Melting and Mantle Flow at Oblique Ultraslow Spreading Ridges

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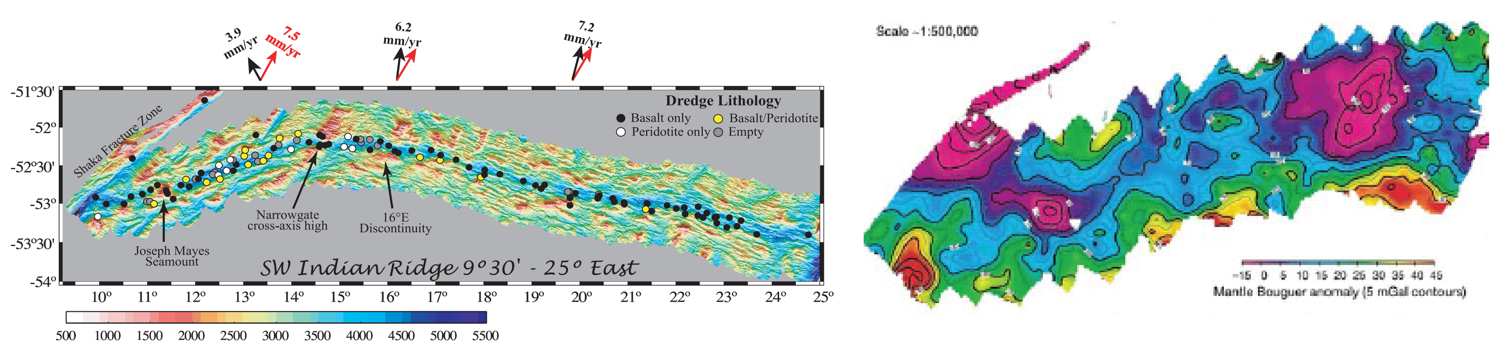
Abstract

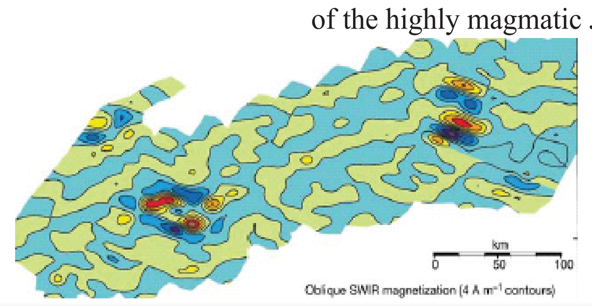
Ultraslow-spreading ridges are a unique endmember of the mid-ocean ridge spreading system. Ultraslow-spreading ridges lack transform faults and often form segments oriented at an oblique angle to the overall spreading direction. These oblique segments are characterized by anomalously thin crust compared to predictions from 2-D models for either passive or buoyant mantle flow based on the full spreading rate, suggesting that the rate of mantle upwelling is inhibited by the oblique ridge geometry. In this study, we model mantle flow and thermal structure at oblique ultraslow-spreading ridges using a three-dimensional finite element model. The model geometry consists of an oblique segment bounded by two orthogonal segments and we account for the effects of passive flow, a simple melting law, and melt migration along the 1200 °C isotherm surface. The models predict that temperature, upwelling rate, and crustal thickness along an oblique spreading ridge are all functions of only the portion of the spreading rate perpendicular to the ridge axis. Comparing our results to the 9-14 °E oblique supersegment of the southwest Indian ridge (SWIR), we find that crustal thickness along a segment oriented 60° relative to the spreading direction is predicted to be ~2.5 km lower than for an orthogonal segment. Including the effects of melt migration towards the bounding orthogonal segment yields a further reduction in crustal thickness with a maximum difference of ~2.6 km between the center of the oblique segment and the bounding orthogonal segments. Intriguingly, the melt migration calculations also predict that melt trajectories at the inside corners of oblique-orthongal segment intersections are focused toward the ends of the oblique segment. However, this focusing is not sufficient to produce crustal thickness anomalies of similar magnitude to the magmatic Narrowgate segment and Joseph Mayes seamounts observed at the ends of the oblique supersegment of the SWIR. Rather we speculate that these magmatic centers may form as the result of along-axis melt migration from the center to the ends of the oblique segment along the sloping 1200 °C isotherm. Further work is needed to determine whether including the effects of buoyancy, temperature-dependent viscosity, and along-axis flow may enhance the magnitude of these segment bounding crustal thickness anomalies to the proportions observed along the SWIR.

Introduction and Background

The Southwest Indian Ridge is characterized by highly oblique spreading (~60° from the spreading direction) between 9°-14°E. This oblique super-segment displays characteristics similar to the ultra-slow spreading Gakkel Ridge, with low gravity-derived crustal thickness, weak magnetic anomalies, and abundant peridotites dredged from the axial valley floor. Dick et al. [Nature, 2003] hypothesized that these changes are caused by the spreading geometry and that along oblique spreading ridges upwelling velocities and mantle thermal structure will be controlled by the portion of the spreading rate perpendicular to the ridge axis (or the effective spreading rate, ESR). In this study, we use numerical models to investigate the effects of ridge geometry on mantle flow, axial temperature structure, melt migration, and crustal thickness.



Bathymetry and dredge lithology along the SWIR from 9° to 25° East (top left) and mantle bouguer gravity (MBA) anomaly from 9° to 16° E (top right). Note the evidence for low crustal thickness, as shown by both the MBA and high concentrations of peridotite along the oblique super-segment (9°-14°E). The ends of the oblique super-segment coincide with the locations of the highly magmatic Joseph Mayes Seamount and the Narrow-gate Segment.

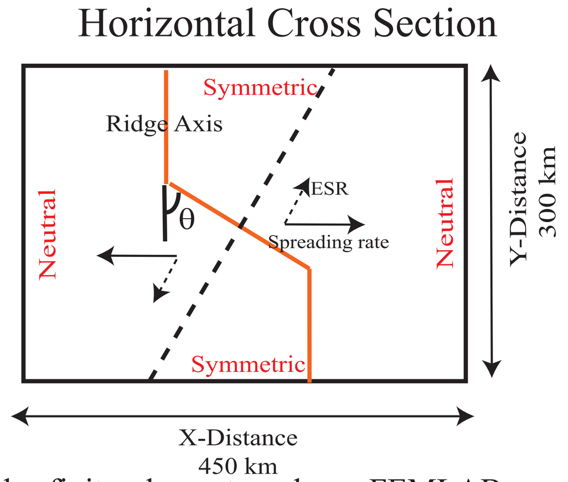


Left: Magnetization from 9° to 16°E along the SWIR. The low magnetization along the oblique super-segment is indicative of low crustal thickness.

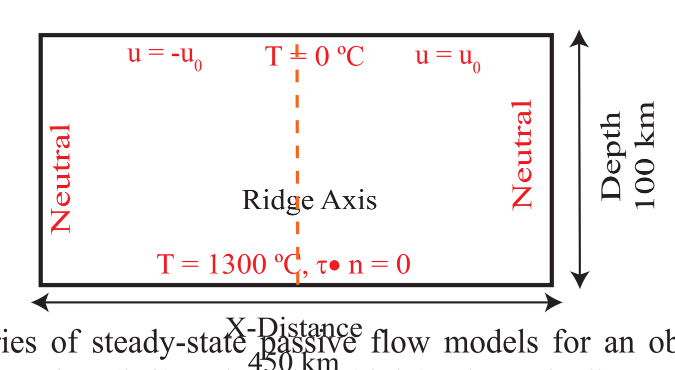
(Figures from Dick, et al [Nature, 2003])

Modeling Technique

Horizontal Cross Section



Vertical Cross Section

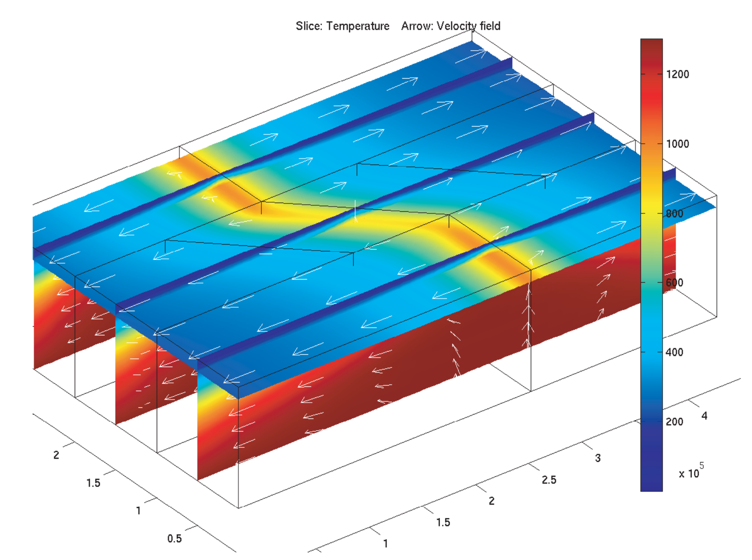


Using the finite element package FEMLAB, we ran a series of steady-state passive flow models for an oblique segment bounded by two orthogonal spreading segments. Top-view (left) and vertical (right) schematic diagrams are illustrated above with boundary conditions shown in red. The obliquity angle is defined by the angle θ and was varied from 0° to 60°, with θ=60° corresponding to the geometry of the SWIR. The model space was 450 x 300 x 100 km. All model runs assumed a constant mantle viscosity and a half spreading rate of 1 cm/yr. The top and bottom of the model space were set to 0°C and 1300°C, respectively. Melt fraction was calculated after Phipps Morgan & Forsyth [JGR, 1988] assuming a melting law that produces 6 km of crust for a full spreading rate of 4 cm/yr.

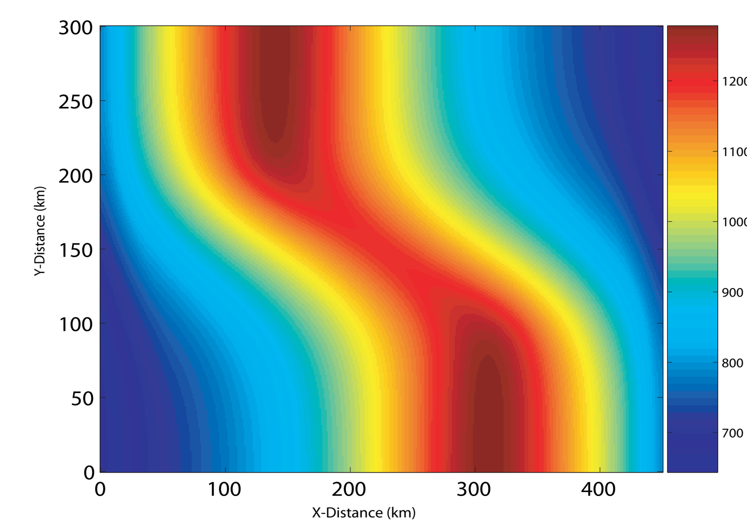
Modeling Technique

Oblique Models: Results

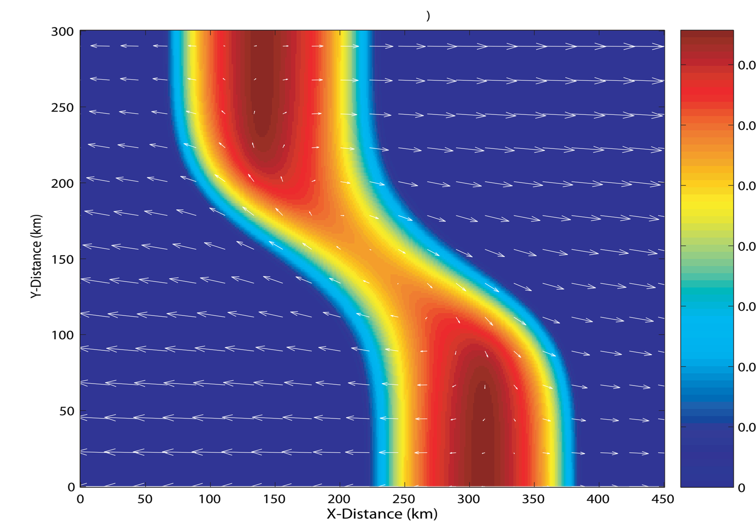
3-D Temperature Structure for 60° Obliquity



Temperature Structure at 30 km Depth for 60° Obliquity

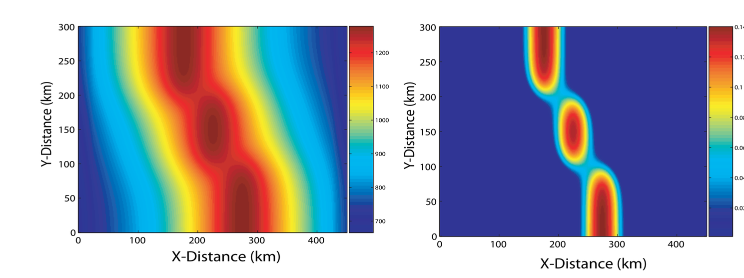


Melt Fraction at 30 km Depth for 60° Obliquity.



(White arrows show mantle flow trajectories)

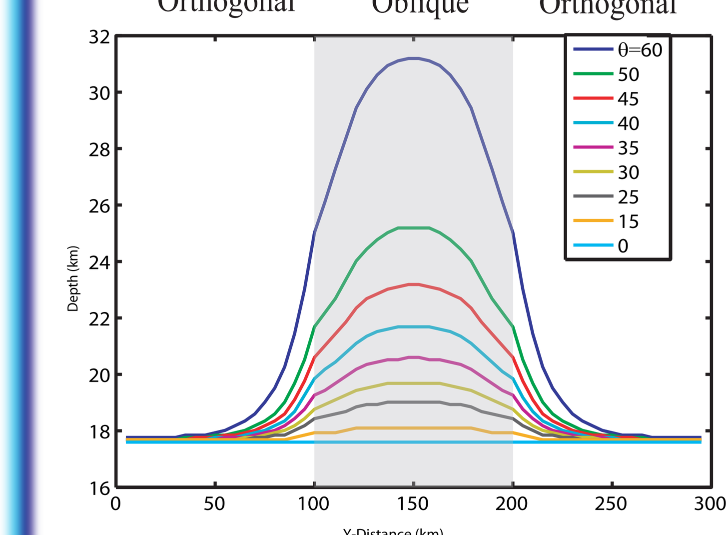
Temperature Structure & Melt Fraction at 20 km Depth for 3 Orthogonal Spreading Segments



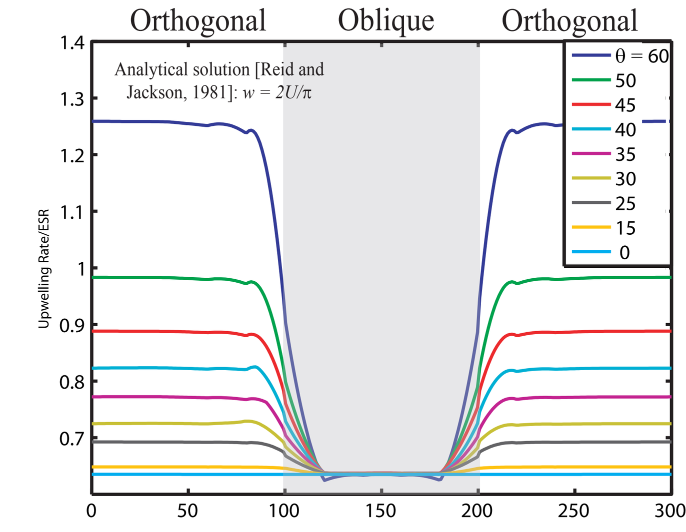
⇒ **Mantle temperature and melt fraction are reduced along oblique spreading segments.**

Oblique Models: Analysis

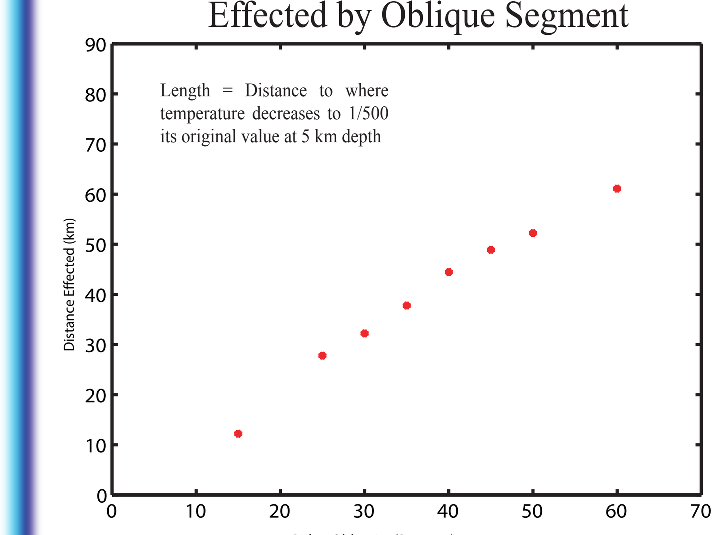
Depth to 1200°C Isotherm Along the Ridge Axis



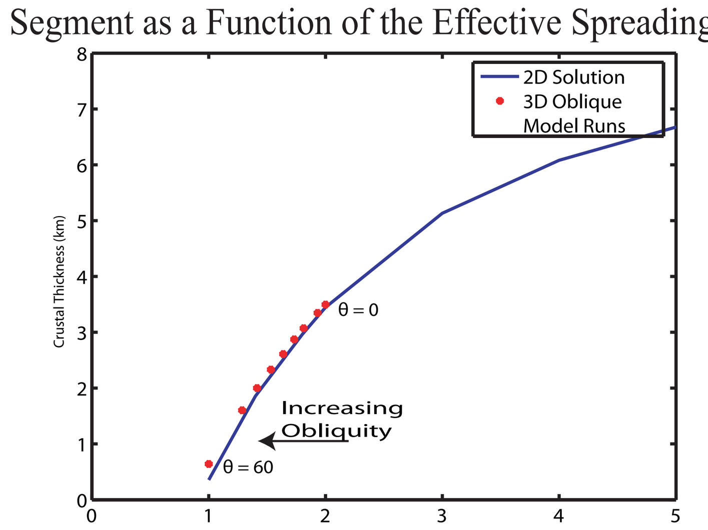
Upwelling Rate as a Fraction of the Effective Spreading Rate Along the Ridge Axis



Length of Orthogonal Segment Effected by Oblique Segment



Crustal Thickness at the Center of the Oblique Segment as a Function of the Effective Spreading Rate

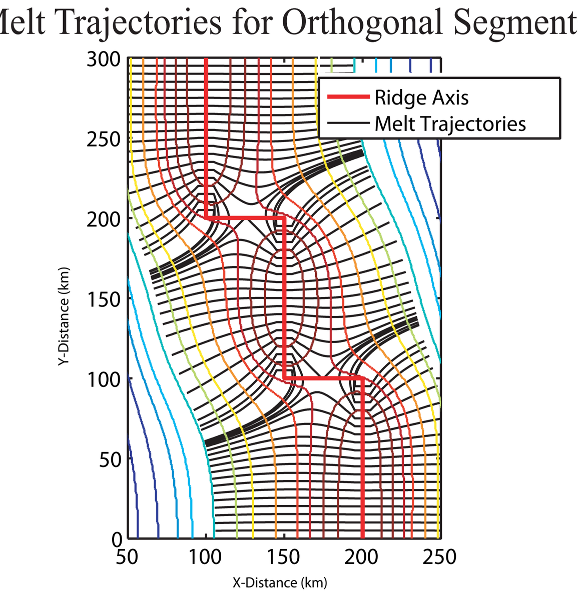


⇒ **Mantle upwelling and crustal thickness are controlled by the effective spreading rate.**

Melt Migration Calculations

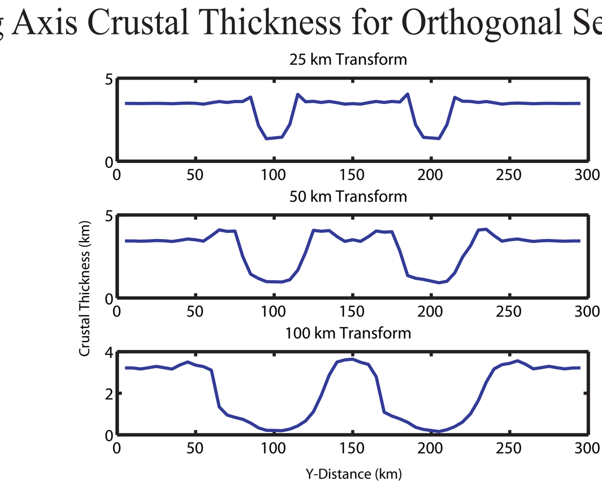
We study the effects of melt migration in creating along-axis crustal thickness variations at oblique spreading ridges following the method of Magde & Sparks [JGR, 1997]. We assume that melt rises vertically until it reaches an impermeable boundary and then flows uphill along this boundary until it is extracted at the ridge axis. The 1200°C isotherm was chosen for this permeability barrier as it represents the approximate temperature at which clinopyroxene begins to crystallize [Kelemen & Aharanov, 1998]. Melt is extracted to the ridge axis once it reaches 7 km from the top of the 1200°C isotherm surface. Crustal thickness is calculated by integrating the melt production rate along the 1200°C isotherm surface. Below we illustrate our approach for orthogonal ridge segments separated by transform faults and then show results for oblique spreading ridges.

Melt Trajectories for Orthogonal Segments

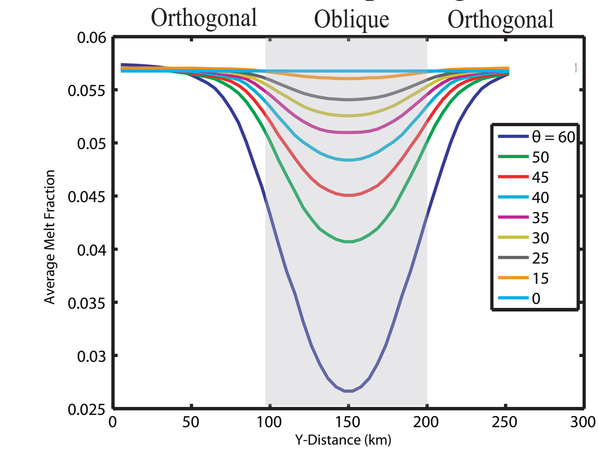


Melt migration calculation for a ridge with two 50 km transform faults separating 100 km orthogonal ridges. The colored contours show the 1200 °C isotherm while the black lines trace particles of melt.

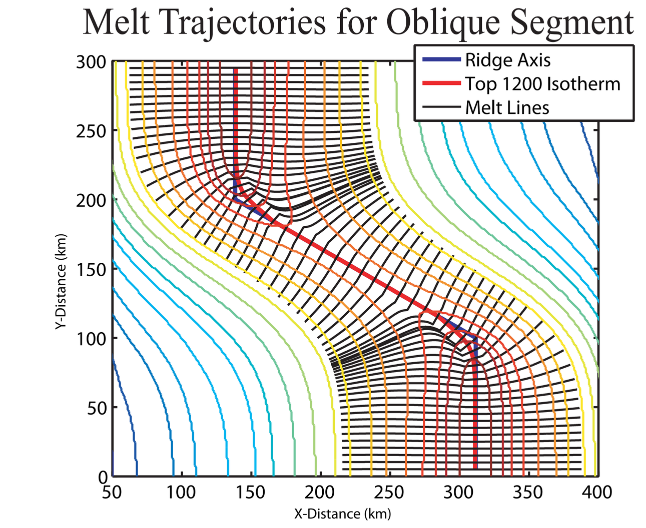
Along Axis Crustal Thickness for Orthogonal Segments



Average Melt Fraction Along Axis for Oblique Segment

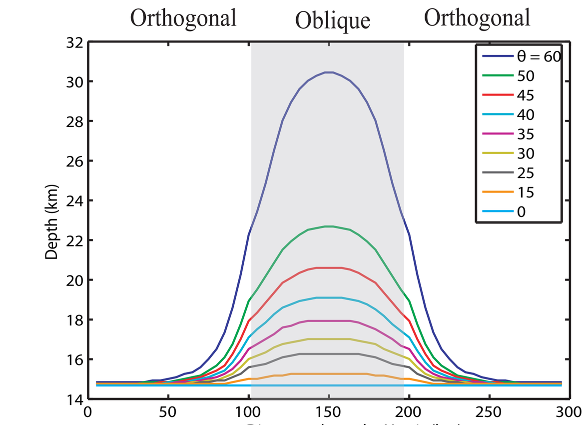


Melt Trajectories for Oblique Segment

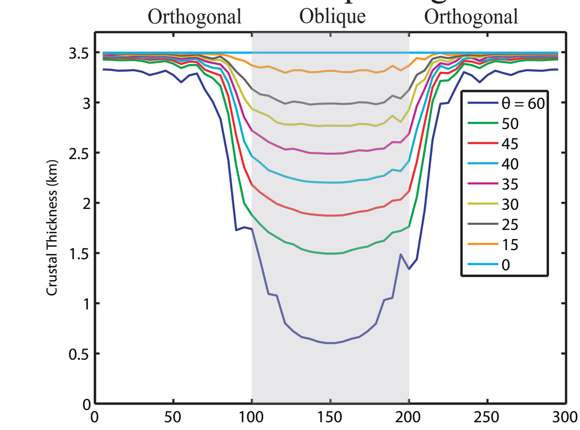


Melt migration calculation for a ridge with a 60° oblique segment. The colored contours show the 1200 °C isotherm while the black lines trace particles of melt.

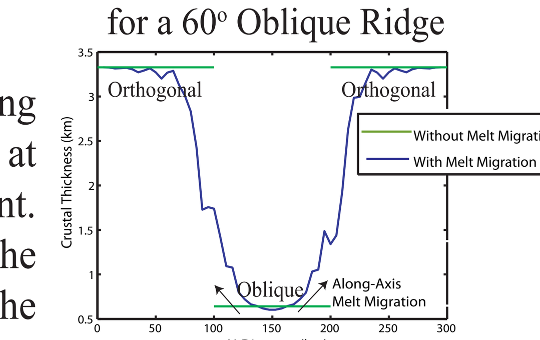
Depth to 1200 °C Isotherm Along Axis for Oblique Segment



Crustal Thickness Along Axis for Oblique Segment



Melt Migration Comparison for a 60° Oblique Ridge



Along highly oblique segments, where the top of the melting regime is deeper than 20 km, melt may migrate along-axis at depth and be further focused towards the ends of the segment. Such along-axis melt migration may explain the presence of the highly magmatic Joseph Mayes Seamount and Narrow-gate at the ends the oblique-supersegment of the SWIR.

Conclusions

We find that mantle upwelling rate, axial thermal structure and crustal thickness along oblique spreading segments are controlled by the effective spreading rate as hypothesized by Dick et al. [Nature, 2003].

Melt trajectories at the inside corners of oblique-orthogonal segment intersections are focused toward the ends of the oblique segment. However this focusing is not sufficent to produce crustal thickness anomalies as large as those observed at the ends of the oblique supersegment of the SWIR.

We speculate that *along-axis* melt-migration along a deep, sloping permeability barrier may focus melt toward the ends of oblique spreading ridge segments.