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TECTONIC FRAMEWORK INDUCED BY SHEAR BANDING: A CASE STUDY OF THE SOUTH TAIWAN ISLAND ARC

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Abstract

The traditional concept of the tectonic framework for the South Taiwan island arc according to which the shallow-sea plate of the South China Sea subducts below the deep-sea plate of the Philippine Sea does not accurately reflect the facts but it has continued to remain in use. In order to address this problem, the South Taiwan island arc is here examined using the GPS velocity vectors distribution map and the results of a shear-banding table simulation test. The results reveal that: (1) under the influence of deep shear banding, the magnitude of GPS velocity vectors induced by the deep-sea plate are larger than the GPS velocity vectors induced by the shallow-sea plate; (2) the current concept of the tectonic framework of South Taiwan that only includes eastward bending of the shallow South China Sea plate and subduction below the South Taiwan island arc and the deep Philippine Sea Plate is inadequate; (3) the tectonic framework should recognize the importance of lateral compression induced by the deep Philippine Sea Plate on the South Taiwan island arc toward the west and generation of a deep shear band that continues to extend toward the west; and (4) the tectonic framework should also incorporate the lateral compression of the shallow South China Sea plate on the South Taiwan island arc and shallow shear banding that terminates at the intersection with the deep shear band. Based on the above conclusions, the authors suggest that the tectonic framework of the South Taiwan island arc proposed in this paper should be adopted so that the tectonic framework is consistent with shear-band displaced landform features.

Keywords: Taiwan island arc, tectonic framework, shear band, GPS velocity vectors.

Introduction

Under continuous lateral compression, a horizontal tectonic plate loses its ellipticity due to plastic strain softening when the strain enters deep into the plastic range. This induces shear bands after localization of deformation occurs (Rice, 1977; Rudnicki and Rice, 975; Hsu, 1987). Figure 1 shows the tilting and uplift effects of a shear band induced by the 921 Jiji earthquake. The plate with higher density on the right is associated with a shear band and has been tilted and uplifted towards the plate with lower density on the left. At the same time, the plate on the left of the shear band has been tilted and uplifted toward the right. The strata with vertical bedding in the shear band are derived from the original inner strata of the right plate with horizontal bedding after being rotated approximately 90° clockwise. Therefore, the shear band in Figure 1 indicates that it is not the right plate that has been bent and subducted toward the lower left but rather that the inner strata of the right plate were tilted and uplifted due to shear banding.

Figure 1. Tilting and uplift effects of a shear band induced by the 921 Jiji earthquake (Zhushan, Taiwan; Hsu, 2018).

Figures 2 and 3 show the location and the $\overline{ABCDEFGH}$ profile of the South Taiwan island arc, respectively. It is evident from Figure 3 that the depth of the sea bed below the South China Sea is shallower than that below the Philippine Sea.

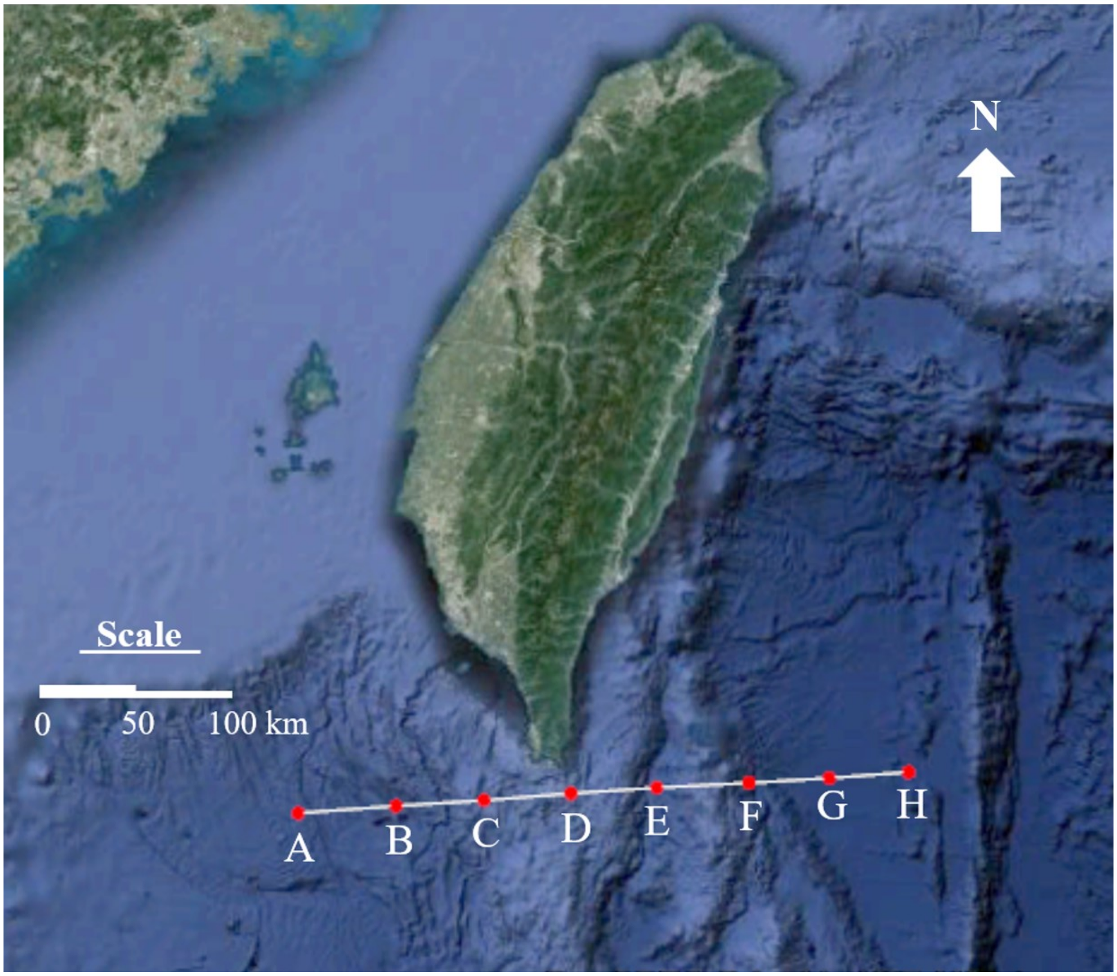


Figure 2. Location of the $\overline{ABCDEFGH}$ profile of the South Taiwan island arc. (Google Earth, 2019)

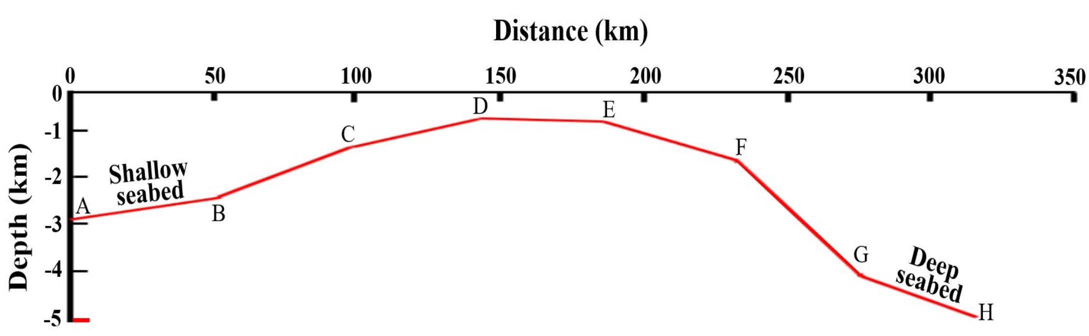


Figure 3. Depth profile of $\overline{ABCDEFGH}$ shown in Figure 2.

Figure 4 shows a tectonic framework of Taiwan proposed by traditional scholars (Angelier, et al., 1986; Lee and Angelier, 1994; Lee, 2004), according to which the South Taiwan island arc was formed by bending of the shallow-sea plate of the South China Sea and subduction eastward towards the island arc followed by subduction below the deep-sea plate of the Philippine Sea.

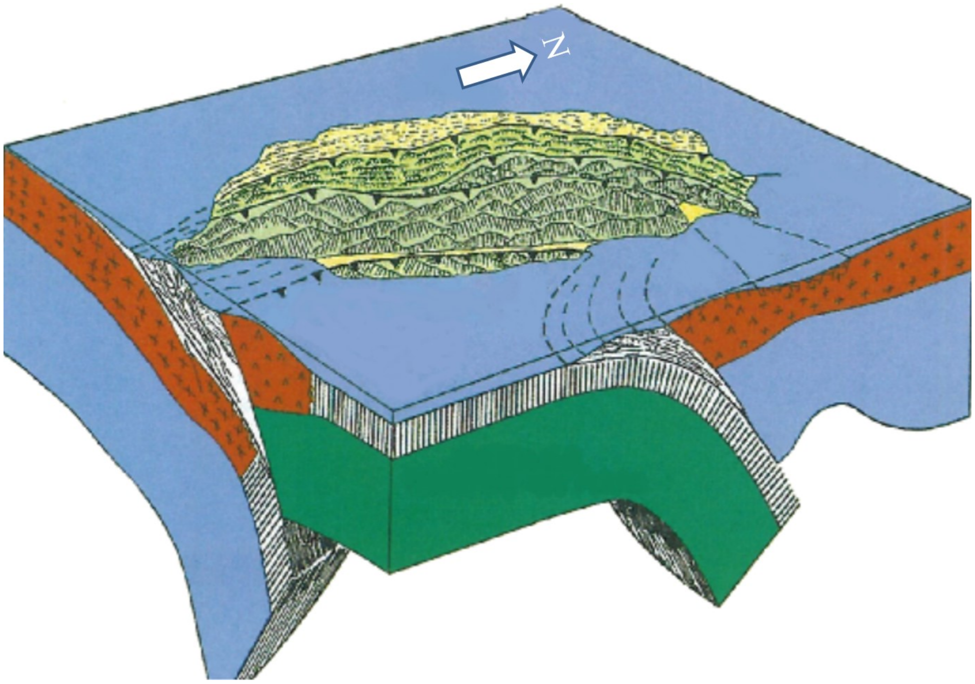


Figure 4. Existing tectonic framework of Taiwan (Lian, 2000).

Since the tectonic framework must conform with the distribution map of GPS velocity vectors associated with drift of tectonic plates and the shear-band displaced landform features, the authors use the distribution map of the GPS velocity vectors and shear-banding table simulation test results to create a new tectonic framework to demonstrate that the current one does not meet the actual physical conditions. Then, a new tectonic framework for the South Taiwan island arc that more accurately represents the actual requirements is described.

GPS Velocity Vector Distribution Map of Taiwan and Surrounding Areas

When a tectonic plate is under lateral compression, the main cause of displacement is caused by shear banding induced by the localization of deformation (Rice, 1977; Rudnicki and Rice, 975; Hsu, 1987). Figure 5 shows the distribution map of GPS velocity vectors in the area surrounding Taiwan (Butler, 1995). It is evident that the deep Philippine Sea Plate moves at a rate of 7.5 cm/yr in the N65°W to N71°W direction, and the shallow South China Sea plate moves at 3.2 cm/yr in the S54°E to S61°E direction. Therefore, these two plates are converging and the magnitude of the drift velocity vectors of the deep-sea plate induced by deep shear banding is 2.34 times that of the shallow-sea plate induced by shallow shear banding. This means that there should be both deep shear banding and shallow shear banding under the South Taiwan island arc.

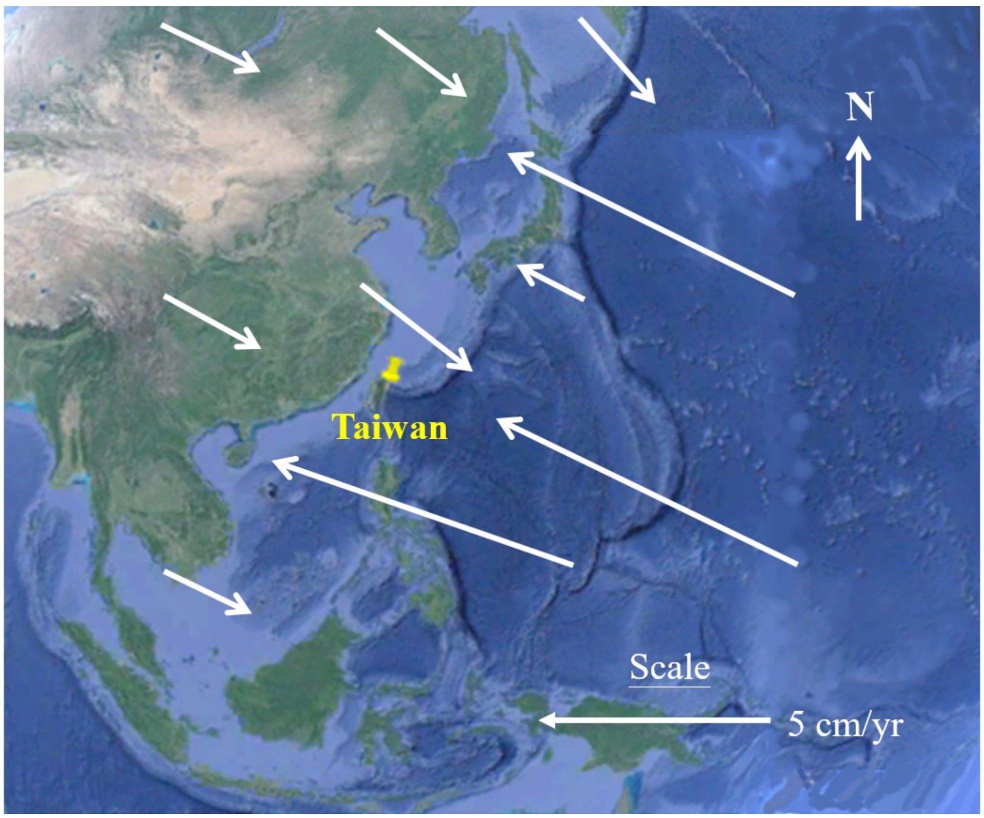
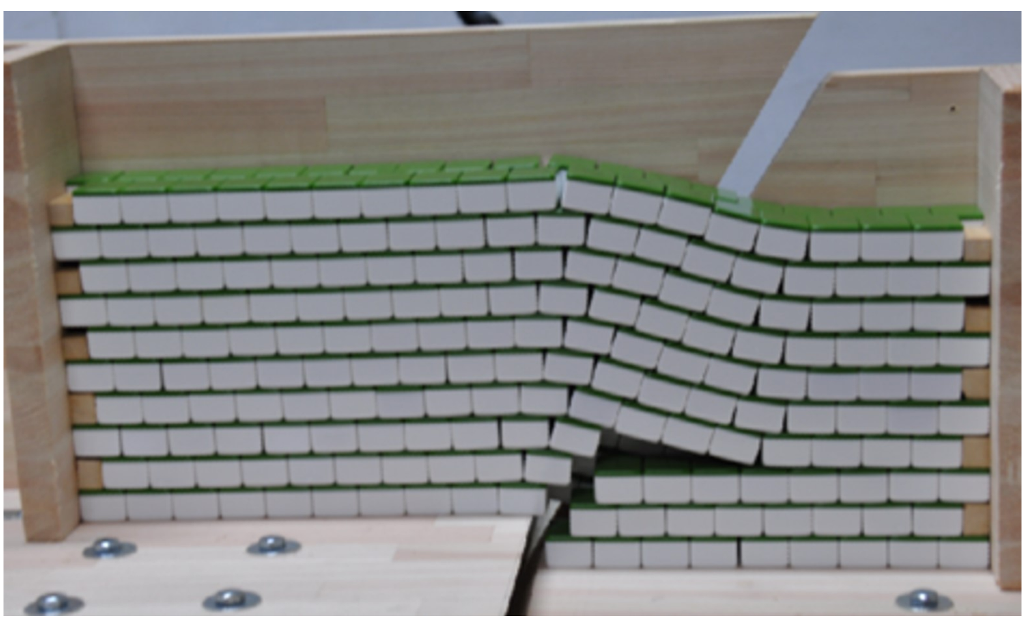


Figure 5. Distribution map of GPS velocity vectors of Taiwan and surrounding areas (Butler, 1995; Google Earth, 2019).

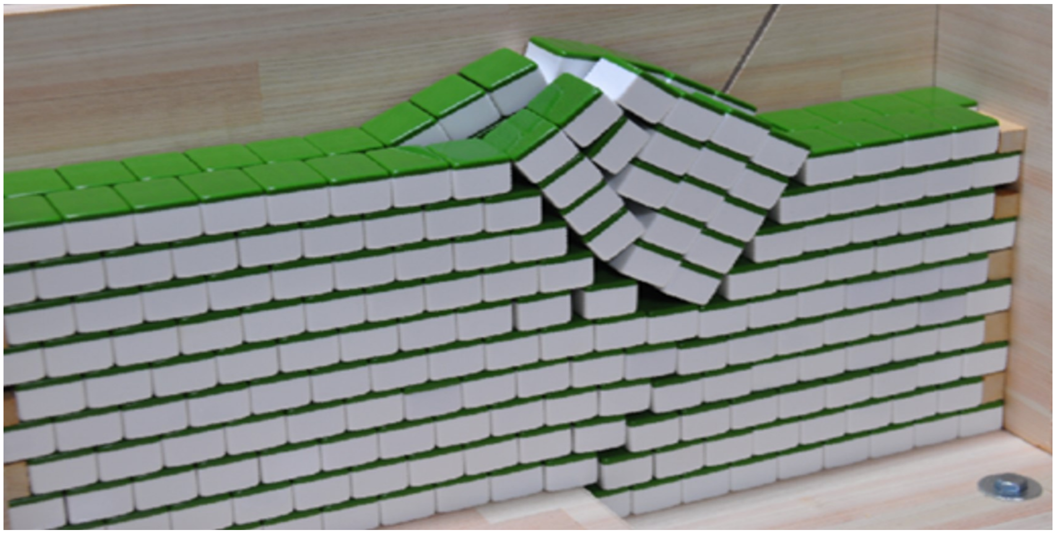
The Formation of an Island Arc Model Test

Figure 6(a) shows a tectonic plate model on a shear banding table, which was stacked horizontally in layers before being subjected to lateral compression. Figure 6(b) shows the model during lateral compression and subsequent shear banding, the left side of the model being tilted and uplifted by shear banding. Figure 6(c) shows that as the tectonic plate model continued to withstand lateral compression, the deep and shallow shear bands developed simultaneously, and under their combined thrust action, the island arc was formed.

(a) Before being subjected to lateral compression.



(b) Tilting and uplift induced by shear banding.



(c) Induced deep shear band and shallow shear band.

Figure 6. Results of shear banding table simulation test for the formation of island arcs.

Comparison and Discussion of Results

1) Figure 1 shows the tilting and uplift effects of the shear band induced by the 921 Jiji earthquake (Hsu, 2018), which originated from the localization of deformation of the tectonic plate. This phenomenon repeats in a stepwise manner (Hsu, 2022) with the result that the Philippine Sea Plate is surrounded by island arcs with different strikes induced by shear banding (see Figure 5).

2) Figures 2 and 3 show that the depth of the Philippine Sea is greater than the depth of the South China Sea. The model depicted in Figure 4 shows that traditional scholars (Angelier, et al., 1986; Lee and Angelier, 1994; Lee, 2004) believe that the shallow plate of South China Sea subducts below the Taiwan island arc and then continues to subduct toward the east below the deep-sea plate of the Philippine Sea, but ignores the subduction of the deep Philippine Sea Plate below the South Taiwan island arc.

3) Figures 7 and 8 show that the deep and shallow shear bands induced by the deep-sea plate and shallow-sea plate, respectively, laterally compress the island arc. After the shallow shear band intersects the deep shear band, extension of the shallow shear band stops but extension of the deep shear band continues.

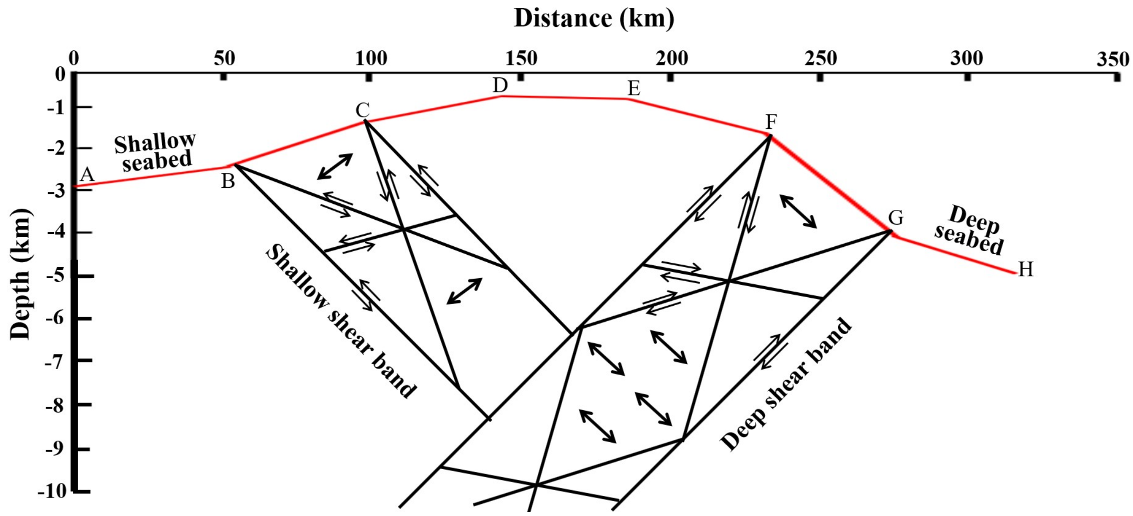


Figure 7. Schematic model of the deep shear band and the shallow shear band jointly derived from the $\overline{ABCDEFGH}$ profile shown in Figure 3.

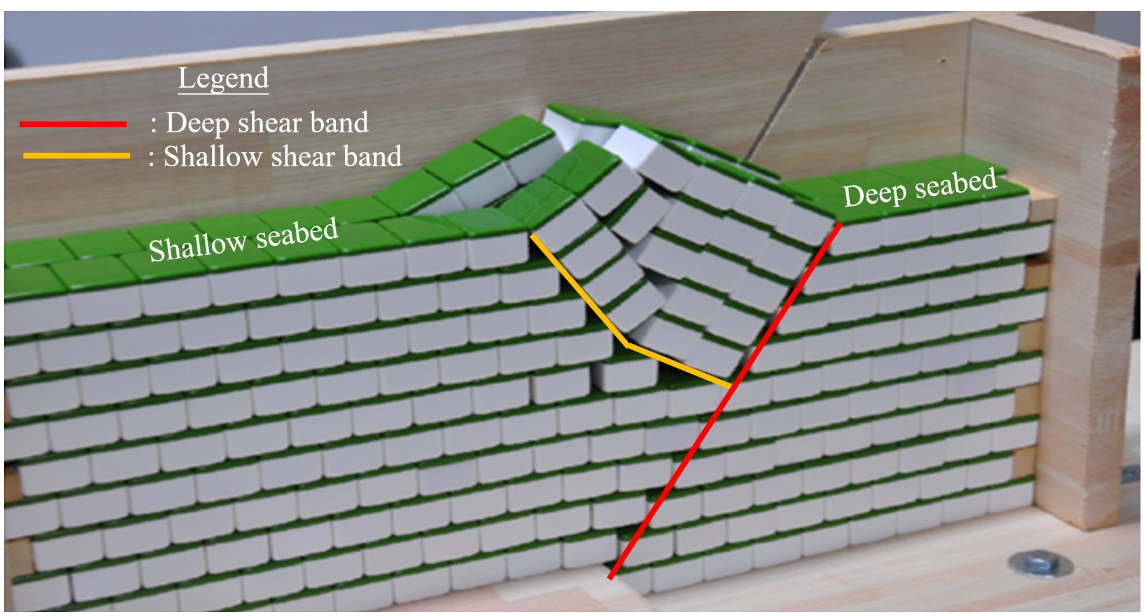


Figure 8. Simulation test results for inducing the deep shear band, the shallow shear band, and the island arc.

4) The model depicted in Figure 4 reveals that traditional scholars (Angelier, et al., 1986; Lee and Angelier, 1994; Lee, 2004) believe the tectonic framework of Taiwan includes the deep-sea plate of the Philippine Sea bending toward the north and subducting northward be-

low the shallower sea plate of the Philippine Sea, whereas the shallow-sea plate of the South China Sea bends toward the east and then subducts eastward below the deep-sea plate of the Philippine Sea. Thus, the tectonic framework of the South Taiwan island arc proposed by traditional scholars contains two conflicting subduction mechanisms.

5) Considering the mechanism for the shallow-sea plate to subduct to the deep-sea plate proposed by traditional scholars (Figure 4), since there is no uplift-tilting effect that would have been induced by shear banding during the subduction process, there is therefore no such subduction mechanism.

6) Figure 2 shows that the eastern half of the South Taiwan island arc has multiple steps of shear banding uplift slopes, and each step has a gentle slope and a steep slope (Hsu *et al*., 2022). Figure 2 also shows that the shallower sea plates of the Philippine Sea have multiple steps of shear banding uplift slopes, and each step also contains a gentle slope and a steep slope.

7) The phenomenon of the subduction of oceanic plates proposed by traditional scholars includes bending of the plate and oblique downward subduction (see Figure 4). However, it is clear that there is a tilting and uplifting phenomenon induced by shear banding and that the inner strata of deep-sea plate were lifted up after brittle fracture during shear banding. This also provides a pathway for magma to erupt upward from the interior of the Earth, i.e., along the fractured shear band.

8) According to the tilting and uplifting mechanism of the shear banding induced by the lateral compression of the tectonic plate, the authors propose the tectonic framework of South Taiwan island arc to be as shown in Figures 7 and 8. These figures indicate that the formation of the South Taiwan island arc was mainly a result of the deep-sea plate of the Philippine Sea laterally compressing the South Taiwan island arc and then inducing a deep shear band sloping downward under the eastern half of the Taiwan island arc, which continued to extend to deeper levels. At the same time, the shallow-sea plate of the South China Sea also laterally compressed the South Taiwan island arc and then induced a shallow shear band sloping downward under the western half of the South Taiwan island arc, at which point it stops extending (i.e., at the intersection with the deep shear band).

Conclusions and Suggestions

The geographical location of Taiwan is special. In addition to the deep-sea plate of the Philippine Sea laterally compressing the shallow-sea plate of the Philippine Sea northward, the deep-sea plate of the Philippine Sea is also laterally compressing the South Taiwan island arc westward. After the deep-sea plate began to compress the shallow-sea plate and the island arc and shear bands of multiple steps formed under the tilting and uplift effect of the shear banding, the elevation of the shallow seabed and the island arc also continued to increase. Because the tectonic framework of the South Taiwan island arc proposed by traditional scholars does not account for the above-mentioned tilting and uplift due to shear banding, a new tectonic framework of the South Taiwan island arc was proposed by the authors along with the following four conclusions:

1) Based on the map of the GPS velocity vectors, the deep-sea plate of the Philippine Sea moves westward, whereas the Taiwan island arc and the shallow-sea plate located at the west side of the Taiwan island arc move eastward. The drift speed of the deep-sea plate is greater than that of the Taiwan island arc and the shallow-sea plate.

2) The simulation test results show that when the plate model continues to be compressed, it will induce a deep shear band and a shallow shear band. Then the shallow shear band and the deep shear band intersect under the induced island arc, at which point the shallow shear band stops extending but the deep shear band continues to extend to deeper levels.

3) The tectonic framework of the South Taiwan island arc proposed by traditional scholars has the shallow-sea plate of the South China Sea as being bent and subducting towards the South Taiwan island arc and the deep-sea plate of the Philippine Sea. Such a tectonic framework cannot respond to the actual drift speeds of the deep-sea plate, the Taiwan island arc, and the shallow-sea plate. It is also impossible to generate the elevation change of the subducted area required for the tilting and uplifting effect.

4) The tectonic framework of the South Taiwan island arc proposed by the authors of this paper is based on a deep shear band induced by the deep-sea plate and a shallow shear band induced by the shallow-sea plate. This tectonic framework is not only consistent with the different drift speeds of the deep-sea plate, the Taiwan island arc, and the shallow-sea plate, but also fully reflects the actual elevation changes of the deep-sea plate, Taiwan island arc, and shallow-sea plate under the tilting and uplifting effect of the shear banding.

Based on the above four conclusions, it is suggested that the tectonic framework of the South Taiwan island arc proposed by the authors should be adopted in the future because it includes a deep shear band and shallow shear band induced by the deep-sea plate and shallow-sea plate after the formation of the South Taiwan island arc. It also accounts for slopes with multiple steps induced by shear-band tilting and uplift. Only in this way can the tectonic framework of the South

Taiwan island arc and GPS velocity vectors measured at different locations be compatible. At the same time, the elevations of the deep-sea plate, Taiwan island arc, and shallow-sea plate can be changed in accordance with the tilting and uplift effect caused by shear banding.

References

Angelier, J., F. Bergerat, and H. T. Chu, "Plate Collision and Paleostress Trajectories in a Fold-and Thrust Belt: The Foothills of Taiwan," Tectonophysics, Vol. 125, pp. 161-178, 1986.

Butler, J. C., Exercise 10: Plate Tectonics, Website: http://www.uh.edu/~jbutler/physical/exercise10.html, 1995.

Google Earth, Website: http://www.google.com.tw/intl/zh-TW/earth/, 2019.

Hsu, Tse-Shan, Capturing Localizations in Geotechnical Failures, Ph. D. Dissertation, Civil Engineering in the School of Advanced Studies of Illinois of Technology, 1987.

Hsu, Tse-Shan, "The Major Cause of Earthquake Disasters: Shear Bandings," A chapter in "Earthquakes - Forecast, Prognosis and Earthquake Resistant Construction," Edited by Edited by Valentina Svalova, DOI: 10.5772/intechopen.74718, 2018.

Hsu, Tse-Shan, "Plasticity Model Required to Protect Geotechnical Failures in Tectonic Earthquakes," A chapter in "Earthquakes-Recent Advance, New Perspectives and Applications," Edited by Walter Salazar, DOI: 10.5772/intechopen.107223. 2022.

Lee, J. C., "Tectonic Framework and Seismotectonics of Taiwan," Website: https://www.earth.sinica.edu.tw/content/zh/8edu/921/921chichi_tectonics.htm, 2004.

Lee, J. C. and J. Angelier, "Paleostress Trajectory Maps Based in the Results of Local Determinations: The "Lissage" Program," Computer Geoscience, Vol. 20, pp. 161-191, 1994.

Lian, Yong- Wang, Crack in the Earth, Professional Aerial Photography, Feihu Cultural Enterprise Co., Ltd., Taichung, Taiwan, 2000.

Rice, J. R., "The Localization of Plastic Deformation," Theoretical and Applied Mechanics, Proceedings, 14th International Congress of Theoretical Applied Mechanics, ed. Koiter, W. T. , North-Holland, Inc., pp. 207-220, 1977.

Rudnicki, J. W., and Rice, J. R., "Conditions for the Localization of Deformation in Pressure-Sensitive Dilatant Materials," Journal of the Mechanics and Physics of Solids, Vol. 23. pp. 371-394. 1975.