Evolutionary Models of Convergent Margins : Origin of Their Diversity

Chapter 1

Deposition and Deformation of Modern Accretionary-Type Forearc Basins: Linking Basin Formation and Accretionary Wedge Growth

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Additional information is available at the end of the chapter

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Abstract

Since a comprehensive review of forearc basins was published by Dickinson more than 20 years ago, a significant amount of new data about them have been published. These recent studies revealed details of depositional and deformation styles in the forearc basins, suggesting the formation processes were not unique. In this chapter, we reviewed modern forearc basins to understand how is the basin stratigraphy related with growth of accretionary wedges. The results indicate forearc basin can be classified into two (single- and two-wedge models) plus one (strike-slip model): (1) the single-wedge model which is characterized by landward tilting of the basin strata ascribed to asymmetrical doubly vergent (single-vergent) uplift of the outer arc high with forethrusts (seaward-vergent thrusts in the pro-wedge); (2) the two-wedge model which is marked by contractional deformation caused by symmetrical doubly vergent uplift of the wedge with forethrusts in the prowedge and back-thrusts (landward-vergent thrusts) in the retro-wedge; and (3) the strike-slip model which is an additional one being represented by transpressional and/or transtensional deformations due to oblique subduction. We speculate that these models spatially and temporally depend on material fluxes at the plate interfaces that affect geometry and mechanical strength of backstops.

Keywords: forearc basin, accretionary wedge, deposition, deformation, plate convergent margin

1. Introduction

Forearc basin is one of the major elements of plate convergent margins (e.g., [1, 2]). The formation is considered to be closely associated with accretion or erosion at frontal and basal parts of accretionary wedge (e.g., [3–5]). Especially, the seaward margin of the basin is directly affected by uplift and subsidence of the outer arc high of accretionary wedge, which acts as topographic barrier of sediments deposited in the basin. Forearc basin generally develops at which interplate coupling is strong [6, 7], meaning the location is underlain by an area where strain release during earthquakes is large. Therefore, styles of deposition and deformation of forearc basins may record long-term average stresses on the plate interfaces over millions of years.

However, the formation and deformation processes of forearc basins are poorly known. Such basin is incorporated into a dynamic system of subduction zone composed of backstop, basin sediments, accretionary wedge, trench fill deposits, subducting plate with conduit for the subducting materials. This system is spatially and temporally influenced by changes of plate configuration (slap dip, obliquity, or convergent rate), activity of volcanic arc (sediment production), topography of subducting slab, strength and geometry of backstop, and material flux at the plate boundary.

The purpose of our study is to develop a tool for reconstruction of paleostress fields by lightening how forearc basin formations respond to subduction zone dynamics that include frontal/basal accretion/erosion and mechanical relationships among the basin, backstop, accretionary wedge, and subducting plate. For the first step of this purpose, we collected modern examples of deposition and deformation of forearc basins in the world. The studied areas are Sunda (Sumatra-Java), Japan, Aleutian-Alaskan, Lesser Antilles, South American (Columbia-Ecuador-Peru-Chile), and Tonga-Kermadec-Hikurangi margins (**Figure 1**). Most of them are classified into the compressional accretionary-type forearc basin [2], which is characterized by growth of accretionary wedge by frontal/basal accretion and compressional deformation in

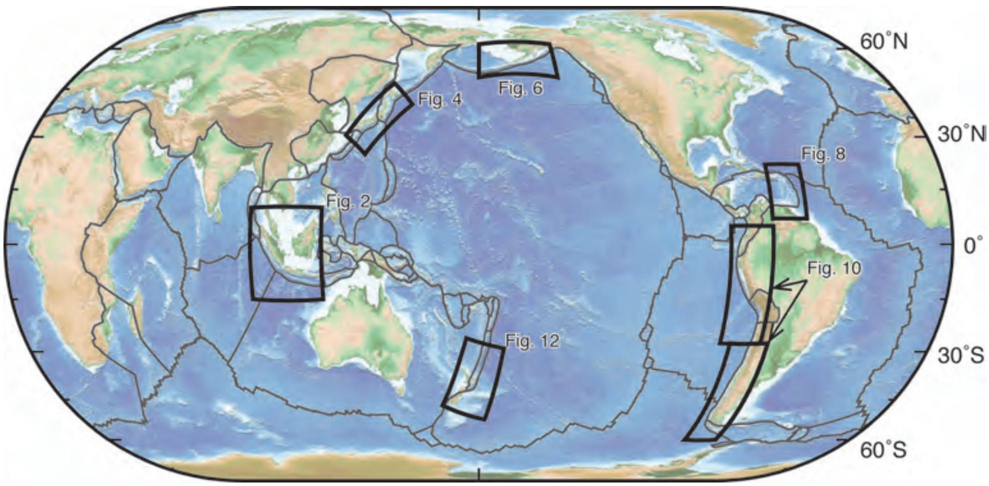

Figure 1. Index map of the study areas. Plate boundaries are based on Ref. [8].

the basins. This paper can contribute a basic understanding about the formation processes of forearc basins along plate convergent margins.

2. Sunda arc (Sumatra-Java)

2.1. Plate configuration

Along the Sunda (Sumatra-Java) arc, the India-Capricorn-Australian plate subducts beneath the Sunda microplate (Eurasian continental plate) with 5–7 cm/yr in the southeastern Asia (**Figure 2**). Under the present configuration, the angle of subduction direction gradually varies from nearly orthogonal off Java Island to almost parallel off Andaman Islands farther north, which leads to development of arc-parallel strike-slip fault systems [9]. Water depth of the trench floor also gradually decreases from east (6000 m water depth off eastern Java) to northwest (4000 m water depth off Sumatra), which is ascribed to an enormous sediment input from the Bay of Bengal [10]. Age of the subducting plate is younging from ca. 130 Ma of east to ca. 50 m.y. of northwest [11].

In the northern part of the forearc (off Sumatra), multiple subbasins separated by structural highs have been formed, indicating transtension and transpression regimes are repeated due to strike-slip deformation along this margin [12]. The central Sunda margin (off western Java to southern Sumatra) is marked by a transition zone from orthogonal convergence in the east to oblique subduction to the northwest.

The subduction along this arc is active since Eocene [13]. The oceanic plate initially subducted beneath continental-type basement rock off Sumatra and oceanic-type one off Java [14, 15]. The convergence rate increased from 5 cm/yr (Eocene to Miocene) to 7 cm/yr during the last 10 My [16].

2.2. Forearc basins

2.2.1. Simuelue basin

The Simuelue basin (**Figure 3**) is a moderate-sized (100 × 260 km) basin with sediments of up to 5 s two-way travel time off Sumatra Island (e.g., [15, 17]). The basement of this basin is considered as the continental backstop of the Sumatran continental crust with a regional horst and graben structures which might be generated from the Late Eocene to Early Oligocene [21] (**Figure 3A**). The northern part of this basin (**Figure 3A**) shows depositional and deformational styles changed between Units 3 and 4. A contractional strain ascribed to landward-vergent thrusts in the retro-wedge was recorded before the deposition of unit 4. On the other hand, the strata of Units 4 and 5 are characterized by seaward tilting and seaward migration of the depocenter, suggesting the seaward side of the basin subsided relative to the landward side during that time.

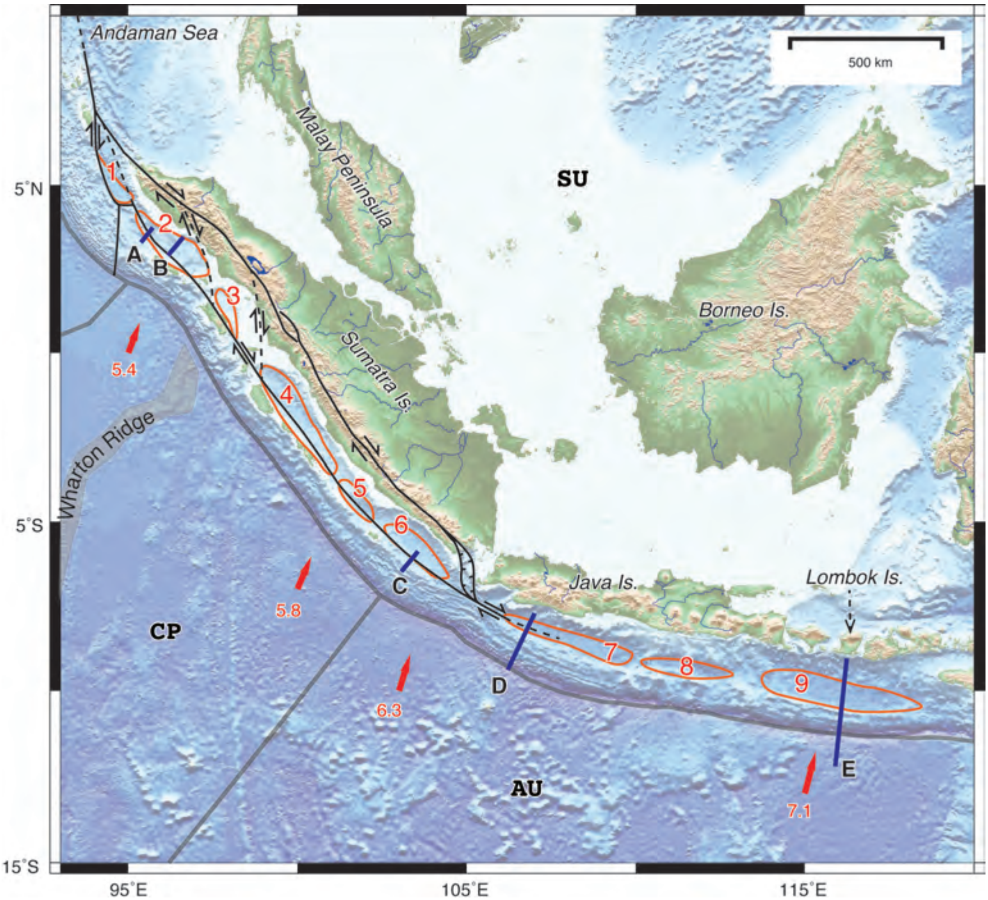

Figure 2. Index of the Sunda margin. Blue lines with labels A–E indicate the locations of survey lines shown in **Figure 3**. Forearc basins: 1—Aceh, 2—Simuelue, 3—Siberut, 4—Bengkulu, 5—Enggano, 6—Mentawai, 7—Western Java, 8—Eastern Java, 9—Lombok basins. Plate names: SU—Sunda, CP—Capricorn, AU—Australia plates. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the Sunda plate based on Ref. [8].

The depositional history of the central part (**Figure 3B**) was divided into four stages [17]. At the end of Paleogene time (ca. 40 Ma), a regional erosional surface was developed after slope sediments covered the topographic lows (Unit 1 in **Figure 3B**). An Early/Mid Miocene stage is marked by a rapid subsidence in the trenchward and thick deposition occurred along the seaward margin of the basin (Unit 2). During the Late Miocene/Pliocene, subsidence continued in the northern and the trenchward region of the Simeulue basin (Unit 3). The basin from Pleistocene to recent was under an influence of strike-slip faults due to the oblique subduction evidenced by a wrench faulting, and subsidence expanded significantly landward (Unit 4).

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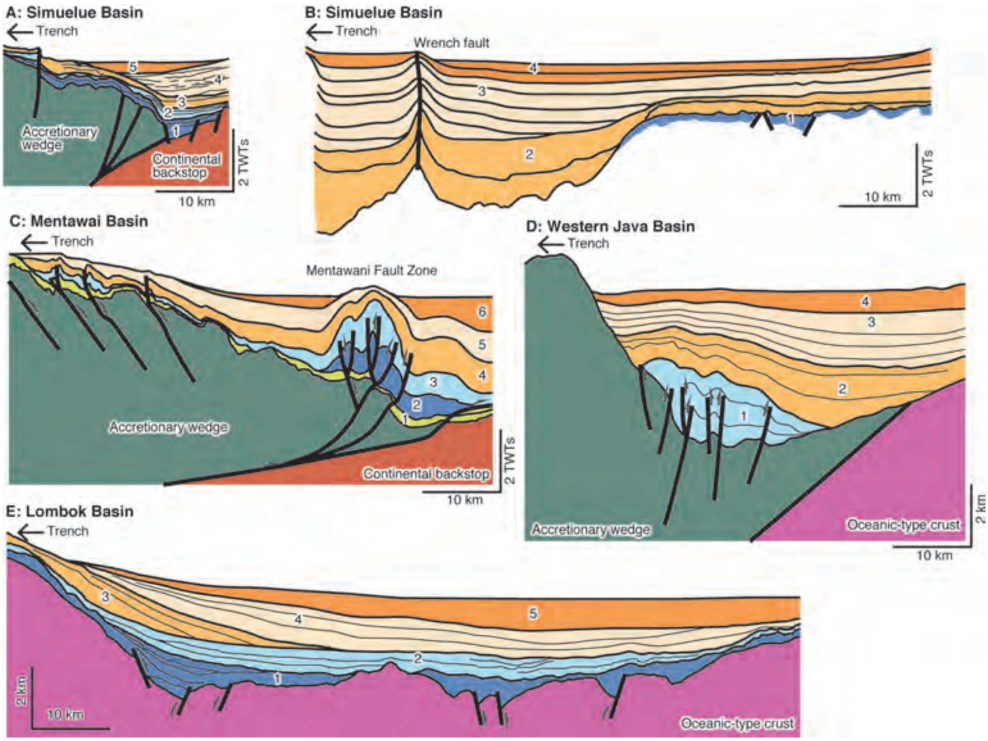

Figure 3. (A) Northern part of the Simuelue basin [15]. (B) Central part of the Simuelue basin [17]. (C) Mentawai basin [18]. (D) Western Java basin [19]. (E) Lombok basin along the Java Trench [20]. Locations of the survey lines are shown in **Figure 2**.

2.2.2. Mentawai basin

Deposition and deformation of the Mentawai basin have been strongly influenced by imbricated seaward-vergent fore-thrusts in the accretionary wedge and landward-vergent back-thrusts in the Mentawai fault zone [18, 22, 23] (**Figure 3C**). This fault zone has both characters of strike-slip fault (e.g., [23]) and back-thrust [18]. The fault zone may have initiated during Early-Middle Miocene and indicates the arc-parallel transpressional features along the boundary between the accretionary wedge and the continental backstop [18]. A continuous contraction developed the fold-thrust belt during Pliocene time.

The oldest deposits in this basin are the Middle Oligocene-Early Miocene, which thinly cover the forearc slope (Unit 1 in **Figure 3C**). Since the latest Early Miocene, uplift of the outer arc high began with imbricated fore-thrusts in the accretionary wedge, which reduced the thickness of forearc basin sediments trenchward to the outer arc high (Units 2–4). At the same time, landward-vergent back-thrusts also developed near the boundary between the accretionary wedge and the continental backstop. Although the activity of these thrusts waned in the early

Late Miocene (Unit 3), it reactivated in the late Late Miocene (Units 4 and 5). This intense deformation might be induced by accretion of thick Bengal Fan sediments and increase of plate convergence rate since the Late Miocene.

2.2.3. Western Java basin

The basement of the forearc basin is considered as an oceanic-type crust underlain by the shallow mantle deduced from large seismic velocities [14, 24] (**Figure 3D**). The seaward margin of the basin is bounded by the outer arc high with a sharp and steep scarp. Up to 4 km, sediments are accumulated along the outer arc high [19]. Depositional ages and sedimentary faces in the forearc basin are unknown, because of no drilling core in and around the basin. Growth of the accretionary wedge might cause a compressional deformation in association with landward-vergent back-thrusts in the early stages of the basin formation (Units 1 and 2), which folded and uplifted the basin strata. The deformation and thickness variations reduced during the following stages (Units 3 and 4). A total displacement is smaller than that in the Mentawai Basin. The steep landward slope of the outer arc high implies that the vertical growth might be contributed by basal accretion beyond the frontal wedge [19].

2.2.4. Lombok basin

The Lombok forearc basin is a large-sized (600 × 120 km) forearc basin with 3.5–4.5 km sediment thickness off Lombok Island [13, 16, 20]. The basement of this basin is also interpreted as an altered, heavily fractured piece of an older oceanic plate [25]. The basement is characterized by horst and graben structures (**Figure 3E**).

A progressive landward retreat of the depocenter in this basin is an evidence of a strong influence by growth of accretionary wedge (**Figure 3E**). Before the formation of the basin (Late Eocene), sediments filled topographic lows of horst and graben structures under an extensional tectonic regime (Unit 1 in **Figure 3E**). After the beginning of the uplift of the outer arc high (Unit 2 of the Early Oligocene), the basin subsided by a pull of the subducting oceanic plate (Unit 3 of the Late Oligocene), resulting in down lapping strata on the unconformity. From Late Oligocene to present (Units 4 and 5), the depocenter of the forearc basin continuously shifted landward without any compressional deformation or thrusting in the seaward margin of the basin.

3. Japan

3.1. Plate configuration

Two contrasting oceanic plates of the Pacific plate (old, cold, and steeply dipping) along the northern Japan and the Philippe Sea plate (young, hot, and gently dipping) along the southern Japan are subducting beneath the Okhotsk (North American) and Eurasian plates, respectively (**Figure 4**). Subduction of the Pacific plate is at a rate of ~9 cm/yr with almost orthogonal angle to the trench. The Japan Trench is one of the well-known examples of tectonically erosive margin (e.g., [26]).

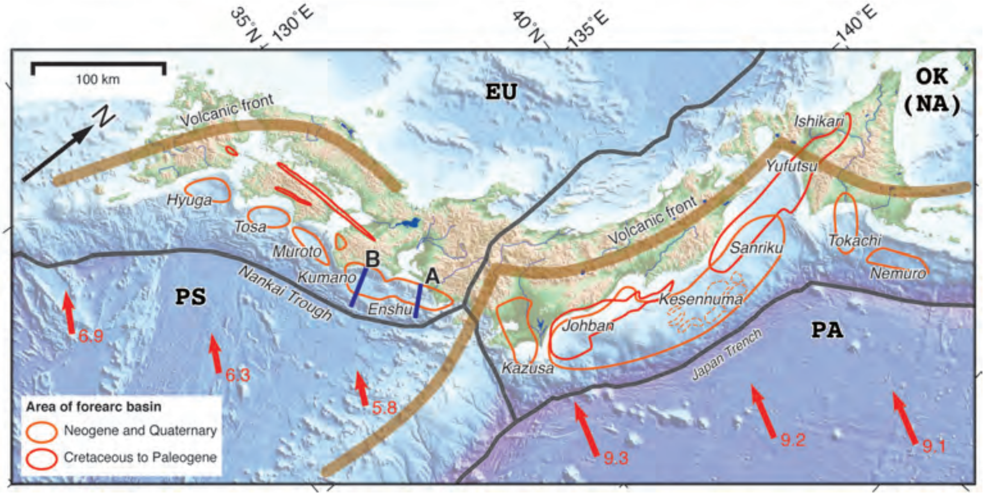

Figure 4. Index map of the Japan margin. Series of forearc basins are developed between volcanic fronts and trenches. Blue lines with labels A and B indicate locations of survey lines shown in **Figure 5**. Plate names: PA—Pacific, PS—Philippine Sea, OK—Okhotsk, NA—North American, EU—Eurasian plates. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the Okhotsk or Eurasian plate based on Ref. [8].

In the southwestern Japan margin, the Philippine Sea plate subducts at a rate of 5–7 cm/yr with moderate obliquity at present. In this margin, the subducting plate changed from the Pacific to the Philippine Sea plate as a migration of a triple junction [27]. Thick accretionary wedge (the Shimanto Complex) and segmented forearc basins have been built from Cretaceous to present between the volcanic front and the Nankai Trough (e.g., [28]).

3.2. Enshu and Kumano basins

Enshu and Kumano forearc basins have been developed along the landward side of prominent outer arc highs associated with regional megasplay faults along the Nankai Trough (**Figure 5**) [29, 30]. Huge amounts of studies about the basins in terms of seismic interpretations (e.g., [31]) and sediment cores obtained from IODP expeditions (e.g., [32, 33] and references therein).

The Kumano forearc basin of the ~3 km sediments has been evolved by combined influences of frontal accretion and megasplay faults (out-of-sequence thrusts). A brief history about the basin can be summarized: (1) small trench-slope basins developed during 6–2 Ma on older consolidated inner accretionary wedge of the Miocene-Pliocene (Units 1 and 2 in **Figure 5**). (2) Splay fault development caused by a shallowing of the decollement (2–1.3 Ma) uplifted the slope basins and merged them into one large forearc basins (Unit 3). The basin floor was draped by submarine-fan turbidities derived from gravity flows through submarine canyons. (3) Diachronous depositional surfaces were formed by spatial and temporal variations of the fault system around the basin during 1.3–0.9 Ma (Unit 4). Hemipelagic sediments were derived from the outer arc high in the seaward side of the basin, while terrigenous sediments were

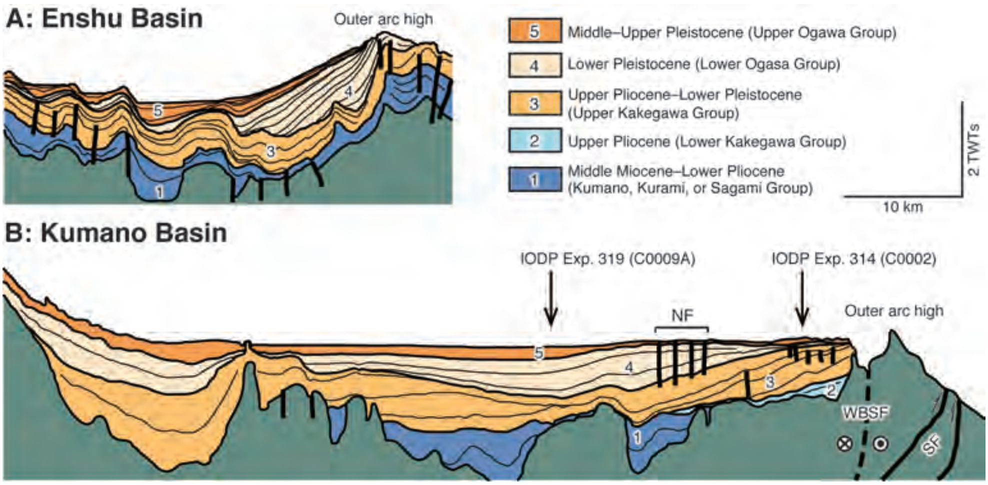

Figure 5. Interpretations of seismic profiles across (A) the Enshu and (B) the Kumano basins (modified from Ref. [37]). Seaward margins of the basins are characterized by landward tilting strata resulted from uplift of the outer arc highs. *Abbreviations*: NF—normal faults, SF—splay faults, WBSF—wedge boundary strike-slip fault. Locations of the profiles are shown in **Figure 4**.

deposited in the landward side. (4) Continuous uplift of the outer arc high by the splay faults resulted in a stable environment as the depocenter migrated landward (Unit 5 of <0.9 Ma). Normal faults and strike-slip faults overprinted the deformation in the seaward margins of the basins under the present condition [34–36]. No contractional deformation was recorded in the seaward side of the Kumano basin.

4. Aleutian-Alaskan forearc

4.1. Plate configuration

The Aleutian-Alaskan margin is a long (~3800 km) and arcuate subduction zone. The present configuration is marked by subduction of the Pacific plate beneath the North American plate at a rate of 6–7 cm/yr with increasing the obliquity from east (Alaskan margin) to west (central Aleutian margin). This margin might be established as a transition from erosional to accretionary margin occurred at ca. 6–3 Ma, triggered by an increase in sediment supply from glacial erosion in Alaska [38, 39].

4.2. Tugidak basin

The eastern Aleutian-western Alaskan margin is an example of double forearc basins where seaward (Sanak, Shumagin, Tugidak, Albatross, Stevenson) and landward (Cook Inlet and Shelikof Strait) basins are separated by the uplifted Kodiak Island and Kenai Peninsula

(**Figure 6**). This separation of forearc basins into two zones were explained by vertical growth of the accretionary wedge resulted from underplating [40] or flexural subsidence of the inland induced by a flat slab subduction [41].

The Tugidak basin is situated between Kodiak and Semidi Islands and at the landward side of the Tugidak anticline (**Figures 6** and **7**). The basin has a broad width and contains as much as 5 km of sediments from the late Miocene to the recent. The strata show that the depocenter shifted landward as the basin was shallowed from slope to shelf [42, 43]. The basin strata are broadly synclinal, but are contracted and thrusted near the Tugidak anticline that uplifted rapidly in Pliocene. On the other hand, normal faults are extensively developed in the landward side of the basin.

Although the depositional age is poorly constrained, a history of the basin development is as follows. The first unit (Unit 1 in **Figure 7B**) is slope-cover deposits unconformably covered on the lower Miocene or older rocks, before the Tugidak anticline uplifted. Deposition of Unit 2 corresponds to growth of the anticline in the Pliocene. The depocenter gradually shifted landward with onlap on both landward and seaward sides of the basin as the anticline uplifted. Nearly constant thickness of the Unit 3 indicates a seaward shift of the depocenter, suggesting that the sediment supply exceeded the rate of uplift or relative uplift of the forearc basement (inner wedge) to the anticline (outer wedge). Units 4 and 5 represented by a broad basin with

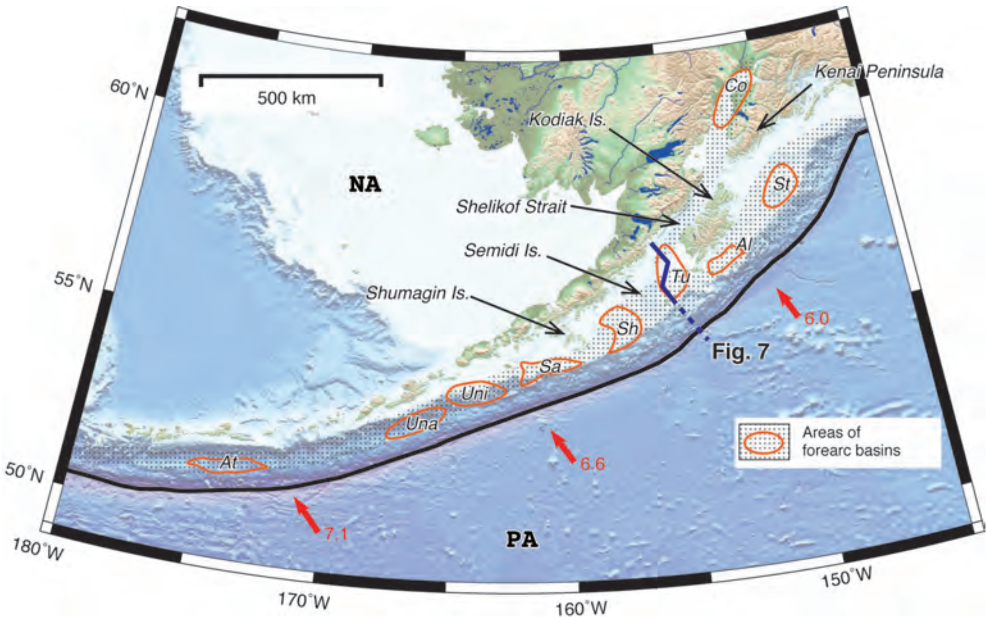

Figure 6. Index map of the Aleutian-Alaskan margin. Forearc basins: At—Atka, Una—Unalaska, Uni—Unimak, Sa—Sanak, Sh—Shumagin, Tu—Tugidak, Al—Albatross, St—Stevenson, Co—Cook Inlet basins. Plate names; PA—Pacific and NA is North American. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the North American plate based on Ref. [8].

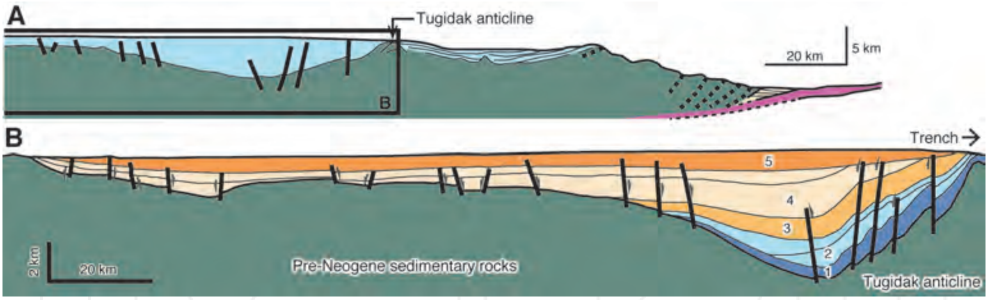

Figure 7. Interpretations of seismic profiles across the Tugidak basin (modified from Ref. [42]). The seaward margin is cut and tilted by several reverse faults related with growth of the Tugidak anticline. On the other hand, central and landward sides of the basin are characterized by numerous normal faults. Locations of the profiles are shown in **Figure 6**.

a landward shift of the depocenter, implying renewed growth of the anticline and regional subsidence of the forearc basement with numerous normal faults.

5. Lesser Antilles margin

5.1. Plate configuration

Caribbean plate was generated in the eastern Pacific as a Late Cretaceous oceanic plateau and advanced eastward between the North American and South American plates since Eocene. Subduction magmatism has constructed the Lesser Antilles island arc on the Caribbean plate during the past 40 m.y. A chain of volcanic islands stretches 800 km, forming a magmatic-arc platform (**Figure 8**). The present configuration in this region is characterized by the subduction of the North American plate (the Late Cretaceous Atlantic oceanic crust) beneath the Caribbean plate at a rate of ~2 cm/yr.

The Barbados ridge accretionary complex (**Figure 8**), which is the largest accretionary complex on Earth, has formed by frontal and basal accretion of sediments from the North American plate to the Caribbean plate since Eocene (e.g., [44]). It is <40 km wide and 7 km maximum thickness in the northern margin and is 300 km wide and up to 20 km thickness in the southern margin. Most of the sediments accreted are sourced from Orinoco River along the trench.

5.2. Forearc basins

The Tobago forearc basin (Tobago Trough) is one of the largest forearc basins in the world [44–47], which has 100 km wide, 200 km long, and more than 10 km-thick sediments (**Figure 9A** and **B**). The basin has formed between the crystalline platform of the Lesser Antilles arc and the Barbados Ridge accretionary complex. Barbados Island is a part of the outer arc high bounding the seaward margin of the basin. The strata near the outer arc high are deformed by landward-vergent thrusts in the retro-wedge (Unit 1 in **Figure 9B**). Development of these thrusts probably began in early Miocene or earlier, which imbricated forearc basin strata as a duplex between the

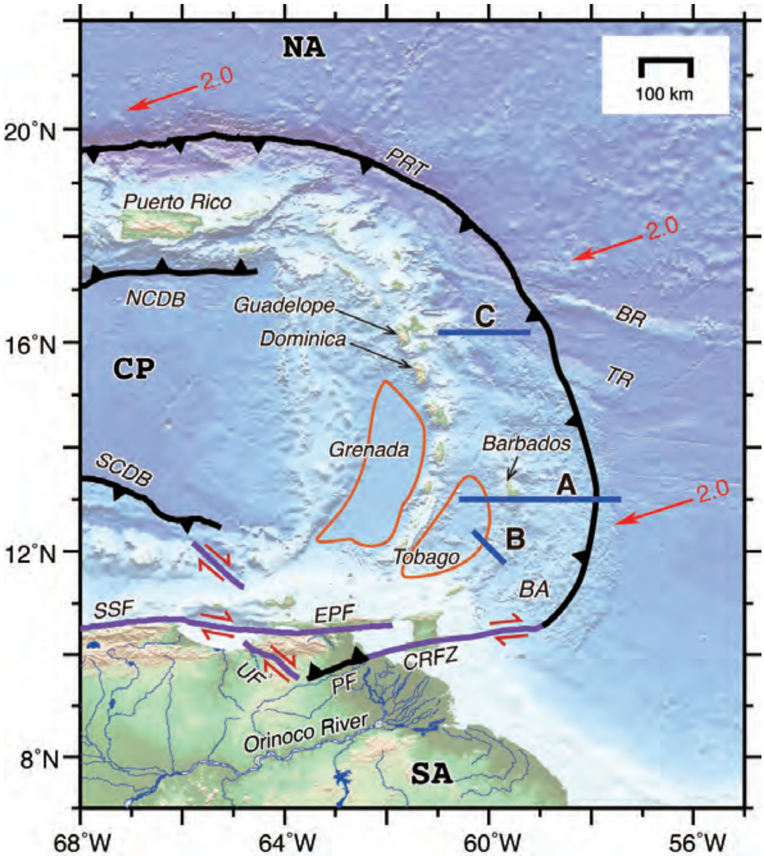

Figure 8. Index map of the Lesser Antilles margin. Blue lines with labels A–C indicate locations of survey lines shown in **Figure 9**. Plate names: NA—North American, CP—Caribbean, SA—South American plates. Other abbreviations: PRT—Puerto Rico Trench, BR—Barracuda Ridge, TR—Tiburon Ridge, BA—Barbados Ridge accretionary complex, NCDB—Northern Caribbean deformed belt, SCDB—Southern Caribbean deformed belt, SSF—San Sebastian Fault, EPF—El Pilar Fault, CRFZ—Central Range fault zone, UF—Urica Fault, PF—Pirital Fault. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the Caribbean plate based on Ref. [8].

accretionary wedge and the early detachment in late Miocene or Pliocene time. The horizontal contraction of the basin was estimated to be between 4 and 45%, increasing southward [45]. Thickened outer arc high due to this contraction might increase tectonic loading, resulting in a large subsidence and trenchward shift of the depocenter in Pliocene and Pleistocene (Unit 3 in **Figure 9B**).

Forearc basins off Guadeloupe and Dominica have been developed in the northern part of this margin where a seismic Barracuda and Tiburon ridges are obliquely subducting (e.g., [48–50]) (**Figures 8** and **9C**). The buoyant crust of the Tiburon Ridge that accreted within the past 3.5 m.y. forms a seaward-dipping backstop in contact with the lower half of the accretionary wedge [48]. As much as half of the sediments underthrust at the toe of the accretionary wedge

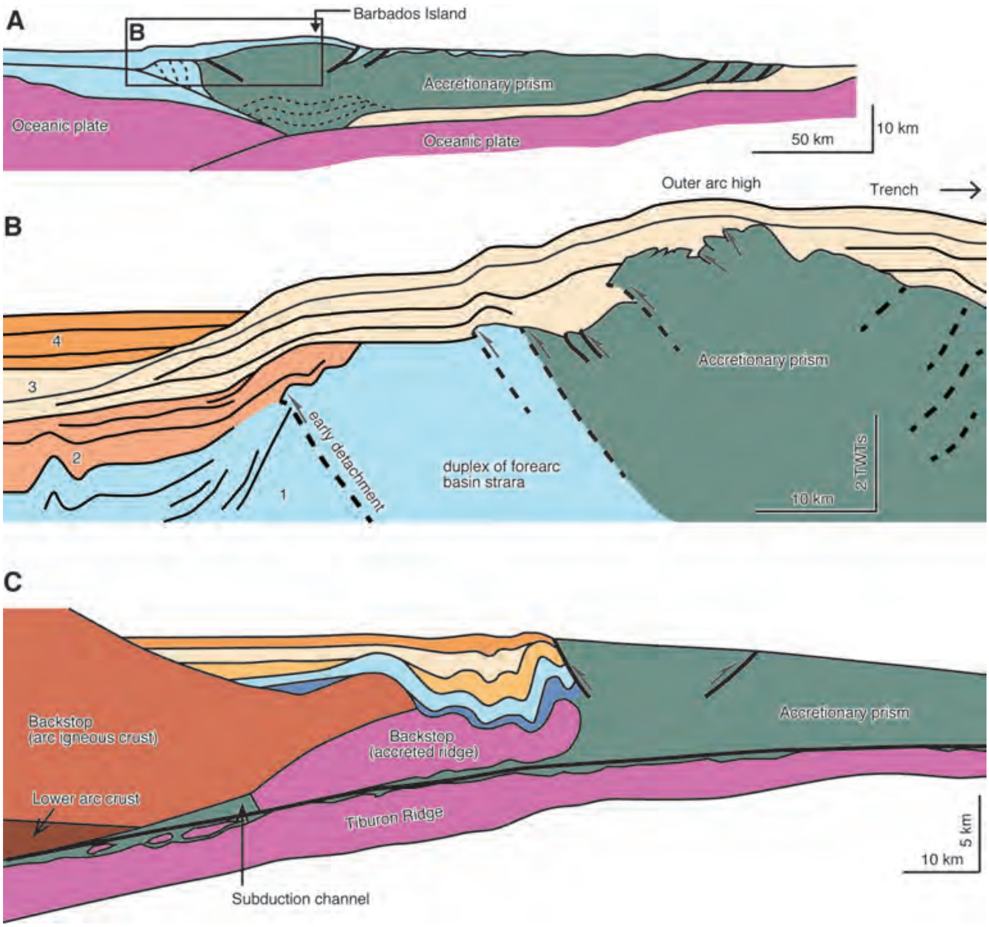

Figure 9. (A) Interpretations of the seismic profiles across the Tobago Trough in the Lesser Antilles forearc. (B) Details of seaward margin of the Tobago forearc basin. Modified from Ref. [45]. (C) A cross section across a forearc basin off Guadeloupe (modified from Ref. [48]). Seaward margins of both basins are deformed and uplifted by backthrusts. Locations of the profiles are shown in **Figure 8**.

appears to be subducted to the toe of the backstop, which were transported through a subduction channel between the subducting oceanic crust and the accretionary wedge.

6. South American margin (Columbia-Ecuador-Peru-Chile)

6.1. Plate configuration

The South American margin is a very long (~8000 km) subduction zone where the oceanic Nazca (6–7 cm/yr) and Antarctic (<2 cm/yr) plates subducts beneath the continental South

American plate (**Figure 10**). Due to its large length, a wide variety of styles of subduction is recognized, in terms of tectonic erosion/accretion [26, 51], oblique subduction [52, 53], and flat-slab and ridge subduction [54]. The width between the shelf and the trench is relatively small, and there are no large accretionary complex that does not exist throughout the margin.

6.2. Forearc basins along the Columbia-Ecuador margin

Along the Columbia margin, double forearc basins elongate parallel to the trench similar with the southwestern Alaskan margin. The inner basin is mainly onshore, being synclinal sags from Paleogene with very large (~10 km) depth (e.g., Tumaco Basin [55]) (**Figure 11A**). On

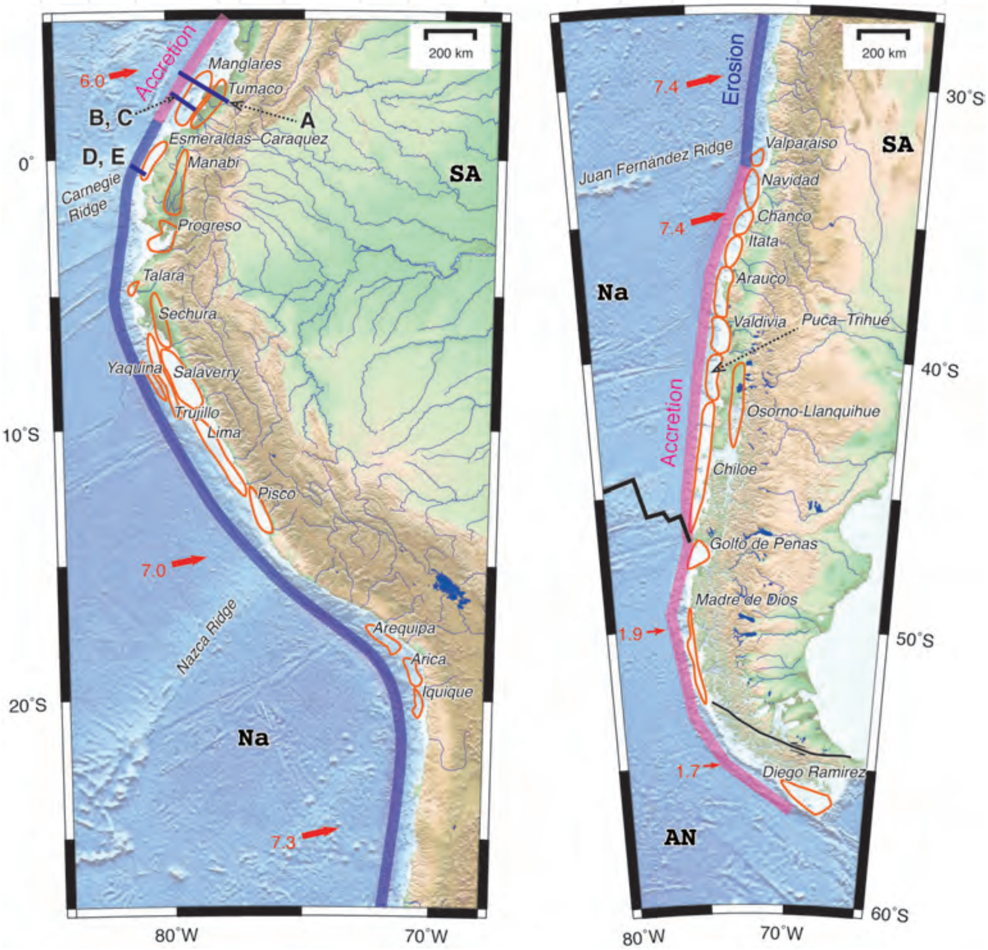

Figure 10. Index map of the South American margin (Colombian-Ecuador-Peru-Chile). Blue lines with labels A–E indicate locations of survey lines shown in **Figure 11**. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the South American plate based on [8].

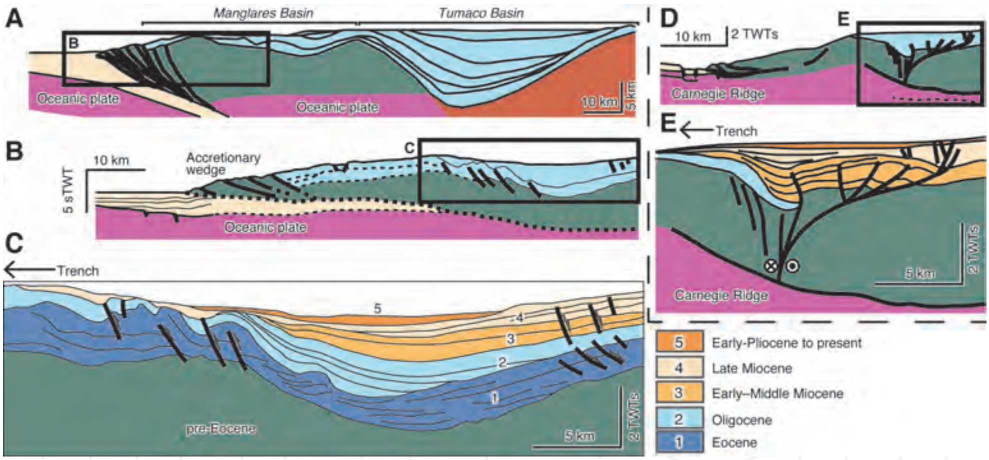

Figure 11. (A) Schematic cross section across the Tumaco and Manglares basins along the north Ecuador and south Colombia margin (modified from Ref. [58]). (B) Enlargement of the box in A. (C) Interpretation of seismic profile of the Manglares Basin (modified from Ref. [56]). Seismic units; 1—Eocene, 2—Oligocene, 3—Early-Middle Miocene, 4—Middle-Late Miocene, 5—Pliocene-Pleistocene. (D) A cross-section across the Ecuador margin (modified from Ref. [57]). (E) Interpretation of seismic profile for the boxed area in (C). Flower-structures are conspicuous. The depositional ages of the seismic units are not determined. Locations of the profiles are shown in **Figure 10**.

the other hand, offshore forearc basins are smaller and shallower than the inner basins (e.g., Manglares Basin [56]) (**Figure 11B** and **C**).

The Manglares basin is fronted by the Colombian accretionary wedge. The substrate of the basin is possibly accreted mass of an oceanic plateau. The basal unit (Unit 1 in **Figure 11C**) is composed of deep-water turbidite of the middle to late Eocene. The constant thickness suggests that they are slope (bathyal) deposits. In the Oligocene to the middle Miocene (Units 2 and 3), the outer arc high began to uplift in response to the plate kinematic reorganization during 40–35 Ma, inferred from landward propagation and onlap of the deposition. Unit 4 (late Miocene) corresponds to the overfilled sediments deposited on the truncated outer arc high, resulting in seaward progradation of the sediments. Sediments in Unit 5 fill the central part of the basin during a relax-phase of subsidence. Seaward-vergent reverse faults have tilted these forearc basin sediments landward.

On the other hand, a forearc basin along the Ecuador margin (southern part of the Esmeraldas-Caraquez Basin) is highly deformed by strike-slip faults, where Carnegie ridge crest is being subducted [57]. Conspicuous flower-structures popped up sediments in the basin. The strike-slip fault system terminates at depth against Carnegie ridge beneath the margin.

7. Tonga-Kermadec-Hikurangi margin

7.1. Margin configuration

Tonga-Kermadec-Hikurangi margin is a more than 3000 km-long boundary between the Pacific and Indo-Australian plates. Along the Tonga-Kermadec margin, a thin and less buoyant oceanic crust with deep water depth subducts beneath island arc crusts of Tonga-Kermadec ridges (**Figure 12A**). The Tonga-Kermadec margin is a typical example of tectonically erosive margins [4]. Along the Hikurangi margin, a thick (10–15 km) and buoyant oceanic crust (Hikurangi Plateau composed of Cretaceous large igneous province) with shallow water depth underthrusts beneath North Island of New Zealand (**Figure 12**). The Hikurangi margin is strongly controlled by westward oblique subduction of the Pacific plate.

At the Hikurangi margin, the subduction began at 25 Ma, when the plate motion reorganized from transtension to convergent. The Axial and Coastal ranges are composed of Mid-Cretaceous-Paleogene passive margin sedimentary rocks and Late Cretaceous accretionary

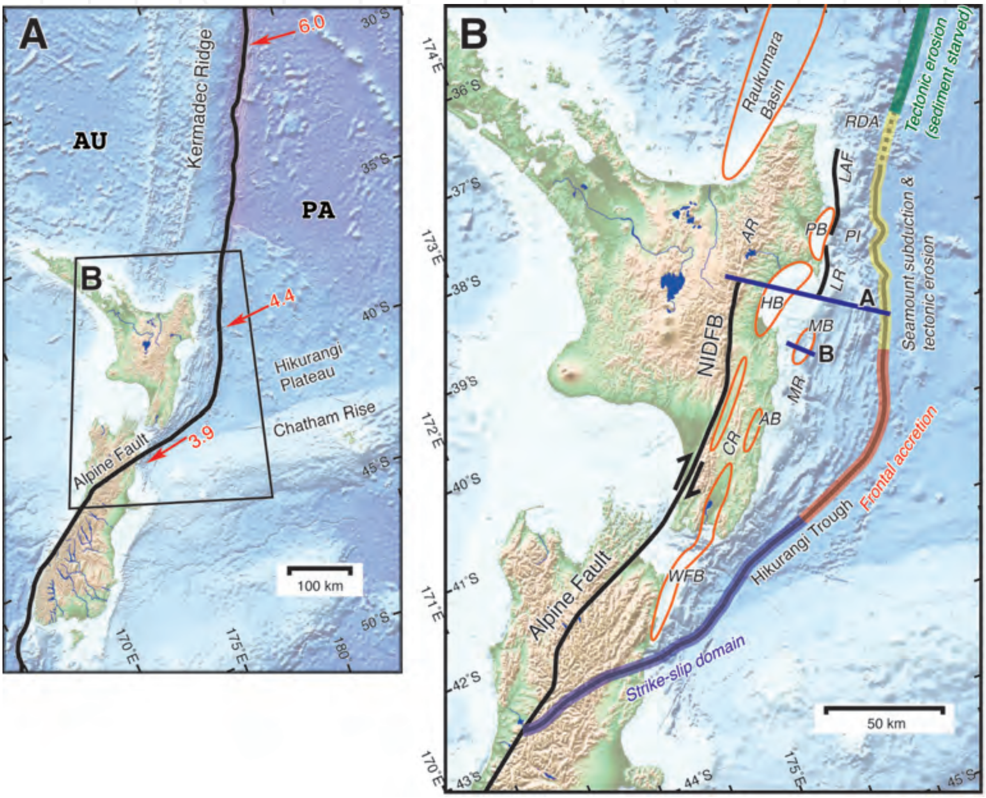

Figure 12. (A) Index map around the Kermadec-Hikurangi margin. Plate names; AU—Australian and PA—Pacific plates. Red arrows indicate the direction and velocity [cm/yr] of plate motion relative to the Australian plate based on Ref. [8]. (B) Tectonic map of the southern Kermadec-Hikurangi margin which can be divided into four domains from the north; tectonic erosion (southern Kermadec), seamount subduction and tectonic erosion (northern Hikurangi), frontal accretion (central Hikurangi), strike-slip (southern Hikurangi). Blue lines with labels A–B indicate locations of the profiles shown in **Figure 13**. Forearc basins; PB—Poverty Bay, HB—Hawke Bay, MB—Motu-o-Kura, AB—Akitio, WFB—Wairarapa-Flaxbourne basins. Abbreviations; RDA—Ruatoria debris avalanche, PI—Poverty Indentation, LAF—Lachlan-Ariel faults, LR—Lachlan Ridge, MR—Motu-o-Kura Ridge, CR—Coastal Range, AR—Axial Range, and NIDFB—North Island Dextral fault belt.

rocks, which have been affected by trench-parallel dextral strike-slip fault (the North Island Dextral Fault Belt) due to oblique subduction and has role of backstops of forearc deformation.

The southern Kermadec-Hikurangi margin can be separated into four sections (**Figure 13B**). The southern Kermadec section is a tectonically erosive (sediment starved) margin where a relatively thin subducting crust and thin trench fill sediments (<1 km) with large orthogonal convergent rate are dominated. The northern Hikurangi section is characterized by not only tectonic erosion but also submarine landslides and debris avalanches, such as Ruatoria debris avalanche and Poverty Indentation.

In the central Hikurangi section, subducting crust of the Hikurangi Plateau is thicker (more buoyant) with smoother surface topography than the north section. Frontal accretion formed a wide (>100 km) accretionary wedge represented by seaward-verging imbricated thrusts and ridges (e.g., [59, 60]), because of thick (~4 km) trench fill sediments supplied through the Hikurangi Trough from an area of high mountains in South Island [61]. The deformation front migrated seaward at 30–100 km/m.y. [59]. In the southern Hikurangi section, the orthogonal

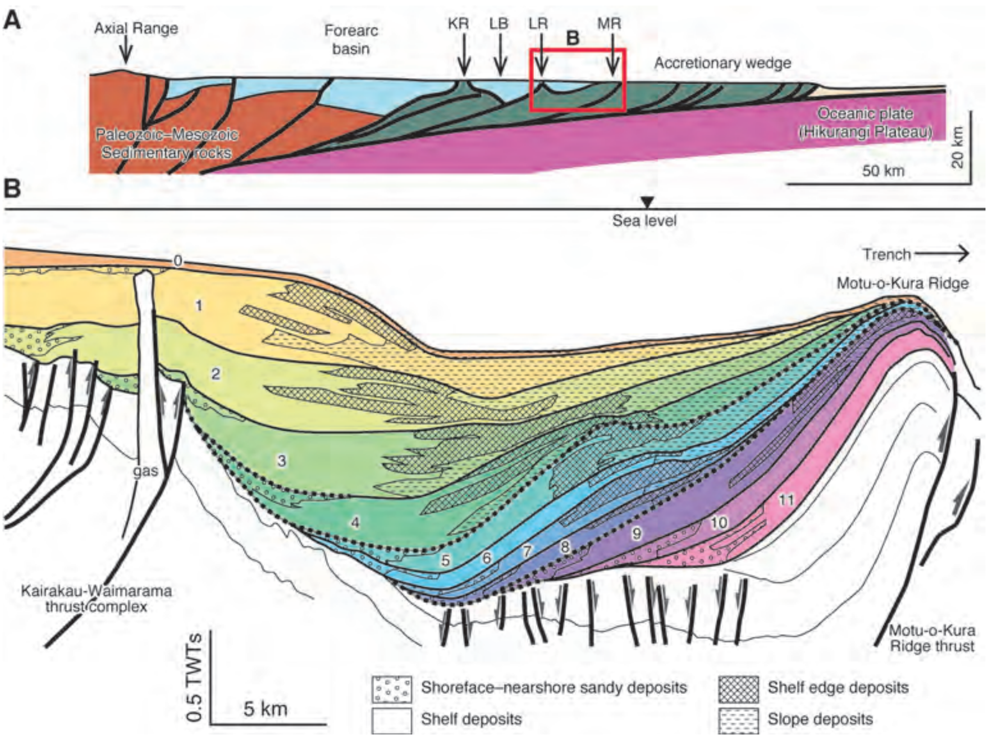

Figure 13. (A) A generalized cross section across the Hikurangi margin (modified from Ref. [64]). *Abbreviations*; MR—Motu-o-Kura Ridge, LR—Lachlan Ridge, LB—Lachlan Basin, KR—Kidnappers Ridge. (B) Details of the sequence units and depositional faces of the Motu-o-Kura Basin (modified from Ref. [63]). This basin is one of the upper trench-slope basins on the accretionary wedge, bounded by Motu-o-Kura Ridge at the seaward margin and Kidnappers Ridge at the landward margin.

convergent rate becomes slow (2.5–3.0 cm/yr). The plate boundary merges into the Alpine Fault strike-slip fault systems at the southern end. Accretionary wedge becomes narrower from central to this section (<50 km).

7.2. Motu-o-Kura basin

The main forearc basin is located inland in the central and southern Hikurangi section and offshore in the northern Hikurangi section (Poverty Bay basin and Hawke Bay basin). Number of trench-slope basins develop offshore (Akitio basin [62] and Motu-o-Kura basin [63]) on the actively growing accretionary wedge (**Figure 13A**). Because some of the basins were emerged several times during their evolutions, the deposition was highly affected by eustatic sea-level changes in addition to tectonics. In addition, the basin depocenters migrated three dimensionally with diachronous unconformities, due to the oblique subduction and segmented geometries of the trench-slope basins.

The Motu-o-Kura basin [63] includes sediments from ca. 1.1 Ma. The lower sequences (Units 9–11 in **Figure 13B**) show constant thickness in the basin and even on the Motu-o-Kura Ridge, which were interpreted as slope deposits before the ridge activated. The middle and upper sequences (Units 0–8) represent a tectonic growth sequence reflecting sedimentation contemporaneous with thrust faulting and uplift of the ridge. The strata in the basin exhibit gentle synclinal folding associated with normal faults in the center of the basin. The Motu-o-Kura Ridge thrust increased the displacement rate in the middle sequences (Units 5–8) are apparent at ca. 800 and ca. 430 ka as revealed by growth strata.

8. Summary

This review showed deposition and deformation styles of accretionary-type forearc basins were much variable. Especially, deformations in seaward margins of forearc basins are highly influenced by evolutional histories of accretionary wedge composed of a prowedge developing on the subducting plate and retro-wedges (e.g., [65–67]). Sandbox analog experiments showed two stages of the wedge evolutions [68]; Stage I was characterized by dominant retro-wedge thrusting and conjugate prowedge kinking and folding and by rapid uplift of the axial zone (outer arc high), and Stage II was characterized by progressive stacking of thrust sheets in the prowedge, by slow retro-wedge thrusting, and by slow to very slow uplift in the axial zone. Transition from stage I to stage II occurred when the growing wedges reached the critical height at which they behaved as a backstop for further prowedge accretion. In addition, the ratio of thickness of backstop (H_b) to thickness of accreted sediments (H_c) was considered as a factor for vergence partitioning in the wedge [69], suggesting the high and low (<1) ratios of H_b/H_c could resulted in proward vergence and doubly (pro- and retro-ward) vergence, respectively.

Deformation of accretionary-type forearc basins can be similarly classified into two models. We propose the following models for accretionary-type forearc basins (**Figure 14**), which are: (A) single-wedge (asymmetrically doubly vergent), (B) two-wedge (symmetrically doubly vergent), and (C) strike-slip models.

Single-wedge model: Forearc basins in this model are less contracted but tilted landward, because the outer arc highs move seaward with displacements of the fore-thrusts (splay faults) in the accretionary wedges. The basin widths are extended by this seaward movement of the outer-arc high as well as landward migration of the depocenter. Subsidence of the basin may be ascribed to an isostatic subsidence due to thickened wedge or tectonic erosion beneath the basin. Examples of this model are Lombok Basin, Nankai Trough (Kumano and Enshu troughs), Hikurangi Trough (Motu-o-Kura basin), and Colombia margin (Manglares basin).

Two-wedge model: The seaward margins of forearc basins in this model are more contracted with folds and faults by landward-vergent thrusts in the retro-wedges. The basin widths enlarge landward with migration of the depocenters. Basin subsidence can be caused by tectonic loading of thickened wedges or basal erosion. Examples of this model are Sunda (Western Java basins), Alaskan (Tugidak basin), and Lesser Antilles (Tobago basin) margins. Back-thrusts-related deformations in these margins are restricted in the early stages of the basin formations. The basin strata in the recent stage are generally undeformed.

Strike-slip model: Obliquity of subducting plates can be an additional factor to modify the basin formations. High obliquity causes a strain-partitioning along the seaward margin of the basins with strike-slip faults. Transpression and transtension lead to compressional and extensional deformations, respectively. They may further overprint the preexisting deformations of single- and two-wedge models. Examples of this model are Sumatra (Simuelue and Mentawai basins), Ecuador, and southern Chile margins.

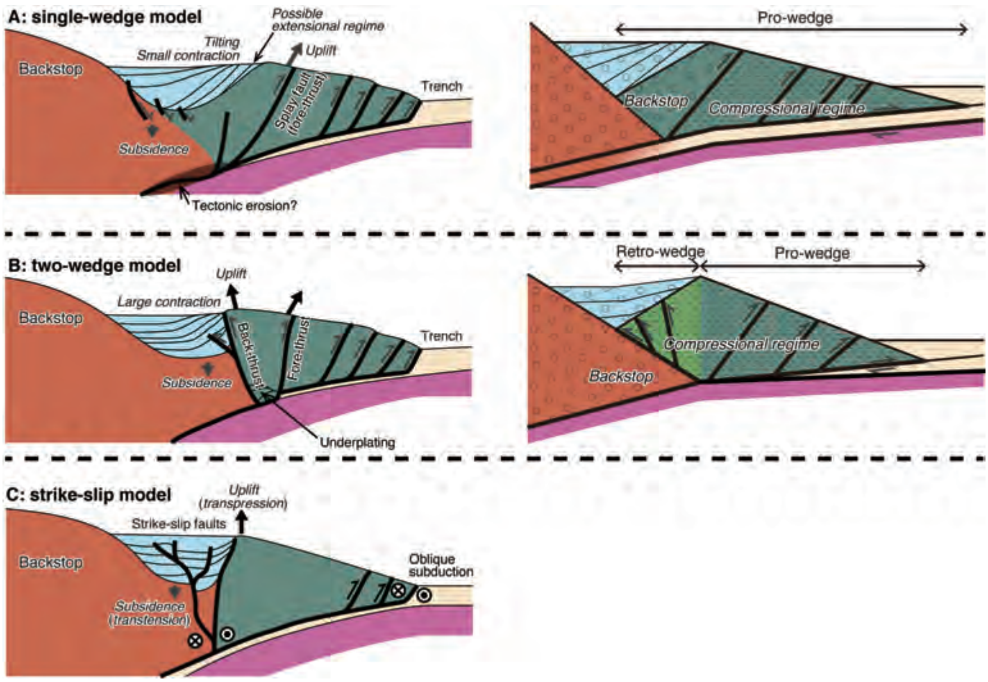

Figure 14. Schematic models of three models of deformation styles in forearc basins. (A) Single-wedge model with asymmetrical doubly vergent (singly vergent) uplift. (B) Two-wedge model with symmetrical doubly vergent uplift. (C) Strike-slip model.

These single- and two-wedge models may be comparable with P-C and P-U-C modes of [70]. The P-C mode, where pro-wedge (P) and conduit of subducting materials (C) are active, is characterized by landward-dipping backstops. Whereas the P-U-C mode (U means uplifted plug) creates an apparent seaward-dipping backstops. Amounts of materials added by underplating (basal accretion) or removed by tectonic erosion (basal erosion) can influence degree of uplift or subside the axes of the wedges (outer arc highs), respectively; the former grows uplifted plug between the pro- and retro-wedges. Therefore, material flux between the subducting and overriding plates can be one of the major causes of the differences between the two models.

Furthermore, we speculate that the retro-wedge is overthrusted on the mechanical backstop, when the cross-sectional widths of the pro-wedge are too small to absorb the total strain caused by underthrusting of the subducting plate. Internal strength (friction and cohesion) and total thickness (tectonic load) of the wedges may be other factors to determine the thrust polarity. For example, basins of the two-wedge models, such as the Western Java and Tobago basins, were deformed by landward-vergent thrusts on the retro-wedges. However, these deformations are recognized only in the lower sequences, indicating the thrust activities waned as the accretionary wedges grew.

Changes of subduction direction could cause oblique subduction, which overwrite the preexistence deformations in single-wedge (e.g., Nankai Trough) and two-wedge (e.g., Mentawai Basin) models by transpressional and transtensional deformations (strike-slip model). Spatial and temporal variations of mechanical conditions at the subduction zones might be recorded as styles of deposition and deformation of forearc basins. Forearc basin is a potentially powerful tool for unraveling histories and mechanisms of subduction zone processes.

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References

[1] Dickinson WR. Forearc basins. In: Busby CJ, Ingersoll RV, editors. Tectonics of Sedimentary Basins, chap. 6. Oxford, United Kingdom: Blackwell Science;1995. pp. 221-261.

[2] Noda A. Forearc basins: Types, geometries, and relationships to subduction zone dynamics. Geological Society of America Bulletin. 2016;**128**(5-6):879-895

[3] Stern RJ. Subduction zones. Reviews of Geophysics. 2002;**40**(4):1012. DOI:10.1029/2001RG000108.

[4] Clift PD, Vannucchi P. Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. Reviews of Geophysics. 2004;**42**(RG2001). DOI: 10.1029/2003RG000127.

[5] Draut AE, Clift PD. Basins in arc-continent collisions. In: Busby C, Azor A, editors. Tectonics of Sedimentary Basins: Recent Advances, chap. 17. Chichester, UK: Wiley-Blackwell; 2012. pp. 347-368

[6] Wells RE, Blakely RJ, Sugiyama Y, Scholl DW, Dinterman PA. Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion? Journal of Geophysical Research. 2003;**108**(B10, 2507). DOI: 10.1029/2002JB002072

[7] Song TRA, Simons M. Large trench-parallel gravity variations predict seismogenic behavior in subduction zones. Science. 2003;**301**(5633):630-633

[8] Argus DF, Gordon RG, DeMets C. Geologically current motion of 56 plates relative to the no-net-rotation reference frame. Geochemistry, Geophysics, Geosystems. 2011;**12**(Q 11001):444. DOI: 10.1029/2011GC003751.

[9] McCaffrey R. The tectonic framework of the Sumatran subduction zone. Annual Review of Earth and Planetary Sciences. 2009;**37**(1):345-366

[10] Moore GF, Curray JR, Moore DG, Karig DE. Variations in geologic structure along the Sunda Fore Arc, northeastern Indian Ocean. In: Hayes DE, editor. The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophysical Monograph, no. 23. Washington, DC, United States: American Geophysical Union;1980. pp. 145-160.

[11] Müller RD, Sdrolias M, Gaina C, Roest WR. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochemistry, Geophysics, Geosystems. 2008;**9**(Q04006). DOI: 10.1029/2007GC001743.

[12] Berglar K, Gaedicke C, Franke D, Ladage S, Klingelhoefer F, Djajadihardja YS. Structural evolution and strike-slip tectonics off north-western Sumatra. Tectonophysics. 2010; **480**:119-132

[13] van der Werff W. Variation in forearc basin development along the Sunda Arc, Indonesia. Journal of Southeast Asian Earth Sciences. 1996;**14**(5):331-349

[14] Grevemeyer I, Tiwari VM. Overriding plate controls spatial distribution of megathrust earthquakes in the Sunda–Andaman subduction zone. Earth and Planetary Science Letters. 2006;**251**(3-4):199-208

[15] Singh SC, Carton H, Tapponnier P, Hananto ND, Chauhan APS, Hartoyo D, Bayly M, Moeljopranoto S, Bunting T, Christie P, Lubis H, Martin J. Seismic evidence for broken oceanic crust in the 2004 Sumatra earthquake epicentral region. Nature Geoscience. 2008;**1**(11):777-781

[16] van der Werff W, Prasetyo H, Kusnida D, van Weering TCE. Seismic stratigraphy and Cenozoic evolution of the Lombok Forearc Basin, Eastern Sunda Arc. Marine Geology. 1994;**117**:119-134

[17] Berglar K, Gaedicke C, Lutz R, Franke D, Djajadihardja YS. Neogene subsidence and stratigraphy of the Simeulue forearc basin, Northwest Sumatra. Marine Geology. 2008; **253**(1-2):1-13

[18] Mukti MM, Singh SC, Deighton I, Hananto ND, Moeremans R, Permana H. Structural evolution of backthrusting in the Mentawai Fault Zone, offshore Sumatran forearc. Geochemistry, Geophysics, Geosystems. 2012;**13**(Q12006). DOI: 10.1029/2012GC004199.

[19] Kopp H, Hindle D, Klaeschen D, Oncken O, Reichert C, Scholl D. Anatomy of the western Java plate interface from depth-migrated seismic images. Earth and Planetary Science Letters. 2009;**288**(3-4):399-407

[20] Lüschen E, Müller C, Kopp H, Engels M, Lutz R, Planert L, Shulgin A, Djajadihardja YS. Structure, evolution and tectonic activity of the eastern Sunda forearc, Indonesia, from marine seismic investigations. Tectonophysics. 2011;**508**:6-21

[21] De Smet MEM, Barber AJ. Tertiary stratigraphy. In: Barber AJ, Crow MJ, Milsom JS, editors. Sumatra: Geology, Resources and Tectonic Evolution, *Memoir*, vol. 31, chap. 7. Geological Society, London; 2005. pp. 86-97

[22] Singh SC, Hananto N, Mukti M, Robinson DP, Das S, Chauhan A, Carton H, Gratacos B, Midnet S, Djajadihardja Y, Harjono H. Aseismic zone and earthquake segmentation associated with a deep subducted seamount in Sumatra. Nature Geoscience. 2011;**4**(5):308-311

[23] Berglar K, Gaedicke C, Ladage S, Thöle H. The Mentawai forearc sliver of Sumatra: A model for a strike-slip duplex at a regional scale. Tectonophysics. 2016; DOI: 10.1016/j.tecto.2016.09.014.

[24] Kopp H, Klaeschen D, Flueh ER, Bialas J, Reichert C. Crustal structure of the Java margin from seismic wide-angle and multichannel reflection data. Journal of Geophysical Research. 2002;**107**(B2). DOI: 10.1029/2000JB000095.

[25] Planert L, Kopp H, Lueschen E, Mueller C, Flueh ER, Shulgin A, Djajadihardja Y, Krabbenhoeft A. Lower plate structure and upper plate deformational segmentation at the Sunda–Banda arc transition, Indonesia. Journal of Geophysical Research. 2010;**115**(B08107). DOI: 10.1029/2009JB006713.

[26] von Huene R, Lallemand S. Tectonic erosion along the Japan and Peru convergent margins. Geological Society of America Bulletin. 1990;**102**(6):704-720

[27] Kimura G, Hashimoto Y, Kitamura Y, Yamaguchi A, Koge H. Middle Miocene swift migration of the TTT triple junction and rapid crustal growth in southwest Japan: A review. Tectonics. 2014;**33**(7):1219-1238

[28] Taira A. Tectonic evolution of the Japanese Island arc system. Annual Review of Earth and Planetary Sciences. 2001;**29**:109-134

[29] Park JO, Tsuru T, Kodaira S, Cummins PR, Kaneda Y. Splay fault branching along the Nankai subduction zone. Science. 2002;**297**(5584):1157-1160

[30] Strasser M, Moore GF, Kimura G, Kitamura Y, Kopf AJ, Lallemant S, Park JO, Screaton EJ, Xin S, Underwood MB, Zhao X. Origin and evolution of a splay fault in the Nankai accretionary wedge. Nature Geoscience. 2009;**2**(9):648-652

[31] Takano O, Itoh Y, Kusumoto S. Variation in forearc basin configuration and basin-filling depositional systems as a function of trench slope break development and strike-slip movement: Examples from the Cenozoic Ishikari–Sanriku-Oki and Tokai-Oki–Kumano-Nada Forearc Basins, Japan. In: Itoh Y, editor. Mechanism of Sedimentary Basin Formation: Multidisciplinary Approach on Active Plate Margins. Rijeka, Croatia: InTech; 2013. pp. 3-25

[32] Moore GF, Boston BB, Strasser M, Underwood MB, Ratliff RA. Evolution of tectono-sedimentary systems in the Kumano Basin, Nankai Trough forearc. Marine and Petroleum Geology. 2015;**67**:604-616

[33] Ramirez SG, Gulick SPS, Hayman NW. Early sedimentation and deformation in the Kumano forearc basin linked with Nankai accretionary prism evolution, southwest Japan. Geochemistry, Geophysics, Geosystems. 2015;**16**:1616-1633

[34] Martin KM, Gulick SPS, Bangs NLB, Moore GF, Ashi J, Park JO, Kuramoto S, Taira A. Possible strain partitioning structure between the Kumano fore-arc basin and the slope of the Nankai Trough accretionary prism. Geochemistry, Geophysics, Geosystems. 2010;**11**(Q0AD02). DOI: 10.1029/2009GC002668.

[35] Moore GF, Boston BB, Sacks AF, Saffer DM. Analysis of normal fault populations in the Kumano Forearc Basin, Nankai Trough, Japan: 1. Multiple orientations and generations of faults from 3-D coherency mapping. Geochemistry, Geophysics, Geosystems. 2013;**14**(6):1989-2002

[36] Tsuji T, Ashi J, Ikeda Y. Strike-slip motion of a mega-splay fault system in the Nankai oblique subduction zone. Earth, Planets and Space. 2014;**66**(1):120. doi: 10.1186/1880-5981-66-120

[37] Goto S, and others. Fuel Resource Geology Map: Eastern Nankai Trough. FR–2. Tsukuba, Japan: Geological Survey of Japan, AIST 2010, p. 10

[38] Scholl DW, Vallier TL, Stevenson AJ. Geologic evolution and petroleum geology of the Aleutian Ridge. In: Scholl DW, Grantz A, Vedder JG, editors. Geology and Resource Potential of the continental margin of western North America and adjacent ocean basins: Beaufort Sea to Baja California, Earth Science Series, vol. 6, chap. 7. Houston, TX, United States (USA): Circum-Pacific Council for Energy and Mineral Resources; 1987. pp. 123-155.

[39] von Huene R, Miller JJ, Weinrebe W. Subducting plate geology in three great earthquake ruptures of the western Alaska margin, Kodiak to Unimak. Geosphere. 2012;**8**(3):628-644

[40] Clendenen WS, Sliter WV, Byrne T. Tectonic implications of the Albatross sedimentary sequence, Sitkinak Island, Alaska. In: Bradley DC, Ford AB, editors. Geologic studies in Alaska, U.S. Geological Survey Bulletin, vol. 1999. U.S. Geological Survey;1992. pp. 52-70.

[41] Jadamec MA, Billen MI, Roeske SM. Three-dimensional numerical models of flat slab subduction and the Denali fault driving deformation in south-central Alaska. Earth and Planetary Science Letters. 2013;**376**:29-42

[42] Fisher MA. Structure and tectonic setting of continental shelf southwest of Kodiak Island, Alaska. American Association of Petroleum Geologists Bulletin. 1979;**63**(3):301-310

[43] von Huene R, Fisher M, Hampton M, Lynch M. Petroleum potential, environmental geology, and the technology for exploration and development of the Kodiak lease sale area #61, Open-File Report, vol. 80-1082. U. S. Geological Survey 1980, 70 p.

[44] Westbrook GK, Ladd JW, Buhl P, Bangs N, Tiley GJ. Cross section of an accretionary wedge: Barbados Ridge complex. Geology. 1988;**16**(7):631-635

[45] Torrini R, Speed RC. Tectonic wedging in the forearc basin: Accretionary prism transition, Lesser Antilles forearc. Journal of Geophysical Research. 1989;**94**(B8):10,549-10,584

[46] Speed R, Torrini R, Smith PL. Tectonic evolution of the Tobago Trough forearc basin. Journal of Geophysical Research. 1989;**94**(B3):2913-2936

[47] Aitken T, Mann P, Escalona A, Christeson GL. Evolution of the Grenada and Tobago basins and implications for arc migration. Marine and Petroleum Geology. 2011;**28**(1):235-258

[48] Bangs NL, Christeson GL, Shipley TH. Structure of the Lesser Antilles subduction zone backstop and its role in a large accretionary system. Journal of Geophysical Research. 2003;**108**(B7, 2358). DOI: 10.1029/2002JB002040.

[49] Laigle M, Becel A, de Voogd B, Sachpazi M, Bayrakci G, Lebrun JF, Evain M. Along-arc segmentation and interaction of subducting ridges with the Lesser Antilles Subduction forearc crust revealed by MCS imaging. Tectonophysics. 2013;**603**:32-54

[50] Evain M, Galve A, Charvis P, Laigle M, Kopp H, Bécel A, Weinzierl W, Hirn A, Flueh ER, Gallart J. Structure of the Lesser Antilles subduction forearc and backstop from 3D seismic refraction tomography. Tectonophysics. 2013;**603**:55-67

[51] von Huene R, Pecher IA, Gutscher MA. Development of the accretionary prism along Peru and material flux after subduction of Nazca Ridge. Tectonics. 1996;**15**(1):19-33

[52] Collot JY, Agudelo W, Ribodetti A, Marcaillou B. Origin of a crustal splay fault and its relation to the seismogenic zone and underplating at the erosional north Ecuador–south Colombia oceanic margin. Journal of Geophysical Research. 2008;**113**(B12102). DOI: 10.1029/2008JB005691.

[53] Polonia A, Torelli L, Brancolini G, Loreto MF. Tectonic accretion versus erosion along the southern Chile trench: Oblique subduction and margin segmentation. Tectonics. 2007;**26**(TC3005). DOI: 10.1029/2006TC001983.

[54] Gutscher MA, Spakman W, Bijwaard H, Engdahl ER. Geodynamics of flat subduction: Seismicity and tomographic constraints from the Andean margin. Tectonics. 2000;**19**:814-833

[55] Borrero C, Pardo A, Jaramillo CM, Osorio JA, Cardona A, Flores A, Echeverri S, Rosero S, Garca J, Castillo H. Tectonostratigraphy of the Cenozoic Tumaco forearc basin (Colombian Pacific) and its relationship with the northern Andes orogenic build up. Journal of South American Earth Sciences. 2012;**39**:75-92

[56] Marcaillou B, Collot JY. Chronostratigraphy and tectonic deformation of the North Ecuadorian–South Colombian offshore Manglares forearc basin. Marine Geology. 2008;**255**(1-2):30-44

[57] Collot JY, Marcaillou B, Sage F, Michaud F, Agudelo W, Charvis P, Graindorge D, Gutscher MA, Spence G. Are rupture zone limits of great subduction earthquakes controlled by upper plate structures? Evidence from multichannel seismic reflection data acquired across the northern Ecuador–southwest Colombia margin. Journal of Geophysical Research. 2004;**109**(B11103). DOI: 10.1029/2004JB003060.

[58] López ER. Evolution tectono-stratigraphique du double bassin avant: arc de la marge convergente Sud Colombienne: Nord Equatorienne pendant le Cénozoïque [Ph.D. thesis]. Nice, France: Université Nice Sophia Antipolis; 2009.

[59] Barnes PM, de Lépinay BM. Rates and mechanics of rapid frontal accretion along the very obliquely convergent southern Hikurangi margin, New Zealand. Journal of Geophysical Research. 1997;**102**(B11):24,931-24,952

[60] Ghisetti FC, Barnes PM, Ellis S, Plaza-Faverola AA, Barker DHN. The last 2 Myr of accretionary wedge construction in the central Hikurangi margin (North Island, New Zealand): Insights from structural modeling. Geochemistry, Geophysics, Geosystems. 2016;**17**:2661-2686

[61] Lewis KB. The 1500-km-long Hikurangi Channel: Trench-axis channel that escapes its trench, crosses a plateau, and feeds a fan drift. Geo-Marine Letters. 1994;**14**:19-28

[62] Bailleul J, Robin C, Chanier F, Guillocheau F, Field B, Ferriere J. Turbidite systems in the inner forearc domain of the Hikurangi convergent margin (New Zealand): New constraints on the development of trench-slope basins. Journal of Sedimentary Research. 2007;**77**(4):263-283

[63] Paquet F, Proust JN, Barnes PM, Pettinga JR. Controls on active forearc basin stratigraphy and sediment fluxes: The Pleistocene of Hawke Bay, New Zealand. Geological Society of America Bulletin. 2011;**123**(5-6):1074-1096

[64] Barnes PM, Nicol A, Harrison T. Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. Geological Society of America Bulletin. 2002;**114**(11):1379-1405

[65] Willett SD, Beaumont C, Fullsack P. Mechanical model for the tectonics of doubly vergent compressional orogens. Geology. 1993;**21**:371-374

[66] Willett SD. Orogeny and orography: The effects of erosion on the structure of mountain belts. Journal of Geophysical Research. 1999;**104**(B12):28,957-28,981

[67] Naylor M, Sinclair HD, Willett S, Cowie PA. A discrete element model for orogenesis and accretionary wedge growth. Journal of Geophysical Research. 2005;**110**(B12403). DOI: 10.1029/2003JB002940.

[68] Storti F, Salvini F, McClay K. Synchronous and velocity-partitioned thrusting and thrust polarity reversal in experimentally produced, doubly-vergent thrust wedges: Implications for natural orogens. Tectonics. 2000;**19**:378-396

[69] Storti F, Marin RS, Faccenna C, Sainz AC. Role of the backstop-to-cover thickness ratio on vergence partitioning in experimental thrust wedges. Terra Nova. 2001;**13**(6):413-417

[70] Beaumont C, Ellis S, Pfiffner A. Dynamics of sediment subduction-accretion at convergent margins: Short-term modes, long-term deformation, and tectonic implications. Journal of Geophysical Research. 1999;**104**:17573-17601

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