Reconstruction of the States of Stress since Rifting in the Mesozoic using Fault-Slip Data from Crystalline Bedrock in Eastern Connecticut

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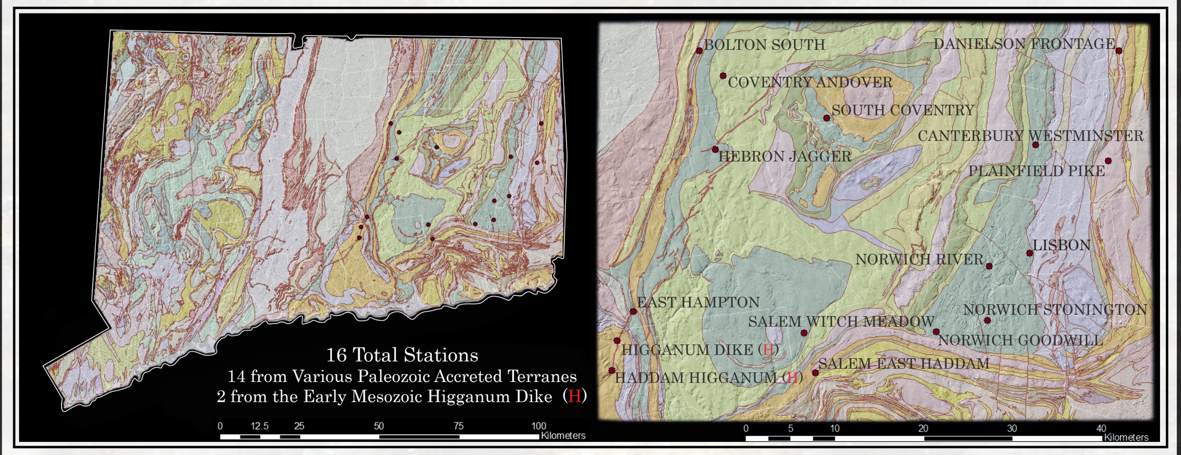
Abstract

The passive margin of eastern North America contains reverse faults and folds in early Mesozoic basin-fill that are not characteristic of extension in the lithosphere during rifting. These observations deviate from the classical understanding of a passive margin and indicate other states of stress since rifting. To strengthen these observations, we have concentrated on brittle structures found in crystalline bedrock east of the Hartford Basin in Connecticut.

We collected 1,060 fault-slip data from various Paleozoic accreted terranes and the Early Jurassic Higganum Dike. Because the dataset is large and heterogeneous, we first processed it using stress orientations based on the trend of the Higganum Dike in order to isolate faults representative of rifting. Paleostress inversion of the remaining faults in combination with age relations observed in the field identifies three additional phases of deformation. Phase 1 consists primarily of normal faults striking in a variety of directions but mainly ~NE-SW and displays a subvertical σ1. Faults in phase 2 have a variety of orientations but are dominated by a conjugate set of ~N-S and ~E-W-striking strike-slip faults and displays a NW-SE σ1. Phase 3 consists of a conjugate set of ~NW-SE and ~NE-SW-striking strike-slip faults and displays a N-S σ1. Phase 4 consists of a conjugate set of ~NE-SW and ~WNW-ESE-striking strike-slip faults and displays an ENE-WSW σ1.

Phase 1 stress orientations indicate flattening strain in the basement during rifting. Phase 2 faults may have developed synchronously with structural inversion of the rift basins. Phase 3 faults are consistent with widespread observations for N-S compression in the region. Phase 4 stress orientations are parallel to the present-day state of stress. In total, our stress inversions for eastern Connecticut identify four tectonic phases and are consistent with other studies in eastern North America of the post-Paleozoic states of stress.

Field Stations



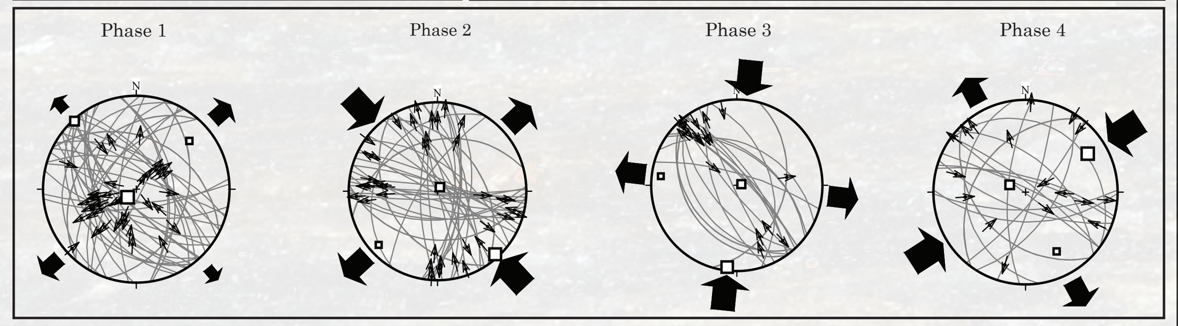
Lisbon, CT

Recently exposed large and sinuous outcrops in eastern Connecticut allowed us to collect a wide variety of fault slip orientations.

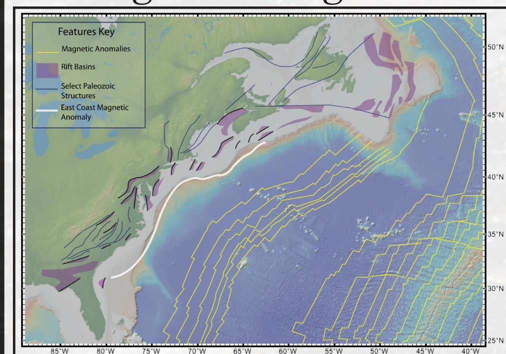
(Above) Gigapan panoramic image of ~30% of the exposed measurable rocks looking northwest.

(Left) Orthoimagery revealing the large size and shape of exposed surfaces.

(Below) Paleostress inversions of 114 fault-slip data collected from this station.

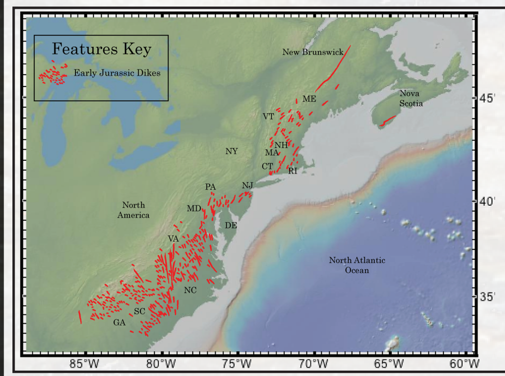


Rifting and Magmatic Activity in Eastern North America



A map view of eastern North America shows Late Triassic to Early Jurassic rift basins related to the extension and attenuation of the lithosphere during early rifting (Withjack and Schlische, 1998). Magnetic anomalies drawn on the sea floor depict the polar reversals of earth's magnetic field as far back as 155 Ma (M-25). These magnetic anomalies show the trajectories of continental drift between Africa and North America. Seismic and well data suggest early sea-floor spreading began before 175 Ma.

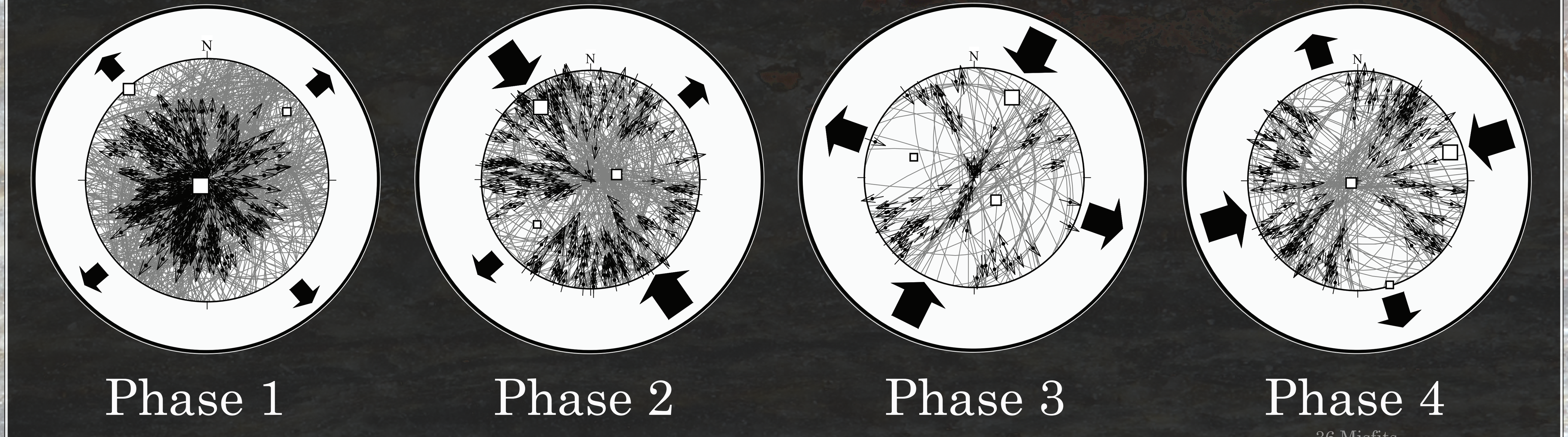
Figure modified from Withjack and Schlische (2005).



A map view of eastern North America (ENA) showing the locations and trends of dikes associated with CAMP igneous activity. ENA magmatic activity occured sometime around ~201 Ma and lasted about 600,000 years. Most dikes trend NW-SE south of Virginia while dikes trend NE-SW north of Maryland and Delaware. The dike trends reflect the state of stress during emplacement. In the north S_{hmax} trends NE-SW and in the south S_{hmax} trends NW-SE.

Figure and explanation modified from Withjack et al., (1998).

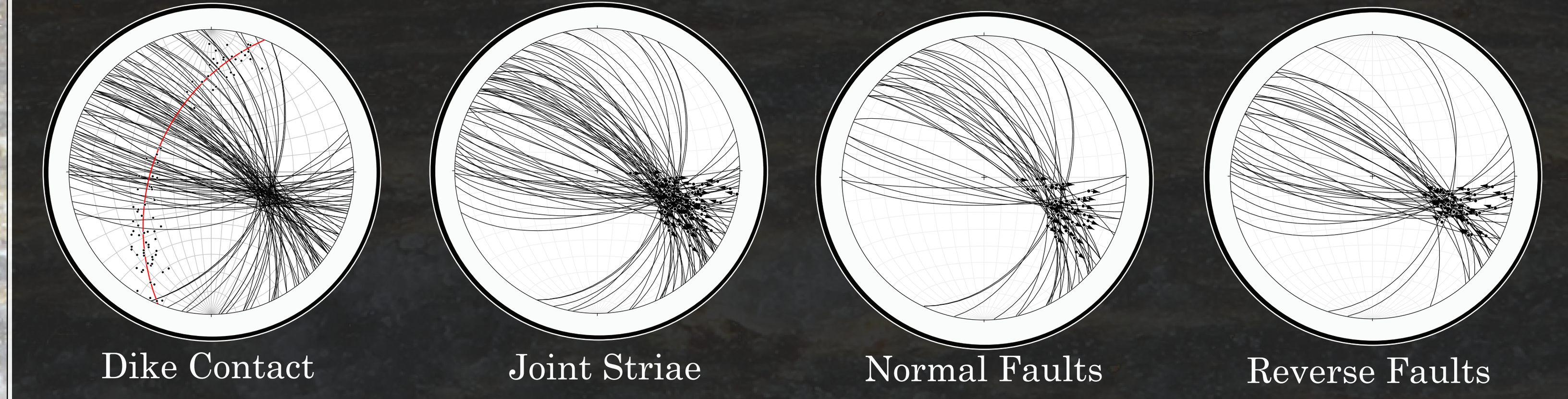
Paleostress Analysis of Paleozoic Accreted Terranes

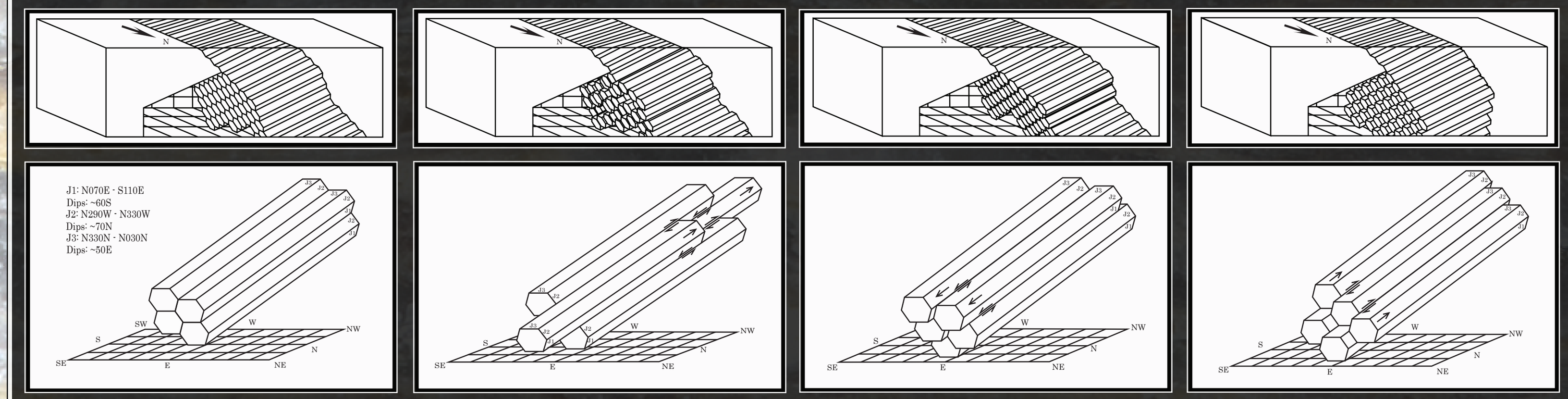


Phase 1	Phase 2	Phase 3	Phase 4 (36 Misfits)
n = 393	n = 240	n = 81	n = 155
Φ = (σ2-σ3)/(σ1-σ3) = 0	Φ = (σ2-σ3)/(σ1-σ3) = 0.1	Φ = (σ2-σ3)/(σ1-σ3) = 0.4	Φ = (σ2-σ3)/(σ1-σ3) = 0.3
Direction of principal stress axes: σ1: 228/82, σ2: 319/00, σ3: 050/08	Direction of principal stress axes: σ1: 326/12, σ2: 080/62, σ3: 230/24	Direction of principal stress axes: σ1: 026/12, σ2: 135/58, σ3: 289/29	Direction of principal stress axes: σ1: 073/07, σ2: 253/83, σ3: 163/00
Relative values of principal stresses: σ1 : σ2 : σ3 = 1 : 0.07 : 0.07	Relative values of principal stresses: σ1 : σ2 : σ3 = 1.1 : 0.18 : 0.08	Relative values of principal stresses: σ1 : σ2 : σ3 = 0.97 : 0.43 : 0.07	Relative values of principal stresses: σ1 : σ2 : σ3 = 0.97 : 0.34 : 0.07

Paleostress Analysis of the Early Mesozoic Higganum Dike

Faults on Cooling Joint Surfaces





The strike and dip of the contact between the Higganum Dike and Bronson Hill Anticlinorium is 202, 46 identified by fitting a plane (red) to the poles of cooling joint surfaces.

Regionally, the Higganum Dike trends 207 in eastern Connecticut.

Fault-slip data show:
A) J1 surfaces are oblique thrust faults.
B) J2 surfaces are oblique normal and thrust faults.
C) J3 surfaces are normal faults.

Analysis of fault-slip data on cooling joint surfaces shows differential slip parallel to column axes.

Normal fault-slip data show:

J2 and J3 surfaces are dominant.

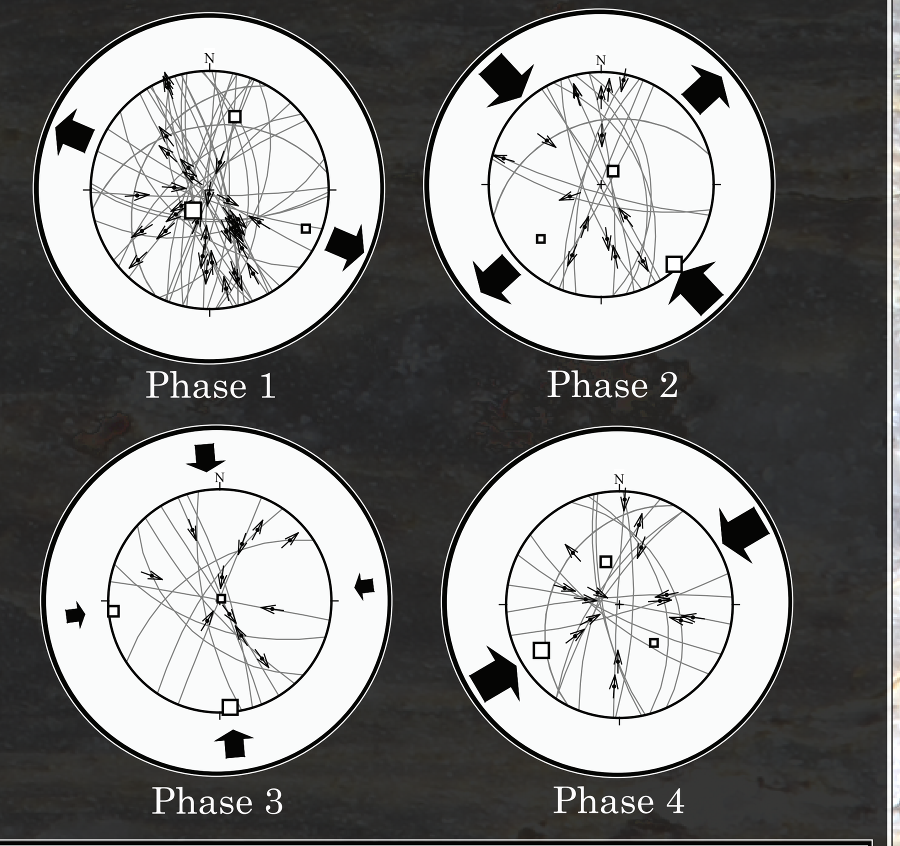
Analysis of normal fault-slip data shows cooling joint surfaces are dominantly dip-slip (striae rake >45° and <135°).

Reverse fault-slip data show:

J1 and J2 surfaces are dominant.

Analysis of reverse fault-slip data shows cooling joint surfaces are dominantly strike-slip (striae rake <45° and >135°).

Faults Oblique to Cooling Joint Surfaces



Paleostress inversions of fault-slip data oblique to cooling joint surfaces are consistent with our paleostress analysis of fault-slip data collected from various Paleozoic accreted terranes and the observations of Sawyer and Carroll (1982). These data suggest the faults post-date the emplacement of the Higganum dike at ~201 Ma.

Phase 1: n = 35, Phase 2: n = 15, Phase 3: n = 11, Phase 4: n = 15

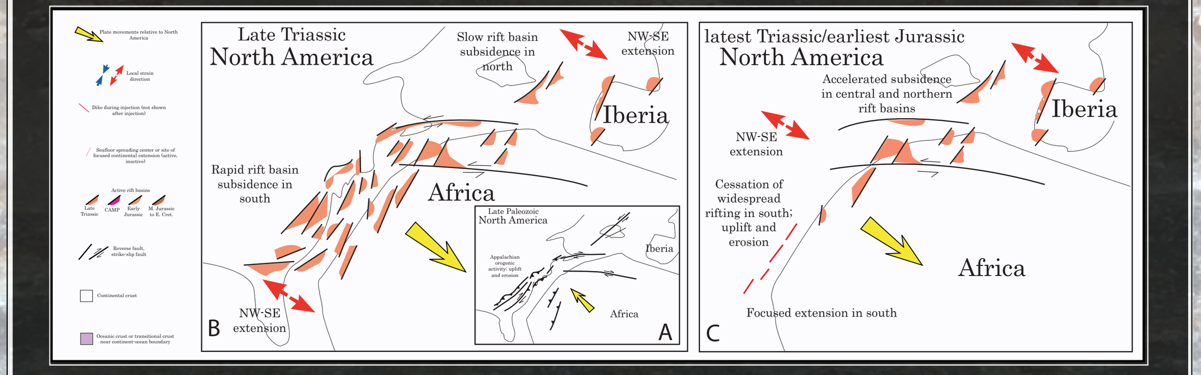
Discussion

Phase 1 Main-stage Rifting

Simplified sketches showing Withjack et al.'s (2012) hypothesized tectonic evolution of eastern North America and northwestern Africa.

a) Supercontinental assembly was complete by the Permian.
b) In the Late Triassic, eastern North America underwent NW-SE extension. Subsidence led to the formation and sedimentation of half-graben basins.
c) In the latest Triassic to earliest Jurassic, the southern basins stopped subsiding while rifting continued in the north.

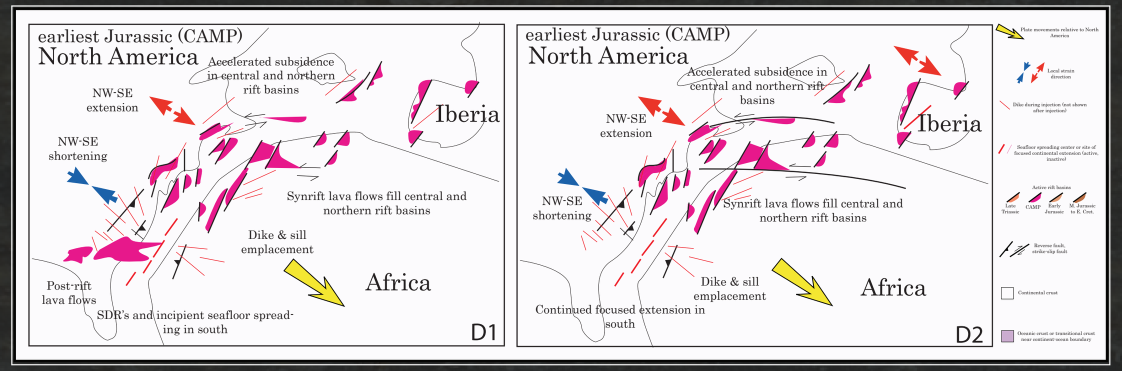
Explanation modified from (Withjack et al., 1998, Schlische 2000 and Withjack et al., 2012).



Phase 2 Post-rift Inversion Stage A

In the earliest Jurassic, the southern region experienced NW-SE shortening. This resulted in the development of reverse faults and folds, and basin inversion. CAMP igneous activity occurred in the latest Triassic to earliest Jurassic.
d1) Seafloor spreading may have started shortly after the cessation of rifting in the south.
OR
d2) Rifting in the south may have become focused in the offshore basins and seafloor spreading may have started later.

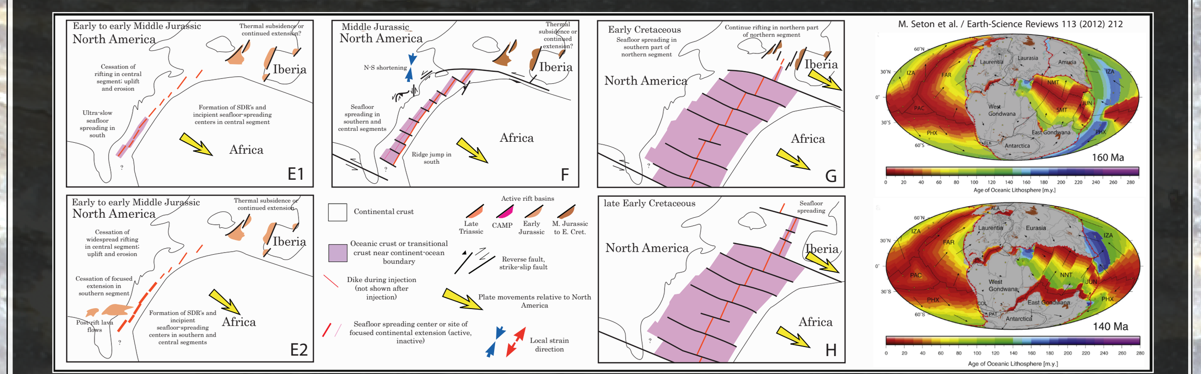
Explanation modified from (Withjack et al., 1998, Schlische 2000 and Withjack et al., 2012).



Phase 3 Post-rift Inversion Stage B

In the Early Jurassic to early Middle Jurassic, rifting continued in the north. In the south, e1) seafloor spreading may have started in the Early Jurassic if post-rift basalts are CAMP related.
OR
e2) seafloor spreading started in the Early to early Middle Jurassic if post-rift basalts are younger than CAMP activity.
f) In the Middle Jurassic 1) seafloor spreading processes continued in the south, 2) "ridge jump" processes developed in the central part of the region and 3) structures associated with ~N-S shortening began to develop in the north.
g-h) In the Early to late Early Cretaceous, subsidence rates increased in the far north by the end of the Early Cretaceous.
Explanation modified from (Withjack et al., 2012).

(Below Far Right) Absolute plate velocity vectors are denoted as black arrows. At 140 and 160 Ma, Laurentia is moving NW relative to West Gondwana. In an absolute reference frame based on a true-polar wander corrected paleomagnetic model, Laurentia is moving NW at 160 Ma, but, at 140 Ma, Laurentia is moving NNE. Spreading propagated northward between the Iberia-Newfoundland margin during Anomaly M20 (~146 Ma). The ending of extensional faulting in the SE Gulf of Mexico and the dating of a post-rift unconformity places the end of seafloor spreading in the Caribbean during the latest Jurassic-earliest Cretaceous between 145 and 135 Ma (M. Seton et al., 2012).

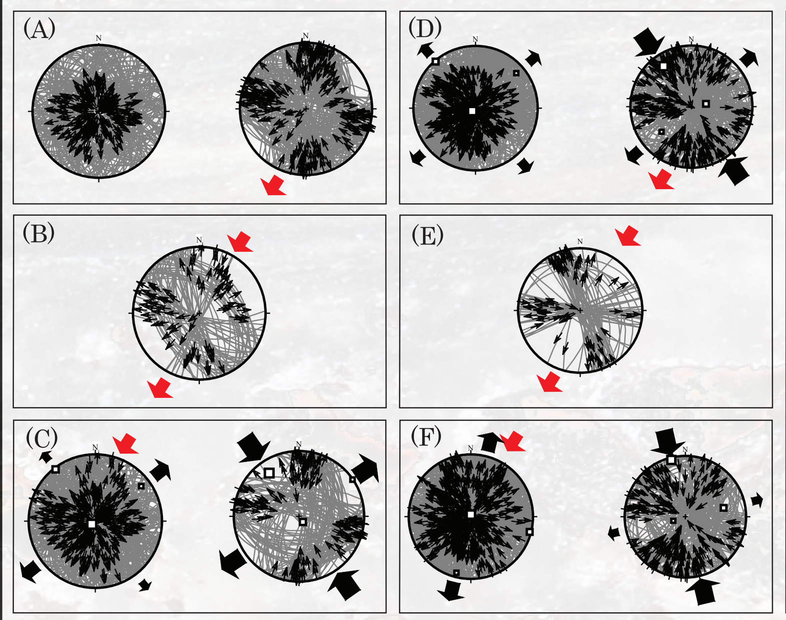


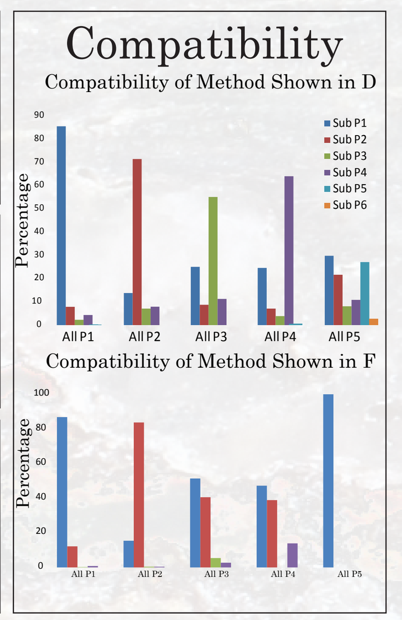
Phase 4 Contemporary State of Stress

The World Stress Map is a global database of contemporary tectonic stress of the Earth's crust. Its uniformity and quality is guaranteed through quality ranking of the data according to international standards and the standardized regime assignment. In the World Stress Map, different types of stress indicators are used to determine the tectonic stress orientation. Data is derived from four categories: earthquake focal mechanisms, well bore breakouts and drilling-induced fractures, in-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter), and young geologic data (from fault-slip analysis and volcanic vent alignments).

World Stress Data Provided by: Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

Methods





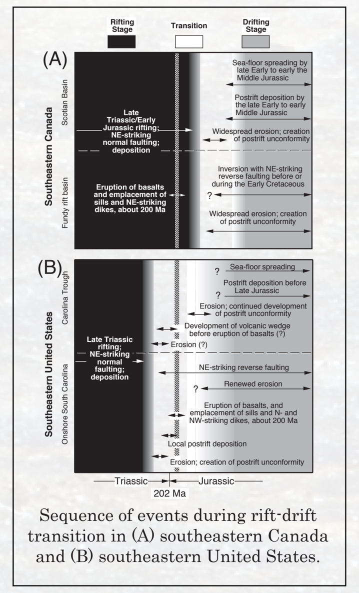
Paleostress inversion of heterogeneous fault-slip data can be difficult if multiple tectonic phases are present and paleostress axes of the phases do not differ significantly in orientation. We generated artificial fault-slip data representative of the principal stresses during rifting and post-rift inversion (A). Paleostress inversion of these artificial data results in the misclassification of faults: in the example shown, 77 faults from post-rift inversion (B) were included in rifting (C). To avoid this problem, we first processed our data using stress orientations based on the trend of the Higganum Dike (σ1 = 207, 89: σ3 = 297, 01). This isolated the faults representative of rifting and allowed us to continue the remainder of the inversion using default settings (D). Processing the inversion without this approach (F) results in the misclassification of faults (E) similar to the faults shown in (B).

Relative Age Dating

To the left is a fault plane from Lisbon, CT with two sets of striae. Strike-slip striae **(red)** dominate the fault plane while dip-slip striae are depressed in a cavity **(blue)**. Strike-slip motion falls into phase 2 and would have post-dated dip-slip motion which falls into phase 1. This observation is one of 6 observations which suggest phase 2 is younger than phase 1. Similar observations suggest that phases 1, 2 and 3 are older than phase 4 and that phase 1 is older than phase 3.

These phases are arranged in agreement with these observations and the results from other

Tectonic Model for Central Eastern North America



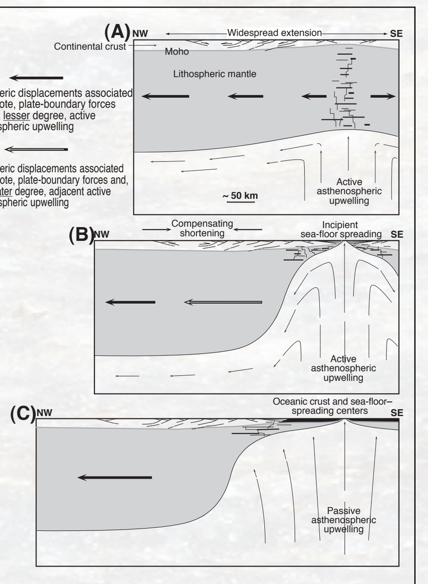
Sequence of events during rift-drift transition in (A) southeastern Canada and (B) southeastern United States.

(A) Early rifting - Distant plate-tectonic forces produce divergent lithospheric displacements and widespread extension. Active asthenospheric upwelling has little influence on lithospheric displacements.

(B) Late rifting - Lithosphere is substantially thinned. Gravitational-body forces and traction forces associated with the hot, low-density asthenospheric upwelling increase substantially. In response, lithospheric displacements near the upwelling exceed those far from the upwelling, causing shortening (inversion) in the intervening zone.

(C) Early drifting - Lithospheric displacements far from the upwelling increase, eventually equaling those near the upwelling. Most shortening/ inversion ceases, and the asthenospheric upwelling becomes passive.

Figures and explanation taken from (Withjack et al., 1998)



Conclusions

The four phases represent data collected from crystalline basement in eastern Connecticut and are consistent with other states of stress observed along the passive margin of eastern North America since rifting began in the early Mesozoic.

Phase 1 shows a subvertical σ1 where σ2 and σ3 have similar magnitudes. This is consistent with NW-SE extension during rifting in the Late Triassic to Early Jurassic.

Phase 2 shows a ~NW-SE σ1 and is consistent with other observations for post-rift inversion in the southeastern United States.

Phase 3 shows a ~N-S σ1 and is consistent with widespread observations for post-rift shortening in New England.

Phase 4 shows a ~ENE-WSW σ1 that fits with the current state of stress in New England.

References

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