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『台灣地震地質研究—台灣西南部活斷層研究』-台灣西南部構造地形與古地震研究-嘉義地區（4/4）

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Abstract

1. Introduction

Thrustbelt is characterized by great earthquakes, crustal shortening deformation, and extraordinary topographic relief and represent a fundamental manifestation of deformation in active orogenic belt. During the Quaternary period, Taiwan Orogen in arc-continent collisional convergent settings occurs as a result of the active thin-skin thrustbelt displaying in the Western Foothills, western Taiwan (Suppe, 1976). The collision has developed several west-verging thrust faults which have experienced an in-sequence shift (Chen *et al.*, 2001; Mouthereau *et al.*, 2001; Yang *et al.*, 2007). The Western Foothills represent a zone of ongoing convergence which shortening occurs in response to the thrusts westward movement. In previous studies were proved that the thrust faults in the Western Foothills are the ongoing structures (Lin *et al.*, 2000). Recent geodetic studies indicate present shortening rates of ca. 50 mm·yr^{-1} within the Western Foothills, southwestern Taiwan (Yu *et al.*, 1997). It suggested high rates of deformation and is often considered to behave as a strong deformation within the southwestern Taiwan. The resultant of westward movement of the thrust sheet deflected down the lithosphere of Eurasian continent to form a foreland basin which has developed between the thrustbelts of the Western Foothills and forebulge on the eastern Taiwan Straits (Chou and Yu, 2002; Chiang *et al.*, 2004).

The study area in the Tainan city is situated in a frontal thrustbelt and foreland basin settings, the structural framework is controlled by several NE trending thrust faults: Lungchuan, Meilin, Chungchou, and Tainan faults from east to west. At the southwest side of the study area, the offshore region of southwestern Taiwan shows a series of imbricate westward vergent thrust faults of an accretionary wedge setting which exposed on the Kaoping slope (Chiang *et al.*, 2004; Yu, 1993). Topographic expression shows that the Penghu canyon sharply bounds with the South China Sea alope and Kaoping slope in the region, the submarine canyon is approximately located on the westernmost thrust of accretionary wedge (Yu *et al.*, 2005). However, the frontal thrust extends northeastward from offshore to onland, where the fault in onland could be connected to the Chungchou-Tainan fault system of the frontal thrust of the orogenic belt.

The currently frontal thrustbelt is a much younger and active. In particular, the forefront thrust fault generally stretch over the metropolis in the western Taiwan, such the study area has three imbricate faults of the Meilin, Chungchou, and Tainan faults cross through the Tainan city (Meng, 1967; Mouthereau *et al.*, 2001). The population distribution of Taiwan probably has 40% of the person residences that are near the frontal thrust faults. Furthermore, the earthquake disaster often took place in these areas in the past 400 years (Hsieh and Tsai, 1985). Therefore, the study is more necessary for assessing the seismic potential of active structures within the metropolitan region.

The western Taiwan is an interesting region for the study of neotectonics where is an ongoning thrustbelt and foreland basin. In particular, the active tectonics of the frontal fold-and-thrust region is usually covered by the Holocene marine-fluvial deposits due to the postglacial sea-level rise (Chen *et al.*, 2004b; Yang *et al.*, 2007). The Holocene marine deposits are commonly exposed at the surface forming an extensive marine terrace on the hangingwall of the frontal thrustbelt. Hence, in this paper we first use continuously core logging and ^{14}C dating data to reconstruct the stratigraphic architecture and estimate of the Holocene slip rate along individual fault. The subsurface geologic data was constructed from 21 core boreholes on the Tainan city from the coastal plain to foothills. Based on core logging and chronological data, we have investigated the upper 80-250 m of the postglacial depositional successions that allow definition of tectonostratigraphic history and document active deformation related to the frontal thrust fault behavior in the southwestern Taiwan orogenic belt.

2. Geologic and structural settings

The western side of the Central Range in the southwestern Taiwan acted as a foreland basin or a wedge-top basin beginning in late Pliocene Covey, 1984; Chen *et al.*, 2001; Chiang *et al.*, 2004). The basin system occurred the basinward migration causing by the resultant development of the westward in-sequence shift of thrust faults (Lacombe *et al.*, 1999; Mouthereau *et al.*, 2001). The thrust-growth sequence indicates that deformation has migrated westward with the successive activation of three major fault systems of the Chaochou fault, the Pingshi-Chishan fault, and the Chungchou-Tainan fault systems which can be subdivided into Central Range, inner Western Foothills, outer Western Foothills, and coastal plain bounded as the three faults in ascending order. Using the relationship of tectonostratigraphic units overlies a thrust sheet, it probably allows for evaluating the fault-growth and basin evolution time. The reconstruction, however, relies on stratigraphic data that the timing of initially deformation of the three tectonic boundary thrust faults formed during the late Pliocene, early Pleistocene, and late Pleistocene, respectively. And the induced thin-skinned tectonics has led to the formation of the Western Foothills that now indicates an active deformation belt, with a decollement lying beneath the belt (Mouthereau *et al.*, 2001; Yang *et al.*, 2006).

Chaochou fault

The Chaochou fault is bounded between the Central Range and the inner Western Foothills. The early Miocene low-grade metamorphic strata in the Central Range lies to the east of the Chaochou fault hangingwall, which is thrust over the middle Miocene and Pleistocene strata. Results from the Bouguer gravity anomalies and total magnetic intensity surveys, these suggested that the Chaochou thrust fault shows a steep fault plane about 70° to eastward (Pan, 1968; Lewis *et al*., 2004).

Pingshi-Chishan fault

The Pingshi-Chishan thrust fault is bounded between the inner and outer Western Foothills with vertical displacement of about 2300 m (Yang *et al*., 2006; Yang *et al*., 2007). The Miocene sedimentary strata lie to the east of the hangingwall, and the thick (>1000 m) Pleistocene molasse deposits on the hangingwall have thus unconformably accumulated on the Miocene strata. Our reconnaissance field investigation is evidenced that the fault is displaced young Holocene (7190±160 yr BP) fluvial sediments, implying that the fault has been active in present since the early Pleistocene.

Chungchou-Tainan fault

In the outer Western Foothills, the Chungchou and Tainan faults of a frontal thrust system are bounded between the modern foreland basin and the outer Western Foothills which consist of the late Pliocene-Pleistocene strata on foreland basin deposits. The fault system is very difficult to discover on the surface because of the Holocene marine sedimentary covers. Results from the seismic reflection profiles, gravity anomalies, and core drilling, it suggested that this area occurred three structural highs of the Tainan, Chungchou, and Takangshn anticlines (Sun, 1963; Meng, 1967; Pan, 1968; Heish, 1970). Based on the geomorphic character and core drilling, the survey shows a well geomorphic indicator that the Chungchou and Meilin (Hsiaokangshan fault in the southern segment) fault traces form a distinctly linear scarp along the western limb of Chungchou, and Takangshn anticline, respectiverly (Meng, 1967).

The Chungchou fault is the major frontal thrust which displaced the Pleistocene strata about several hundred meters in height, that the fault is broken through the western limb of Chungchou anticline. The Meilin and Lungchuan faults represent a subordinate fault within the Chungchou thrust sheet. The Meilin fault is exposed along the backlimb of Chungchou anticline. And the Lungchuan fault is an emergent thrust fault along the hinge of Kengnei anticline, wherein fold crowding results in axis shortening associated with breakthrough thrusts near the core. The Tainan fault is located at western part of the Chungchou fault, it is interpreted a shallow and gently east-dipping detachment fault underlying the Tainan tableland based on the seismic reflection profile and core drilling. The balanced cross section implies depths of the detachment of about 4-5 km toward the east in the frontal thrustbelt.

The frontal thrust system that is bounded by an E-W trending right-lateral tear fault of the Shinhua fault on the northward. The fault was ruptured during the 1946

M_S 6.3 Tainan earthquake which created a visible surface rupture that was 6 km long, and trenching study indicates that the other paleoseismic events occurred 9550-8640 yr BP and 1870-1690 yr BP (Chen *et al*., 2004a). On the southern thrust sheet of the fault, the thrust front along the Tainan fault therefore advances on the more westward compared to the northern thrust sheet. Based on the geodetic observation, it is also indicate that the slip rate of the study area is more quickly than the northern thrust sheet across the Shinhua fault (Hou *et al*., 2003).

3. Tectono-geomorphological background

In thrustbelts, deformation creates relief more complex and quickly than in orther geodynamic environments. In particular, the frontal thrust is a more younger active structure that geomorphological features are well preserved. We are able to observe the primarily topographic features and date since they can provide information on uplift rate and deformation character. In the study area is a ongoing deformation front which is dominated by a NE-SW trending structure fabric that consist of three active thrust faults. The topographic expression, which preserves a young surface features, is made up of five tectono-geomorphic provinces of the Western Foothills, Chungchou marine terrace, Dawan lowland, Tainan lableland, and Chianan coastal plain from east to west. The surface is deposited by poorly indurated Holocene shallow marine deposits which unconformably overlie on the late Pleistocene strata. Holocene deposits, ranging in thickness from several tens meters to hundreds meters, subsequently cover the five provinces. Based on the core logging, thick of Holocene deposits are highly variable which represents a poorly known control on the deformation character and old geomorphic surface.

The Western Foothills, Chungchou marine terrace and Tainan tableland provinces due to the tectonic uplift were created during the late Pleistocene, which response to the fault-bend and fault-propagation deformations by the Meilin, Chungchou and Tainan faults. The Chungchou marine terrace province formed a westward dip surface which collected from a series of NE trending gentle fault scarps bounded between the Dawan lowland and Chungchou marine terrace provinces, that the scarp ranging in height from 10 to 20 meters is displaced by the Chungchou fault. The eastern margin of the marine terrace is defined by the Western Foothills and a linear topographic scarp. Holocene marine terrace lying in both sides of the scarp is interpreted to have controlled by the east-dipping Meilin fault.

The Tainan tableland province is a Holocene uplift that the culmination stands ~35 m above the coastal plain. The tableland occurs a highly asymmetric warped surface which shows a gentle westward slope on the forelimb and steeply eastward backlimb. The short and abrupt backlimb fold defining an anticlinal axis along the tableland crest suggests to form by the Houchiali blind backthrust fault. The uplift tableland is inferred to be growth in response to slip on an underlying detachment fault and a west-dipping backthrust . Therefore, each uplift province correlates with a thrust sheet of the Meilin, Chungchou, and Tainan thrust faults. The Chianan coastal plain and Dawan lowland provinces in both sides of the uplift tableland are located on the footwall of the Tainan and Chungchou faults, respectively, where are a ongoing subsidence basin. As the basins have accumulated more than five hundred meters thick of late Pleistocene deposits (Meng, 1967).

Fluvial drainage pattern is a highly sensitive indicator and record evidence of active tectonics (Schumm, 1986). The terrace and tableland surfaces were formed by marine process during the early Holocene period. The surface forms the relative level and smooth which is still well preserved and undissected, that is composed of few subsequent creeks which are less incised, narrow, and smaller catchment area. It reveals that the uplift and up-warp surfaces indicate a younger deposition surface. Results from ^{14}C dating suggest that the surficial topographic features of marine terrace and tableland occurred since the middle Holocene.

4. Stratigraphic architecture and depositional environment

Although paleoenvironmental studies shown evidence the eustatic sea-level rising about 120 m from 18 ka BP to about 6 ka BP (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996; Rohling *et al.*, 1998). In this area, analysis of landform, ^{14}C ages, and marine deposits evidenced that the shoreline had already retreated landward (eastward) to the frontal Western Foothills during the early Holocene (Chen *et al.*, 2004; Yang *et al.*, 2007). Therefore, the early Holocene shallow marine deposits were extensively covered up the frontal foothills. In the study, we reconstructed from 21 core boreholes of A-A` and B-B` transect sections for detailed descriptions and discussion of ^{14}C dating data, it will enable us to reconstruct stratigraphic and sedimentologic architectures during the postglacial epoch.

Two stratigraphic A-A` and B-B` transect sections were produced using data from a series of 10 core boreholes through the modern shoreline to foothills . Drilling provided continuous-core boreholes that varied from 35 to 260 m in depth, hence core records allow description of sedimentary structures and stratigraphic correlation in detail.

During the last 18-6 ka, the sea-level transgression rose from an elevation some 120 m below present at a rapid rate about 1 m per century (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996; Rohling *et al.*, 1998). Stratigraphic investigations reveal the late Pleistocene-Holocene fills overlie weathered soil or Pleistocene basement. The core logging therefore indicates the marine deposits throughout over from coastal plain to foothills, where thickness of deposits above an unconformity is varied range from 30 to 200 m thick . The postglacial sequence can be recognized as an unconformably boundary which is divided into erosive disconformity and angular unconformity. The disconformity can be traced to the subsided coastal plain and lowland provinces where the weathered condition indicates subaerial exposure and erosion during the last glacial epoch. The angular unconformity shows that the Holocene deposits rest unconformably above the late Pleistocene strata occurring in the uplift tableland, marine terrace, and foothills provinces.

The sea-level rising has resulted in a complete sedimentary sequence which occurs wave- and tidal-dominated environment including offshore, shoreface, intertidal, and fluvial systems which coincide with the modern coastal processes. The four environmental systems developed during the postglacial fluctuations in sea-level and are interpreted here within a sequence stratigraphic framework (Posamentier and Allen, 1999). The sequence is recorded in a deepening-upward transgressive system tracts during 18-ca. 8 ka and shallowing-upward highstand system tracts since ca. 8 ka. Three main depositional stages concerning the basin development can be inferred. First, during the last maximum glacial epoch (25-18 ka), the shoreline was retreated to the seaward due to the sea-level fall. From the coastal plain to terrace provinces was subaerially exposed and eroded where created an extensive unconformity. Second, the unconformity surface subsequently overlaid by sediments of the transgressive system tracts when the sea-level rises after the last maximum glacial epoch (18-ca. 6 ka). The shoreline was prograded at least 20 km landward to the frontal foothills. The depositional environment forming a deepening-upward succession was in turn progradated from intertidal, shoreface to offshore zones. Third, since the middle Holocene (6 ka), the sea-level rising rate is gradually slow down, accompanied by sediments bypass to the seaward. The environment, forming a shallowing-upward succession of the highstand system tracts, was prograded from the offshore through the shoreface, intertidal to fluvial zones. The shoreline was again retreated to the modern coast.

Isochronous surface

In this study we get more ^{14}C dating data which can be correlated with three time-lines (isochronous surface) of 9200, 8000, and 7300 yr BP which conspicuously extend the stratigraphic cross-sections from coastal plain to foothills. The isochronous surface within a basin fill succession can represent a specific paleosea-level which is considered to approximate to as a same time bedding. Depositional surface on the nearshore slope occurs less than 1^{o} in the Taiwan strait, therefore, the isochronous surface itself is approximately to a horizontal surface. The isochronous surface is expressed as a curved surface in stratigraphic section and hence it would be considered to be in response to deformation, if we rule out the possibility that it did not affect by the irregular landform. Based on the significantly chronostratigraphic correlation, the stratigraphic architecture from the A-A` and B-B` cross-sections present some meaningful structural features of a curved-shape isochronous surface and thickness variations. The possible explanation for the curved isochronous surfaces is an effect produced by differential tectonic deformation, for example, the greatest differential relative depth of 9200 yr BP time-line can reach about 100 m between the coastal plain and tableland provinces. We suggest that such discrepancy in depth can get rid of differential compaction.

Thickness of late Pleistocene-Holocene deposits above the unconformity is highly variable, such as the coastal plain and lowland provinces host more thick sediment accumulations. The thickness variation between each isochronous surface is also interpreted as producing by tectonics. Additionally, gradual thinning of sediment wedges overlaying the basement also demonstrates the differential vertical movement on both sides of the tableland province. The thickness variation and curved isochronous surface indicate to influence by the complex tectonics which is inferred to cause by the growth fold.

5. Holocene vertical deformation rate

Complex tectonic uplift or subsidence has occurred marine terrace and basin in this area, the study for analysis the tectonic deformation rate is aimed to advance the understanding of tectonic processes. Particularly, the high-precision ^{14}C dating is available to estimate the vertical deformation rate of these tectonic provinces which is determined by relating known paleosea-level elevations, altitude distribution of Holocene deposits and paleodepth. The large uncertainties for uplift rate mainly arise from the estimation of paleosea-level elevations and paleodepth. Comparing with the postglacial sea-level elevations, the previous studies in the western coast of Taiwan (Chen and Liu, 2000; Hsieh *et al.*, 2006), where is a tectonically active area, were inconsistent with the sea-level data observed at Barbados, Tahiti, and Papua New Guinea (Fairbanks, 1989; Bard *et al.*, 1996; Chappell and Polach, 1991). We therefore refer to paleosea-level elevations of the above-mentioned areas.

In recent years, uplift marine terrace has been studies in this area that has provided the estimates of Holocene uplift and incised rates (Chen and Liu, 2000; Hsieh and Knuepfer, 2001). More study through marine terrace has to determine the paleosea-level position which commonly investigated and measured the terrace shoreline angles. In this study we address through the results of core logging data, that the postglacial marine deposits can be divided into intertidal (foreshore), shoreface, and offshore zones. One of the contributors to the uncertainty of uplift rate is the paleodepth determination. The following estimation of paleodepth is based on referring to the modern environment in the southern Taiwan Strait. In the study area, observation of the mean tidal range is about 1.5-2 m (Jiangjyun tide station, Anping harbor; Lin *et al.*, 2000), we use an uncertainty between 1 and -1 m depth in the intertial zone. The shoreface depth is varied in each area. We have assumed that the shoreface depth is simplistically defined as 10 m, because it is a common depth marked on most areas (Stutz and Pilkey, 2002).

In this study a total number of 52 charcoal and shell samples from 20 core boreholes were submitted for accelerator mass spectrometry (AMS) dating. Previous studies have demonstrated that the most reliable ^{14}C dating data performing on wood and shell samples were collected from marine terraces (Hashimoto, 1972; Hsu *et al.*, 1968; Wu, 1990; Chen, 1993; Hsieh and Kunepfer, 2001; Chen and Liu, 2000; Lin *et al.*, 2007). We have calculated the vertical deformation rates of the individual estimates for each site. On the basis of tectonic setting, all the 20 core boreholes were separated into five tectonic provinces in order to discuss these estimated vertical rates.

Chianan coastal plain

The Chianan coastal plain in the more west area, the urban development over the past hundred years has seriously changed the coastal environment. Therefore, the primarily intertidal zone causes by the artificial fills to become a coastal plain, the shoreline advanced seaward up to 5 km. The 4 core boreholes (TN1～TN4) are situated in coastal plain, and a total number of 16 downcore samples were radiocarbon-dated. Based on the ^{14}C dates and lithofacies analysis, the 4 core boreholes consist of 150-220 m thick of the postglacial marine successions which disconformably overlain the last glacial deposits. Overall, the deformation occur subsidence that the subsided rates decrease eastward, from -6.8±0.9 mm·yr^{-1} (TN1) on the west to -0.3±0.2-0.4±0.2 mm·yr^{-1} (TN2, WT3) on the east.

Tainan tableland

The 7 core boreholes in this study (TN5～TN11) and 8 sites for core boreholes drilling and foundation excavation in the previous studies are situated in Tainan tableland. The results of core logging show that the Pleistocene formation is unconformably overlaid by the postglacial marine deposits. Strata of the postglacial deposits above the unconformity surface, which formed an antiform surface, thinned toward the Tainan anticline axis (tableland crest). The tableland forming a flexural topographic expression is interpreted to relate an underlying structure which was controlled by the blind Tainan fault and the blind Houchiali backthrust. The axis terminates at both ends for surficially expression. Most ^{14}C dating data enable us to better constrain the vertical deformation rate around the anticline which occurs the increasing toward anticline axis. Our findings indicate the uplift rates of transecting the anticline in the forelimb, from 0.4±0.2 mm·yr^{-1} (WT3) on the west to 4.5±0.4 mm·yr^{-1} (CG2) and 4.3±0.5 mm·yr^{-1} (TN10) on the east.

Dawan lowland

The Dawan lowland is situated between the Tainan tableland and the Chungchou marine terrace. A N-S trending lowland is consistent with the Houchiali blind backthrust and the Chungchou fault trends. However, geomorphic indicator of Holocene folding and faulting forms within the lowland along this trend. The lithologic character is similar to the coastal plain, the lowland is covered by a complete the postglacial marine deposits about 120-130 m thick. The 3 core boreholes in this study (TN12～TN14) and 3 core boreholes in the previous studies are situated in Tainan tableland. The borehole transects show the deformation in the lowland occurring a subsidence tectonics that the subsided rates decrease eastward, from -1.8±0.1 mm·yr^{-1} (CG1) to -0.2±0.2～0.6±0.3 mm·yr^{-1} (TN12).

Chungchou marine terrace

The Chungchou marine terrace forms a gently westward dip of surface. Shallow subsurface investigation for core drilling shows that the postglacial marine deposits, which are preserved throughout this area, are unconformably overlaid on the Pleistocene strata, the unconformity surface forms an uneven surface and dipping to the west. Results from the ^{14}C dating data, the deformation reveals an eastward increasing in uplift rate from 0.9±0.1 mm·yr^{-1} (TN15) on the west to 3.8±0.5 mm·yr^{-1} (TN18) on the east. The spatial distribution of uplift rate provides the maximum uplift rate occurs near the Chungchpu anticline axis.

Western Foothills

The eustatic sea-level is reasonably well constrained with a rapidly rising of about 14 mm·yr^{-1} during the early Holocene (Fairbanks, 1989). Therefore the shoreline had rapidly retreated landward (eastward) to the frontal Western Foothills. Within this area, the identification of the remaining marine deposits is provided evidence for sea level expanded flooding within the frontal foothills. Currently the exposed early Holocene marine deposits in the Western Foothills are unconformably overlaid on the Pleistocene strata. Emerged Holocene marine deposits here proposed by tectonic uplift. Previous studies indicated an uplift rate of 4.7±0.7 (TT11)～7.2±0.2 mm·yr^{-1} (HK2) in the frontal foothills (Chen and Liu, 2000; Hsieh and Knuepfer, 2006).

Eustatic sea-level has been more or less stable during the late Holocene, therefore, the marine and fluvial sediments have been developed to upward aggradation and westward progradation becoming a series of river terrace along the upper stream of the Erhjen river (Hsieh and Knuepfer, 2006). They inferred that the creation of higher relative elevation of late Holocene terraces dues to the incision by climate, and sea-level falling, and proposed that the incision rate is closed to the long-term tectonic uplift rate. Because these terraces are underlain by weakly resistant Pleistocene mudstone which forms a badlands landscape. Hsieh and Knuepfer (2006) estimated for a long-term tectonic uplift rate of about 10.3 $mm \cdot yr^{-1}$ for the river terraces near the Kengnei anticline in the upper stream area.

6. Discussions

The ongoing collision between the Eurasian and Philippine Sea plates has resulted in convergence and uplift of the Taiwan orogenic belt. Based on the Global positioning system (GPS) data, the present rate of convergence in the fold-and-thrust belt of the Western Foothills in the southwestern Taiwan is the order of 40-50 $mm \cdot yr^{-1}$, indicating that the active thrust belt is responsible for about 50% accommodation over the past decade. The thrustbelt that its convergent deformation is distributed accommodation by those imbricated active thrust faults of the Pingchi-Chishan, Lungchuan, Meilin, Chungchou, and Tainan faults in the study region.

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二、與會心得

歐洲的活動構造研究主題相較於 AGU 少，而地質災害的議題相對較多。