論文の内容の要旨

Geologic processes controlling physical properties in forearc wedge

（沈み込み帯前弧ウェッジの岩石物性を支配する地質過程）

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One of the key controls on subduction processes and upper plate deformation in convergent margins is the topography on the subducting plate. Understanding the nature of seamount subduction is important to reveal its influence on the forearc wedge deformation, subduction erosion, and seismogenic behaviors along the plate interface. Uplift, subsidence, and faulting in the upper plate associated with seamount subduction have been indicated in previous studies by anomalies in the morphology and structures of the margin such as reentrants, bulges, scarps, and faults found from seafloor bathymetry and seismic surveys. However, the direct geological observation and sampling of the inferred offshore deformation structures during seamount subduction have been limited, and the quantitative features of the upper plate deformation and subduction erosion have been poorly defined.

The Middle America Trench offshore Osa Peninsula, Costa Rica, is known to be an erosive margin with active seismicity where the aseismic Cocos Ridge and associated subsequent seamounts on the Cocos Plate subduct beneath the Caribbean plate, creating an opportunity and necessity to investigate the geologic processes associated with seamount subduction. Previous offshore seismic reflection and multi-beam bathymetry studies have mapped clear high-amplitude widespread seismic reflectors beneath the slope considered to be a major unconformity developed between the slope cover and the more consolidated, intensely deformed upper plate material that exhibit a domed-structure along the plate boundary indicative of a subducted seamount. Abundant normal faults are identified to cut into the slope, and the high-amplitude reflections along faults, pockmarks and mud mounds as signs of abundant fluid seeps were previously reported suggesting an inter-relationship between deformation and fluid flow. The nature of the seismic reflectors in the forearc wedge and the high consolidation state of the upper plate material beneath the widespread unconformity in the wedge slope has been one of the major unknowns in this margin, but direct geologic observations of these structures and lithology have been limited, though they are important to understand the tectonic-depositional history, sediment-fluid interaction, and the processes related with seamount subduction.

To investigate the geological processes occurring at the Costa Rica margin, the Integrated Ocean Drilling Program (IODP) Expeditions 334 and 344: Costa Rica Seismogenesis Project, Program A Stages 1 and 2 (CRISP-A1, A2) have drilled into this margin offshore Osa Peninsula. In 2012, I have participated in IODP Expedition 344 as a physical property scientist and conducted physical property measurements (porosity, density, P-wave velocity, resistivity, natural gamma ray, magnetic susceptibility, thermal conductivity, shear/compressive strength) during the cruise. IODP Expeditions 334 and 344 have penetrated the major unconformity beneath the middle and upper slopes. Beach deposits and fault zones were observed to distribute across the unconformity beneath the slope, indicating the events of uplift to nearshore environment, erosion, and faulting.

In the present study, to investigate the nature of the seismic reflectors in the forearc wedge, the high consolidation state of the upper plate material, and the roles of fluids at the Costa Rica margin and to quantify the deformation events during seamount subduction, I focused on the consolidation process and physical property transitions of the sediment samples that correlate with the seismic reflectors across the major unconformity and examined the burial condition and the maximum burial depth range of the sediments below the unconformity. On the basis of sediment microstructural observations, physical property measurements, and geochemical composition analyses using the sediment cores from the middle-slope Site 1380 recovered during IODP Expedition 344, I investigated the effects of burial diagenesis and fluid-sediment interaction on the porosity-depth transition to extract the initial burial compaction curve. I assessed the maximum burial conditions below the unconformity from the porosity-depth curve and quantified the tectonic events of uplift, subsidence, surface erosion, and fault displacement that have occurred across the unconformity as described below.

The upper plate material below the unconformity at the middle slope consisting of lithified terrigenous sediments of clayey siltstone (Units 2, 3) and the slope sediments above consisting of silty clay (Unit 1) were revealed to be characterized by consolidation due primarily to burial compaction and mineral precipitation of zeolites. A Na-type zeolite analcime which formed during burial diagenesis was observed to be present only below the unconformity, whereas a Na/Ca type zeolite heulandite and a Ca-type zeolite laumontite were precipitated due to interaction with high-temperature fluid (~100°C) that has likely localized in the vicinity of the unconformity. The experienced maximum temperature of the sediments below the unconformity based on the formation of analcime during burial diagenesis is estimated to range from 86°±5°C to 122°±2°C, which is higher than the current geothermal gradient. The change in zeolite assemblage indicates that the events of uplift from a greater depth, the transition of pressure-temperature (P-T) conditions, and sediment removal have occurred across the unconformity.

By quantifying the weight percentages of zeolites, I estimated the effect of laumontite and heulandite precipitation on porosity and recalculated the porosity-depth curve eliminating the effect of the fluid-sediment interaction. Based on microstructural observations, the lithology difference across the unconformity was minimal and the burial compaction trend was consistent among Units 1, 2 and 3, enabling to assume a composite initial porosity-depth curve of the sediments. The depth along the approximate curve of the porosity-depth transition of Unit 1 that matches the porosity of the sediments at the top of Unit 2 corresponds to the maximum burial depth range of the sediments below the unconformity: 1000±400 meters below the seafloor (mbsf).

The distribution of the beach deposits consisting of shell fragments and the damage zones of normal fault regime across the unconformity were observed from the drilled cores, indicating that the sediments that have experienced the maximum burial depth range of 1000±400 mbsf have likely uplifted to the ocean surface and reached the current depth through surface erosion and/or fault displacement.

In this study, the examination of the maximum sediment removal (surface erosion) (Model 1) and maximum fault displacement (Model 2) during uplift and subsidence events were made from the porosity gap across the unconformity and the burial compaction curve derived from the porosity-depth relationship of the sediments. The results suggest that after the initial burial, the sediments uplifted ~500 m (Model 2) to 1500±400 m (Model 1) to near sea level, followed by ~1050 m subsidence, associated with a mass movement of 1000±400 m maximum (Model 1) and/or normal fault displacement of 450±400 m maximum (Model 2) to reach the current depth range. Under an approx. 10°–30° dip angle of the slope and fault plane, this thickness of maximum mass movement and normal faulting would correspond to the distances of 4600±3400 m (Model 1) and 2500±2400 m (Model 2) parallel to the slope and fault, respectively.

These events occurred during the time range between 2.20±0.25 Ma and 1.71±0.24 Ma inferred from nannofossil age, which is likely to be consistent with the timing of the onset of the subduction of the Cocos Ridge and the subsequent seamount chains reported by previous studies. The observations in this study suggest that the major unconformity in the wedge slope at the Costa Rica margin were developed through the geologic processes during Cocos Ridge/seamount subduction, in which significant uplift occurred mirroring the topography of the undergoing seamount, causing over-steepening of the wedge, followed by subsidence and erosion due to normal faulting, mass movement, and basal erosion.

The erosional unconformity, slope sediment cover, mass transport deposit, faulting and folding are indicated by 2D seismic reflection data near the middle-slope Site 1380, and they are consistent with the geologic events quantified from the sediment cores in this study. The events of uplift and subaerial erosion across the unconformity are supported by the seismically imaged erosional unconformity that cuts the landward-dipping reflectors in the margin wedge below. The uplift events have likely induced multiple events of landslide and mass movement, associated with normal fault and reverse fault displacement. The slope sediments and mass transport materials deposited on top of the unconformity, possibly creating additional unconformity due to erosion in the shallower region. The major unconformity and the sedimentary layers were later folded, cut by and accompanied with abundant faults. The fluid paths that enable the significant sediment-fluid-thermal interaction in high temperature which caused zeolite precipitation promoting sediment consolidation revealed from this study may be related to the transitions in hydrologic properties during seamount subduction that initiated abundant fluid flow along the landward- and seaward-dipping high-amplitude reflectors that penetrate from greater depths and occasionally cut the unconformity.

The geologic events across the widespread unconformity observed in both the upper and middle slopes are likely to be regional. However, when comparing the major unconformity developed in the Costa Rica margin between the middle and upper slopes, the unconformity is shallower in the middle slope and the porosity gap and the indicated amount of sediment removal is larger in the upper slope. Although the unconformity is continuous along the slope due to sequential seamount arrival, the depth and age of the unconformity may be heterogeneous due to structural variations corresponding to multiple events of subsequent seamounts.

My investigation of the balance among tectonic events of uplift, sediment removal, normal faulting and subsidence during seamount subduction revealed that these processes resulted in a significant exhumation of deeper rocks to a shallower region through surface erosion (gravity collapse, mass movement) and/or extension (normal faulting), contributing to the high consolidation of the forearc wedge. The exhumation of the lithified, deeply buried sediments preserving the higher paleo-isotherm in the upper plate may thus have lifted the up-dip limit of the seismogenic zone to a shallower depth range.