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Tectonic Evolution and Structural Styles of Cenozoic Basins around the Taiwan Area

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Abstract: The ocean margin island of Taiwan is a geodynamic body of young and complex build. It is the site of an ongoing arc-continent collision between the Eruasian plate and the Phillippine Sea plate. The most manifest tectonic movements responsible for the deformation of this island arc are tephrogenic, collisional, and wrenching. These movements played an important role in the Cenozoic tectonic evolution of Taiwan and formed various types of hydrocarbon accumulated geologic structures.

The continental margin crust around the Taiwan area was attenuated by rifting and developed north-northeast-trending Cenozoic basins. These basins have various graben-horst structures and are bounded by large faults. Extensional structure styles have prevailed in Cenozoic basins in offshore Taiwan, with listric faults, and tilted-blocks in the basement, and detached faults, growth faults, and roll-over anticlines or drape fold in the cover rocks. However, in onshore Taiwan, with the collision of Luzon island arc, those basins show a strong response to the stress imposed upon the Cenozoic rocks by this Tertiary continent-arc collision. The collision remobilized the Mesozoic tectonized basement rocks and refolded them on various scales. Compressional and wrenching deformations are thus prevailed, with thrust faults, right-slip reverse faults and en echelon arranged folds in the cover rocks.

The Cenozoic basins around Taiwan area have undergone different tectonics. In onshore areas the extensional structures have been changed into contractional structures. In offshore areas, those Cenozoic basins have extensional geologic structures until today. Since different tectonic evolution types and different structural styles in different tectonic levels, these Cenozoic basins around Taiwan area have complicated hydrocarbon accumulations.

INTRODUCTION

Taiwan is a spindle-shaped big island on the northwest edge of the Pacific Ocean. It is separated in the west from the eastern edge of continental China by the Taiwan Strait of 200 km in width. As known by many geologits, Taiwan is the site of an ongoing arc-continent collision between the Asian plate and the Phillipine Sea plate. Thus, the Cenozoic basins around the Taiwan area include two geographic-geotectonics groups: western extensional (rifted) basins and eastern compressional-wrenching basins.

Extensive seismic-reflection surveys and drilling data show that there were five crustal movements recognized around the Taiwan area (Sun, 1981). The oldest movement folded and uplifted the Cretaceous and older rocks. The second movement folded and uplifted the Paleocene formations which were eroded away at the structurally higher parts. The third movement took place in the early Oligocene and deformed and uplifted the Eocene rocks. The fourth movement occurred from the Middle Miocene to the early Pliocene. Normal faulting

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and uplifting were the main tectonic activities in the offshore areas, but strong folding and metamorphism took place on the eastern half of the island of Taiwan. Therefore, this movement grouped the Cenozoic basins around Taiwan into extensional and compressional-wrenching basins. The fifth orogenic movement reached its climax in the Early Pleistocene, compression plus wrench are also prevailing in this movement, and strongly folded and thrusted the rock sequences on the island of Taiwan, but it diminished in intensity from the east toward the west (Sun, 1981).

The Cenozoic basins around the Taiwan area have undergone different tectonic evolution and have different structural styles in different tectonic levels. The resultant tectonic models for the different evolution of the basins may have important controls on hydrocarbon accumulation and may be applicable to similarly extensional and compressional tectonic provinces elsewhere.

GENERAL GEOLOGY OF TAIWAN

Taiwan island is the site of Cenozoic geosynclinal deposition on a pre-Tertiary metamorphic basement filled with Tertiary sediments to a thickness of more than 10,000 meters. In the plate tectonic model, the island of Taiwan is situated on the juncture between the continental Eurasian plate on the west and the oceanic Philippine Sea plate on the east. It can thus be divided into two major geologic or tectonic provinces, separated by a linear and narrow fault-bounded valley that marks the collision suture of the two converging plates.

The western tectonic province is the foreland fold-thrust belt on the Eurasian plate and occupies the greater part of the island. Geographically this province includes from east to west the Central Range, the western foothills, the coastal plain and terraces, and the Penghu Island Group in the Taiwan Strait. The pre-Tertiary metamorphic basement is exposed along the eastern flank of the Central Range. Overlying the basement, the western fold-thrust belt is composed of a thick sequence of Tertiary to Pleistocene clastic sediments. A thick series of Paleogene marine argillaceous sediments forms the immediate cover series of the basement. It is exposed along the crest of the Central Range and its western and southeastern flanks. The argillaceous sediments have been altered largely into an argillite-slate belt with subordinate metamorphosed sandy interbeds. The Neogene rocks are distributed in the western foothills west of the argillite-slate belt, separated by an intervening upthrust throughout the whole island (Ho, 1982).

The eastern tectonic province is represented by the long and slender Coastal Range on the Pacific coast and the two southeastern offshore islands in the Pacific Ocean. This is the remnant of a west-facing Neogene island arc, the Luzon Island Arc, on the leading edge of the Philippine Sea plate.

The Longitudinal Valley from Hualien to Taitung in eastern Taiwan is the collision suture between the Central Range and the Coastal Range and is bordered by a high-angle thrust on each side. This valley is also the locus of many earthquakes and is tectonically very active at present. The faulting is characterized by a component of left-lateral motion aligned along the valley. An elongate belt of Plio-Pleistocene ophiolitic melange is developed along the hills on the southwestern flank and southern end of the Coastal Range. This melange has been interpreted to be a product of trench tectonics related to continent-arc collision.

The pre-Tertiary metamorphic complex has a complex tectonic history and must have experienced more than one phase of magmatism, deformation, and metamorphism. The detailed history is still not well known due to pervasive metamorphism of the rocks. Deposition of these old rocks probably began in late Paleozoic and extended into late Mesozoic in a marine and geosynclinal environment. Marine sedimentation proceeded on the Asian continental shelf and slope with more oceanward deep sea trench deposition in the east. These rocks were later tectonized and metamorphosed or recrystallized into a great variety of metasediments and metavolcanics which constitute the basement complex of Taiwan. The major orogenic movement may take place in late Mesozoic time and is named the Nanao orogeny. In plate tectonic analysis, the most important pre-Tertiary tectonic event is the westward subduction of the paleopacific plate underneath the ancient Asian continental margin mainly in late Mesozoic time, representative of a Mesozoic arc-trench system in eastern Taiwan. This may be the wrench fault tectonics and may cause the range-basin province of the Tertiary basins. The geology of Taiwan is shown in figure 1.

THE CENOZOIC BASINS

After the late Mesozoic orogeny, initial marine transgression in this range and basin province brought in a thick sequence of argillaceous sediments and deposition continued from Eocene, Oligocene to early middle Miocene. Locally subsea fan conglomeratic deposits, fan delta deposits and submarine volcanic effusion were formed. These argillaceous sediments graded into arenaceous sediments toward the western shelf zone. In onshore Taiwan, they were transformed into argillite, slate, and phyllite during the upper Miocene-early Pliocene and the Plio-Pleistocene Pengli orogenies. These sub-metamorphosed rocks have been folded, cleaved, and faulted, generally deformed into broad folds of great length and separated from Neogene clastic sediments of western foothill province by strike faults.

Since there is an obvious and widespread unconformity existing between the Eocene and the Oligocene, the tectonic framework of lower and upper rock sequences in these Cenozoic basins should be discussed (Sun, 1981).

Maps showing the major tectonic framework of Paleogene and Neogene basins are shown in figures 2 and 3 by Sun (1981). From these maps we can see the range and basin province caused by the late Mesozoic orogeny and later erosion in the Paleogene tectonic framework. The tectonic framework of Neogene basins is greatly affected by the spreading of the South China Sea.

TECTONIC EVOLUTION

After the late Mesozoic orogeny, the Cenozoic basins developed on the basement of the Cretaceous rocks. Basin subsidence probably resulted from downwarping and extensional faulting of an old wrench faulting. These basins are called transtension basins in wrench fault sense (Liu, 1986). Following the diminution of crustal extension, the Cenozoic basins were transformed into an extensive continental shelf during a quiescent Miocene interval. Contemporaneous volcanism, chiefly of submarine basalt pyroclastics with a few lava flows, took place sporadically during deposition of the Miocene sediments. These rocks erupted from various fissures and openings and transgressed Miocene strata of different ages (Fig. 4).

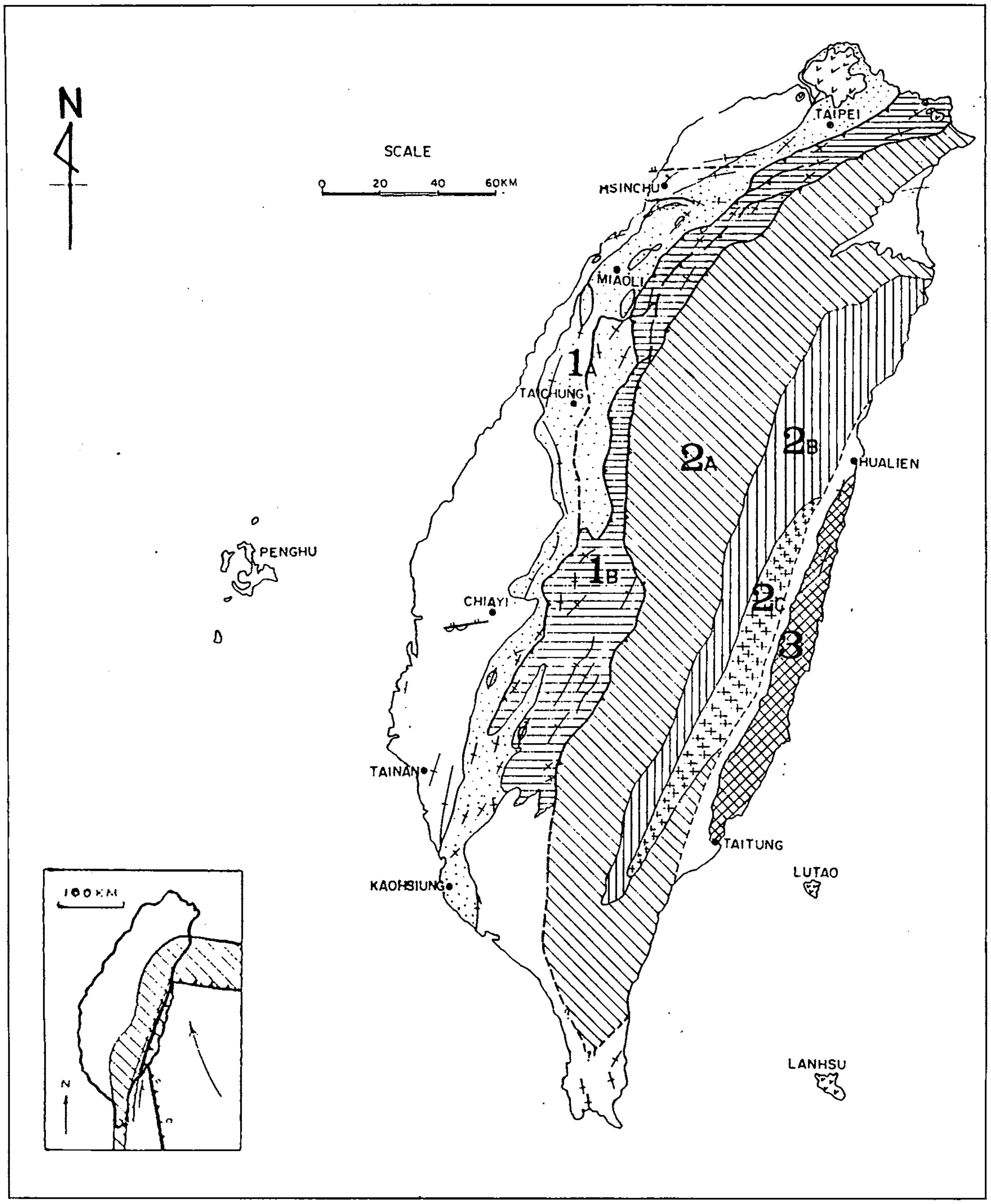

Figure 1: Tectonic sketch map of Taiwan. Geographic and tectonic units: 1A, Outer Foothill Zone; 1B, Inner Foothill Zone; 2A, Central Range; 2B, Central Range of Mesozoic subduction complex reconstituted into basement complex; 3, Coastal Range of impinging allochthon folding of late Tertiary arc massif and subduction complex; Open closures are oil and gas fields. The obliquely ruled area includes the Central Range of Taiwan and Ryukyu Arc, both on the edge of the Eurasian plate; the stippled area includes the Coastal Range of the Philippine Sea plate. Their convergent plate boundary is depicted with saw-teeth lines indented on the overiding side. The long arrow indicates the general direction of the movement of the Philippine Sea plate (modified from Ho,1975: Bia *et al.*, 1985).

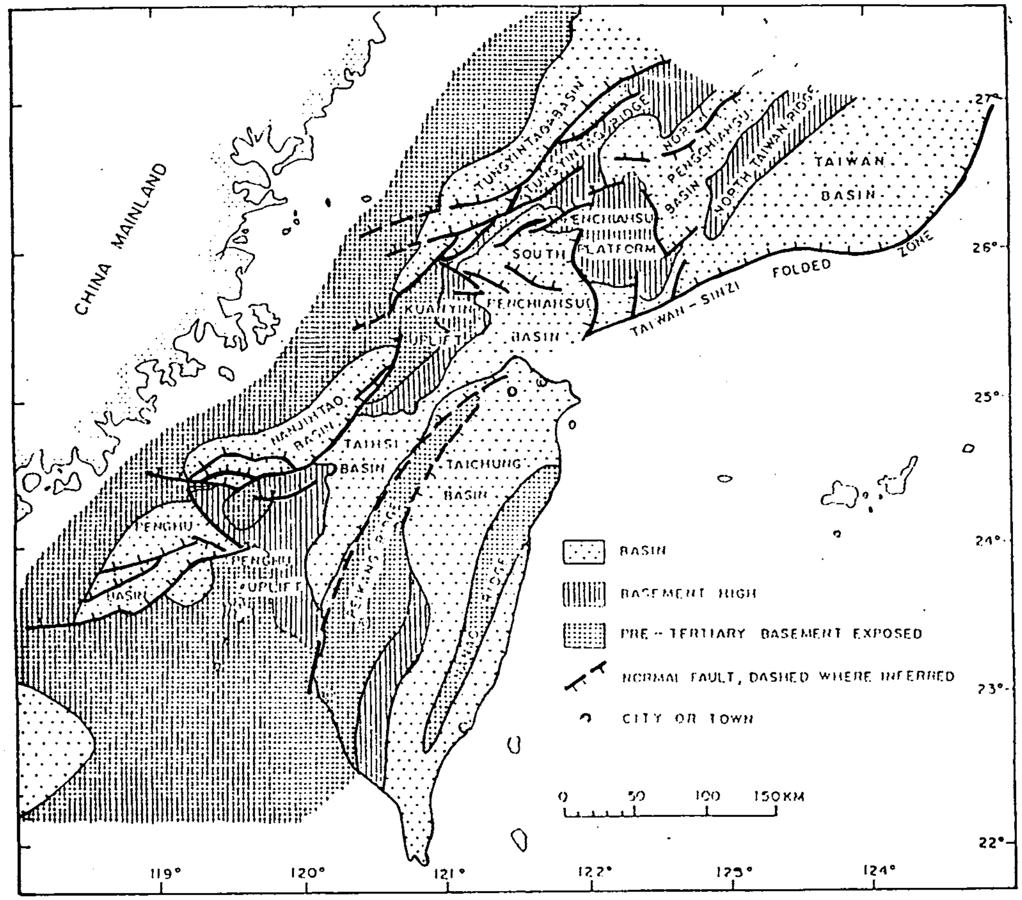

Figure 2: Map showing the major tectonic framework of Paleogene basins (Paleocene and Eocene) outlined from an isopach map on offshore Taiwan and the geologic data of onshore Taiwan. (Sun, 1981).

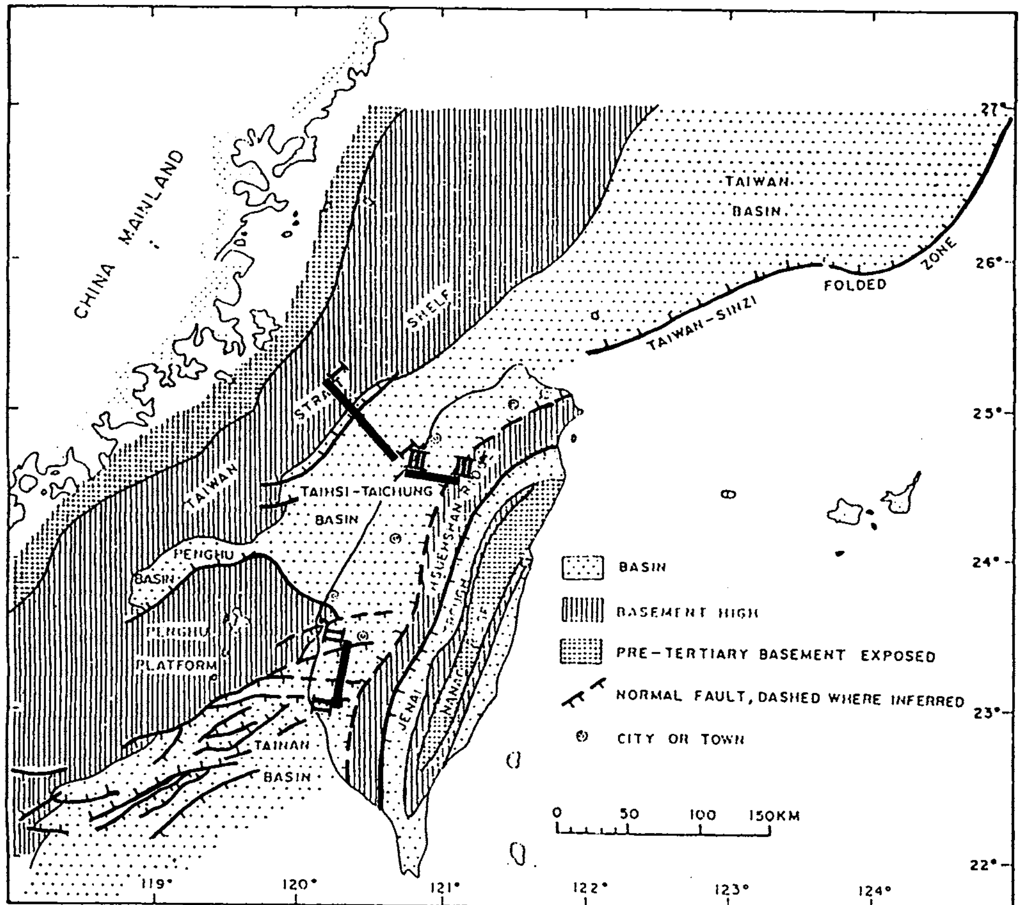

Figure 3: Map showing the major tectonic framework of Neogene basins (upper Oligocene to Pleistocene), outlined from an isopach map on offshore Taiwan and the geologic data of onshore Taiwan. (Straight lines are cross sections in figures 4, 5, and 6 modified from Sun, 1981).

Contemporaneous with the shelf buildup was the development of the distant west-facing Luzon Arc and its subduction zone. Inching evercloser toward Taiwan, this arc, in late Pliocene time, finally touched at its northern extremity the shelf at a point near the Taiwan-Ryukyu junction. As a result of the lateral variation in timing along the shelf edge, this collision shows at the present time an ensemble of structural features in various stages of development that reveal an overall southward and westward progressive decrease in age and intensity of tectonization (Figs. 4, 5 and 6).

After this collision, extensional structure styles and quiescent shelf deposition have prevailed in Cenozoic basins in westward offshore Taiwan and southward Taiwan coast plain area. However, in onshore Taiwan, with the collision of Luzon island arc, those basins show a strong response to the stress imposed upon the Cenozoic rocks by this Tertiary continent-arc collision. The collision remobilized the Mesozoic tectonized basement rocks and refolded them on various scales. This collision also metamorphosed the Cenozoic rock in the Central Range of Taiwan and left only the foothills of this Central Range to be hydrocarbon prospective area.

STRUCTURAL STYLES IN RIFTED BASIN

The structural styles in the rifted basins in offshore Taiwan and in the SW Taiwan coastal plain are characterized mainly by extensional structures. There are listric normal faults, tilted fault blocks, growth faults and rollover anticlines. Most of the normal faults that controlled the development of grabens or half grabens in offshore Taiwan and SW Taiwan coastal plain areas are characteristically growth faults; the development of the faults was closely related to sedimentation or accumulation of volcanic rocks at the Middle Miocene to the Lower Pliocene movement. Antithetic normal faults often caused further extension in basins and developed a series of half grabens (Figs. 4, 5). Those antithetic fault series form very good fault traps. This structural style is the main type of hydrocarbon trap in the SW Taiwan coastal plain and Taiwan offshore Taishi basin.

In the nearshore part of the Taishi basin, with the termination of rifting stage, initial faulting was succeeded by reverse faults from compressional stress which was originated from the Plio-Pleistocene Pungli orogeny extending from the east toward the west. With this tectonic inversion, a complicate fault trap was formed (Figs. 7 and 8).

STRUCTURAL STYLES IN CONTRACTILE BASIN

Orogenic deformation in the Contractile western Neogene basin in onshore Taiwan from east to west in the foothills belt is characterized by tight to gentle superficial folding, abundant faults, but no metamorphism. A series of low-angle thrusts is particularly predominant along which southeast-dipping imbricated thrust blocks have slid considerable distances to the west (Fig. 9). The middle to upper Miocene formations are exposed in the inner-foothills tightly folded zone to the east and the Pliocene to Pleistocene in the outer-foothills gently folded zone to the west. All these formation were thus stacked up with a combination of folds and faults. (Fig. 10).

The folds are usually bounded by major thrust faults that may be traceable for considerable distances. Many of these faults are great low-angle thrusts and some are bedding thrusts over certain distance. Many thrusts cut across the bedding at a steep angle through the

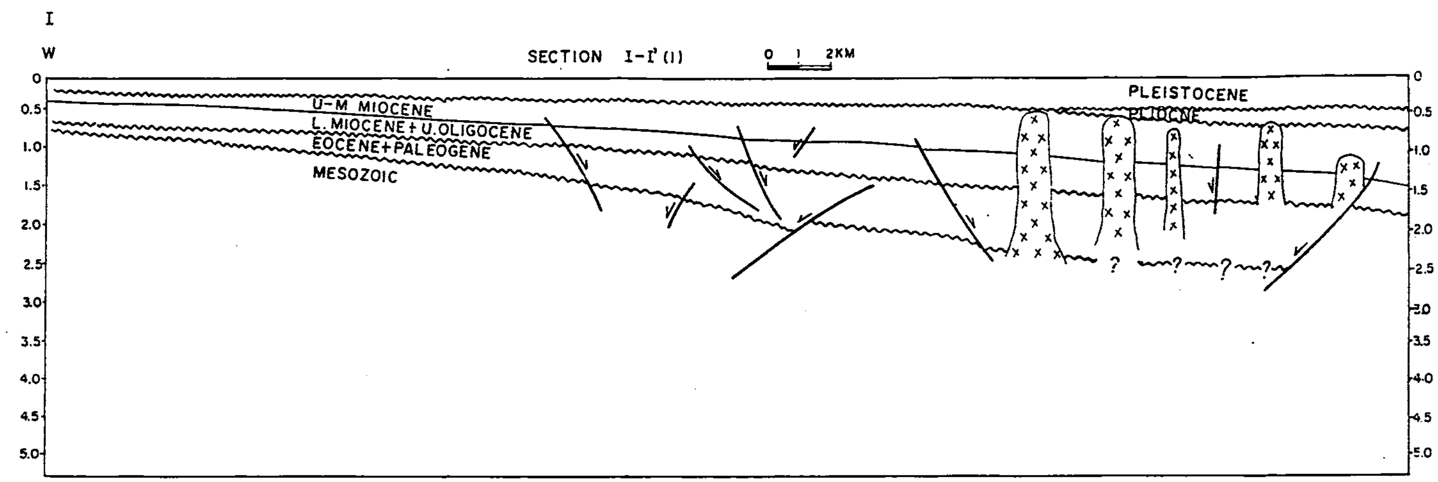

Figure 4: Geologic cross section I-I (in two parts) shows major unconformities, volcanic channel and normal faults in Taiwan offshore Basins (modified from Liu and Pan, 1984).

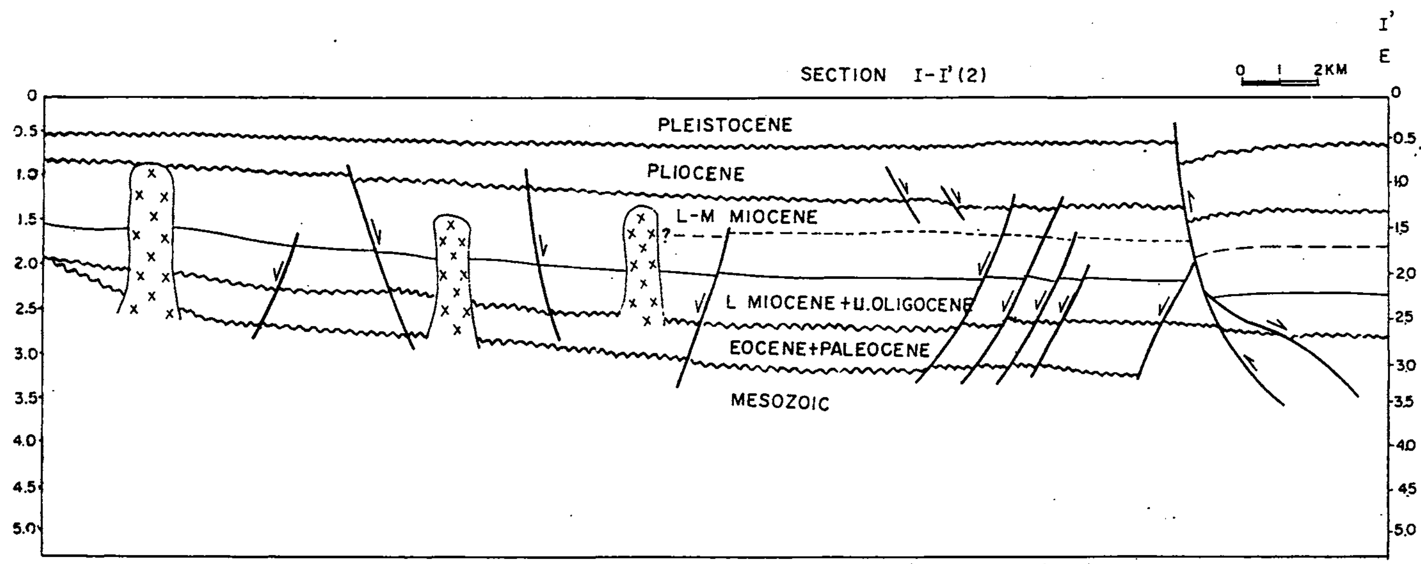

Figure 4: (Continued)

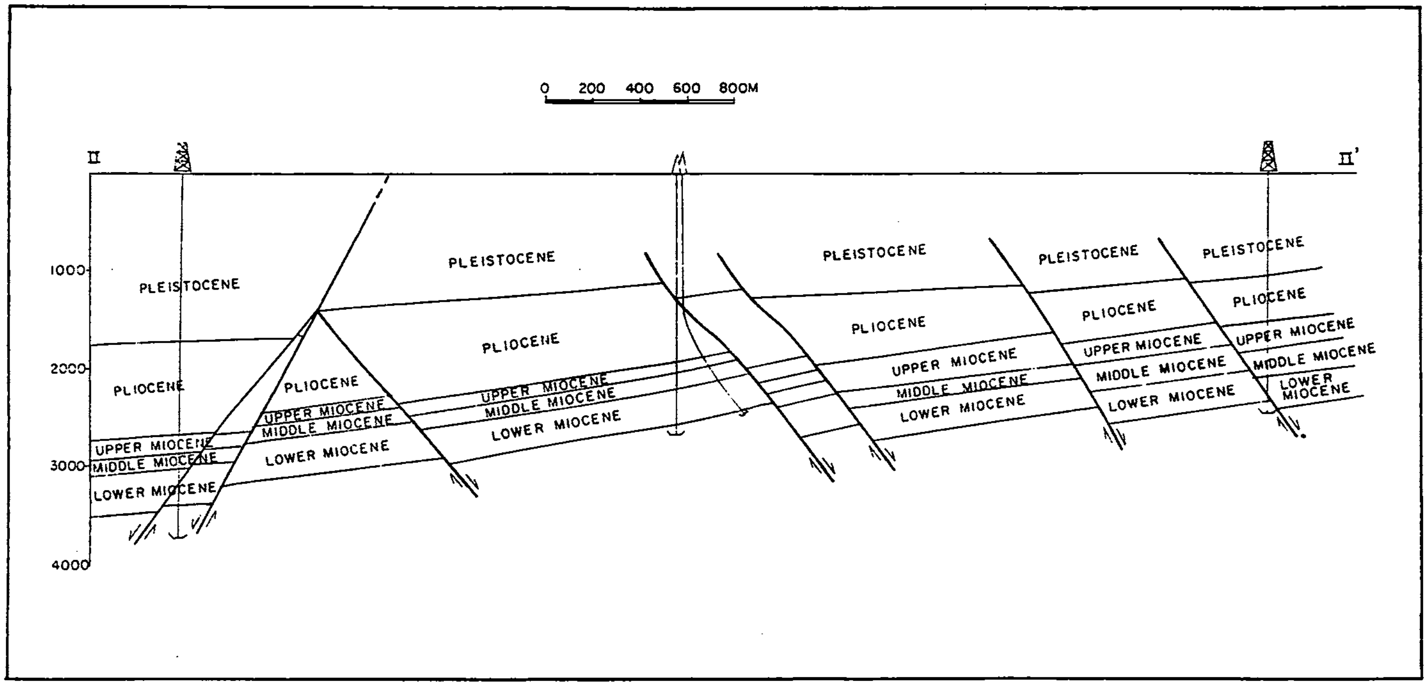

Figure 5: Geologic cross section II-II' passing through SW Taiwan Coastal plain shows a series of antithetic normal faults and rotation of the fault block (Leu, *et al.*, 1985)

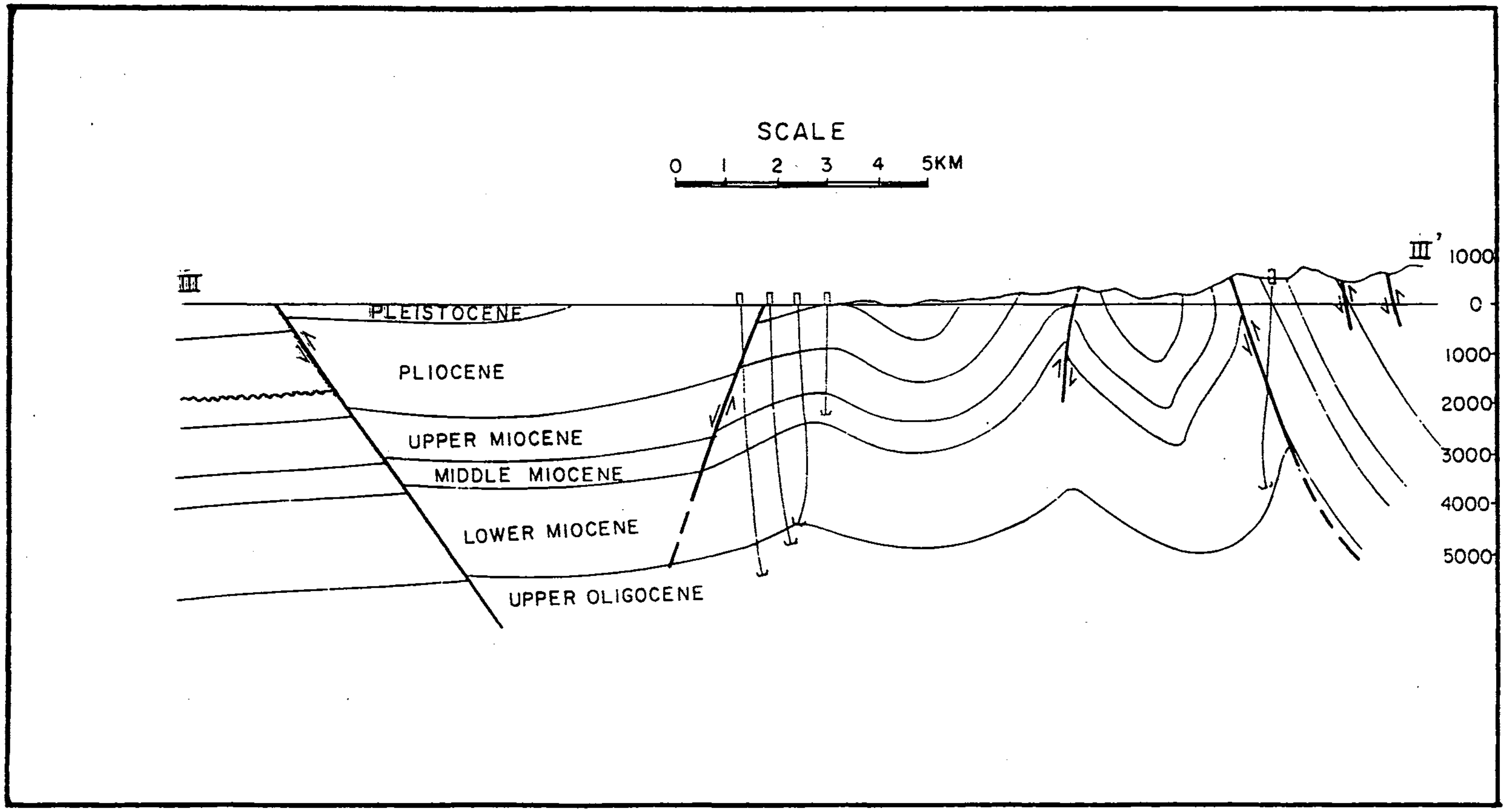

Figure 6: Geologic cross section III-III' passing through NW Taiwan foothill areas shows compressional stress diminished in intensity from the east toward the west.

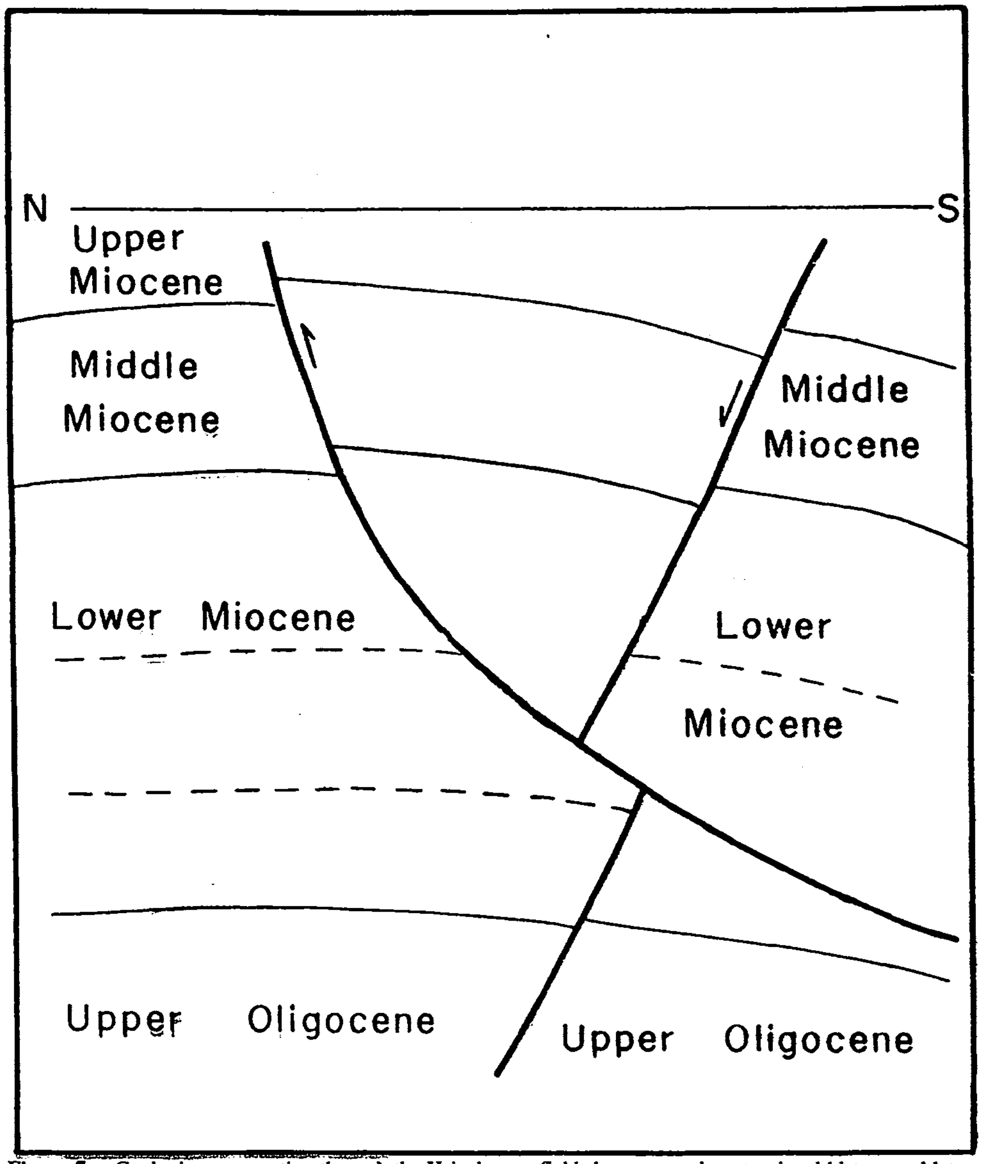

Figure 7: Geologic cross section through the Hsinchu gas field shows an early extensional history and later interrupted by the thrust fault, production from an old rollover anticlinal structure (modified from Wu *et al.*, 1986)

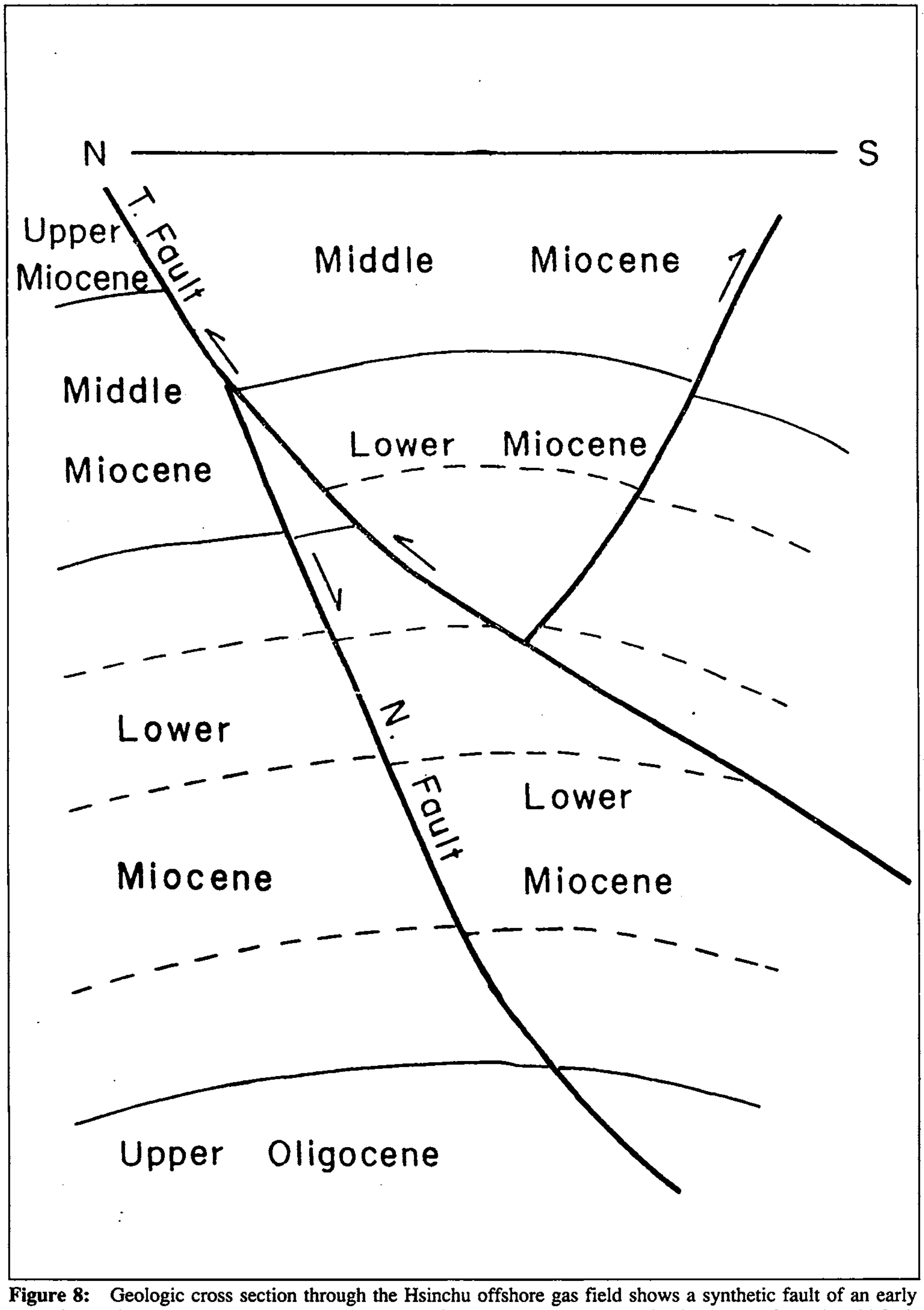

Figure 8: Geologic cross section through the Hsinchu offshore gas field shows a synthetic fault of an early extensional history and later truncated by the thrust fault and back thrust. Production comes from the old fault upthrown block (modified from Wu *et al.*, 1986).

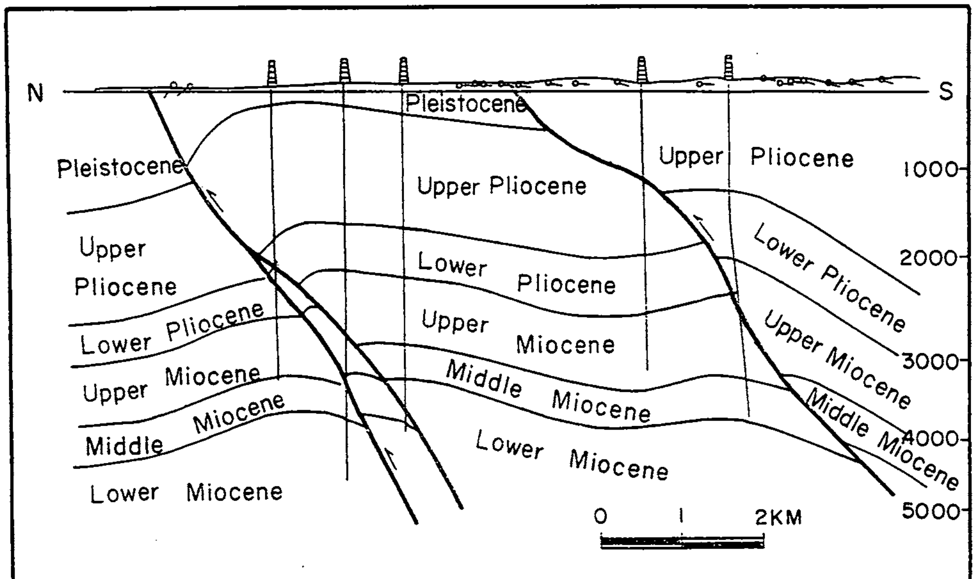

Figure 9: Structural cross section through the Chingtsaohu and Paoshan structures shows the imbricated thrusting and fold-thrust structure. (modified from CPC files).

superficial beds so that they appear to be high-angled on the surface and generally die out along the strike at varying distances.

The mechanism for bringing about of these thrust faults and folds may not be merely the stacking-up of Neogene sediments by lateral compression from the east or southeast. Gravitational gliding may also play an important role in the development of the thrust sheets and may cause some sort of wrench faulting (Meng, 1962) (Fig. 14).

At the contact between the folded Neogene formations and their substratum, a decollement structure has been interpreted. Neogene rocks were thus sheared off from their underlying basement Paleogene or Cretaceous rocks, along a major detachment plane. However many of these folds are concentric folds and show different structural styles at different levels. In these folds, the downward tightening in the anticline and upward tightening in the syncline lead to a volumeric problem of rock in both folds (Brown, 1984).

Many anticlines in the inner foothill area show a highly compressional structural and have stacking of faults at axe-sejectif style in Brown's words (1984). (Figs. 11, 12). The intensity of deformation decreases from the eastern inner foothill region toward the western outer foothill area where the structural style is characterized by much gentler folds (Fig. 13).

WRENCH FAULT TECTONICS

Based on the tecto-morphological relationship of the island of Taiwan to the Ryukyu in the north and the Philippines in the south, and such features as the difference in character of

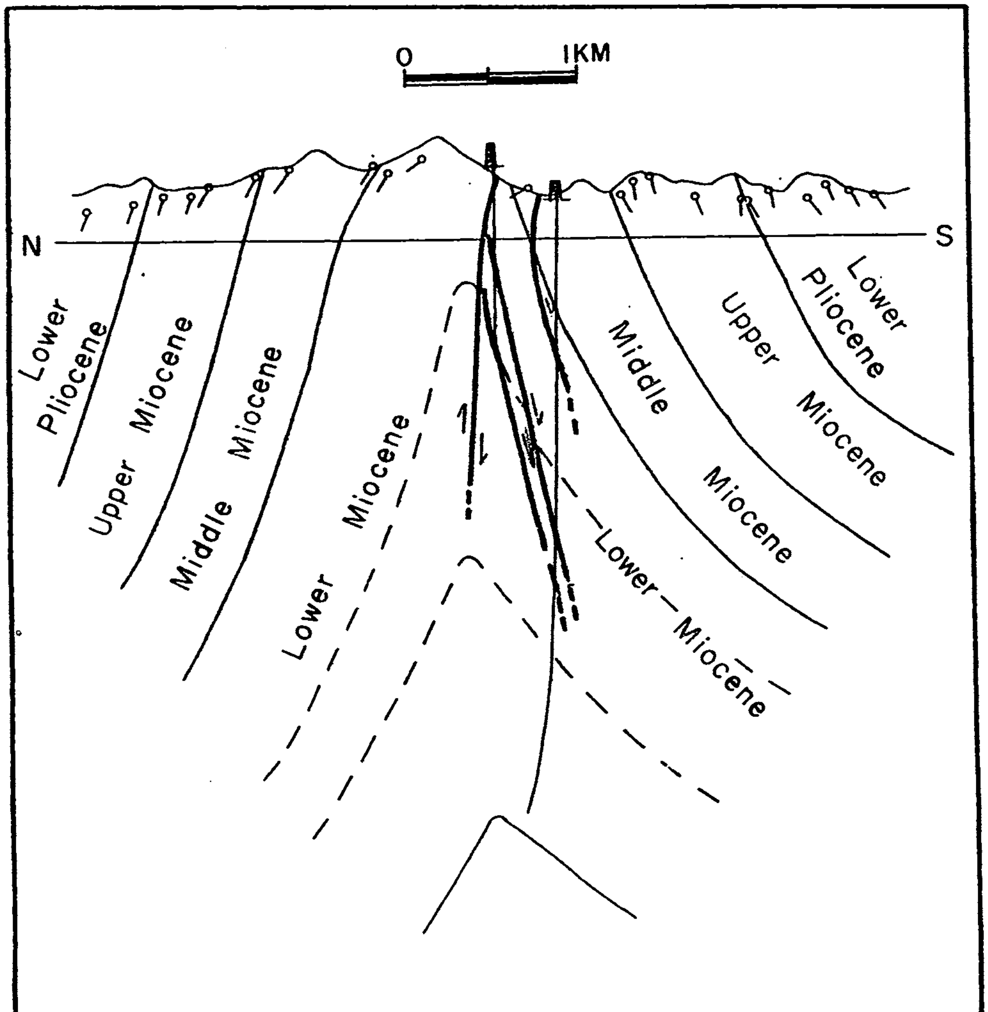

Figure 10: Structural cross section through the Chuhuangkeng oil and gas field shows the stacking of faults at the axis due to high compression. (modified from CPC file).

two blocks east and west of the main fault along the Central Range expressed by surface geology, the evident bending of the north end of the island as a whole toward the northwest, the difference in lithologic facies of the Neogene deposits in the Eastern Coastal Range and at the southern tip of Taiwan from the deposits of the same age in the western part of Taiwan (Fig. 1). Meng (1962) made the assumption that the main tectonic style in Taiwan is wrench faulting (Fig. 14). However, even we do not completely understand how the Mesozoic subduction activity controlled local wrench tectonism within evolving sedimentary basins around Taiwan area, The Neogene deposition pattern of western Taiwan, the existence of en echelon folding, and the rhombohedral pattern of the faults may be the result of the Neogene wrench fault tectonism.

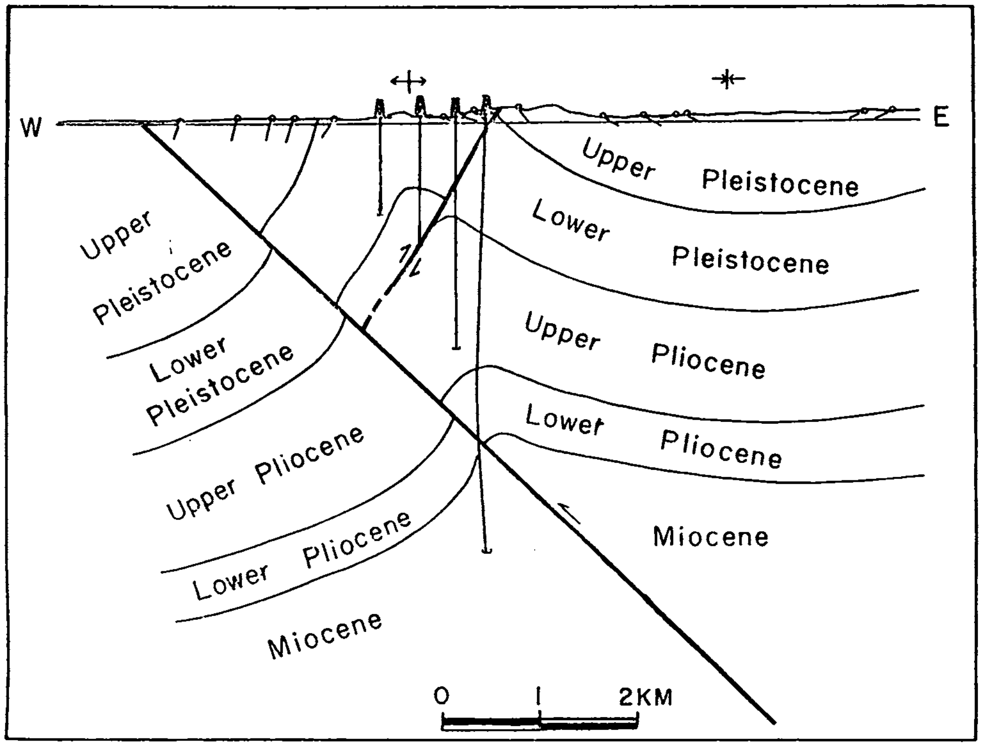

Figure 11: Structural cross section through the Niushan gas field shows the faulted anticlinal structure. The minor fault is a back thrust due to compressional volume problem (modified from Chang, 1962).

This kind of shearing deformation results elliptical en echelon anticlinal traps, and fault traps with different throws and pay zones along the same fault.

HYDROCARBON ACCUMULATION

In the offshore basins, petroleum and natural gas within Cenozoic reservoirs occur in traps formed by fault traps and fault-anticlinal structures. In addition, hydrocarbons trapped beneath Neogene sediments occur within tilted Paleogene strata capping buried hills or basement highs covered and flanked by Neogene strata can be found in south west offshore area. Small scale rollover anticlines and unconformity truncated upper Neogene strata can trap small quantity of gas in south west Taiwan coastal plain area.

However, more hydrocarbon bearing traps are to be expected in buried paleotopographic high structures, submarine canyon and fan sands in these rifted basins.

Hydrocarbon accumulation in the Taiwan foothill areas occur mainly within anticlinal traps, which commonly include multiple reservoir horizons. Reverse faults locally help produce closure or define downdip reservoir limits. Many anticlines in inner foothill area have stacked faults at the crest which may complicate hydrocarbon accumulations.

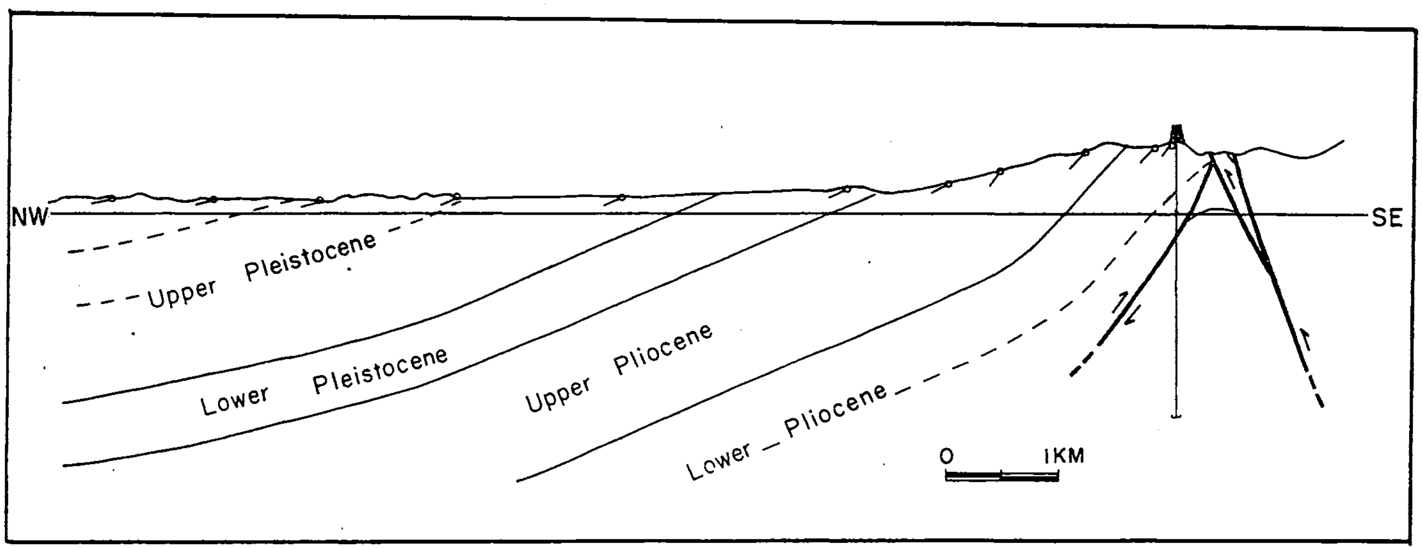

Figure 12: Geologic cross section through the Chulun structure, Chiayi shows the style ejective structural level of concentric fold (modified from Chang, 1962).

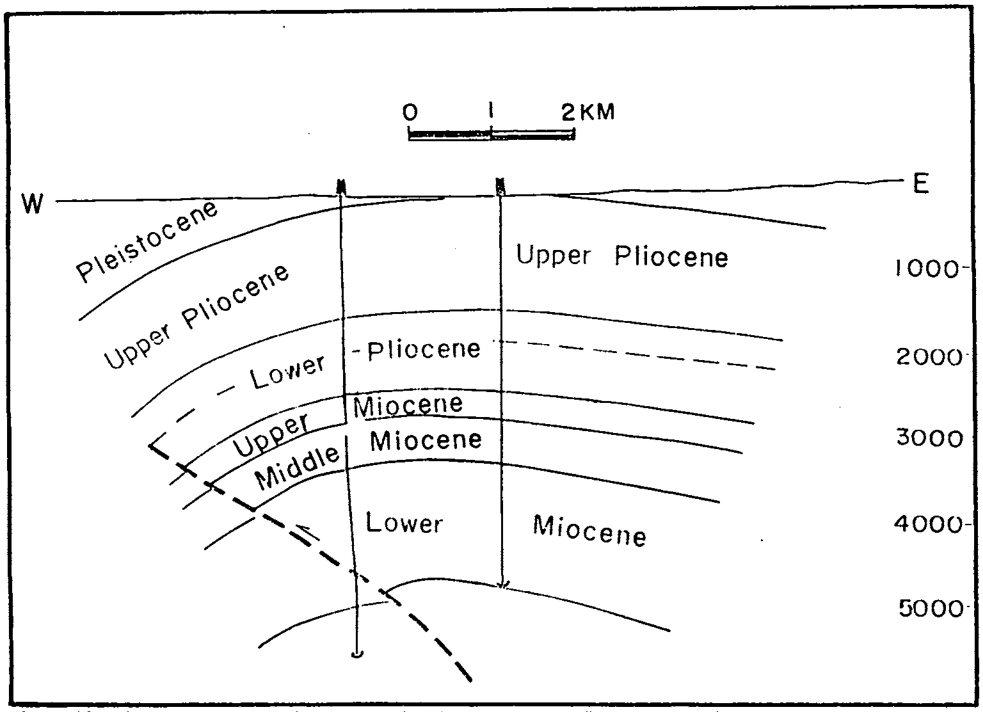

Figure 13: Structural cross section through the Tiehchenshan gas field shows the fold-thrust structure (modified from Chang, 1962)

CONCLUSIONS

The continental margin crust around theTaiwan area was attenuated by rifting since the begin of Cenozoic. However, the Taiwan main island is the site of an ongoing collision of Luzon island arc. Therefore, the Cenozoic basins around the Taiwan area have undergone different tectonics. One is the extensional passive continental margin type the other is the compressional active island arc type.

Extensional structure styles have prevailed in offshore Taiwan, with listric faults, tilted blocks, growth faults, and roll-over anticlines or drape fold in the cover rocks. In onshore Taiwan, Cenozoic basins show a compressional-wrenching structure styles with imbricate thrust faults, right-slip reverse faults and en echelon arranged folds.

The intensity of compressional deformation decreases from the eastern high mountain region in Taiwan toward the west where the structural styles are characterized by much gentler folds in outer foothill area, and by tectonic inversion of normal faults and reverse faults in nearshore area.

Since different tectonic evolution types and different structural styles in different tectonic levels, this area has complicated hydrocarbon accumulations and may be applicable to similar geologic provinces elsewhere.

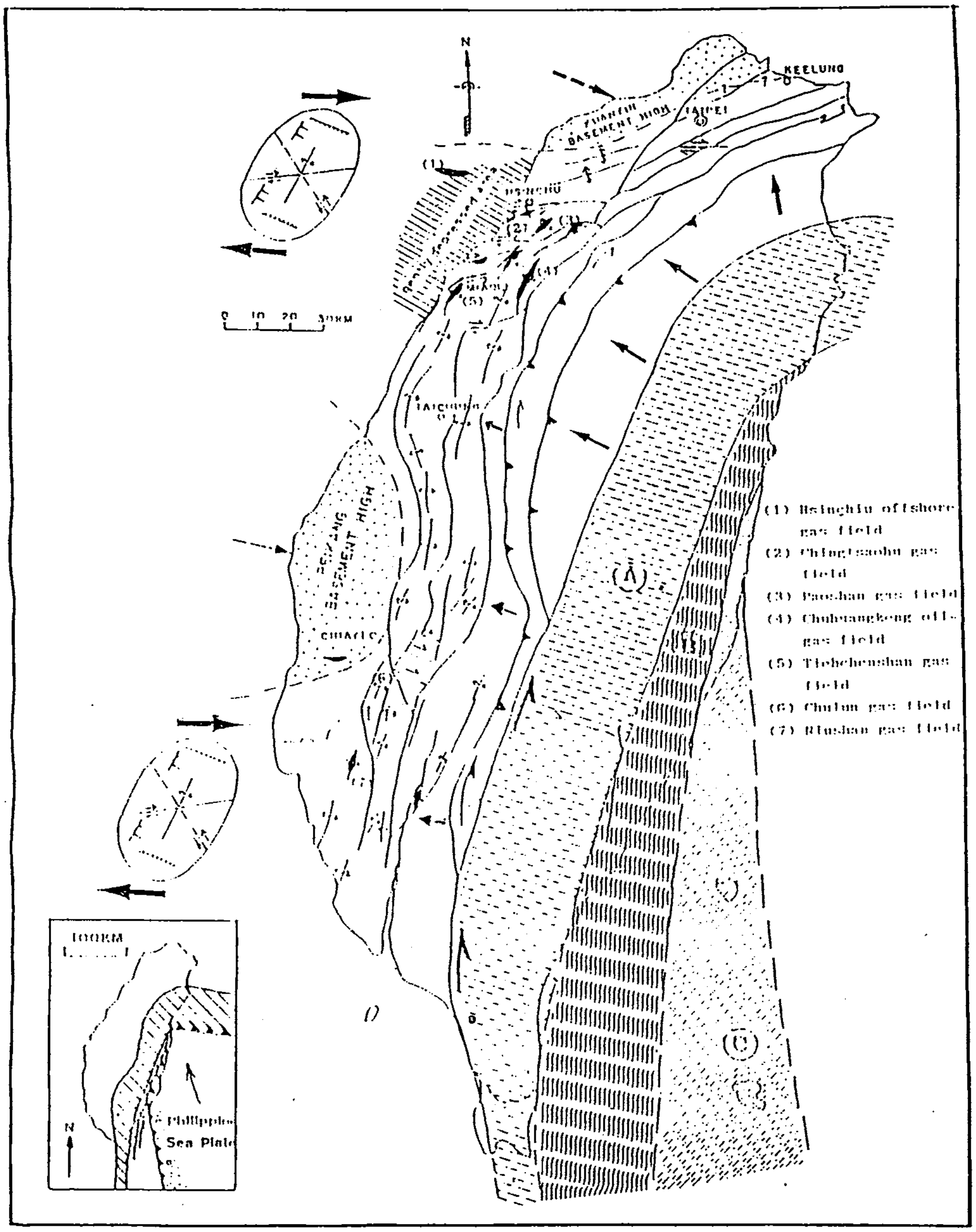

Figure 14: Wrench fault tectonism and its relationship to *en echelon* arranged anticlines and parallel right-slip-reverse faults in Taiwan. (A) may be the allochthonous block joined to the Taiwan island through the subduction-collision-slippage tectonism in late Mesozoic. (C) is the well-known Luzon volcanic island arc which collided with Taiwan through the same tectonism since late Pliocene. (B) is the suture zone of the collision. Black elliptical spots are anticlinal oil and gas fields. Numbers show their cross sections in the aforsaid figures (modified from Meng, 1962).

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