Reports

Seismic-Reflection Signature of Cretaceous Continental Breakup on the Wilkes Land Margin, Antarctica

Abstract. *The passive (rifted) continental margin of Wilkes Land, Antarctica, is characterized on seismic reflection records by (i) in the south, a block-faulted sequence of highly stratified continental beds overlain by two distinct unconformities; (ii) a transitional, greatly thinned continental crust overlain by material interpreted to be flood basalt; and (iii) in the north, oceanic crust with a boundary ridge at its edge. The Mohorovičić discontinuity can be followed across the continent-ocean boundary and shows a progressive thinning of continental crust to a minimum of 2.5 kilometers at its northern edge.*

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The deep crustal structure of the continent-ocean boundary at Atlantic-type continental margins is commonly obscured by thick blankets of sediment and by complex and masking stratigraphy such as carbonate reefs or salt layers. Thus there are relatively few locations where this fundamental crustal boundary has been clearly observed with seismic techniques. Of those passive margins that have been studied, two "end-member" types appear to emerge: volcanic-rich margins, such as the Norwegian margin, where large outpourings of lavas, perhaps subaerial, are associated with the breakup (*1*); and volcanic-poor margins, such as the margin off western France, where the continental crust has thinned and downfaulted along listric normal faults to a juncture with oceanic crust (*2*). Intermediate between these are areas, of which the continent-ocean transition off southwest Africa is typical, that are marked by volcanic deposits interspersed with faulted and subsided continental crust, of rift-stage origin (*3*). We report on seismic measurements made on the east Antarctic margin, a passive margin of an intermediate type which, because of relatively thin sediment cover and lack of acoustic masking strata in the section, show the stratigraphy and structure across the transition from continental to oceanic crust.

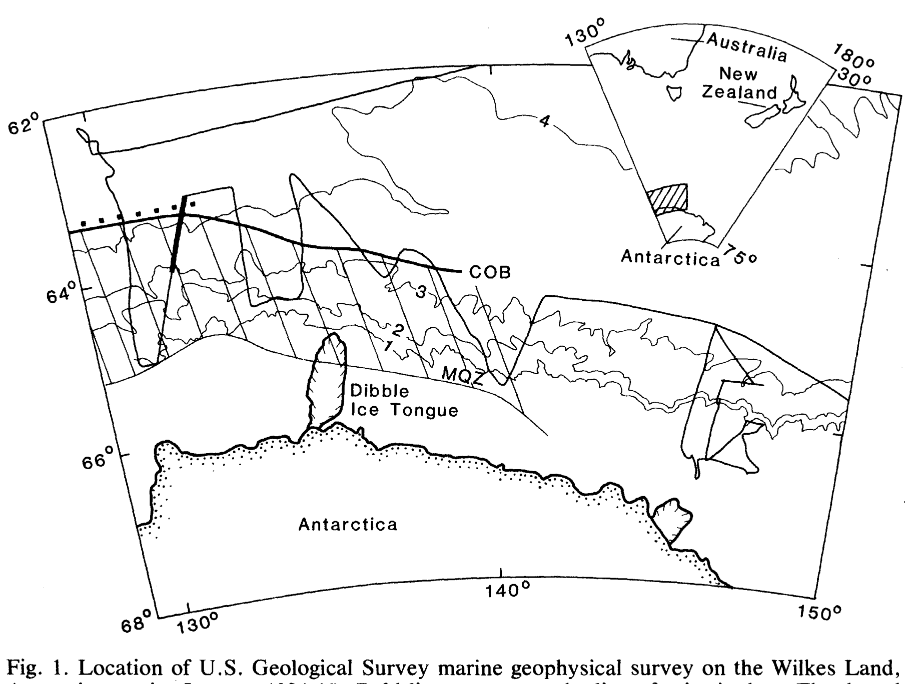

Fig. 1. Location of U.S. Geological Survey marine geophysical survey on the Wilkes Land, Antarctic margin, January 1984 (*6*). Bold line represents the line of seismic data. The dotted line, after (*4*), marks the oldest identified oceanic crust magnetic anomaly, anomaly 34. The continent-ocean boundary (COB) is the southern edge of oceanic crust as seen in the seismic data. Bathymetric contours are in kilometers. MQZ, magnetic quiet zone.

Between the continents of Australia and Antarctica the oldest sea floor–spreading magnetic anomaly identified with the oceanic crust has been interpreted to be anomaly 34 and the oldest oceanic crust to be 96 million years old (*4*). On the south Australian margin a zone of quiet magnetic field, about 120 km wide, extends landward from the edge of clearly defined oceanic crust to the upper or lower continental slope. Gravity and magnetic models and seismic reflection and refraction data suggest that this magnetic quiet zone consists of thin, subsided continental or rift-stage crust with highly variable thickness and seismic velocity (*5*). There is a similar magnetic quiet zone due south on the conjugate Antarctic margin (*4*).

A geophysical survey carried out by the U.S. Geological Survey in January 1984 on the Wilkes Land continental margin was conducted principally south of the 96-million-year-old magnetic anomaly and in the magnetic quiet zone (Fig. 1). Geophysical measurements included 24-channel seismic reflection, seismic refraction, gravity, and magnetics (*6*).

The continent-ocean boundary can be identified on the westernmost seismic lines where the overlying sediments are thinnest. The profile in Fig. 2 illustrates the character of the Wilkes Land continent-ocean boundary on one of these lines and shows features similar to those seen on the other adjacent lines.

The continental rise is underlain, at a depth of about 5 km, by a parallel-bedded, well-stratified sequence that is down-dropped to the north along shallow-dipping normal faults. The beds of this stratified sequence have seismic interval-velocities averaging 4.2 km per second, suggesting well-consolidated sediment. The high velocity of this sequence and its block faulting suggest a continental deposit that was faulted by extensional tectonics during continental rifting; we call this unit the prerift sequence. The shallow-dipping faults flatten with depth to become tangent to a reflecting horizon at depths of about 10 to 12 km. We interpret this reflection horizon to be a décollement surface, perhaps a zone of weakness separating upper from lower crustal layers (MSD in Fig. 2).

At the north end of the profile, the reflections from acoustic basement have a rough, reverberant character, dominated by hyperbolic reflections in unmigrated seismic data, and no internal crustal layering is recorded. These reflections are typical of those recorded in ocean basins from the top of volcanic basement, or oceanic layer 2 (*7*). The continent-ocean boundary is defined here as the southern edge of this crustal type. A boundary ridge is located at the edge of oceanic crust on this profile as well as on the adjacent profiles of the data set. The magnetic anomaly interpreted to be anomaly 34 or an edge-effect anomaly of 96-million-year-old crust (*4*) is associated with the continent-ocean boundary here and with this boundary ridge.

A transitional zone is situated between oceanic basement on the north and the block-faulted prerift sequence of continental crust on the south and is distinguished by a reflector package, R, 0.5 km thick, which is highly reflective and has a sinuous appearance at a depth of 8.5 km. This reflector package is deeper than the oceanic crust to the north and onlaps the stratified, high-velocity reflectors of the prerift sequence to the south. The stratified units of the prerift sequence continue beneath R and abut the edge of oceanic crust. Beneath the transitional zone, reflections from the Mohorovičić (Moho) discontinuity are observed at depths ranging from 12 to 16 km.

Reflector package R is overlain by about 1.5 km of strata characterized by closely spaced (less than 100 m), seaward-dipping reflectors (PG in Fig. 2) whose interval velocity averages 3.9 km per second. The upper boundary of this sequence is a regional unconformity, K1. At its lower boundary, the dipping reflectors PG lap downward onto reflector package R. The PG reflectors are assumed to be prograded clastic sedimentary material on the basis of (i) its location in the section, (ii) its seaward-dipping, closely spaced stratifications bounded at top and bottom by unconformities; and (iii) its seismic velocity.

Above the prerift sequence, two prominent unconformities are seen in the sedimentary section (Fig. 2). The uppermost one, K1, is erosional in places, defines the uppermost level of penetration of faults that cut the prerift sequence, and can be followed northward to where it onlaps the edge of oceanic crust. Sediment older than K1 has not been deposited on oceanic basement. The lower unconformity, K2, is an erosional unconformity along the tops of the fault blocks of the prerift sequence. Therefore, we define K1 as the breakup unconformity and K2 as the rift-onset unconformity. Unconformity K2 represents the erosional remnants of the subaerial continental surface that existed before rifting. Sediments between K1 and K2 are synrift deposits that were partly derived from erosion of high-standing fault blocks and have filled the small basins between blocks and the broader, rifting-induced regional basin. Seismic stratigraphic and drill-hole studies on the Australian margin have identified similar rift-onset and breakup unconformities in the sedimentary section there (*8*).

The Moho discontinuity, clearly defined in the vicinity of the continent-ocean boundary, ranges in depth (below

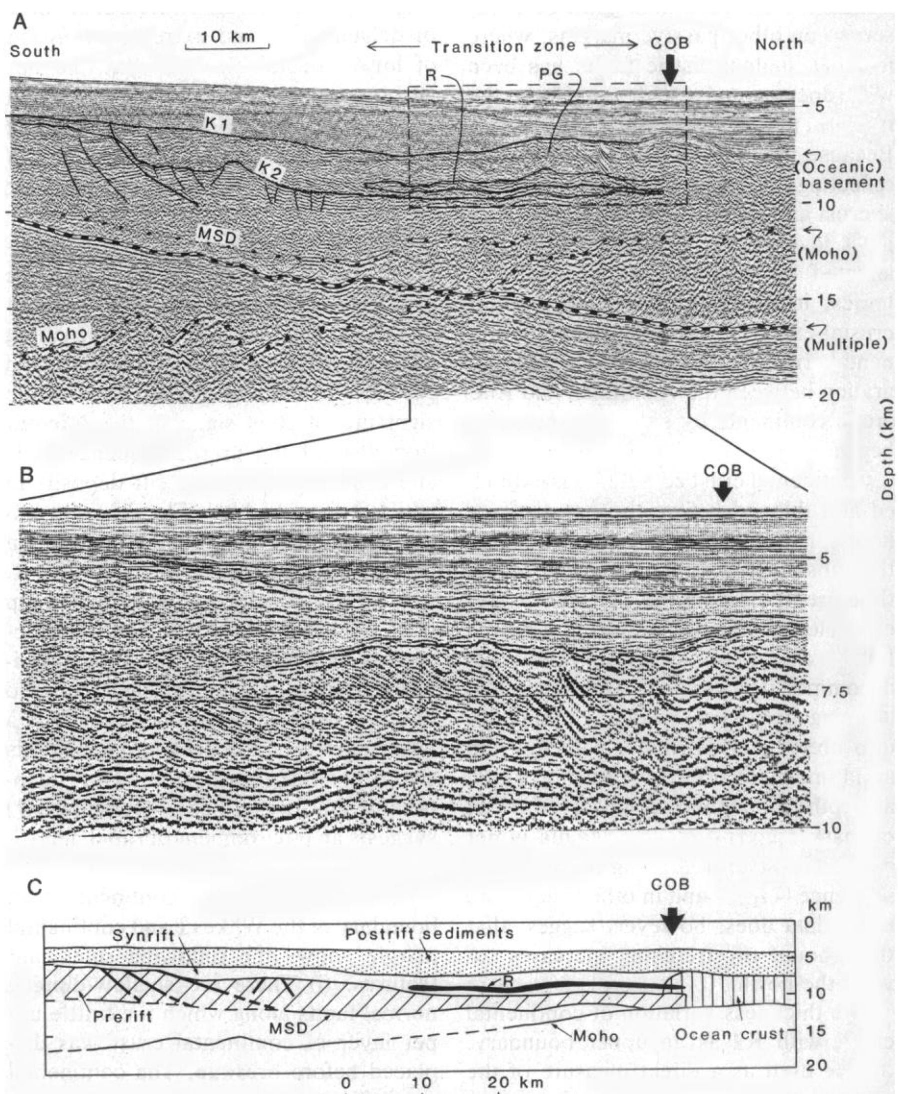

Fig. 2. (A) Migrated seismic-reflection record (depth display with 24-fold stacking) across the continent-ocean boundary (COB); vertical exaggeration, 2.7:1. The seismic system consisted of a 2.4-km hydrophone array and 21-liter air-gun array. K1, the Cretaceous breakup unconformity; K2, the rift-onset unconformity at the top of the prerift sequence; MSD, master surface of décollement, a deep crustal reflection inferred to be a zone of weakness and a décollement surface between upper and lower crust; R, a highly reflective unit that is inferred to be flood basalt and is overlain by PG, prograded clastic strata. (B) Enlargement shows seismic stratigraphy adjacent to the COB. Note the northward-dipping reflectors inferred to be prograded clastic strata deposited on top of flood basalt. (C) Interpretive section with no vertical exaggeration, showing principal seismic units and structures.

sea level) from 12 km under ocean crust to 17 km under attenuated continental crust. On the three westernmost north-south seismic lines, Moho shows an abrupt increase in depth at the continent-ocean boundary or just landward of it. The Moho reflections are mostly low-frequency single events, although in limited areas under continental crust the boundary consists of multiple reflections.

Extension of the Antarctic continental crust before and during breakup is evident in our profiles from the series of normal faults beneath the continental rise. This faulting is similar, for example, to styles of faulting in the Basin and Range province of the western United States (*9*). Crustal thinning has been observed on other passive margins, where movement along listric faults has been well documented, such as along the northern margin of the Bay of Biscay (*2*). Because unconformity K1 is the oldest reflecting horizon in contact with oceanic crust and because it defines the uppermost level in the sedimentary section affected by significant extensional tectonics, it marks the end of the major crustal-extension episode when continental crustal stretching ceased and separation between the Australian and Antarctic continents by sea floor spreading began.

Continental crust commonly is extended and thinned before the onset of sea floor spreading (*2, 10*). To accommodate the substantial thinning required (*11*) by the observed amount of subsidence (for example, as inferred here from near sea level to a depth of 7 km), fault planes that accommodate crustal stretching and thinning must have low dip. Although we do observe normal faults with low dip and some that flatten to nearly horizontal at depth, the amount of observed offset of marker horizons across faults is not great. The style of faulting of the prerift sequence (Fig. 2) and in other lines from these data does, however, suggest that the amount of stretching increases toward the north.

The thickness variation of continental crust, with K2 as an upper boundary, can be used as a direct measure of the amount of thinning, by comparison to an assumed prerift crust of normal thickness of 35 km. Crustal thickness varies from 12 km at the left profile edge to 2.5 km near the continent-ocean boundary (Fig. 2). Relative to normal unrifted continental crust, thinning by factors of from 3 to 12, respectively, is implied. This much thinning cannot be accounted for by measurements of displaced strata along the observed extensional faults. Measurements of displaced strata and the dips of strata in the blocks of the prerift sequence indicate upper crustal extension of less than 20 percent. Other studies (*12*) have also shown that observed stretching in upper crustal layers falls far short of values required to account for the degree of observed thinning.

An alternative to the simple stretching model of lithospheric thinning and subsidence is the model that incorporates a detachment at the base of the upper crust which allows movement of brittle blocks of upper crust independent of the lower crust (*13*). In this way extension can occur over a narrow region (~100 km) of the lower crust, by either ductile flow or delamination and extreme extension of lower crustal blocks, while the upper crust can respond to the extension over a wide zone (~1000 km), allowing a more modest thinning factor. Such a model appears to better explain our data.

Inasmuch as reflector R of the transitional zone lies below, and therefore predates, the breakup unconformity, it must have been created during the rifting phase before sea floor spreading, and perhaps just before breakup. The seismic signature of R is significantly different from that of the prerift sequence beds and from that of the synrift deposits in which it is embedded. Flood basalt, extruded on top of thinned continental crust, is the preferred explanation for R. The 1.5 km of sediment deposited on top of R is probably a clastic sequence deposited in a submerged rift-valley environment. The maximum relief recorded on the prograded foreset beds suggests a basin at least 1.5 km deep into which this sediment was transported. The steepness of the foreset beds (averaging 10°) suggests an environment of rapid deposition.

In summary, the continent-ocean boundary of the Wilkes Land continental margin shows the following significant features. (i) There are shallow-dipping normal faults along which the brittle upper layer of continental crust was displaced before breakup. The continental crust thins progressively toward the continent-ocean boundary, reaching a minimum thickness of 2.5 km adjacent to this boundary as measured from the prerift subaerial surface, K2, to Moho. (ii) There is a boundary ridge at the edge of oceanic crust, approximately 10 km wide, which is similar to that proposed to exist elsewhere on passive margins (*14*). Such boundary ridges are not always present where detailed seismic data are available (*3, 15*), and their study may lead to a better understanding of magma budgets and the tectonics of asthenospheric upwelling during the early-opening phases of ocean basins. (iii) The continental crust is thinned and subsided in the magnetic quiet zone landward of the oldest sea floor–spreading magnetic anomaly, in accordance with similar observations on the conjugate Australian margin (*5*). (iv) There is a transitional zone landward of the continent-ocean boundary, 7 to 30 km wide, in which Moho dips landward and a high-amplitude, distinctive reflector is deposited on top of extremely thinned continental crust. This reflector is interpreted to be a flood basalt that was deposited before initiation of sea floor spreading and was overlain by rapidly deposited prograded clastic sediment.

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