

Oblique subduction of the Gagua Ridge beneath the Ryukyu accretionary wedge system: Insights from marine observations and sandbox experiments

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Abstract

The Gagua Ridge, carried by the Philippine Sea Plate, is subducting obliquely beneath the southernmost Ryukyu Margin. Bathymetric swath-mapping, performed during the ACT survey (Active Collision in Taiwan), indicates that, due to the high obliquity of plate convergence, slip partitioning occurs within the Ryukyu accretionary wedge. A transcurrent fault, trending N95° E, is observed at the rear of the accretionary wedge. Evidence of right lateral motion along this shear zone, called the Yaeyama Fault, suggests that it accommodates part of the lateral component of the oblique convergence. The subduction of the ridge disturbs this tectonic setting and significantly deforms the Ryukyu Margin. The ridge strongly indents the front of the accretionary wedge and uplifts part of the forearc basin. In the frontal part of the margin, directly in the axis of the ridge, localized transpressive and transtensional structures can be observed superimposed on the uplifted accretionary complex. As shown by sandbox experiments, these N330° E to N30° E trending fractures result from the increasing compressional stress induced by the subduction of the ridge. Analog experiments have also shown that the reentrant associated with oblique ridge subduction exhibits a specific shape that can be correlated with the relative plate motion azimuth.

These data, together with the study of the margin deformation, the uplift of the forearc basin and geodetic data, show that the subduction of the Gagua Ridge beneath the accretionary wedge occurs along an azimuth which is about 20° less oblique than the convergence between the PSP and the Ryukyu Arc. Taking into account the opening of the Okinawa backarc basin and partitioning at the rear of the accretionary wedge, convergence between the ridge and the overriding accretionary wedge appears to be close to N345° E and thus, occurs at a rate close to 9 cm yr⁻¹. As a result, we estimate that a motion of 3.7 cm yr⁻¹ ± 0.7 cm should be absorbed along the transcurrent fault. Based on these assumptions, the plate tectonic reconstruction reveals that the subducted segment of the Gagua Ridge, associated with the observable margin deformations, could have started subducting less than 1 m.y. ago.

Introduction

West of the Ryukyu Arc/trench system, the Luzon Arc, carried by the Philippine Sea Plate (PSP), impacts the south China Block (SCB) passive margin causing uplift of the Taiwan Range (Figure 1). The deformation of the Chinese passive margin by the Luzon Arc indenter has produced a westward bend of the southern Ryukyu Arc (Letouzey and Kimura, 1985; Sibuet et al., 1987). Consequently, east of Taiwan, the sub-

duction of the PSP beneath the Ryukyu Arc occurs at an oblique angle of about 40° according to recent geodetic data (Lallemand et Liu, 1998). Oblique subduction along convergent margins has already been discussed in the Central Aleutian Arc (Scholl et al., 1983; Lewis et al., 1988; Ryan and Scholl, 1989), along the New-Zealand Hikurangi margin (Collot and Davy, 1998) and also in western Indonesia (Diament et al., 1992; Malod et al. 1993; Bellier and Sébrier, 1995). In such framework strain partitioning and lat-

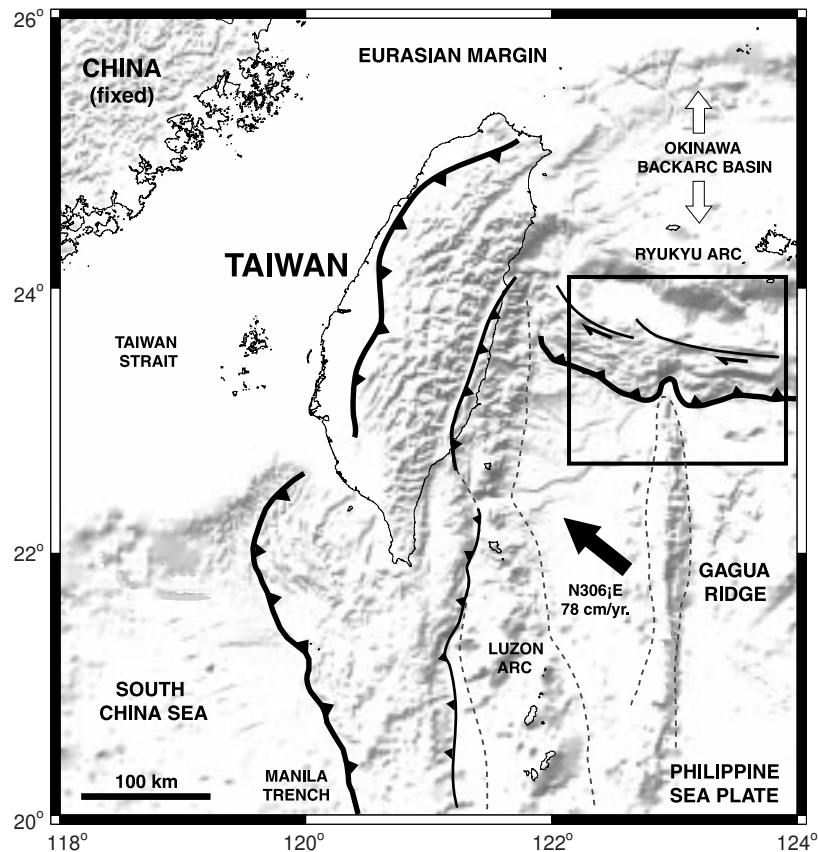


Figure 1. General tectonic setting around Taiwan and location of the study area. Black arrow corresponds to displacement vector of the Philippine Sea Plate with respect to the South China Block (SCB). White arrow represent the opening of the Okinawa back-arc basin. The rectangular box delimits the survey area.

eral migration of the forearc along one or more major strike-slip faults associated with oblique reverse faults could be expected within the overriding plate (Fitch, 1972; McCaffrey, 1992).

In the studied area, the oceanic crust of the PSP is characterized by an important basement high trending N–S, called the Gagua Ridge, which intersect the Ryukyu Trench near longitude 123° E (Figure 1). Previous works (Ballance et al., 1989; Collot et al., 1989; Fisher et al., 1991; Lallemand et al., 1990; von Huene and Scholl, 1991; von Huene et al., 1995; Moore et al., 1995; Dominguez et al., 1998; Park et al., 1999) have clearly shown that the subduction of such oceanic feature greatly influence the tectonic evolution and seismicity of the overriding plate margin.

The western termination of the Ryukyu arc-trench system offers, then, an ideal area to investigate the interaction of a ridge subduction with the forearc in such an oblique convergent tectonic setting.

Data acquisition

During the ACT cruise (Active Collision in Taiwan), high resolution multibeam bathymetry (Simrad EM12) was recorded by the French R/V *L'Atalante* at the western end of the Ryukyu Margin and trench. As a result, most of the survey area now has 100% swath-mapping coverage except near the Yaeyama Japanese islands located in the north of the mapped area.

The swath-bathymetric data have been processed to produce 2D and 3D shaded hill relief images in order to study the detailed morphology of the studied area (resolution is about 50 m to 150 m depending on the water depth). Along the same ship tracks, multi-channel seismic reflection data (6 channel streamer) were recorded to image the internal structure of the accretionary wedge and the forearc basins. Nine N–S and one E–W seismic profiles were acquired across the Ryukyu Margin (Figure 2). Simultaneously, mag-

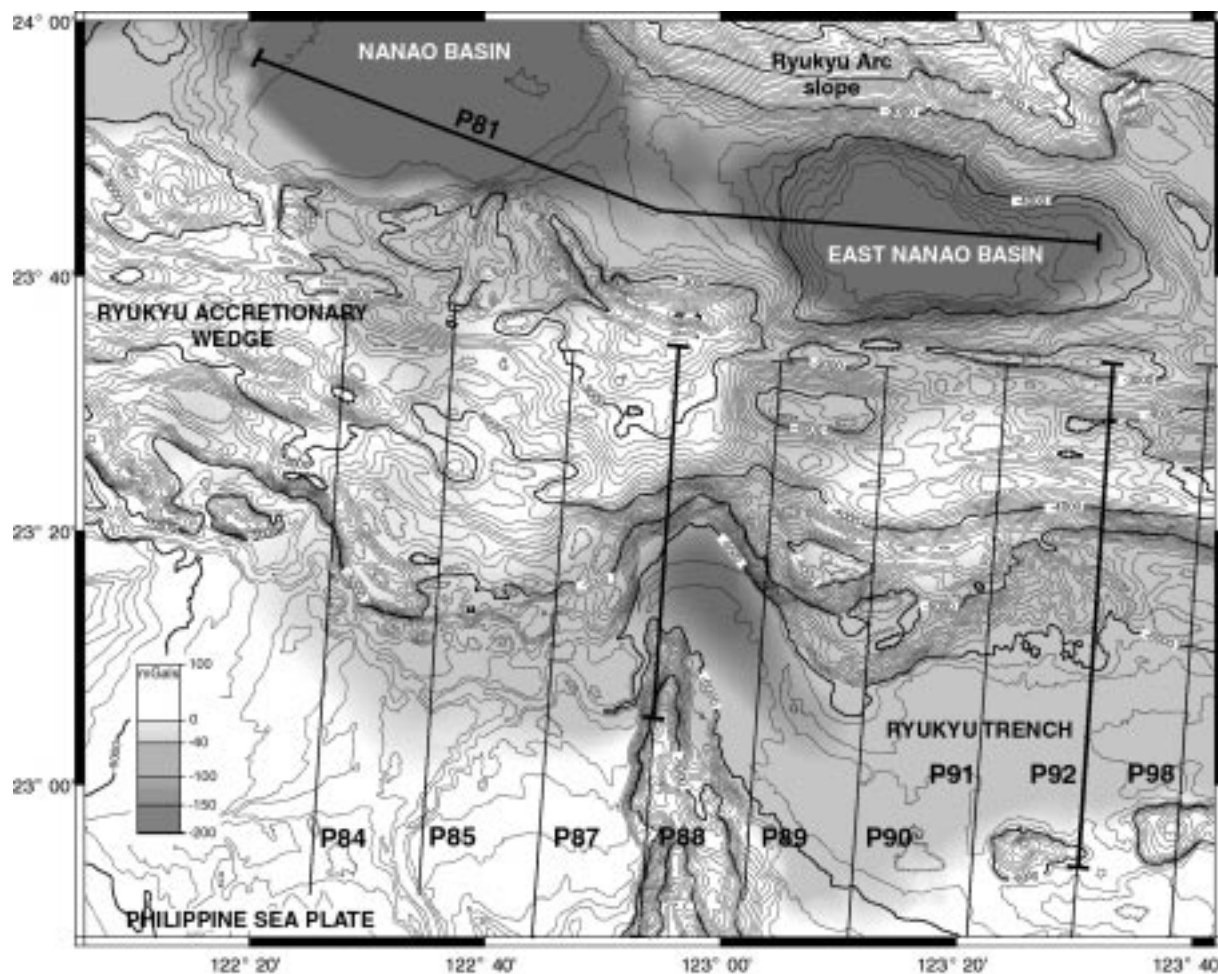


Figure 2. Multibeam bathymetric map of the survey area showing location of the seismic profiles recorded during ACT cruise (Bold lines correspond to the seismic profiles presented in this paper) and preliminary gravimetric map (Free air anomaly). The two negatives anomalies in the north of the map correspond to the sediments of the Nanao forearc basins. A third significant anomaly, observed at the intersection between the Gagua Ridge and the trench axis, is associated with a local interruption of the Gagua Ridge. The positive anomaly links with the subducted portion of the Gagua Ridge is also observed in the middle slope of the Ryukyu accretionary wedge.

netic and gravimetric data were recorded along the ship tracks to complete the geophysical survey of the oceanic crust and the Ryukyu Margin. Part of these data are presented in this paper to outline the geological structures of the Ryukyu frontal margin (Hsu et al., 1996, 1998). The intensity of the free air anomaly has been superimposed on the bathymetric map in Figure 2.

Tectonic setting of the western end of the Ryukyu Arc-trench system

The PSP has been subducting beneath the South China margin since, at least, Late Cretaceous (Le Pichon

et al., 1985). The present motion is 78 cm yr^{-1} along $N306^\circ \text{ E}$ azimuth (Seno et al., 1993; corrected by Heki, 1996). The studied area can be divided into four main structural domains from south to north (Figures 2 and 3). The PSP, the Ryukyu accretionary wedge and trench, the forearc basin (Nanao basin and East Nanao basin), and the Ryukyu arc slope.

In the survey area, the PSP consists of an Eocene oceanic crust (Hilde and Lee, 1984). The main topographic feature is the Gagua Ridge (350 km long), trending N–S, with an average height above surrounding seafloor of about 2500 m. The ridge, probably originated from a deformed Eocene fracture zone (Deschamps et al., 1997), divides the PSP into two basins,

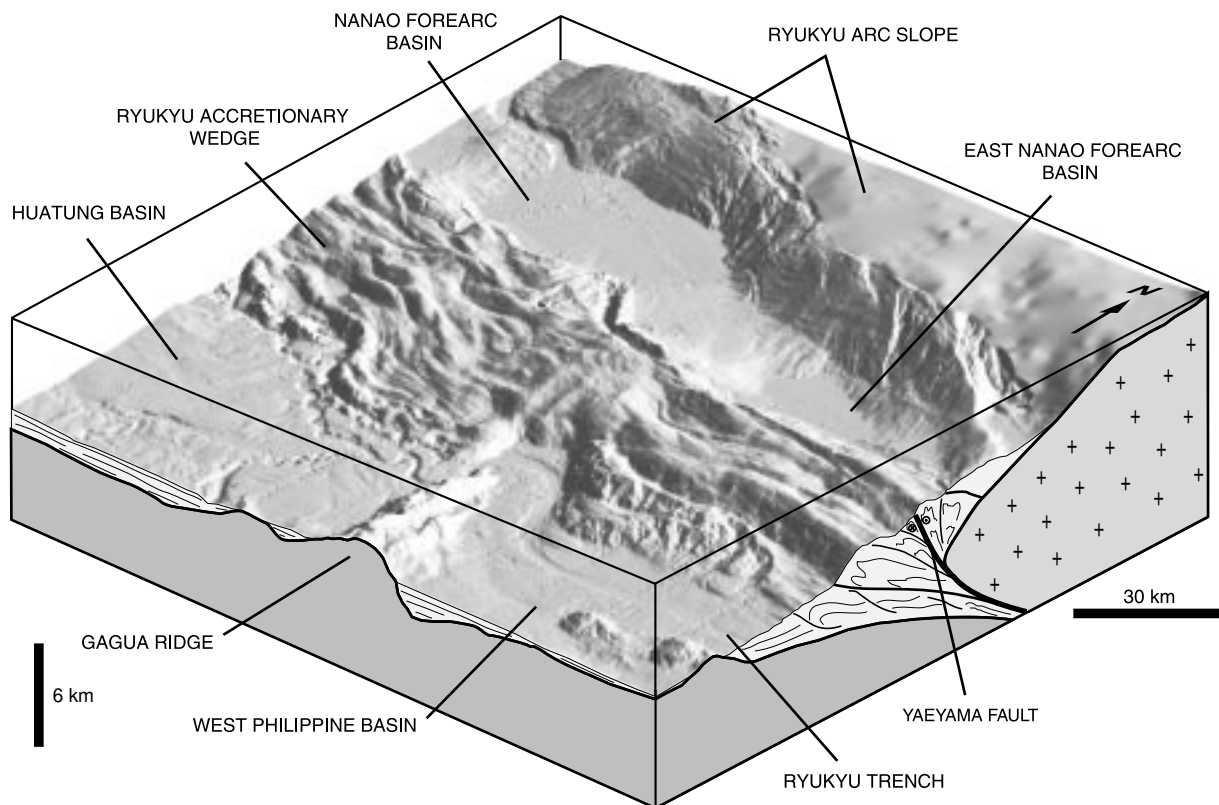


Figure 3. 3D shaded view of the survey area, based on composite grid of ACT swathbathymetric data and processed using GMT software (Wessel and Smith, 1991). The studied area can be divided into four main structural units: The Philippine Sea Plate (PSP), The Ryukyu accretionary wedge, the Nanao forearc basins and the Ryukyu arc slope.

called the Huatung Basin to the west and the West Philippine Basin to the east. East of the Gagua Ridge, an important basement high, intruded by several magnetic seamounts and affected by $N130^{\circ} E$ normal faults, is observed.

The Ryukyu Trench, trending E–W, has an average 6000 m depth. The trenchfill sediments are probably mainly derived from the erosion of the Taiwan mountain range and its thickness is roughly constant, about 1600 m to 2000 m (1.4 to 1.6 s TWT).

The morphology of the deformation front and the middle slope of the Ryukyu Margin differs from east to west. In the eastern part of the study area, seismic data (Figure 4) reveal that the frontal margin corresponds to an accretionary prism composed of imbricated thrust units trending E–W. The folding of the trench-fill layers is clearly observable in the seismic profiles and indicates active frontal accretion. In the lower slope of the Ryukyu Margin, a very large and steep ridge, trending E–W, is observed (Figures 2 and 3). At the base of this ridge, seismic profiles show a low dip-

ping detachment as well as some scattered reflectors, dipping gently to the north in its upper part (Figure 3). Based on these observations, we interpret this structure as a major landward dipping out-of-sequence thrust (Lallemand et al., 1999).

On the upper part of the margin a linear fault, at least 150 km long and parallel to the trench, is observed (Figures 2 and 3). This shear zone is interpreted as a major right lateral strike slip fault (Lallemand et al., 1999), comparable to the Mentawai fault in the Sumatran margin (Diament et al., 1992). Since no other transcurrent faults are observed in the forearc basin or in the Ryukyu Arc, this shear zone, hereafter called the Yaeyama Fault, probably accommodates a significant part of the oblique convergence between the Ryukyu accretionary wedge and the PSP.

In the central part of the studied area, a very broad reentrant in the deformation front, is observed in the axis of the Gagua Ridge. It is bounded to the north by a very steep slope, and laterally by several imbricate thrusts. Landward of this reentrant, a wide uplifted

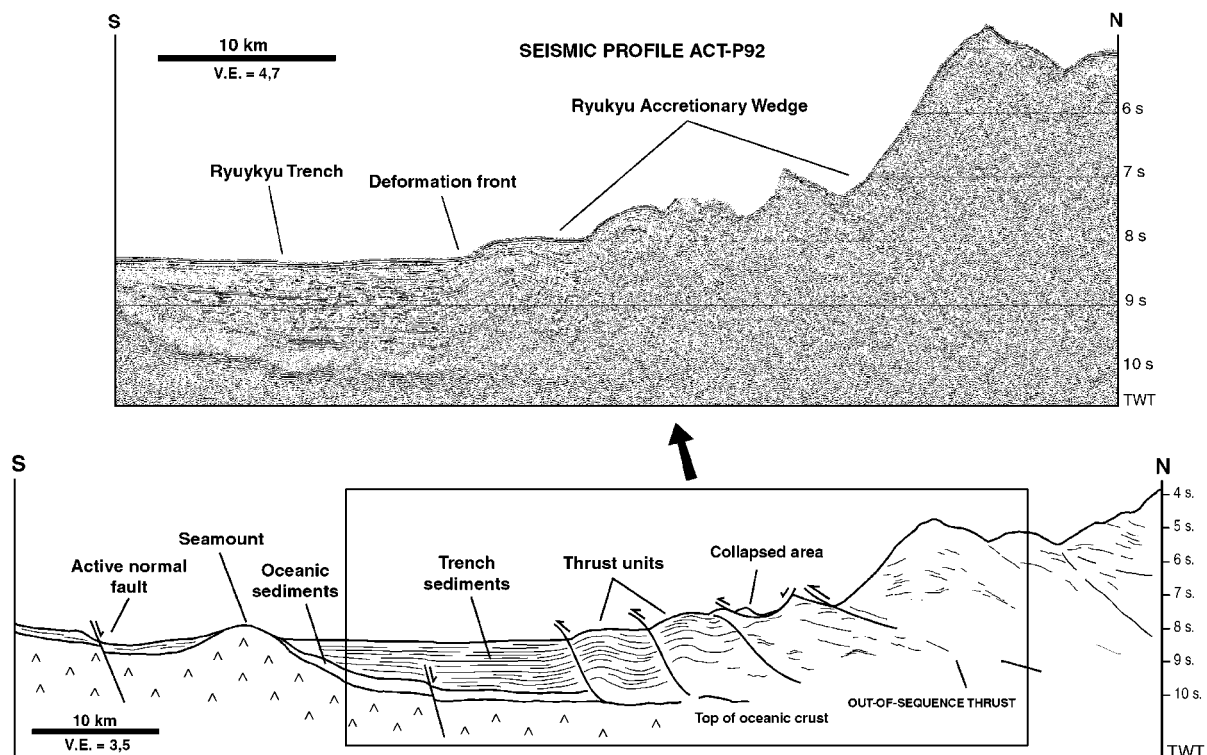


Figure 4. Seismic time migrated profile P92 and line drawing (see location on Figure 2) showing the internal structure of the Ryukyu Margin, east of the Gagua Ridge. The thick trenchfill and the frontal thrust units are well imaged. The very steep E-W ridge, interpreted as an out-of sequence thrust, contains some landward dipping reflectors.

area, characterized by a very disrupted morphology, is observed, suggesting recent deformation and uplift of this region.

In the western part of the Ryukyu Margin, the frontal part of the Ryukyu accretionary wedge consists of many sinuous transverse ridges, trending roughly N300° E (Figures 2 and 3). The morphology of these ridges suggests stretching in the direction of convergence, as demonstrated by their sigmoidal shape and the numerous bathymetric highs and lows interpreted as transpressive and transtensive structures trending N300° E.

The middle slope of the Ryukyu Margin is characterized by 30–35 km wide forearc Nanao basins (Figures 2 and 3). A bathymetric high, directly in the axis of the Gagua Ridge, separates the Nanao Basins into two morphotectonic basins, the Nanao Basin s.s. and the East Nanao Basin.

The Ryukyu Arc basement is composed of Cretaceous metamorphic rocks (Kizaki, 1986) and provides the consolidated backstop against which the

offscraped oceanic sediments are accreted (Figures 2 and 3).

In the survey area, the Ryukyu arc exhibits a highly tectonized structure. Swath-bathymetric data reveal that the whole arc slope is affected by a dense fracture network.

Structural analysis of the Ryukyu Margin deformation associated with the Gagua ridge subduction

The indentation of the inner trench slope, the intense deformation of the Ryukyu accretionary wedge and the broad uplift of the Nanao forearc basins lead to the conclusion that a pronounced topographic high of the PSP subducts beneath the Ryukyu margin (Figures 2 and 3). These major deformational features are all aligned in the axis of the Gagua Ridge, trending N–S, and suggest that a prolongation of this ridge is presently buried beneath the Ryukyu Margin. However, as revealed by the swathmapping bathymetric data, there is no expression of the ridge observable at

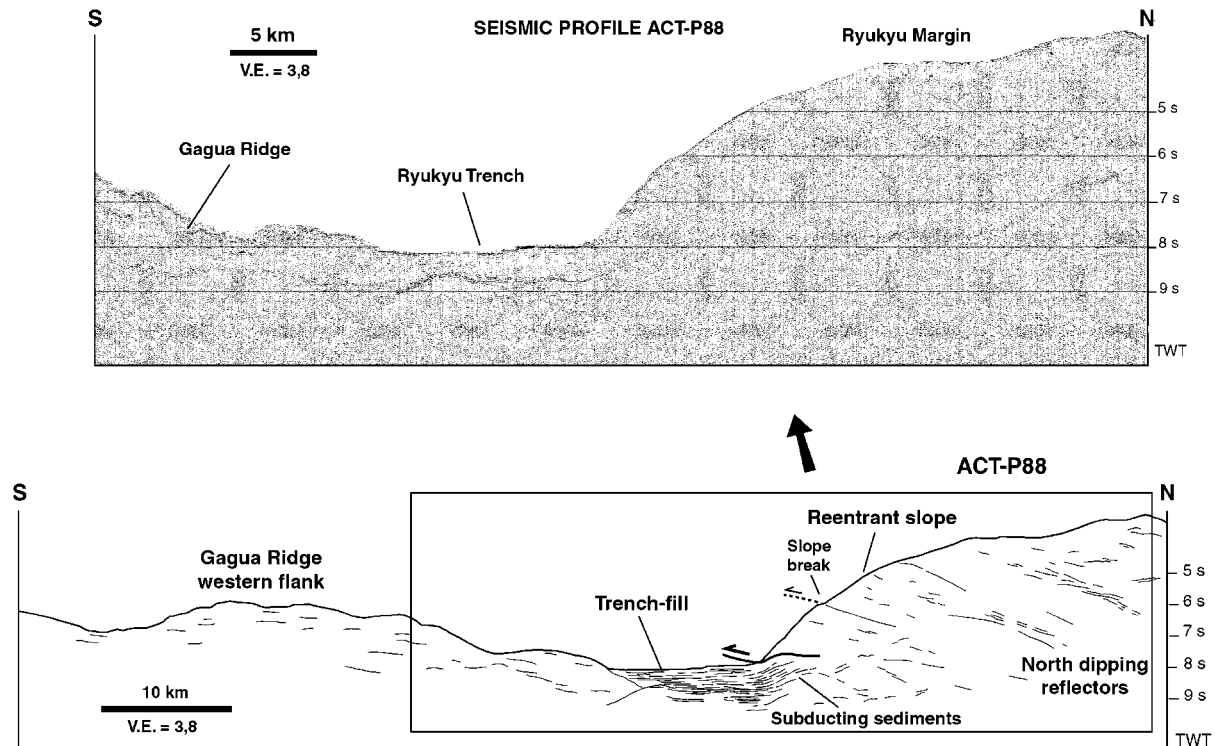


Figure 5. Seismic time migrated profile P88 showing the internal structure of the Ryukyu Margin near the axis of the Gagua Ridge. The whole trenchfill sequence appears to subduct beneath the frontal margin without significant deformation. Its thickness, about 1000 m (1 to 2 s TWT) suggests that, in this area, the ridge is only represented by a very small oceanic basement high.

the trench axis. Furthermore, a low of -140 mgal is observed in the free air anomaly at the ridge/trench intersection (Figure 2). The analysis of seismic profiles show that the height of the ridge and its width progressively decrease northward, even taking into account the bending of the subducting plate and the infill of the trench. At the intersection between the Gagua Ridge and the frontal margin, seismic profile P88 shows that 1 s TWT (at least 1000 m) of sediments fill the trench (Figure 5). Thus, in this area, the Gagua Ridge consists only of a small basement high, less than 500 m in height with respect to the surrounding oceanic crust.

The Ryukyu accretionary wedge and the reentrant area

The margin reentrant located in the axis of the ridge is 23 km wide and affects the margin over 21 km along strike (Figure 6). Its dimensions suggest that the subducted oceanic feature, presently buried beneath the Ryukyu Margin, could be comparable in size to the part of the Gagua Ridge lying on the Philippine Sea Plate (about 2000 m high and 20 to 25 km width). In the reentrant area, the frontal margin shows a very

steep slope (up to 20°) with a small bench in its middle part (Figures 5 and 6). Despite this overcritical slope, in terms of Coulomb behavior (Davis et al., 1983), there is no evidence of large mass wasting at its base. The morphology of the trench, in this region, is very smooth and slightly eroded by a channel that flows toward the East in the Ryukyu Trench. Along seismic profile 88, there is no evidence of disruption of the trenchfill in the reentrant area (Figure 5). The whole sequence of oceanic sediments appears to subduct beneath the frontal part of the Ryukyu accretionary wedge without observable deformation.

The margin reentrant related with the Gagua Ridge subduction exhibits a pronounced asymmetrical shape (Figure 6):

- The western boundary of the reentrant trends N–S, parallel to the Gagua Ridge axis. In this region, the morphology of the frontal margin suggests recent deformation and uplift related with the Gagua Ridge subduction, as demonstrated by NE–SW folds superimposed on the frontal thrust units (Figure 6).
- The eastern flank boundary of the reentrant is composed of two large frontal thrust units curved land-

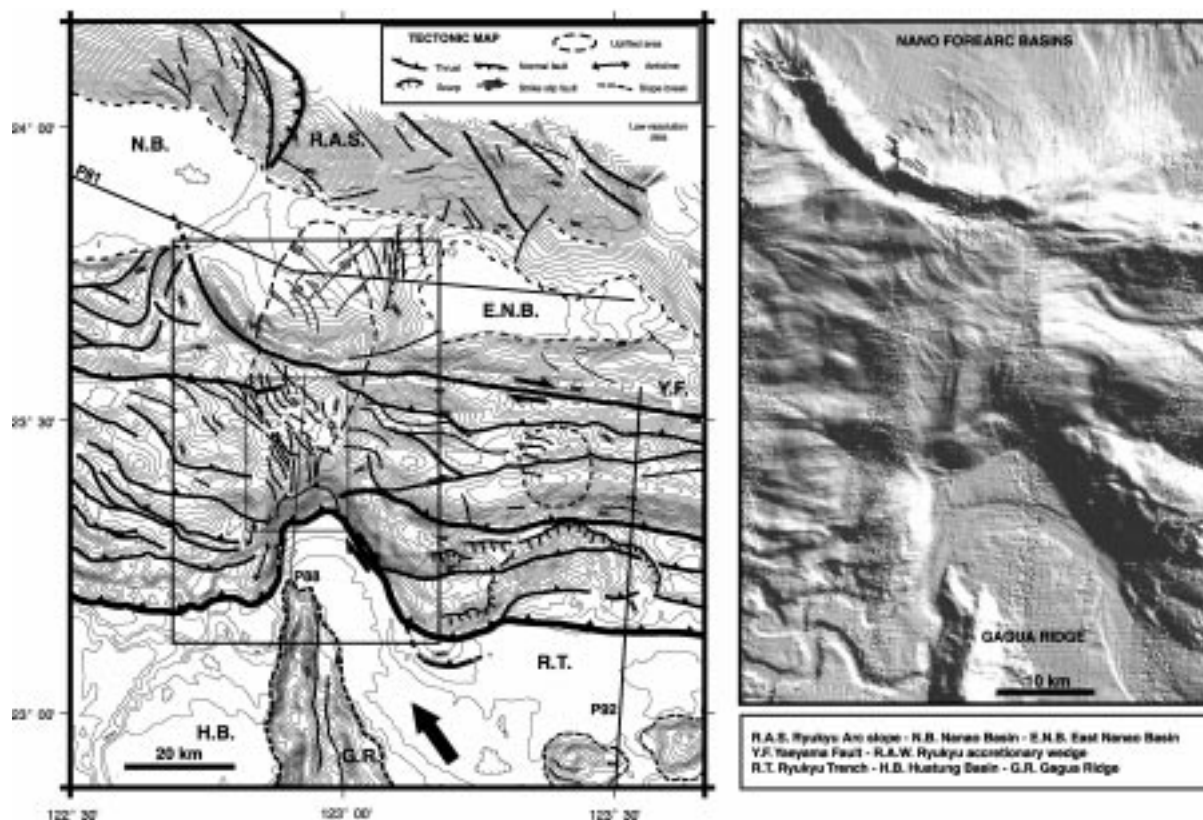


Figure 6. General tectonic map of the study area and 2D shaded view of the reentrant area. Black arrow indicates the relative convergence between the PSP and the Ryukyu Arc, taking into account the opening of the Okinawa back-arc basin. The rectangular box shows the EM12d imagery data used in the study of the reentrant area. The diverging fault network, generated by the subduction of a segment of the Gagua Ridge, is observable superimposed on the thrusts units of the Ryukyu accretionary wedge. The eastern part of the frontal margin reentrant appears to be parallel to the PSP/Ryukyu Arc convergence azimuth.

ward. Their very large size, compared to those located west of the reentrant, are related to a thicker trench-fill filling a narrow trough trending N–S, east Gagua. In the reentrant zone, these two thrust units join together to form a single slope break with a common base trending linearly N324° E (Figure 6).

Previous studies dealing with seamount subduction (Collot and Fisher, 1989; Lallemand et al., 1990; 1994; Dominguez et al., 1994, 1998, in press), have shown that the reentrant shape is controlled by spacial variations of the basal décollement geometry associated with the subduction of the bathymetric high (Figure 7). During the initial stages, the subducting high indents and uplifts the frontal margin. The décollement follows the subducted flank of the asperity and is thus deflected upwards. At this stage, it emerges in the upper part of the frontal margin where sedimentary mass sliding occurs and a large scar is observed. As a result, frontal accretion is inhibited as long as

the seamount maintains the décollement in a high position. The oceanic sediments and part of the frontal margin, located trenchward of the seamount trailing flank, are dragged behind the seamount. On both sides of the reentrant, frontal accretion is still active. The new imbricate thrust slices curve landward in the vicinity of the reentrant to join the décollement level emerging high at the front of the margin, in the wake of the subducting feature. This mechanism generates two transfer zones which laterally delimit a shadow zone where frontal accretion is temporally inhibited (Figure 7).

The subduction of the Gagua Ridge also deforms the central part of the accretionary wedge (Figures 2 and 6). A large knoll (30 km × 40 km) is observed and the margin appears to be uplifted more than 1000 m, compared to the average margin seafloor depth on both part. This area is highly fractured by a very unusual fault pattern, very well imaged in the shaded views

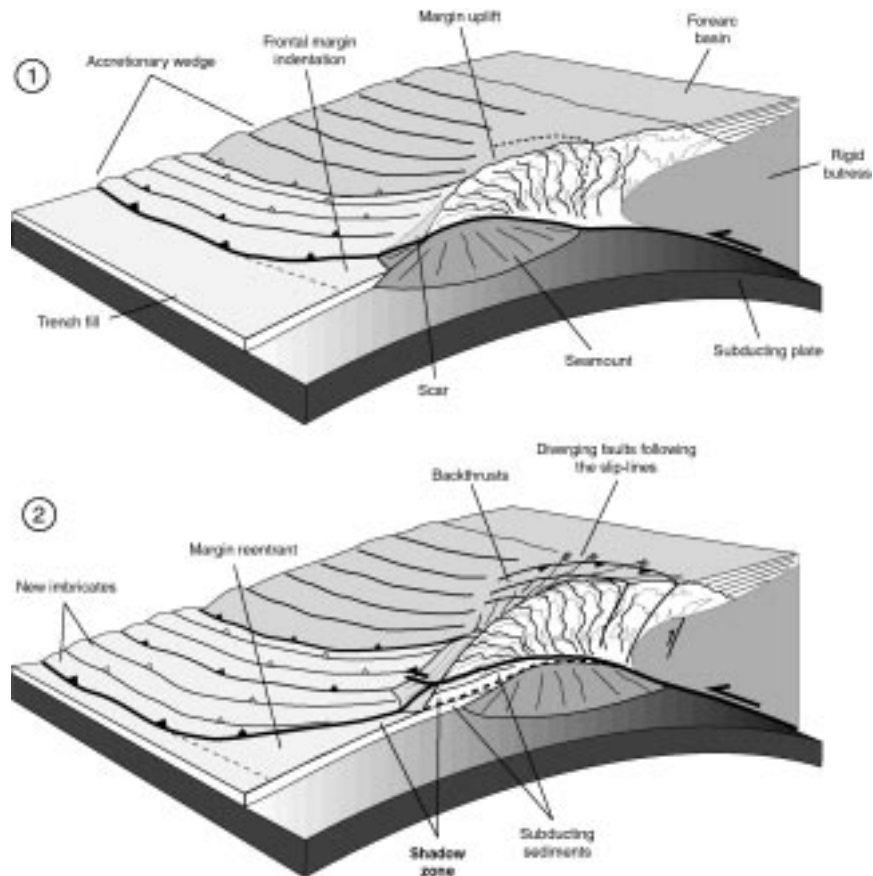


Figure 7. Synthetic perspective views of two stages of a sandbox experiment of seamount subduction in frontal convergence. In the wake of the subducting high a shadow zone develops because the seamount deflects the basal decollement upward in the reentrant area. Consequently, frontal accretion is inhibited and part of the frontal margin and the trenchfill sediments is dragged into subduction.

(Figure 6) and also in the ship imagery (Figure 8). This fault network appears to be composed of well developed diverging fractures. Their general distribution is N–S trending, directly above the presumed location of the subducted segment of the Gagua Ridge but individually they trend N330° E and N30° E.

This very particular type of fault network has been previously studied using sandbox experiments (Dominguez et al., 1994, 1995) and has been observed above seamounts subducting beneath the Costa-Rica convergent margin (Dominguez et al., 1998). This fault pattern results from increased compressional stress caused by the subduction of the seamount (Figure 9). The Gagua Ridge locally indents and uplifts the Ryukyu Margin. As a consequence, the slip-lines of the stress field diverge on each parts of this indenter and conjugate strike-slip faults develop following the slip-lines.

The marine observations and experimental results suggest that the southern end of the subducted segment of the Gagua Ridge is still located close enough to the front of the margin to maintain the décollement in an upper position (probably just above the subducting sedimentary sequence). Consequently, the sediments sliding into the reentrant area are continuously dragged into the subduction simultaneously with the trenchfill sediment sequence. This could explain the lack of large slump deposits at the base of the scar.

The upper part of the Ryukyu accretionary wedge located in the axis of the Gagua Ridge is also uplifted (Figure 6). However, the main observable deformation is the northward bend of the Yaeyama Fault. This feature is probably not directly related to the subducted high because this deformed zone is located westward of the axis of the Gagua Ridge and outside the uplifted area. The deformation zone, with a diamond shape, associated with this northward virgation can

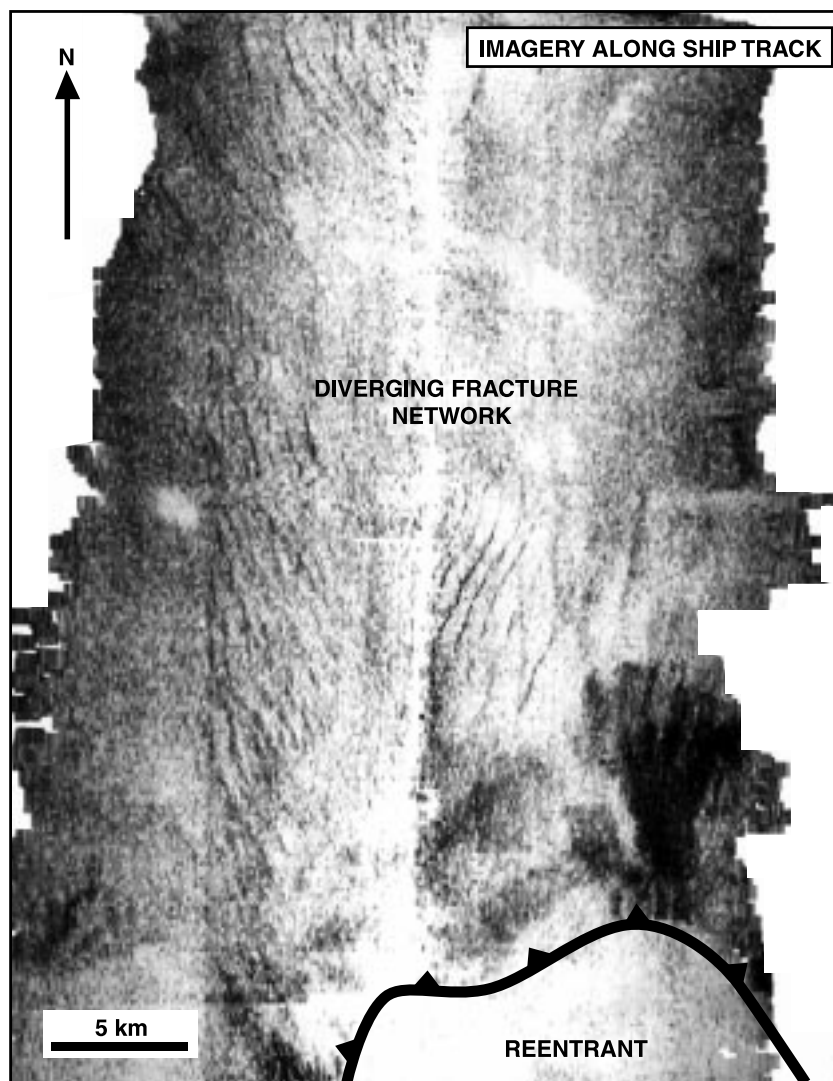


Figure 8. Imagery data of the reentrant area (see location on Figure 6). The diverging fracture network (slip-line) previously observed in the swathbathymetric data is very well imaged and appears to be quite symmetric.

be interpreted as a transpressive structure related to the general deformation of the Ryukyu Arc slope. As demonstrated by geodetic data (Imanishi et al., 1996; Lallemand and Liu, 1998), due to the opening of the Okinawa trough back-arc basin, the Ryukyu Arc moves towards the south and is broken into several tectonic blocks with different relative velocities. As a result, the propagation of the Yaeyama Fault is locally disturbed and deviates northward in this area.

In the axis of the Gagua Ridge, the Yaeyama fault appears to be uplifted about 1000 m but its morphology and azimuth remain roughly the same. Some minor strike slip faults apparently affect this region.

Locally, they offset the Yaeyama Fault, mainly in the eastern part of the uplifted area (Figure 6). These features could be related with the compressional stress induced by the subducted portion of the Gagua Ridge.

The forearc basins

In the Nanao forearc basin, due to the high sedimentation rate, the deformation associated with the subducted high is less evident in the morphology. Nevertheless, seismic profiles show that the basement underneath the Nanao forearc basins, consisting of the seaward end of the Ryukyu Arc, is deformed and uplifted (Figure 10).

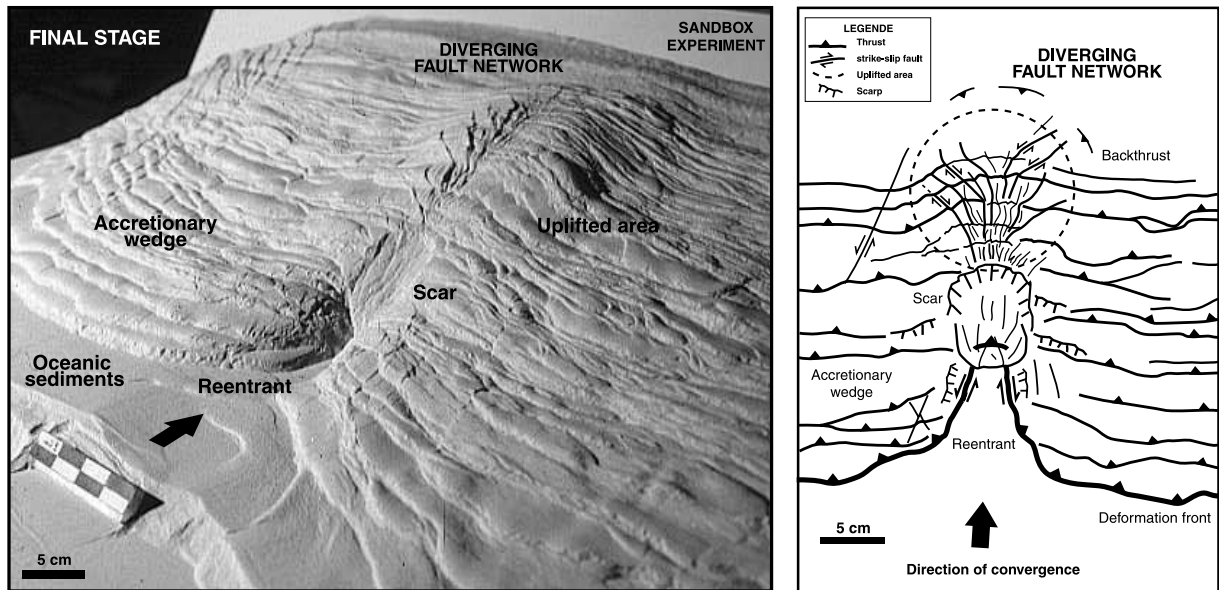


Figure 9. Sandbox experiment showing the particular fault network generated by the subduction of a conical seamount. Conjugate diverging strike slip faults and backthrusts accommodate the shortening of the frontal margin associated with the compressional stress induced by the seamount.

Seismic profile 81 reveals that the Ryukyu Arc is uplifted about 1 s TWT relative to its position beneath East and West Nanao basins (Figure 10). The basement rise is overlain by about 1 s TWT of relatively undeformed sediments. This sedimentary sequence can be clearly identified extending across the entire seismic profile. It corresponds to the lower sedimentary sequence (LSS) of the Nanao forearc basin. The LSS sediments are draped over the Ryukyu basement rise which suggests that they have been mainly deposited prior to the Ryukyu Arc basement uplift (Figure 10). West of the basement rise, the LSS is down flexed and has recorded the compressional stress associated with the uplift of the Ryukyu arc termination. In this region, the LSS is overlapped by a more recent syntectonic sedimentary sequence which comprises the upper sedimentary sequence of the Nanao forearc basin (USS). The fan geometry of the strata of the USS suggests deposition during the uplift of the seaward ending of the Ryukyu Arc. East of the Nanao basement rise, the LSS is significantly tilted westward and probably affected by listric normal faults with eastward increasing offsets (see enlargement on Figure 10). East of the present subsiding area, the tilted sediments of the LSS are sealed by the overlapping sediments of East Nanao basin.

These observations suggest that the forearc Nanao basins sedimentation is controlled mainly by the west-

ward migration of the Ryukyu Arc basement rise. This rise is compatible with a westward sweeping of the Nanao basins by the subducted portion of the Gagua Ridge. Nevertheless, in the eastern part of the seismic profile, the LSS layers lie again conformable on the Ryukyu Arc basement and show only minor deformation. None of the previously described tilted sedimentary layers are observable in this region. This suggests that this area has never been affected before by the westward migration of the Ryukyu Arc basement rise. As a result, we propose that the beginning of the uplift of Nanao forearc basin was first recorded in an area located just eastward of the present basement rise location (see the star on Figure 10, line drawing). In this case, taking into account the obliquity of the plates convergence azimuth, the significant slowing down in the filling of East Nanao basin could be very recent (probably less than 250 000 yr., according to the previous assumptions).

The Ryukyu Arc slope

At the northern boundary of the survey area, major fractures, trending NW-SE, lacerate the Ryukyu arc slope (Figure 3). Superimposed on this set of fractures, two other conjugate fractures trending N50° E and N35° W are observed. They cross-cut the arc slope in the axis of the Gagua Ridge but also on either sides.

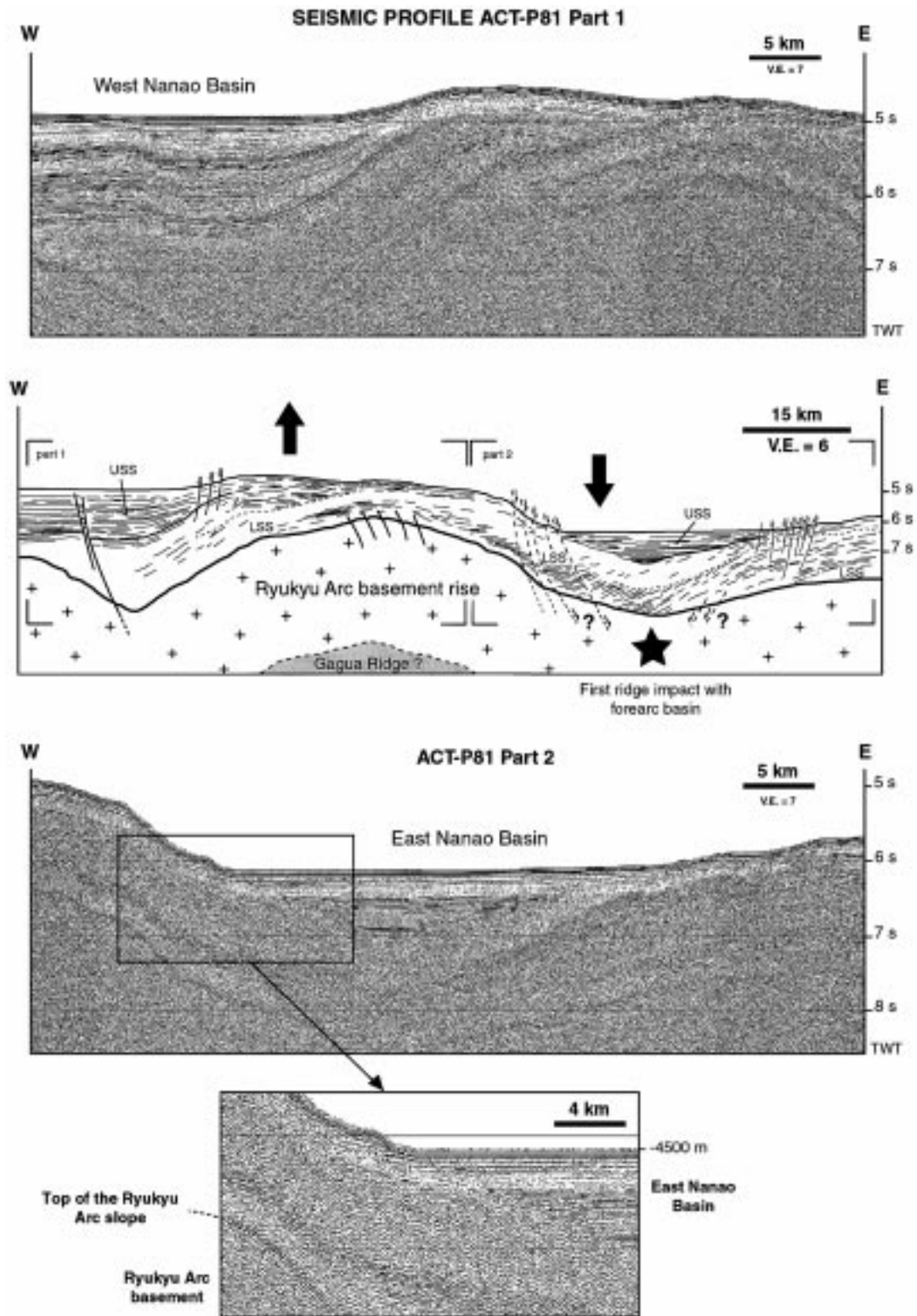


Figure 10. Seismic time migrated profile P81 recorded across the Nanao forearc basins. The recent syntectonic sediments of East and West Nanao basin clearly onlap the lower sedimentary sequence (LSS). These sediments were deposited mainly before the Ryukyu Arc uplift associated with the subduction of a portion of the Gagua Ridge. The deformation they record suggests a limited westward sweeping of the Ryukyu Arc basement rise.

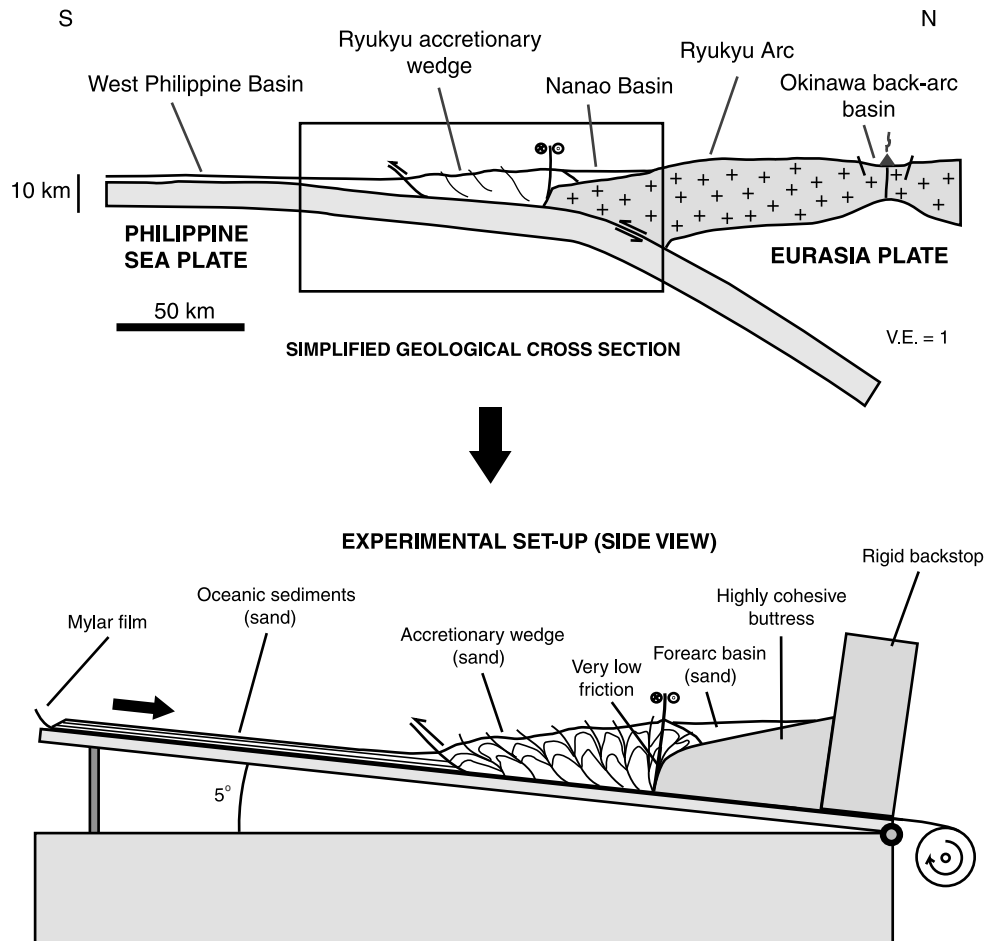


Figure 11. Cross section of the experimental set-up showing the geometry and the different materials constituting the sandbox model. Simplified geological cross section of the Ryukyu arc-trench system close to Taiwan, used to performed the experiments.

The whole arc slope appears to be significantly deformed, probably as a result of the opening of the Okinawa trough backarc basin and the obliquity of the plate convergence (Imanishi et al., 1996; Lallemand and Liu, 1998). As a consequence, no clear deformation of the Ryukyu arc slope can be directly attributed to the Gagua Ridge subduction.

Sandbox experiments of ridge subduction

To better understand the mechanisms of the oblique subduction of a linear structural high, several analog experiments were performed using granular materials. In this paper, we present one of these experiments that best illustrates the main results of this study. In this experiment, nearly 50% of the oblique convergence is accommodated along a major shear zone, situated at

the rear of the accretionary wedge, comparable to the Yaeyama Fault.

Experimental set-up

The experimental set-up is based on an apparatus which reproduces the basic mechanisms of a subduction zone (Figure 11). This experimental set-up is identical to the one used by Malavieille (1984), Malavieille et al. (1991), Lallemand et al. (1992) and Dominguez et al. (1995, 1998). Analog materials are essentially well rounded eolian sands with a grain size of $200 \mu\text{m}$. Their rheologic properties (angle of friction of 30° and very low cohesion) make them a good analog of natural sedimentary rocks (Dahlen, 1984; Dahlen and Suppe, 1984).

The experiment is performed on a 5° inclined PVC plate (2.2 m long \times 2 m wide). A mylar film, carrying

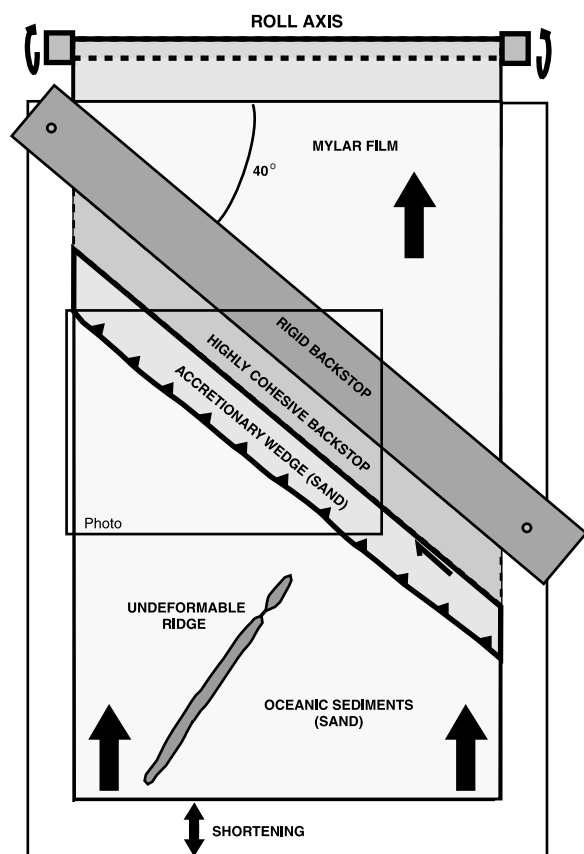


Figure 12. 2D view of the experimental set-up used to performed the sandbox experiment. The adjustable obliquity of the backstop allows testing different convergence azimuths.

a layer of sand, simulates the motion of the oceanic plate and its sediments. The sheet is pulled beneath a rigid buttress (backstop) and rolled up around an axis. The coefficient of basal friction along the mylar-sand interface is close to 0.45, which represents an intermediate basal friction. The backstop, representing the undeformable part of the overriding plate, is oriented 40° oblique with respect to the direction of convergence to conform the obliquity of the relative motion between the Ryukyu Arc and the PSP (Figure 12). As a result, the oceanic sediments, consisting of several layers of sand, are dragged towards the rigid buttress and finally accreted against the backstop. Thus, an accretionary wedge develops progressively. Colored sands are used to trace a regular colored grid, on the model surface, to observe the kinematics of the deformation during the experiments and estimate the degree of strain partitioning.

Sandbox experiment

The initial conditions of this experiment is based on a simplified cross-section of the Ryukyu-Arc trench system (Figure 11). A highly cohesive prism, with a steep termination, represents the seaward end of the Ryukyu Arc. A sand wedge simulates older accreted oceanic sediments (Figure 11).

During the first centimeters of convergence, new imbricate slices are added to the front of the preexisting sand wedge and an accretionary wedge develops. At the same time, above the seaward end of the cohesive backstop, oblique Riedel fractures initiate. They are related with an incipient right lateral shear zone, trending parallel to the backstop.

After 35 cm of convergence, this shear zone has evolved into a well defined right lateral transcurrent fault which accomodates the greatest part of the trench parallel motion of the accretionary wedge (Figure 13A).

After 55 cm of convergence, some backthrusts, related to the growth of the accretionary wedge, initiate in its landward part and slightly disturb the development of the major transcurrent fault. As a result of the general uplift of the rear part of the accretionary wedge, a longitudinal trough is generated where a forearc basin could develop (Figure 13B). Since the beginning of the experiment, a total of 17.5 cm of trench parallel motion has been accomodated, mainly along the major transcurrent fault. At this stage, the degree of strain partitioning appears to be close to 50% (total partitioning will result into a trench parallel component close to 35 cm).

After 75 cm of convergence, the first topographic high starts uplifting the front of the accretionary wedge. At this stage, the frontal thrust units are only passively uplifted and no significant deformation is observed (Figure 13C). The transcurrent fault remains active and some conjugated faults initiate due to the progressive uplift of the rear part of the accretionary wedge.

After 95 cm of convergence, the subduction of the topographic high generates a large reentrant in the frontal margin associated with a huge scar and a topographic knoll (Figures 13D and 13E). As discussed before, the subducting high generates a shadow zone in its wake where frontal accretion is inhibited and where sediments are dragged into subduction. The shape of this shadow zone is greatly influenced by the oblique component of the convergence vector. On both sides of the reentrant, frontal accretion is still

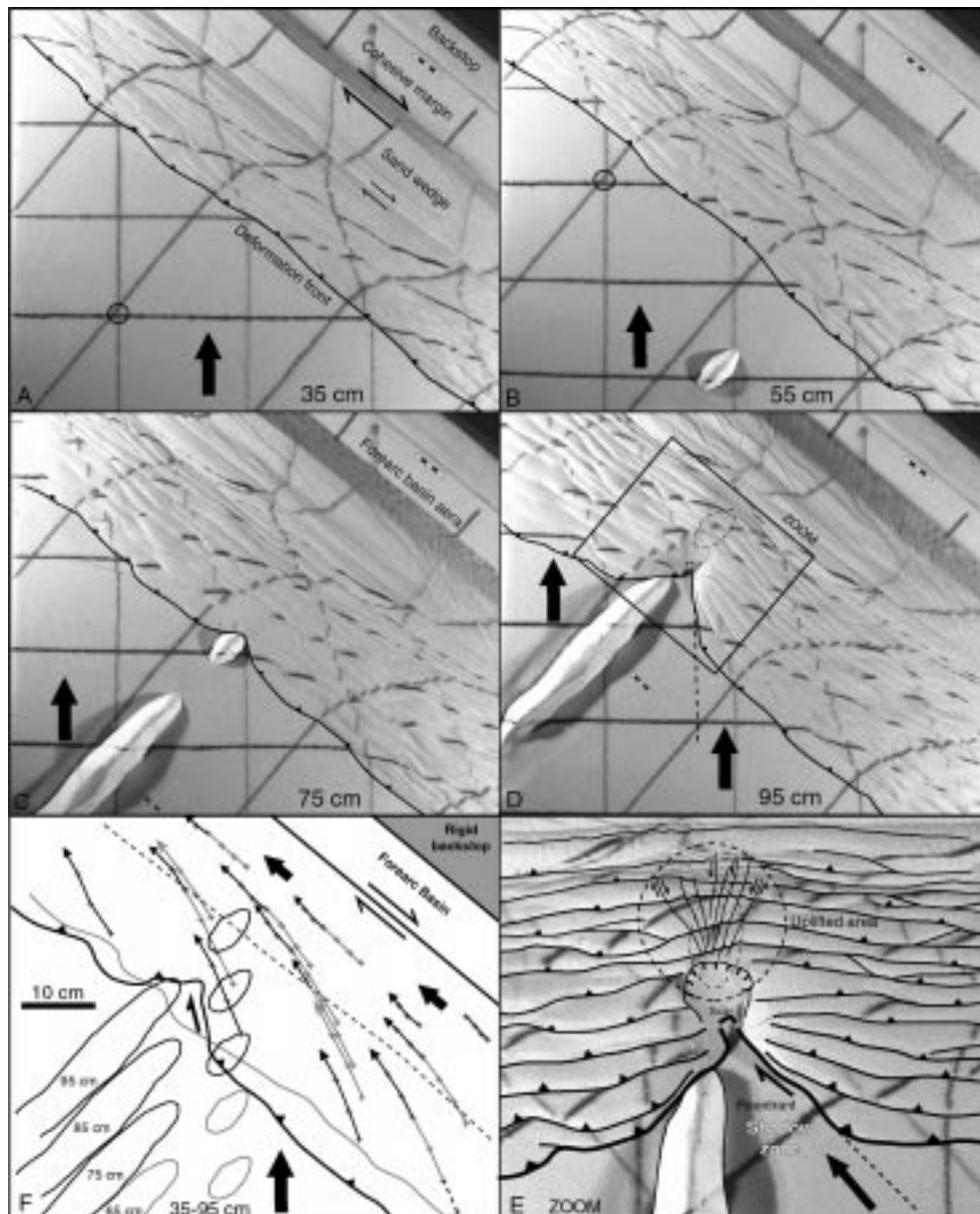


Figure 13. Planar photos of a sandbox experiment illustrating four stages of ridge subduction under oblique convergence. The convergence rates are 35 cm, 55 cm, 75 cm and 95 cm. Black and gray arrows indicate the motion of surface markers every 10 cm of convergence, respectively after and before the ridge subduction. The enlargement of picture D shows the reentrant area. A diverging fracture network, following the slip-line defined by the major stress component, is observed as well as the shadow zone trending in the direction of the convergence.

active and new thrust units initiate. In the vicinity of the shadow zone, transfer zones develop to connect these frontal thrusts with the décollement level which crops out in the scar slope during the first stages of the seamount subduction and at the base of the scar when the seamount is more deeply subducted.

We have observed that the new frontal imbricate slice, situated on the right side of the shadow zone, always initiates with a transfer zone trending very close to the direction of the convergence (Figures 13D and 13E). This remark is valid even in other experiments where the degree of partitioning was different.

Above the subducting high, a diverging fault network, associated with incipient backthrusts, develop. It corresponds to the indentation of the margin by the subducted segment of the ridge. This fault network propagates landward at the same time as the subducting high and intensively deforms the accretionary margin morphology and structure.

Experimental results

In this experiment, performed under 40° of oblique subduction, at least 50% of the oblique component of the convergence is accommodated along a major shear zone located at the rear of the accretionary wedge. The initiation of such a structure is apparently favored by a steep seaward termination of the overriding plate basement and a low friction on this interface. In this mechanical setting, a great part of the accretionary sand wedge (the most compacted) moves parallel to the backstop without observable internal shearing (Figure 13F). In the active part of the accretionary wedge, the trench parallel component of the convergence is distributed over the whole frontal margin along the preexisting thrust planes.

Sandbox experiments reveal that due to the obliquity of the convergence, the trend of the shadow zone, generated by the subducting ridge segment, tends to elongate parallel to the relative plates motion because of the stress field induced by the subducting asperity. This observation could be a useful means to estimate the direction of relative plate convergence in such a geodynamic setting.

Reconstruction of the Gagua Ridge subduction over the last million of years

The data recorded during the ACT cruise, have revealed that slip partitioning occurs along the Ryukyu Margin (Lallemand et al., 1997, 1999) but the azimuths and velocities of the different tectonic blocks have yet to be determined.

Geodetic data proceeding from a compilation of GPS data (Imanishi et al., 1996; Yu et al., 1997) show that the Ryukyu Arc is presently moving southward with respect to the South China Block. This motion is presently occurring at a velocity of 4 cm yr^{-1} along $N184^\circ \text{ E}$ azimuth (Figure 14). Based on a simple geometric reconstruction, the resulting convergence between the Ryukyu Arc and the PSP should be 10.7 cm yr^{-1} , along $N325^\circ \text{ E}$ azimuth (Lallemand and Liu, 1998).

One can notice that this direction is very similar to the one that can be deduced from the study of the Gagua Ridge reentrant. Indeed, the sandbox experiments show that the direction of the eastern limit of the margin reentrant, associated with the shadow zone generated by the subducting high, is typically parallel to the relative plates convergence. Assuming the deformation mechanisms observed in the sandbox experiments are comparable to those in convergent margins, and taking into account the trend of the eastern part of the Gagua Ridge reentrant, the predicted convergence azimuth between the ridge and the Ryukyu Arc is, thus, close to $N324^\circ \text{ E}$.

The main question to be answered, now, is what is the azimuth of the relative convergence between the PSP, carrying the Gagua Ridge, and the Ryukyu accretionary wedge?

One way to estimate this relative convergence is to study the deformation of the frontal margin east of the Gagua Ridge in more detail. As seen before, there is a slump scar located in the frontal margin with a semi-circular shape 15 km wide. It is situated just north of the volcanic plateau and the two seamounts previously described on the PSP (Figures 2, 6 and 14). Northwest of this reentrant, a circular bulge is observed in the bathymetry. This uplifted area is also traversed by oblique fractures (Figure 14). These observations suggest that a minor seamount, comparable in size to those observable on the PSP, is presently subducting beneath the accretionary wedge front. Based on this observation, the frontal part of the margin where the seamount started subducting and its present location can be estimated with relatively good precision (Figure 14). We can then, determine the subduction azimuth of this seamount which is assumed to be roughly the direction of the relative convergence between the PSP and the accretionary wedge. This azimuth appears to be close to $N345^\circ \text{ E}$ which is a direction of convergence less oblique than the PSP/Ryukyu Arc convergence azimuth ($N325^\circ \text{ E}$). This is consistent with a westward motion of the accretionary wedge with respect to the Ryukyu Arc related to slip partitioning at the rear of the Ryukyu accretionary wedge. This azimuth of relative convergence is also compatible with the strike of the northern limit of the reentrant, i.e., normal to it (Figure 14).

Consequently, we propose that the subduction of the Gagua Ridge, beneath the Ryukyu accretionary wedge, presently occurs with only 15° to 20° of obliquity. In this case, near 20° of the plate convergence azimuth could be absorbed along the Yaeyama strike

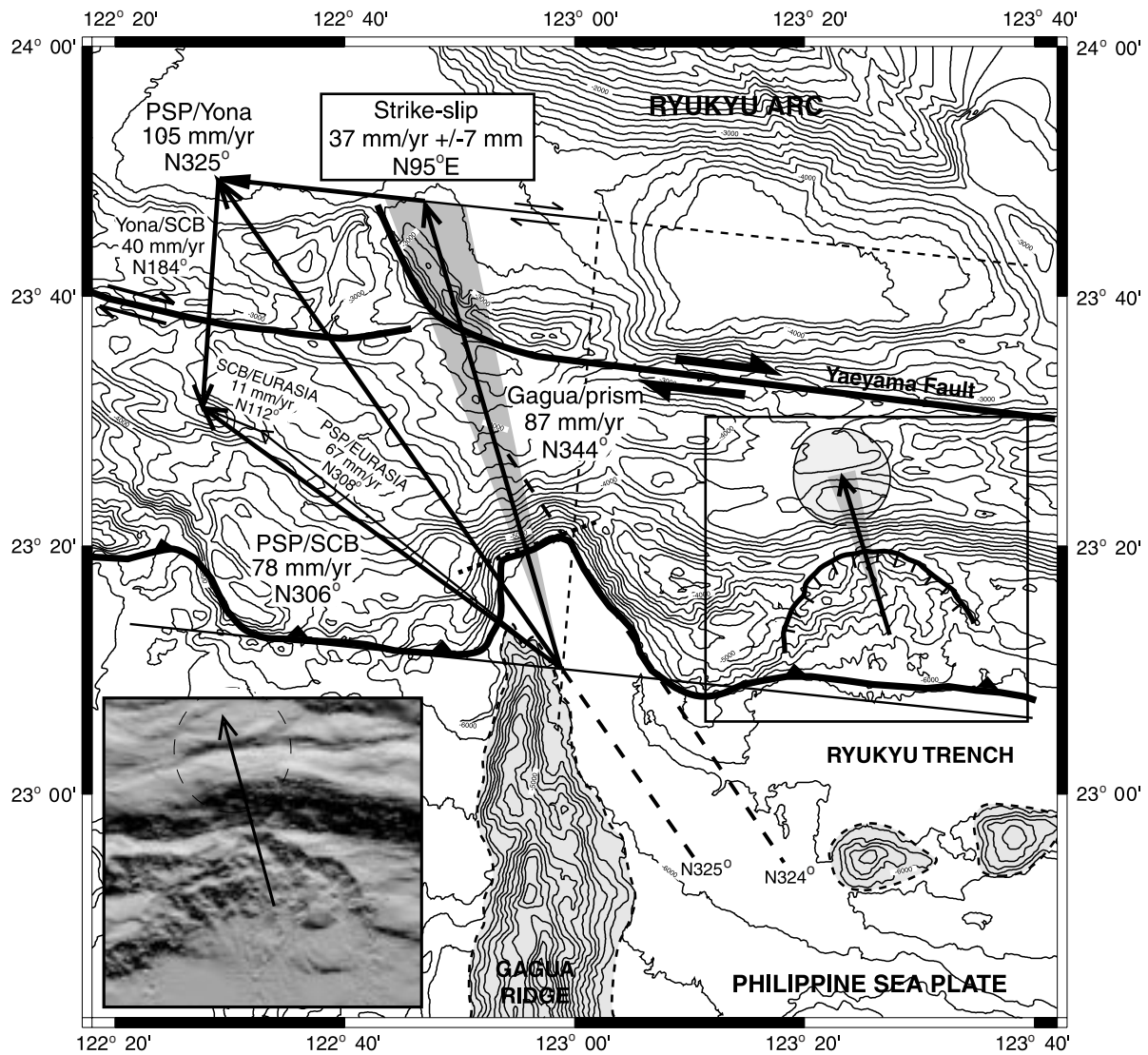


Figure 14. Bathymetric map showing the relative plates motions deduced from global plate motion calculator, GPS data, and ACT data. The geometric reconstruction allows to estimate the velocity and the degree of strain partitioning along the Yaeyama Fault. In the hypothesis that the Yaeyama fault accommodates the whole trench-parallel motion of the accretionary wedge, the calculated velocity is about $3.7 \text{ cm yr}^{-1} \pm 0.7 \text{ cm}$ and the degree of strain partitioning close to 55%.

slip fault. The resulting motion along the Yaeyama Fault could then, reach $3.7 \text{ cm yr}^{-1} \pm 0.7 \text{ cm}$, along N95° azimuth, if the whole trench parallel motion of the accretionary wedge is absorbed along this major fault (Figure 14). Based on this assumption the degree of partitioning appears to be close to 55% along the Yaeyama Fault, considering that a total partitioning (100%) will result in a velocity close to 7 cm yr^{-1} .

The last difficulty, before reconstructing the Gagua Ridge subduction, is to estimate the length of the subducted segment of the ridge. Sibuet et al. (1998), based

on anomalous volcanism in the Okinawa Trough have proposed that the ridge extended northward beneath the Okinawa back-arc basin.

If we examine the Ryukyu accretionary wedge structure in the survey area, there is no evidence of deformation eastward of the ridge related to an uplift and/or a westward sweeping of the Ryukyu accretionary wedge produced by the Gagua Ridge. The only unusual structure is the previously described out-of-sequence thrust trending E-W in the eastern part of the Ryukyu Margin. This structure is probably not directly

RECONSTRUCTION OF THE GAGUA RIDGE SUBDUCTION OVER THE LAST ONE MILLION YEARS

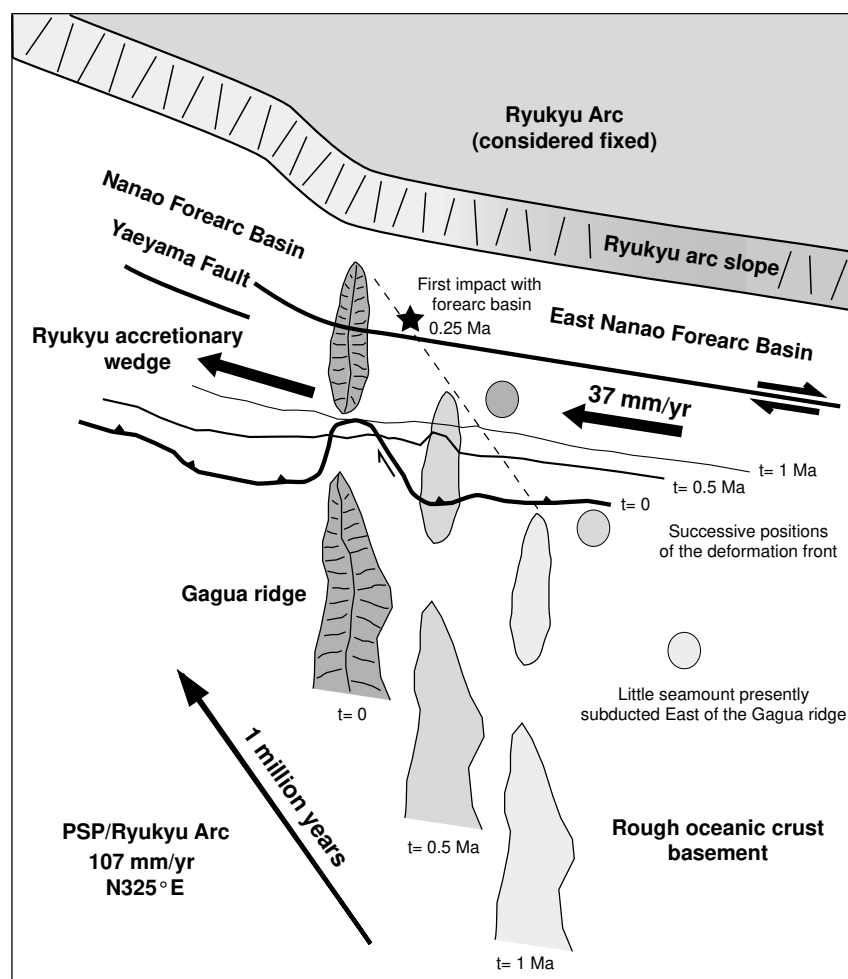


Figure 15. Proposed reconstruction of the Gagua Ridge subduction over the last 1 Ma, based on a westward motion of the accretionary wedge of 3.7 cm yr^{-1} .

related to the subduction of a portion of the Gagua Ridge, as previously suggested by Schnurle et al. (1998). As seen before, the basement of the oceanic crust east of the Gagua Ridge is very rough. Several bathymetric highs, such as seamounts and a large volcanic plateau can be observed. The subduction of such a rugged oceanic crust locally modifies the basal friction along the décollement and might generate a regional out-of-sequence thrust. Moreover, ACT data reveal that, none of the very specific, and previously described, deformation features affecting the uplifted zone above the subducted Gagua Ridge segment, can be identified further eastward. The frontal thrust units,

recently accreted east of Gagua, doesn't show imbricated oblique transfer zones. These structures would be expected if the Gagua Ridge swept this portion of the margin in the recent past. Indeed, in this case, each new imbricate should have recorded the westward motion of the shadow zone, situated in the wake of the subducting relief. In the survey area, such structures are only observed in the reentrant area generated by the portion of the Gagua ridge presently buried beneath the accretionary wedge. Furthermore, the study of the Nanao forearc basin deformation reveals a localized uplift in the axis of the ridge associated with a limited westward sweeping of the forearc basin.

Based on the previous observations and remarks, and taking into account the different convergence rates calculated, we propose the following reconstruction of the Gagua ridge subduction (Figure 15). 700 000 to 600 000 years ago, the northern end of the Gagua Ridge starts to dam the trench axis and uplift the front of the Ryukyu Margin. 600 000 to 500 000 years ago, the subduction of the ridge strongly indents the frontal margin and a scar generates. At this time, the reentrant morphology was slightly different and the frontal thrust units, presently located on both sides, had not yet accreted (Figure 15). Laterally, frontal accretion is still active and new thrusts units are added to the frontal margin.

250 000 to 200 000 years ago, the portion of the Gagua Ridge, presently subducted beneath the Ryukyu accretionary wedge, started to uplift the seaward end of the Ryukyu Arc and the Nanao forearc basins. More recently, the incipient uplifted zone dammed the sediments proceeding from Taiwan which now only fill the Nanao basin.

Due to the subduction of the Gagua Ridge beneath the Ryukyu accretionary wedge, compression is recorded in the margin west of the ridge. This compressional stress, trending in the direction of the convergence, induces an overall shearing of this part of the margin and greatly disturbed the accretionary wedge structure.

Conclusion

The western end of the Ryukyu arc trench system is a unique area to study oblique ridge subduction together with strain partitioning. Geophysical data (swathbathymetry and seismic reflexion) acquired during ACT cruise allow a detailed study of the geomorphology of the margin and its internal structure.

Based on these data, we have demonstrated that the Gagua Ridge subduction greatly influenced the tectonic evolution of the Ryukyu Margin near Taiwan, at least since the last one million of year. The Gagua Ridge strongly disturbs the frontal accretion but also deforms the whole margin and, more recently, controls the sedimentation in the forearc Nanao and East Nanao basins.

Analog experiments of ridge subduction, performed at 40° of obliquity, show that the tectonic evolution of the margin reentrant, caused by the ridge subduction, is linked with the azimuth of the plate convergence. In such a tectonic setting, the study of

margin deformations associated with seamount subduction allows, also, a good estimate of the relative convergence between the subducting plate and the accretionary wedge. Available geodetic data have confirmed these predicted azimuths and help to determine the azimuth and velocity of the different tectonic blocks.

It appears that, due to strain partitioning, the Ryukyu accretionary wedge moves parallel to the trench towards the west, at a rate of about $37 \text{ mm yr}^{-1} \pm 7 \text{ mm}$. As a result, the subduction of the ridge beneath the accretionary wedge occurs with only 15°/20° of obliquity instead of the 40° predicted by local kinematics deduced from GPS data.

The marine observations and the kinematic data suggest that the segment of the Gagua Ridge responsible for the strong margin deformations observed in the ACT survey area, started probably subducting 0.7 m.y. to 0.6 m.y. ago. Sibuet et al. (1998) proposed that the Gagua Ridge prolongates far away beneath the Ryukyu Arc. We found no arguments to support or to reject this hypothesis, mainly because such evidences have to be investigated eastward of the ACT survey area where the resolution of available bathymetric and geophysical data is still poor.

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