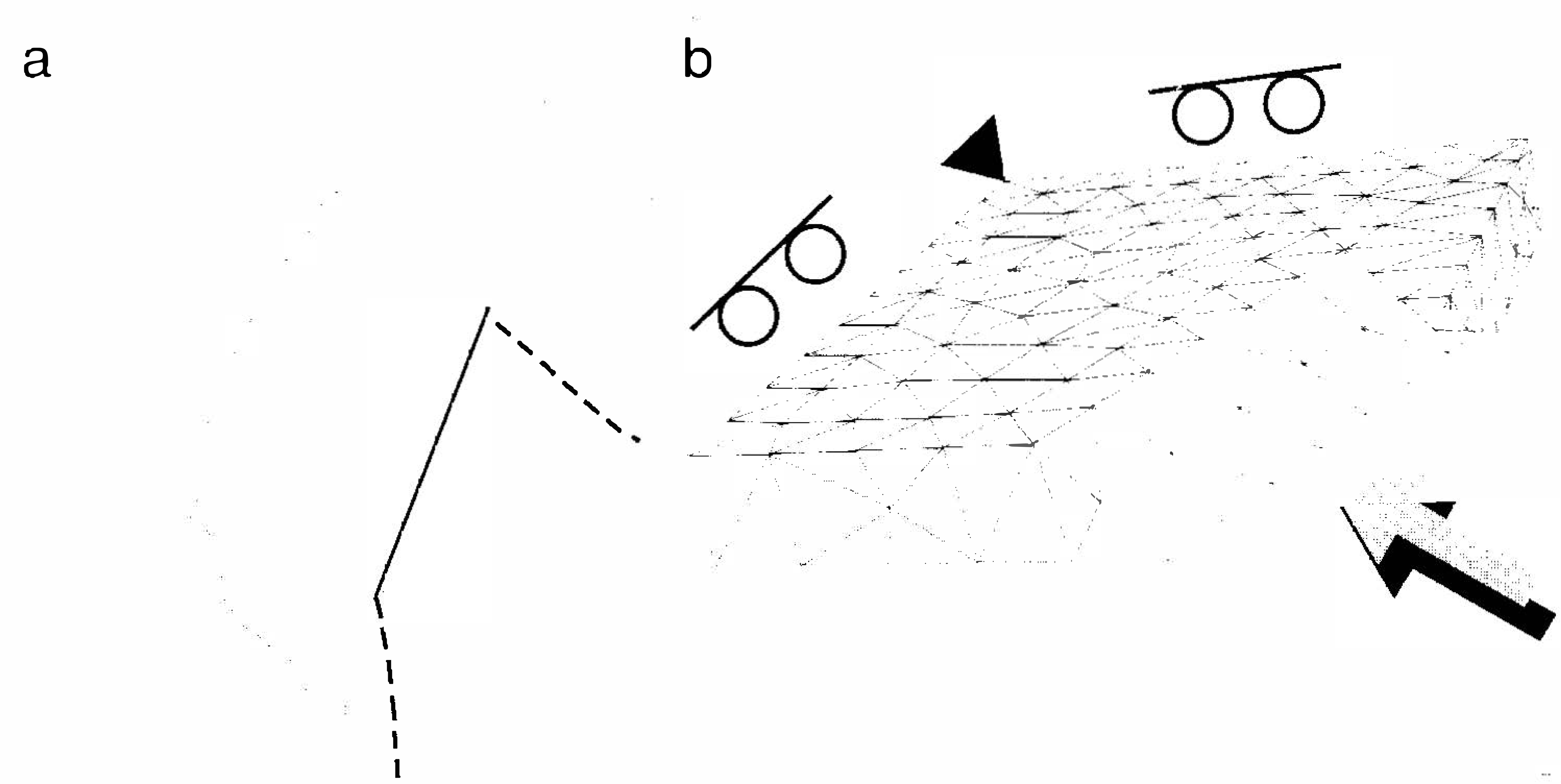

Fig. 5. A preliminary 3-D distinct-element model of Taiwan collision. (a) Location of the model in map. (b) Geometry and boundary conditions of the distinct-element model of eastern Taiwan (Philippine Sea plate indenter removed to show dips of boundaries). Boundary conditions: Solid triangles, fixed boundary. Open circles with bar, roller in one direction. No symbol, free segments. Large arrow, direction of displacement based on plate kinematics.

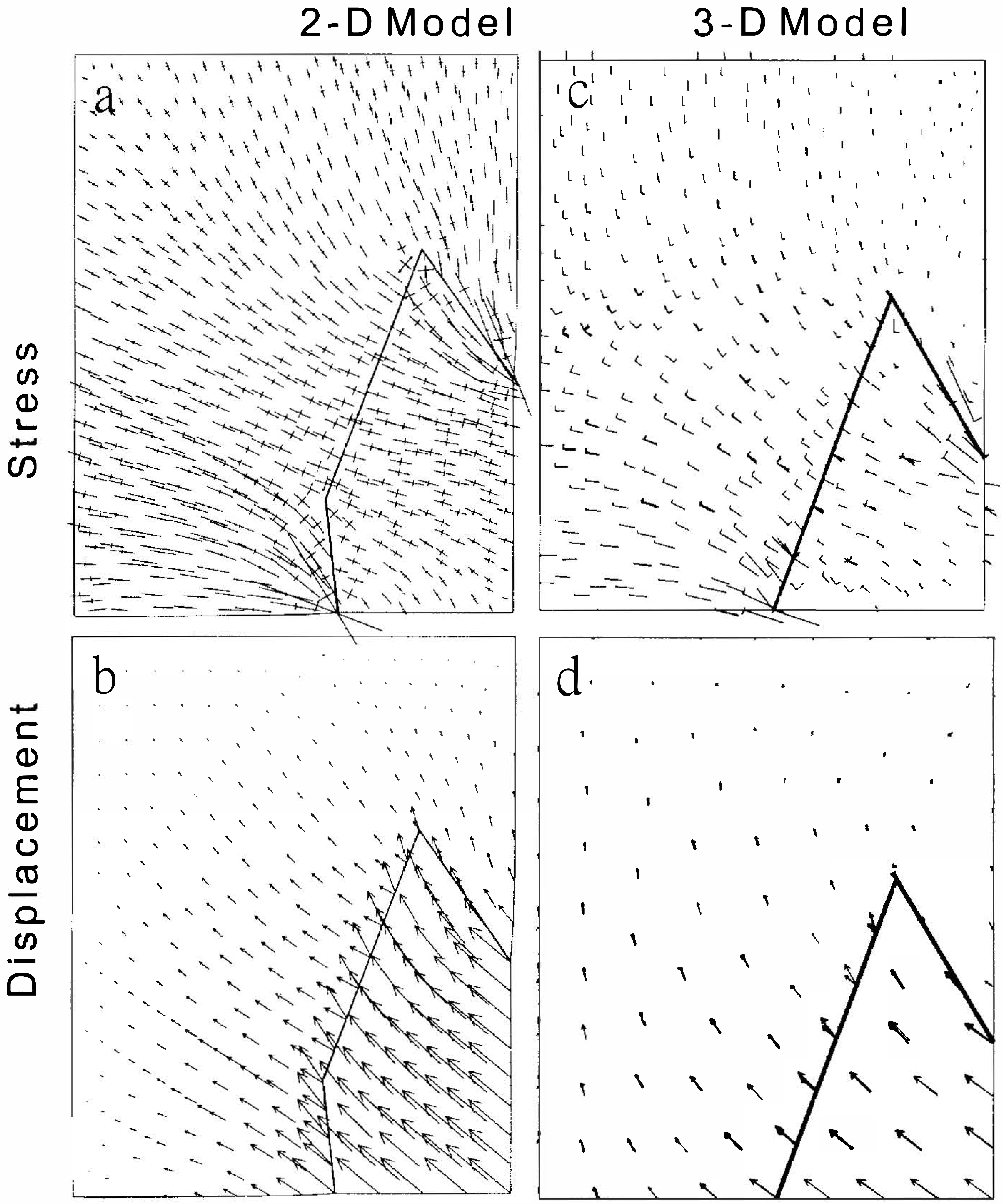

Fig. 6. Distinct-element model of eastern Taiwan. (a) Computed stress distribution in the 2-D model. (b) Trends of velocity fields in the 2-D model. (a) Computed stress distribution in the 3-D model. (b) Trends of velocity fields in the 3-D model.

50° dip of the major Longitudinal Valley Fault zone in the 3-D model as compared to the implicit vertical attitude in the 2-D model, the stress (Figures 6a and c) and velocity (Figures 6b and d) patterns obtained in the 2-D and 3-D models respectively are quite similar. It is therefore conclude here that the 2-D approximation is a reasonable simplification at least in this case. This inference is important in that 2-D numerical modeling is easier to handle and, for a similar memory size and run time, allows for the use of a more sophisticated representation of regional patterns than 3-D modeling.

4. RESULTS OF MODELING

4.1 Fit With Regional Stress Fields

The 2-D finite-element elasto-plastic model previously presented by Hu *et al.* (1996) covered a much wider area, including not only the whole Taiwan Orogen but also the neighboring arc-and-trench systems (Figure 1a). The main constraints used to adjust this general finite-element model came from the geological and geophysical reconstruction of stress fields in Taiwan (Angelier *et al*, 1986; Barrier and Angelier, 1986; Lee, 1986; Angelier *et al.*, 1990; Chu, 1990). The comparison between the observed and reconstructed stress fields is summarized in Figures 7a and b, respectively. In Figure 7b, an interpolation procedure proposed by Lee and Angelier (1994) was adopted to construct smoothed trajectories with large numbers of local paleostress results. Several major geodynamic problems were addressed in this earlier modeling, including that of the relationships between the Taiwan collision, the Okinawa back-arc opening and the Ryukyu trench retreat, which strongly influence the distribution of strain-stress fields in northern Taiwan.

In its counterpart in Figure 7a, this finite-element modeling at the scale of several hundred km is unable to account for the deviations analyzed herein at the scale of several tens of km. The effects of mechanical decoupling across discontinuities are ignored, although they result in significant deviations of principal stress. These effects were taken into account in the new distinct-element modeling (Figures 6 and 7).

4.2 Fit With Regional Deformation Fields

In the earlier steps of numerical modeling, the stress-paleostress fields were extensively used for constraining the model . More recently, accurate data on the present-day deformation became available because of the development of GPS studies in southern Taiwan (Yu and Chen 1994). To verify and refine the general interpretation of the relationships between active deformation and geological structure, two independent numerical modeling techniques (finite- and distinct-element codes) were thus used with the constraints of the deformation field as revealed by GPS measurements (Yu and Chen 1994). Figure 7c summarizes the results of the last model and shows both the observed velocity fields (from the GPS results: with trajectories indicating dashed lines) and the computed velocity fields of the distinct-element model (with trajectories indicating by solid lines). The patterns of trajectories were drawn using an interpolation smoothing procedure proposed by Lee and Angelier (1994).

With both the simplifying assumptions of the numerical modeling and the various sources of uncertainties taken into account, the azimuthal fit between the GPS results and the final reconstruction modeling is, in general, rather good. Some local misfits are notable, especially around the Peikang High area: the trajectories based on the GPS show stronger deviations than those of the final model presented here, which may be explained by lateral extrusion processes near the Peikang High due to indentation.

The fit, however, must be considered not just in terms of trends; on the contrary, it must be viewed in terms of velocity magnitudes (not shown in Figure 7c). First, there is a general

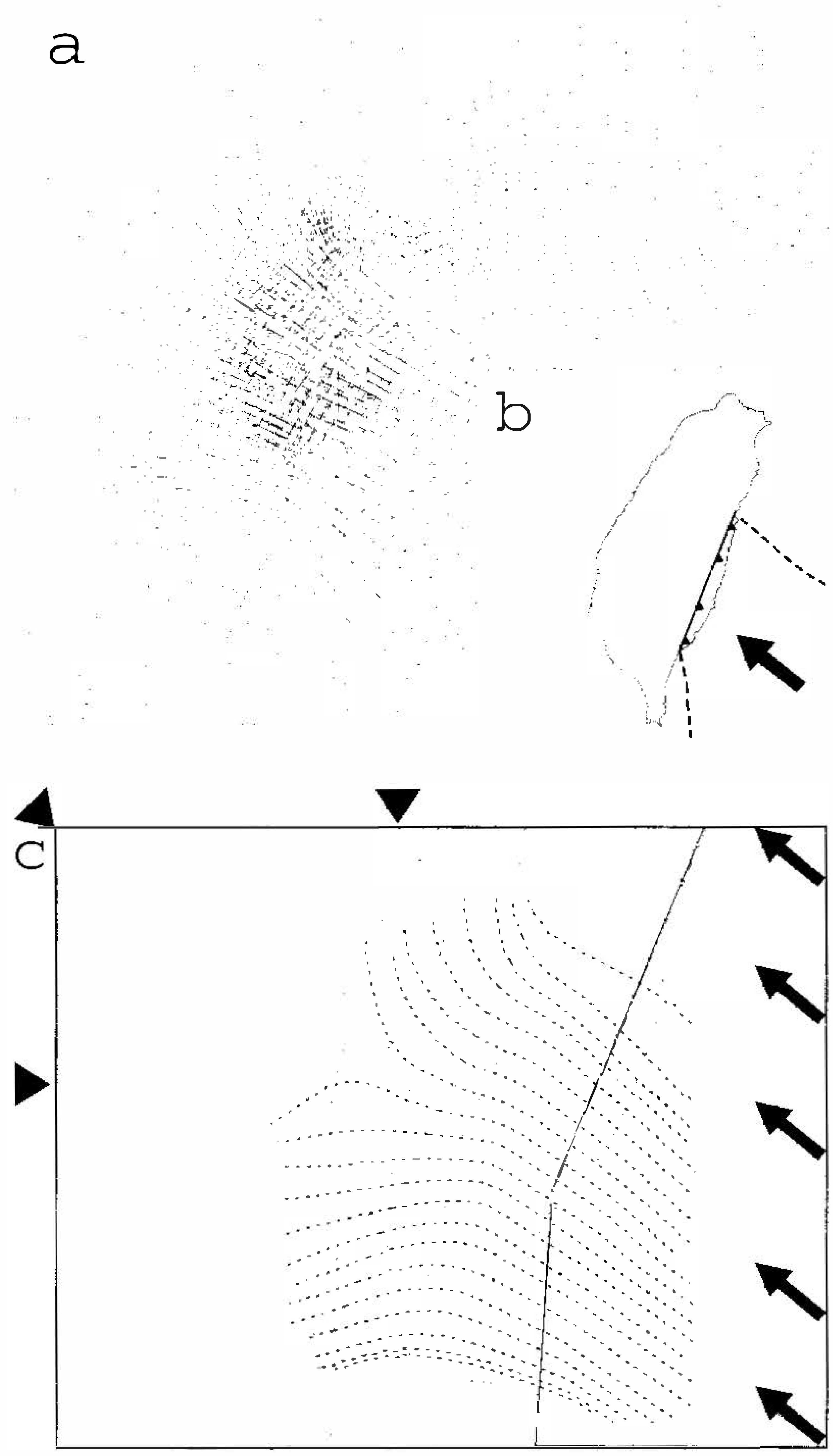

Fig. 7. (a) Stress distribution calculated in the convergence-trench retreat elasto-plastic model. Structure, rheology and boundary conditions defined in Fig. 2d. Principal stresses in the horizontal plane, shown as small couples of arrows. Pairs of convergent arrows represent maximum compressive stress. Note the stress concentration in the Taiwan collision zone, the fan shaped distribution throughout the island and the pronounced stress trajectory deviation near the northwestern corner of the Philippine Sea plate. Pairs of divergent arrows represent minimum extensional stress, especially northeast of Taiwan, in the Okinawa Trough area. (b) The distribution of Quaternary and present-day stresses throughout Taiwan. Main compressional stress field associated with the Quaternary collision from various sources (focal mechanisms, borehole breakouts and Quaternary fault-slip data). Plate boundary added as thick line with triangles on the upthrust side. Vector of relative plate motion as black arrow. (c) Trends of velocity fields in the final model: computed trajectories (thin continuous lines) and observed trajectories based on GPS data (dashed lines). Boundary conditions and rheological properties also illustrated (2, 3, 4, discontinuities as for Figure 4b).

agreement between the regional distributions of computed and observed velocities. Second, the largest azimuthal misfits occur for the smallest velocities and, thus, cannot be considered very significant within the general frame of the model. Such minor perturbations near the Peikang High are dependent on local structure, which cannot be taken to represent the scale of the model here and are poorly known anyway; consequently, a more complex model cannot be regarded reliable (Figure 3). In Summary, the misfits are small in terms of both the azimuths and the velocities for all the stations with a large displacement relative to the stable foreland of the Taiwan collision belt. Again this shows that the accuracy of a realistic model as well as the choice of technique adopted largely depends on the scale of the analysis and on the extent of data available.

5. EVOLUTION OF THE COLLISION

The results of brittle tectonic analyses, especially in terms of the distribution of compressive deformations during a succession of events related to the Plio-Quaternary Taiwan collision were used in an attempt to model the evolution of collision. The authors here aimed at understanding the relationships between the earlier kinematics of plate convergence and paleostress distributions. Numerical modeling experiments can be carried out for earlier situations, provided that the actual shape of the collision zone is considered at each step of the collision, instead of merely the present configuration. The kinematic reconstruction of the collision between the Luzon arc and the Asian continent can be obtained by restoring the pre-collisional pattern of the Asian continental margin and the travel path of the Luzon arc-trench system (Figure 8). It should be noted that because this reconstruction is based on the conventional reconstruction of the arc-continent collision between the Luzon arc and the Asian continent (Teng, 1990), so that the alternate interpretation in terms of arc-arc collision proposed by Hsu *et al.* (1995) is not considered herein.

The motion of the Philippine Sea plate can apparently be divided into two stages in the last 15 Ma (Seno and Maruyama, 1984). The change of motion from north-north-westerly to west-northwesterly is believed to have taken place at around 5 Ma (Seno and Maruyama, 1984). By following the motion of the Philippine Sea plate, the travel path of the Luzon arc-trench system can be backtracked (Figures 8a, 8b). Based on the reconstructed Luzon volcanic arc, the paleopositions of the Manila trench can be established by extending the trace of the trench (Figure 8c). For the deformed segment in the deformation front, the paleopositions are restored by geometric interpolation of the Taiwan collision, the trend based on the final structure and the calculation of the motion of the Philippine Sea plate (Figure 8d).

Although a complete presentation of the results cannot be done herein (for details, see Hu, 1995), Figure 9 shows the two major steps (5 Ma and 2 Ma), based on the results of 2-D finite-element modeling including the reconstruction of the paleopositions of the major boundaries and structural units from present-day to 9 Ma (Figure 8). So as to represent the average mechanical behavior of different regions, the models used include a variety of subdomains with different material properties (simplified in Figure 9; for details, see Hu, 1995). For the parameters of the boundary conditions, the velocities are used instead of forces in the present study. The northwestern corner of the model is fixed; the imposed displacement in the model at 2 Ma (Figure 9a) is 7 cm/yr along the azimuth 320°. For the model at 5 Ma, the corresponding

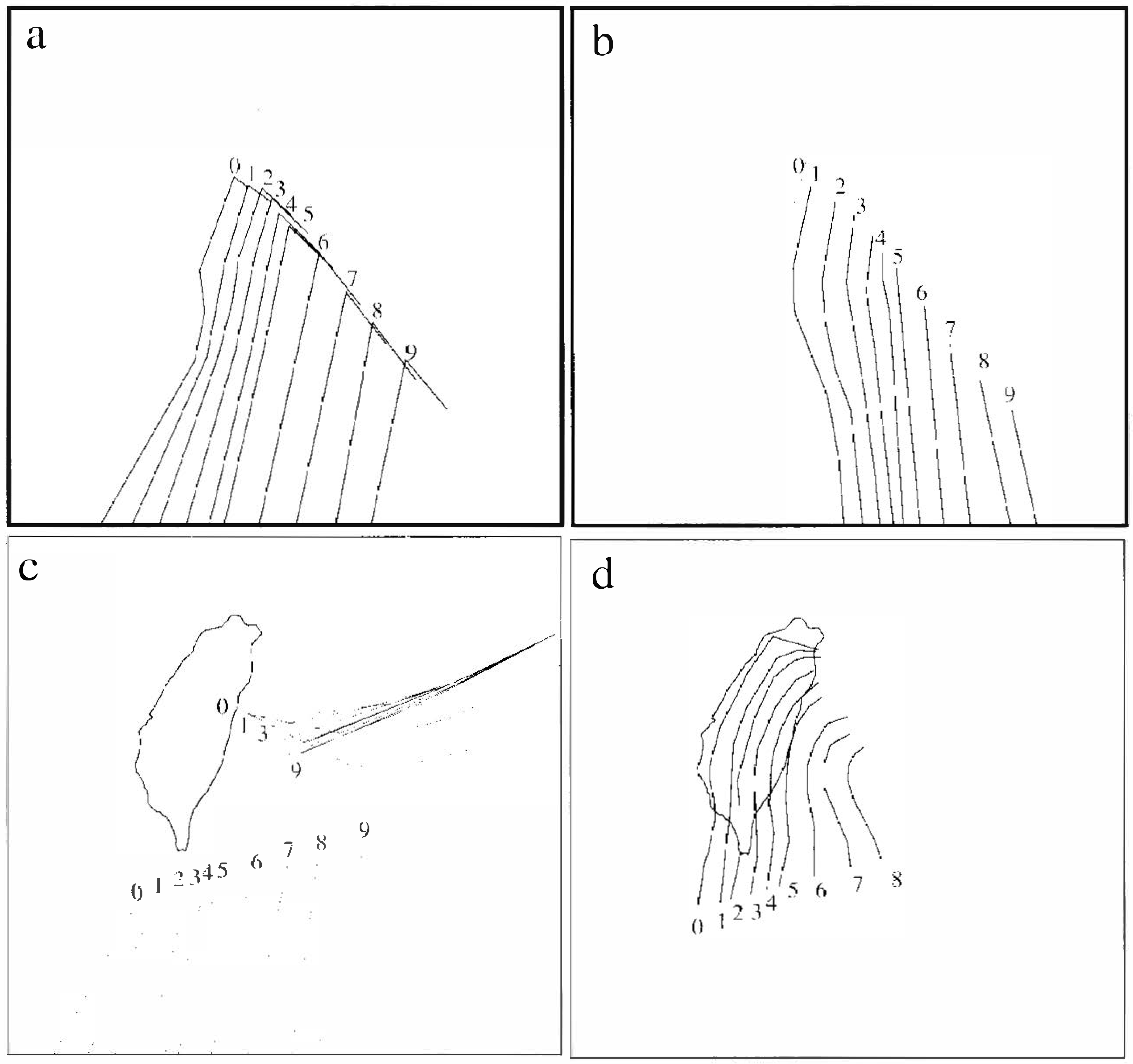

Fig. 8. Paleopositions of the major structural boundaries used in the Taiwan retrotectonic models, from present-day to 9 Ma. Numbers denote different stages in Ma. (a) Migration of western boundary of the Luzon Arc. (b) Migration of the boundary of the Luzon Arc-Philippine Sea Plate. (c) Migration of subduction zones (Ryukyu and Manila). (d) Migration of the deformation front due to Taiwan collision (shaded area indicates Chinese margin).

azimuth of convergence is 335°. It is worth pointing out that in Figure 9a an additional displacement is applied at the Ryukyu trench in order to simulate the opening of the Okinawa Trough as discussed before, whereas in Figure 9b this displacement is absent, because, according to Letouzey and Kimura (1986), extension in the Okinawa Trough began until approximately 2 Ma.

The stress data used to constrain the model are complicated. Based on brittle tectonic analyses, Angelier *et al.* (1990) divided the paleostress distribution in the Hsuehshan Range in northern Taiwan into five main events; for all of Taiwan island, Chu (1990) identified six events. Regardless of thus discrepancy, it is doubtful that the kinematic history of the plate convergence has changed dramatically since the beginning of the Taiwan orogen. Lee *et al.* (1991), based on their study of magnetic fabric analysis and taking into account rotations revealed by paleomagnetism, pointed out that two principal lineations were observed in the eastern Coastal Range, which they said were indicative of two trends of compressional tecton-

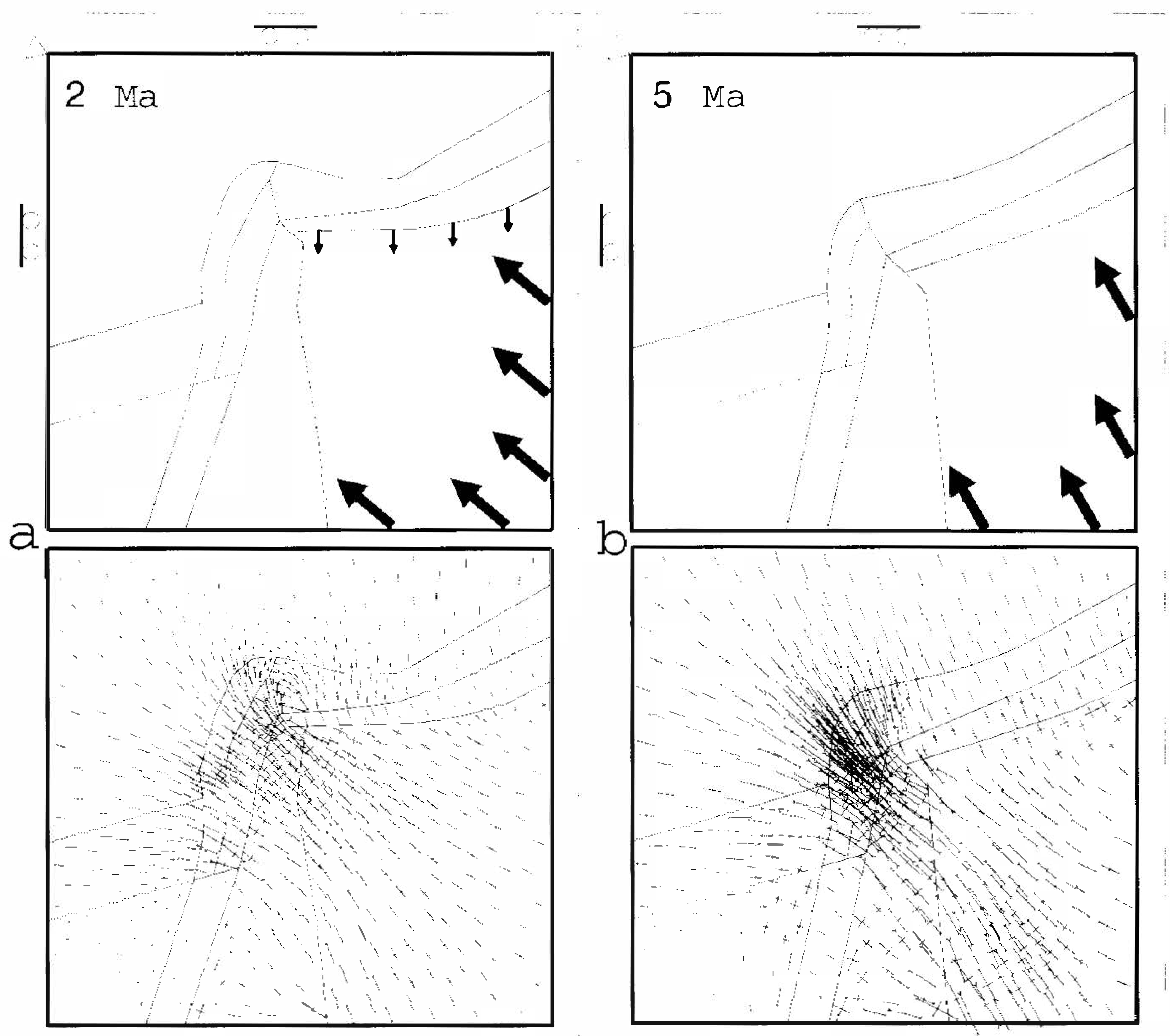

Fig. 9. - Example of stress distributions calculated in the 2-D finite-element elasto-plastic model of the retrotectonic evolution of Taiwan collision. Structure, rheology and boundary conditions such as for Fig. 2d. Principal stresses in the horizontal plane shown as small couples of arrows. Pairs of convergent arrows represent maximum compressive stress. (a) 2 Ma. (b) 5 Ma.

ics. This observation was consistent with the earlier identification of two major compressional events during the Plio-Quaternary collision (Angelier *et al.*, 1986); according to that study, for the older event was characterized with NNW-SSE to NW-SE regional trends of compression, compatible with an azimuth of convergence of about 335° (Figure 2a, left), whereas for the younger event, compressional trends were NW-SE to W-E, for an azimuth of convergence of about 300° (Figure 2a, right).

The changes in the direction of motion of the Philippine Sea plate relative to Eurasia resulted in changes in the average trends of the fan-shaped patterns of maximum compressional stress trends (Figure 9 compared with Figure 7a), and the results of modeling were interesting in terms of relationships between amplitudes of rotations suggesting that the configuration of boundaries at the northwestern corner of the Philippine Sea plate played a larger role than the direction of convergence, in terms of the resulting patterns of compressional trends. The situation of stress distribution that prevailed during the latest step of the collision

(2 Ma, Figure 9a) differs from the beginning of the Plio-Quaternary collision (5 Ma, Figure 9b) because both the direction of motion has changed, and also the configuration of the plate boundary itself has shifted about 15° counterclockwise. Although the kinematic change is relatively simple, the apparent complexity of the actual successive distribution of regional paleostress mainly results from the presence of multiple perturbations in stress trajectories related to inhomogeneities (major fault structures and stratigraphic discontinuities) and from the rotations of blocks during the successive collision events in Taiwan. As a consequence, it is suspected that the models mentioned here are not directly applicable to the earlier steps of the Taiwan collision, because both the structures and stress become increasingly poorly constrained back in time.

6. DISCUSSION AND CONCLUSION

Zoback *et al.* (1989) concluded that in several plate interiors the maximum horizontal stress is subparallel to the direction of absolute plate motion; however, in many other cases, such as those in mountain belts, stress direction may significantly differ from plate directions. Numerical modeling provides a way to confirm and quantify the relationship between the geological structure, the kinematic boundary conditions, and the stress or strain fields. How detailed their analyses can actually go depends on the data constraints (quality, consistency and accuracy of the data). The most realistic results, however, are obtained through a process of progressively increasing the complexity of the model until a satisfactory fit is obtained; too complex models should be avoided because available data cannot constrain them (Figure 3). We conclude that under certain limitations the presence of 'weak' mechanical discontinuities is well accounted for by distinct-element modeling and that this new modeling is particularly suitable in the case of southern Taiwan, where several sources of inhomogeneity concur, thereby producing complex deformations. These sources are related not only to the presence of a relatively rigid promontory at the front of the active belt (the Peikang High), but also to the existence of a weak domain to the south (the accretionary prism at the northern tip of the Manila subduction zone) and of several major 'weak' shear zones (the front thrusts of the Taiwan belt to the west and the LVF to the east).

The case of the Taiwan collision belt involves a sharp corner of the plate boundary which gives rise to a complex distribution of stress and deformation (Figure 2). It is shown here that although the problem of relationships between kinematics, structure and stress-strain field, albeit three-dimensional in essence, can be clarified through a combination of elaborate 2-D model processing (Figures 2d, 4 and 7) and simplified 3-D modeling control experiments (Figures 5 and 6), this approach takes advantage of the capability of 2-D modeling to account for more realistic geographic shapes and the requirement for a 3-D validation of geodynamic problems, especially concerning obliquely dipping boundaries (Figure 5).

To conclude, such a numerical modeling can be used to investigate earlier steps of regional tectonics provided that the evolution of a geometrical structure is taken into account through reconstruction. The displacement-deformation fields bring strong constraints when the present-day evolution is modeled (Figure 7b). In order to verify the retrotectonic models, the stress pattern obtained (Figure 9) in this way should be compared with actual paleostress patterns reconstructed by means of geological tectonic analyses.

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