Transition from buckling to subduction on strike-slip continental margins: Evidence from the East Sea (Japan Sea)

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ABSTRACT

Initiation of subduction is rarely encountered in modern tectonic environments due to its ephemeral and destructive nature. We report the geological and geophysical evidence indicating a transitional phase from buckling to embryonic subduction along the eastern Korean margin. The transition appears to be caused by compressional reactivation of the strike-slip boundary between the continental (Korean Peninsula) and oceanic (Ulleung Basin) crusts since the Early Pliocene. Evidence for compressional reactivation includes (1) a west-dipping major thrust and coincident crustal buckling of the Ulleung Basin; (2) an east-west structural asymmetry inferred from the gravity anomaly and P-wave tomography; and (3) ongoing crustal uplift and high-angle faults along the eastern Korean margin. The juxtaposition of underthrusting and buckling of the crust in the Ulleung Basin, and its associated ubiquitous reverse faulting on the eastern Korean margin, imply the potential development of a new subduction system along the western margin of the East Sea (Japan Sea). We propose that the East Sea comprises two incipient subduction margins (i.e., the Korean and Japanese sides), which are now competing to reach a self-sustaining subduction stage.

INTRODUCTION

The opening of an oceanic basin eventually ceases, and occasionally the basin switches to the closing regime accompanied by subduction initiation (SI). SI is a transient phase, before the onset of a mature subduction system, which can develop under tectonic conditions associated with preexisting mechanical heterogeneities and/or external stress transmission (Stern and Gerya, 2017). However, evidence for SI is rarely observed in either modern tectonic environments or geological records because SI itself is a destructive process. Due to such limitations, the understanding of SI mostly relies on inferences regarding an embryonic phase preserved in some mature subduction systems (e.g., Whatam and Stern, 2015) and on numerical simulations (e.g., Gurnis, 1992).

Many efforts have been made to find a link between hypothetical models of SI and known geological examples, including seismic reflection analysis of structural components (Duarte et al., 2013), focal mechanism and aftershock analysis of seismicity along a master thrust fault (No et al., 2014), and P-wave velocity tomography of deep lithospheric structures (Eakin et al., 2015). However, no consensus has been achieved on the criteria for defining ongoing SI in modern tectonic settings. Therefore, to identify SI and unravel its geodynamic mechanism, geological and geophysical data on surface-level to crustal-level deformation should be integrated.

Our study reports a new example of the transitional phase from buckling to SI observed in the western margin of the East Sea (Japan Sea). Observations are based on multi-scale deformation structures constrained by seismic reflection, gravity, and P-wave velocity data. We focus on the formative processes and mechanical relationship between deep-crustal deformation features, and discuss the geodynamic driving forces for SI in this region. For the stratigraphic and structural analysis, we utilized ~10,700 km of multi-channel seismic reflection data (Fig. 1). Digital SEG-Y (Society of Exploration Geophysicists standard) data were loaded into the PETREL software system (Schlumberger, https://www.software.slb.com/products/petrel) for stratigraphic correlation and mapping. The complete spherical isostatic gravity anomaly data of the World Gravity Map (WGM; Bonvalot et al., 2012) was then used to identify the gravitational manifestation of crustal-level deformation imaged by the seismic reflection data.

NEOTECTONIC FEATURES OF THE EAST SEA MARGINS

The East Sea, one of the major marginal basins in the western circum-Pacific (inset in Fig. 1), has experienced pull-apart–style backarc extension and subsequent multi-phase tectonic reactions during the Cenozoic (Jolivet et al., 1992).

Though typical oceanic crust is only evident in the northern region of the East Sea, the crust in the south is also regarded as oceanic, which was thickened (~11 km) by magmatic underplating (Sato et al., 2014). The western (i.e., Korean side) and eastern (i.e., Japanese side) boundaries of the sea, developed originally as strike-slip principal displacement zones of the pull-apart system, are currently under a transverse shortening regime (Jolivet et al., 1992). In particular, the eastern margin of the sea is regarded as an incipient subduction boundary based on compressional structures and large-magnitude earthquakes (e.g., the A.D. 1983 M7.7 Nihonkai-Chubu earthquake) hosted by an east-dipping reverse fault (No et al., 2014, and references therein). The western margin of the sea, which exhibits a drastic transverse transition from oceanic to continental crust (Cho et al., 2004), also displays evidence of ongoing compressional deformation, such as high-angle reverse faults (Yoon and Chough, 1995), marine terraces (Choi et al., 2008), and moderate-sized earthquakes (e.g., the 2004 M5.1 Uljin earthquake; Kang and Baag, 2004).

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Figure 1. Bathymetric map of study area showing location of seismic reflection data grids. Bathymetry is in meters. Blue triangles represent locations of marine terraces (after Park et al., 2017). Focal mechanism solutions are after Choi et al. (2012). Plate abbreviations: AM—Amur, OH—Okhotsk, YZ—Yangtze, PS—Philippine Sea, and PA—Pacific.

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RESULTS

Ulleung Neotectonic Boundary

The Ulleung Basin is filled with a >5-km-thick sedimentary succession deposited since the Early Miocene (Kim and Yoon, 2017). The entire succession is divided into syn-extensional (SS) and post-extensional (PS) sequences with respect to a sequence boundary that marks the termination of backarc extension at ca. 12.5 Ma (Fig. 2). The PS, comprising mostly submarine mass-transported deposits, is divided into lower (LPS) and upper (UPS) sequences with respect to the Ulleung Neotectonic Boundary (UNB). This UNB is a sequence boundary with an age constrained to ca. 3.8 Ma (Lee and Kim, 2002). In contrast to the concordantly stratified LPS, the UPS comprises growth strata that divergently fill the topography of the UNB with repetitive onlap stratigraphic termination (Figs. 2F and 2G). The growth strata suggest that, since ca. 3.8 Ma, submarine sediments have gradually filled the topography concurrent with deformation of the basin floor.

Major Thrust

In the western margin of the Ulleung Basin, the UNB and underlying strata display an east-down monoclinal fold (Fig. 2). The limbs of the monoclinal strata become shorter and steeper with depth (occasionally overturned at the deepest level), and exhibit the shape of a tri-shear zone (Figs. 2D and 2E). The tri-shear zone can be interpreted as a fault-tip fold structure that accommodates differential mass movement in front of a fault tip propagating from deeper in the crust (e.g., Pei et al., 2014). The tri-shear zone is marked by a bottom-to-the-west reverse sense and along-strike lateral continuity over 100 km (Fig. 3A). This west-dipping reverse boundary fault and its downward extension are together referred to as the “major thrust” (MT). The tri-shear zone extends upward to the UNB (Figs. 2D and 2E), which indicates that the major thrust was initiated at ca. 3.8 Ma. Growth strata over the UNB suggest that the major thrust is still under development (Figs. 2F and 2G). The second small-scale thrust farther to the east (Fig. 3A) implies a higher amount of compressional deformation in the south compared to the north.

Folding of the Basin Floor

Interpretation of stratal architectures and isochronal mapping of the UNB reveal two elongate, regional-scale topographic highs (i.e., central and western highs, CH and EH) and lows (i.e., western and eastern lows, WL and EL) in the NNW-SSE direction (Figs. 2 and 3A). The growth strata above the UNB suggest that such topographic variation resulted from regional folding of the basin floor since ca. 3.8 Ma. Each fold structure extends over 150 km along axis, with a wavelength of 60–70 km and an amplitude of 0.15–0.2 km. Isopach mapping reveals two depocenters of the Plio-Pleistocene sedimentary sequence (UPS) that overlap with the two topographic lows on the UNB (Fig. 3B).

Deep Crustal Anomalies

The isostatic gravity anomaly shows a NNW-SSE-oriented, 25–40-km-wide zone with relatively low gravity anomalies (LAZ) (Fig. 3C). The eastern boundary of the LAZ follows the strike of the major thrust (Fig. 3C). Comparison between a gravity profile (GP2) and equivalent seismic tomographic model (modified after Cho et al., 2004) indicates that the LAZ correlates with the zone underlain by a thickened, high P-wave velocity anomaly (6.0–7.0 km/s) (Fig. 3D). Given the west-dipping geometry of the major thrust, the LAZ and thickened seismic anomaly appear to be associated with the major thrust. This further suggests that the crust has been thickened by thrusting along the eastern Korean margin (Fig. 4). Similar crustal asymmetry has been recognized from the Gagua Ridge in the western Philippine Sea, where a subduction zone failed during its incipient stage (Eakin et al., 2015).

DISCUSSION

Tectonic Model for the East Sea Margins

The neotectonic evolution of the eastern Korean margin is characterized by juxtaposed compressional deformation features at diverse crustal levels. These deformation features include a west-dipping major thrust, thickened crust beneath the thrust zone, regional-scale folding of the Ulleung Basin floor, and ubiquitous structural inversion in association with uplifting of the eastern Korean margin. We argue that underthrusting of the Ulleung Basin beneath the eastern Korean Peninsula is the fundamental control on the juxtaposition of deformational features (Fig. 4). The structures identified in this study are identical to those recognized from modern incipient subduction zones. Examples of these include a major thrust fault caused by crustal rupturing (e.g., Yelles et al., 2009), crustal downwarp and incipient trench formation (e.g., Collot et al., 1995), and differential uplift caused by crustal shortening transverse to the subduction boundary (e.g., Duarte et al., 2013). However, evidence for the sustaining stage of subduction, such as subduction-related magmatism or an incipient Benioff zone, have yet to be reported. This implies that subduction is most likely in its embryonic phase.

Transient Regime from Buckling to Subduction Initiation

In the Ulleung Basin, there are two regional-scale folds, the axes of which appear parallel...
to the NNW-SSE strike of the major thrust (Fig. 3A). The folds infer buckling of the oceanic lithosphere accommodating east-west compressional stress in the Ulleung Basin. Previous studies of focal mechanism solutions have revealed that the background compressional stress in the East Sea mainly originates from subduction of the Pacific Plate along the Japan trench (e.g., Choi et al., 2012). The horizontal force per unit length required to sustain a subduction system should be on the order of ~10¹² N/m (Copley et al., 2010), which is comparable to the theoretical value for buckling of viscoelastic-plastic oceanic lithosphere (Schmalholz and Mancktelow, 2016).

We suspect that buckling of the oceanic lithosphere along with shear zone (major thrust) formation is a strong indicator of future SI, as proven by several numerical studies (e.g., Thielmann and Kaus, 2012). The probability of SI becomes even greater considering the young oceanic crust (ca. 12 to ca. 20 Ma) of the Ulleung Basin (Kim and Yoon, 2017), which is similar to the estimated optimal age for SI (Cloetingh et al., 1989). Moreover, lithospheric weakening, induced by stress from thick sediments (>5 km) on the western continent-ocean boundary of the basin (So et al., 2012), may lead to SI even without compressional background stress (Regenauer-Lieb et al., 2001).

We argue that the crustal asymmetry recognized from P-wave tomography and a gravity anomaly (Fig. 3D) indicates regional uplift of the eastern Korean Peninsula (i.e., overriding plate) by underthrusting of the Ulleung Basin. Age dating of Quaternary marine terraces on the eastern Korean margin (blue triangles in Fig. 1) support ongoing uplift of the hanging wall at a rate of 0.26–0.67 m/k.y. since at least 0.3 Ma (Choi et al., 2008). Similar localized uplift of the overriding plate by SI was reported in the Fiordland Region of New Zealand (House et al., 2002). We also suspect that folding of the oceanic lithosphere and Quaternary fault movements in the continental Korean Peninsula (Yoon and Chough, 1995) accommodated the horizontal compression. Evidence for both underthrusting and buckling are found simultaneously, suggesting that the western margin of the East Sea is under a transitional regime toward SI.

Based on the observed geological evidence and mechanical plausibility, we propose that the Korean side of the East Sea is another candidate for SI, along with the well-known incipient subduction boundary on the Japanese side. Neither the Korean nor Japanese side of the East Sea appear to have reached a state of self-sustaining subduction. We suggest that the two incipient subduction zones are competing with each other to evolve into a self-sustaining system, as shown by the ancient case of the Gagua Ridge (i.e., failed SI) and the Manila subduction zone (i.e., successful SI) in the western Philippine Sea Plate (Eakin et al., 2015). While both margins...
exhibit geological characteristics of SI, the seismicity appears to favor the eastern margin as a stronger candidate over the western margin (No et al., 2014). However, such differences in seismicity may not be the only critical factor in determining an ongoing SI, because the process of SI has a time scale of ~5 m.y. (Toth and Gurnis, 1998). Instead, we speculate the eastern and western margins of the East Sea are under different stages of SI processes.

CONCLUSIONS

The compressive neotectonic evolution of the western strike-slip margin of the East Sea was investigated using seismic reflection and gravity anomaly data, along with a P-wave tomographic model. Based on newly recognized multi-scale deformation structures, we have drawn the following conclusions:

1. The tri-shear zone at the slope break of the eastern Korean continental margin suggests strain localization across the continental-oceanic boundary in the manner of a west-dipping major thrust.

2. The regional folding structure suggests buckling of the oceanic lithosphere by ENE-WSW compressive horizontal stress, comparable to the general tectonic stress required to sustain a subduction system.

3. The isostatic gravity anomaly and P-wave tomographic model reveal that the crust around the major thrust is thickened by underthrusting of the Ulleung Basin crust beneath the eastern margin of the Korean Peninsula.

4. Simultaneously, the thrust causes pervasive uplift over the eastern Korean margin related to structural inversion since the Early Pliocene. Therefore, we propose that these concurrent geophysical signatures for buckling and SI in the East Sea and the eastern Korean continental margin represent a transitional regime from buckling to the onset of SI.

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