Opening of the Drake Passage: Does this event correlate to climate change and biotic events from the Eocene La Meseta Formation, Seymour Island, Antarctic Peninsula?

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Summary The time frame for opening of the Drake Passage, which resulted in the onset of Antarctic climatic cooling and then to the development of ice sheets on the Antarctic Peninsula, is hypothesized to be an early Oligocene event. Rock units from the topmost levels of the La Meseta Formation on Seymour Island, Antarctic Peninsula exhibit evidence of ice sheet formation. The date for ice sheet development is at the Eocene-Oligocene boundary. Thus the opening of the Drake Passage is hypothesized to be at Eocene-Oligocene boundary. However, fish teeth extracted from deep-sea cores were analyzed to provide data on a deepwater opening of the Drake Passage correlated to the Late Eocene (ca. 41 Ma). The data from vertebrate paleofaunas and associated paleofloras from the La Meseta Formation can be used to relate the opening of the Drake Passage to climatic indicators from these fossil remains.

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Introduction

The time frame for opening of the Drake Passage, which resulted in the development of the Antarctic Circumpolar Current, subsequent onset of Antarctic climatic cooling, and leading to the development of an earliest Oligocene ice sheet on the Antarctic Peninsula is considered to be an Oligocene event (Zachos et al., 2001). Ivany et al. (2006) described rock units from the topmost levels of the La Meseta Formation on Seymour Island, northeastern Antarctic Peninsula and overlying horizons, which indicate ice sheet formation. Data from dinoflagellates and strontium dating place the date for ice sheet development at the Eocene-Oligocene boundary. Thus the date for the opening of the Drake Passage is hypothesized to be at the Eocene-Oligocene boundary and correlated to a sharp drop in ocean temperature.

Scher and Martin (2006) utilized a rare earth element, neodymium (Nd), contained in fish teeth extracted from deep-sea cores to provide data on a deepwater opening of the Drake Passage. They used ratios of $^{143}Nd/^{144}Nd$ to determine the transition from non-radiogenic to radiogenic Nd values in Atlantic waters, which would mark the flow of the more radiogenic Pacific waters into the Atlantic ocean as the signal for the deepwater opening of the Drake Passage in the Late Eocene (ca. 41 Ma). A shallow water opening of the Drake Passage of less than 1000 meters deep may have formed as early as 50 Mya based on tectonic evidence in the Weddell Sea (Livermore et al., 2005). The formation of new tectonic basins in the region, that later formed the Scotia Arc and the northern Antarctic Peninsula, is correlated with a drop in Southern Ocean temperatures. Based on oxygen isotope data from benthic foraminifera, this is hypothesized to represent the initial shallow water opening between South America and Antarctica (Livermore et al., 2005).

La Meseta Formation

It is possible to examine these hypotheses regarding the time frame for the opening of the Drake Passage from what is currently known in a locality much closer to the site of the actual opening at Seymour Island (Isla Marambio). The La Meseta Formation (LMF) occupies nearly all of the northern third of the island and represents a 720 m thick, stratified, sequence of fossiliferous sands, silts, mudstones and shell beds, which spans nearly all (if not all) of the Eocene including the Eocene-Oligocene boundary (Ivaney et al., 2006). The oldest dates (52-54 Ma), based on $^{87}Sr/^{86}Sr$ isotopic ratios (Dutton et al., 2002) come from the 150 m level in Telm 2 of Sadler (1988) at the boundary of the Valle de las Focas and Acantilados Allomembers of Marenssi and Santillana (1994). Consequently, the base of the LMF should be close to the beginning of the Eocene at 54.8 Ma (Gradstein et al., 2004). Ivany et al. (2006) report a date from the top of the LMF of 33.57-34.78 Ma ($^{87}Sr/^{86}Sr$) and this date is consistent with a previous date for the topmost LMF of 34.2 Ma (Dutton et al., 2002). Thus, the La Meseta Formation should contain a near complete record of the transition from the warm Early Eocene conditions, through the transitional cooling of the Middle Eocene to the greater cooling in the latest Eocene and finally to the onset of Early Oligocene ice sheet development. A question that can be asked is to what degree is there a correlation between the opening of the Drake Passage, ocean temperatures and climatic indicators based on megafossil evidence of the local paleofloras and the La Meseta paleofaunas?

With the potential of added dates within the LMF from Marenssi (2006) where he correlated the unconformities between the La Meseta stratigraphic units to low sea level stands of Haq et al. (1987), it is then possible to fit the Eocene portion of the ocean temperature curve of Zachos et al. (2001) to the La Meseta stratigraphy. Therefore, it is possible to relate the ocean temperature fluctuations with the deep-water opening of the Drake Passage and the biotic events documented by the paleofloras and paleofaunas from the La Meseta Formation.

Paleofloras and paleofaunas

The Late Paleocene Nordenskjöld (= Cross Valley; Francis et al., 2003) paleoflora from the Cross Valley Formation on Seymour Island is dominated by angiosperm taxa with some thirty-six species, thirteen of which have entire leaf margins, while twenty-three species exhibit toothed leaf margins indicating a warm temperate forest (Francis et al., 2003). Additionally, there are both araucarian and podocarp conifers and at least three fern species (Case, 1988). When the leaf morphology of the angiosperm species are examined via CLAMP analysis, a warm Mean Annual Temperature (MAT) of 13.5°C is predicted for the Antarctic Peninsula with an average precipitation of 2110 mm/yr in the late Paleocene (Francis et al., 2003).

There is a distinct change between the Late Paleocene, Nordenskjöld paleoflora and the Early Eocene, Acantilados (= Cross Valley; Case, 1988) paleoflora from the Acantilados allomember. An increase in leaf size was noted in response to the warm Early Eocene conditions with presumably increased precipitation as well (Case, 1988).

The Middle Eocene, La Meseta paleoflora from the Cucullaea I allomember, exhibits a decrease in leaf size from the paleofloras both from the Nordenskjöld and the Acantilados paleofloras, suggesting a drop in temperature (Case, 1988). CLAMP analysis of the La Meseta paleoflora suggests only a small drop in MAT to 11-13°C but with a significant change to a highly seasonal climate with a Mean Winter Temperature (MWT) of -3 to 2°C (Gandolfo et al., 1998a,b). This cool temperate rainforest includes podocarp, araucarian and cupressacean gymnosperms and at least three species of fern (Case, 1988). Torres et al. (1994) indicate the fossil wood taxa have affinities with extant taxa living today in cold-temperate rainforests of the Valdivian region of southern South America (Poole and Cantrill, 2006). Modern counterparts of the Eocene mammal paleofauna from the La Meseta Formation, also live in these same Valdivian rainforests of southern Chile and Argentina (Woodburne and Case, 1996). This Valdivian rainforest-like environment represented by the La Meseta paleoflora with cold wet winters, but drier than that predicted for earlier paleofloras where precipitation was reduced to 1534 mm/yr in the Middle Eocene (Francis et al., 2003).

The Middle Eocene Antarctic terrestrial vertebrate paleofauna from the La Meseta Formation exhibits a wide, but bimodal, range of body sizes from small marsupials (also a rodent-like gondwanathere) to large-sized ungulates along with a large-bodied sloth and cursorial birds including ratites and phororachoid birds. The paleofauna lacks medium-sized marsupials and notoungulate mammals and thus the fauna has a U-shaped, bimodal distribution of body sizes. This bimodal body size distribution pattern also appears in higher latitude living mammalian faunas as a response to cold winter temperatures at these latitudes (Case, 2006). If the Patagonian Late Paleocene to Early Eocene mammalian paleofaunas are the source for the La Meseta Paleofauna (LMP), then a high degree of faunal similarity would be expected, but the LMP shows a distinct endemism at the generic or species level. The degree of endemism in the LMP may be the result of a vicariant barrier that could either be climatic (dropping of temperature, especially MWT) or physical (the opening of the Drake Passage) or the interaction of both vicariant phenomena (Reguero and Marenssi, in press).

The Marine Vertebrate Paleofauna from the La Meseta Formation shows some relationship with the changes in ocean temperature and potentially to the deep-water opening of the Drake Passage. Sharks are very abundant in Telm 3-5 (Acantilados through Cucullaea I (Case, 1992) with penguin fossils found frequently and the occasional whale material recovered in these same units. The vertebrate record changes significantly in Telm 7 (Submeseta) in that only the large ungulates and giant birds are present (Reguero and Marenssi, in press), while the smaller marsupials appear to drop out of the record. Among marine vertebrates, sharks have nearly disappeared, while the abundance of penguins dramatically increases and whale material is much more frequent.

The change in the vertebrate record in the mid- to upper portions of the La Meseta Formation are suggestive of a significant change and would certainly correlate well with a deep water opening of the Drake Passage at 41 Ma (Scher and Martin, 2006). The change from Middle Eocene Climatic Optimum to cooler Late Eocene conditions is consistent with the vertebrate faunal changes, which probably occurred in Telm 6 (Cucullaea II).

The point of uncertainty is whether the floral changes between the Early Eocene, Acantilados paleoflora and the Middle Eocene, La Meseta paleoflora and the proposed climatic changes are correlated with the originally shallow breaching of the Patagonian-Antarctic Isthmus resulting in the Drake Passage. Alternatively, these biotic changes could be the result of cooling caused by significant drops in atmospheric carbon dioxide levels (DeConto and Pollard, 2003), which would also have the potential to cause the development of ice sheets in the Antarctic Peninsula.

A full test and determination of the relationship of the opening of the Drake Passage to climatic events can only be achieved with further study, which is the intent of a current proposal by the author to the National Science Foundation.

Summary

The La Meseta Formation contains a very complete record of the Eocene timeframe in Antarctica. The effect of the opening of the Drake Passage (hypothesized to be at or prior to 41 Ma) on climatic and biotic change can be examined through the paleofloras and vertebrate paleofaunas collected from that Formation. The degree of correlation between timing of the formation of the Drake Passage and climatic and biotic changes can then be tested.

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