Effects of trench-perpendicular ridge subduction on accretionary wedge deformation: Clues from analogue modelling

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Funding information
National Programme on Global Change and Air-Sea Interaction, SOA, Grant/Award Number: GASI-GEOE-01; Key Laboratory of Ocean and Marginal Sea Geology, Chinese Academy of Sciences, Grant/Award Number: OMG17-03; Scientific Research Fund of the Second Institute of Oceanography, SOA, Grant/Award Number: JG1607; National Natural Science Foundation of China, Grant/Award Numbers: 41606051, 41506070, 41676037 and 41176040; National Basic Research Programme of China (973 programme), Grant/Award Number: 2015CB755905

Handling Editor: S. Li

Basement highs (e.g., seamounts and ridges) often exist on subducted oceanic plates. However, their effects on the deformation of accretionary wedges have not been well understood, in particular the sequential cross-sectional evolutionary processes caused by ridge subduction. To evaluate the effects of ridge subduction on accretionary wedges, analogue models were run to observe the deformation processes in both plan and cross-sectional views. The results show that ridge subduction induces an inverted-U-shaped uplifted area, while seamount subduction always causes a circular uplifted area in plan view. Both ridge and seamount subduction will result in a radial fan-shaped strike-slip fault system in plan view, with opposite slip directions of the faults in the two wings. During ridge subduction, the faults in the left wing of the ridge axis are sinistral, and those in the right are dextral, which is reverse to that of seamount subduction. This may result from the backward flow in the overlying sediments during the rapid subsidence in the wake of the seamount, which would reverse the initial movement along the strike-slip faults. The subducted ridge induces migration of wedge material from the frontal margin to the distal part, expressed by changes in structural geometry and kinematics (e.g., reduction in wedge length and taper angle and increase in wedge height). The accretionary prism adapted to the variation of taper angle by the development of back-thrust faults and out-of-sequence thrust fault. Our model results shed lights on understanding the interior structural deformation pattern and mechanism caused by natural cases of ridge subduction, such as Gagua Ridge and North d’Entrecasteaux Ridge.

KEYWORDS
accretionary wedge, analogue modelling, interior deformation characteristics, ridge subduction

1 | INTRODUCTION

The surface of the ocean crust is rugged because of the common presence of basement highs (e.g., seamounts, ridges, and volcanic plateaus) related to magmatism and/or tectonic events. Subduction of those basement highs always influences the plate-margin seismicity, potentially concentrating seismicity (e.g., Cloos, 1992; McIntosh et al., 2007; Scholz & Small, 1997) or decreasing the degree of coupling and limiting megathrust earthquakes (Kodaira et al., 2006; Kodaira, Takahashi, Nakanishi, Miura, & Kaneda, 2000; Park, Moore,
In addition, subduction of these basement highs is responsible for dramatic changes in the dynamics and kinematics of subduction zones (e.g., Rosenbaum & Mo, 2011). Basement high subduction can both change the kinematics of the subducting slab and affect the deformation of the overriding plate. Analogue modelling and numerical modelling are effective methods to explore deformation mechanisms and have been widely used in many previous studies to evaluate the role that basement highs play in convergent margins (e.g., Ding & Lin, 2016; Dominguez, Lallemand, Malavieille, & Schnürle, 1998; Dominguez, Lallemand, Malavieille, & von Huene, 1998; Dominguez, Malavieille, & Lallemand, 2000; Espurt et al., 2008; Hampel, Adam, & Kukowski, 2004; Lallemand, Malavieille, & Calassou, 1992; Lallemand, Schnürle, & Malavieille, 1994; Li, Sun, Hu, & Wang, 2013; Martinod, Fucicillo, Facenna, Labanieh, & Regard, 2005; Martinod et al., 2013; Morgan & Bangs, 2017).

In the aspect of deep slab kinematics, large-scale analogue models (including lithosphere and mantle) show that buoyant ridge subduction results in a diminution of the velocity of the subducting plate and a steeper dip below the ridge under slab free-sinking conditions (Martinod et al., 2005). Martinod et al. (2013) also presented analogue models using kinematic boundary conditions, which shed light on the relation between the subducting ridge and the downgoing slab. They argued that ridge subduction diminishes the dip of the slab and leads to the appearance of a horizontal slab segment in cases in which the boundary conditions impose rapid convergence. The subducting oceanic plateau also exert important effects on the overriding plate topography. The overriding plate shortening rate increases if the subducting oceanic plateau is large enough to decrease the slab pull effect (Espurt et al., 2008). According to the numerical work of Gerya, Fossati, Cantieni, and Seward (2009), the surface uplift may exceed the original ridge height due to additional uplift resulting from the overriding plate shortening.

At shallower levels, geophysical data (e.g., multibeam and multichannel seismic data) can visualize the shallow morphology and structure. However, the surface morphology is easily obscured by hemipelagic sediments or currents, which makes the original surface deformation caused by the subduction of topographic highs be ephemeral. Therefore, it is difficult to assess the role of basement highs during long-term structural processes (Morgan & Bangs, 2017). Furthermore, although seismic profiles succeed in imaging the structure of the overriding plate (e.g., Bangs, Gulick, & Shipley, 2006; Dominguez et al., 2000; Geersen, Ranero, Barckhausen, & Reichert, 2015; Marcaillou et al., 2016; Singh et al., 2011), the interior structures within the accretionary wedge become tough to be distinguished between the seafloor high subduction-induced features and the original ones formed before the seafloor high subduction, and the structural evolution processes are difficult to be understood. Many previous analogue or numerical modelling studies on the relations between subduction of basement highs and deformation of the overriding plate focused generally on the effects of subducted basement highs on accretionary wedges. The 2-D numerical modelling studies mainly focused on the fault patterns caused by the seamount subduction, such as pair of fore-thrust and back-thrust faults (Ding & Lin, 2016), increasing fault spacing and activating splay faults (Morgan & Bangs, 2017), while some work focused on the fracture of the subducted seamount itself and argued that the seaward flank of the seamount may be more apt to break (e.g., Baba et al., 2001). Recently, 3-D numerical models were constructed to study the ridge or seamount subduction effects. Zeumann and Hampel (2015) used a 3-D finite element method to investigate the deformation of forearcs related to the migrating or non-migrating aseismic ridges subduction and found that the displacement and strain fields above the migrating or non-migrating ridges were asymmetric with respect to the ridge axis unless both ridge and plate convergence directions were perpendicular to the trench. They also argued that the height and width of the ridges as well as the friction coefficient of the plate interface were the most dominant factors in controlling the forearc deformation pattern, whereas the mechanical strength of the forearc played a subordinate role (Zeumann & Hampel, 2016). Ruh (2016) used 3-D high-resolution numerical experiments to simulate the submarine landslides caused by seamounts collision and stated that submarine landslides occurred only if the seamounts were not completely buried, and the volume of the avalanche depended on the volume of the entering seamount.

Analogue models of seamount or ridge subduction were mostly 3-D, making deformation of both plan and cross-section views visible, leaving much space for the sequential tectonic evolution processes to be well understood. These processes in cross section were recorded only if the basement highs were paved in the sidewall of the transparent sandbox and orthogonal to the accretionary wedge. Deformations in plan view, including demonstration of episodes of uplift and subsidence, reactivation of inherited thrusts, formation of normal and strike-slip faults, and indentation of the margin, have been considered (e.g., Dominguez, Lallemand, Malavieille, & Schnürle, 1998; Dominguez, Lallemand, Malavieille, & von Huene, 1998; Hampel et al., 2004; Lallemand et al., 1994; Li et al., 2013), but the interior structure related to the ridge subduction and its sequential tectonic evolution processes in cross-section remain under constrained (except for the work of Lallemand et al., 1992 and Dominguez et al., 2000). Comparison of deformations in plan view between the ridge and seamount subduction has never been addressed. In this study, we performed two analogue experiments to explore the interior deformation processes of an accretionary wedge caused by perpendicular ridge subduction in both plan and cross-sectional views. And the geometrical evolution processes as well as the deformation mechanism of the wedge were analysed. The experimental results were used in two natural cases, the Gagua Ridge and the North d’Entrecasteaux Ridge which have not yet been well understood due to low quality of seismic images, to constrain interpretations of interior structures.

2 | ANALOGUE MODELLING

2.1 | Experimental materials and model design

Dry quartz sand, which has an angle of internal friction of about 30° and low cohesion, has commonly been used as a good analogue of natural sedimentary rocks such as sandstone and limestone or marine
sediments (e.g., Ding & Li, 2016; Dominguez et al., 2000; Hampel et al., 2004; Lohrmann, Kukowski, Adam, & Oncken, 2003; Sun et al., 2014; Sun, Zhou, Zhong, Zeng, & Wu, 2003; Wang, Chen, Cheng, & Li, 2013). A 30-cm-long rigid bar with a cross-section approximating to a half cylinder (radius 2.5 cm) was used as the analogue of the subducting ridge. As a ridge which is mostly constituted by basalt, gabbro, or other competent rocks is much less deformable than an accretionary wedge, we could focus on deformation of the accretionary wedge caused by the ridge subduction rather than the ridge itself.

To explore deformation processes in plan and cross-sectional views, two models were run in a transparent Plexiglas sandbox with dimensions of 90 cm × 40 cm × 40 cm (Figure 1). Model 1, which was used to study the episodic deformation of the accretionary wedge in plan view, was divided into two steps, with the first step simulating formation of accretionary wedge and the second step as an analogue of ridge converging with the wedge. In Step 1, the sand layers were compressed by 25 cm at a constant velocity of 0.02 mm/s. The left wall was movable to simulate the formation of an accretionary wedge, while the right wall was fixed. In Step 2, the half-cylinder rigid bar was set on the right wall. During this step, the left wall where the accretionary wedge had been formed previously was set to be unmovable, while the rigid bar was movable. The rigid bar was placed in the middle of the sandbox so that deformation pattern in plan view can be well illustrated. The accretionary wedge on the left remained still as the ridge kept converging with the wedge at a constant velocity of 0.05 mm/s. Model 2 was designed to explore the episodic interior deformation in cross-sectional view. In this model, the rigid bar was set to be unmovable, while the opposite wall was set to be movable. The rigid bar as analogue for the ridge was placed near the transparent glass side wall (Figure 1) so that deformation in cross-sectional view can be monitored. Before convergence of the accretionary wedge and the ridge, the glass side walls were well lubricated using a dehydrated alcoholic solution to avoid boundary effects. Three digital cameras were used to take photographs at 1-min intervals to monitor the deformation from the top and both sides. Each experiment was run twice to ensure repeatability.

FIGURE 1 The initial set-up of the analogue model. Model 1 (a) and Model 2 (b) were designed to explore the deformation processes in plan and cross-sectional views, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
2.2 | Model scaling

Analogue modelling experiments should conform to the principle of similarity, which demands that the model be properly scaled in geometry, kinematics, and dynamics (e.g., Hubbert, 1937; Ramberg, 1981; Weijermars & Schmeling, 1986). Brittle Coulomb materials such as quartz sand, for which the deformation is independent of strain rate (Sonder & England, 1986), do not have to be scaled precisely in terms of deformation rate (Persson & Sokoutis, 2002). In the models, relatively small rates of 0.02 and 0.05 mm/s were used to simulate the formation of an accretionary wedge and the convergence of ridge and wedge, respectively. The dynamical similarity can be expressed by the following equation: 

\[
\sigma^* = \rho^* g^* l^*
\]

(Weijermars & Schmeling, 1986), where the (*') represents the model-to-nature ratio for each parameter, \( \sigma \) is the cohesion, \( \rho \) is the density, \( g \) is the gravity acceleration, and \( l \) is the length. The density of quartz sand in the laboratory is about 1,350 kg/m\(^3\), and the density of natural sedimentary rocks is about 2,000–2,500 kg/m\(^3\) (Couzens-Schultz, Vendeville, & Wiltschko, 2003); hence, the density ratio \( \rho^* \) is about 0.6 (assume the average density of natural sedimentary rocks is 2,250 kg/m\(^3\)). The gravity acceleration ratio \( g^* \) was 1 in the modelling, since both the analogue experiments and the natural prototype are under a normal gravitational field. It is worth noting that different filling techniques (e.g., pouring or sifting) will generate different cohesion of sand (Gomes, 2013; Lohmann et al., 2003; Schellart, 2000). In our experiments, the model layers were paved similarly to those of Wang et al. (2016) by pouring the sand from a height of approximately 10 cm, generating cohesion in the sand of about 100 Pa (Eisenstadt & Sims, 2005; Gomes, 2013). The cohesion of natural sedimentary rocks varies from 10 to 20 MPa (Handin, 1966), and the average cohesion strength of sediments within the accretionary wedge is assumed to be about 16 MPa. Thus, the cohesive strength ratio of the accretionary wedge between the models and the prototype was about \( \sigma^* = 6 \times 10^{-6} \). According to equation: 

\[
\sigma^* = \rho^* g^* l^*
\]

(Weijermars & Schmeling, 1986), the linear dimension ratio \( l^* \) was determined as \( 10^{-5} \), that is, 1 km in nature was simulated by 1 cm in the model.

3 | ANALOGUE MODELLING RESULTS

3.1 | Model 1

The progressive evolution of Model 1 is illustrated in Figure 2. During Stage 1 (3.5 cm of convergence), an accretionary wedge was formed in a forward-breaking sequence, with well-developed landward-dipping thrust faults. The ridge contacted with the deformation front and was ready to subduct into the wedge (Figure 2a). During Stage 2 (10.5 cm of convergence), as the ridge and the accretionary wedge collided, the front margin was indented and uplifted, producing a round uplifted area on the surface. Meanwhile, some strike-slip faults with limited displacement initiated in the surface above the ridge (Figure 2b). In Stage 3 (15.0 cm of convergence), the surface uplift and the strike-slip faults gradually propagated landward. An apparent scarp nucleated at the seaward end of these strike-slip faults (Figure 2c). During Stages 4 and 5 (20.0 and 22.0 cm of convergence, respectively), the extent of the uplift continued to enlarge and almost reached the left end of the accretionary wedge. The surface traces of former thrust faults were markedly bent toward to the land (Figure 2d,e).

To illustrate the structural characteristics of the surface morphology clearly, we enlarged the structural interpretation of the deformation area in Figure 2, as shown in Figure 3. The deformation of the overriding plate induced by ridge subduction was mainly concentrated on the uplifted area where an arc-shaped back-thrust fault marked the leading edge (Figure 3). Above the ridge, a series of conjugated strike-slip faults accommodated the displacement of the margin. A remarkable deformation feature developed in the centre of the uplifted area: these radial fan-shaped divergent strike-slip faults with small displacement were divided into two parts by the ridge axis, with those in the left wing of the axis appearing sinistral and those in the right appearing dextral. As a result of gravitational effects, many scarp developed, controlled by normal faults with small displacement (Figure 3).

3.2 | Model 2

Model 2 was designed to study the interior deformation processes related to ridge subduction in a cross-sectional view (Figure 4). After a shortening of 14.5 cm, an accretionary wedge was produced, containing four major thrust faults and one basement décollement fault (Figure 4b). With a shortening of 18.0 cm, the ridge started to subduct beneath the wedge. Two thrust faults with opposite dipping directions initiated in the hanging wall of the décollement fault, resulting in a pop-up structure (Figure 4c). With continued shortening, a new seaward-dipping thrust fault developed in the hanging wall, and the former seaward-dipping thrust fault was rotated. Meanwhile, the décollement fault extended and reached the ridge surface (Figure 4d). When the shortening reached 28.5 cm, the accretionary wedge was shortened with well-developed small seaward-dipping thrust faults in the hanging wall of the décollement fault. The seaward-dipping thrust fault system began to cut through the former landward-dipping thrust faults in the wedge (Figure 4e). It is worth noting that the ridge subduction induced a huge landward-dipping thrust fault in the hanging wall of the décollement, which bounded the seaward-dipping thrust faults in the bottom. With continued shortening, it turned into an out-of-sequence thrust and absorbed most of the shortening (Figure 4e). With a shortening of 35.0 cm, the interior structures of the wedge were intensively remodelled by the ridge subduction. Most of the former landward-dipping thrust faults were cut through by the new seaward-dipping faults, resulting in a complex fault network within the wedge (Figure 4f).

3.3 | Morphological changes in the wedge during ridge subduction in Model 2

To clearly show the morphological changes in the wedge caused by ridge subduction, we drew topographic profiles of the accretionary wedge during representative stages of ridge subduction (Figure 5). Ridge subduction played a major role in reshaping the topography of the accretionary wedge. During the early stages of interaction between the ridge and the accretionary wedge (stages b–d in Figure 5), uplift occurred only in the front of the wedge. As the ridge
gradually subducted farther into the wedge, the distal part of the wedge started to uplift (stage e in Figure 5). With continued subduction, the topography of the wedge was approximately horizontal in the distal part, but with an apparent slope break in the front part (stage f in Figure 5). All these topographical changes were directly reflected by the lengths and the heights of the wedge. The length of the wedge was gradually shortened by 10 cm (from 30 to 20 cm) after the ridge subduction (Figure 6). Compared with the limited increase in the height of the distal wedge (height 2 in Figure 6), the height of the frontal wedge (height 1 in Figure 6) was increased to more than doubled from 2.4 to 5.8 cm (Figure 6). We noted that the ridge height was about 2.5 cm, which means that the extra 0.9 cm (the final height of the frontal wedge [5.8 cm] minus the sum of ridge height [2.5 cm] and original sand thickness [2.4 cm]) of thickening was accommodated by the displacements of ridge-induced thrust faults. Gerya et al. (2009) also demonstrated in their numerical modelling that the surface uplift could exceed the original ridge height due to additional uplift resulting from the overriding plate shortening.

FIGURE 2  Plan view of progressive deformation of Model 1 after shortening of (a) 3.5 cm, (b) 10.5 cm, (c) 15.0 cm, (d) 20.0 cm, and (e) 22.0 cm (left) and the interpretation (right). Red dashed lines denote the uplifted area above the ridge; black dashed lines mark the shape of the subducted ridge. Thick black lines are the thrust faults; red lines show the strike-slip faults [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 3  Detailed structural interpretation of accretionary wedge deformation with ridge subduction. Left is the original image, and right is the interpretation. See location in Figure 2e [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 4  Cross-sectional view of the progressive deformation of Model 2 after a shortening of (a) 0 cm, (b) 14.5 cm, (c) 18.0 cm, (d) 20.5 cm, (e) 28.5 cm, and (f) 35.0 cm, respectively. White lines are the former thrust faults within the accretionary wedge; yellow lines indicate thrust faults related to ridge subduction [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5  Topographic profiles of the accretionary wedge during ridge subduction, corresponding to stages b (14.5 cm of shortening), c (18.0 cm of shortening), d (20.5 cm of shortening), e (28.5 cm of shortening), and f (35 cm of shortening) in Figure 4. The arrows mark the tip of the subducted ridge at each stage [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 6 Statistics of the length and the heights of the front and rear parts of the accretory wedge during different stages of ridge subduction. Stages b: 14.5 cm of shortening; stage c: 18.0 cm of shortening; stage d: 20.5 cm of shortening, stage e: 28.5 cm of shortening, and stage f: 35 cm of shortening [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

4.1 | Mechanics of accretionary deformation induced by ridge subduction

Since the critical tapered wedge theory was proposed in the early 1980s (e.g., Dahlen, 1984, 1990; Dahlen, Suppe, & Davis, 1984; Davis, Suppe, & Dahlen, 1983), it has been successfully applied to explain the deformation mechanism and kinematic evolution in fold-and-thrust belts or accretionary wedges (e.g., Buitert, 2012; Ford, 2004; Lallemand et al., 1994; Morley, 2007; Sun et al., 2017; Wang et al., 2013). In general, according to the critical tapered wedge theory, an accretionary wedge will deform internally until it reaches a constant critical taper angle (the sum of the surface slope $\alpha$ and basement décollement thrust slope $\beta$), which is determined by the basal friction coefficient and the cohesion of the wedge (Dahlen, 1984). If no additional material is input in the front, the wedge will slide along the basement detachment stably without any deformation. Whenever new materials accrete at the toe of the wedge, a new thrust fault will develop, and the taper angle will drop temporarily. With continued shortening, the accretionary wedge will regain its critical taper angle, resulting in cyclical variation of the taper angle. This self-similar cyclical variation of the thrust wedge can be interrupted in many conditions, such as with syn-thrusting sedimentation and erosion. Wang et al. (2013) demonstrated that syn-thrusting sedimentation in the front of the wedge decreases the wedge taper below the critical taper, causing the wedge to be in a subcritical state. And internal deformation (e.g., back thrusting and basal accretion by duplexing) will increase the taper angle, making the wedge regain the stable critical taper. Erosion of the wedge by local sediment removal will also result in a subcritical state, which will limit the forward propagation of thrust wedges and reactivate the existing thrust faults (e.g., Konstantinovskaya & Malavieille, 2011; Persson & Sokoutis, 2002).

In addition to the effects of syn-thrusting sedimentation or erosion, the modelling results in this study indicate that the subducted ridge plays an important role in disturbing the cyclical variation in taper angle self-similarity. In Model 2, the plots of taper angle variation against shortening show that the cyclical material accretion process was interrupted sharply by ridge subduction (Figure 7). During the first ~5 cm of shortening, two thrust sheets were formed. The wedge taper was very unstable, as indicated by the dramatically changed $\theta_1$ ($\theta_1$ is the taper angle of the distal part of the wedge). During Stage 1 (the first ~15 cm of shortening), the taper angle $\theta_1$ changed oscillatory until a stable taper angle of about 16° was reached (Figure 7). Then the ridge subduction began to control the taper angle of the front part of the wedge, visible as the gradual increase of $\theta_2$ ($\theta_2$ is the taper angle of the front part of the wedge) with the development of seaward-dipping back-thrust faults. During Stage 2 (shortening from 15 to 26 cm), the deformation was mainly focused on the leading edge of the subducting ridge. The taper angle of the distal part of the wedge ($\theta_1$) remained stable during this stage (Figure 7). During Stage 3 (shortening from 26 to 35 cm), as the ridge subduction proceeded, the wedge was gradually thickened and uplifted with gradually decreased $\theta_1$ and $\theta_2$. At the end of subduction, $\theta_1$ and $\theta_2$ reached almost the same value of about 3° (Figure 7). The deformation process of the wedge shows that the basement décollement fault reached the ridge surface as soon as the ridge had subducted into the accretory prism (Figure 4), which resulted in an increase in the basement décollement thrust slope $\beta$. The critical taper angle is the sum of the surface slope $\alpha$ and the basement décollement thrust slope $\beta$. Thus, as $\beta$ increases, the surface taper angle (such as $\theta_1$ and $\theta_2$) will gradually decrease. At the end of subduction, the surface slope $\alpha$ and the basement décollement thrust slope $\beta$ reached values of 2.5° and 7.5°, respectively, resulting in a taper angle about 10° (Figure 8). As mentioned above, the stable angle of the wedge was about 16°, which means that after the beginning of ridge subduction, the wedge was in a subcritical condition. To maintain the critical taper, internal deformation is required within the wedge (Dahlen et al., 1984; Davis et al., 1983). Hence, back-thrust and out-of-sequence thrust faults are an integral part of thrust wedge formation (Morley, 1988). Generally, a thrust wedge will deform in a normal forward-breaking style if no external conditions act to change the taper of the wedge. Out-of-sequence and back-thrust faults will develop under many conditions that change the slope angle of the wedge, such as syn-thrusting sedimentation or erosion (e.g.,
Konstantinovskaya & Malavieille, 2011; Malavieille, 2010; Storti, Salvini, & McClay, 2000; Wang et al., 2013; Wu & McClay, 2011).

Our modelling results demonstrate that ridge subduction could lead to the formation of an out-of-sequence thrust fault dipping at a low angle (Figure 8). Because the out-of-sequence thrust fault has a much larger displacement than the basement décollement fault during the late period of deformation, a slope break develops in the front part of the wedge (Figure 8). The out-of-sequence thrust fault plays an important role in the deformation evolution of the accretionary wedge, such as helping to thicken the wedge or inducing a slope break in the front of wedge (Miyakawa, Yamada, & Matsuoka, 2010), and may also trigger earthquakes (Kao & Chen, 2000; Kimura et al., 2007).

4.2 Comparison of surface deformation caused by ridge and seamount subduction

Seamounts are active or extinct undersea volcanoes and represent a significant portion of the volcanic extrusive budget for the oceanic seafloor (Wessel, Sandwell, & Kim, 2010). Ridges can be ancient spreading axes, hotspot chains, remnant arcs, or uplifted oceanic slices (Lallemand, Collot, Pelletier, Rangin, & Cadet, 1990). Both seamounts and ridges are the common features above the seafloor, and they are mostly of magmatic origin but vary greatly in their morphology. Generally, seamounts are of short-wavelength bathymetry with a conical shape, sometimes flat-topped, whereas ridges are always of long-wavelength bathymetry with an elongated shape. Although great efforts have been made to study the deformational features in accretionary wedges related to seamount subduction (e.g., Dominguez, Lallemand, Malavieille, & Schnürle, 1998; Dominguez, Lallemand, Malavieille, & von Huene, 1998; Li et al., 2013), the differences in outcomes of the accretionary wedge between with seamount subduction and with ridge subduction remain rarely addressed. In this study, these differences were analysed by comparison of the results of ridge subduction with previous findings of seamount subduction by Dominguez, Lallemand, Malavieille, and Schnürle (1998; Figure 9a).

We compared the surface deformation of accretionary wedges caused by these two different bathymetric units to evaluate their similarities and differences (Figure 9). Both seamount and ridge subduction will increase the compressional stress on the overriding plate, resulting in a specific fault system in the accretionary wedge. A seamount and a ridge will always cause an intense indentation in the trench, and the two sides of indentation are confined by large-displacement conjugated strike-slip faults. However, the strike-slip faults formed during ridge subduction would be active much longer than those formed during seamount subduction, since a longer wavelength bathymetry will result in a longer deformation (Morell, 2016). After entering the accretionary wedge, both seamount and ridge will cause uplift within the wedge, but the uplift shapes are totally different. Seamount subduction forms a circular uplifted area in plane view (Figure 9a), which is also observed in a numerical simulation. Ding and Lin (2016) conducted numerical experiments to simulate elastoplastic deformation of the overriding plate induced by a seamount and revealed that a pair of thrust faults (landward-dipping...
fore-thrust fault and seaward-dipping back-thrust fault) initiated from the top and the base of the seamount; in addition, a significant dome-shaped surface uplift formed above the thrust faults. However, ridge subduction will cause an inverted-U-shaped uplift (Figure 9b), indicating that the shapes of seafloor bathymetric units play an important role in controlling the uplift in the accretionary wedge. Furthermore, seamount subduction would result in rapid subsidence after uplift because of its short-wavelength bathymetry, that is, after the seamount passes through the subduction channel, apparent subsidence will take place, forming big scarps in the back margin of the subsidence area. However, because of the longer wavelength bathymetry, ridge subduction will cause uplift over a longer period of time assuming the same convergence velocity, and the subsidence will occur at the trailing edge only after the entire ridge has passed through the subduction channel. In addition, some smaller scale scarps will form in the uplifted area as a result of gravity (Figure 9b). Both seamount and ridge subduction trigger a network of radial fan-shaped divergent strike-slip faults above the uplift. The strike-slip faults are sinistral in the left and dextral in the right during ridge subduction, which is opposite to those in seamount subduction (Figure 9). During ridge subduction, the sediments overlying the ridge are passively shifted by the movement of the basal subducting ridge. The overlying sediments located near the ridge axis are thinner than those at the ridge edges, which make them respond more directly to the ridge movement. Thus, sediments located near the axis of the ridge will move faster than those farther away from the ridge axis. This process is also indicated by the landward-bending surface traces of the former thrust faults. Bending of the fault trace is extremely distinct in the central area and gradually reduces toward the sides (Figure 9b). Numerical modelling experiments of ridge subduction (e.g., Zeumann & Hampel, 2015, 2016) demonstrated a similar phenomenon, of which the horizontal displacement near the ridge axis is larger than that away from the axis. This phenomenon may explain the opposite properties of the strike-slip faults on different sides of the ridge axis.

However, as for seamount subduction, the movement directions of strike-slip faults in the uplifted area are opposite, that is, the strike-slip faults are dextral on the left wing and sinistral on the right (Figure 9a). As mentioned above, seamount subduction will cause apparent subsidence in the rear part of the seamount (Figure 9a), which may result in backward flow of the sediments above the uplift toward the subsidence area. The particles above the uplift centre are at a higher elevation than those in the side areas and will move faster because of the effect of gravity, which may result in the strike-slip faults being dextral on the left wing and sinistral on the right (Figure 9a). At the beginning of seamount subduction, the properties of the strike-slip faults may be the same as those of the faults that form during ridge subduction; however, as the backward flow of sediments occurs, the properties may be reversed.

4.3 | Implications for structural interpretation for natural cases

4.3.1 | Gagua Ridge subduction

A typical natural case of ridge subduction is the Gagua Ridge, which lies east of Taiwan (Figure 10). The ridge is a north–south-trending linear feature that is 300 km long, 25 km wide, and 2.5 km high, which is being subducted under the Ryukyu Trench at a speed of about 7.1 cm/a (Schnürle, Liu, Lallemand, & Reed, 1998; Seno, Stein, & Gripp, 1993). The origin of this prominent ridge is still controversial, treated as either an extinct spreading centre (Bowin, Lu, Lee, & Schouten, 1978), or an early-active fault zone in the ocean crust (e.g., Deschamps et al., 1998; Hilde & Lee, 1984; Mrozowski, Lewis, & Hayes, 1982), or a plate boundary between the Philippine Sea and Huatung plates that was uplifted in the subsequent compression (e.g., Lallemand, Font, Bijwaard, & Kao, 2001; Sibuet & Hsu, 1997). In any case, the formation mechanism of the ridge is out of the scope of this study. Herein, we mainly focus on the effects of the Gagua Ridge on the accretionary wedge and try to interpret the interior deformation of the wedge. Seismic line ACT-P88 is perpendicular to the Ryukyu Trench and located just north of the axis of the Gagua Ridge (Dominguez, Lallemand, Malavielle, & Schnürle, 1998). Unfortunately, because of the low quality of the seismic image, the interior structure of the accretionary wedge is poorly constrained (Figure 11). Our analogue modelling results could shed light on structural interpretation of the interior of the wedge.
As the ridge subducted into the accretionary wedge, the basement décollement fault jumped onto the surface of the ridge. Then, an out-of-sequence thrust fault and some minor seaward-dipping thrust faults developed in the hanging wall of the décollement (Figure 12a). These seaward-dipping thrust faults cut through the former landward-dipping faults. On the basis of the modelling results, we
reinterpreted the interior structural deformation of the wedge (Figure 12b). The north-dipping reflectors in the accretionary wedge (Figure 11) may represent the former landward-dipping thrust faults. These reflectors are not continuous and are very likely interrupted by the seaward-dipping thrust faults (Figure 12a). As mentioned above, one important structural deformation caused by ridge subduction is the development of an out-of-sequence thrust fault in the hanging wall of the décollement fault (Figure 12a). Miyakawa et al. (2010) performed numerical simulations to study the effect of increased shear stress along a plate boundary fault on the formation of an out-of-sequence thrust and demonstrated that an out-of-sequence thrust always produced a slope break within an accretionary wedge. The analogue modelling results in this study also indicate that a slope break formed in the front of accretionary wedge because of the activity of the out-of-sequence thrust fault (Figure 8). We propose that the location of the slope break in the seismic line (Figure 11) may represent the outcrop of the out-of-sequence thrust fault as shown in Figure 12b.

It should be noticed that a natural prototype is too complex to include all factors into the modelling, and the analogue models are always homogeneous and simplified. In our models, the accretionary wedge was represented by homogeneous quartz sand, and a rigid bar was used as an analogue of the ridge. This set-up results in invariant rheology of the ridge when entered the subduction channel. Furthermore, the ridge subduction direction was set to be stable and perpendicular to the trench to view the continuous evolution in cross section. However, the Gagua Ridge is subducting under the Ryukyu Trench together with the Philippine Plate in a NW-trending direction, which means that the Gagua Ridge has a westward movable component along the trench margin. In our models, we have not considered this westward migration along the trench. We believe that our models can still yield some key information on the deformation mechanism to explore the interior structure of the accretionary wedge, including the development of seaward-dipping back-thrust faults and the formation of out-of-sequence thrust fault, especially when seismic images cannot show the internal structure clearly (Figure 11).

4.3.2 | North d’Entrecasteaux Ridge

The North d’Entrecasteaux Ridge, an east–west-trending aseismic ridge with a height of 2–4 km and width of 40 km, is subducting beneath the New Hebrides Trench with an average convergence rate of 10 cm/year in the direction of N76°E, nearly perpendicularly to the trench (Collot, Greene, Fisher, & Geist, 1994; Fisher, Collot, & Geist, 1991). Latest Palaeocene to early Oligocene mid-oceanic ridge basalt (MORB) were dredged from the North d’Entrecasteaux Ridge (Maillet, Monzier, Selo, & Storzer, 1983), which may have been subducted since about 2 Ma (Collot, Daniel, & Burne, 1985; Daniel & Katz, 1981). A seismic line 104 passes through the unsubducted part of the ridge as well as the accretionary wedge that is situated on top of the subducting ridge (Figure 13). However, due to the low quality of the image, the interior structure pattern as well as the deformation mechanics are not well understood. Fisher et al. (1991) suggested that the reflector D2 was the subducted ridge top and the décollement surface, which supposedly marked a prominent angular discordance between overlying wedge rocks and underlying rocks of the subducted ridge (Figure 14). Above the reflector D2, a flat reflection A could be traced discontinuously westward to a seafloor break, and Collot et al. (1994) suspected that it was a low-angle thrust fault.
Our modelling result demonstrates that after the basement décollement fault jumped onto the ridge top, a low-angle out-of-sequence thrust fault would develop in the hanging wall of the décollement fault (Figure 12a), resulting in a significant slope break in the toe of the wedge (Figure 8). The strong similarities between our analogue modelling results and the suggested interior structure caused by the North d’Entrecasteaux Ridge indicate that the reflector A probably represents an out-of-sequence thrust fault that was induced by the ridge subduction. The seismic reflectors within the accretionary wedge are not continuous, some of which are pulled up and distorted (Figure 14). The distortion maybe related to the development of seaward-dipping back-thrust faults (Figure 12a).

5 | CONCLUSIONS

Analogue models were run to study the effects of ridge subduction on accretionary wedge deformation in both plan and cross-sectional views. The main conclusions of the study are as follows:

(1) The shapes of seafloor bathymetric units play an important role in controlling the uplift in the accretionary wedge. Ridge subduction causes intense indentation of the margin and an inverted-U-shaped uplift in the accretionary wedge, while seamount subduction always causes a circular uplifted area in plan view. A radial fan-shaped strike-slip fault system developed in the uplift area. During ridge subduction, the strike-slip faults developed in the left of the ridge axis were sinistral, whereas those in the right were dextral. Whenever under seamount subduction, the movement directions of strike-slip faults in the two wings are opposite to those in ridge subduction. This may result from the backward flow in the overlying sediments during the rapid subsidence in the wake of seamount, which would reverse the initial movement along the strike-slip faults.

(2) The ridge subduction induced migration of wedge materials from the frontal margin to the distal part, resulting in dramatic variation in the wedge geometry, expressed by reduction in length and increase in height. The jump of the basement décollement thrust onto the ridge would increase the basement thrust angle, resulting in a decrease in the slope angle of the wedge. The accretionary wedge adapted to this variation of taper angle by development of seaward-dipping back-thrust faults and out-of-sequence thrust fault. A slope break would preferentially form at the outcrop of the out-of-sequence thrust fault.

(3) In cross-sectional view, ridge subduction plays a major role in remoulding the structural deformation characteristics. Based on the analogue modelling results, we improve the understanding of interior structural deformation patterns caused by natural subducting ridges, such as the Gagua Ridge and the North d’Entrecasteaux Ridge.

ACKNOWLEDGEMENTS

We really appreciated the constructive comments from the two anonymous reviewers, Dr. Fucheng Li and the Editor Prof. Sanzhong Li, which significantly improved the manuscript. This work is supported by the National Programme on Global Change and Air-Sea Interaction, SOA (No. GASI-GEOGE-01), Key Laboratory of Ocean and Marginal Sea Geology, Chinese Academy of Sciences (OMG17-03), the Scientific Research Fund of the Second Institute of Oceanography, SOA (Grant JG1607), the National Natural Science Foundation of China (Grants 41606051, 41506070, 41676037, and 41176040), and the National Basic Research Programme of China (973 programme; 2015CB755905). The GMT software (Wessel & Smith, 1995) was used to draw Figures 10a and 13. The analogue models were carried out in the structural analogue modelling lab of Zhejiang University.

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