Arctic Lena Trough is an ultramafic continental margin

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Jonathan E. Snow[1], Eric Hellebrand[1], Anette von der Handt[1], Steffen Gauger[2], Peter Lemke[3]

[1]Max-Planck-Institut für Chemie, Mainz, 55020 Mainz, Germany
[2]FIELAX GmbH, Bremerhaven, Germany
[3]Alfred-Wegener-Institut für Polar- und Meeresforschung, Columbusstr, Bremerhaven, Germany

The breakup of continents is closely linked with the opening of oceanic gateways as key processes in the evolution of the Earth's crust and climate. The opening of Lena Trough, the gateway between the Arctic and N. Atlantic oceans, is the most recent and final event in the separation of the North American from the Eurasian continent and the opening of the Arctic Ocean to deep water circulation. Here we report new mapping and sampling results from Lena Trough that show that it belongs to the newly defined non-volcanic class of continental margins, and exposes nearly exclusively ultramafic mantle rocks. Without significant basaltic infilling of the nascent ocean basin, subsidence to very great depths (>4000m) probably occurred rapidly after transtensional motion began on the plate boundary in the Miocene. The Lena Trough is thus the only known modern analog of the Iberia Margin, the conjugate Newfoundland Margin, as well as the ophiolite complexes of the Western Alps. The rapid opening of this deep water gateway had profound effects both on the thermohaline circulation of the Arctic Ocean and of the rest of the world.

Introduction

Lena Trough is located on the Arctic side of Fram Strait, and is a 350 km long bathymetric deep connecting the Arctic and Atlantic Oceans. It is a key region in the world's oceans in several respects. First, it is the only deep-water connection between the Arctic Ocean and the rest of the world's oceans. Second, it is the only connection between the ultraslow spreading Gakkel Ridge [1,2] with the rest of the world's mid-ocean ridge system. Thirdly, until about the Miocene it was the last connection between the North American and Eurasian Plates, and the final act in the breakup of the supercontinent Pangea, which began in the Permian. Until recently, little was known about the nature and evolution of Lena Trough, in part due to year-round ice cover and the transarctic current funneling of large amounts of arctic sea ice through Fram Strait **(ref!)**. Indeed, the existence of Lena Trough as a deep water channel was not established until the 1960's[3] -- earlier maps had shown a narrow isthmus of shallow water connecting the two continents [4]. Initial mapping and sampling of southern Lena Trough occurred in 1999[5], and of Northern Lena Trough in 2001[6].

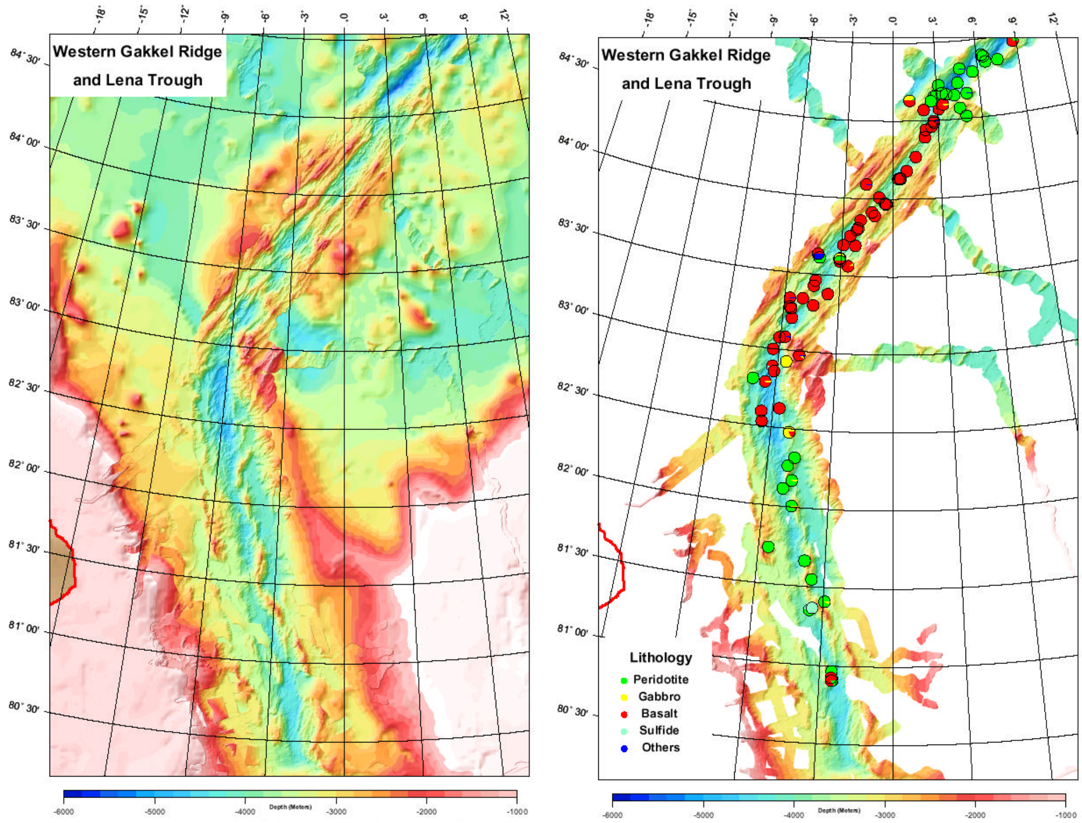

Figure 1: Bathymetry and petrology of Lena Trough **(Provisional – is being redrafted)**. 1a) Data from Polarstern ARK XV-2, XVII-2, XX-2 , USCGC Healy 0102 and IBCAO **(Refs)**. 1b) Dredging positions are pie charts using the colors given in the legend.

Another important feature of Lena Trough is its geometry and ultra slow spreading rate. Among mid-ocean ridges, and important distinction is made between those that spread slowly (between 20 and 40mm/yr) and ultraslow ridges, whose expansion rate is less than 20mm/yr [7]. Both types of ridges form preferentially along plate boundaries related to the breakup of Pangea since the Permian. The trend of Lena Trough however does not conform to the usual pattern of mid-ocean ridge rifts, where magmatic segments orthogonal to the spreading direction are intersected by large transform faults perpendicular to the spreading direction [8]. Instead the rift trends obliquely to the spreading direction by about 55 degrees [5,9]. Until now it was unclear how this obliquity in the geometry of the plate boundary was accommodated however. One possibility was a series of en echelon spreading segments linked by fracture zones. Another was that the rift tectonics themselves are oblique to the spreading direction[7], with mixed basalt, serpentinized peridotite and gabbro making up a composite ocean crust[10]. Nonetheless, the initial results had found basaltic volcanism in Lena Trough[5], and evidence for extensive melt interaction in the peridotites[11]. This led to the conclusion that normal mid-ocean rift spreading was occurring in Lena Trough[5]. Tectonic models for this key region until now differed only in the number and length of orthogonal spreading segments and transform faults[2,12-15].

In Summer 2004, Leg ARK XX-2 of the research icebreaker PFS Polarstern (Alfred-Wegener Institute for Marine and Polar research) conducted the first extensive mapping and sampling operations in Lena Trough. During the entire time, pack ice conditions (9/10 coverage) prevailed over most of Lena Trough and Gakkel Ridge. Approximately 50,000 km^2 of the rift axis of Lena Trough were mapped using the onboard Hydrosweep DS-2 bathymetric mapping system **[Steffen, is this correct?]** and combined with data from previous expeditions to delineate the tectonic features of the region (Figure 1). 38 dredge hauls on Lena Trough and Gakkel Ridge were carried out in 17 station days with no material losses, returning approximately 4 tons of basalt, gabbro, peridotite and hydrothermal lithologies (Figure 1, inset).

A deep, oblique-spreading mid-ocean rift

Lena Trough as a tectonic plate boundary connects the Gakkel Ridge in the North with the Spitzbergen Fracture zone, Molloy Deep and finally the Knipovitch ridge to the south (Figure 1). The morphology of Lena Trough is unique among mid-ocean spreading center rift zones. The walls of the deep are constructed by steeply dipping fault surfaces which strike parallel to the trace of the Eurasian-North American plate boundary, and the nearby margins of the North American and European continents, but are oblique to the spreading direction of the two plates by about 45 degrees. The floor of the trough is partly filled by large sediment ponds, which are over a kilometer deep in some places [16]. Though it is part of the mid-ocean ridge system, and unlike Gakkel Ridge, Lena Trough itself cannot be termed a mid-ocean ridge because there are no rift mountains to form a positive bathymetric ridge, only a single rift complex descending from both continental margins to the basin floor.

At the northern end of Lena Trough, faults curve into the direction of Gakkel Ridge, and secondary faults in the floor of the rift are parallel to Gakkel Ridge. This fault pattern has been observed before in oblique sections of mid-ocean ridges such as the Knipovitch Ridge [17,18] and the Southwest Indian ridge[7]. Generally, this outcrop pattern is linked with magmatic activity, with more magmatic areas showing more orthogonal secondary fault topology and more tectonic areas showing rift-parallel (ie oblique to the spreading direction) secondary fault topology. Sampling along these features returned pillow basalt, diabase and gabbro, confirming the magmatic nature of the northern transition of Lena Trough into the Western Volcanic Zone of Lena Trough

Through these sediment ponds protrude median basement ridges of two to three thousand meters height above the valley floor that wander down the center of the trough. Their strike is sub- parallel to the walls of the valley, however it is difficult to orient them along a flow line to their original position in the valley wall. Sampling of these basement ridges returned mantle rocks with a small number of highly vesicular basalts at the southern end. Towards the south, Lena Trough is increasingly sedimented [16], which makes sampling more difficult.

A major point of uncertainty concerning Lena Trough at the outset was the issue of segmentation. The ultra slow spreading Gakkel ridge further north is magmatically segmented, even though no first order segmentation by fracture zones is present. Lena Trough has often been thought of as requiring a stairstep geometry to accommodate the obliquity of the plate boundary[2,12-15]. In fact, Lena Trough consists of a single first order oblique segment, with no transform faults, fracture zones or obvious magmatic centers present. Even individual volcanoes could not be recognized in the ocean floor survey, by stark contrast to the robustly magmatic Western Volcanic Zone[6,19,20] of Gakkel Ridge further north, where hundreds of volcanoes are easily identifiable on Hydrosweep/Seabeam survey records. From a morphologic and tectonic point of view, Lena Trough is an amagmatic accretionary plate boundary, where mantle rock is exposed by pure shear of the tectonic plates without a significant basaltic cover. This finding makes Lena Trough the longest magma-starved spreading segment, and the longest oblique spreading segment in the world.

Petrologic results

The rock types recovered during dredging in Lena Trough include basalt, diabase, gabbro, peridotite and hydrothermal rocks (Figures 1b,2). The basalts already recovered from Lena Trough are of a unique high-Al, variety, which has very high alkali element contents and is extremely vesicular. While some Gakkel ridge basalts are as vesicular as the Lena Trough rocks[19], it is remarkable that all of the Lena Trough basalts are so vesicular. The presence of vapor bubbles in a magma is generally suppressed by water pressure in the ocean depths. The presence of highly vesicular rocks implies that either the vapor pressure in the magmas was very high (a distinct possibility, given the geochemistry of the samples known so far) or that the samples were erupted at shallow depths, and have subsequently subsided. The latter would be a consequence of the opening of Lena Trough, so that the basalts may in fact predate the opening of the Lena Trough gateway.

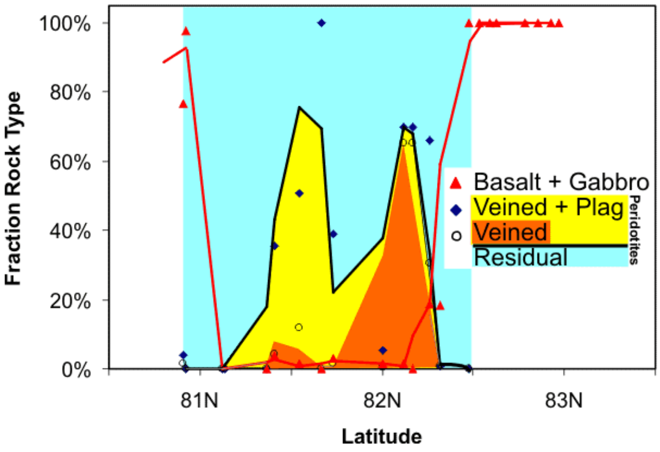

Figure 2: Petrologic variations along Lena Trough. Red symbols and line (smoothed with a 2-point moving average) and are the fraction of basalt in each dredge haul. Dark symbols are fractions of melt-stagnation-related peridotite lithologies (veined and plagioclase-bearing) among all peridotites. Lines and fields for these data are also smoothed with a 2-point moving average.

The petrography of peridotites on board indicates that Lena Trough is amagmatic only in a broad sense. While it is true that there was little if any volcanic activity, nearly all the sampling stations show some signs of magmatic activity. Melting in the upper mantle is a requirement for the generation of basalt, and is observed variably in the compositions of Lena Trough minerals. for example, spinels measured using the on-board electron mini-probe (CITL Ltd., Cambridge, UK), as well as previously measured spinels from two 1999 dredge hauls [11] all show a strong variability in Al content, as expressed by their molar Cr/(Cr+Al) ratio or chrome number [21], which is known to be an indicator of melt depletion (Figure 3).

The details of the petrography reveal traces of a magmatic segmentation in Lena Trough. Mantle lithologies indicating melt production and stagnation in the mantle are more predominant at the center of Lena Trough than at either end point.

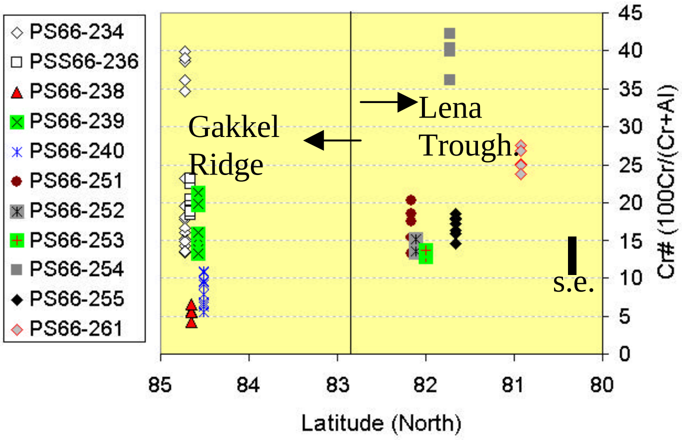

Figure 3: Cr/(Cr+Al) results for Lena Trough Spinels. Data collected using an onboard electron beam device with an energy dispersive X-Ray spectrometer with 20KeV accelerating potential and 400nA beam current. Results calibrated against secondary in-house standards. Standard error of analysis is shown.

The fundamental mantle rock type found in Lena Trough is fertile spinel lherzolite, which indicates a general low degree of partial melting in the mantle, or possibly none at all. Clinopyroxene-bearing harzburgites, typical of higher degrees of partial melting, are found there also. Plagioclase bearing peridotites and late stage gabbroic veining caused by melt stagnation, are found predominantly in the center of Lena Trough (Figure 2). On both ends of the ‘amagmatic’ region, dredge hauls containing basalt also contain predominantly residual lithologies. Magmatic activity has apparently been present along all of Lena Trough, in the form of melting and melt transport, but the magmas did not escape from the mantle. This may be a general feature of the transition from magmatic to ‘amagmatic’ spreading as seen at Gakkel Ridge [6,7,19] and other locations: The difference may be not so much a variation in melt production as in melt extraction. Inefficient melt extraction may thus be an important mechanism in generating what is generally referred to as amagmatic or sparsely magmatic crust[10].

Hydrothermal activity was found in at least two sites, both of which have been sampled and show indicaitons of active hydrothermal venting. The first of these is the previously reported AURORA site in northern Lena Trough [6,22] and the second is the Lucky B site[5]. At this site, massive carbonates, ultramafic outcrop, lack of basaltic outcrop and temperature/transmissivity anomalies in the water column point to active ultramafic-hosted hydrothermal venting.

Non-volcanic continental breakup and gateway opening

In the middle Miocene, Lena Trough was part of the continental crust joining Greenland to the european continent[15]. As rifting along the nascent Mid-Atlantic ridge propagated northward, spreading ensued in the Labrador sea. This caused Greenland to migrate northwards, initiating shortening on Ellesmere island, Morris Jessup and Yermak plateaus, and on Svalbard. At that time, it is probable that due to compression, the entire Lena region was land. It is entirely possible that the Arctic was a landlocked basin at that time. However, after about the XX, subduction had ceased again. The mid-Atlantic ridge propagated up the Greenland Sea and the branch in the Labrador Sea/Narres Strait failed. The final separation of Greenland from Europe began with Lena Trough as a narrow isthmus connecting Svalbard with northeastern Greenland[17].

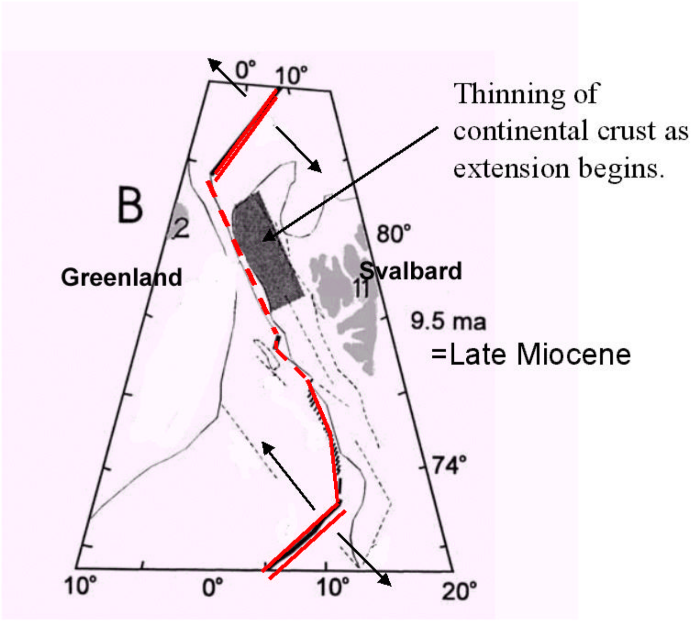

Figure 4: Miocene Paleogeography **(Provisional Figure)**. At this point the gateway was probably open to shallow water circulation, but the opening of the deep channel had not yet begun.

The opening of a shallow water gateway probably occurred first, as transtension began at Lena Trough. Had Lena Trough been more magmatically robust, volcanism might have kept the gateway a shallow one for some time. As an amagmatic plate boundary, however, the subsidence was not balanced by infilling volcanism. Also, the faults observed in Lena Trough are all steeply dipping, leading to rapid subsidence for a given amount of expansion compared to shallow dipping faults. The subsidence of Lena Trough was thus probably dramatic and rapid. This means that shallow circulation through the gateway (warm Gulf stream water in, ice out) and deep circulation (mostly salty arctic deep water out) probably began at about the same time.

Pre-Miocene Arctic thermohaline circulation

During parts of the early Cenozoic, the arctic basin was closed or nearly closed to circulation from the world's oceans (ref), much like the Mediterranean Sea. The prime difference between the two is the formation of ice however. This produces a top layer of freshwater that is convectionally stable with respect to the saline deep water. The Lena gateway is a major pathway for the export of freshwater from the Arctic in the form of ice. Therefore, convective overturn must have been very limited in the arctic basin during that time, ice formation leading to the formation of a permanent, deep and persistent freshwater layer compared to the relatively ephemeral and shallow freshwater layer seen in the Arctic today (ref). The extension along the Lena plate boundary would have had two efects: First the initial subsidence would allow sea-ice to be exported, as it is today, then the rapid formation of a deep rift would open the gateway to deep water circulation. At the same time, once the Gulf Stream became stabilized, the influx of warm surface water into the arctic would contribute to the ventilation and convective overturn of the Arctic basin.

Figure 5: Placeholder for illustration of circulation before and after gateway opening.

The effects of sea-ice export and deep water export through Fram Strait on global thermohaline circulation are opposed to each other. The freshwater from sea ice tends to stabilize the Greenland Sea against the cooling and formation of the North Atlantic Deep Water, however the export of Arctic deep water tends to counterbalance this trend. After gateway opening there was probably a period of reaction as the arctic fresh and deep water were largely exported to form the stable steady-state equilibrium seen today.

Analogs in the geologic record

Previously, this type of rifted plate margin was only known from "fossil" plate margins on the Iberia/Newfoundland margins (130 Ma), and in the western Alps (250 Ma) [23]. In these places, initial continentals rifting took place by amagmatic processes, and the formation of true oceanic crust was delayed by many tens of millions of years. Lena Trough appears to be a modern analog for these regions, and shows all of the characteristics that these more ancient complexes show. In particular the ultramafic basement blocks shown in Figure 1 are a tectonic feature whose origin is considered a key question in the genesis of amagmatic continental margins. These basement blocks are the tectonic equivalent of the basement blocks sampled on X drilling legs of the ODP at the Newfoundland/Iberia conjugate margins.

Some observations are significant by their absence. In this case, there is no evidence for the presence of foundered continental crust, which has been suspected in other areas [24]. This might have been expected given the relative youth of the Lena Trough rift. Another surprise was the absence of clearly defined low-angle detachment faulting. The current leading model for the exposure of mantle rock at non-volcanic continental margins calls for low-angle detachment faulting, of a type commonly observed along the mid-Atlantic Ridge, and which produces characteristic rilled topography (refs) along broad dome-shaped fault surfaces. Evidence for such low-angle detachment faulting in Lena Trough is conspicuous by its absence.

Lena Trough has thus proved to be a sort of “living fossil”, a major type of continental margin plate boundary known from the geologic record that has now been found today at a modern continental margin. It thus forms a natural laboratory for the study of the formation of continental margins and their early subsidence.

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