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Offshore Taiwan accretionary prism : new insights from reprocessed multichannel seismic data

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**OFFSHORE TAIWAN ACCRETIONARY PRISM:
NEW INSIGHTS FROM REPROCESSED MULTICHANNEL
SEISMIC DATA**

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Tuan Anh Nguyen

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ABSTRACT

OFFSHORE TAIWAN ACCRETIONARY PRISM: NEW INSIGHTS FROM REPROCESSED MULTICHANNEL SEISMIC DATA

By Tuan Anh Nguyen

Twelve-fold seismic data acquired by the Lamont-Doherty Earth Observatory in 1980 were reprocessed to provide better imaging of the subduction region of the offshore Taiwan accretionary prism. The lower slope domain of the prism is growing by frontal accretion and underplating through duplex formation. The domain may be a relatively young feature since shortening, related to fluid expulsion and thrust faulting, is less than expected from plate convergence over the past 1 million years. Out-of-sequence thrusting, possibly in response to seamount subduction, causes significant uplift of the prism at the boundary between the domains of the lower and upper slope. Tectonic wedging at the rear of the prism results in uplift and shortening within North Luzon Trough strata. Finally, strike-slip faulting is identified along the North Luzon Ridge, presumably related to the lateral component of oblique convergence between Eurasian and Philippine Sea plates.

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INTRODUCTION

Convergent plate boundaries and accretionary prisms in particular, are dynamic tectonic features, which can grow or retreat through time. During subduction along a convergent plate boundary, sedimentary materials can be transferred from the lower plate to the upper plate, thus forming accretionary prisms. Sediment, which is carried to the plate boundary on the subducting oceanic lithosphere, may be offscraped and accreted at the front of the prism (*offscraping*) by imbricate thrusting [Karig and Sharman, 1975] or carried beneath the prism and accreted along its base (*underplating*) through duplex formation [Scholl et al., 1980; Silver et al., 1985] or by viscous flow [Cloos, 1982; Cloos and Shreve, 1988]. Prism growth may also result from forearc sediment being incorporated into the rear of the prism through backthrusting or tectonic wedging [Westbrook, 1982; Silver and Reed, 1988]. Collisions of accretionary prisms with seamounts, oceanic plateaus, and continental margins on the subducting plate may result in the accretion of crustal rocks, producing significant changes in width of the prism and vertical movement of the sea floor [von Huene and Lallemand, 1990; Lallemand et al., 1994]. Taiwan island is one example of the collision process, forming as a result of the juxtaposition of continental lithosphere of the Eurasian plate with the Luzon island arc along the northwestern edge of the Philippine Sea plate [Suppe, 1984; Ho, 1988].

Recent studies of the offshore Taiwan accretionary prism provide a framework for understanding the initial stages of the Taiwan orogeny [Lundberg et al., 1992; Reed et al., 1992]. The collision has produced rapid growth and uplift of the prism, closure of the

forearc basin, and, ultimately, accretion of the Luzon island arc to the Eurasian continent along the eastern coast of Taiwan. This thesis examines the structural framework, growth processes, and distribution of shortening in the region bounded by the Manila Trench on the west and the backarc region in the Philippine Sea on the east, in the region of subduction south of Taiwan. Studies of this region are critical for understanding the structure of the forearc prior to modification by the active collision. Previous offshore studies around southern Taiwan were based on low-fold seismic reflection data or unmigrated stacked sections, which do not fully resolve the structure of the accretionary prism [Lewis and Hayes, 1989; Reed et al., 1992]. Twelve-fold multichannel seismic (MCS) data were, therefore, acquired from the Lamont-Doherty Earth Observatory (LDEO) for reprocessing in order to enhance seismic imaging of the prism. New efforts in data processing, which included frequency-wavenumber (F-K) and finite difference (F-D) migrations, integrated with marine magnetic and gravity data, and conversion of seismic sections from time to depth provide important new information about the structure of the accretionary prism. The principal results of these analyses are:

- 1) the style of deformation in offscraped strata along the lower slope is documented by examining the geometry of thrust ramp anticlines and the distribution of fault slip across the lower slope of the prism;
- 2) the mechanism by which subducted strata are underplated to the base of the prism in the lower slope domain is, for the first time, clearly identified in this region;
- 3) a major low-angle east-dipping thrust is identified at the boundary between the lower slope domain and the upper slope domain; this structure may be an out-of-sequence

thrust that causes the significant uplift of the upper slope domain [Reed et al., 1992] or a "top decollement", which is described as the scar resulting from seamount subduction beneath the accretionary prism [Lallemand et al. 1994];

4) a blind thrust, which rises up from the top of the island arc basement and cuts through the forearc basin strata, is clearly identified along the rear of the prism; this feature exhibits a small amount of shortening in the region of subduction compared to that observed where the forearc basin has closed in the region of collision [Reed et al., 1992]; and

5) a major strike-slip fault is identified within an intra-arc basin along the east side of the island arc; this feature accommodates a part of the lateral component of oblique convergence between the Philippine Sea plate and the Eurasian plate as initially hypothesized by Lewis and Hayes [1989].

Observations of accretionary structures are combined into an interpretation of the evolution of the lower slope domain of the prism.

GEOLOGIC SETTING

Near Taiwan the Philippine Sea plate is moving to the northwest relative to the Eurasian plate at a rate of 71 km/my, based on analyses of regional plate kinematics and earthquake slip data [Seno, 1977; Seno, 1993]. Plate convergence is accommodated along northeastern Taiwan by the subduction of the Philippine Sea plate beneath the Eurasian plate whereas, south of Taiwan, the Philippine Sea plate is underthrust by oceanic lithosphere of the Eurasian plate along the Manila Trench (Fig. 1). Taiwan, in the region between the two subduction zones, is the site of an active arc-continent collision between the Luzon island arc along the western edge of the Philippine Sea plate and the Chinese continental margin of the Eurasian plate. Recent global positioning system (GPS) studies have estimated convergence rates of as much as 86 km/my in the vicinity of southern Taiwan, between the islands of the North Luzon Ridge and Paisha, one of the Penghu islands along the Chinese continental margin [Yu and Chen, 1994].

The mountainous island of Taiwan has formed by the oblique collision between continental lithosphere and the Luzon island arc, beginning in northern Taiwan between 4 and 5 millions years ago [Chi et al, 1981; Teng, 1991] that has since propagated southward at a rate of 84 km/my [Suppe, 1988; Byrne and Crespi, 1997]. Presently, the point of incipient collision lies offshore between 21°45' N and 21°30' N. North of this region, the subduction-related prism has been modified and enlarged by arc-continent collision [Reed et al., 1992; Lundberg et al., 1992; Lallemand et al. in press, 1997]. However, south of 21° 30' N, oceanic lithosphere of the South China Sea subducts eastward beneath the Philippine Sea plate, producing a small accretionary prism that has yet to be modified significantly by collision [Bowin et al., 1978; Hayes and Lewis, 1984; Lewis and Hayes, 1984; Reed et al., 1992]. Plate convergence in this region is oblique to the trend of the Manila Trench. Based

Figure 1: Bathymetry map offshore southern Taiwan, location of the V3618.49 line, and seismic cross-section A-A', which crosses the collision zone, and section B-B', which crosses the subduction zone. Inset at the upper left corner shows rate and direction of convergence between the Eurasian and Philippines Sea plates.

on the concept of time-space equivalence of Suppe (1984), this region, located 170 km south of the collision, likely represents the structure of the subduction system in the vicinity of Taiwan approximately 2 million years prior to the initiation of the arc-continent collision. The subduction-related prism, forming initially by sediment accretion along the inner slope of the trench, provides an important modern analog for the pre-collision structural framework of the forearc involved in the Taiwan orogen.

PREVIOUS WORK

The shallow structure of the offshore Taiwan accretionary prism at the transition from subduction to collision has been mapped with SeaMARC II side-scan sonar and 6-channel digital seismic data acquired by the *R/V Moana Wave* in 1990 [Fuh et al., 1997; Hirtzel, 1996; Liu et al., 1992; Lundberg and Reed, 1991; Lundberg et al., 1992, 1995, 1997; Reed et al., 1991, 1992, 1995]. Recently, high-resolution sea floor mapping has significantly improved the understanding of the complicated upper crustal structure in the collision region southeast of Taiwan [Lallemand et al., in press, 1997].

In the collision region, the prism reaches a width of 110 km near Taiwan and exhibits a broad and gentle surface slope (Fig. 2, A-A'). In contrast, the prism is considerably narrower, 70 to 80 km-wide (Fig. 2, B-B'), in the region of subduction to the south, and exhibits a steep and rough surface.

In both the collision and subduction regions, the prism is composed of three distinctive structural domains: 1) a lower slope domain, 2) an upper slope domain, and 3) a backthrust domain. The width of each domain varies considerably between the two regions.

The lower slope domain consists of a series of fold-and-thrust structures that form prominent ridges. Each anticlinal ridge is underlain by a thrust ramp extending downward to a subhorizontal decollement marking the base of the accretionary prism [Reed et al., 1992].

The sea floor slope increases significantly at the boundary between the lower slope and upper slope domains, producing a major regional topographic feature with relief between 1 and 3 km in some regions. This boundary marks the onset of sediment underplating beneath the prism or out-of-sequence thrusting within offscraped strata [Reed et al., 1992]. To the east of the scarp, the upper slope domain is distinctively different from the lower

Figure 2: Cross-section A-A' and B-B' of Taiwan accretionary prism in the regions of incipient collision and subduction (modified from Reed et al., 1992).

slope domain, contrasting in both morphology and structure. Low-fold seismic reflection data of previous studies acquired across the domain boundary and within the upper slope domain do not fully resolve the internal structure, presumably because of intense deformation of previously accreted strata. A few shallow-dipping reflectors have been observed within the domain and may be associated with the onset of out-of-sequence thrusting [Reed et al., 1992].

Uplift of the prism is caused in part by frontal accretion of trench-fill sediment and the incorporation of forearc basin sediment into the rear of the prism along the backthrust domain [Lundberg and Reed, 1991]. The latter domain is narrow in the subduction region, comprising between 10 and 15% of the surface area of the prism. This domain has been interpreted as a tectonic wedge with a west-dipping floor thrust located along the surface of the forearc basement and an east-dipping roof thrust beneath upturned forearc basin strata of the North Luzon Trough [Reed et al., 1992]. Near Taiwan, the width of the backthrust domain increases significantly, as east-directed backthrusts in this domain extend to the sea floor. Increased crustal shortening in this region of the collision has resulted in the closure of the forearc basin and incorporation of the entire forearc basin sequence into the rear of the accretionary prism, thereby forming the Huatung Ridge [Reed et al., 1992; Lundberg et al., 1997]. Recent GPS studies show that as much 40 to 50 mm/yr of crustal shortening, or more than 50% of the motion between the Philippine Sea and Eurasian plates, is accommodated along the rear of the prism in the region of collision [Yu and Chen, 1994].

DATA PROCESSING

In order to better resolve the internal structure of the accretionary prism in the region of subduction, 12-fold stacked seismic, gravity and magnetics data, collected along line V3618.49 by the R/V Vema, were acquired from the Lamont-Doherty Earth Observatory (LDEO). These data are part of a regional grid of MCS profiles from which many of the stacked (unmigrated) common depth point (CDP) sections have formed the basis of previous studies in the region [Hayes and Lewis, 1984; Lewis and Hayes, 1984, 1989].

The stacked data underwent additional processing at the seismic reflection laboratory at San Jose State University using the SIOSEIS system. The ability of these data to image the internal structure of the prism was enhanced through F-K migration at 100 m/s velocity increments between 1300 m/s and 2300 m/s. Results of this stepwise, iterative imaging procedure were integrated into a regional velocity model for input into several iterations of finite-difference (45°) migration. The latter technique improved imaging of the intermediate and deep structure of the prism by allowing migration velocities to vary smoothly with depth (Fig. 3).

Regional velocity information from ocean bottom seismographs (OBS) [Nakamura et al., 1996] and MCS data [Reed et al., 1996], associated with the TAICRUST experiment, combined with velocity information from other studies of accretionary prisms [Bangs and Westbrook, 1991; Flueh et al., 1998], provided the basis for an initial time-to-depth conversion model of the migrated sections (Fig. 4).

Time sections of the F-K migrations and finite-difference migrations were compared and integrated with gravity and magnetics data in the region, which provide information on

Figure 3: Data processing sequence (see text for discussion).

Figure 4: Velocity model applied to V3618.49 line for conversion time to depth.

the structure and depth of the subducting oceanic crust and forearc basement in the region where their positions cannot be identified on seismic profiles.

DATA INTERPRETATION

General Overview

Reduced-scale images of the depth-converted seismic section and associated cross-section are presented in Figure 5 (a and b). The prism reaches a width of 80 to 85 km in this region, 40% of which is composed of the lower slope domain. This domain extends eastward from the frontal thrust at CDP 980 to CDP 1700, a distance of approximately 35 km, and reaches its shallowest water depth of 3600 m at CDP 1600. Numerous ramp anticlines overlie west-directed thrusts across the domain. As described by previous studies [Reed et al., 1992], the surface of the accretionary prism is rough and irregular with a prominent topographic feature marking the boundary between the lower and upper slope domains at CDP 1700.

The structure of the upper slope domain, located between CDP 1700 and CDP 2450, a distance of more than 37 km, is complicated and not as clearly resolved as that in the lower slope domain. The domain, covering approximately 45% of the prism, rises to a water depth of 1600 m. Several packages of east-dipping reflectors, of limited lateral extent, are observed in the domain and interpreted as multiple stacks of thrust sheets. West-dipping reflectors are also recognized along the upper slope domain near CDP 2030 and may represent deformation associated with backthrusting, possibly during the early stages of prism development. The boundary between the upper slope domain and the backthrust domain to the east is marked by a change from dominantly east-dipping to west-dipping reflectors.

Figure 5a: Depth-converted section of the V3618.49 seismic profile (CDP 800 to CDP 3500), associated magnetic (MAG) and free-air gravity anomalies (FAA), and line drawing interpretation. Locations of Figures 6, 8, 10, 11, 14, 15 and 16 are shown on the seismic profile.

Figure 5b: Depth-converted section of the V3618.49 seismic profile (CDP 3500 to CDP 6200), associated magnetic (MAG) and free-air gravity (FAA) anomalies, and line drawing interpretation. Locations of Figures 17, 18 and 19 are shown on the seismic profile.

The backthrust domain exhibits a stack of discontinuous, west-dipping, low-amplitude reflectors across a 10 to 12 km-wide region. East of the domain, the sea floor descends to a depth of 3700 m, where it joins the smooth, horizontal sea floor of the North Luzon Trough. The free-air gravity anomaly increases by only 25 mgal from the North Luzon Trough over the backthrust domain, even though the sea floor rises approximately 850 m, suggesting that the backthrust domain and eastern margin of the upper slope domain are composed of thick sequences of thrust-deformed sediments, at least as far west as CDP 2400.

The North Luzon Trough is an asymmetric forearc basin lying between the prism and the island arc, covering a distance of more than 40 km from CDP 2630 to CDP 3460. The basin-fill sequences in the trough thicken westward towards the rear of the prism, similar to the observations [Hirtzel, 1996] in regions to the north, and reach a thickness in excess of 2500 m at CDP 2760.

The surface of the island arc forms the east flank of the forearc basin in this region. This chain of seamounts and volcanic islands is characteristic of a typical island arc system, resulting in this area from the subduction of oceanic lithosphere of the South China Sea [Cardwell et al., 1980]. The arc reaches a water depth of 500 m at CDP 4170 and decreases eastward where it forms the basement beneath the Gagua basin, an intra-arc basin between CDP 4400 to CDP 5600. The eastern side of this basin is bounded by a basement high, the Gagua Ridge, which steps down eastward to the oceanic crust of the West Philippine basin.

Structure and Stratigraphy of the Manila Trench

South of 21°N, the outer slope of the Manila Trench, is composed of oceanic lithosphere of the South China Sea that is overlain by pelagic/hemipelagic sediments and turbidite deposits, the latter being derived from the Taiwan orogen to the north [Lewis and Hayes, 1984; Reed et al., 1992]. The regional structure and stratigraphy of the South China Sea basin have been described by Taylor and Hayes (1980) and, more recently, by Nissen and others (1995) and Hayes and others (1995). On line V3618.49, the smooth, horizontal sea floor in the South China Sea is underlain by a combination of strongly and weakly reflective, layered units (Fig. 6), which have been interpreted by Lewis and Hayes (1984, 1989) as pelagic and hemipelagic sediments. Directly overlying the top of the oceanic crust is a thin, poorly reflective layer of pelagic strata between 200 and 600 m-thick (0.15-0.4 sec), which, in turn, is overlain by a 300-700 m-thick (0.2-0.5 sec) unit of coherent, layered reflections associated with hemipelagic and turbidite strata.

Oceanic lithosphere in the South China Sea is believed to be late Oligocene to Miocene in age [Taylor and Hayes, 1980]. The surface of the crust is rough and irregular with many basement ridges and broad swells in the vicinity of line V3618.49. High amplitude crustal reflections can be seen to a depth of 2.8 seconds below the basement surface (depth of 5.5-6.5 km), suggesting a complicated history of crustal formation. Numerous normal faults that bound horst and graben structures, seamounts and volcanic ridges are observed west of the Manila Trench. With few exceptions, these features are buried beneath layers of pelagic and hemipelagic strata indicating that they originated either during or shortly after plate formation. Few of the normal faults offset sedimentary

Figure 6: Seismic profile across the Manila Trench showing turbidite and pelagic/hemipelagic sequences resting on the oceanic crust of the South China Sea.

units or the sea floor in the vicinity of line V3618.49, in contrast to observations along the outer trench slope to the south where recent normal faulting is associated with flexure of the subducting plate [Hayes and Lewis, 1984]. Magnetic anomaly maps published in Liu and others (1992) show several seamounts in the region, which together form a southeast-trending linear zone that extends across the Manila Trench and beneath the toe of the accretionary prism in the region of line V3618.49 (Fig. 7). The decreased number of recent offsets along normal faults in this region of the trench may reflect variations in elastic plate behavior in response to flexural bending of thickened oceanic crust during underthrusting of the prism.

Lower Slope Domain

The lower slope domain extends from CDP 980 to CDP 1700 on the seismic profile. At least 13 fold-and-thrust structures are identified within offscraped strata in this region, with six major fold-and-thrust structures observed between CDP 980 and 1350 (Fig. 8). Trench-fill sediments are offscraped along the frontal thrust, which offsets the sea floor at CDP 980. The frontal thrust extends downward to a subhorizontal decollement located at 5.3 km beneath the sea surface. Highly reflective units of offscraped trench deposits are deformed and separated by individual thrust faults, which underlie ramp anticlinal ridges at a spacing of 2.0–3.3 km. Stratigraphic thicknesses of offscraped units increase eastward, toward the interior of the prism, from approximately 400 m at the frontal thrust to 800 m at the sixth thrust. A backthrust is observed dipping westward at an angle of 60° from the sixth thrust. Fold amplitudes, amount of dip separation on underlying thrusts, and the dips of the

Figure 7: Regional magnetic anomaly map offshore southern Taiwan, modified from Liu et al., [1992] showing N-W trending seamount chain and location of the V3618.49 line.

Figure 8: Depth-converted section of the lower slope domain showing offscraped, underplated, and subducted sequences.

thrusts all increase to the east within offscraped strata of the lower slope domain. The frontal thrust has a dip of 22° and a dip separation of 100 m whereas the sixth thrust has a dip of 55° and 350 m of dip separation (Fig. 9). East of CDP 1350 the sea floor is rough, highly irregular, and cut by numerous channels or possibly by mud volcanoes, thereby reducing the number of coherent reflectors in this region. At least three ramp anticlines can be identified in the shallow offscraped section east of CDP 1460, with several kilometers of deformed strata underlying these structures and overlying the decollement and underlying oceanic crust (Fig. 10).

A 200 to 600 m-thick (0.15-0.4 sec) sedimentary unit, which overlies a coherent, high amplitude reflector associated with the top of the oceanic crust, is subducted beneath the frontal thrust (Fig. 8), similar to observations to the south by Hayes and Lewis (1984). The top of the oceanic crust dips eastward at $\sim 10^{\circ}$ and can be tracked from the frontal thrust eastward beneath the prism to at least CDP 1620, a distance of more than 30 km. The ramp of the frontal thrust connects with the roof thrust of a duplex structure at CDP 1100. The roof thrust of the duplex separates offscraped sediments from underplated units, and a second decollement, or floor thrust, separates underplated sediments from subducted sediments and the oceanic crust. The flat segment of the roof thrust extends eastward from the frontal thrust ramp as a horizontal, low amplitude seismic reflector at a depth of approximately 5.3 km (3.3 sec). The floor thrust is marked by a horizontal reflector at a depth of nearly 6.3 km (4.0 sec) that ramps upward at CDP 1160 to connect with the upper decollement at CDP 1100. This ramp marks the onset of sediment underplating in the form of a duplex structure composed of imbricated units, or horses, that dip approximately 22° eastward with respect to the floor

Figure 9: Graphs showing dip separation and thrust dip versus distance from the frontal thrust.

Figure 10: Seismic section across the boundary between the lower slope and upper slope domains.

thrust (Fig. 11). The complex structure of underplated strata makes it difficult to identify the exact number of horses within the duplex. A reflection associated with the fault tip from the floor thrust is observed at the CDP 1145 within the underthrust hemipelagic/pelagic strata at the base of the prism, indicating that duplex formation is currently active (Figs. 8 and 11)

A balanced cross section has been constructed across the western half of the domain in an attempt to reconstruct the initial geometry of the offscraped strata (Fig. 12) and estimate the amount of shortening represented by deformation in offscraped units. The result of this effort is a shortening estimate of 3.0 km in offscraped units between CDP 980 and CDP 1350. A plot of cumulative shortening in offscraped units within the first six major thrust sheets shows a linear increase in shortening with distance from the frontal thrust at CDP 980 (Fig. 13). There is no evidence of involvement of the oceanic basement in accretion or underplating at this point or anywhere beneath the lower slope domain. Instead, a 900 to 1000 m-thick (0.8 sec) layer of subducted sediment, along with the oceanic crust, can be identified beneath the duplex structure in the lower slope domain.

Structure of Boundary between Lower and Upper Slope Domains

The upper slope domain is separated from the lower slope domain by an 1800 m-high scarp at CDP 1700 (Fig. 10). The scarp has a westward slope of 11° and is underlain by a more than two km-thick section of gently east-dipping reflections, marking a stack of imbricated thrust sheets. This thrust stack is underlain by a low-angle, high amplitude reflection marking a thrust plane that begins at the base of the sea floor scarp near CDP 1700 and which can be tracked eastward to at least CDP 1850, a distance of 7.5 km.

Figure 11: Seismic section showing detailed structure of the lower slope domain with a duplex structure bounded by a roof thrust and a floor thrust.

Figure 12: Balanced cross-section of the lower slope domain based on the restoration of offscraped sedimentary unit (shaded).

Figure 13: Graphs showing shortening versus distance from the frontal thrust in the lower slope domain. Continuous line: observed data; dashed line: extrapolation through the entire lower slope domain.

The footwall of this thrust is composed of a coherent sequence of east-dipping reflectors that are part of the backlimb of the easternmost ramp anticline of the lower slope domain (Figs. 10 and 14). This structural geometry, which is herein recognized for the first time in this region, clearly shows that the boundary between the lower and upper slope domains is an east-dipping thrust, which has accommodated a significant component of intraprisim shortening, probably far in excess of any individual thrust in the lower slope domain.

Upper Slope Domain

The upper slope domain is composed of a broad bathymetric ridge between the lower slope domain and forearc basin. Seismic reflectors within the domain are discontinuous and of limited lateral extent, suggesting intense and possibly multi-stage deformation. Water-bottom multiple reflections are observed at 3.2 km-depth and at 4.8 km-depth in the region bounded by CDP 1850 and CDP 1950. In the same region, an anomalous seismic reflector is identified at a depth of 4.2 km within the prism (Fig 10). This reflector extends from a depth of 6 km at CDP 1750 to 5 km at CDP 1800. The concave-downward seismic structure has its highest point at a depth of 4.1 km. The region of this reflector also underlies regional anomalies in the free-air gravity and magnetics data, suggesting the presence of accreted igneous rocks beneath a portion of the upper slope domain (Fig. 14).

Backthrust Domain

The backthrust domain is located along the eastern margin of the accretionary prism, where the surface of the prism descends from a water depth of approximately 2000 m in the

Figure 14: Seismic section and associated geophysical data across portions of the lower and upper slope domains. Magnetic (MAG) and free-air gravity (FAA) anomalies are identified over an anomalous reflector.

upper slope domain to 3700 m near the boundary with the North Luzon Trough. The structure of the domain is characterized by a series of ridges that are separated by east-directed thrusts at CDP 2400, 2470, 2530 and 2620 (Fig. 15).

The structure of the region is complicated with tectonic wedging and backthrusting likely at the rear of the prism [Reed et al., 1992]. The backthrust system consists of a west-directed roof thrust below upturned North Luzon Trough strata and an east-directed floor thrust along the top of the island arc basement. The two thrusts outline a tectonic wedge that propagates eastward above the basement surface of the forearc. The island arc basement is characterized by a high-amplitude seismic reflector, which extends westward beneath the prism. The high magnetic anomaly of the island arc crust can be traced westward to CDP 2350 (Fig. 5), whereas the free-air gravity anomaly increases by only 25 mgal across the region. Two blind thrust faults are clearly defined within the forearc basin strata from CDP 2700 to 2740 (Fig. 16). The major thrust dips 35 °- 45° westward at CDP 2740 and cuts upward through horizontal forearc basin strata to a depth of 5.0 km. This fault exhibits evidence of growth faulting with approximately 200 m of dip separation along the fault plane in the lower sedimentary unit, but with separation decreasing significantly in the overlying units. The thicknesses of seismic sequences decrease westward across the fault, possibly indicating a component of oblique slip along the thrust.

North Luzon Trough: Forearc Basin

The North Luzon Trough contains more than 2500 m of undeformed turbidites. These strata compose a westward-thickening wedge of horizontal, coherent seismic layers

Figure 15: Seismic section across the backthrust domain.

Figure 16: Seismic section across the North Luzon Trough adjacent to the accretionary prism. Blind thrusts rise from the island arc basement.

(Fig. 16) that are believed to be of Miocene to recent age [Lewis and Hayes, 1984]. This type of forearc basin is classified as a terraced, ponded, and unfilled forearc by Dickinson and Seely (1979). The sedimentary units lap onto the volcanic massif of the North Luzon Ridge, which forms the east flank of the basin. Forearc basin deposits are observed as sheet and wedge-shaped seismic sequences that were likely deposited by sediment gravity flows from the island arc and the Taiwan orogen. Mass wasting along the rear of the prism also contributes debris to the forearc basin [Hirtzel, 1996]. The strata are upturned and decrease in thickness as they lap onto the rear flank of the prism, indicating uplift of the accretionary prism during sedimentation. The internal reflector geometry of the basin shows that the uplift of the prism has been contemporaneous with basin deposition. However, the accretionary prism has remained higher than the horizontal forearc basin floor, indicating that the rate of sediment supply to the forearc basin has been less than the rate of uplift of the prism throughout the history of the forearc region.

North Luzon Ridge: Island Arc

The North Luzon Ridge is composed of Miocene to Recent volcanic islands of andesitic breccia, basalt, and tuff [Huang et al., 1992]. Radiometric dating of the volcanic rocks from North Luzon Ridge has produced K-Ar ages of 4-5 Ma and older [Richard et al., 1986; Ho, 1988]. The cessation of volcanic activity in this region has presumably resulted from the onset of collision to the north between the Eurasian and Philippine Sea plates. In seismic profile V3618.49, the rough surface of the island arc exhibits a high amplitude reflection; normal faults along the western slope of the ridge offset sedimentary strata of

strata of slope apron deposits (Fig. 17). Also, a high-angle fault at CDP 3870, within the intra-arc basin, exhibits variable stratigraphic separations that can be explained by strike-slip displacement. The ridge reaches its highest point at CDP 4170 and gradually increases in water depth toward the east where it forms the structural basement of the Gagua basin (Fig. 18) between CDP 4300 and CDP 5700. The east flank of this basin is formed by the Gagua Ridge (Fig. 5). Sedimentary units lap onto the rough basement surface of the ridge near CDP 5050. In contrast, deformation is widespread throughout the western part of the basin, where normal, reverse, and strike-slip faults are observed. Normal faults in the arc basement bound grabens and cut through basin strata that have accumulated in a depression in the sea floor between CDP 4520 and 4570 (Fig. 19). Between CDP 4750 and 4950, the sea floor rises to a water depth of 2000 m, where a series of high-angle reverse faults are observed. These faults appear to merge into a narrow zone of deformation in the arc basement, resembling a positive flower structure within a transpressional system (Fig. 19).

Figure 17: Seismic section across the western slope of the North Luzon Ridge showing basin geometry and faulting.

Figure 18: Seismic section across the Gagua intra-arc basin along the eastern slope of the North Luzon Ridge.

Figure 19: Seismic section showing detailed structure in the Gagua intra-arc basin.

DISCUSSION

The improved seismic image of the V3618.49 line, produced by F-K and F-D migrations, has greatly expanded and modified aspects of the earlier interpretations of the forearc structure along the Manila Trench between Taiwan and the Philippines. New insights are provided into the structure, stratigraphic configuration, and accretionary processes that have formed the lower and upper slope domains of the accretionary prism. Evidence of tectonic wedging has been identified at the rear of the prism and within the forearc basin and a region of transpressional deformation has been recognized within the North Luzon Ridge.

Shortening in the Lower Slope Domain

The amount of shortening in accreted strata of the lower slope domain can be determined from an estimate of the volume reduction due to sediment dewatering and the results of the balanced cross section analysis. Shortening in accreted sediments is initially caused by fluid escape from pore spaces before and during offscraping. Studies of horizontal shortening within sediments at the toe of the Nankai accretionary prism have estimated that fluid expulsion accounts for 30% to 70% shortening [Morgan and Karig, 1994, 1995]. In the case of the Taiwan prism, the width of the lower slope domain in the vicinity of line V3618.49 is 36 km. If the midpoint (50%) of the estimated range of shortening by fluid escape in the Nankai prism is applied to the lower slope domain of the Taiwan prism, then fluid escape may account for as much as 36 km of shortening in the domain. Balanced cross-section analysis across the first six major thrust faults within the lower slope domain yields

an additional 3 km of shortening (Fig. 12). Extrapolating the latter value across the entire domain produces 6.7 km of shortening due to thrusting and folding (Fig. 13). The lower slope domain may, therefore, have experienced 42.7 km of shortening during its development, 36 km by fluid escape from pore spaces within offscraped sediments and 6.7 km through folding and faulting.

Eurasian-Philippine Sea plate convergence is oblique to the Manila Trench in the region [Seno, 1987] with the component of convergence in the plane of the cross-section estimated to be 61 km/my at 270° , the east-west direction of the seismic profile. The 42.7 km of shortening estimated within the lower slope domain is small compared to that expected from rates of plate convergence. That is, this amount of shortening could have taken place in as little as 0.7 Ma (e.g. 42.7 km divided by 61.0 km/my). Consequently, the lower slope domain is likely to be a relatively young feature of the prism. Additional shortening may be taken up elsewhere in the forearc-arc system, such as along the boundary between the lower and upper slope domains, at the rear of the prism, or within the island arc, thereby increasing the age estimated for the lower slope domain.

Implications of the Underplating Process

The cross section of the lower slope domain between the sea floor and the underthrust oceanic crust is composed of about 50% offscraped strata, 25% underplated strata and 25% subducted strata (Fig. 8). Uplift of the prism is caused by offscraping at the toe of the prism and underplating, through duplex formation, beneath the lower slope domain. Hayes and Lewis (1984) used a steady-state accretion model, which combined the

thickness of offscraped strata, plate convergence rate and cross-sectional area of the prism, to estimate the age of the prism at 10 Ma. If the past underplating contribution was similar to that observed today, 33% of total accreted strata (Fig. 8), then the age of the prism may be significantly younger than previously believed.

Recent studies on the Alaskan accretionary prism by Gutscher et al. (1998) show that the growth of prisms can be episodic, with phases of frontal accretion by imbricate thrusting alternating with episodes of underplating beneath the prism. These studies build on the Coulomb wedge theory presented by Davis et al. (1983), in that the growth of the prism is controlled by the critical taper angle, which is a function of the material strength and basal friction along the decollement. Large taper angles, produced by steep surface slopes, may stimulate frontal accretion and thrust front migration by offscraping, whereas small, subcritical taper angles resulting from low surface slopes may initiate uplift and thickening of the prism through underplating. Thus, underplating beneath the prism in the region of study is likely to be a process to regain the critical taper, which is very small, $\sim 3^\circ$, compared to the $\sim 10^\circ$ observed in the upper slope domain or in other well-characterized prisms. It is suggested that the current phase of underplating may have followed an episode of rapid westward migration of the frontal thrust during sediment offscraping, thus forming a relatively young lower slope domain.

Boundary Between the Lower and Upper Slope Domains

The identification of a low-angle fault plane reflection at the toe of the upper slope domain supports the earlier interpretation of an out-of-sequence thrust fault system, which

has produced the significant uplift of the interior of the prism [Reed et al., 1992]. This fault can also be interpreted as a "top decollement", or a scar formed as a seamount subducts beneath a prism [Lallemand et al., 1994]. Seamount subduction results in uplift of the prism by active compressive indentation in the thrust front, followed by subsidence of the prism along the rear of the seamount as it passes beneath the prism (Fig. 20). A new decollement is formed in the wake of the subducting seamount, followed by trenchward propagation of the frontal thrust and generation of a new segment of the accretionary prism, the lower slope domain in this case. Evidence of an irregular basement surface can be found in the stratigraphic geometry of accreted sediments. Offscraped sedimentary units increase in thickness toward the interior of the prism (Figs. 6 and 8) and likely developed over a structural basin bounded on the west by a basement high, possibly associated with one of many seamounts in this area. Moreover, seamount subduction in this area is supported by geophysical data collected along the V3618.49 seismic line, including the identification of an anomalous reflector beneath the upper slope domain, an increase in the free-air gravity anomaly of 35 mgals over the proposed subducted seamount, and a series of magnetic anomalies identified from the regional magnetic map produced by Liu et al. (1992) (Fig. 7).

Tectonic Wedging at the Rear of the Prism

The blind thrusts observed within forearc basin strata provide evidence for tectonic wedging or backthrusting along the rear of the prism as proposed by Reed et al (1992). A forward-dipping backstop model has been proposed at the rear of the prism, where a tectonic wedge composed of material of the accretionary prism is bounded at its base by the west-

Figure 20: Sketch of the seamount subduction process beneath an accretionary prism with formation of a top decollement (from Lallemand et al., 1994); 1) uplift and shortening after seamount is subducted beneath the prism, decollement steps upward, and a new prism segment develops in the wake of the seamount; 2) top decollement forms on the top of the seamount, decollement steps down to the basement; 3) seamount subducts far beneath the prism, top decollement may be seen as a fault plane at the boundary between the old segment of the prism and the newly formed portion in the toe region.

dipping thrust surface along the interface with the island arc basement and along its top by an east-dipping roof thrust (Fig. 15). The amount of shortening along this structure appears to be small, and is probably less than 2 km [Chi et al., 1998]. Though present in the region of subduction, backthrusting along the rear of the prism is limited and does not result in significant shortening until transitional crust of the Chinese continental margin enters the subduction zone. At this point, a significant component of plate convergence is transferred to the rear of the prism, resulting in the closure at the forearc basin through significant shortening along the backthrust.

Strike-Slip Faulting within North Luzon Ridge

Deformation within the North Luzon Ridge has resulted from the convergence between the Eurasian plate and the Philippine Sea plate that is oblique to the plate boundary along the Manila Trench. As first described by Lewis and Hayes (1989), the present plate boundary configuration between Luzon and Taiwan, on both the eastern and western flanks of the North Luzon Ridge, represents a transitional and short-lived boundary between the two plates. Deformation is complex, consisting of crustal thickening through thrust faulting, normal faulting, and lateral migration of crustal blocks along strike-slip faults in a region of "non rigid" plate behavior.

Along the western slope of the North Luzon Ridge, deformation by strike-slip faulting appears to be minor and localized within small sedimentary basins. However, along the eastern slope, significant deformation occurs within the Gagua intra-arc basin. This basin extends approximately 70 km eastward from CDP 4300 to CDP 5700 and is cut by an

upward-branching fault system, which is interpreted to result from transpressional strike-slip faulting within the island arc (Fig. 19). The trend and extent of this fault system cannot be determined solely from the seismic data in this study and detailed bathymetric data are not currently available in the area. The strike-slip structures, which are observed on both the western and eastern flanks of the island arc, likely accommodate a portion of the lateral component of oblique plate convergence in the region. Thus, the development of the intra-arc basins in the region is not solely the product of arc-continent collision as inferred by Huang et al., (1992).

CONCLUSIONS

The lower slope domain has formed by sediment offscraping and underplating. Underplated material is accreted along the base of the prism within a duplex structure. The age of the prism is likely to be younger than 10 Ma, the age estimated by previous studies, because of the additional contribution of underplated material to the growth of the prism. The amount of shortening in offscraped strata of the lower slope domain is small compared to the rate of convergence, suggesting a very young age (less than 0.7 Ma) for the domain or that a significant component of plate convergence is accommodated elsewhere in the forearc-arc system.

A fault plane reflector marks the boundary between the lower and upper slope domains. This feature supports the hypothesis that out-of-sequence thrust faulting has caused significant uplift of the upper slope domain. This fault plane reflector also may be interpreted as a top decollement produced by seamount subduction beneath the accretionary prism. Following an episode of seamount subduction, the frontal thrust propagated rapidly westward within an eastward- thickening wedge of basin strata. The lower slope domain and its small wedge taper were formed rapidly above a weak decollement during this period. Underplating of underthrust sediments may be in response to the instability of the small taper angle within the recently formed lower slope domain.

Tectonic wedging or backthrusting is the main deformation process within the forearc basin at the rear of the prism, although it produces only a small amount of shortening. In the

region of collision, to the north, the forearc basin has closed and this process accommodates more than half of the plate convergence in this region.

The observed strike-slip fault systems on both sides of the North Luzon Ridge are consistent with previous descriptions of the plate boundary configuration between Taiwan and Luzon [Lewis and Hayes, 1989]. Deformation in this region results in crustal thickening through reverse and thrust faulting with the lateral migration of crustal blocks along strike-slip faults accommodating a component of the relative motion between the Philippine Sea plate and the Eurasian plate.

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