Preliminary Kinematic Model of Afar Triple Junction, -22 Ma to 5 Ma

by

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A Thesis

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ABSTRACT

The Afar Triple Junction is a relatively young ridge-ridge-ridge (RRR) triple junction that divides the Arabian, Nubian, and Somalian plates. The East African Rift System, Red Sea Rift, and Aden Ridge that make up the triple junction's limbs are each transitioning from continental rift systems to oceanic spreading ridges, providing geoscientists with a field opportunity unique to Earth's surface: a extensional region in which both early continental breakup processes and active oceanic ridge emplacement are preserved and can be observed as a part of the same system. Here, I present a preliminary kinematic model of the Afar Triple Junction, from its place of initiation to future modeled locations. By using the best current data of individual plate motion in a NNR reference frame (Kreemer and others, 2014) recast in a hot spot reference frame (Wang and others, 2017), we are able to establish velocity vectors for each of the Arabian, Nubian, and Somalian plates. Pairings of distinct geographic control points adjacent to each plate boundary are chosen and rotated in a cycloid model in reverse time until the East African Rift closes, signaling the initiation of the Afar Triple Junction at -22 Ma (Cronin, 2017). The location of the triple junction and its limbs are then modeled from -22 Ma through time to its present location 600 km eastward (0 Ma) and to a future location 120 km northeastward (5 Ma).Modeling the finite motion of points associated with the Afar Triple Junction allows for evaluation of the continued extensional nature of each rift system surrounding the triple junction.

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I would like to thank my advisor, Dr. Vince Cronin, for allowing me the opportunity to work on this and other research projects as an undergraduate, as well as for his mentorship, constant encouragement, and direction as I begin navigating a career in geoscience research. I am thankful to have been encouraged to engage in undergraduate research early on by Dr. Cronin and Dr. Kenny Befus. I would also like to thank the Department of Geosciences at Baylor University for their academic and financial support during my undergraduate research experience. Lastly, I would like to thank my family and friends for their support throughout my undergraduate career.

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INTRODUCTION

The Afar region is defined by a ridge-ridge-ridge (RRR) triple junction that joins the Arabian, Nubian, and Somalian tectonic plates. As a relatively young tectonic feature, the Afar Depression presents an opportunity to investigate the initiation of a triple junction, early continental rifting processes, and the formation of oceanic crust in adjacent ridge systems at a triple junction on a modern time scale. This is because the three rifts that define Afar Triple Junction were continental rifts in once-stable craton but are now transitioning into oceanic spreading centers. Because of their young extensional history, each of the plate margins along the Afar Triple Junction remain easily correlated across their adjacent rifts. This presents us with the opportunity to "rewind the clock" on the triple junction by developing a purely kinematic model of the region through which we can determine how long ago the triple junction formed, where exactly it is now, and where it could be in the future.

BACKGROUND

The Afar Depression is a topographically low, triangular-shaped region that spans modern-day Ethiopia, Somalia, and Djibouti. The Afar Depression is the only region above sea level where the transition from early plume-induced continental rifting to active extensional tectonism at a spreading ridge can be observed (Hammond and others, 2013). Herein lies the Afar Triple Junction (Fig. 1). However, much of the geologic record of early continental rifting is buried beneath brecciated sediments and basaltic dikes (Tesfaye and others, 2003). The crustal thickness in the Afar region ranges from ~45 km beneath the highlands to ~16 km beneath the oceanic spreading center of the East African Rift (Hammond and others, 2011).

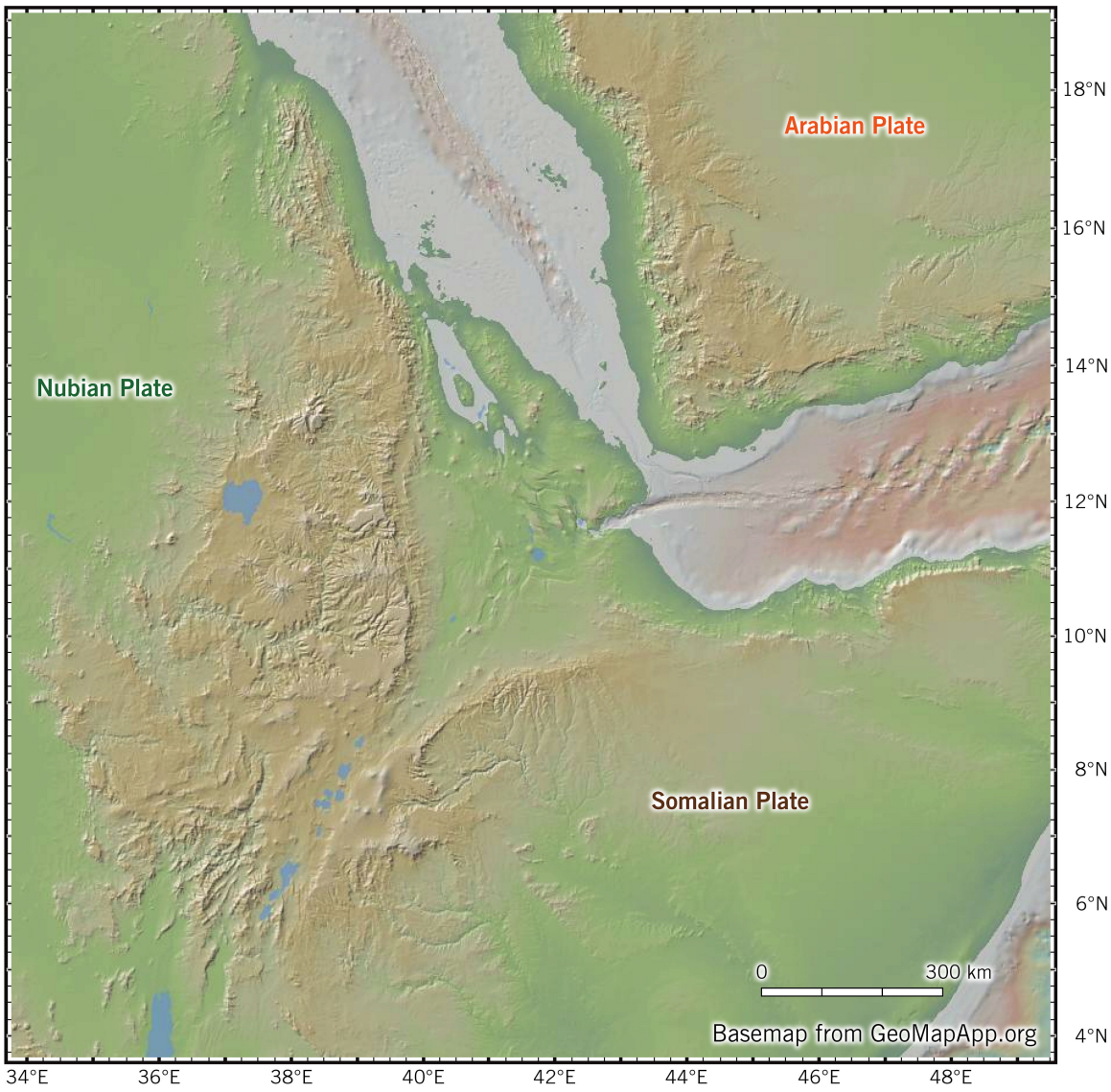

Figure 1: Afar study region.

There is a general consensus that the earliest rifting in the Afar region began localizing ~35 Ma in the Gulf of Aden and ~33 Ma in the Red Sea Rift, before initiating in the East African Rift ~20 Ma (Hammond and others, 2011; Leroy and others, 2012). However, ArRajehi and others (2010) suggest that the simultaneous rifting of the Red Sea Rift and Aden Ridge was initiated ~24 Ma. This was based on the width of each rift, the present Arabian plate motion rates, and a 70% estimated increase in Arabia-Nubia relative motion at 13 Ma. Though the East Africa Rift was certainly slower to rift than the Red Sea Rift or Aden Ridge, it is not an alaucogen but remains an active divergent boundary. Differing rates of extension across the three rifts of RRR triple junctions demand that the triple junctions migrate with time (e.g. Le Pichon, Franceteau, and Bonnin, 1973).

METHODS

Reference Frame Modification

I used the most accurate plate-velocity data available to develop this kinematic model of the Afar Triple Junction. Kreemer and others (2014) published a global plate motion model that utilizes highly accurate GPS data to model the velocity of individual plates relative to the Pacific plate. Wang and others (2017) combined the MORVEL56 relative motion model (Argus and others, 2011) and the average rate of hot spot motion to provide us with the velocity of each individual plate relative to the Hawaiian hot spot. Adding the Pacific plate velocity relative to the Hawaiian hot spot (Wang and others, 2017) to the velocities of the other plates (Kreemer and others, 2014) results in a set of plate-velocity data expressed in a reference frame fixed to the Hawaiian hotspot.

A *Mathematica* notebook was written to produce the necessary plate-velocity data

for the analysis of the Afar Triple Junction (Cronin, 2019). Input data for that code included Euler poles and associated angular speeds for the Somalian, Nubian, Arabian plates (Kreemer and others, 2014) and Pacific plates (Wang and others, 2017). The Euler pole geographic coordinates are then converted to Cartesian coordinates, made into unit location vectors, and converted to angular velocity vectors by multiplying the unit location vectors by the angular speed. The angular velocity vector of the Pacific plate was added to the angular velocity vectors for the Somalian, Nubian, and Arabian plates to produce a set of plate-motion data in a hot-spot reference frame. The length of the resulting angular velocity vectors is measured to determine the angular speed of each. Finally, the unit vectors of each angular velocity vector were found and converted into geographic coordinates (Fig. 2). Plate velocities in this reference frame are assumed constant for all model times in this study.

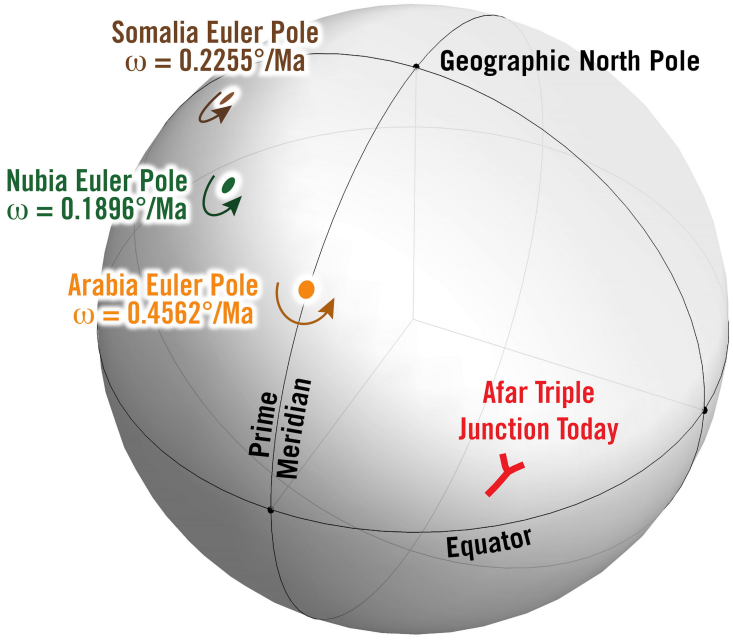

Figure 2: General location of Euler poles related to Afar Triple Junction. Pole locations are modified from Kreemer and others (2014) and Wang and others (2017).

Point Selection & Projection

With an established reference frame and velocity data for each plate, we turn our attention to determining when and where the Afar Triple Junction initiated. Several points along the undeformed edge of the continental crust of the Arabian, Nubian, and Somalian plates at the Afar Triple Junction are selected and grouped by which rift they are adjacent to: the Red Sea Rift, East African Rift, or Aden Ridge (Fig. 3). Each point is selected because of some defining feature that could be easily projected across its adjacent rift and identified on either side; each point has a near identical, matching point on an adjacent plate (Fig. 4). Examples of features used as points include a volcano bisected by normal faults on either side of the East African Rift and aligning drainage systems across the Red Sea Rift. Points selected have the capacity to show magnitude of displacement since the rifting caused by the origin of the triple junction.

Closing the East African Rift

Each of these points are then moved along their respective cycloid finite-motion trajectories until overlap occurs in the pairs of points adjacent to the East Africa Rift (EAR) approximately 22 million years ago (Fig. 5; Cronin, 2017). This is when the Afar Triple Junction is inferred to have begun to extend. To make this assertion, we must assume that the current angular velocity vectors for the Arabian, Nubian, and Somalian plates are constant, have remained so for the past 22 Ma, and will continue to be constant in the next few million years. We also assume symmetric rifting in the East African Rift since its initiation.

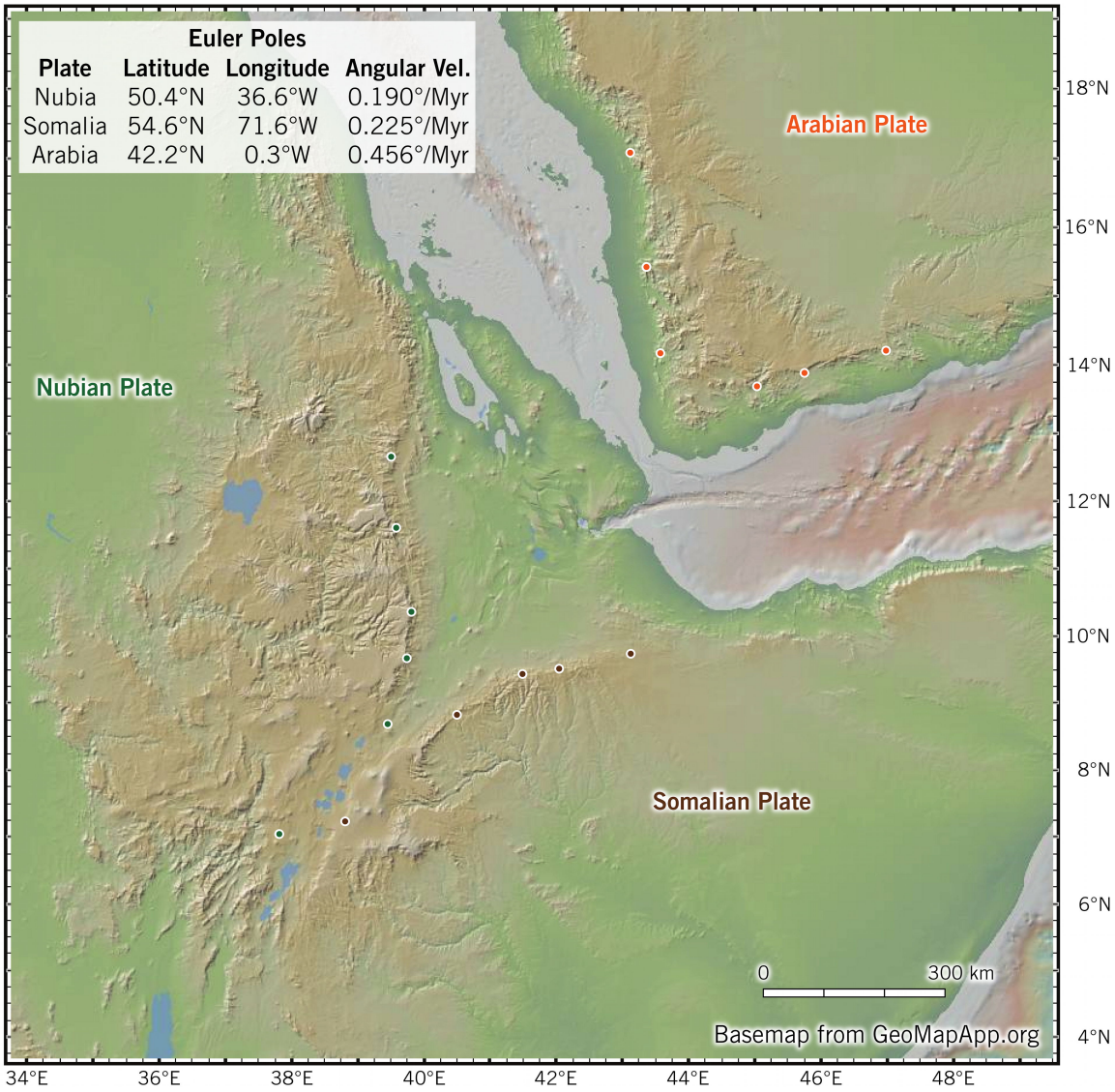

Figure 3: Selected geographic control points delineate the undeformed edge of continental crust along the boundaries of the Arabian, Nubian, and Somalian plates.

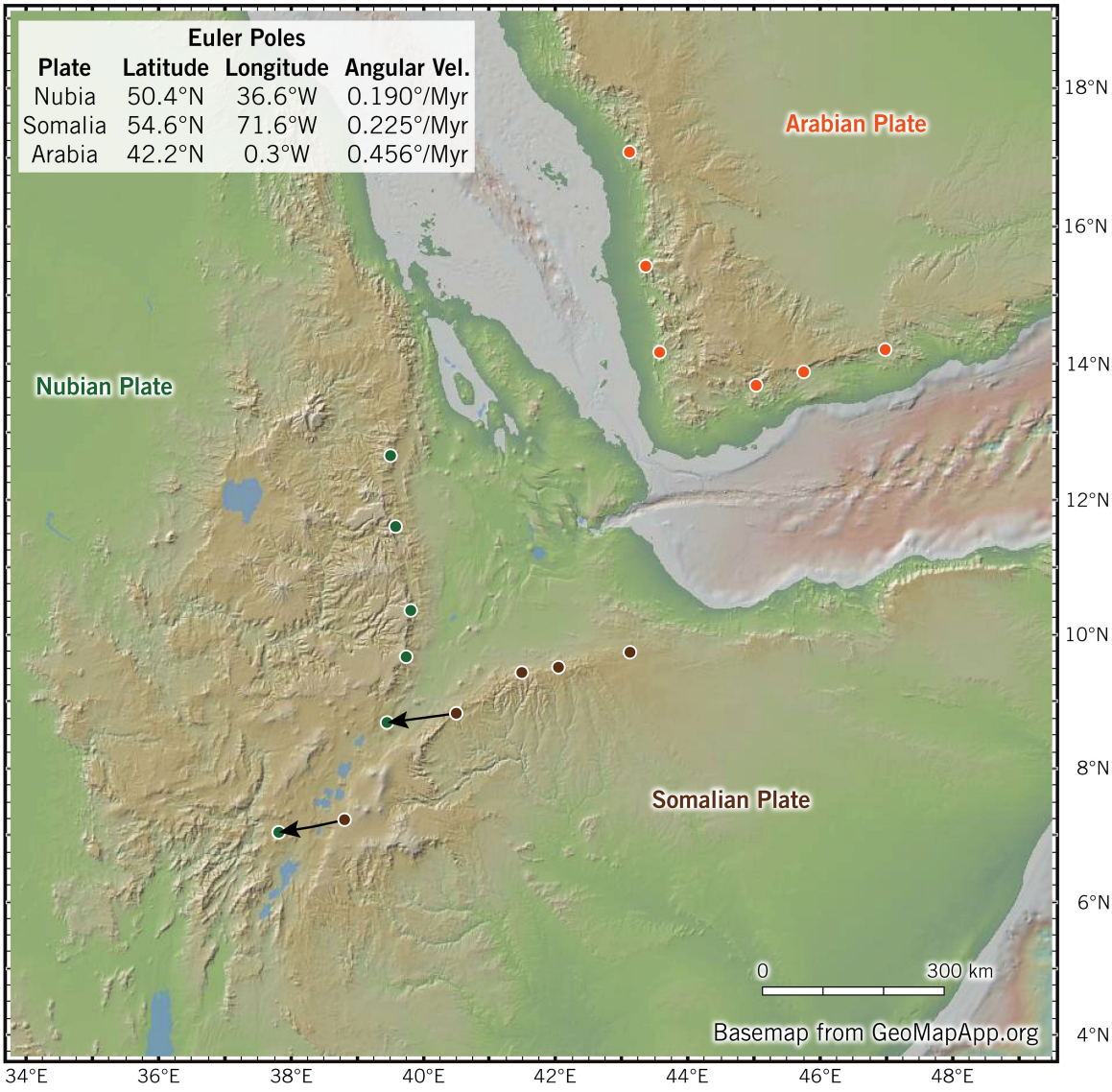

Figure 4: Projection of matching control points across the East African Rift.

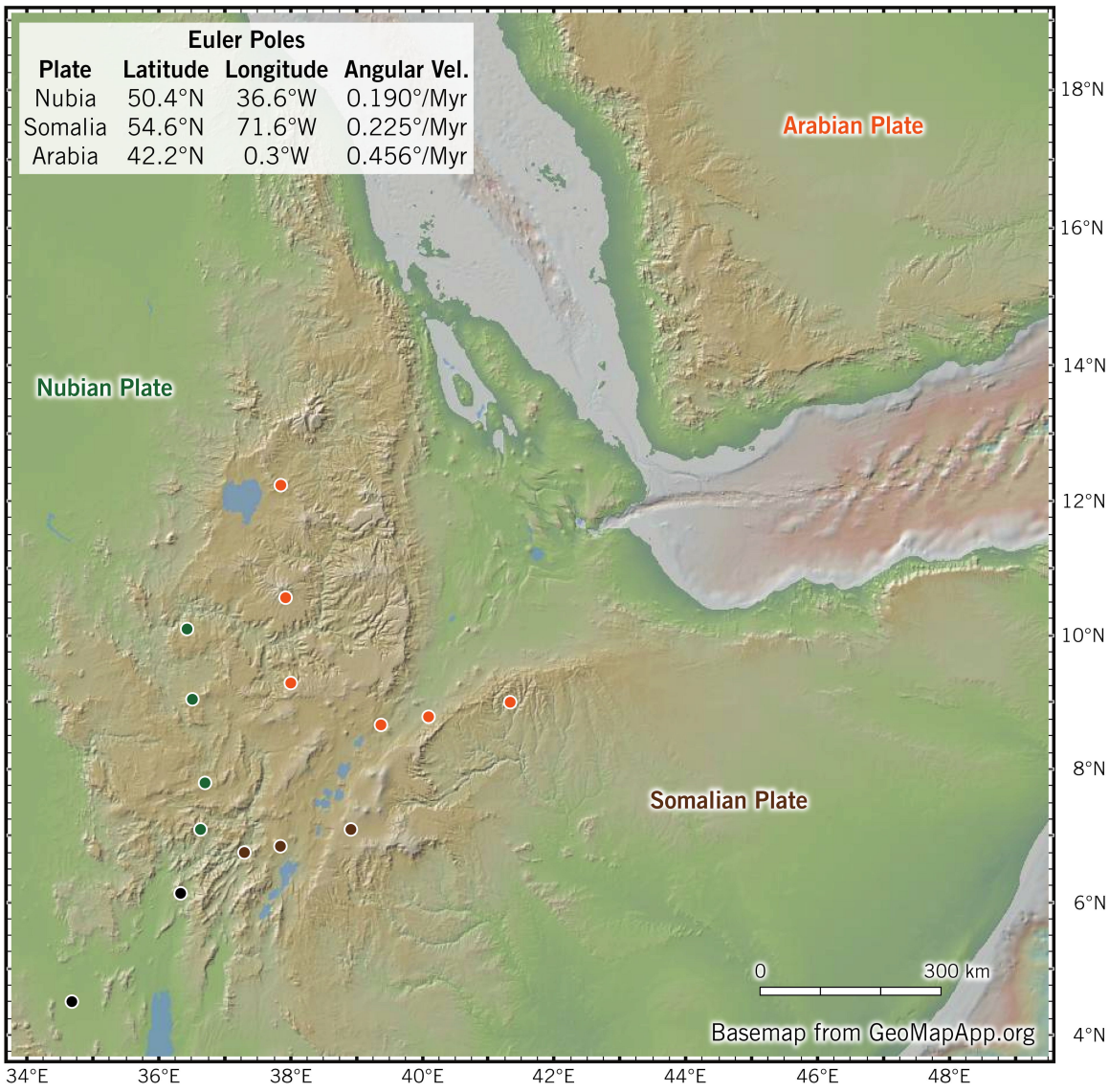

Figure 5: Closing of the East African Rift as represented by control points, -22 Ma.

Pinpointing A Triple Junction

To locate the triple junction at model time -22 Ma, we first locate the midpoint between each set of control points along the Red Sea Rift and Aden Rift (Fig. 6). We then project three great circles, each containing the midpoints of a rift. As is typical of ridge-ridge-ridge triple junctions, the three great circles do not perfectly align to mark the triple junction, but instead intersect in three distinct points to form a triangle (Fig. 7). In order to acquire a single control point for the triple junction location, we assume that the average of those three intersecting points will provide the approximate location of Afar Triple Junction at -22 Ma (Fig. 8; Cronin, 2017).

Making Future Projections

The Afar Triple Junction at -22 Ma is defined by seven control points: one for the triple junction and two for each limb (Fig. 8). The triple-junction point is common to all three plates and the remaining two control points along each rift are common to the two plates bounding that rift. For example, the two control points along the Red Sea Rift at -22 Ma, along with the triple-junction point, mark the common boundary of the Nubian and Arabian plates at that time. As the Nubian plate rotates around its Euler pole and the Arabian plate rotates around its (different) Euler pole, each of the control points clones to become two points that diverge from one another across the widening rift. We assume that the rift axis at any time after -22 Ma will be mid-way between each pair of cloned points. That midpoint becomes the new control point along the rift at that time. We do this for the two control points along each of the three rifts at the triple junction, define the new rift axis as a great circle between the two new control points, and define the triple-junction point as we did for -22 Ma (Collins and Cronin, 2019).

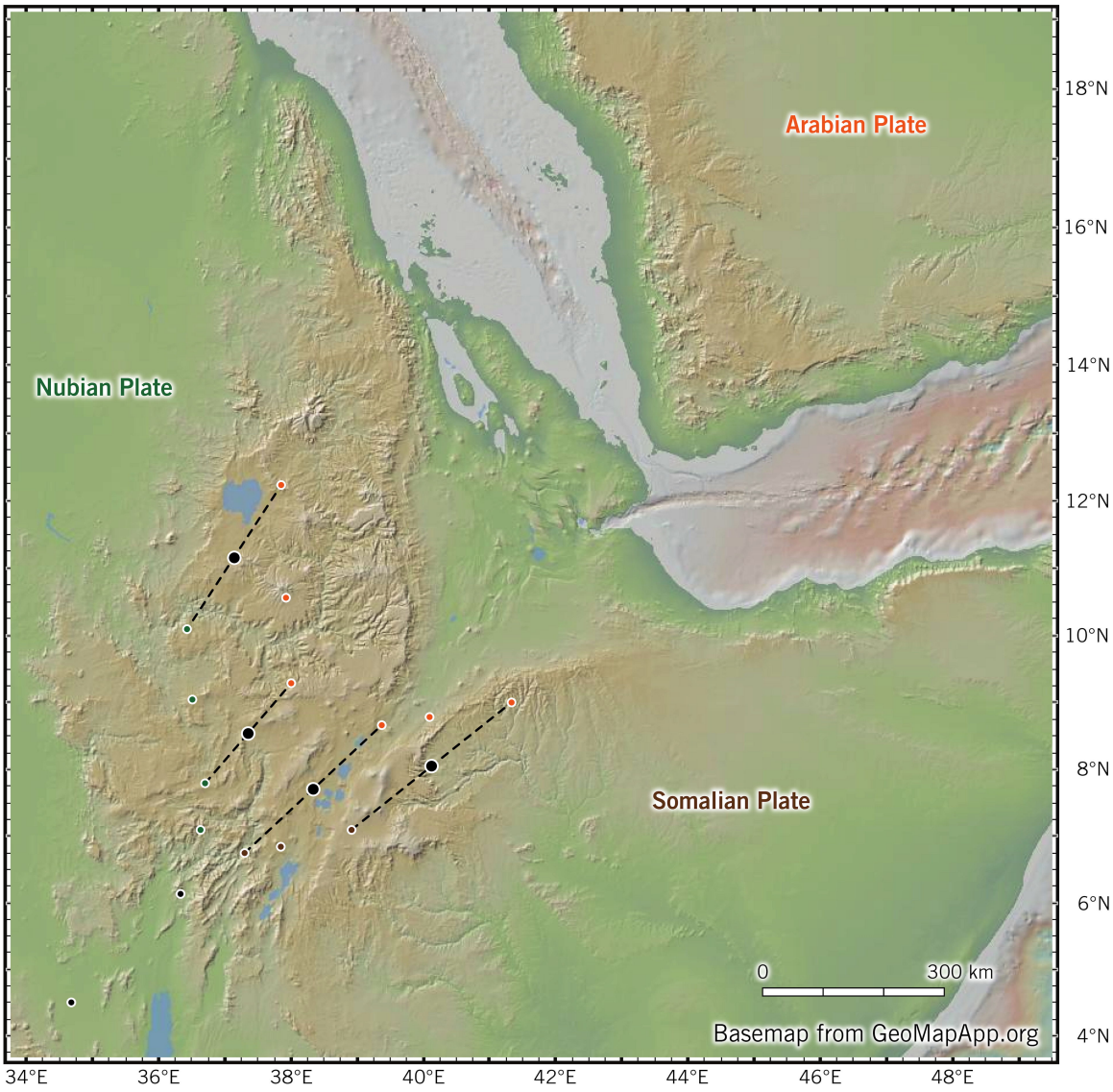

Figure 6: Midpoints between control points along continental edges (black points along dashed lines) are used to establish the location of the Red Sea Rift and Aden Ridge prior to the initiation of the Afar Triple Junction.

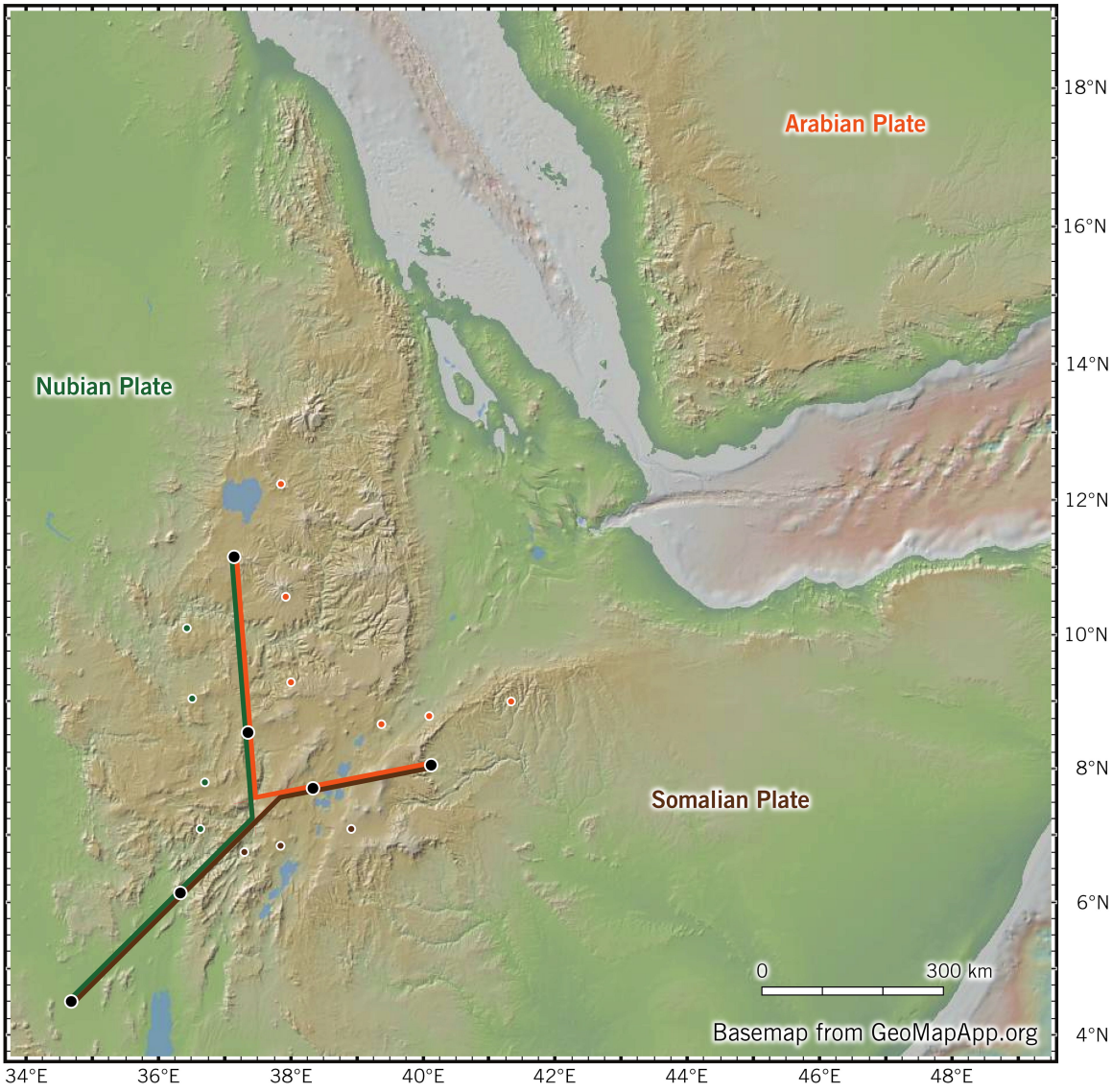

Figure 7: Great circles defined by rift midpoints delineate each rift system. The great circles intersect to form a triangle.

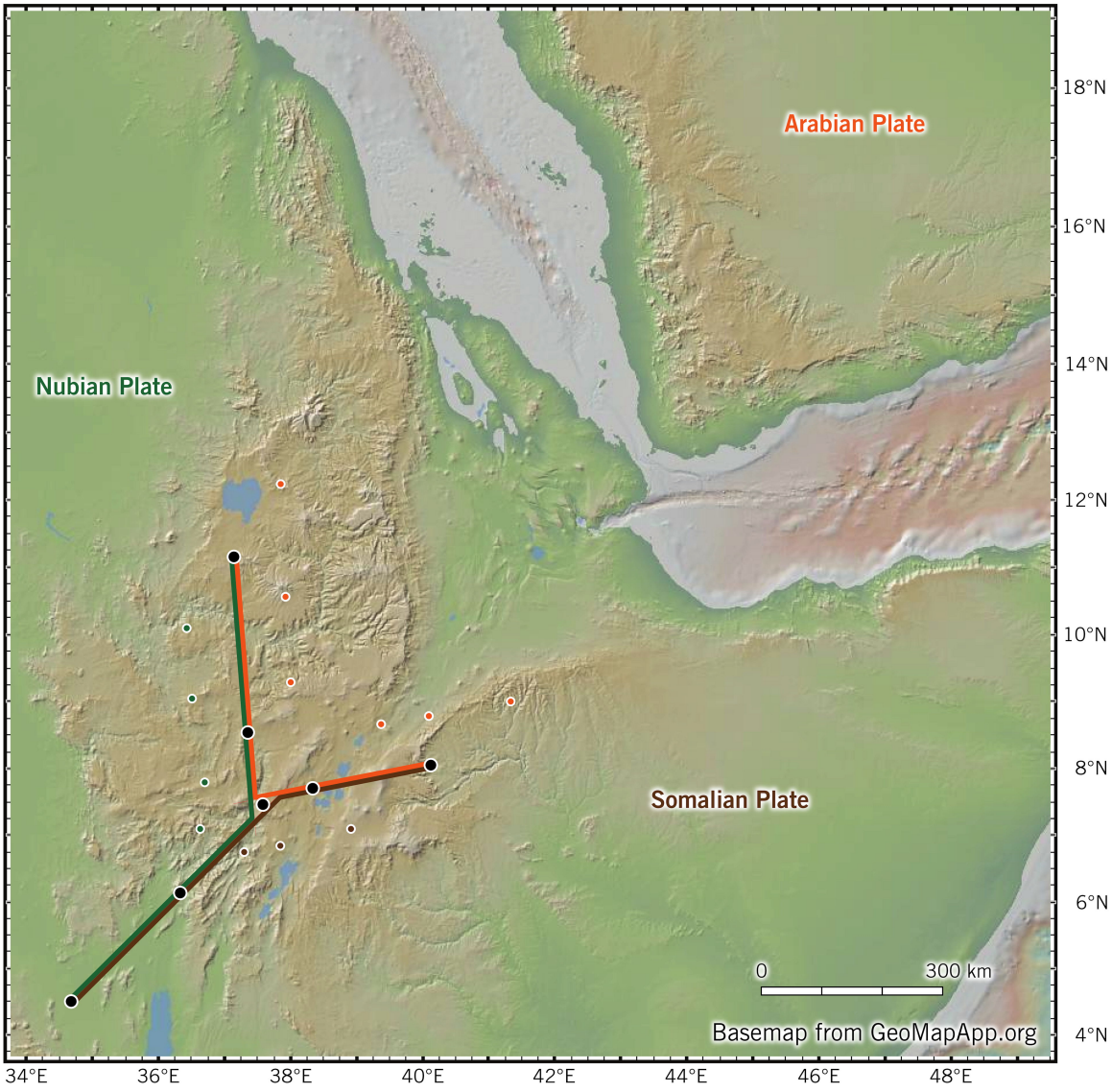

Figure 8: The triple-junction point is the center of the triangle formed by the three great circles along the rifts at -22 Ma.

RESULTS

Afar modeled at -22 Ma

By rolling back the clock, we are able to see that the Afar Triple Junction initiated at -22 Ma when the combined African plate began rifting into the present Nubian and Somalian plates. While the East African Rift was beginning to rift -22 Ma, it is clear from the location of our geographic control points in Figure 9 and the highlighted region of Figure 10 that the rifting of the Red Sea and Gulf of Aden had already begun by this point. A pre-East African Rift history of extension is the most likely cause of this, however our study is limited to the kinematic history of the Afar Triple Junction so we will not investigate the tectonic history of the region prior to the East African rifting event. (Prior to -22 Ma, the Nubian and Somalian plates made up one combined African plate, the former velocity of which we cannot measure.)

Afar modeled at 0 Ma

By rotating each of the seven points that define Afar Triple Junction at its initiation around their respective Euler poles, cloning them, and averaging them, we are able to project our best estimate of the location of the Afar Triple Junction and its rifts at present (0 Ma). As seen in Figure 11, the triple junction has migrated over 600 km eastward since its initiation and the length and orientation of each associated rift system have become further extended. Unsurprisingly, the brecciation of material due to extension in the rifting zone can be quickly identified in the relatively flat "nose" of the southwestern corner of the Arabian plate.

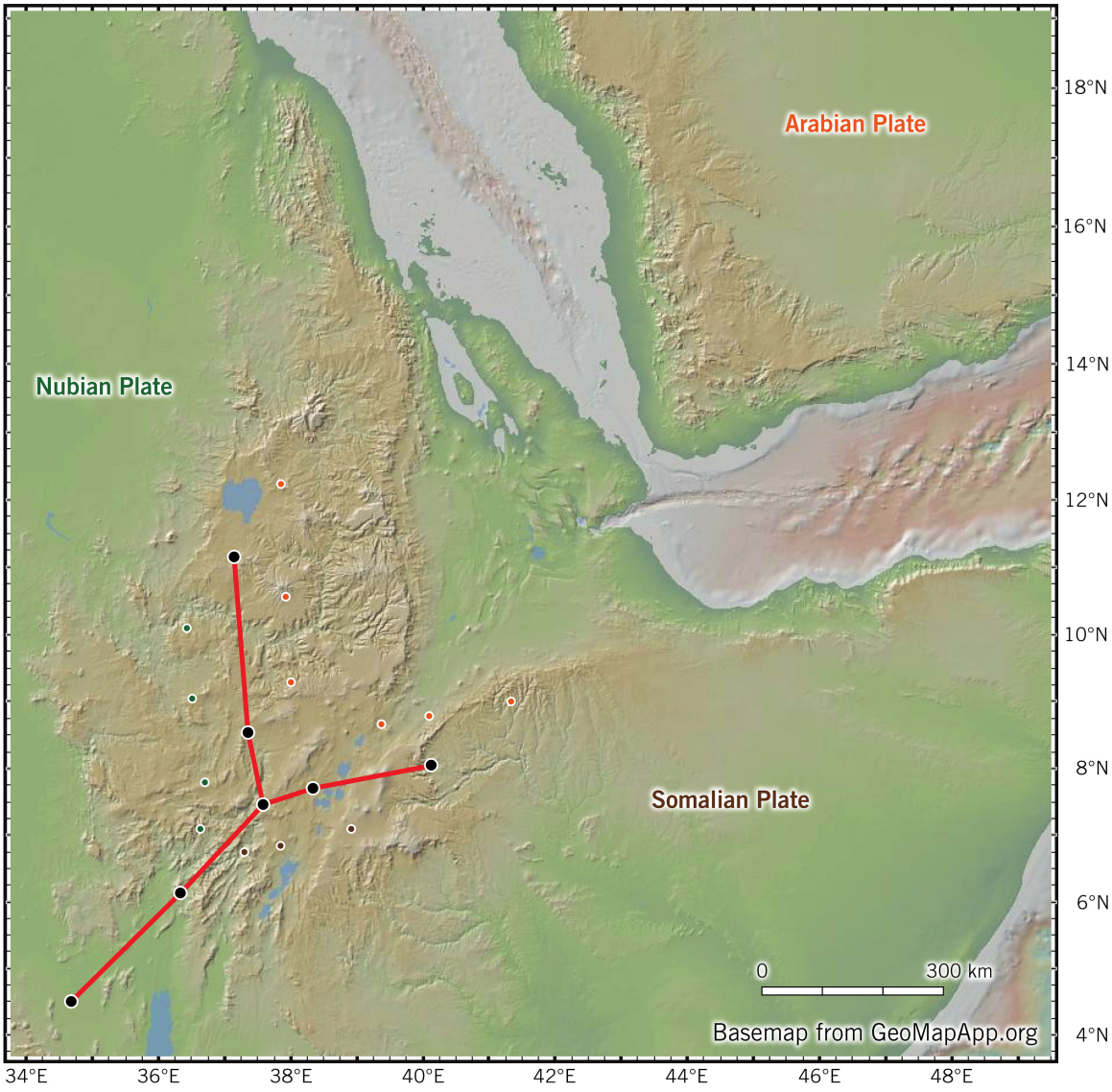

Figure 9: Afar Triple Junction, modeled at -22 Ma.

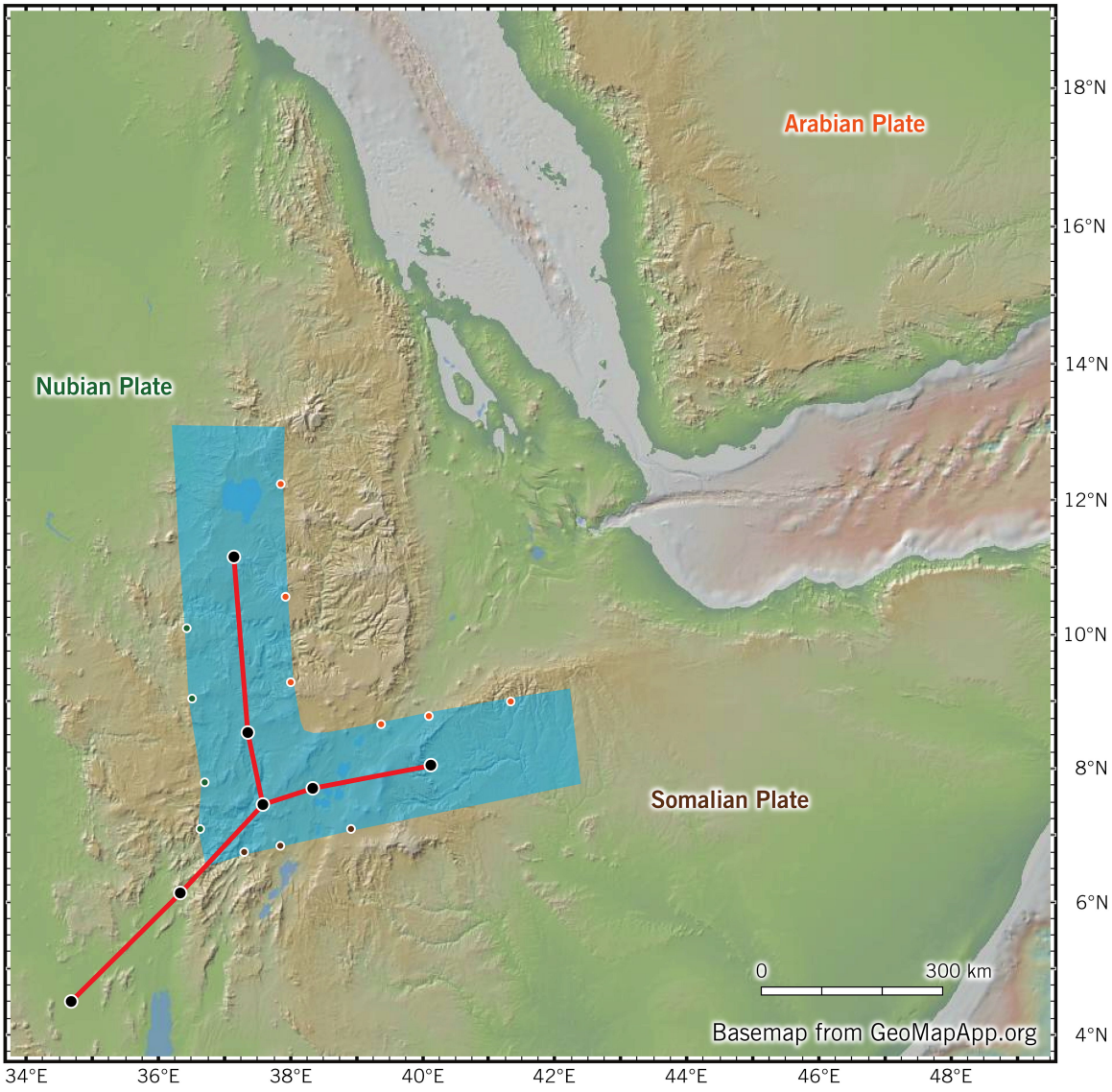

Figure 10: Red Sea Rift and Aden Rift might have been active prior to the initiation of Afar Triple Junction, -22 Ma. The blue area indicates the results of early rifting prior to extension along the East Africa Rift.

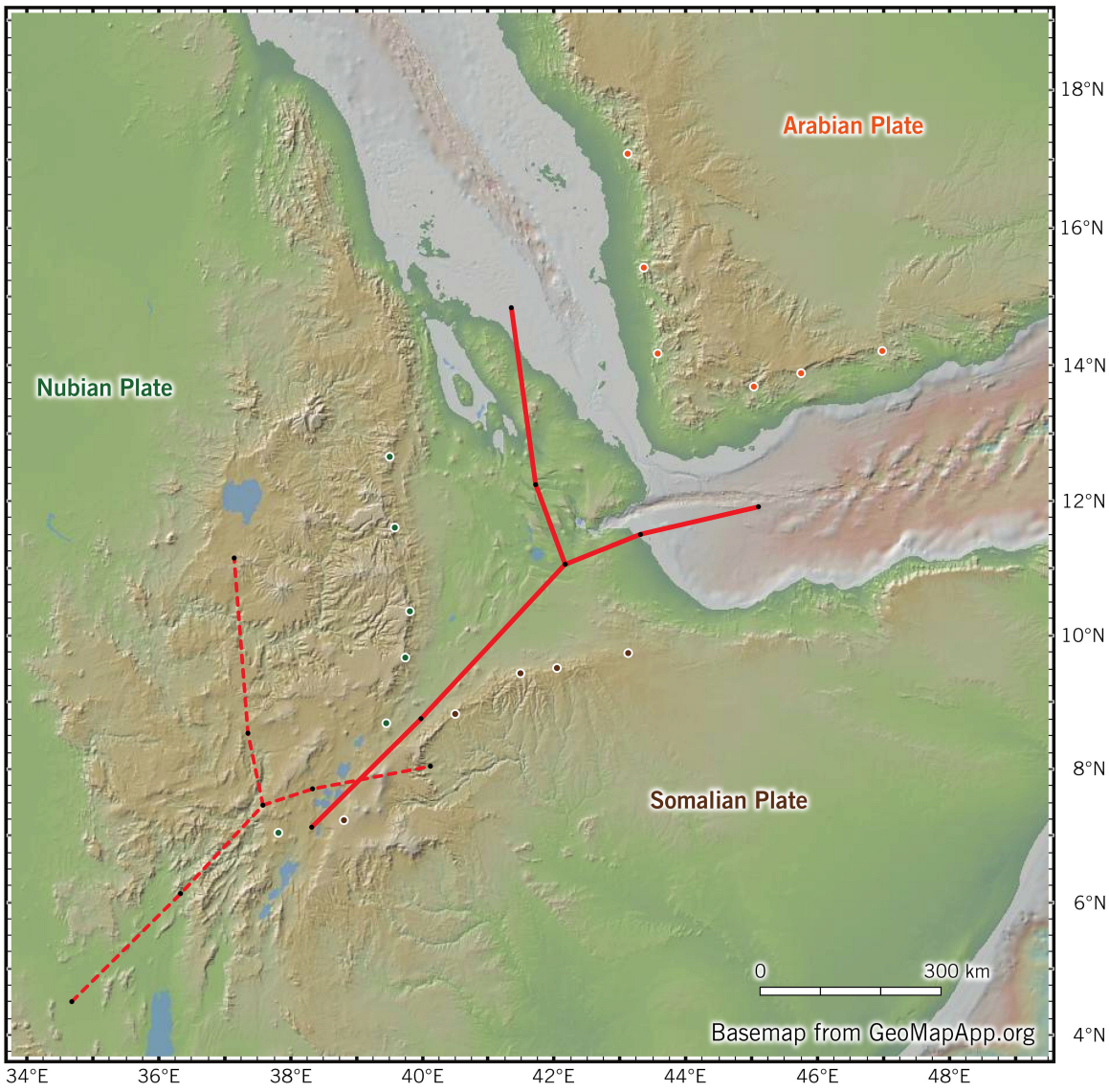

Figure 11: Afar Triple Junction modeled at 0 Ma (solid red), based on model at -22 Ma (dashed red). Original modern control points along the undeformed continental edges of the three plates are shown for reference.

Afar modeled at 5 Ma

Following this same method used to project the modern location of the Afar Triple Junction, we model the future location of the triple junction at 5 Ma. Our original control points migrate and become displaced, now delineating what will eventually become the location of the undeformed edge of each plate (Fig. 12). The triple junction at 5 Ma will have migrated over 120 km to the northeast compared with its current location. The developing rifts will likely fill the blue region of Figure 13.

DISCUSSION

Implications and Future Work

Though preliminary, our work in establishing a "start date" of 22 Ma for the initiation of Afar Triple Junction and developing a model that can project its location at specified time intervals has two broad applications for contextualizing future work. First, dating the triple junction's initiation and being able to project it through time provides kinematic context for those researchers interested in investigating triple junctions and their initiation on a more recent time scale. Secondly, our work can serve as a handy initial guide for those interested in studying the Afar region's geodynamics or the transition of a rift system from the mechanics of continental rifting to those of an oceanic spreading center.

The work presented in this thesis is fundamentally a preliminary kinematic model for the Afar Triple Junction and surrounding region. Though our work can aid in providing context for understanding geological, geophysical, and geochemical observations, further on-site geologic study and geodynamic modeling are the recommended next step to furthering our understanding of the region's kinematic history

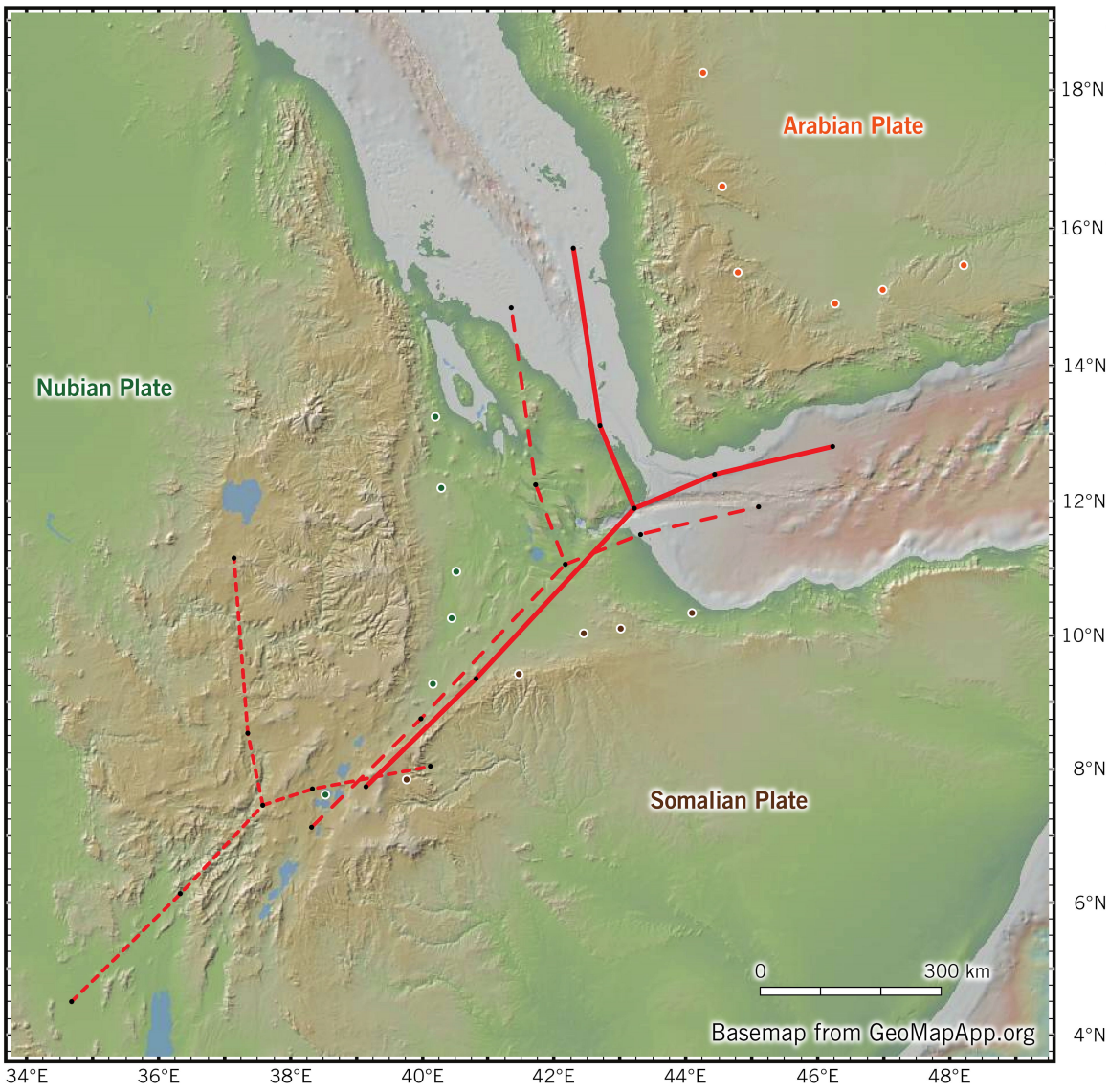

Figure 12: Afar Triple Junction modeled at 5 Ma (solid red) and 0 Ma (medium dashed red), based on model at -22 Ma (small dashed red). Original control points become displaced to a new location for the undeformed continental edge for the plates.

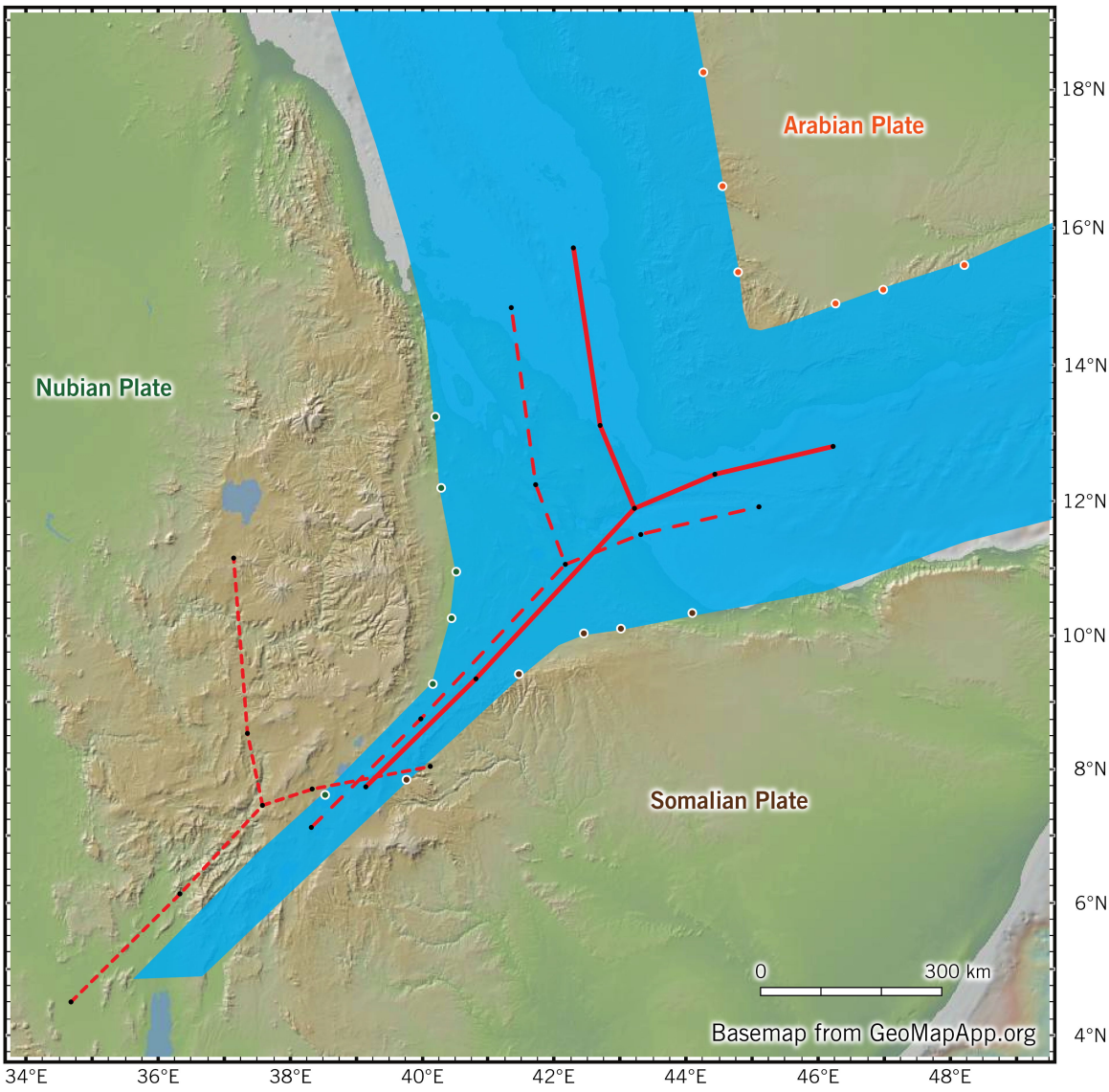

Figure 13: Extended rift zone created by Afar Triple Junction, 5 Ma.

and tectonic development.

Operational Assumptions and Uncertainties

A number of operational assumptions were made in the development of this model. We first assumed all plates maintain a constant velocity over our modeling interval as they are moved in the cycloid model around their individual Euler poles in the no-net-notation (NNR) reference frame. We also operate under the rigid plate assumption, which dictates that plates remain rigid up to their distinct boundaries. There is also a level of uncertainty in the selection of pairs of geographic control points across each rift. We assume the symmetric rifting of each of the limbs of the Afar Triple Junction when approximating ridge locations via mid-lines and, similarly, assume that a triple junction's location simply lies at the center of the triangle created by its three rift systems. When projecting the location of the triple junction after its initiation, the practice of "cloning" and plotting the mid-points of the two clones makes assumptions about underlying geology that we cannot verify without a field survey that should be accounted for. Lastly, our kinematic model does not calculate uncertainties for each output measurement, which means there is a small rolling error in our geographic controls that remains unaccounted for.

CONCLUSIONS

The location of Afar Triple Junction at its initiation -22 Ma was modeled and used to define the current location of the triple junction (0 Ma) and a future location of the triple junction in 5 Ma. This was accomplished first through the modification of a plate-motion model in a NNR reference frame (Kreemer and others, 2014) by adding the Euler velocity of the Pacific plate as observed in the Hawaiian hot-spot reference frame (Wang

and others, 2017). Distinct geographic control points were identified across each of the three rifts. These points were moved back along cycloid finite-motion trajectories until the control points along the East Africa Rift overlapped at -22 Ma, marking the approximate time of Afar Triple Junction's initiation. The location of the triple junction was found by taking the averages of the remaining pairs of points adjacent to the still-open Red Sea Rift and Aden Ridge, drawing a great circle through the mid-points of each rift, and then taking the average of their triangular-shaped intersection. Once established, the location of the triple junction and its three rifts were modeled from -22 Ma to 0 and 5 Ma. By modeling the triple junction at 0 Ma and 5 Ma, I infer that the Afar Triple Junction is extensional along all three of its boundaries and is migrating toward the northeast.

APPENDIX

Input Data

Table 1: Euler Poles Used in Cycloid Model

Pole of rotation	Lat. (°N)	Long. (°E)	Angular Speed (°/Ma)
Arabia Euler pole	42.155	-0.270986	0.456179
Nubia (west Africa) Euler pole	50.3991	-36.5919	0.189645
Somalia Euler pole	54.6131	-71.5876	0.225471

Table 1: The Euler poles used in our cycloid model are based on the most accurate velocity data for individual plate motion data in a NNR reference frame (Kreemer and others, 2014), recast in a hot spot reference frame (Wang and others, 2017).

Table 2: Geographic Points Used to Define Undeformed Plate Edges

Plate	Latitude (°N)	Longitude (°E)
Arabia	17.095	43.124
Arabia	15.441	43.37
Arabia	14.179	43.576
Arabia	13.693	45.035
Arabia	13.885	45.756
Arabia	14.218	46.986
Nubia	12.662	39.507
Nubia	11.613	39.59
Nubia	10.367	39.814
Nubia	9.674	39.744
Nubia	8.69657	39.4531
Nubia	7.0467	37.8161
Somalia	7.235	38.818
Somalia	8.833	40.5044
Somalia	9.44	41.493
Somalia	9.518	42.047
Somalia	9.748	43.128

Table 2: The geographic control points used to represent the undeformed edge of the three plates were selected in GeoMapApp for some defining characteristic which could be projected across to a matching point, also listed here, on the opposite side of the rift.

Output Data

Table 3: Positions of Points Defining Continental Edges as Modeled Through Time

Identified Geographic Point	Position at -22 Ma		Position at 0 Ma		Position at 5 Ma	
	Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)
Nubia	10.09874825	36.43423421	12.662	39.507	13.25	40.20503288
Nubia	9.048812668	36.50316972	11.613	39.59	12.201	40.29093452
Nubia	7.800184556	36.70984031	10.367	39.814	10.955	40.51855345
Nubia	7.108084592	36.63173152	9.674	39.744	10.262	40.45015888
Nubia	6.134295598	36.33043776	8.69657	39.4531	9.284	40.16122947
Nubia	4.505876756	34.68021559	7.0467	37.8161	7.6299	38.52625988
Somalia	4.508843731	34.68022654	7.235	38.818	7.845	39.76789675
Somalia	6.134293315	36.33047769	8.833	40.5044	9.4358	41.46378967
Somalia	6.758484724	37.3017727	9.44	41.493	10.038	42.4568907
Somalia	6.846503041	37.85054756	9.518	42.047	10.114	43.01225073
Somalia	7.096746228	38.91963888	9.748	43.128	10.339	44.09632737
Arabia	12.23594522	37.85506449	17.095	43.124	18.269	44.26691221
Arabia	10.56655838	37.92444988	15.441	43.37	16.621	44.55277934
Arabia	9.290962149	37.99737406	14.179	43.576	15.363	44.78864151
Arabia	8.667746152	39.37551695	13.693	45.035	14.908	46.26606079
Arabia	8.791028445	40.09942626	13.885	45.756	15.114	46.98667439
Arabia	9.00870692	41.33380279	14.218	46.986	15.472	48.21626277

Table 3: The geographic control points selected from GeoMapApp to outline the undeformed edges of the continents were processed through our cycloid model in reverse time to identify their position at the initiation of the Afar Triple Junction at -22 Ma. These points from -22 Ma were then projected at 0 Ma and 5 Ma using the same cycloid model.

Table 4: Position of Points Defining Afar Triple Junction as Modeled Through Time

Identified Geographic Point	Position at -22 Ma		Position at 0 Ma		Position at 5 Ma	
	Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)
Nubia	11.16818361	37.14203326	14.8537	41.3544	15.718	42.29548282
Nubia	8.546104829	37.35234858	12.2503	41.7206	13.119	42.69621865
Nubia	7.465354661	37.57996792	11.0651	42.166	11.894	43.21924339
Nubia	6.134294456	36.33045773	8.76515	39.9787	9.3621	40.81216013
Nubia	4.507360243	34.68022107	7.14112	38.3169	7.7394	39.14660837
Somalia	4.507360243	34.68022107	7.14112	38.3169	7.7394	39.14660837
Somalia	6.134294456	36.33045773	8.76515	39.9787	9.3621	40.81216013
Somalia	7.465354661	37.57996792	11.0651	42.166	11.894	43.21924339
Somalia	7.714363399	38.33630455	11.511	43.3131	12.396	44.43726712
Somalia	8.054490511	40.12387073	11.9189	45.1035	12.818	46.23008607
Arabia	11.16818361	37.14203326	14.8537	41.3544	15.718	42.29548282
Arabia	8.546104829	37.35234858	12.2503	41.7206	13.119	42.69621865
Arabia	7.465354661	37.57996792	11.0651	42.166	11.894	43.21924339
Arabia	7.714363399	38.33630455	11.511	43.3131	12.396	44.43726712
Arabia	8.054490511	40.12387073	11.9189	45.1035	12.818	46.23008607

Table 4: Using the geographic control points for continental margins output at -22 Ma (see Table 3), the position of the Afar Triple Junction at initiation was established and then projected forward through time to 0 Ma and 5 Ma using our cycloid model.

Supplemental Information

The Mathematica code used for all calculations is accessible via croninprojects.org/Vince/Collins/index.htm. This includes the code used to convert the Kreemer et al. plate-motion model (2014) to a NNR reference frame fixed to the Hawaiian hotspot via the Wang et al. model (2017), the code used to model the initiation of the opening of the northern East Africa Rift, and the code used to model the kinematic evolution of the Afar Triple Junction from -22 Ma to 0 Ma to 5 Ma.

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