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Oblique nonvolcanic seafloor spreading in Lena Trough, Arctic Ocean

Jonathan E. Snow

Department of Geosciences, University of Houston, Houston, Texas 77204, USA (jesnow@uh.edu)

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany

Eric Hellebrand

Department of Geology and Geophysics, University of Hawai'i at Mānoa, Honolulu, Hawaii 96822 USA

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany

Anette von der Handt

Institut für Geowissenschaften, Albert-Ludwigs-Universität, Albertstraße 23b, D-79104 Freiburg, Germany

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany

Francois Nauret

Laboratoire Magmas et Volcans, Université Blaise Pascal, 5 rue Kessler, BP 10448, F-63000 Clermont-Ferrand, France

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany

Yongjun Gao

Department of Geosciences, University of Houston, Houston, Texas 77204, USA (jesnow@uh.edu)

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany

Hans Werner Schenke

Alfred-Wegener-Institut für Polar- und Meeresforschung, D-27568 Bremerhaven, Germany

[1] Passive rifting and the early non-volcanic formation of ocean basins are fundamental aspects of the plate tectonic cycle. Cenozoic plate margins where this has occurred are rare. Here we present new observations from Lena Trough in the Arctic Ocean that bear on the early phase of oceanic spreading in such rifts. Lena Trough is an oblique seafloor rift system bounding the North American and Eurasian plates, and connecting neighboring Gakkel Ridge with the rest of the global mid-ocean ridge system. Mapping and sampling show widespread mantle outcrop along two parallel basement ridges bounded by steeply dipping normal faults. Volcanism is limited to the intersection with Gakkel Ridge and to minor eruption of strongly potassic alkali basalts in a single location. Non-eruptive magmatism is shown by an increase in plagioclase- and vein-bearing lithologies over residual peridotite in the center of Lena Trough. Normal mid-ocean ridge stairstep geometry and obvious low-angle detachments as seen at other ridges are absent. Lena Trough thus is an example of a young nonvolcanic continental rift that is just now beginning the transition to oblique nonvolcanic seafloor spreading. This style of oblique rifting, without the formation of striated large-scale low-angle detachments appears to be a major mode of crust formation on ultraslow spreading ridges.

The sharp transition from the continental margins on either side to nonvolcanic rifting, with mantle slab exhumation in the rift may provide a model for the early evolution of oblique continental rifts, such as the Cote d'Ivoire/NE Brazil conjugate margins.

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1. Introduction

[2] Continental breakup begins the formation of new ocean basins, and ultimately of new passive margins. Instead of a rapid transition from continental rifting to volcanic seafloor spreading, some rifts undergo extreme tectonic extension without appreciable volcanism, resulting in a zone of exhumation of mantle rocks between the edge of the continent and the onset of volcanic seafloor spreading [Boillot and Froitzheim, 2001; Lavier *et al.*, 1999; Lavier and Manatschal, 2006]. These types of margins have been identified in the geologic record, occurring in passive margin sequences found in the Western Alps [Desmurs *et al.*, 2002; Manatschal, 2004], including those that formed the basis for the ophiolite concept [Steinmann, 1905]. This may occur on an orthogonal plate boundary, as at the Iberia/Newfoundland conjugate margin, or at an oblique rift such as the NE Brazil/Côte d'Ivoire conjugate margin.

[3] Geologic models of orthogonal nonvolcanic rifted margins (NVRM) are largely based on the discovery of large-scale low-angle detachment faults on the ocean floor [Blackman *et al.*, 1998; Cann *et al.*, 1997; Karson and Dick, 1983; Tucholke *et al.*, 1998], which are key features in the formation of oceanic core complexes (OCC). These were related to on-land analogs in zones of continental extension in the western United States [Wernicke and Burchfiel, 1982]. OCC provide a mechanism for the exhumation of deep-seated lithologies, including mantle rocks, to the seafloor, and thus have provided a geologic model for NVRM formation. The obliquely spreading Lena Trough [Hellebrand and Snow, 2003; Snow *et al.*, 2001], between the Greenland and Spitzbergen rifted margins, could

be expected to form by similar mechanisms, as it has been proposed to have a plate margin with a typical stairstep ridge-transform geometry [Jackson *et al.*, 1982; Engen *et al.*, 2008]. Recently, new mapping and geophysical results have become available that place the petrology of Lena Trough and its relationship to continental breakup and amagmatic seafloor spreading in a new light [Läderach *et al.*, 2011].

[4] Lena Trough is the continuation of the Mid-Atlantic ridge system into the Arctic Ocean. Spreading at a rate of 13mm/yr [Ehlers and Jokat, 2009], it is one of the slowest spreading divergent late boundaries in the world. Lena Trough is also an oblique rift system [Snow *et al.*, 2001], and is no older than 21 million years [Brozena *et al.*, 2003; Crane *et al.*, 2001]. Before the Early Miocene, Lena Trough was a continental shear zone connecting the last remnants of the supercontinent of Pangea [Brozena *et al.*, 2003; Engen *et al.*, 2008]. Only since then has a deep water passage formed in Fram Strait, the only deep water connection between the Arctic Ocean and the rest of the world's oceans [Jakobsson *et al.*, 2007].

[5] Until recently, Lena Trough was nearly entirely unmapped because of thick year-round ice cover. As a result, and because of its key plate tectonic position, a variety of models exist in the literature as to the configuration and nature of the Lena Trough plate boundary. Alternative tectonic models in the literature differ primarily on the length and placement of postulated orthogonal transforms and rifts to accommodate the known oblique trend of the rift valley [Engen *et al.*, 2003; Jackson *et al.*, 1982; Lawver *et al.*, 1990; Savostin and Karasik, 1981; Srivastava, 1985; Sundvor and Austegard, 1990].

The only previous expedition to the area (ARK XV-2, in 1999) was able to penetrate only to 81°N, 100 km from the southernmost extent of the 2001 AMORE survey [Michael *et al.*, 2003; Thiede and the Shipboard Scientific Party, 2002], which included part of the northern Lena Trough. The expedition ARK XX/2 of PFS Polarstern mapped and sampled Lena Trough in a systematic fashion [Snow and Petrology Group ARK-XX-2, 2007]. Here we present and interpret observations of the petrologic makeup of Lena Trough and re-examine the available geophysical evidence of crustal construction mechanisms.

2. Data and Results

[6] The Lena Trough bathymetric data were collected mostly on the cruise ARK XX/2 of the polar research vessel PFS Polarstern [Budeus and Lemke, 2007] using the onboard Hydrosweep DS-3 multi-beam echosounding system with a 90° spread pattern of 59 beams perpendicular to the ship's long axis. The width of the measured swath is $\sim 2 \times$ the water depth (90° swath angle) with a precision of $\sim 1\%$ of the water depth. Water column refraction was corrected via automatic crossfan correction. Errors in ship's position and in individual ping readings caused by heavy icebreaking operations (19 of 43 days) were corrected by hand-editing the data set to remove outliers and cross-track mismatch. Gridded data sets were constructed on a grid spacing of ~ 100 m with minimal smoothing, and overlaid on the existing 2500 m grid of the IBCAO data set (International Bathymetric Chart of the Arctic Ocean) for this region (Figures 1 and 2). The underlying data have been previously published [Läderach *et al.*, 2011], with different gridding, smoothing and shading.

[7] Dredging operations in Lena Trough were carried out on ARK XV/2 in 1999 [Jokat, 2000a; Snow *et al.*, 2001], ARK XVII/2 (AMORE 2001) [Snow and Petrology Group ARK-XVII-2, 2002] and ARK XX/2 in 2004 [Snow and Petrology Group ARK-XX-2, 2007]. The 20 successful basement dredging stations were mostly conducted in heavy pack ice and thus targeted individual specific slopes with short (~ 500 m) bottom tracks. Over 1000 discrete rock samples were described petrographically, about 3500 kg. The results are shown in Figures 1 and 2 as individual pie charts for each dredge station, color coded by rock type. In 8 dredge hauls recovered in the Northern Lena Trough (North of

82°30'N) with the exception of one peridotite, all were basalt, diabases and gabbros. From about 82°30'N to 81°N eleven dredge hauls recovered entirely or primarily mantle peridotites [Snow and Petrology Group ARK-XX-2, 2007] with minor gabbro. In the south-central portion of Lena Trough, 80°55'N and 2°30'W, 3 dredge hauls recovered glassy vesicular basalt, interspersed with peridotites and serpentine fragments essentially from the same slope (red arrow in Figure 1). Hydrothermal sulfide-rich rocks were recovered in three dredge hauls from two localities from this region as well (the "Lucky B" hydrothermal field; light green symbols in Figure 1) [Snow *et al.*, 2001]. Mantle lithologies recovered included residual, plagioclase bearing and vein-bearing assemblages. Figure 3 illustrates these relationships in detail, showing the incidence of basaltic magmatic rocks including diabase and gabbro (red line) as well as a breakdown of mantle rock types in to residual (green), plagioclase-bearing (light orange) and veined (dark orange) assemblages.

3. Discussion

3.1. Lena Trough Morphology

[8] The overall morphology of the Lena Trough rift valley (Figure 1) is unusual for mid-ocean ridges. Even the term ridge does not really apply: The walls of Lena Trough fall directly from the continental margins of Europe and North America on either side to the rift floor without rift mountains in the normally accepted sense. The characteristic stair-step transform-rift geometry of normal mid-ocean ridges [Morgan, 1968] is also lacking in Lena Trough. There are some slopes that are either normal or parallel to the spreading direction, but these are arranged in no systematic fashion. Oceanic transform faults are not present, though there is a clear strike slip component to many of the inferred faults, as can also be seen in fault plane solutions [Engen *et al.*, 2003; Läderach *et al.*, 2011]. Two "fracture zones" have been proposed [Engen *et al.*, 2003], at about 81°20'N (S. Lena FZ) and another at 81°50'N (N. Lena FZ). The lack of evidence for the offset of identifiable magnetic isochrons [Engen *et al.*, 2008], or linear basement structures [Läderach *et al.*, 2011], and the lack of typical fracture zone morphologic features such as a principal tectonic deformation zone, inside corner highs or nodal basins [Fox and Gallo, 1984] make the designation of transforms or fracture zones at these locations highly debatable.

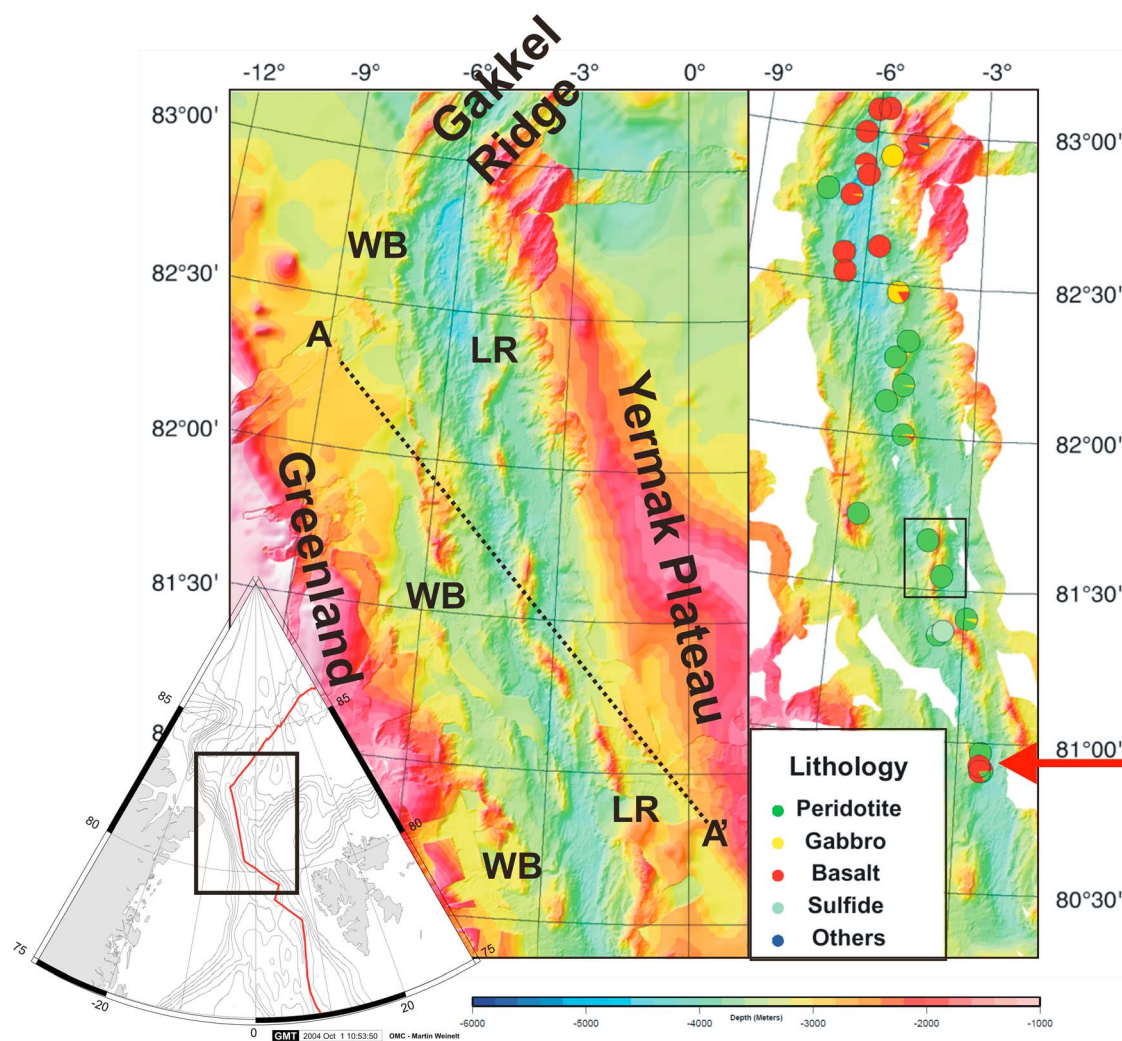


Figure 1. Bathymetry and petrology of Lena Trough. (left) Data from Polarstern ARK XV-2, XVII-2, XX-2, USCGC Healy 0102 and IBCAO. (right) Bathymetry and lithology, shown by pie charts (color key in legend). Arrows indicate the position of dredged alkali basalts [Nauret *et al.*, 2011] and hydrothermal rocks. Right panel shows area of Figure 2. The broken line A-A' shows the approximate cross section represented by the schematic interpretation in Figure 4. WB: Western Block; LR: Lucky Ridge (see text for discussion).

[9] Lena Trough thus consists of a long first order oblique spreading segment, with no major transform faults, fracture zones or major magmatic centers present. Individual volcanoes are also absent, by stark contrast to the robustly magmatic Western Volcanic Zone of neighboring Gakkel Ridge [Jokat *et al.*, 2003; Michael *et al.*, 2003; Snow and Petrology Group ARK-XVII-2, 2002], where hundreds of volcanoes are easily identifiable on similar bathymetric survey records made with the same equipment. From a morphologic and tectonic point of view, Lena Trough is an oblique nonvolcanic rifted plate boundary, where crust is generated without significant basaltic volcanism.

This finding makes Lena Trough the longest magma-starved spreading segment yet found.

3.2. Lucky Ridge

[10] Lena Trough has a central basement uplift known as “Lucky Ridge” near the middle of the overall rift valley. It is a ~1500 m tall semi-continuous ridge stretching from 82°20'N to the intersection of Lena Trough with the Spitzbergen Fracture Zone at 80°20'N, about three quarters of the total length of Lena Trough (Figure 1). Läderach *et al.* [2011] refer to this configuration as being “two rift valleys,” Lucky Ridge being the divider between

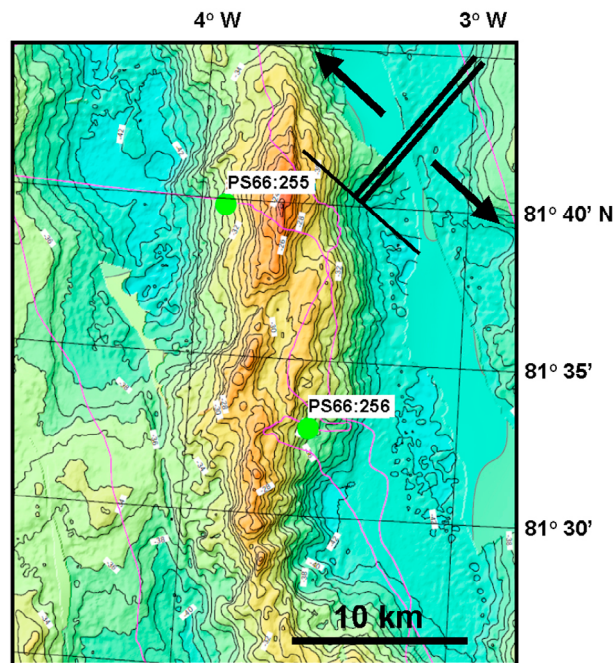


Figure 2. Detail of Lucky Ridge. Note the lack of tectonic corrugations on the sides of the basement block. Double line indicates a great circle azimuth to the NA-EUR spreading pole [DeMets *et al.*, 1990, which should be parallel to normal abyssal hill scarps. Thick single line is a small circle normal to the spreading pole, which would be parallel to any transform faults in normal magmatic crust. Circles are dredging locations (for lithologies see Figure 1). Purple lines are ship tracks.

these two seismically active valleys. The ridge has a sigmoidal shape, and pinches out at intervals (Figure 1). The ridge summit of Lucky Ridge is sharp, with little or no break in slope suggestive of a flat-topped horst. Steep sides extend at a nearly constant dip of 20–25° into the sediment basins on either side. To the west, there is a parallel basement block with an apparently flat top (marked WB in Figure 1) and a slightly shallower inward facing slope, but no detected teleseismicity [Läderach *et al.*, 2011]. It is possible that this is one side of a conjugate pair of rift mountains, the eastern side of which is hidden by the sediment drift that covers the eastern wall of Lena Trough [Jokat, 2000b]. Both of these structures expose mantle rock, as discussed below.

[11] Lucky Ridge is a rift floor structure with few if any direct analogs elsewhere on the ocean floor. The clustering of teleseismic events on either side of the ridge strongly suggests that Lucky Ridge marks a zone of active symmetric uplift on its

boundary faults [Läderach *et al.*, 2011]. Significant numbers of off-axis events occur west of the Lucky Ridge in the southernmost 50 km [Läderach *et al.*, 2011] and there are few events of any kind in the northernmost 60 km of the rift valley. Similar sharp basement ridges crop out on Gakkel Ridge [Michael *et al.*, 2003], but are always on the periphery of the rift valley, a feature of the rift mountains. The hypothesis that Lucky Ridge represents normal fault rotation [Smith *et al.*, 2008] would explain the ridge itself but not the symmetric seismicity or the outcrop pattern, which is ultramafic on both sides of the ridge (Figure 2).

[12] Mantle outcrop on many slowly spreading ridges occurs on domal surfaces exhuming lower crustal and mantle rocks on curved normal detachment faults [Cann *et al.*, 1997; Tucholke *et al.*, 1998]. Figure 2 shows detailed bathymetry of a typical basement outcrop on Lucky Ridge. The top of the ridge is sharp, with two subparallel crests running N-S, and no visible striations on slopes dipping east and west. The T-shaped symbol in Figure 2 shows the great circle azimuth to the NA-EUR spreading pole [DeMets *et al.*, 1990] as a double line. This would correspond to the directions of normal faults bounding a normally spreading magmatic rift. Along the entire length of Lucky Ridge, few obvious planar surfaces have this orientation. The single line on the orientation symbol shows the small circle direction corresponding to the expected orientation of transform faults or the stria on OCC surfaces of an orthogonally spreading rift.

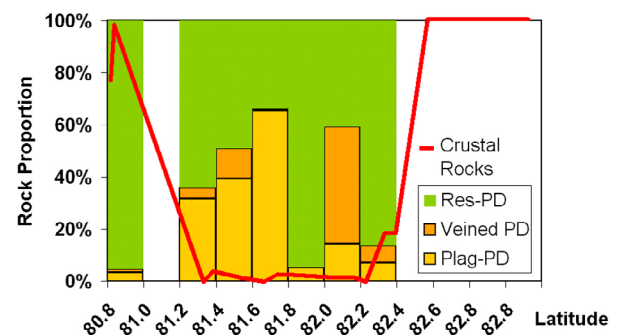


Figure 3. Proportion by weight of crustal and mantle rock types sampled along Lena Trough. Bars represent proportion of total peridotites sampled, including texturally residual (green), gabbroic-veined (light orange) and plagioclase-bearing (dark orange) peridotites. Red line represents the proportion of crustal rocks (basalt, diabase and gabbro) in total recovery. A greater proportion of veined and plagioclase-bearing peridotites occurs in the center of Lena Trough, where little or no crustal rocks were sampled.

Once again, features corresponding to either of these are not systematically present in the detailed bathymetry (cf. Figure 2) in any part of Lena Trough.

3.3. Mantle Exhumation and Magmatism

[13] Most of Lena Trough is ultramafic (Figure 1). Volcanic rocks found to the North are related to the Western Volcanic Zone of the Gakkel Ridge [Michael *et al.*, 2003], both geographically and geochemically [Nauret *et al.*, 2011]. Most of the mantle rocks were dredged from Lucky Ridge, while two peridotite dredge hauls were recovered from the basement block to the west of Lucky Ridge (Western Block, Figure 1). In the South-central region of Lena Trough, three dredge hauls containing alkali basalts were recovered from essentially the same location at 80°55'N, 2°15'W (red arrow in Figure 1). These have a composition unlike other enriched MORB [Nauret *et al.*, 2011; Snow *et al.*, 2001]. Their high-silica (>51% SiO₂) and potassic (~2% K₂O) character sets them distinctly apart from both normal MORB and E-MORB, which typically have silica less than 49 wt. % and K₂O less than 0.5%. They are far more alkaline than MORB from neighboring Gakkel Ridge [Goldstein *et al.*, 2008; Mühe *et al.*, 1997] and are interpreted as melts of the nearby subcontinental lithosphere [Nauret *et al.*, 2011]. Their noble gas signature however shows only MORB sources [Nauret *et al.*, 2010], suggesting that any ancient continental component was degassed prior to mixing with the peridotite melts. Chemically similar basalts have so far been found at only one other location on the SW Indian Ridge [le Roex *et al.*, 1992; Standish *et al.*, 2008]. Recovery of serpentine fragments and peridotites in the same dredge hauls, and the fact that there are no observable volcanic cones or sheet flows in the bathymetric data suggests that these volcanic rocks are relatively minor in volume, erupting directly onto mantle peridotite and are not indicative of normal mid-ocean ridge magmatic crustal construction.

[14] The mantle rocks exposed along Lena Trough could either be ancient continental mantle from the Greenland-Spitzbergen margin, or recently cooled asthenospheric mantle, depending on the rate of lithospheric thinning by the rift. Preliminary Os isotopes in the peridotites tend to support the latter hypothesis [Lassiter and Snow, 2009]. A further test may be derived from the distribution of rock types along Lena Trough (Figure 3). At both ends of the mapped region of Lena Trough, eruptive

basalts occur together with peridotites that are relatively residual in petrographic character, showing little evidence of veining or plagioclase impregnation (Figure 3) [Snow and Petrology Group ARK-XX-2, 2007]. At the center of Lena Trough, where no basalt is present, melt impregnation features are more common. This pattern suggests that non-eruptive magmatic activity (impregnation and intrusion) varies systematically along the trough, as might be expected in an active rift as opposed to passively exhumed continental lithosphere. Lithospheric entrapment of melts [Müntener *et al.*, 2010] has thus been more efficient in the center of Lena Trough, producing thick lithosphere and thin (or non-existent) eruptive crust. At the ends, melts though small in volume, have been more able to penetrate the lithosphere. This is particularly the case for the northern region of Lena Trough, where geochemically normal MORB [Nauret *et al.*, 2011] is able to ascend along orthogonal faults related to Gakkel Ridge.

3.4. Tectonic Model

[15] The Lena Trough as shown in Figures 1 and 2, is an oblique linear rift bounded by continental crust, with a narrow valley, mantle exposure both on its western margin, and on a central ridge made of mantle peridotite. We interpret Lucky Ridge as a central tectonic horst block across which active symmetric extension of the rift system is occurring, consistent with teleseismic, microseismic and magnetic data from the region [Läderach *et al.*, 2011]. Figure 4 is a cartoon illustrating the central aspects of our conceptual model for the subsurface structure of Lena Trough. Lucky Ridge may be analogous to tectonic ridges sampled in the subsurface of the Iberia Margin [Boillot and Froitzheim, 2001], though these may have had a complex post-spreading history [Jagoutz *et al.*, 2007]. The Western Block is a mantle basement block that may be the conjugate to a basement block identified in seismic profile in the southern part of the trough [Jokat, 2000b], though it is currently not active [Läderach *et al.*, 2011]. Extension in Lena Trough is dominantly tectonic, accommodated by faults that do not flatten and rotate and thus do not form domal surfaces. Figure 4 shows our interpretation of steeply dipping faults rooted in symmetric upwelling of newly formed sub-oceanic lithospheric mantle, consistent with recent numerical modeling of amagmatic continental rifts [Nagel and Buck, 2004]. Ancient subcontinental lithospheric mantle (SCLM) shown in this model is displaced by necking to either side of the

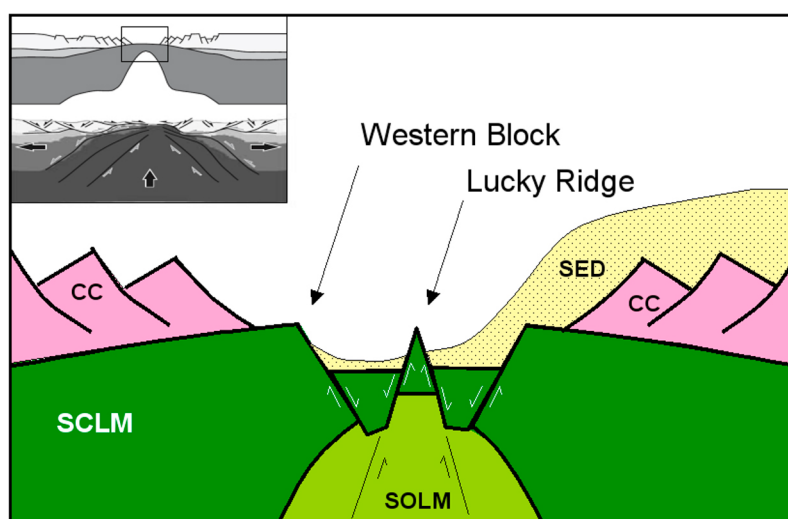


Figure 4. Geologic interpretation of Lena Trough. Cross section taken parallel to spreading direction. Inset shows Figures 6a and 4d from *Nagel and Buck* [2007]. SCLM: Subcontinental Lithospheric Mantle; SOLM: Sub-Oceanic Lithospheric Mantle; CC: Continental Crust; SED: Sediment.

rift, as young, recently cooled asthenosphere rises beneath the rift [*Nagel and Buck*, 2004, 2007]. This is marked SOLM (sub-oceanic lithospheric mantle), as it is analogous to the suboceanic lithosphere. Alternatively (not shown), the SCLM may have rifted completely, exposing young asthenosphere.

[16] One reason for supposing relatively steep faulting, and resulting rapid uplift of asthenospheric mantle, besides the steepness of the slopes exposed at Lena Trough, is that this plate boundary was a continental shear zone through most of the Cenozoic [*Brozena et al.*, 2003; *Crane et al.*, 2001; *Engen et al.*, 2008], and thus would likely have established a near-vertical zone of weakness prior to the onset of oblique rifting approximately 10 million years ago. Thus, asthenospheric material (SOLM in Figure 4) would be expected to rise relatively rapidly to seafloor levels and might even be exposed in the rift.

3.5. Nonvolcanic Seafloor Spreading

[17] Engen and coworkers [*Engen et al.*, 2008] interpreted the seafloor spreading anomalies and gravity of the region to indicate that seafloor spreading in the normal magmatic sense was occurring in Lena Trough, with only a narrow ocean-continent transition of a few km. The lithologies of the dredged samples show instead that Lena Trough is entirely floored by serpentinized ultramafic mantle lithosphere exposed on a vertically uplifted central slab of ultramafic rock on relatively

steep symmetrical bounding faults (as opposed to low-angle normal detachment faults often seen elsewhere). This may provide a model not only for understanding other instances of nonvolcanic seafloor spreading, but also for comparable examples of the ocean continent transition stage of oblique passive margin formation.

[18] Significant nonvolcanic seafloor spreading occurs at two other locations worldwide. On the SW Indian Ridge oblique supersegment, oblique spreading occurs along a distance of 220 km, at about the same angle of obliquity seen at Lena Trough [*Dick et al.*, 2003]. Unlike Lena Trough, however, about 25% of the dredge hauls within the oblique supersegment contained basalt, suggesting that basaltic volcanism, though minor, was present along most of the length of the oblique rift. The other example of modern nonvolcanic rifting is the 3°E region of the Gakkel Ridge [*Michael et al.*, 2003; *Snow and Petrology Group ARK-XVII-2*, 2002]. That region is 180 km of predominantly mantle outcrop with little or no volcanism. The unique characteristic of the Gakkel Ridge 3°E region is its orthogonal spreading. None of these show significant evidence of low-angle detachment faulting such as domal structures or widespread spreading-parallel striations. Lena Trough and the SWIR oblique segment provide a good on-axis model for generation of ancient ocean crust that is devoid of striations (“smooth crust”) [*Cannat et al.*, 2006] off-axis on the SWIR, much of which is quite oblique. Apparently, oceanic core complex

formation plays only a minor role in oblique non-volcanic seafloor spreading on ultraslow spreading ridges. This is not to say that normal detachment faulting is completely absent, just that the characteristic topographic expression of large scale detachment faulting is not observed.

3.6. Nature of the Plate Boundary

[19] Figure 4 shows a symmetric model for oblique spreading in Lena Trough. Although asymmetric spreading is common (for example) along the Knipovitch Ridge, and *Läderach et al.* [2011] argue for asymmetric spreading from the distributed nature of seismicity in the southernmost region, this gives a skewed picture of Lena Trough as a whole: Most of the seismic events (27/30) north of the Southern Lena boundary line are grouped around Lucky Ridge and are thus displaced more to the East than to the west of the inferred center of symmetry of the rift. This supports a strong inference that the bounding faults of Lucky Ridge are the primary locus of current seafloor tectonic extension in Lena Trough at present, and that Lucky Ridge is undergoing active symmetric extension and uplift.

[20] Magnetic anomalies clearly present and identifiable on Gakkel Ridge are much more diffuse and indistinct in Lena Trough, many are lost altogether. In particular, the central magnetic anomaly seen on most of the world's ridges is absent in Lena Trough. This can be explained by the nature of the magnetic sources: basaltic volcanism is not and has not been present to provide a high quality shallow source layer, and peridotite-rich crust, though rich in magnetite, is not coherently magnetized in such a way as to produce clear linear spreading anomalies. In comparison, a weak central anomaly was always present on Gakkel Ridge where significant mantle peridotite was present in outcrop [*Jokat et al.*, 2003].

3.7. Implications for Oblique Nonvolcanic Rifted Margins

[21] An important enigma surrounding nonvolcanic margins is the origin and emplacement of basement ridges consisting of mantle rocks to the seafloor during early phases of seafloor spreading [*Jagoutz et al.*, 2007; *Péron-Pinvidic et al.*, 2007]. The center of Lena Trough is 110 km along a flow line from the continental margins of both Greenland and the Yermak Plateau. This is much less, for example, than the 340 km distance between the rift and continental margins of Iberia and Newfoundland

in the late Cretaceous, when that basin was still apparently completely nonvolcanic. Lena Trough may provide an alternative type of nonvolcanic margin, where the spreading is oblique to the margins of the rift. An oblique tectonic model for the evolution of amagmatic continental margins is suggested by these data and by numerical modeling of ultraslow rifts that involves steep lithospheric master faults dipping away from the axis of rifting [*Nagel and Buck*, 2004] and rooted in the brittle-ductile transition. At Lena Trough, present-day extensional faulting is restricted to the rift axis directly beneath Lucky Ridge [*Engen et al.*, 2003], such that the passive extension of the continental crust on the sides of Lena Trough has ceased. This would result in an extremely sharp Continent-Ocean-Boundary.

[22] Though oceanic detachments do exhume mantle rocks, they are striated in the direction of spreading, exhume large volumes of gabbro [*Olive et al.*, 2010], and require significant magmatic activity to form [*Tucholke et al.*, 2008], they are usually linked to transform faults, and they produce gentle domal structures. Lena Trough exhumes mantle rocks while having none of these other characteristics. While there is some divergence in strike at Lena Trough, this is probably due to oblique rifting, a key difference to the Newfoundland Margin. Otherwise Lena Trough provides a clear present-day alternative model to the Newfoundland/Iberia Margin model for the case where rifting is oblique. The Brazil/Cote d'Ivoire conjugate margin [*Peirce et al.*, 1996] might provide an example of a similar tectonic setting in the geologic record, however the nature of its deep basement is currently not well explored.

4. Conclusions

[23] Lena Trough is the only known example of a young active oblique non-volcanic rifted margin. As such, it provides a logical geologic analog to the formation of such margins worldwide. Lena Trough shows little affinity to mid-ocean ridges or to oceanized young rifts such as the Red Sea and Gulf of Aden, which are magmatically robust. Some of the unusual aspects of Lena Trough may be a result of the pre-existing continental transform fault (the De Geer megashear [*Engen et al.*, 2008]), or the especially cold thermal structure of ancient continental lithosphere.

[24] Lena Trough spreads obliquely and amagmatically – that is, none of the symmetric structures

most commonly associated with magmatic crustal construction at mid-ocean ridges are present, including spreading normal rift mountains and spreading-parallel transform faults. At the same time, clearly asymmetric structures associated elsewhere on slow spreading ridges with mantle uplift and exposure are also lacking. These include spreading-normal corrugations and domal oceanic core complex uplift structures. Instead, mantle uplift appears to have occurred symmetrically by simultaneous movement on both sides of steeply dipping faults delineating the central tectonic horst block (Lucky Ridge). This agrees with the results of a variety of models of crustal formation at very low rates of magmatism compared to extension [Nagel and Buck, 2004]. As the rift evolves, such steep structures are likely to produce a very sharply delineated transition from continental crust to peridotitic basement, with steep-sided peridotite basement ridges preceding the onset of basaltic volcanism. This may help explain apparent steep-sided mantle basement structures on the NE coast of Brazil-Côte d'Ivoire margin [Peirce et al., 1996] that may help explain in those regions, and may ultimately form an alternative model to low-angle detachment for some kinds of late stage continental rifting. Alternatively, Lena Trough may still be at such an early stage of oceanic rifting that low-angle structures have not yet had time to form, or may be insufficiently magmatic for the formation of oceanic core complexes.

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