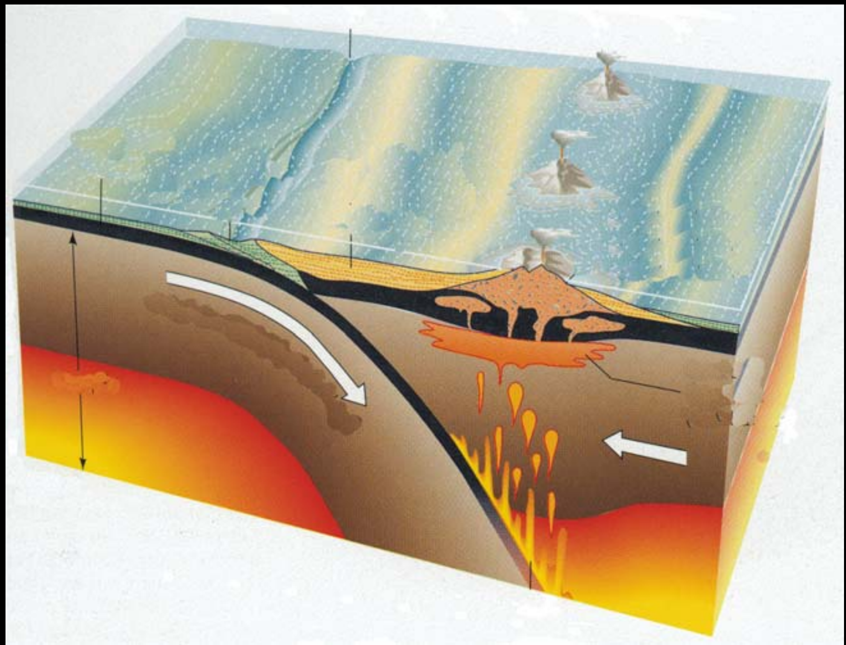
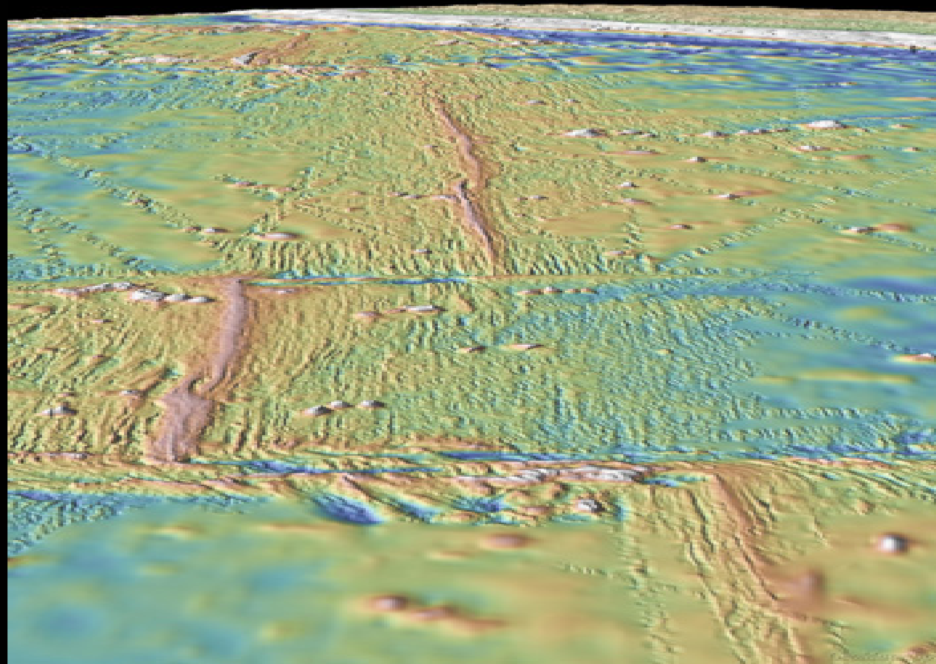
Initiation of subduction and oceanic spreading in nature and models





Taras Gerya, Ksenia Nikolaeva, Thibault Duretz, Marina Armann

Geophysical Fluid Dynamics, ETH-Zurich

1970 - 2011

1406 MINEAR AND TOKSÖZ (1970)

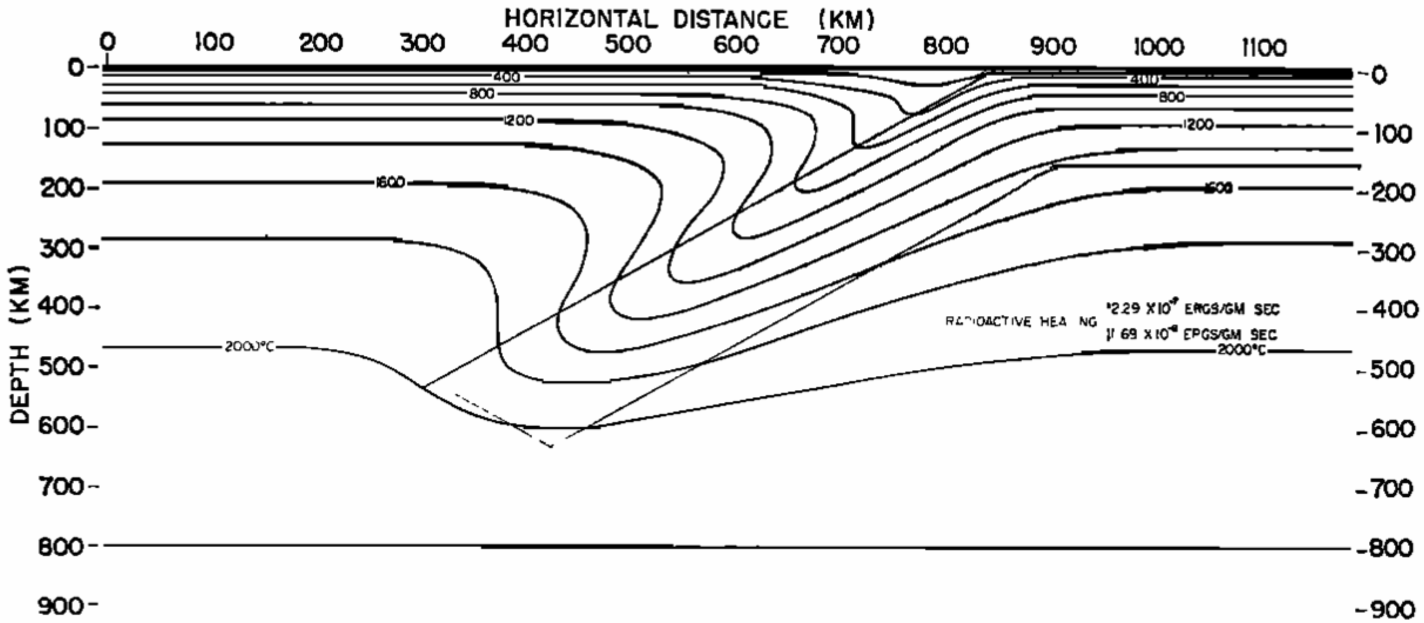
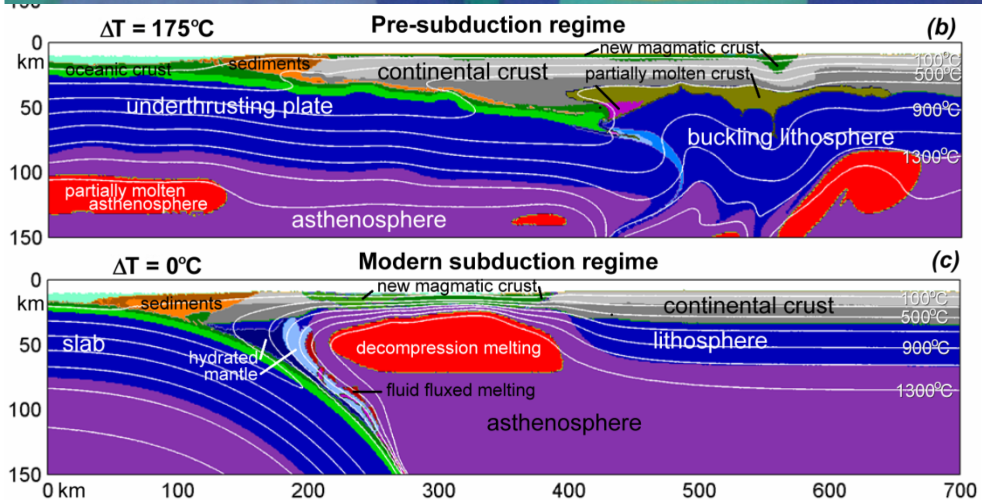


Fig. 5. Temperature regime for a spreading velocity of 1 cm/yr with conductive heat transfer only.

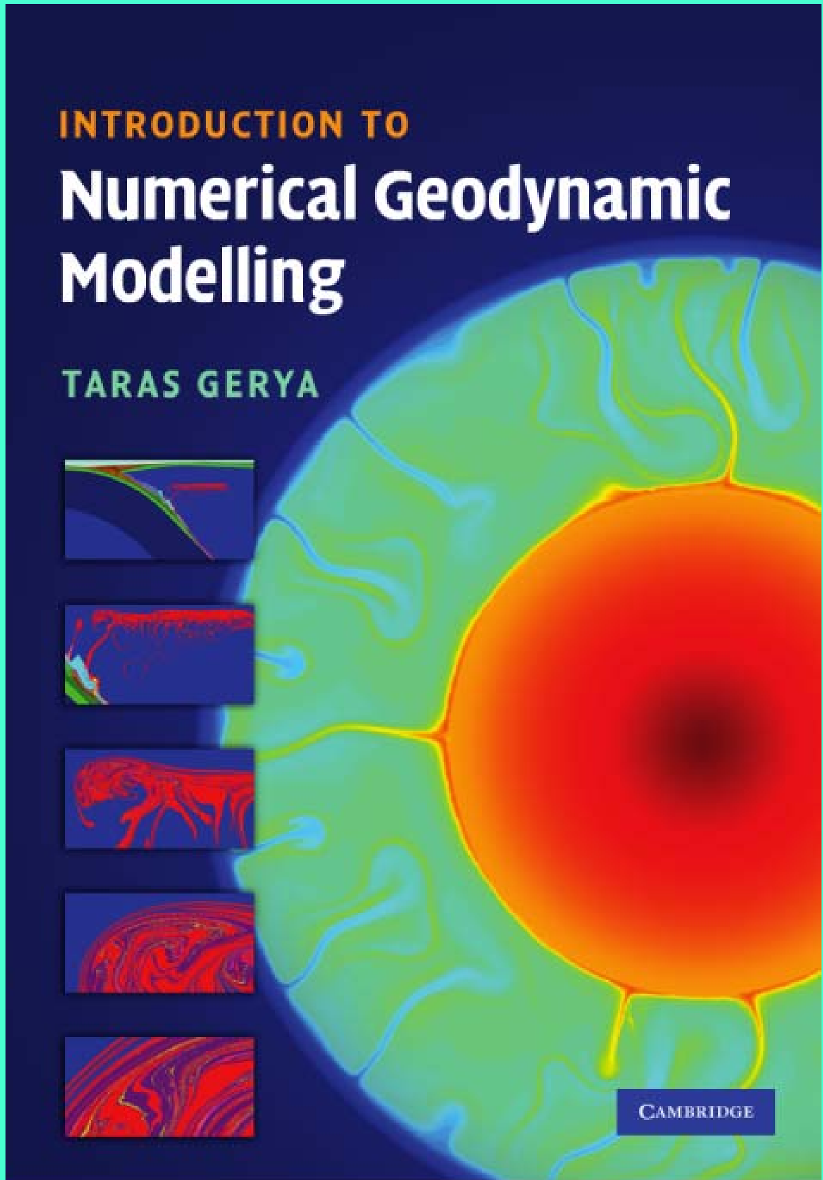
41 years of subduction modeling

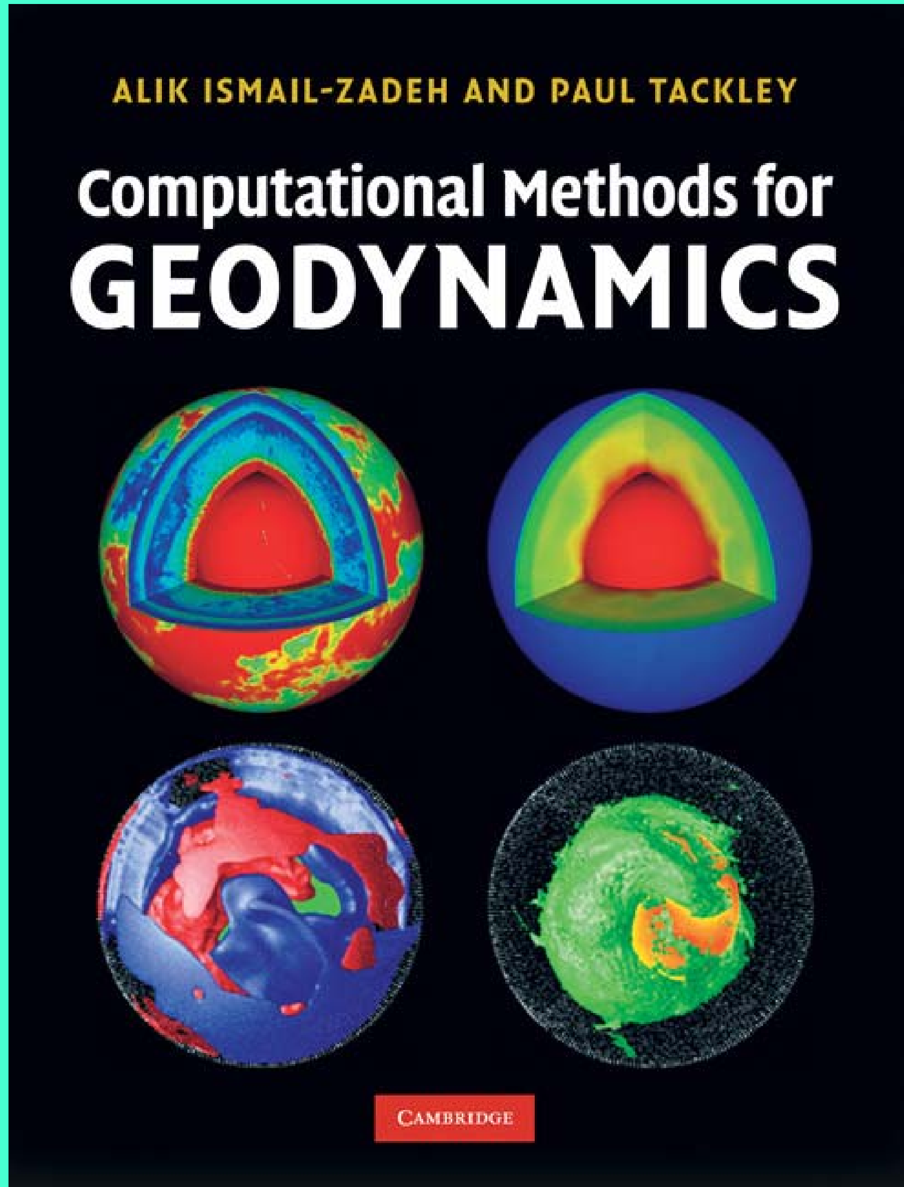
Elena Sizova



40 years anniversary of subduction modeling

2010

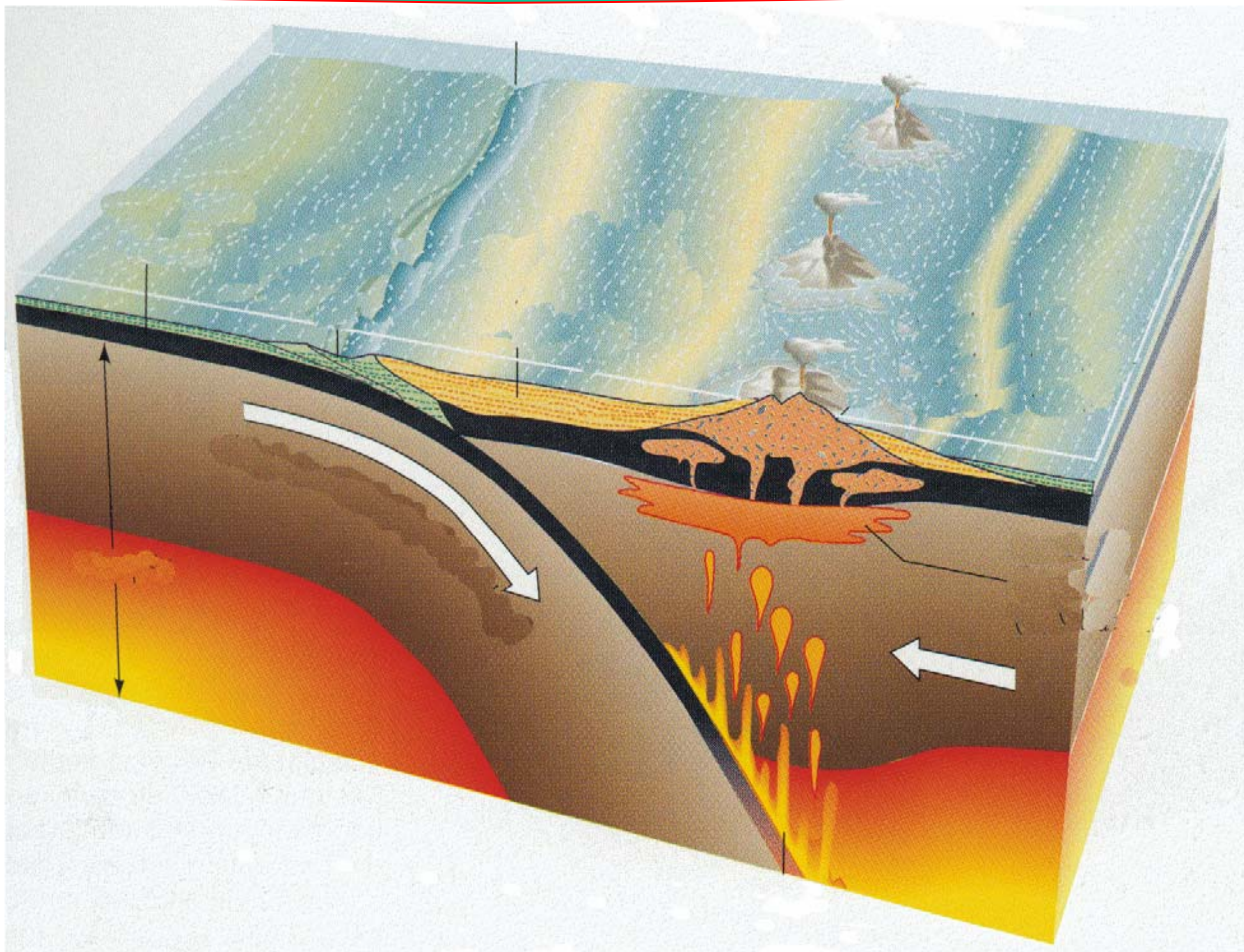




40 years anniversary of subduction modeling

How does subduction initiate?

?

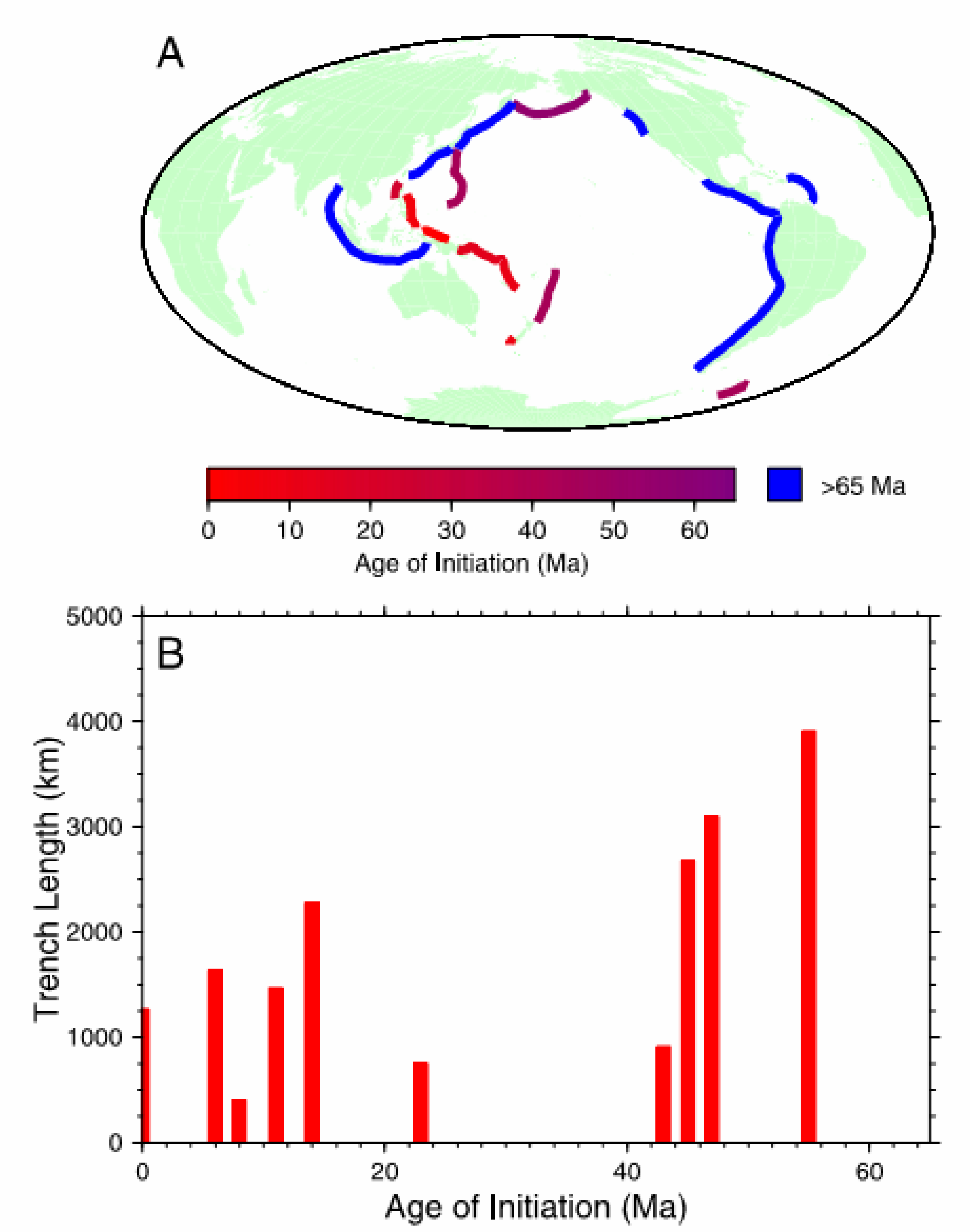


Subduction initiation is enigmatic...

At least fourteen hypotheses of subduction initiation :

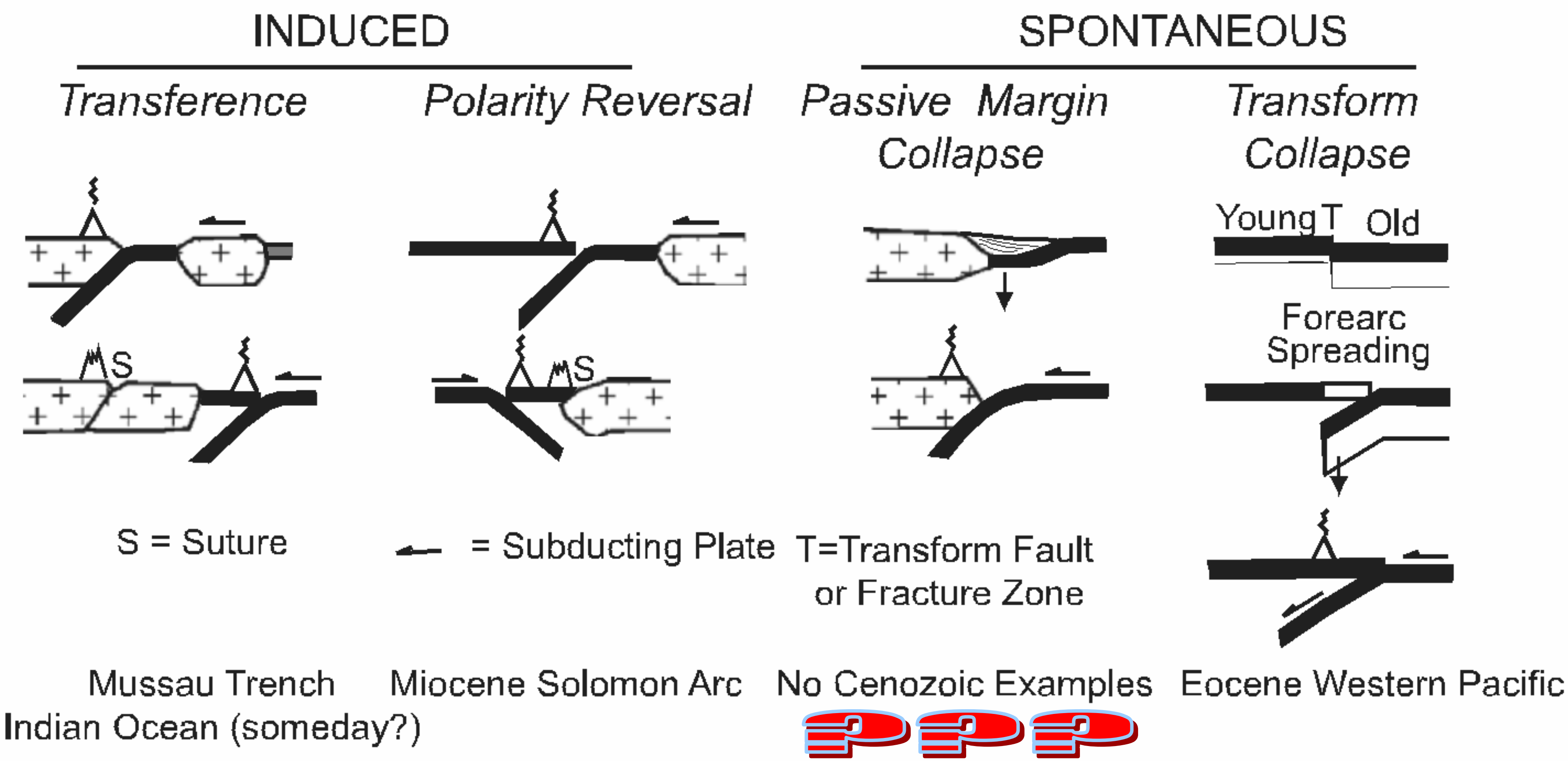
(1) Plate rupture within an oceanic plate or at a passive margin (e.g. McKenzie, 1977).
(2) Reversal of the polarity of an existing subduction zone (e.g. Mitchell, 1984).
(3) Change of transform faults into trenches (e.g. Uyeda and Ben-Avraham, 1972).
(4) Sediment or other topographic loading at continental/arc margins (e.g. Dewey, 1969).
(5) Forced convergence at oceanic fracture zones (e.g. Mueller and Phillips, 1991).
(6) Spontaneous initiation of retreating subduction due to a lateral thermal buoyancy contrast at oceanic fracture zones separating oceanic plates of contrasting ages (e.g. Gerya et al., 2008).
(7) Tensile decoupling of the continental and oceanic lithosphere due to rifting (Kemp and Stevenson, 1996).
(8) Rayleigh-Taylor instability due to a lateral thermal/compositional buoyancy contrast within the lithosphere (e.g., Matsumoto and Tomoda, 1983).
(9) Addition of water into the lithosphere (e.g., Regenauer-Lieb et al., 2001).
(10) Spontaneous thrusting of the buoyant continental/arc crust over the oceanic plate (e.g., Mart et al., 2005).
(11) Small-scale convection in the sub-lithospheric mantle (Solomatov, 2004).
(12) Interaction of thermal-chemical plumes with the lithosphere (e.g., Ueda et al., 2008).
(13) Large asteroid impacts (Hansen, 2007).
(14) Shear□heating induced localization along spontaneously forming lithospheric-scale fracture zones (Crameri and Kaus, 2010).

Subduction initiation is easy...



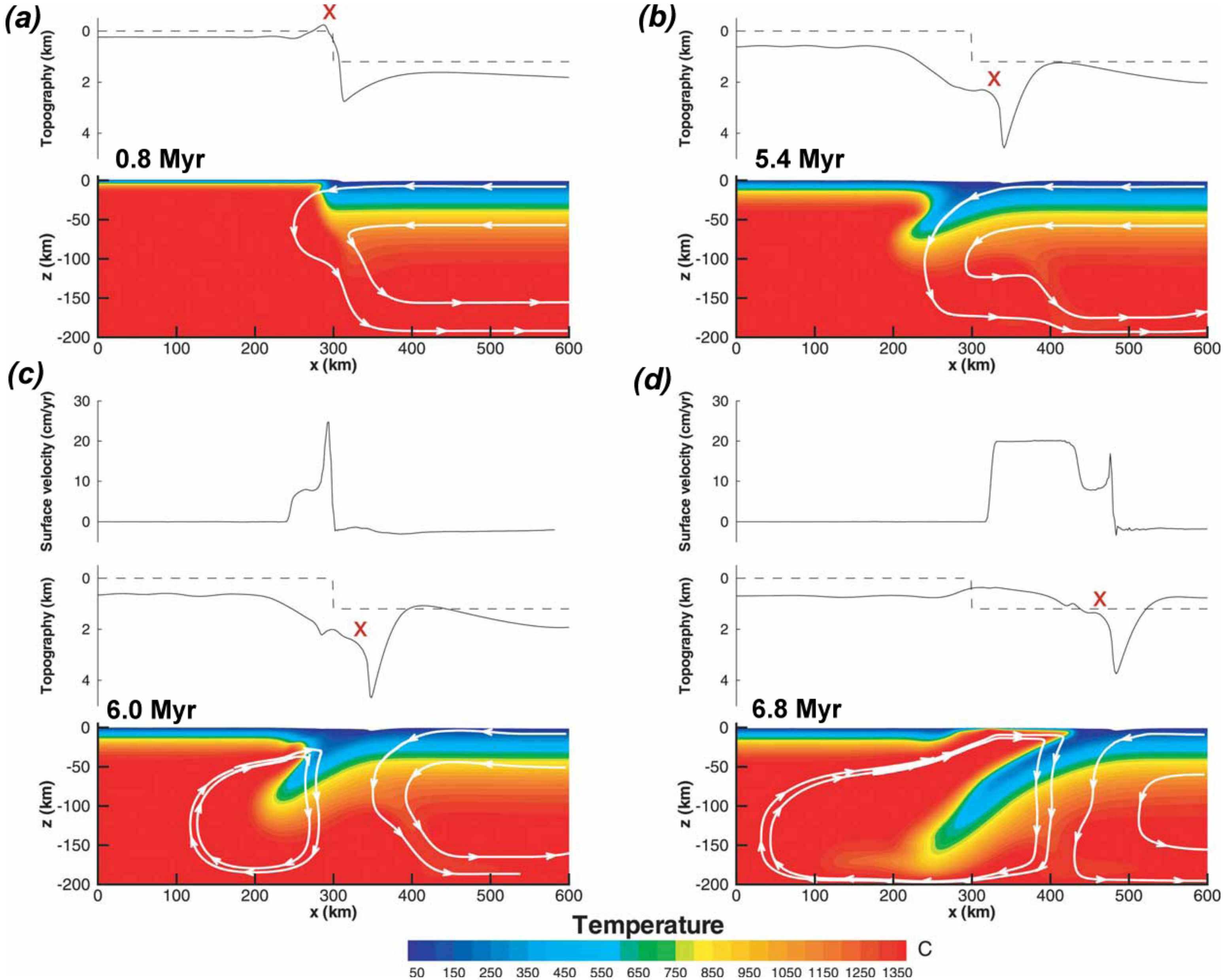
Gurnis et al. (2004):
"Nearly half of all active subduction zones initiated during the Cenozoic."

Subduction initiation types



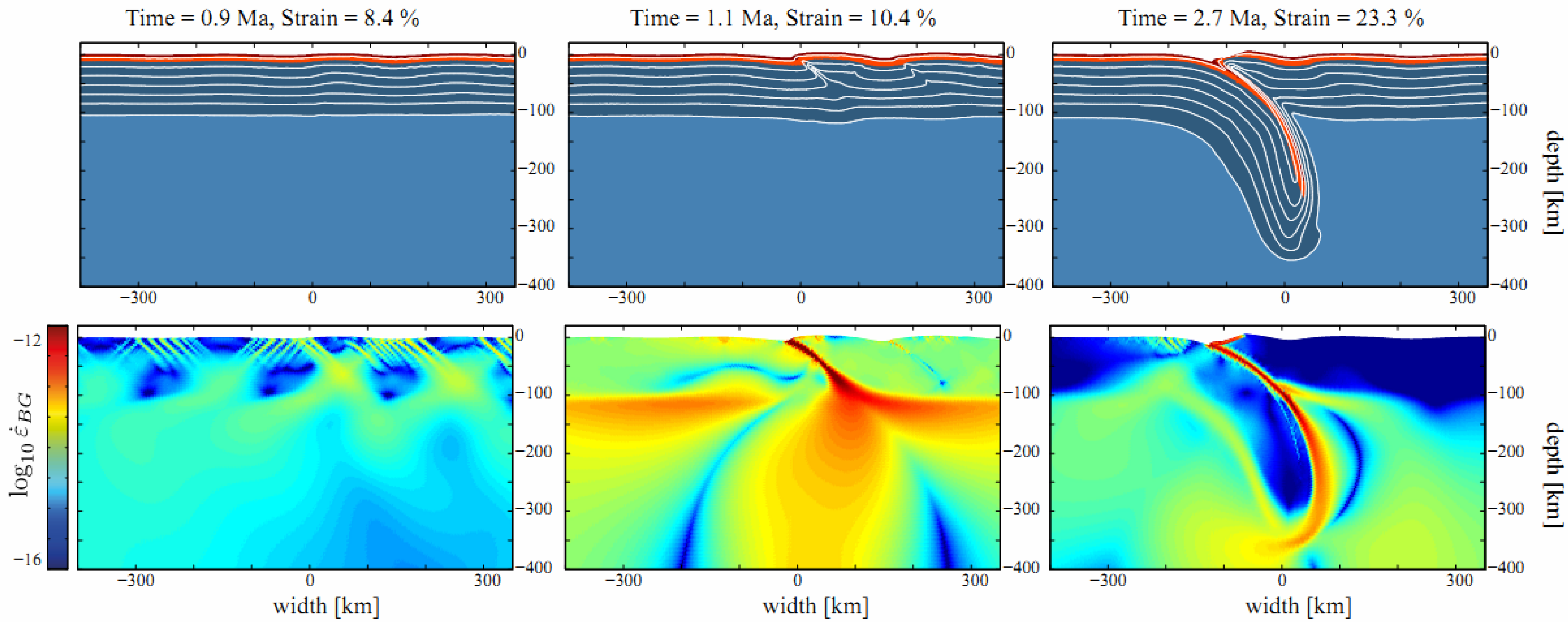
Stern (2004)

Induced initiation



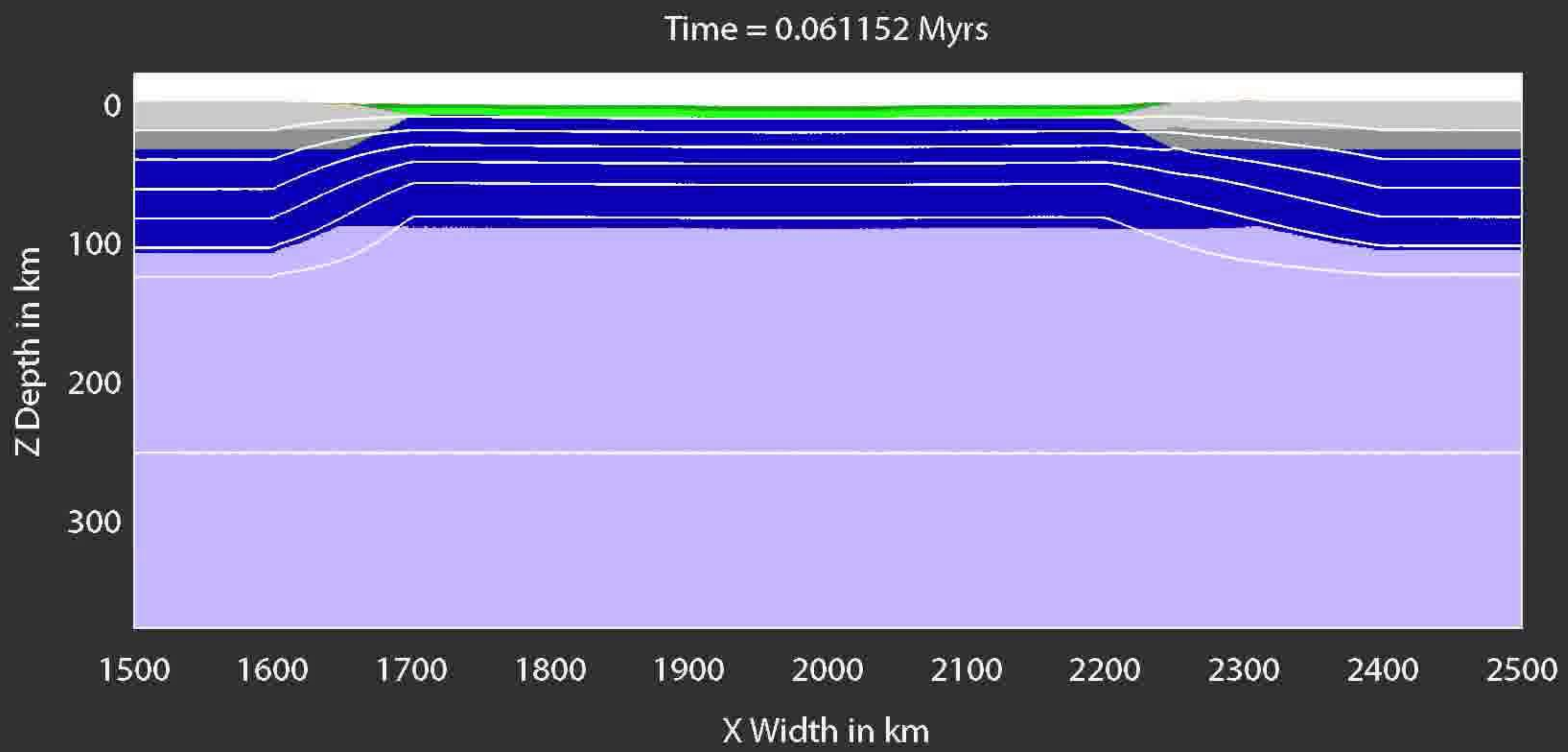
Hall et al. (2003)

Induced initiation



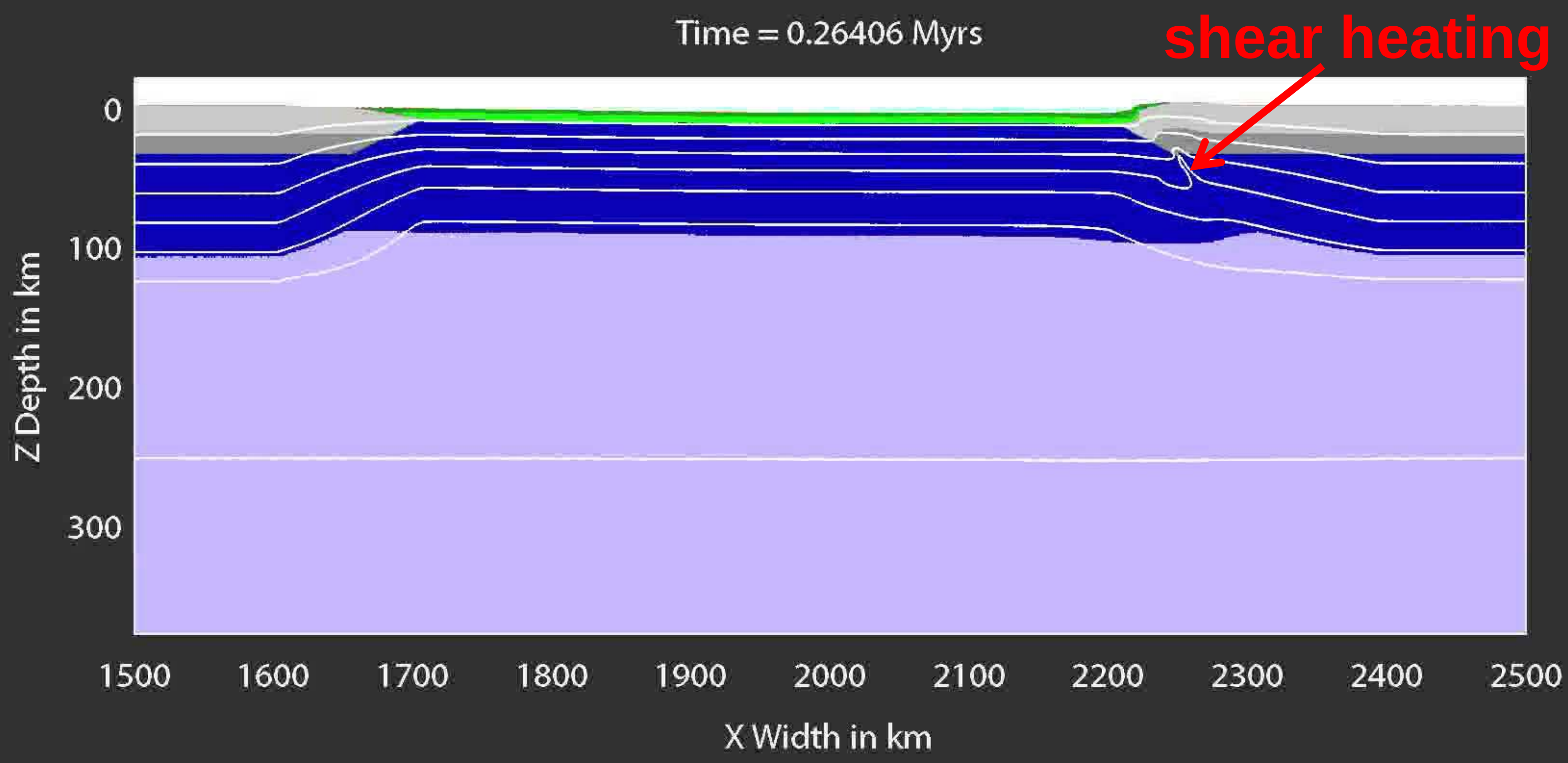
Marcel Tielmann

Induced initiation

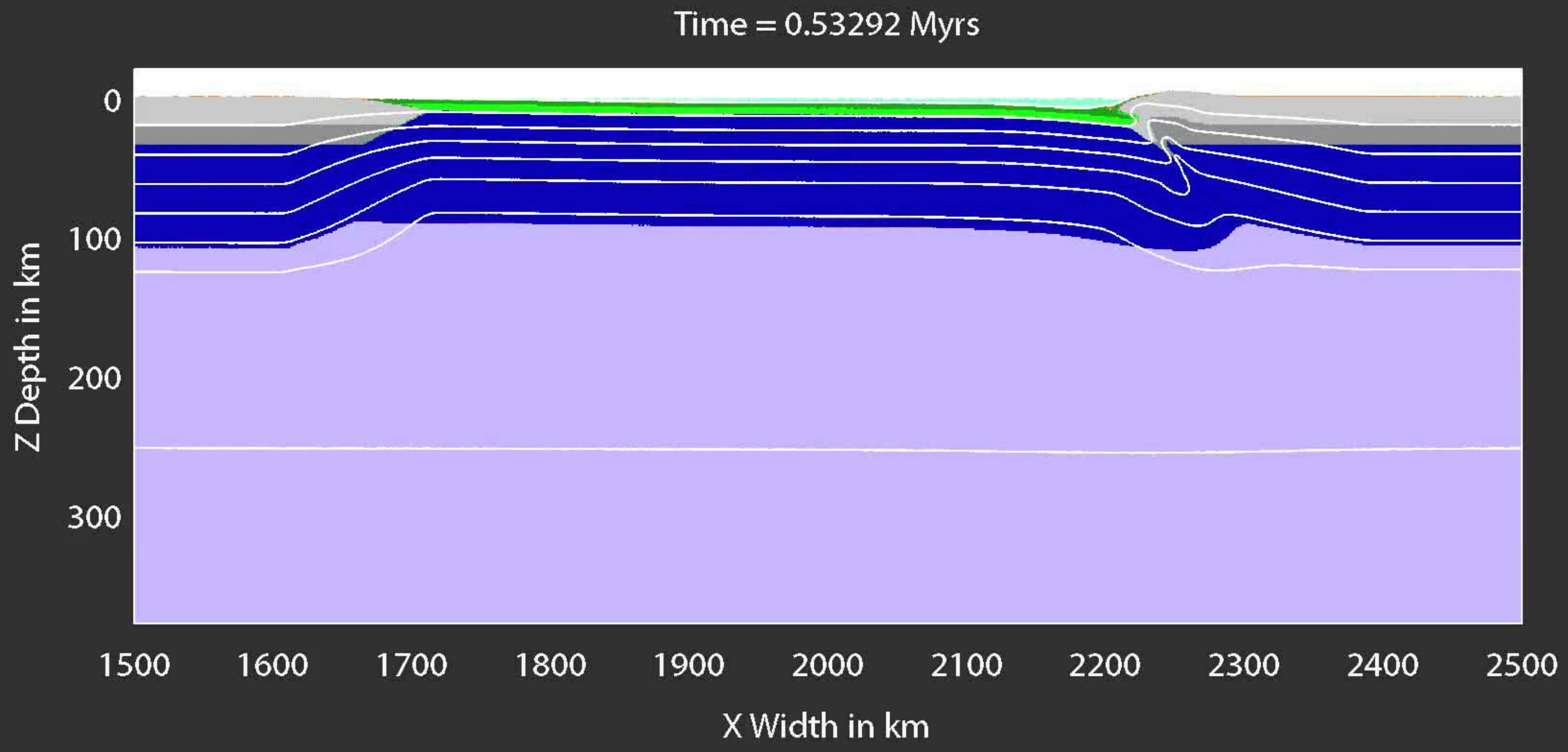


Thibault Duretz

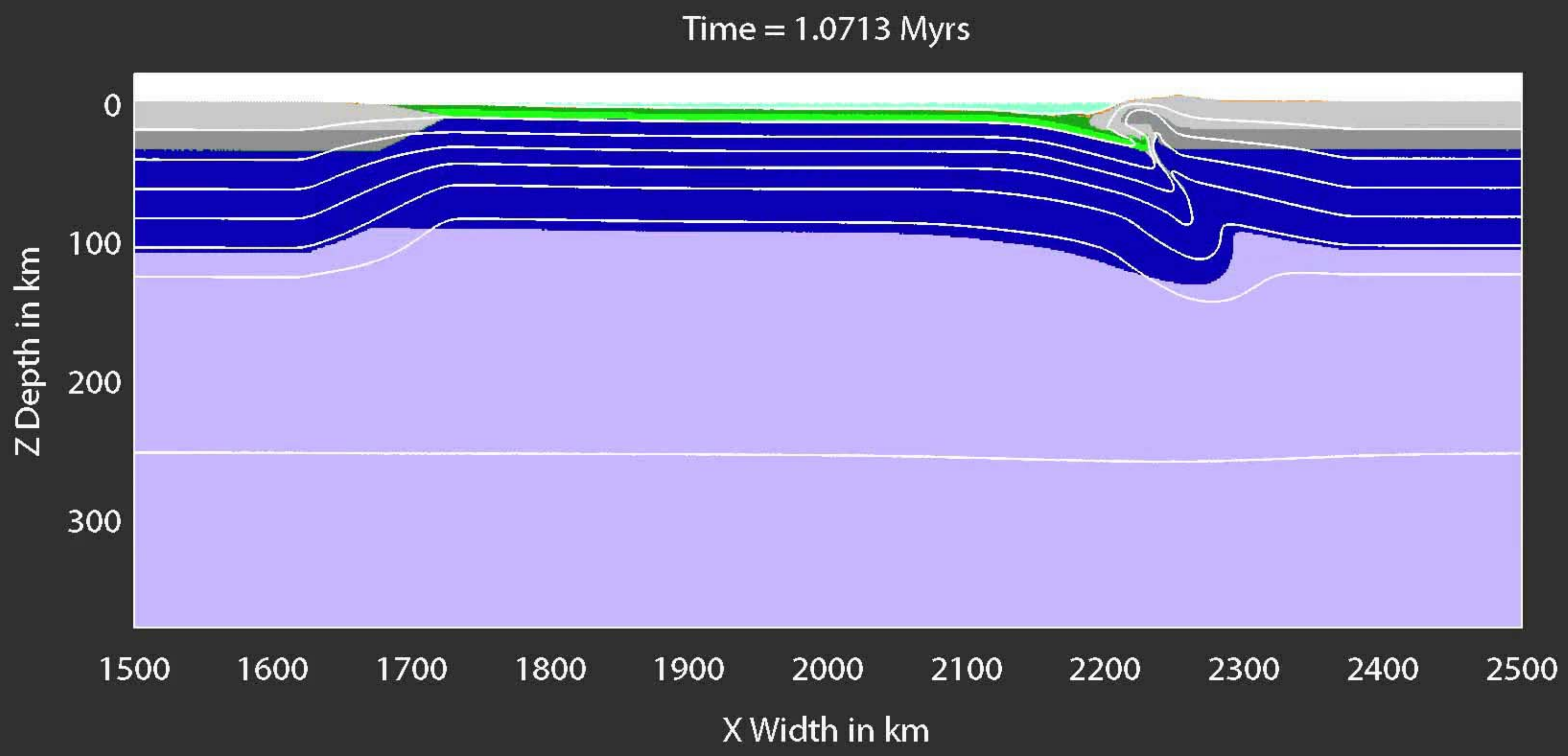
Induced initiation



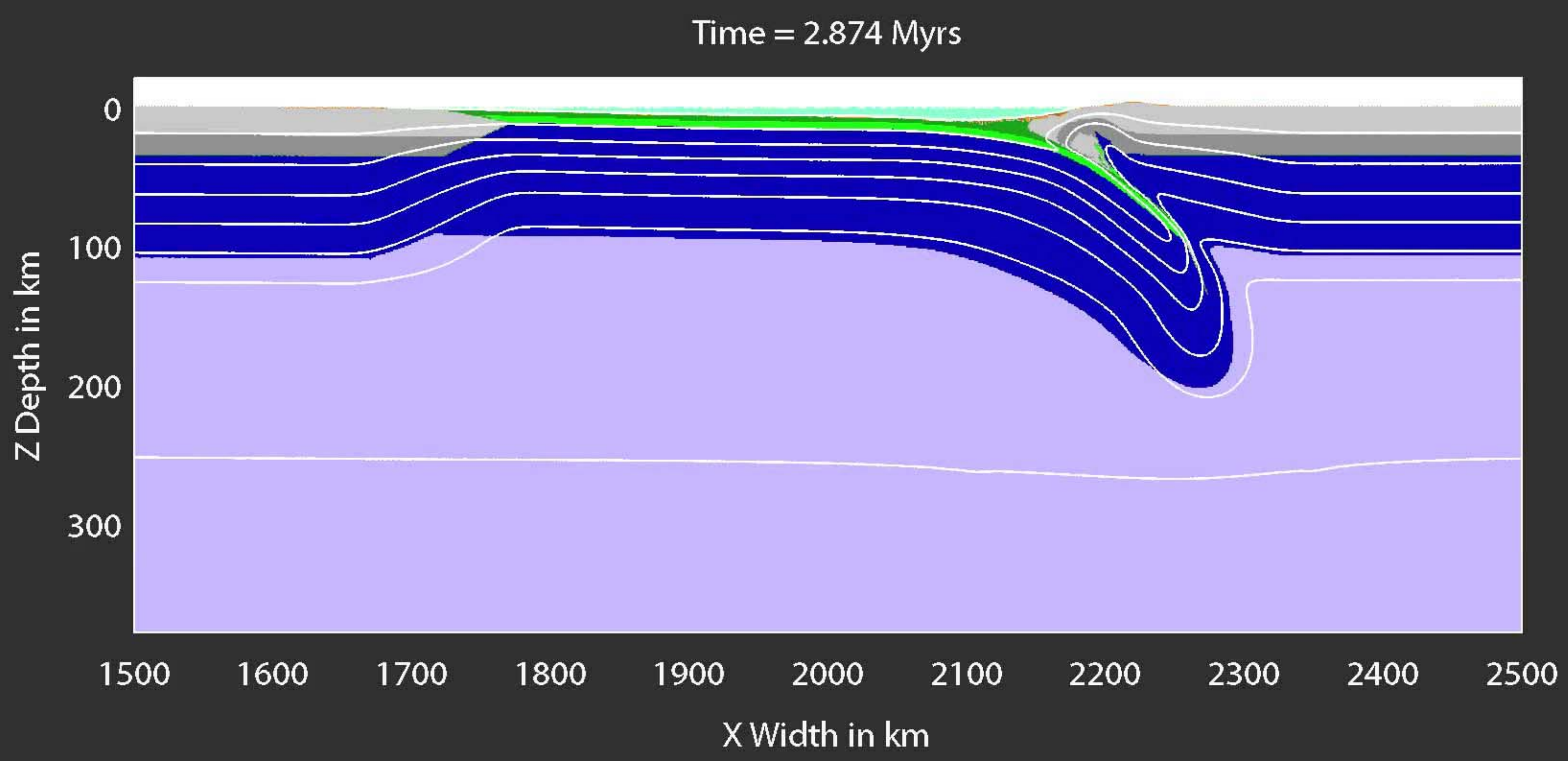
Induced initiation



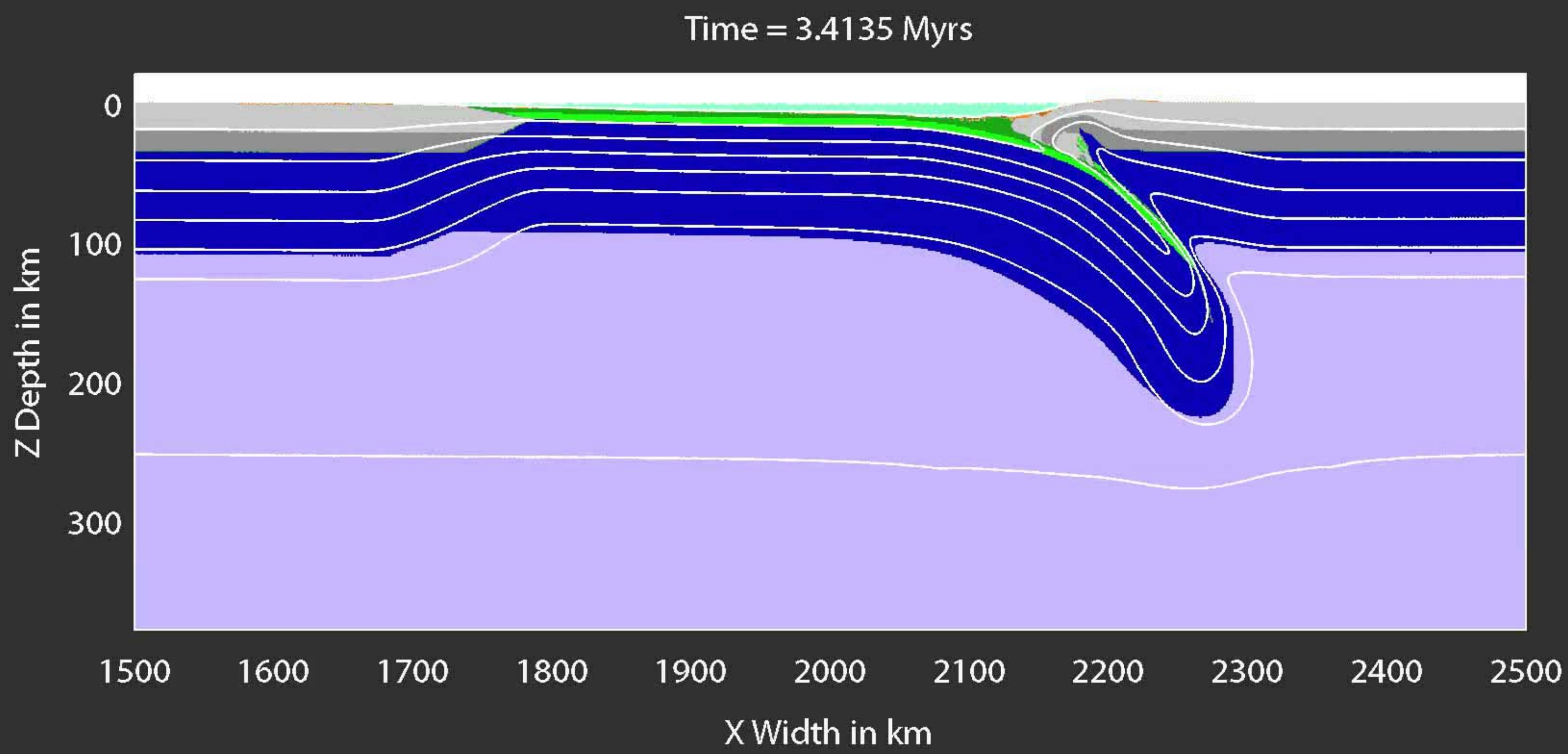
Induced initiation



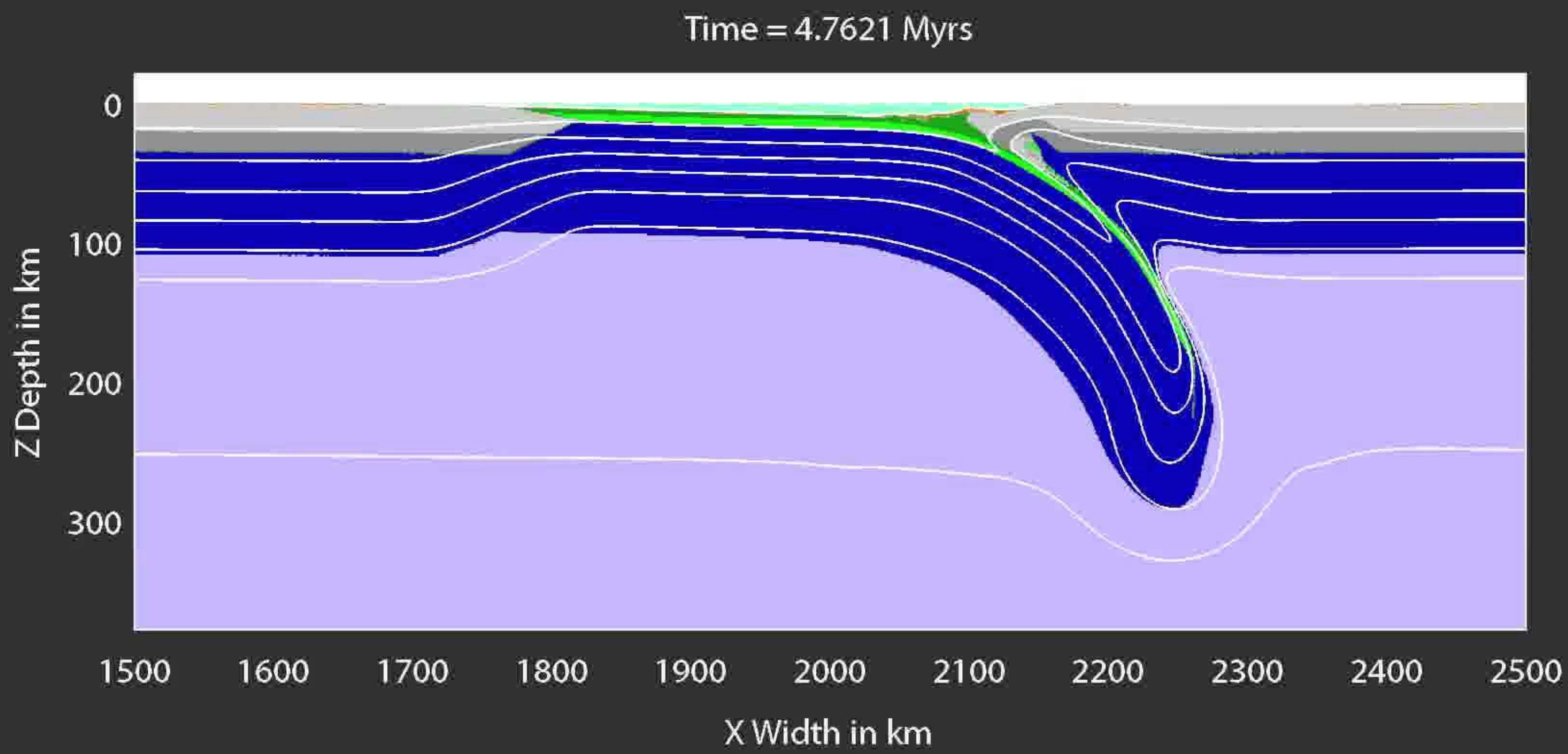
Induced initiation



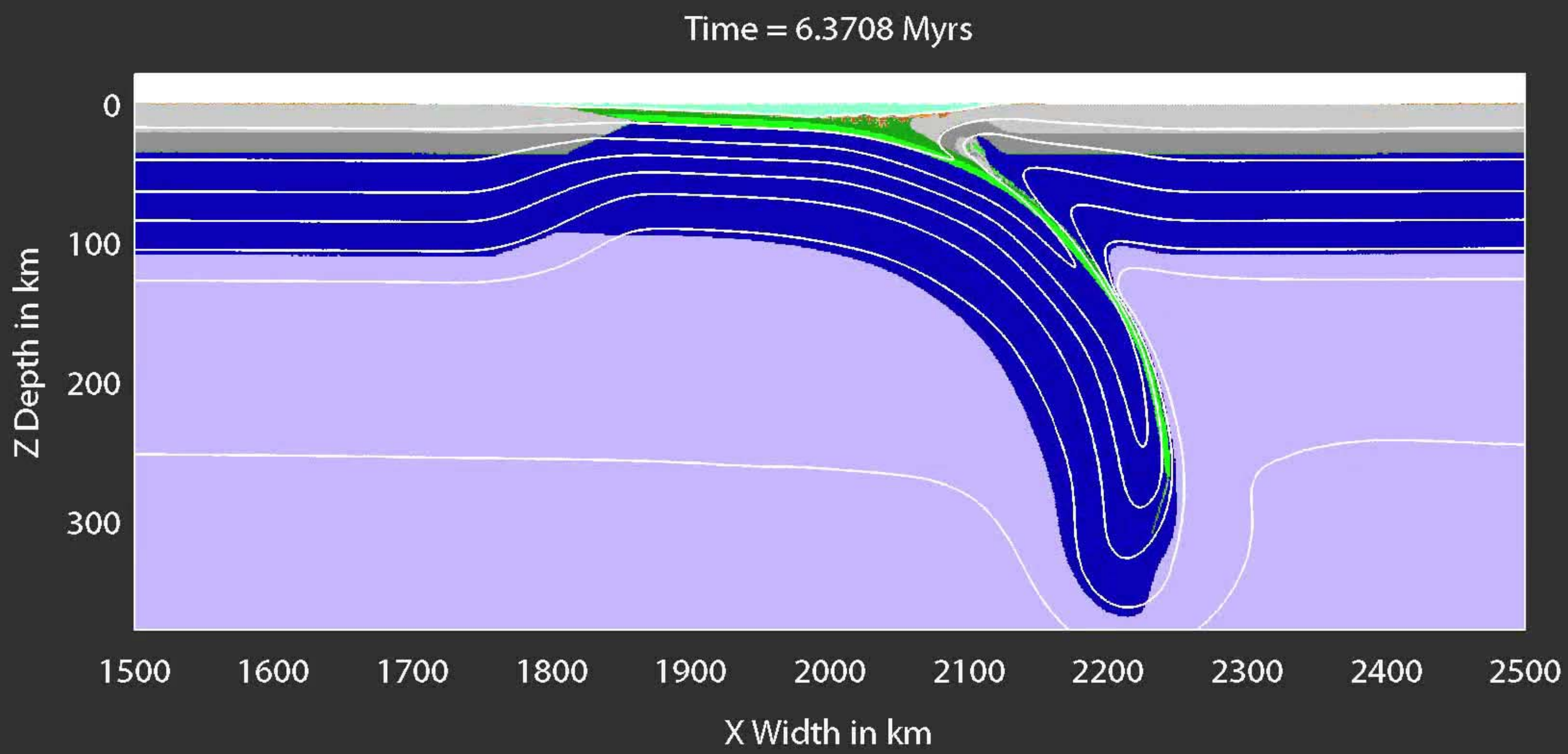
Induced initiation



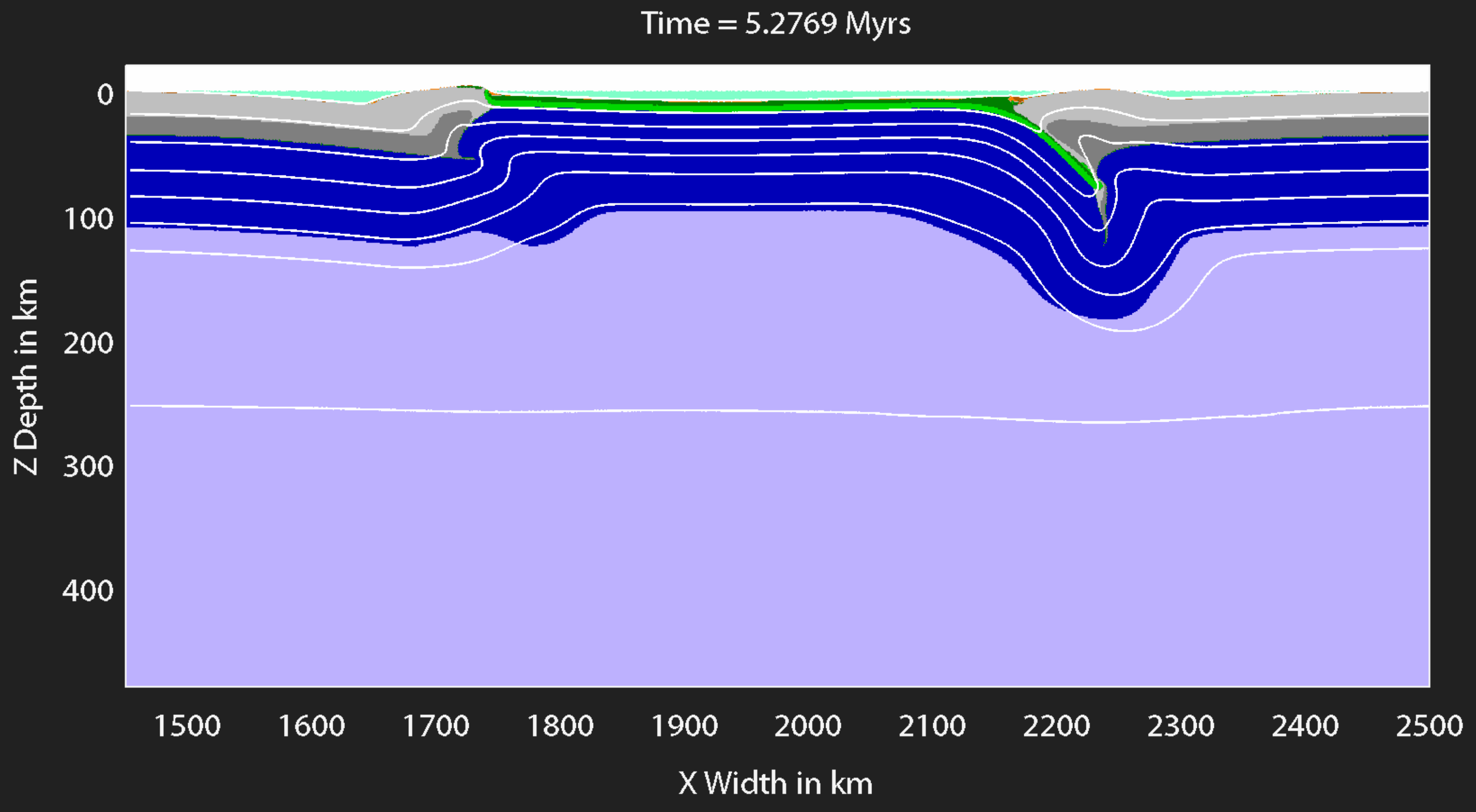
Induced initiation



Induced initiation

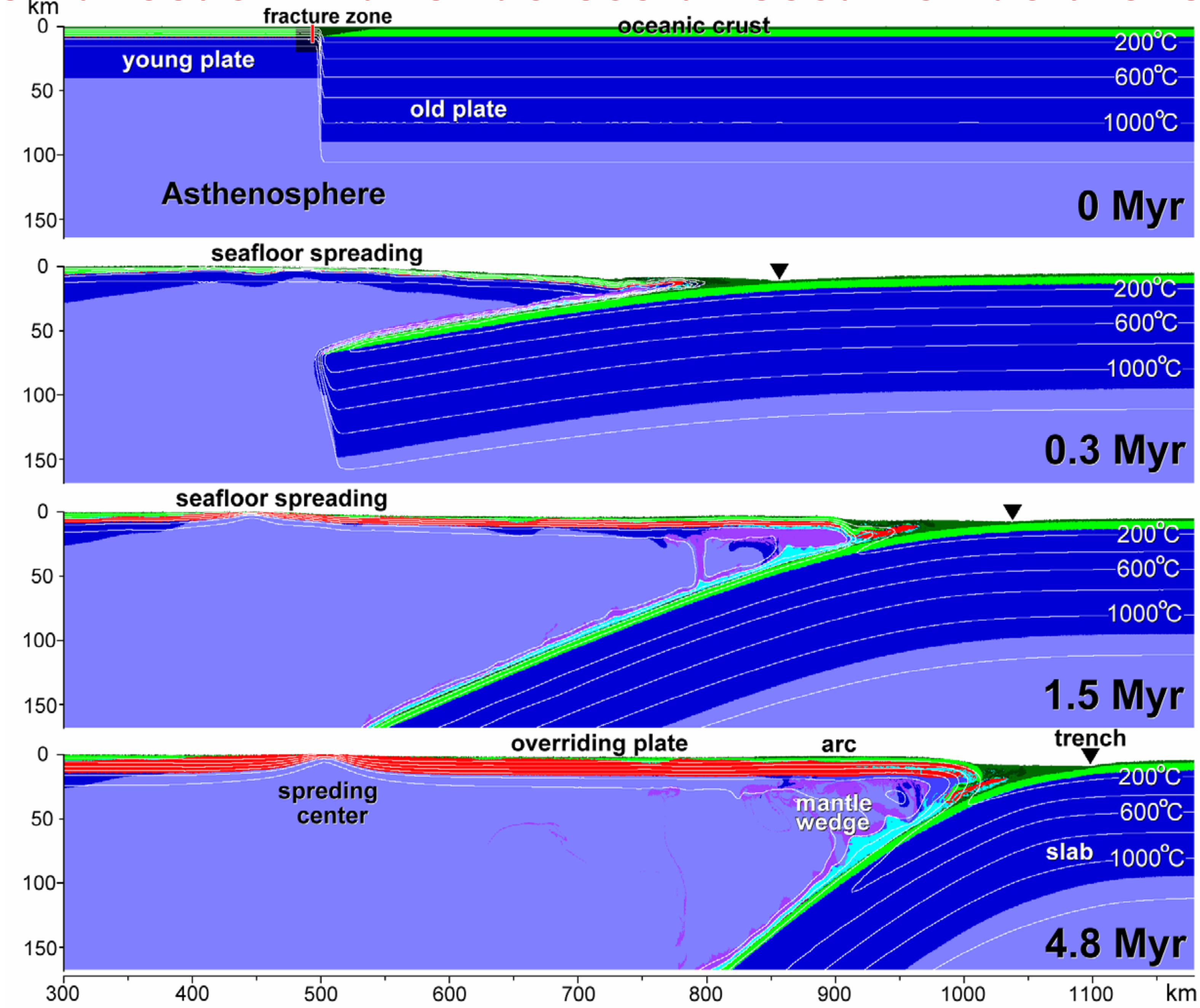


No Peierls deformation and no shear heating – no subduction



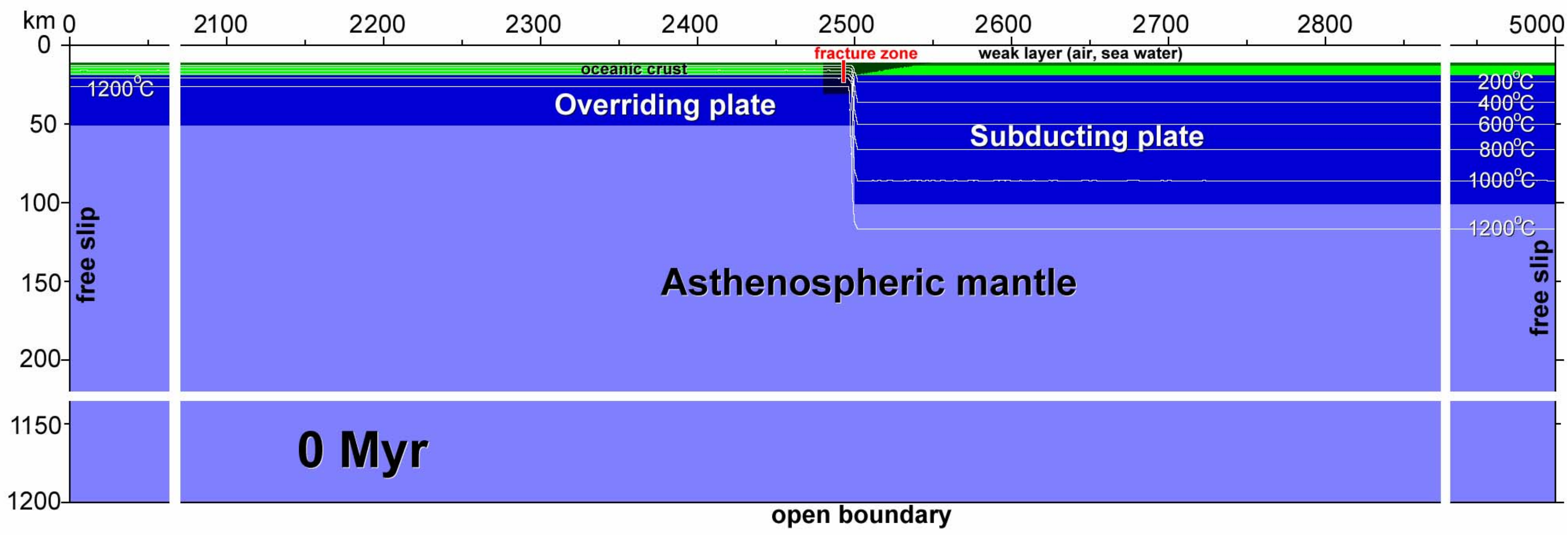
Duretz et al. (in progress)

Spontaneous initiation across an oceanic fracture zone

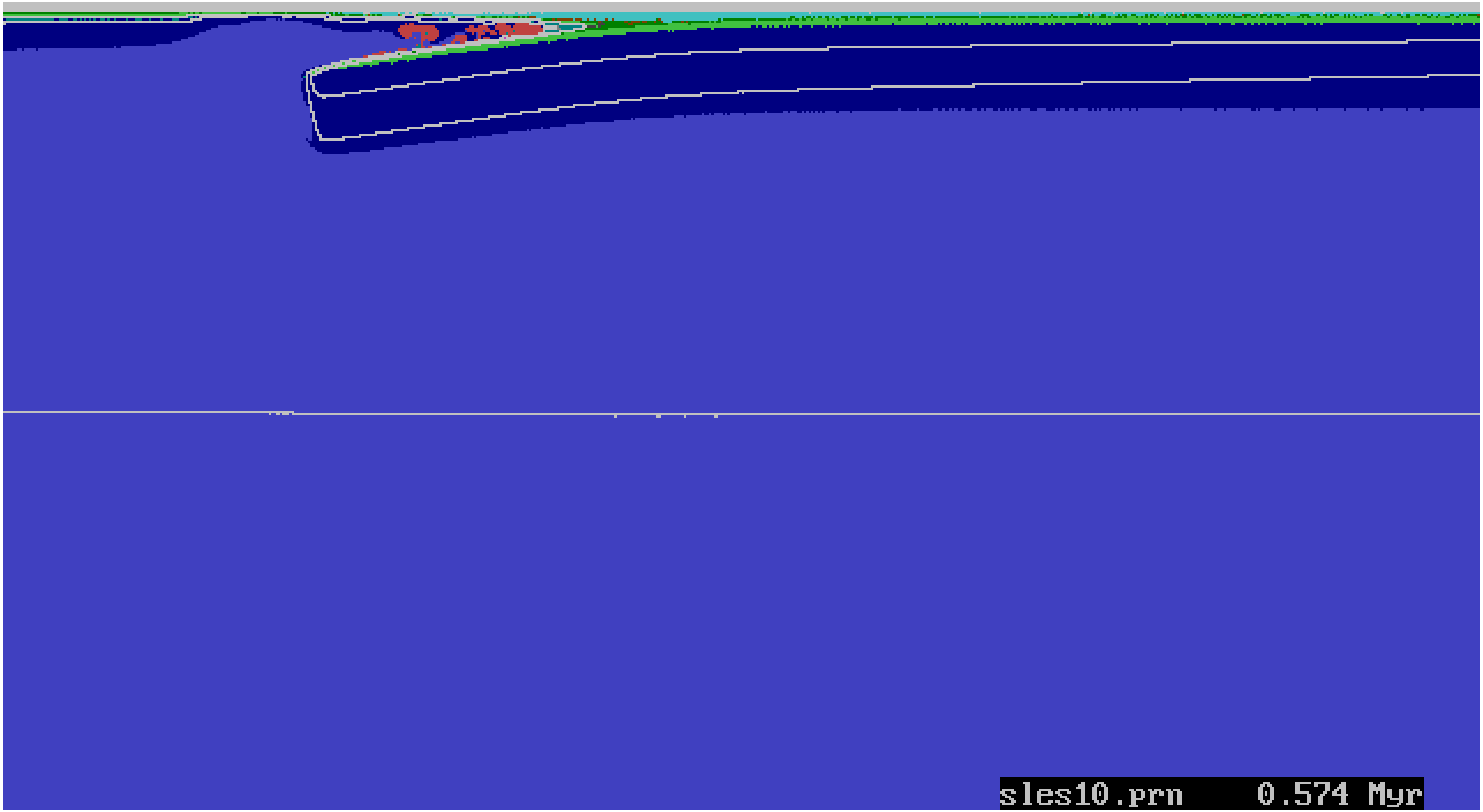


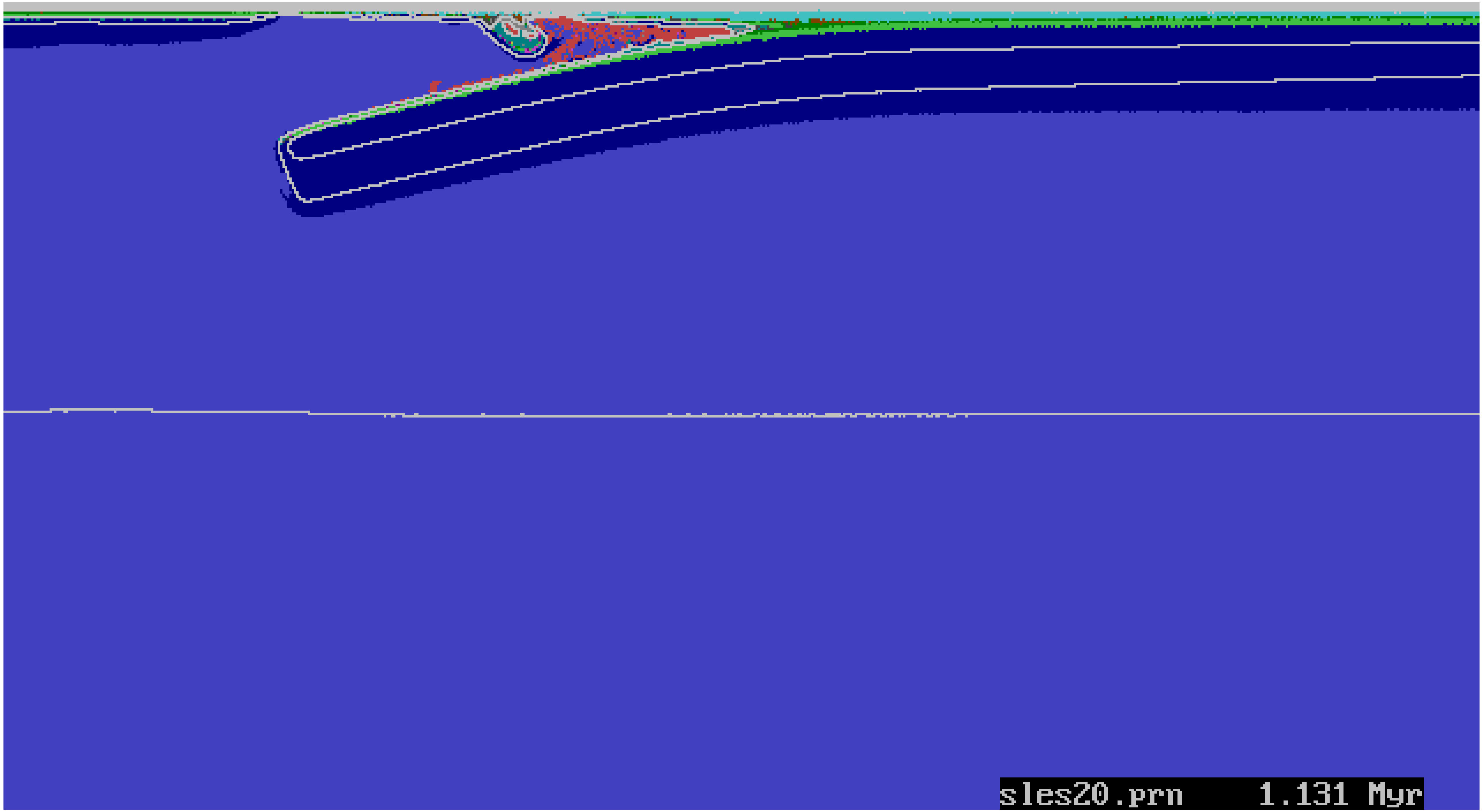
Gerya et al. (2008)

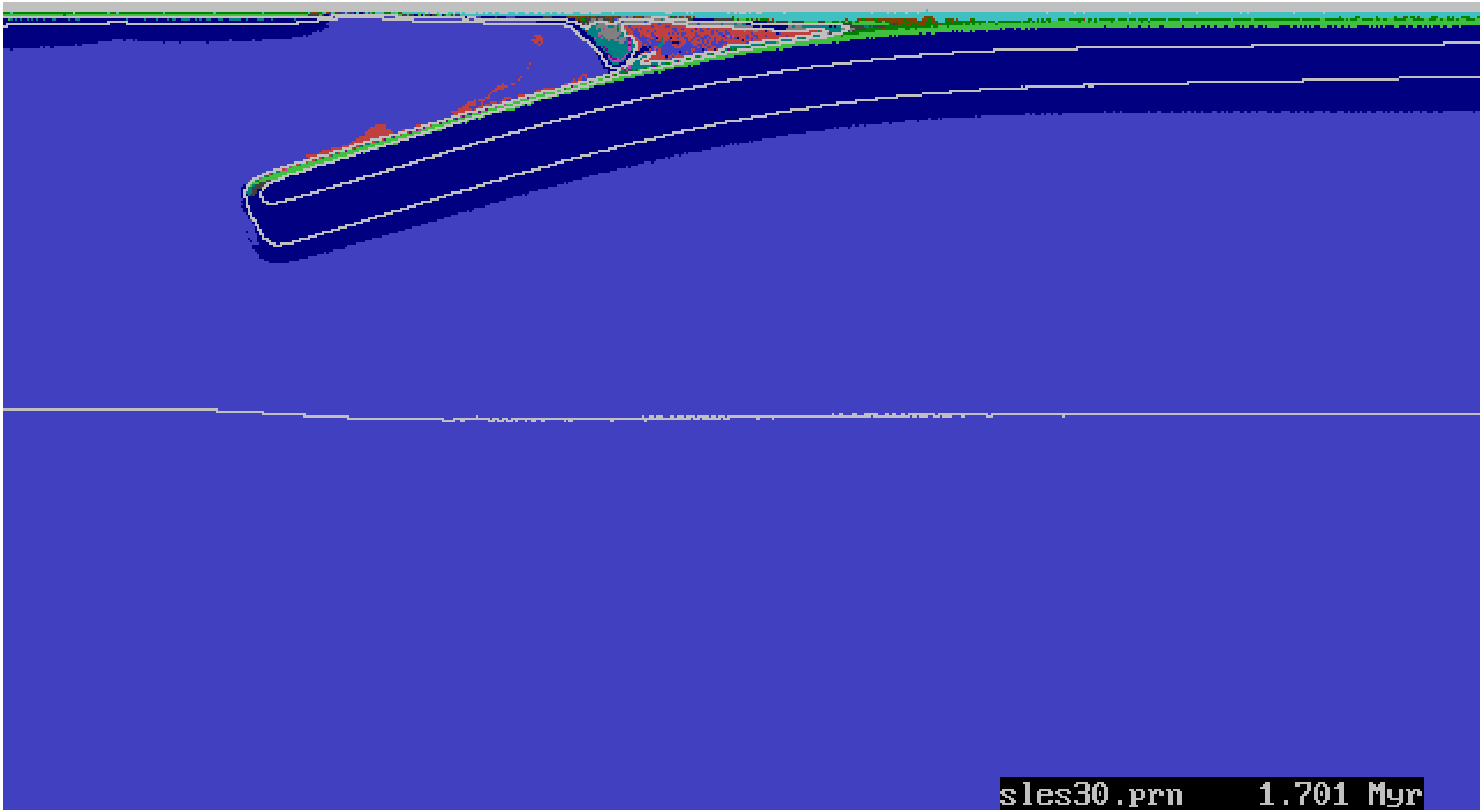
Numerical setup

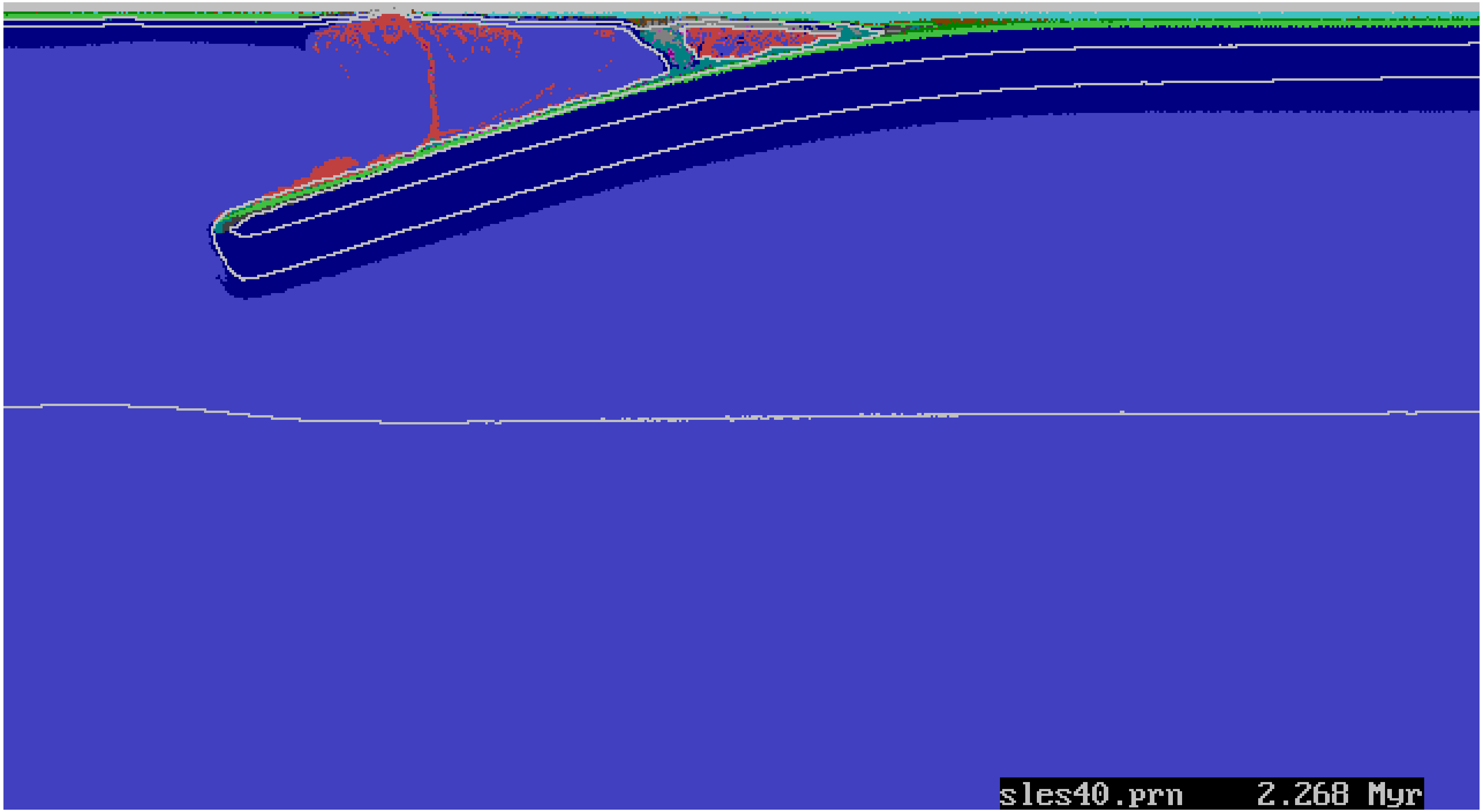


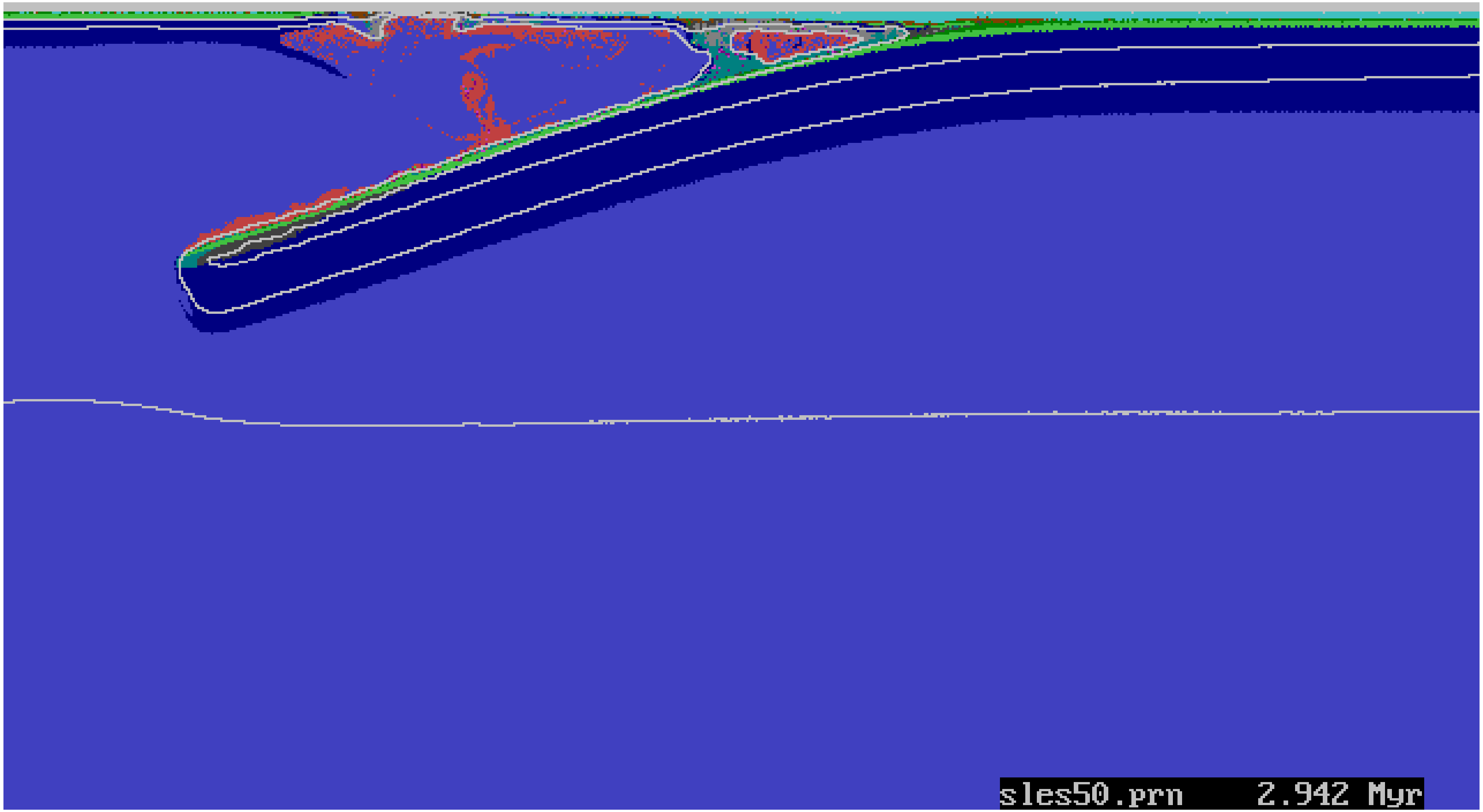

sles0.prn 0.000 Myr

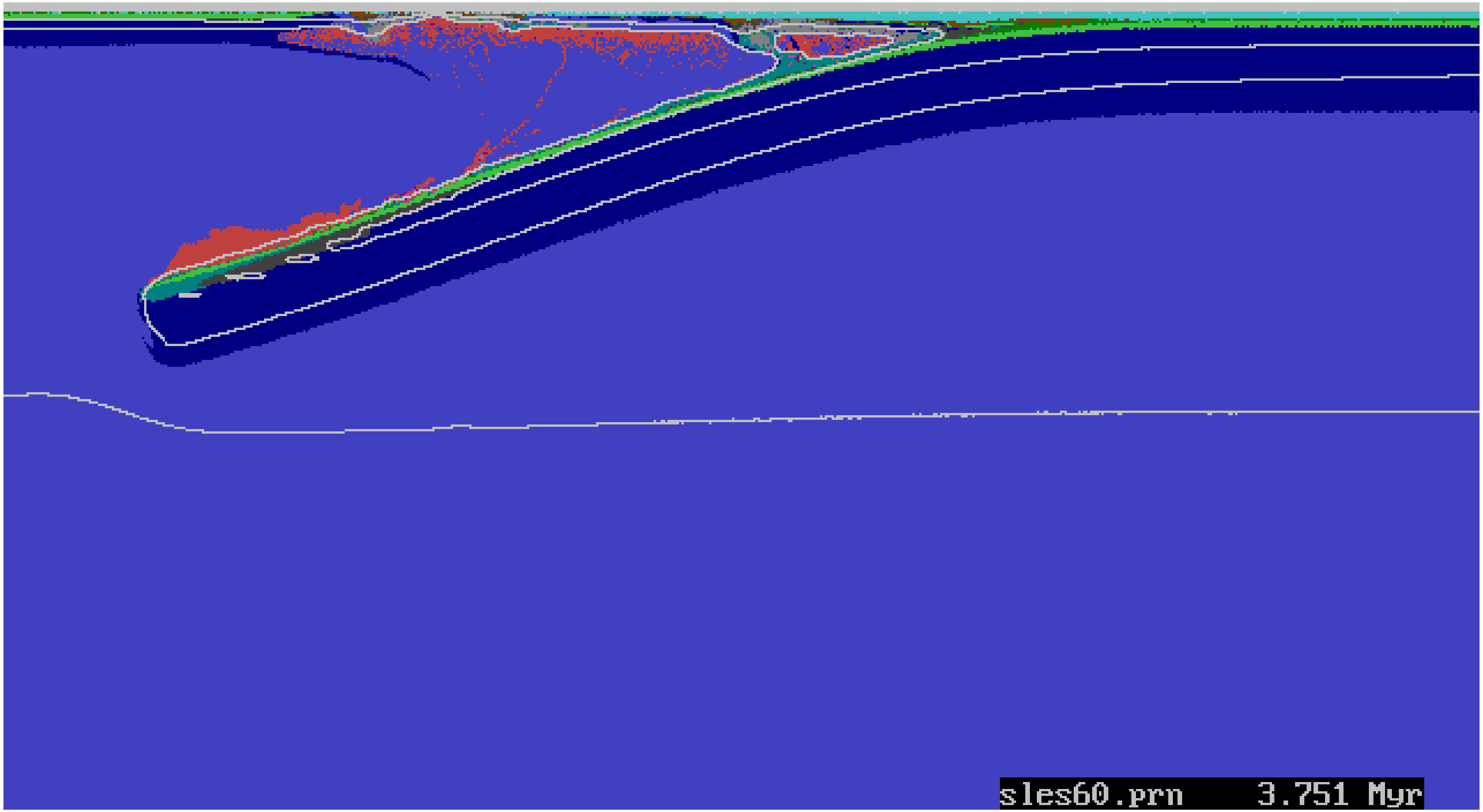

sles10.prn 0.574 Myr

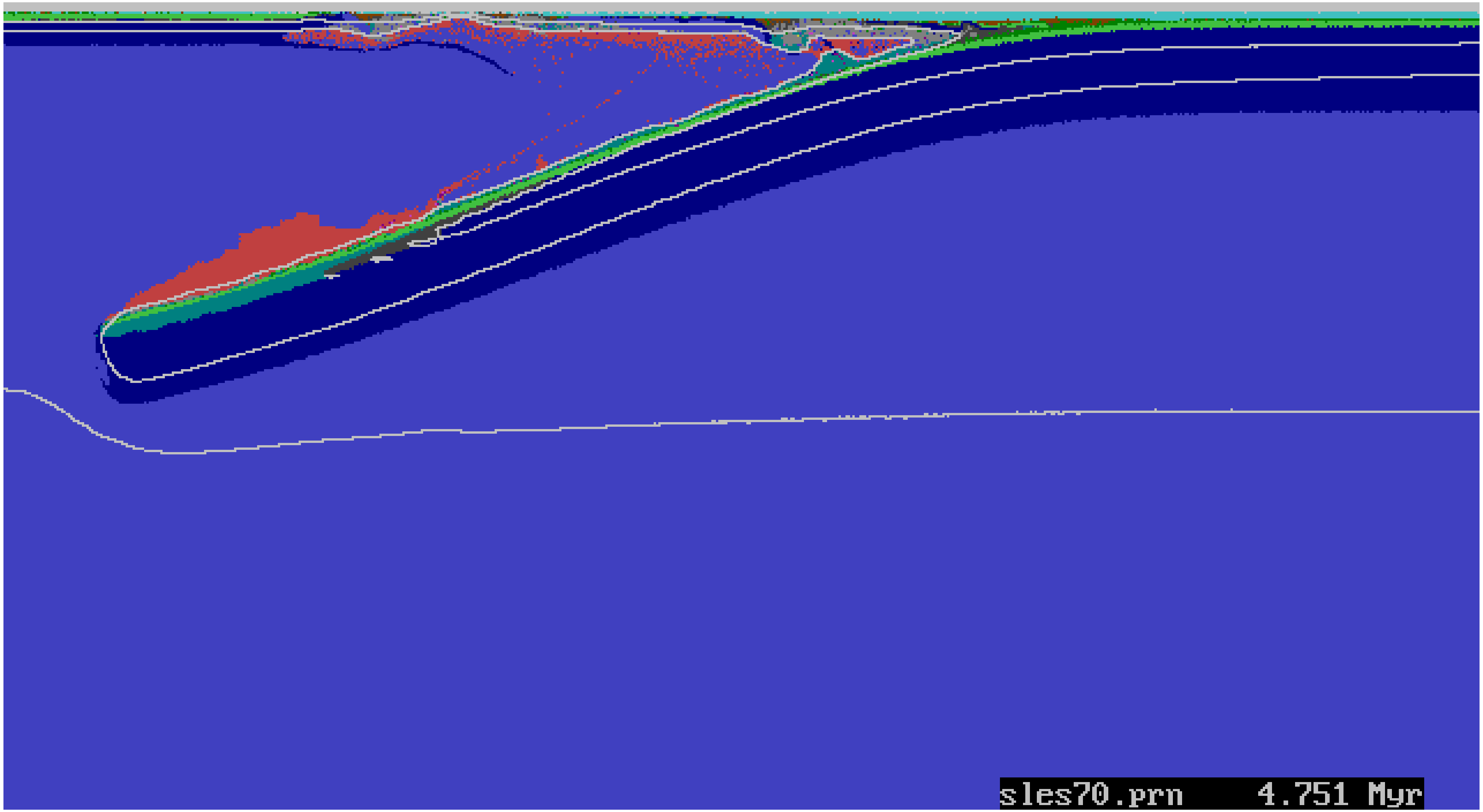

sles20.prn 1.131 Myr


sles30.prn 1.701 Myr

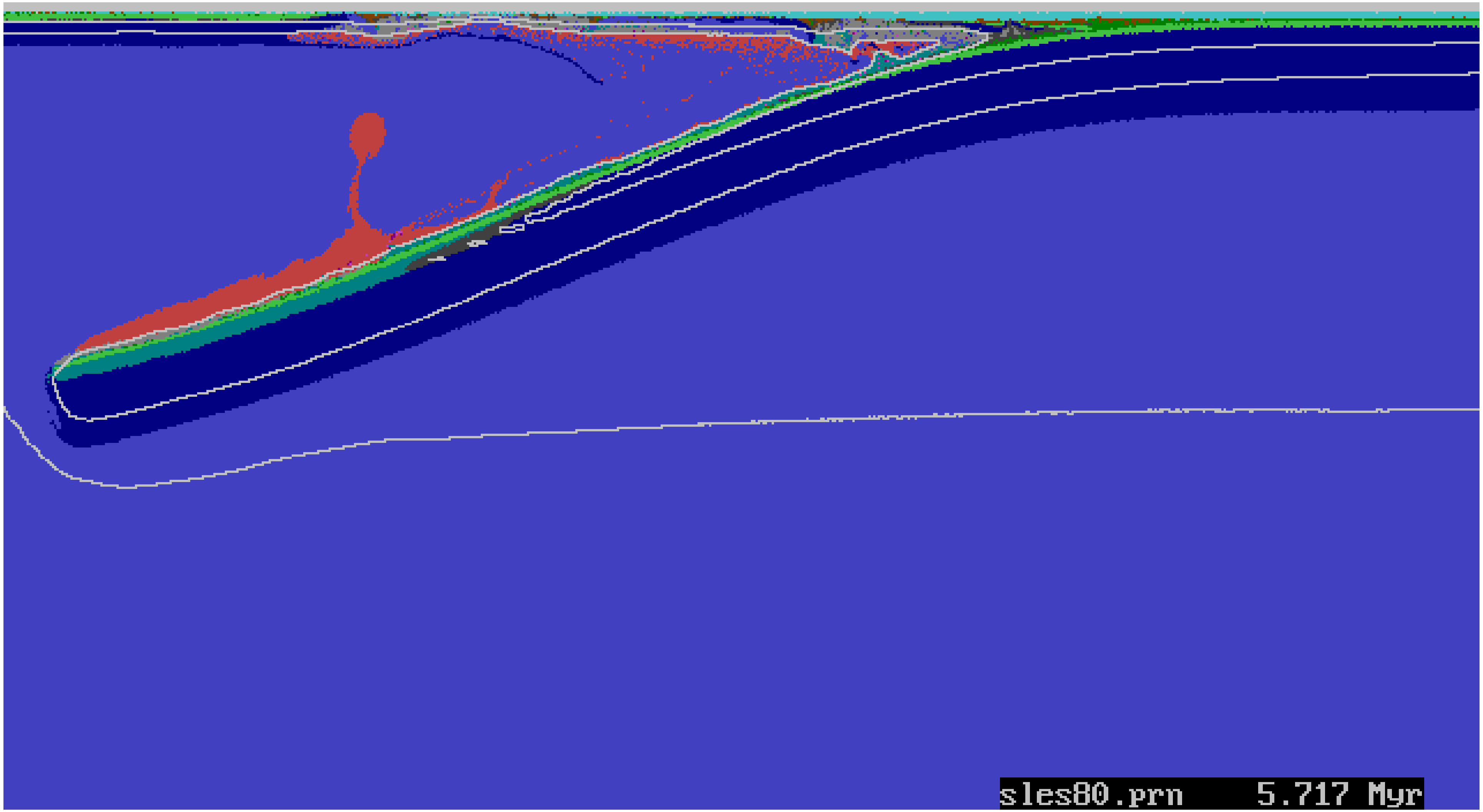

sles40.prn 2.268 Myr

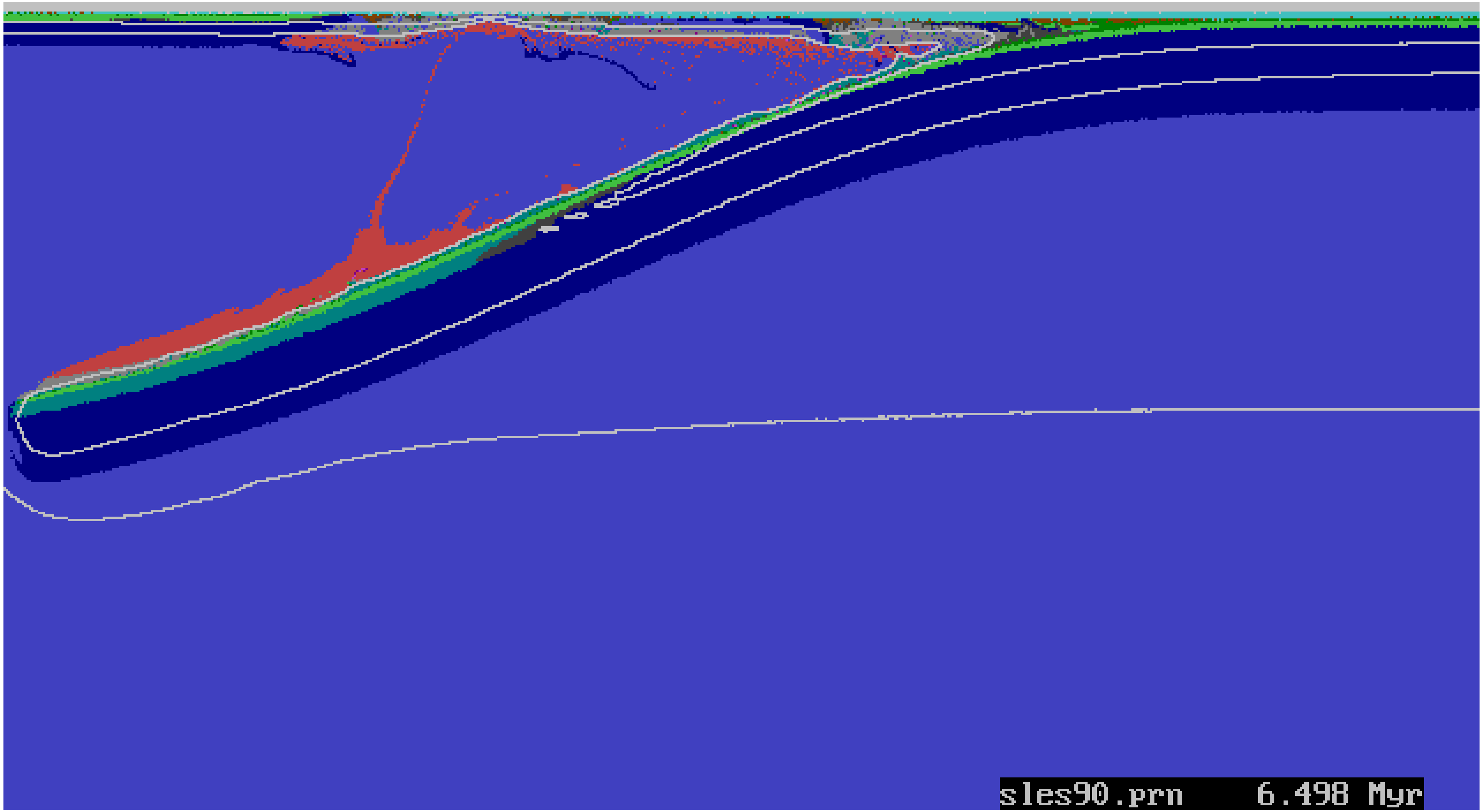

sles50.prn 2.942 Myr

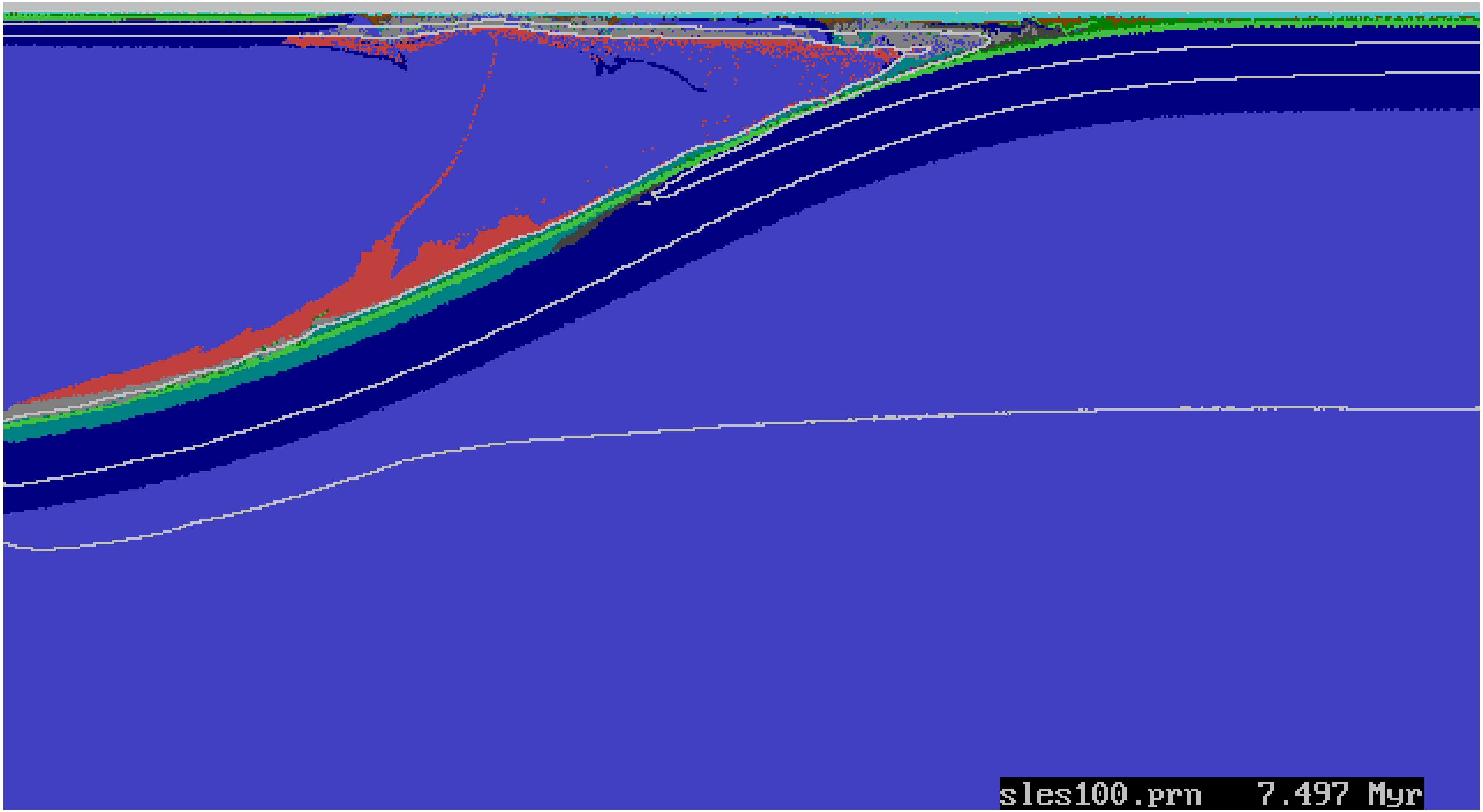

sles60.prn 3.751 Myr

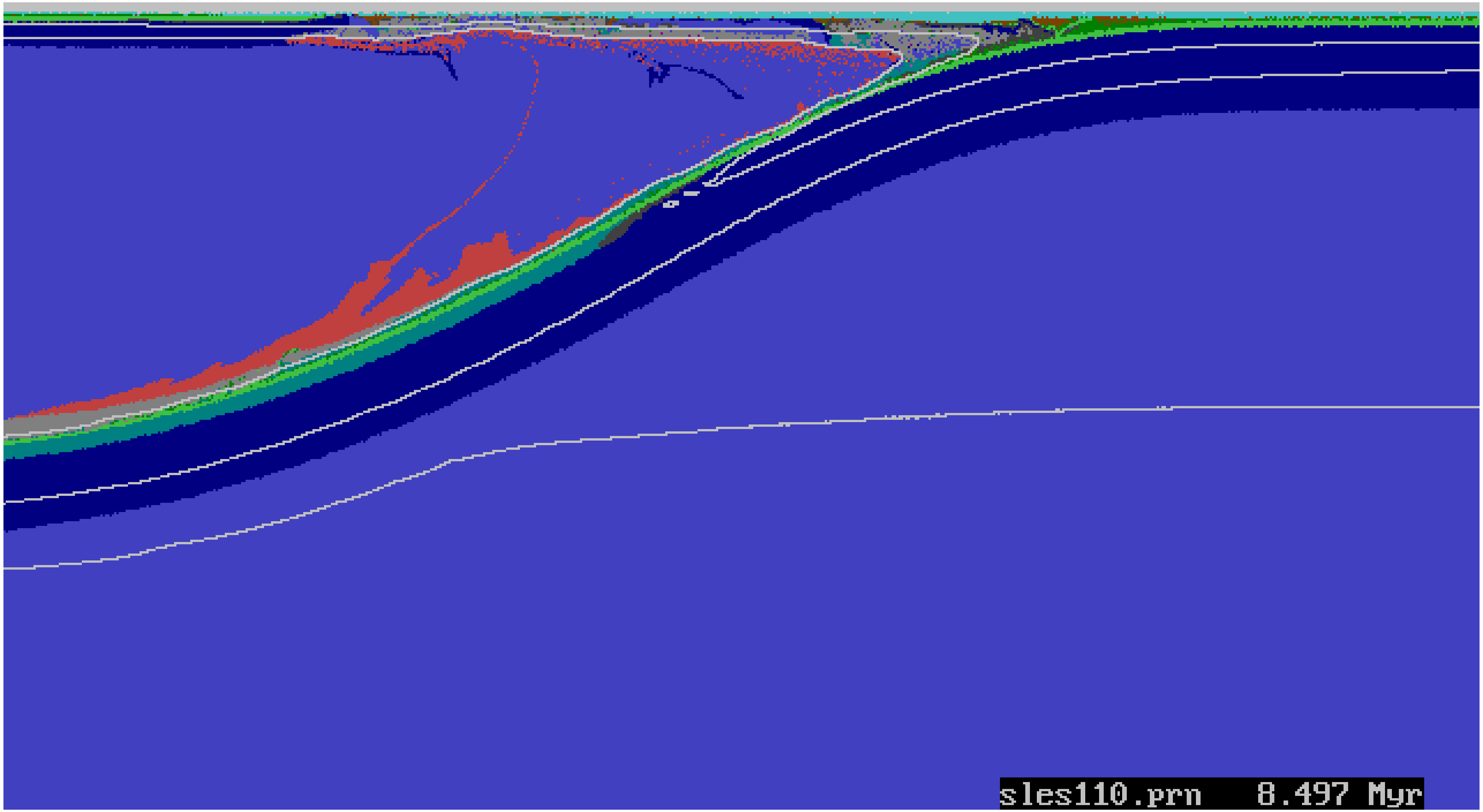


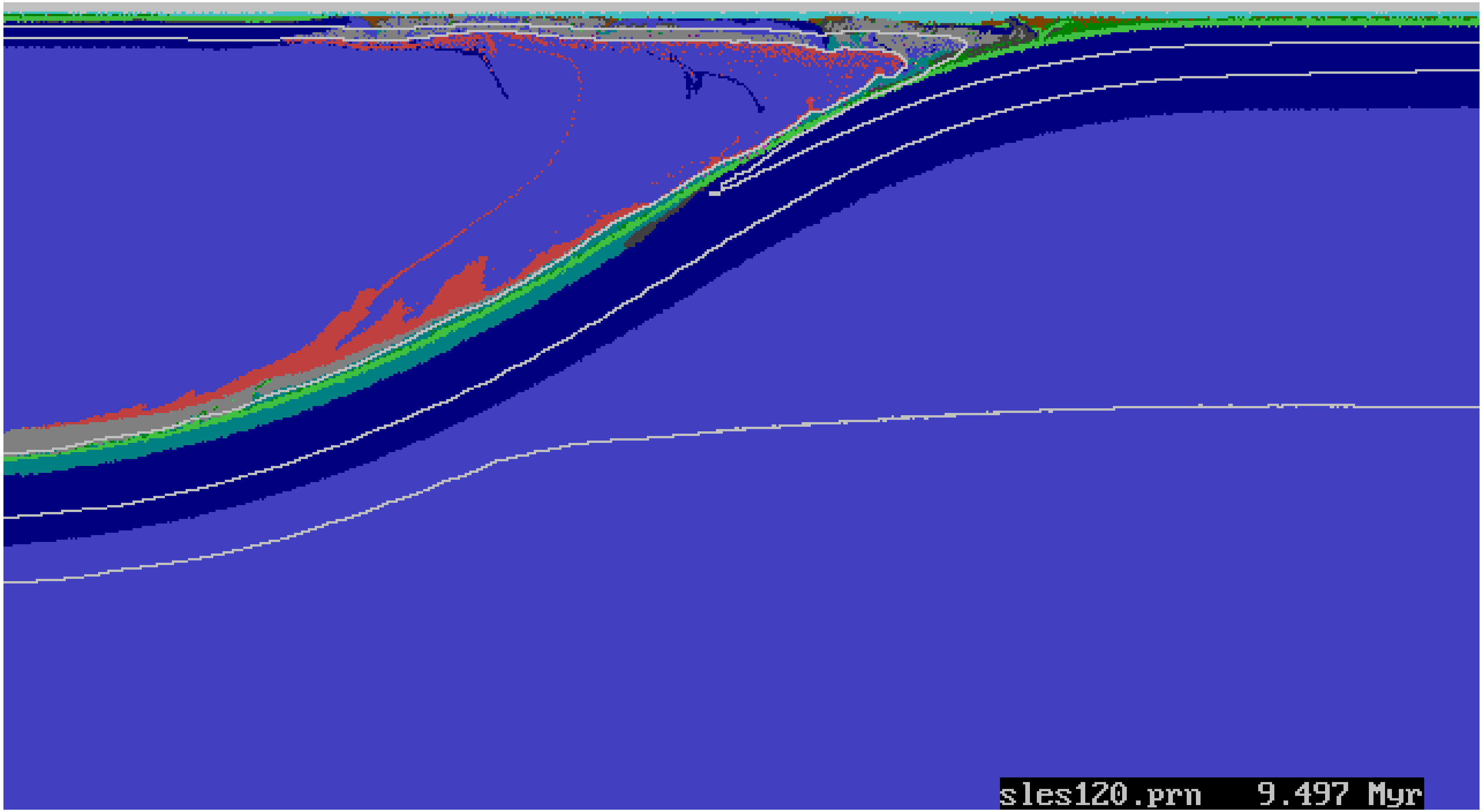
sles70.prn   4.751 Myr

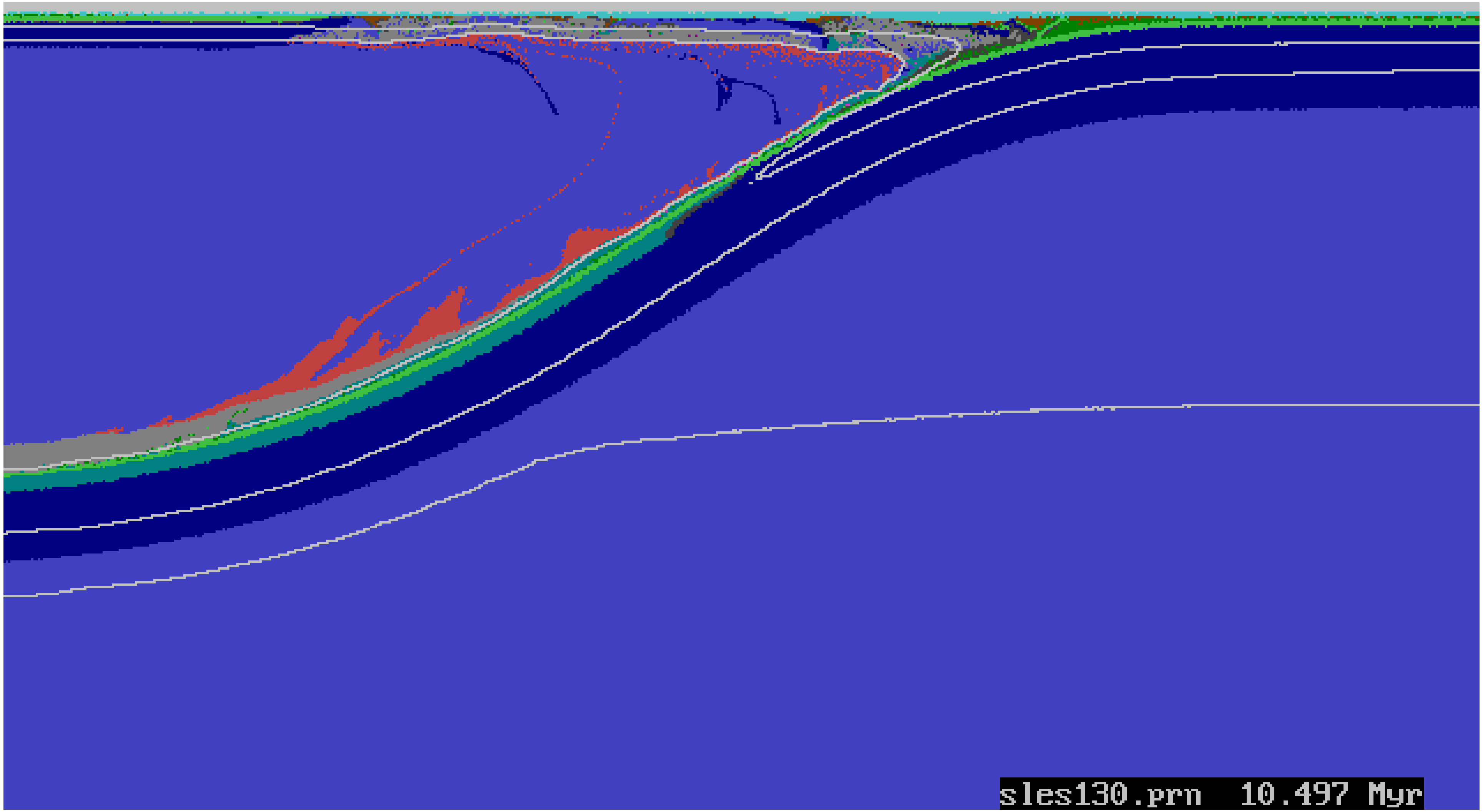

sles80.prn 5.717 Myr

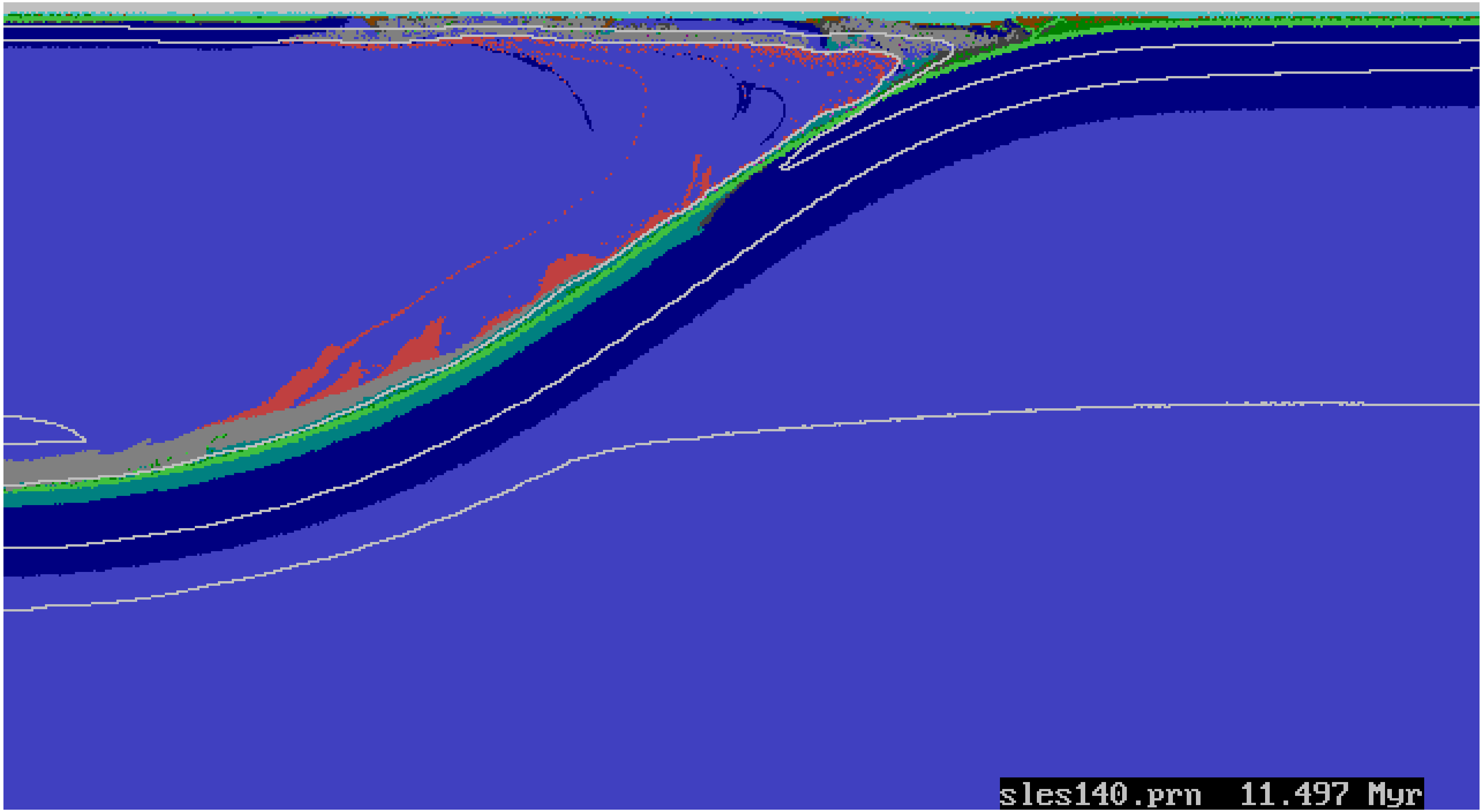

sles90.prn 6.498 Myr

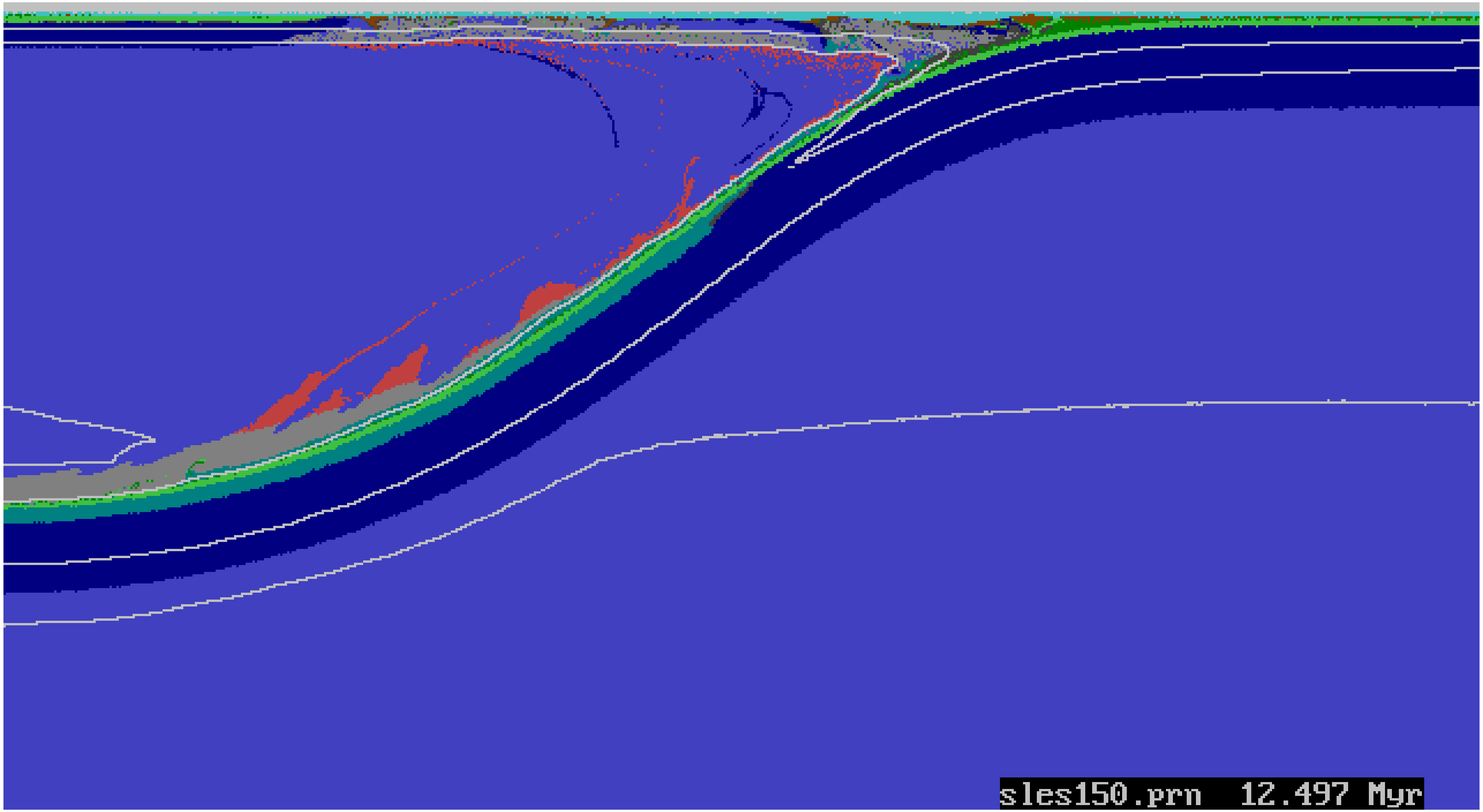

sles100.prn 7.497 Myr

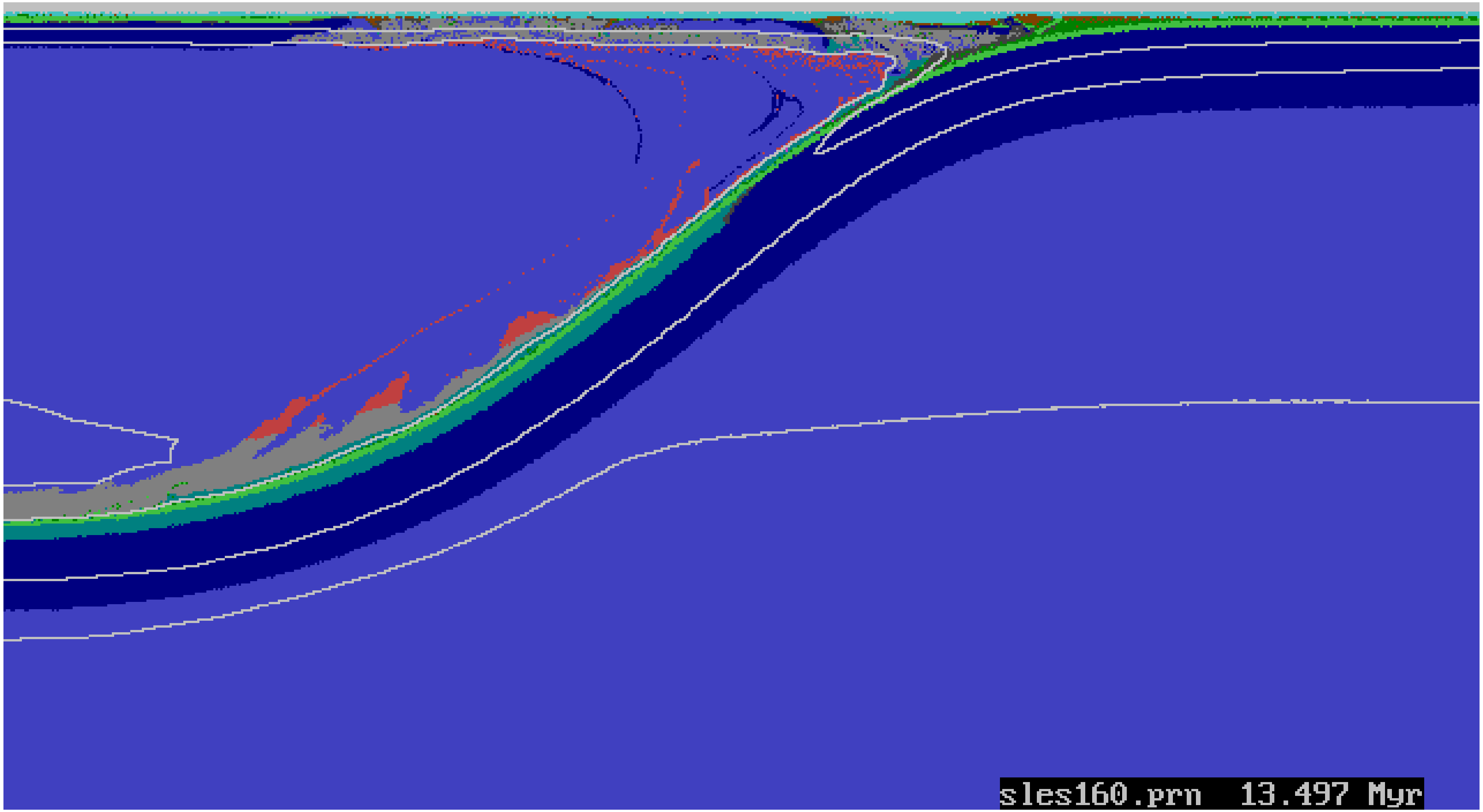

sles110.prn 8.497 Myr

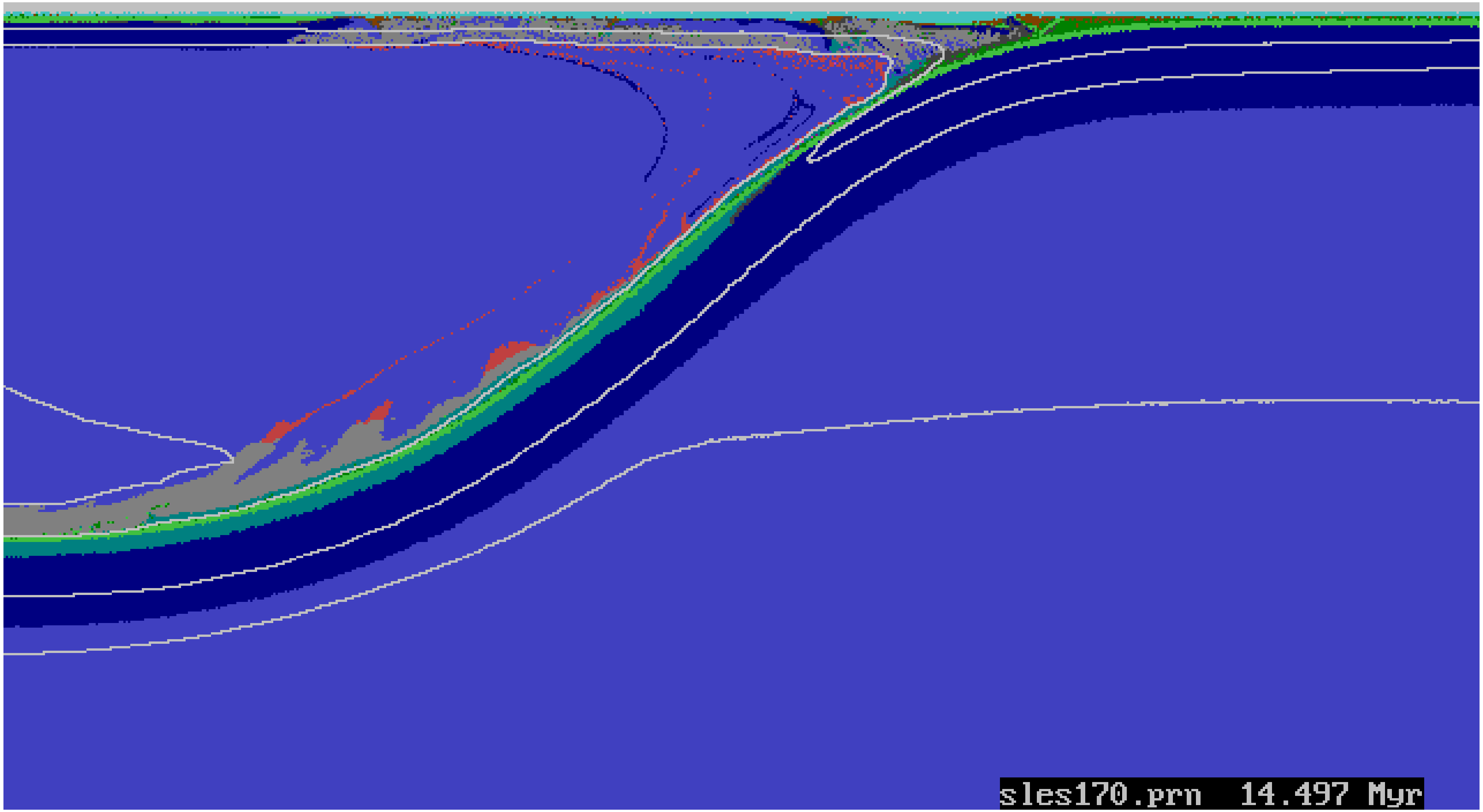

sles120.prn 9.497 Myr

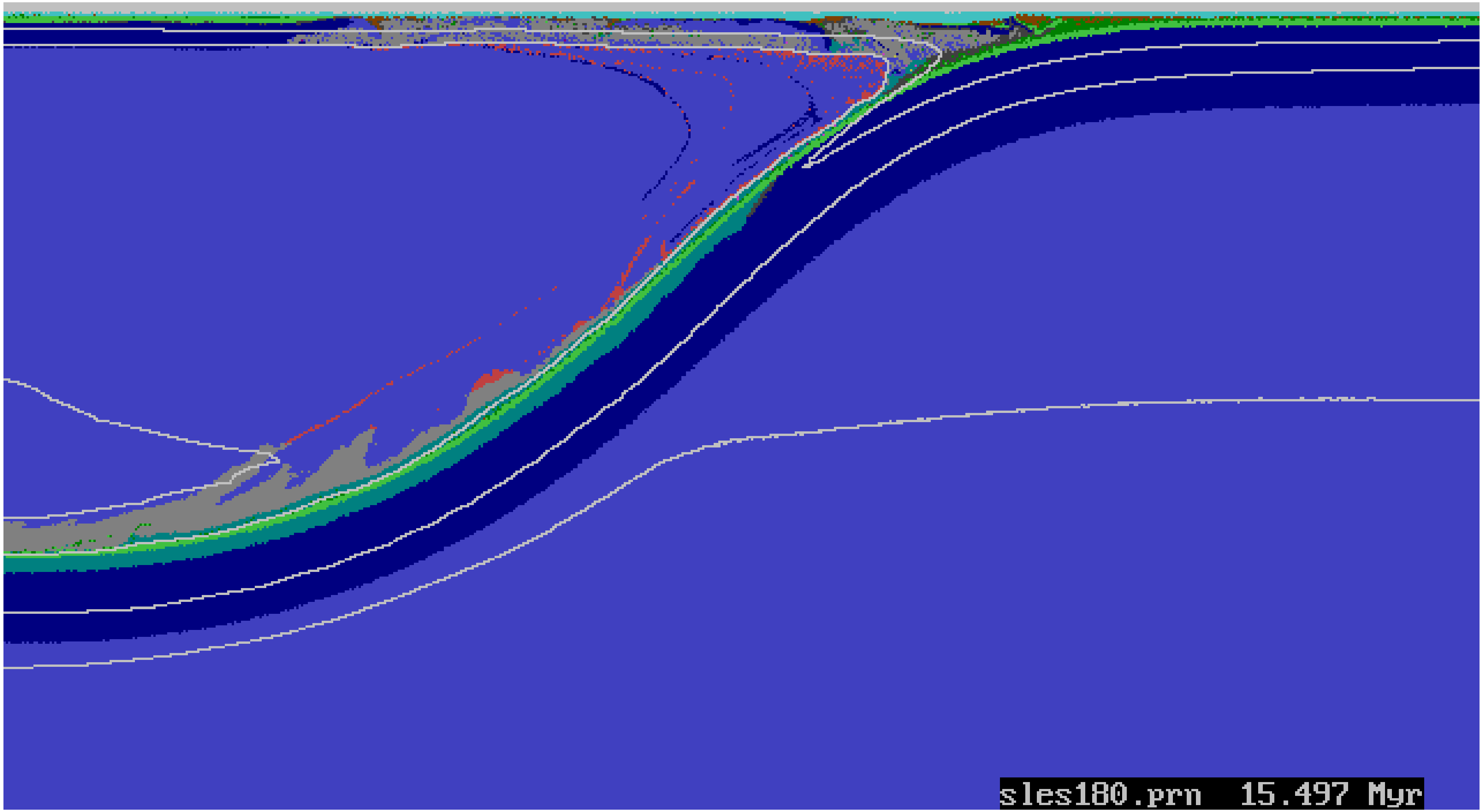

sles130.prn 10.497 Myr

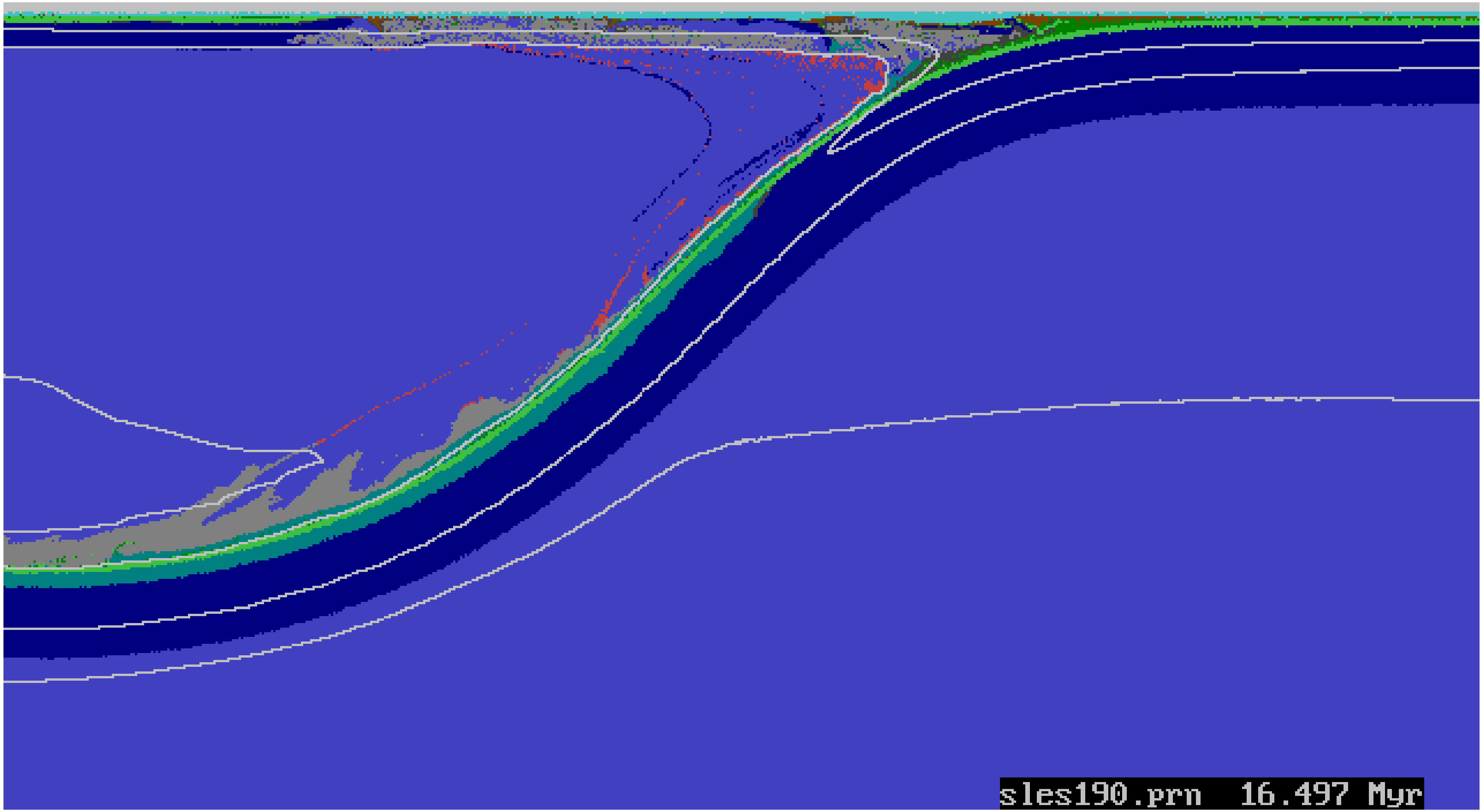

sles140.prn 11.497 Myr

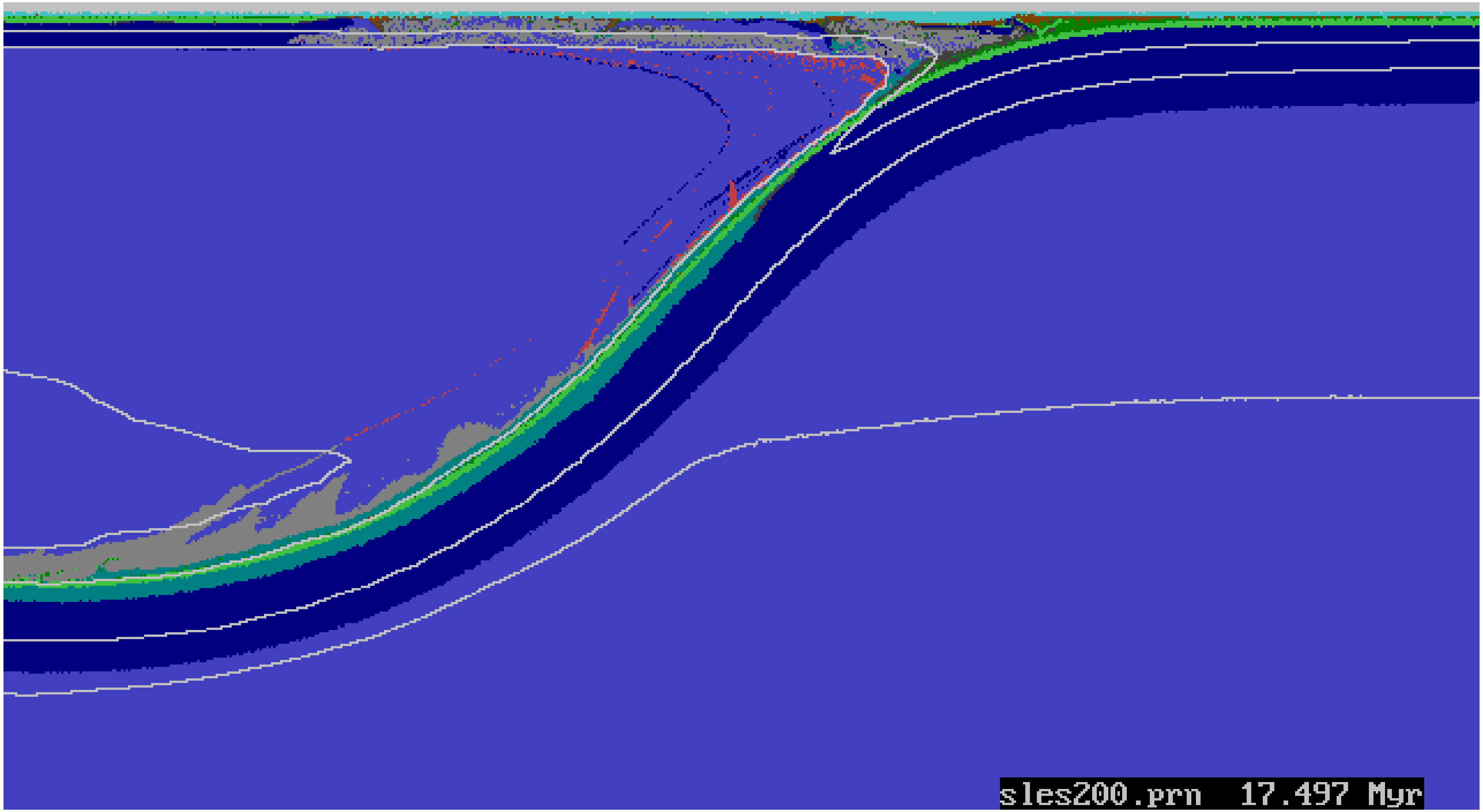

sles150.prn 12.497 Myr

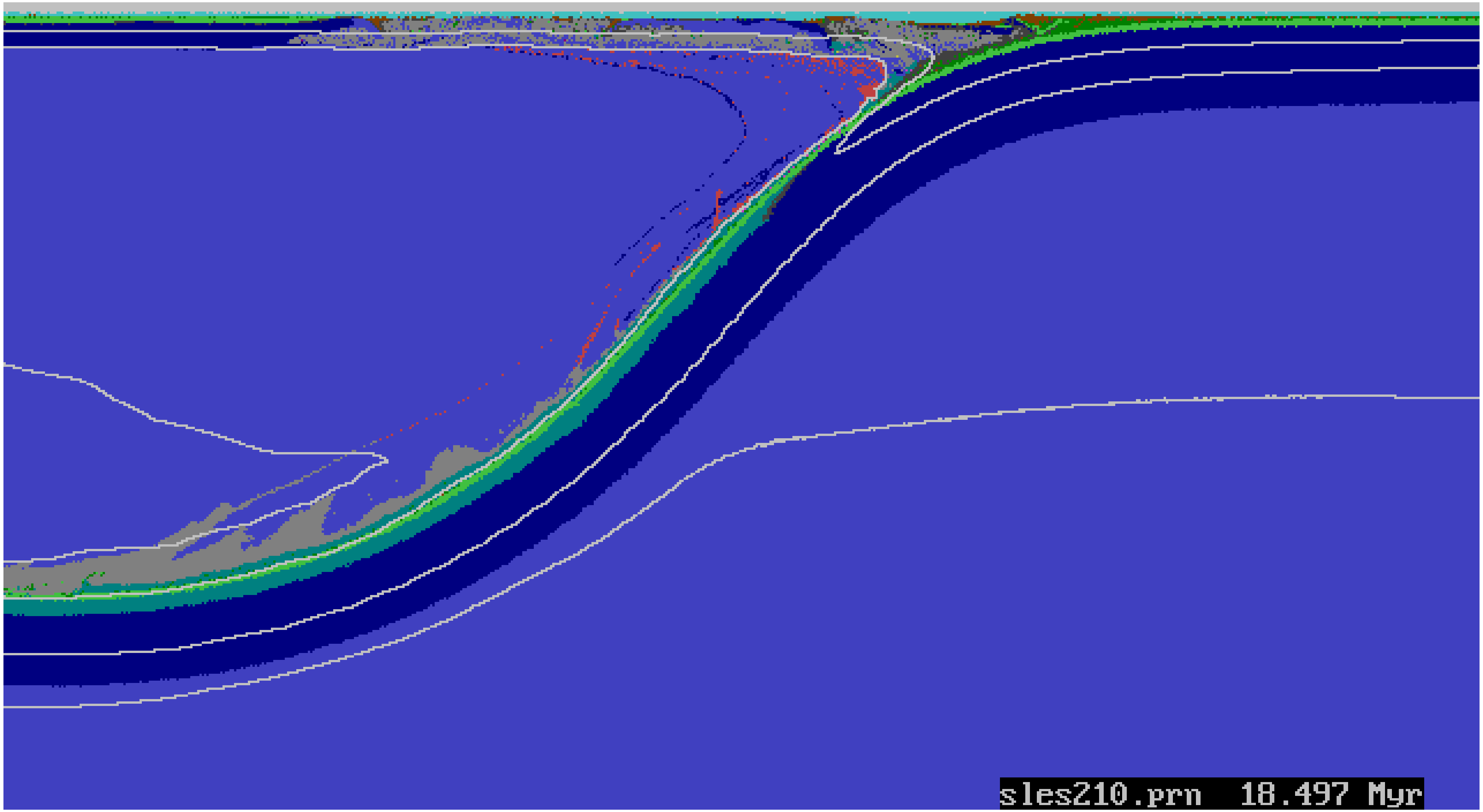

sles160.prn 13.497 Myr

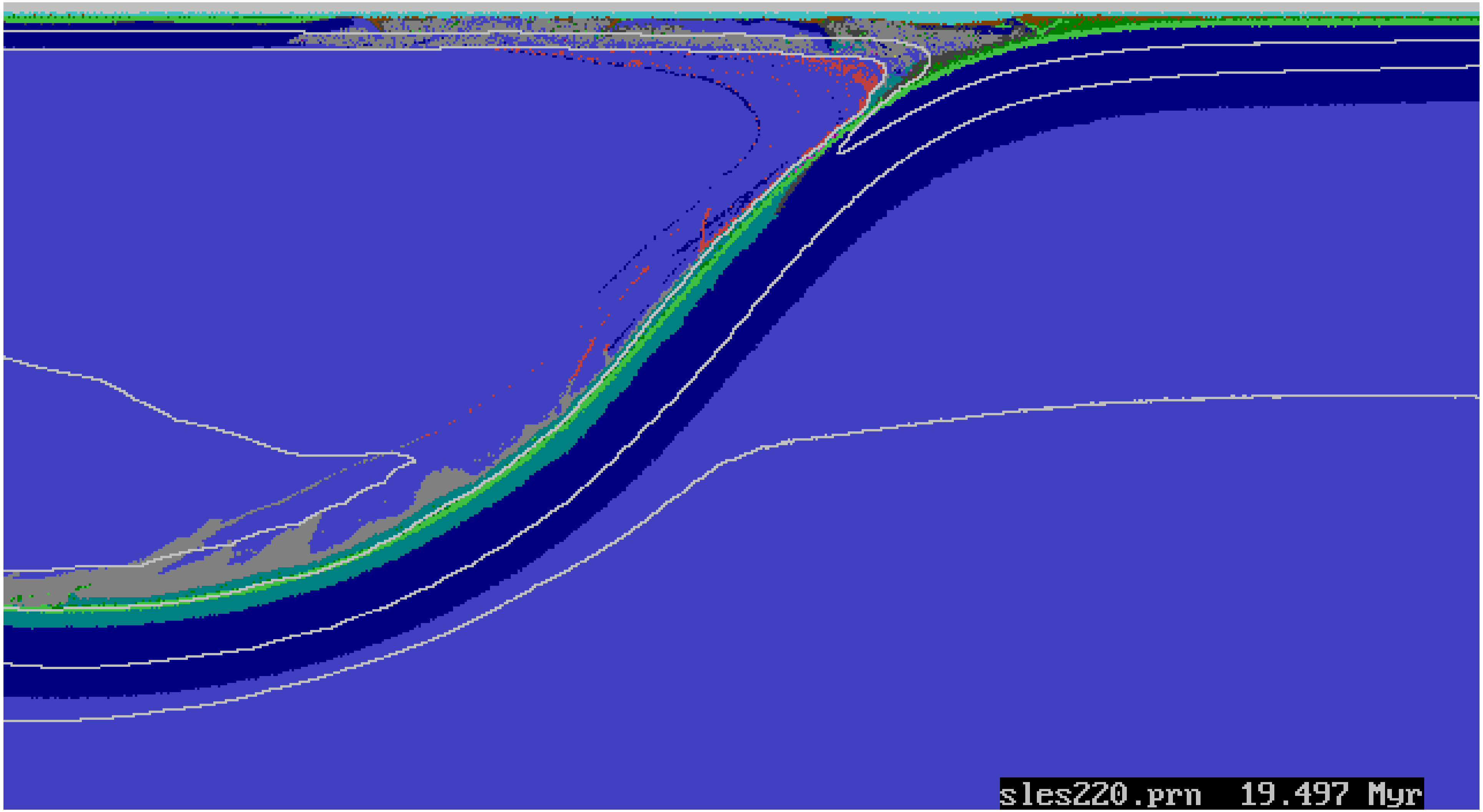

sles170.prn 14.497 Myr

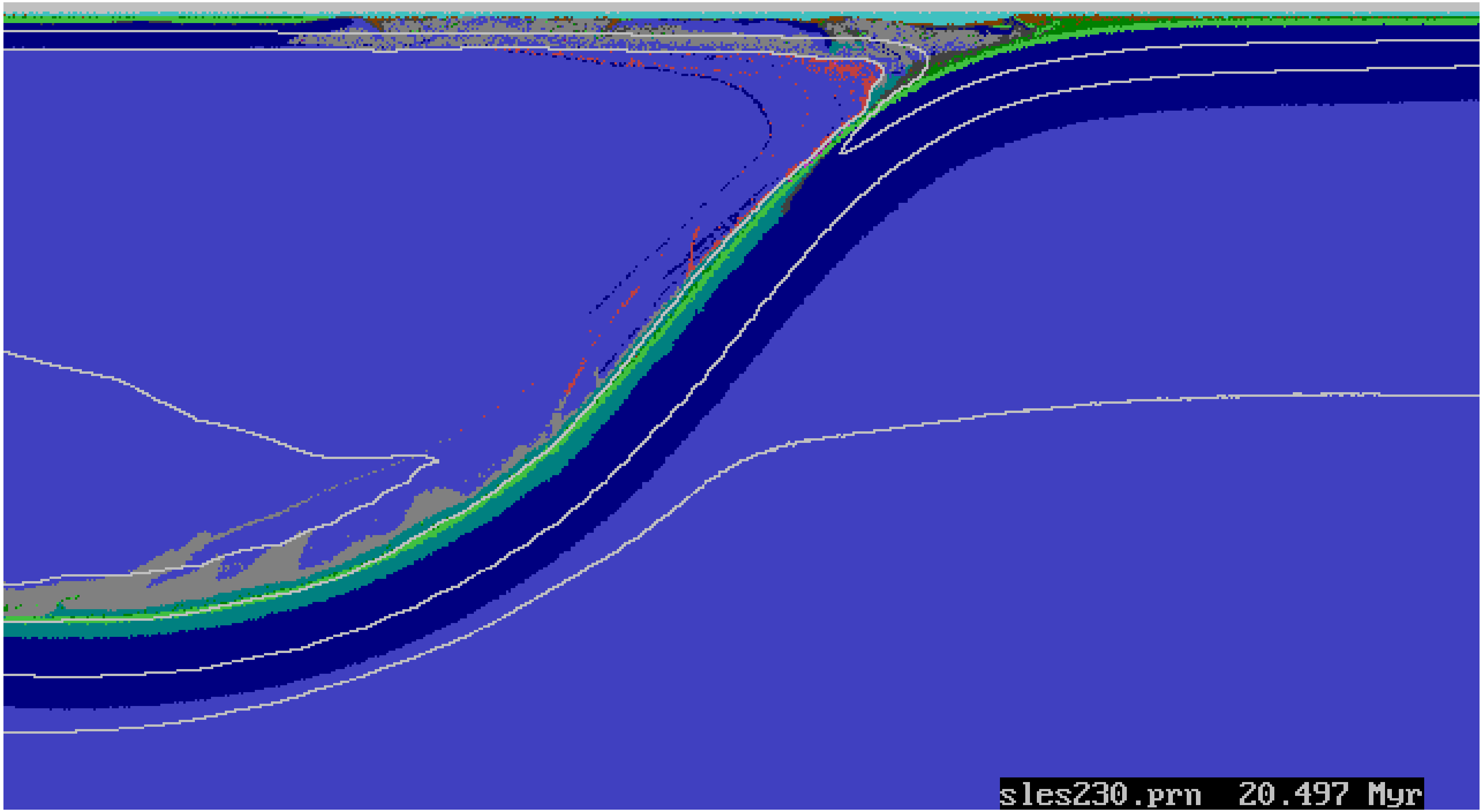

sles180.prn 15.497 Myr

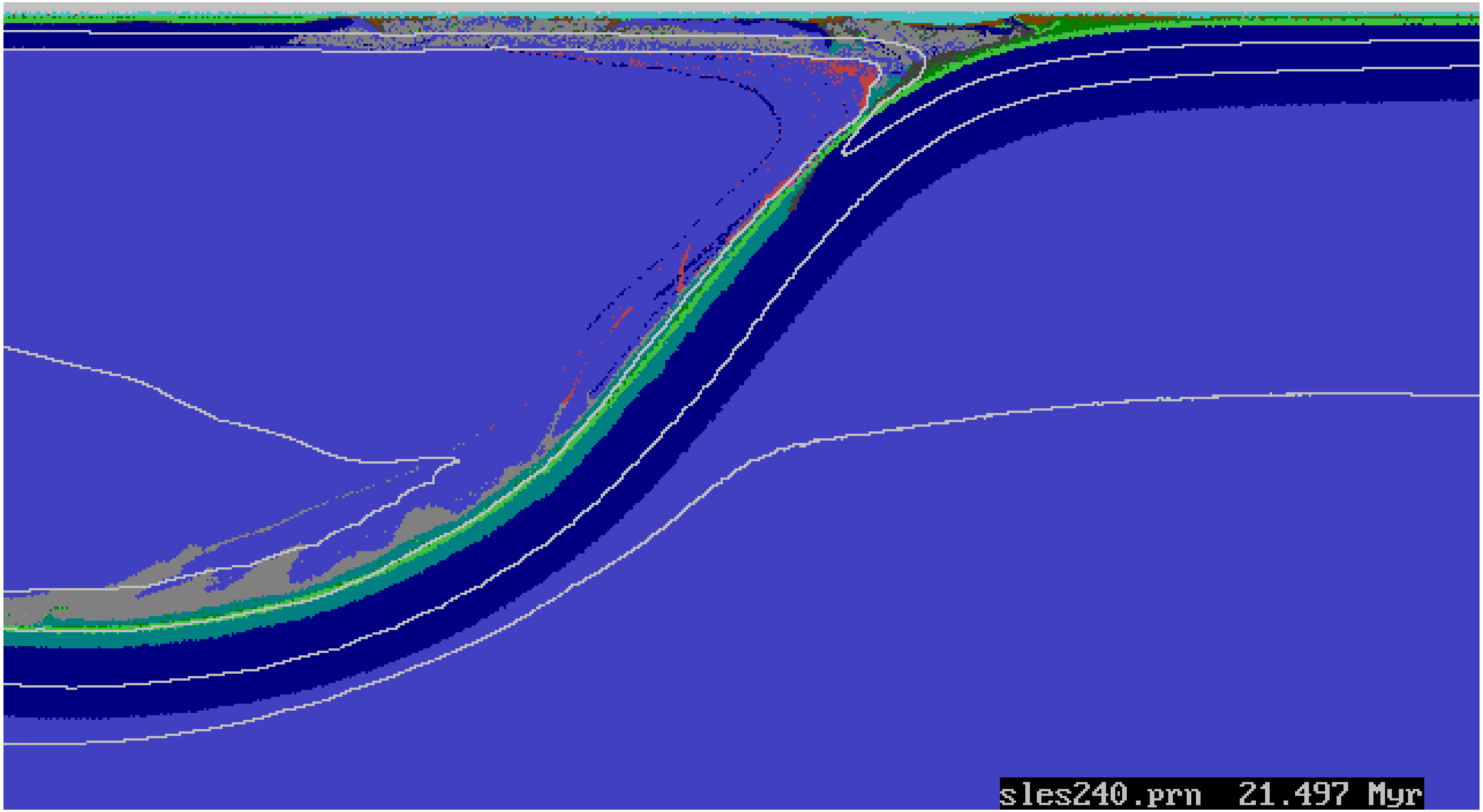

sles190.prn 16.497 Myr

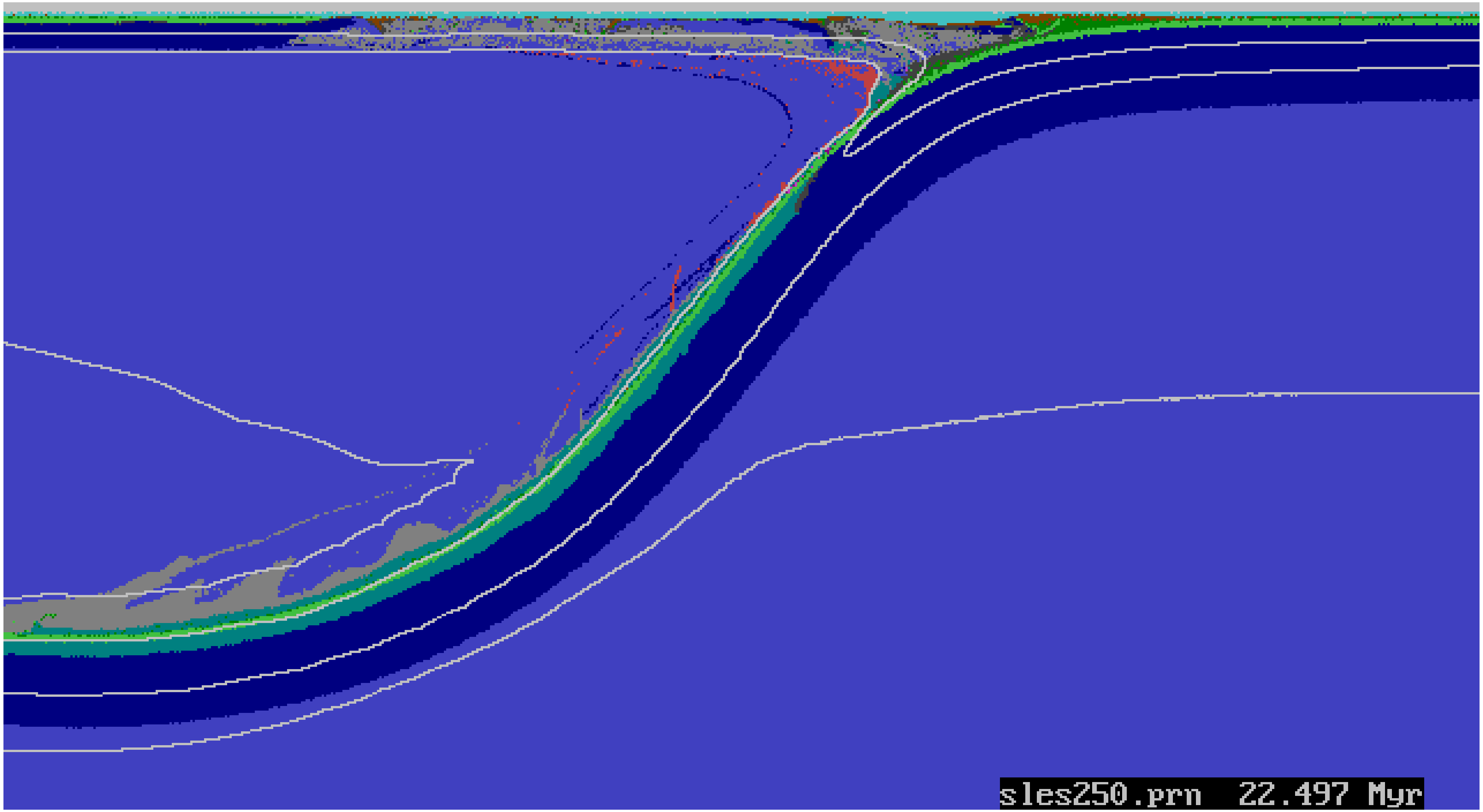

sles200.prn 17.497 Myr

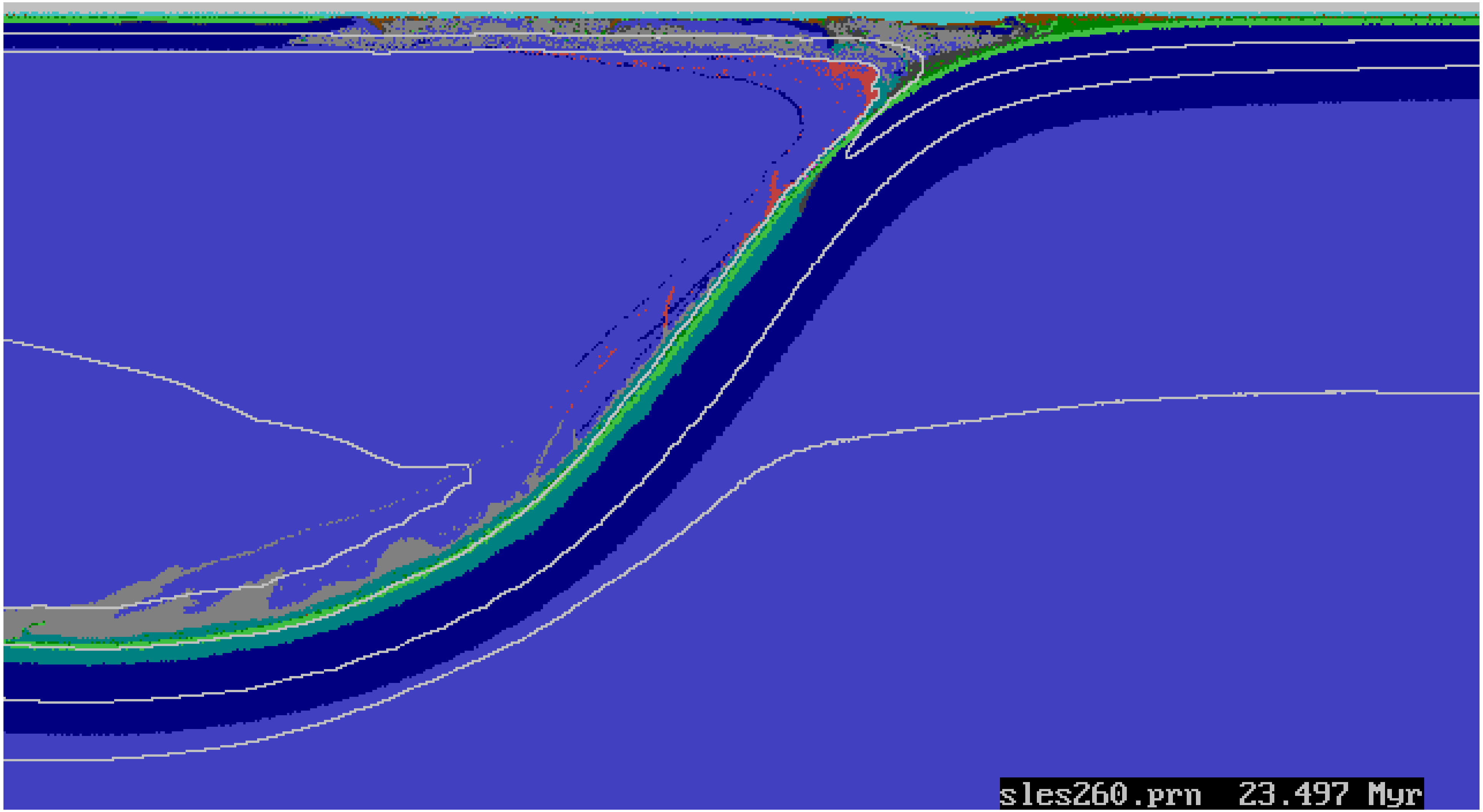

sles210.prn 18.497 Myr

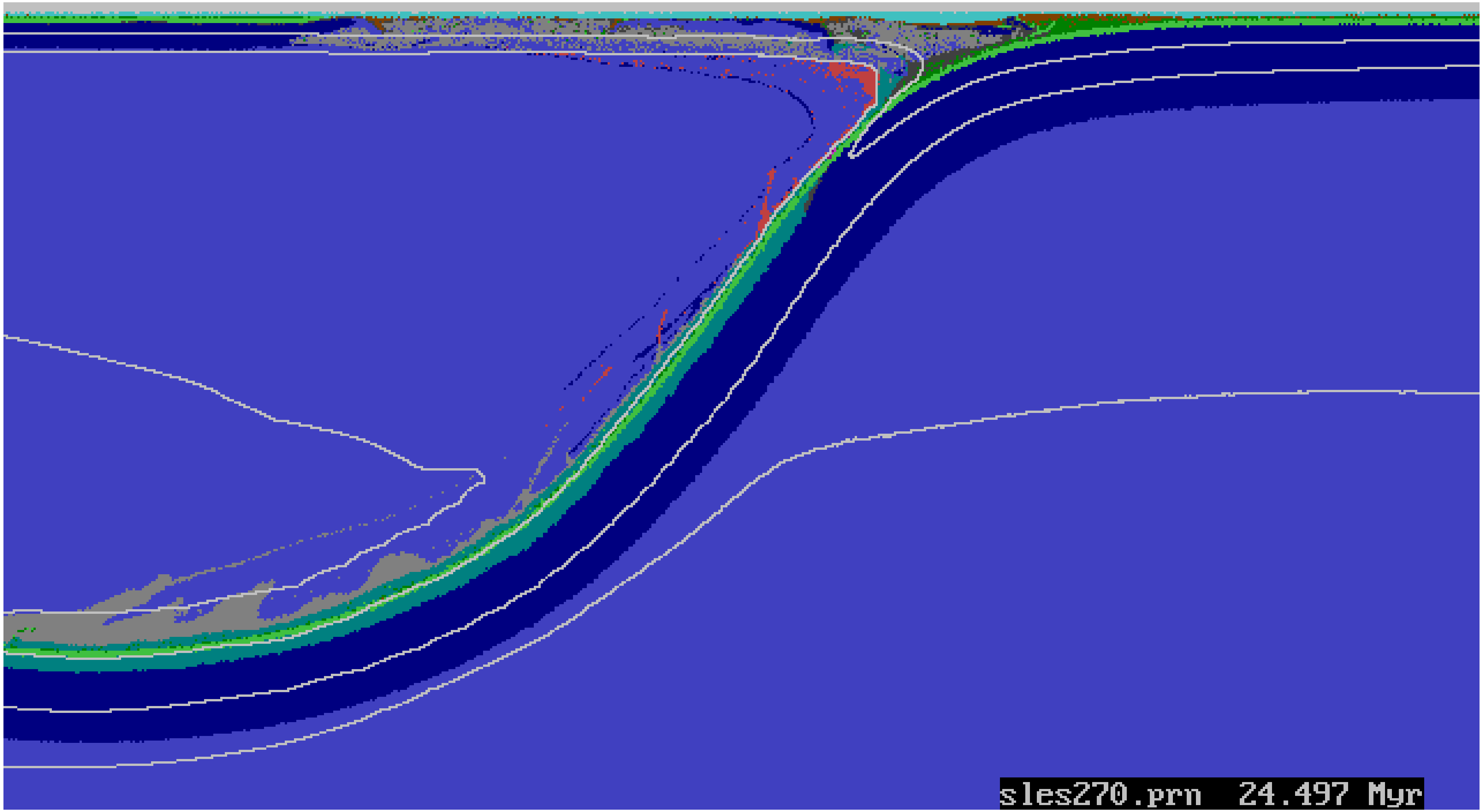

sles220.prn 19.497 Myr

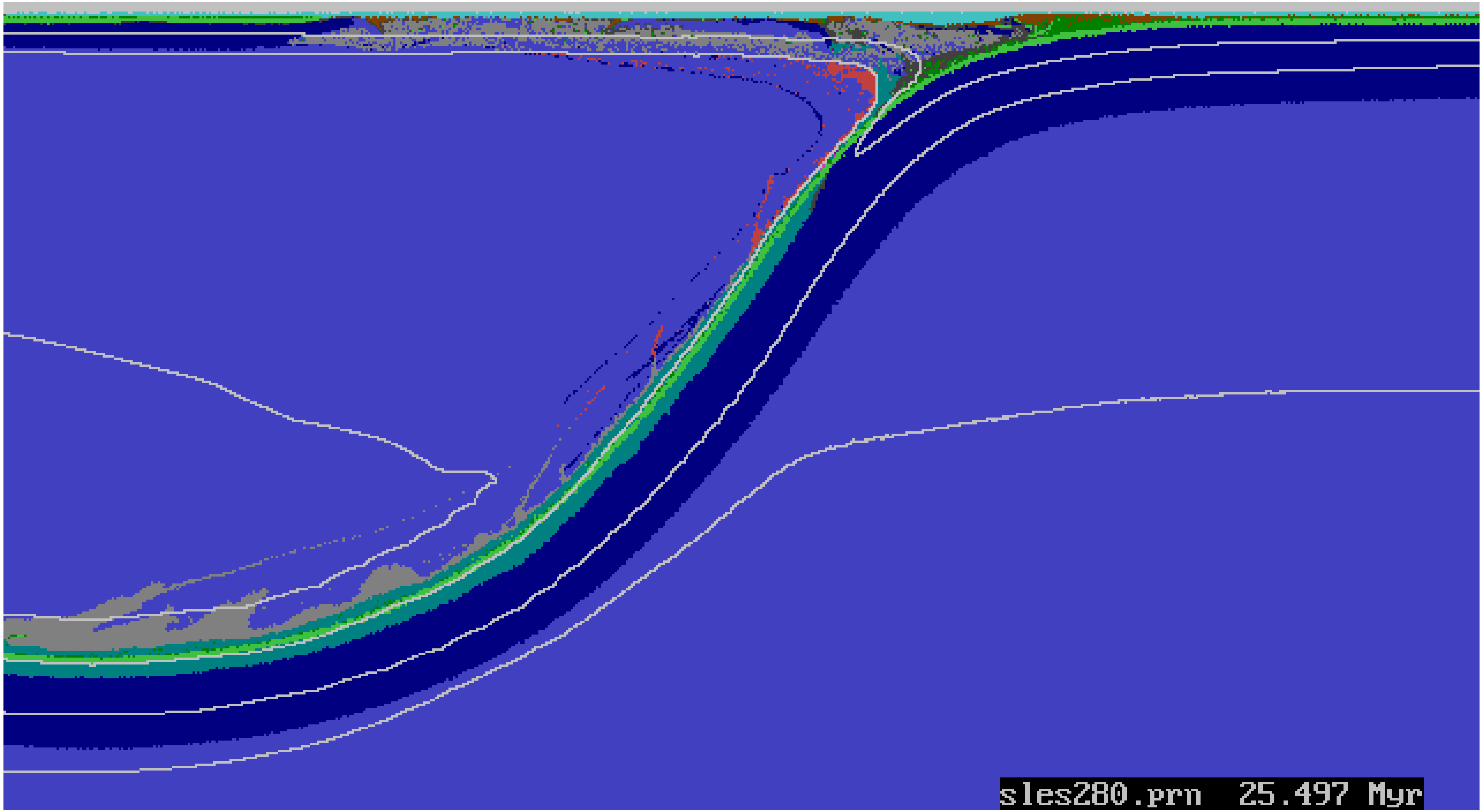

sles230.prn 20.497 Myr

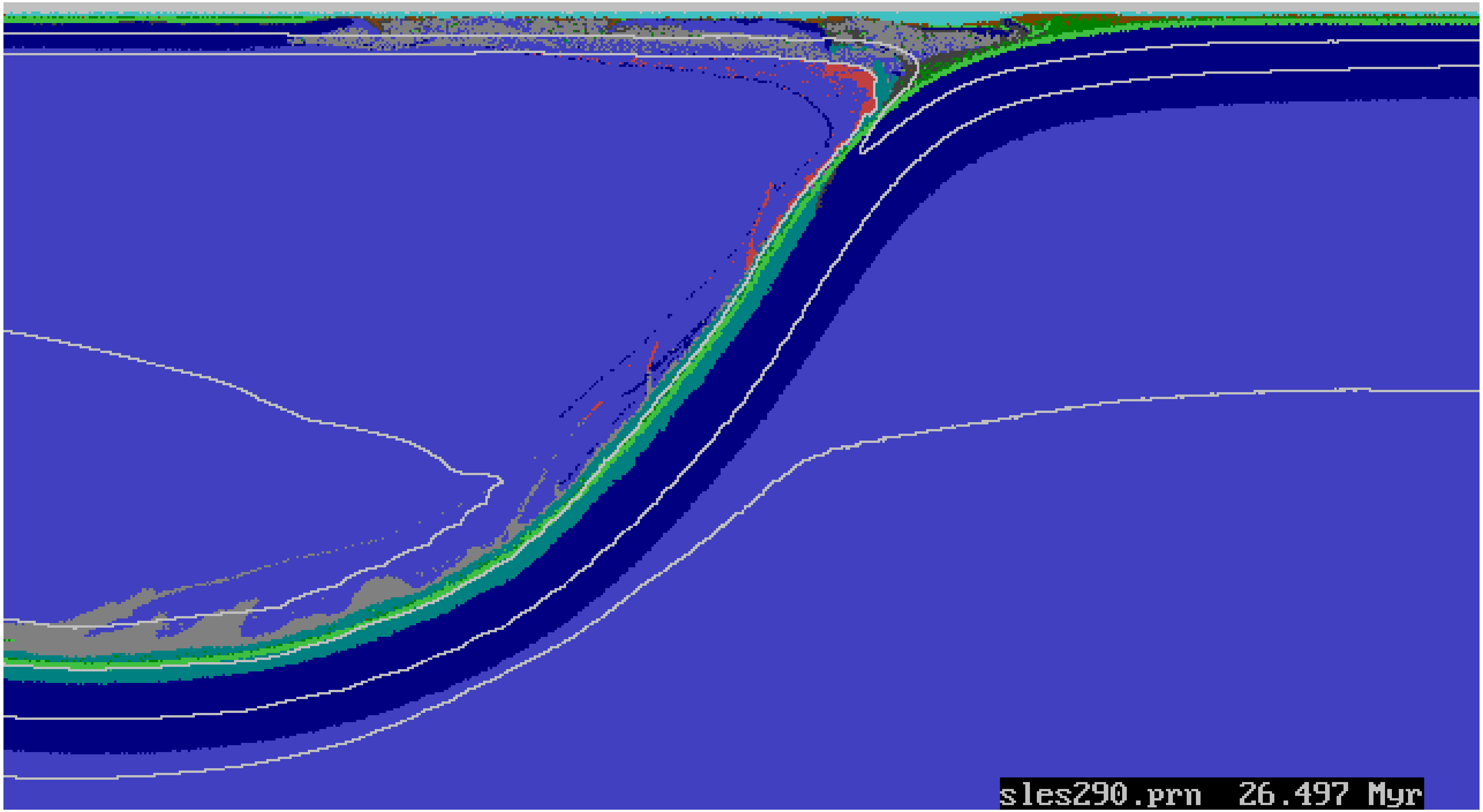

sles240.prn 21.497 Myr

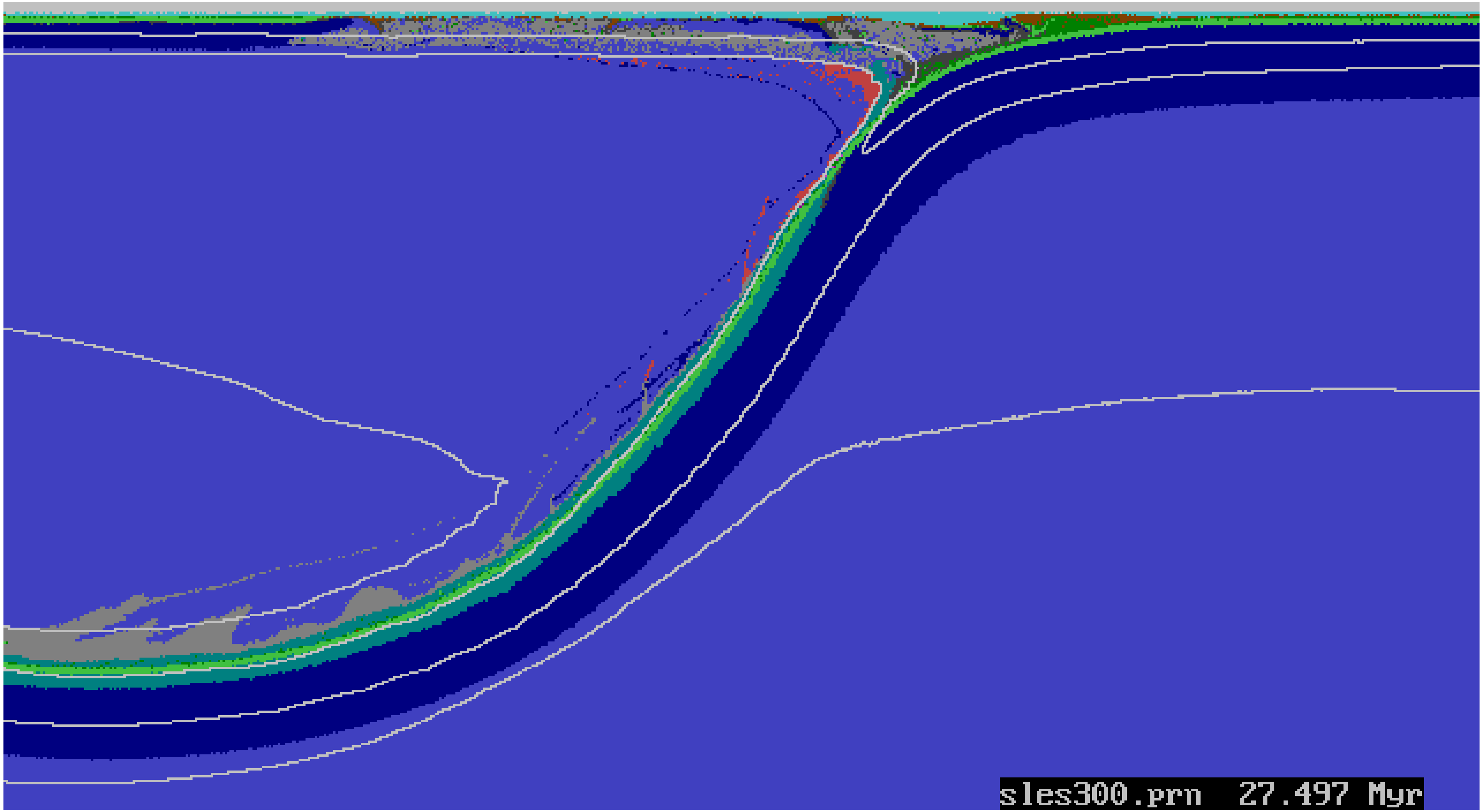

sles250.prn 22.497 Myr

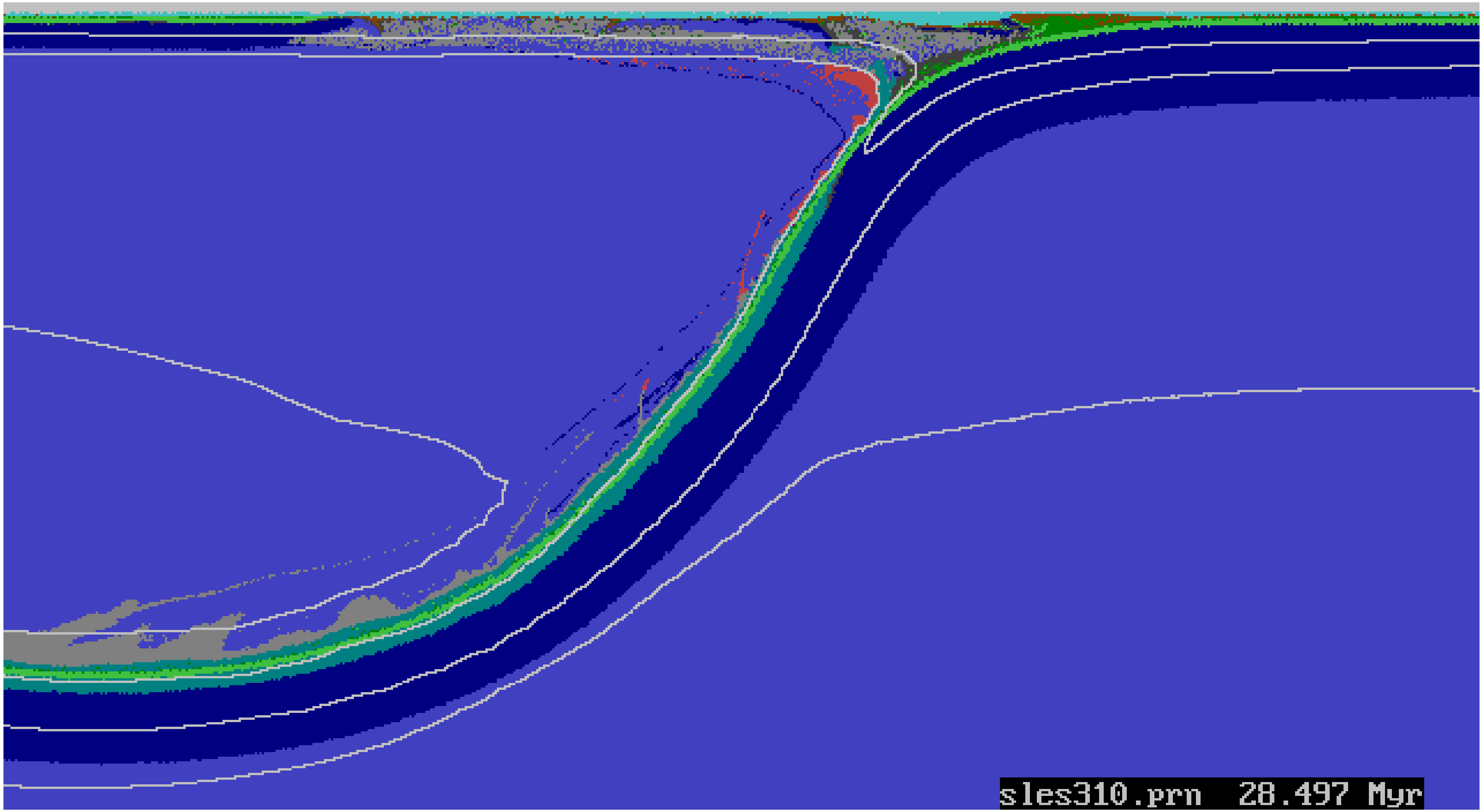

sles260.prn 23.497 Myr

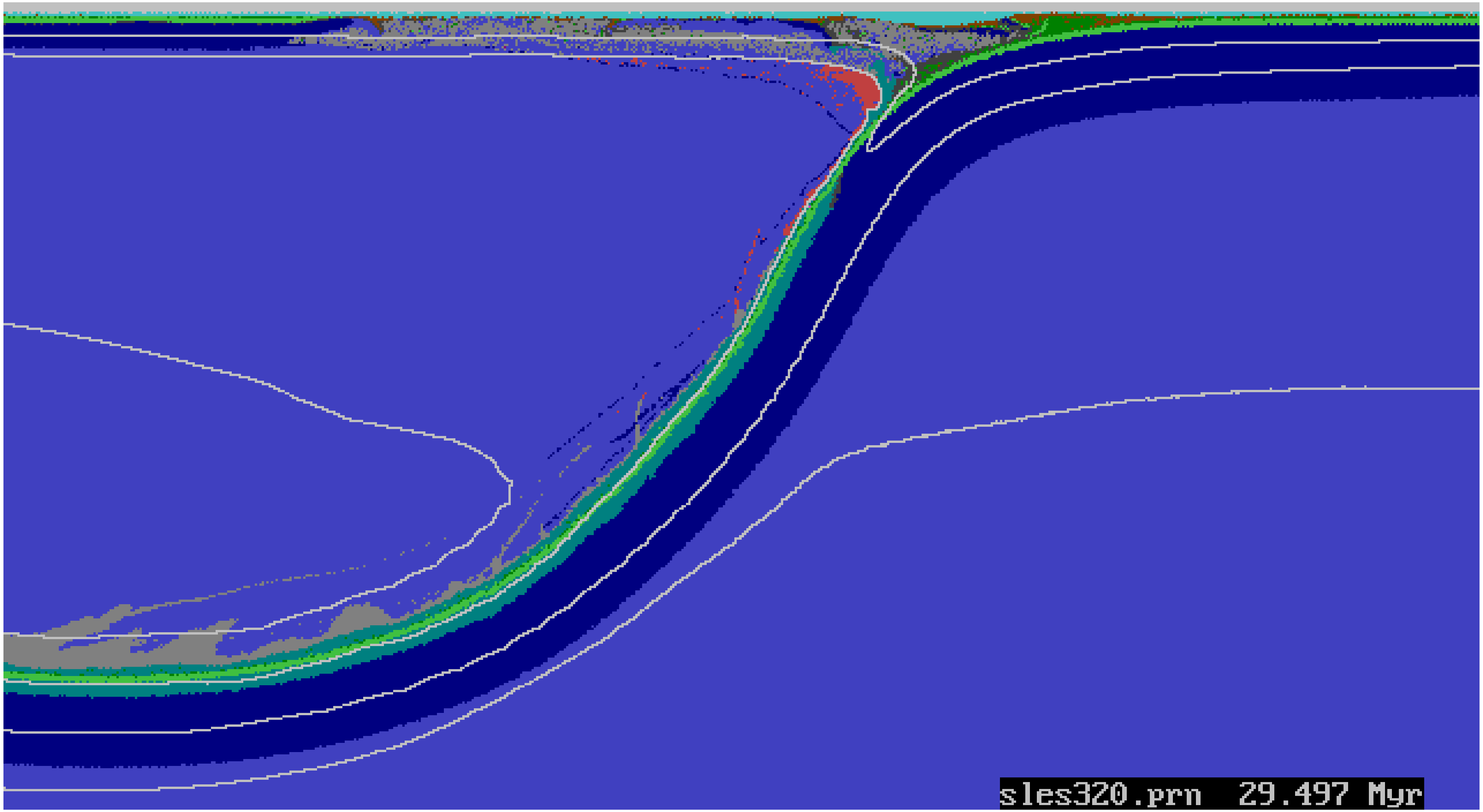

sles270.prn 24.497 Myr

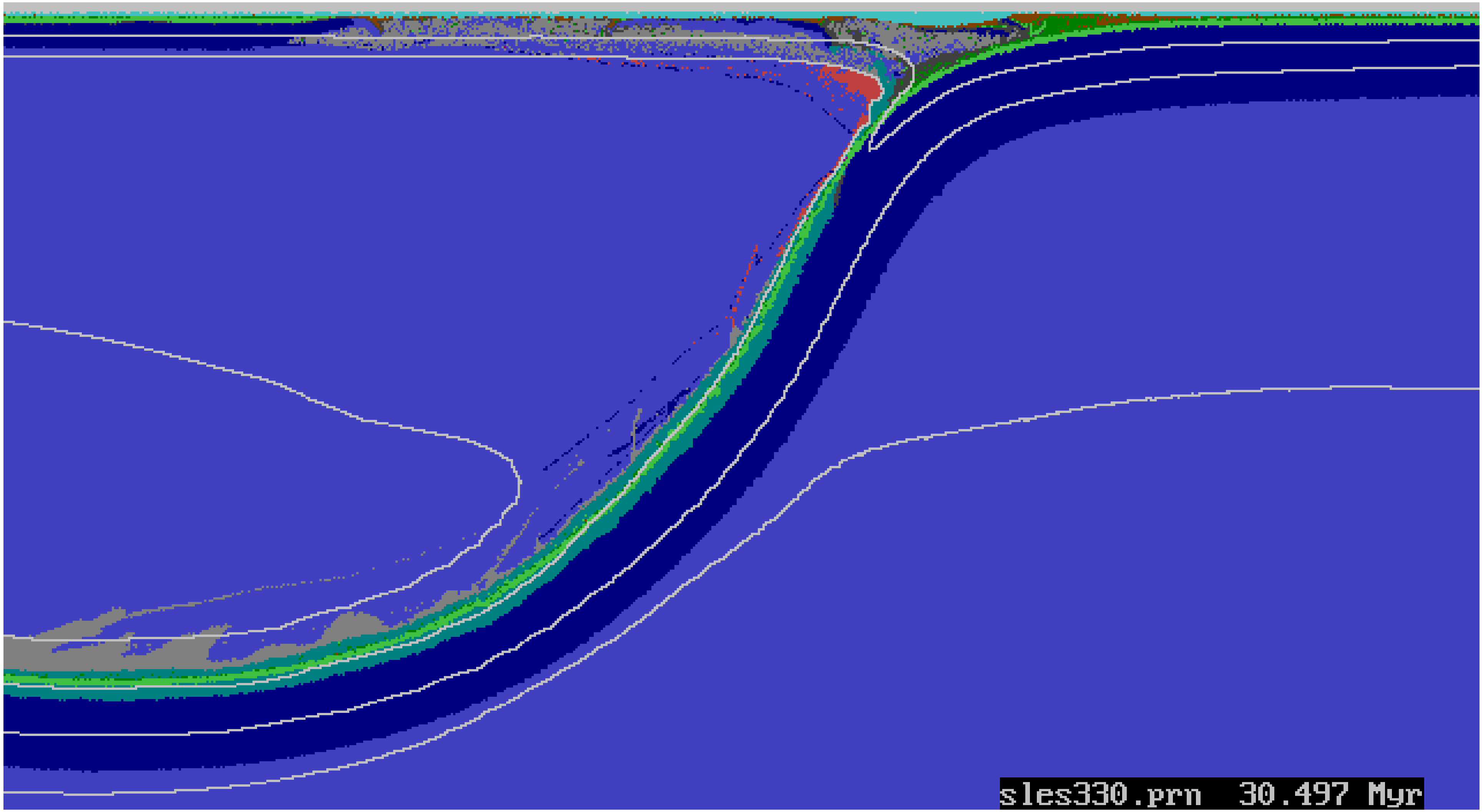

sles280.prn 25.497 Myr

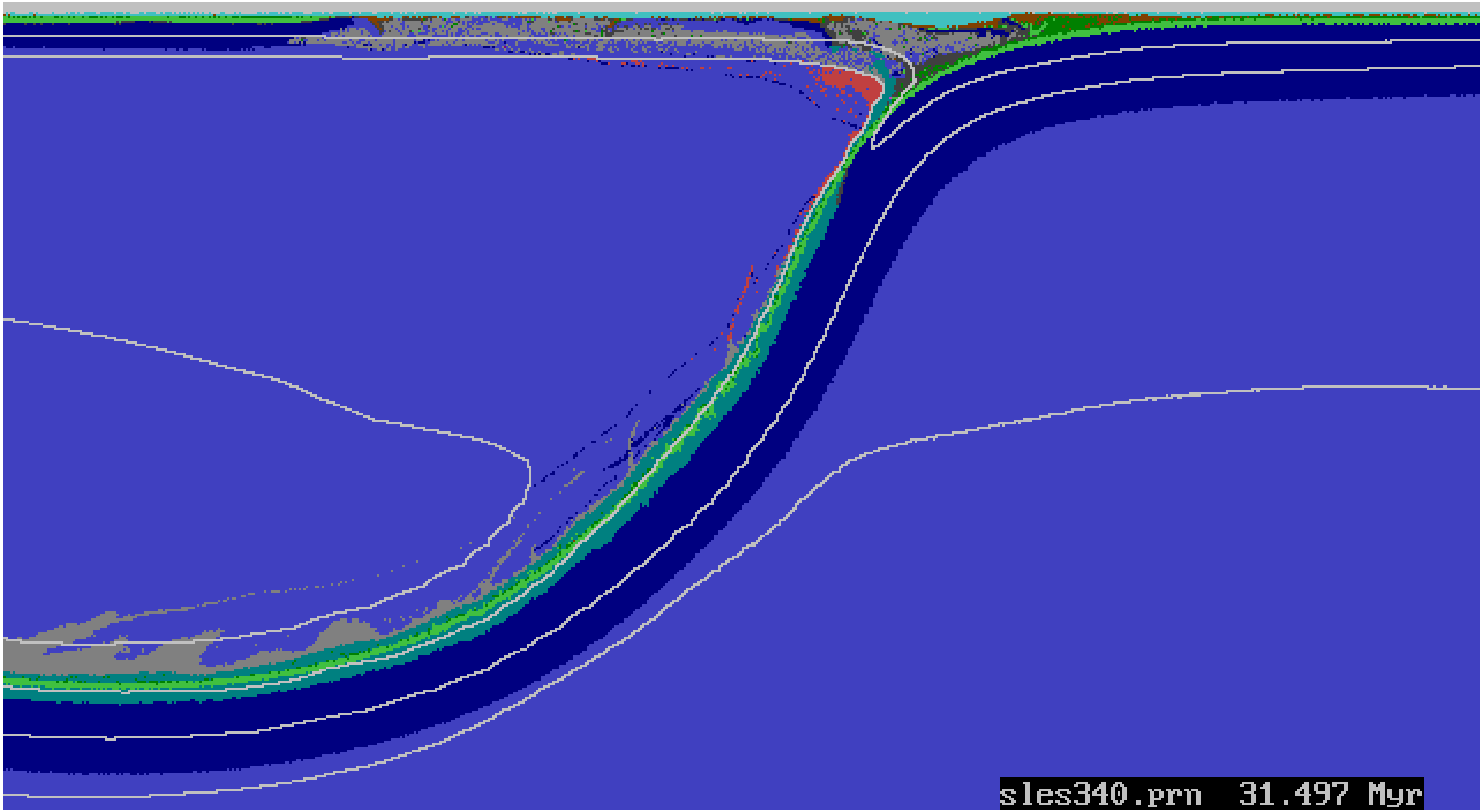

sles290.prn 26.497 Myr

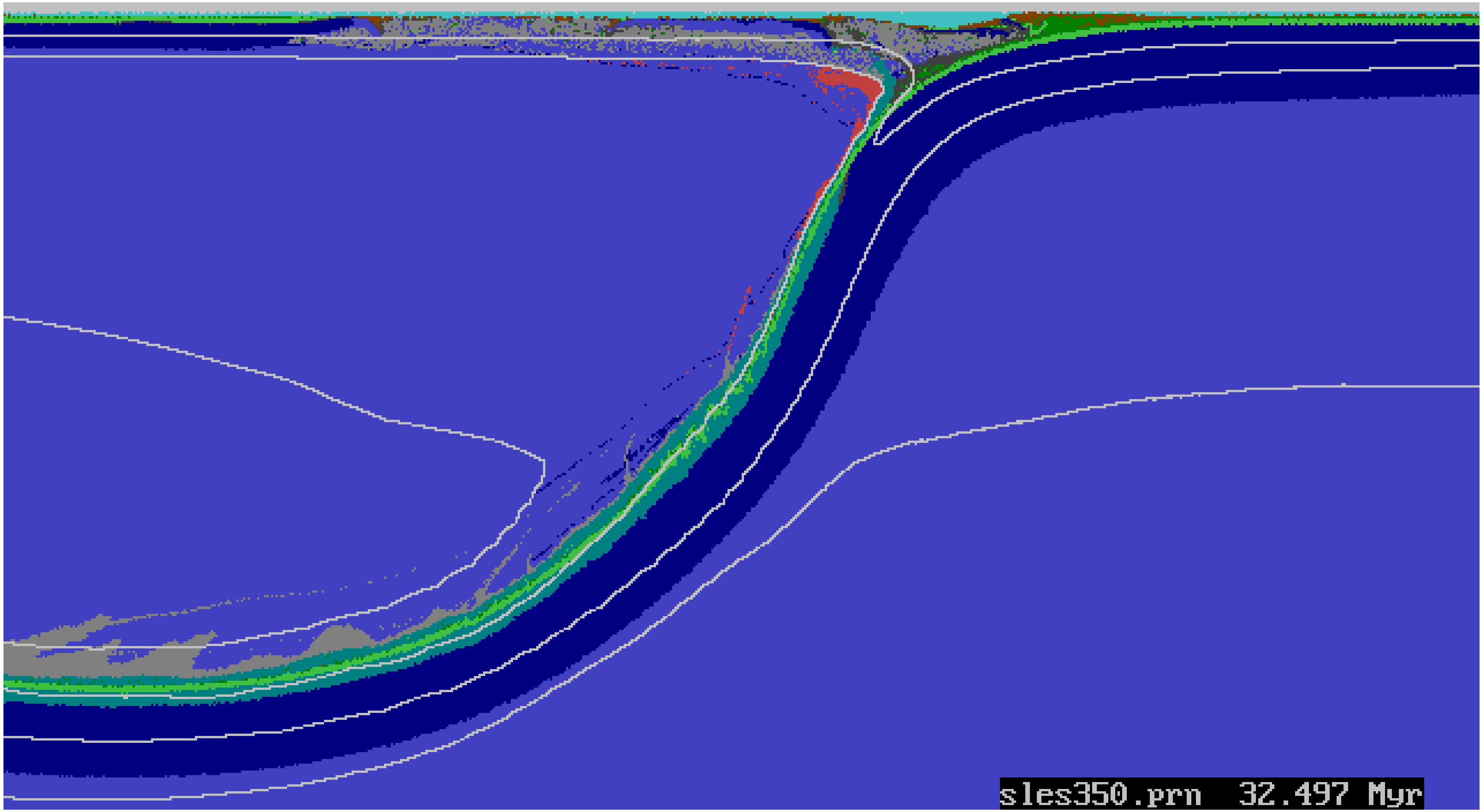

sles300.prn 27.497 Myr

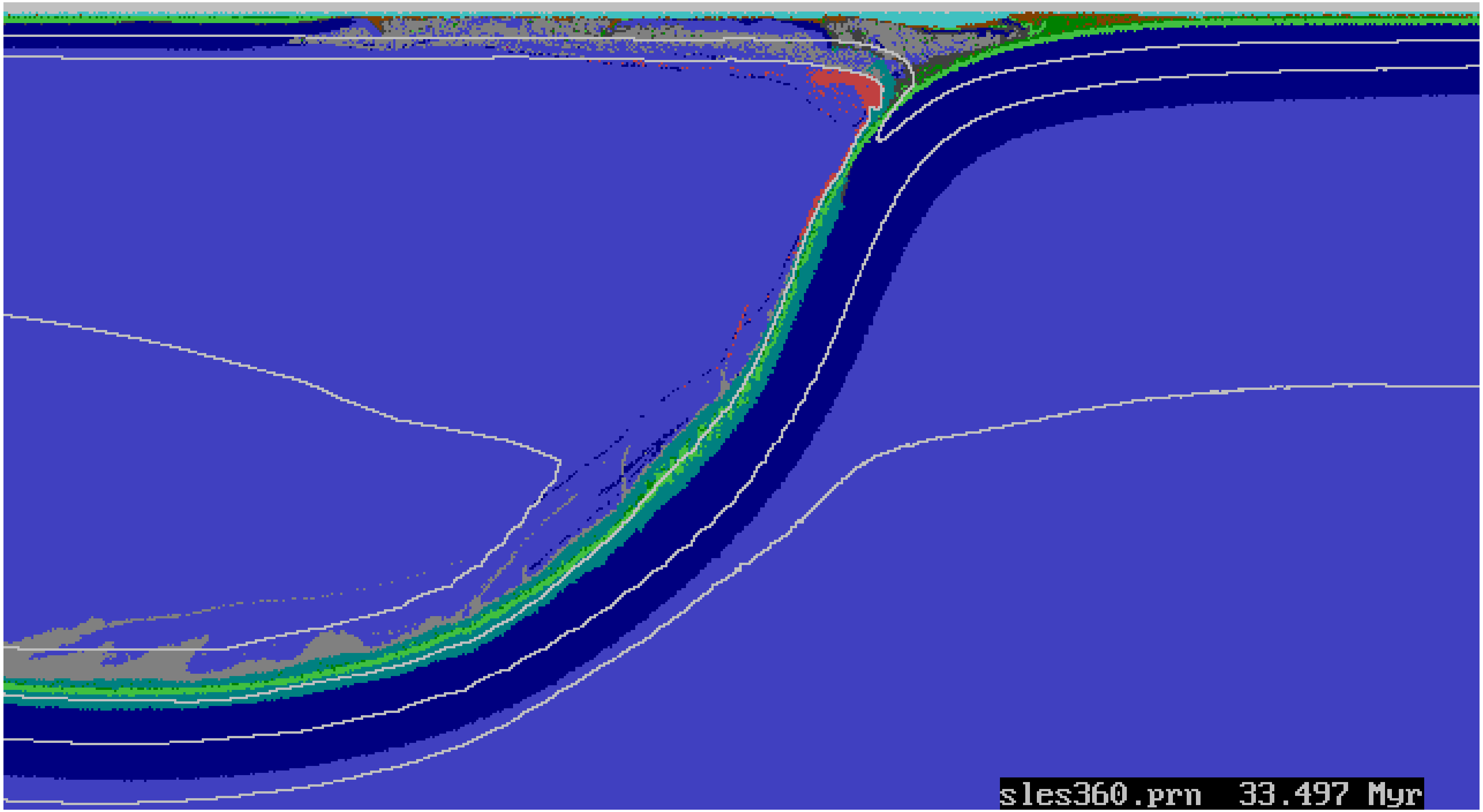

sles310.prn 28.497 Myr

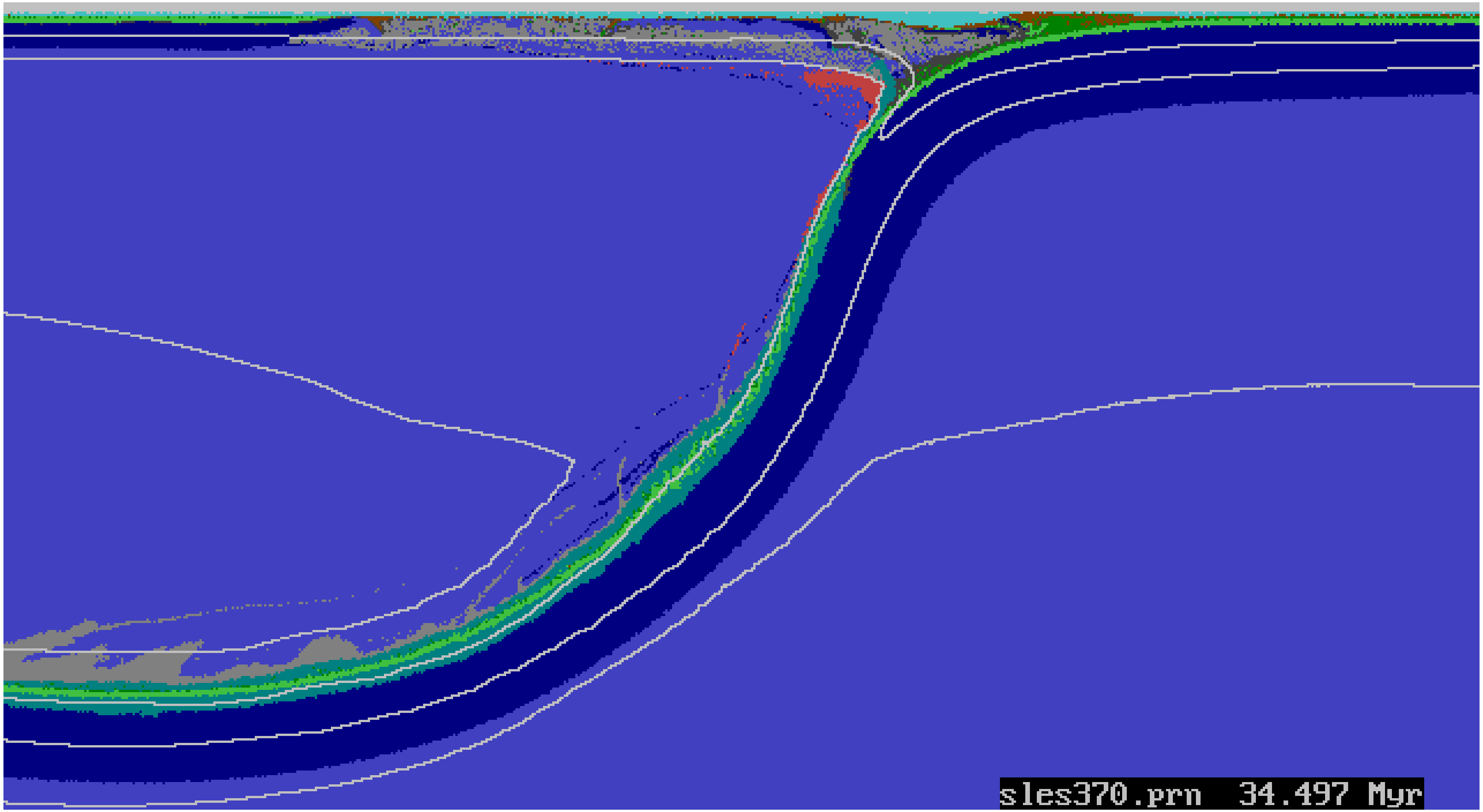

sles320.prn 29.497 Myr

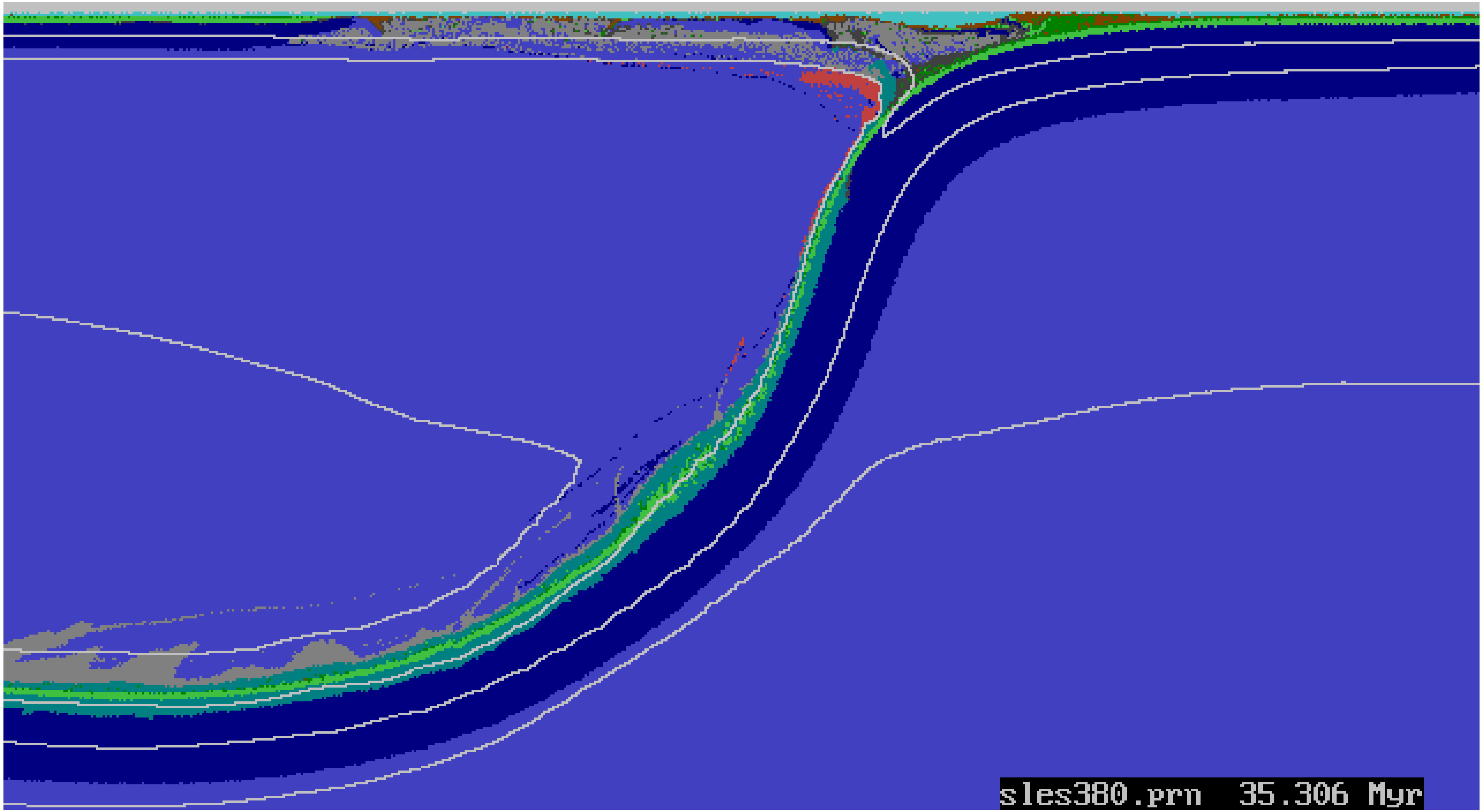

sles330.prn 30.497 Myr

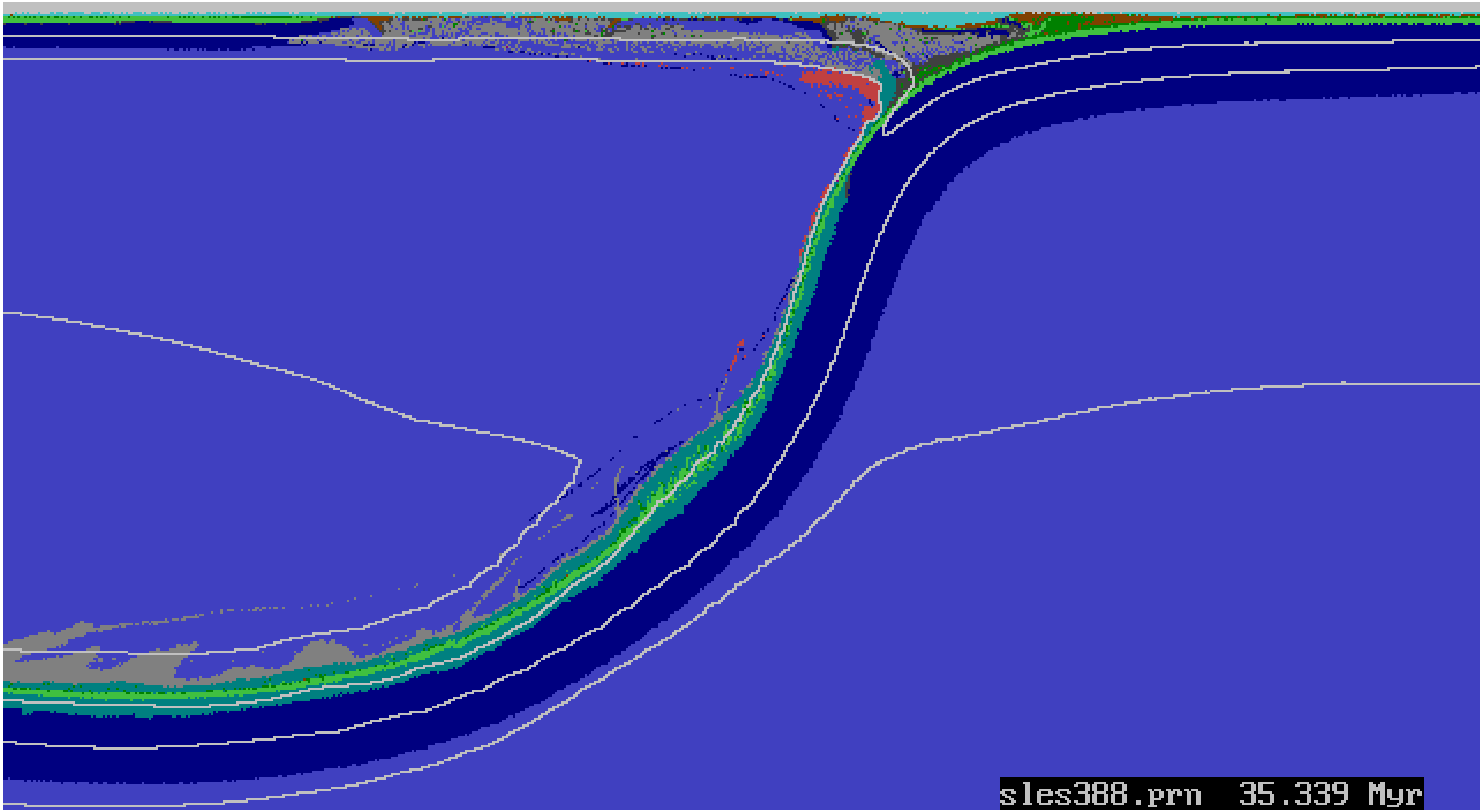

sles340.prn 31.497 Myr


sles350.prn 32.497 Myr

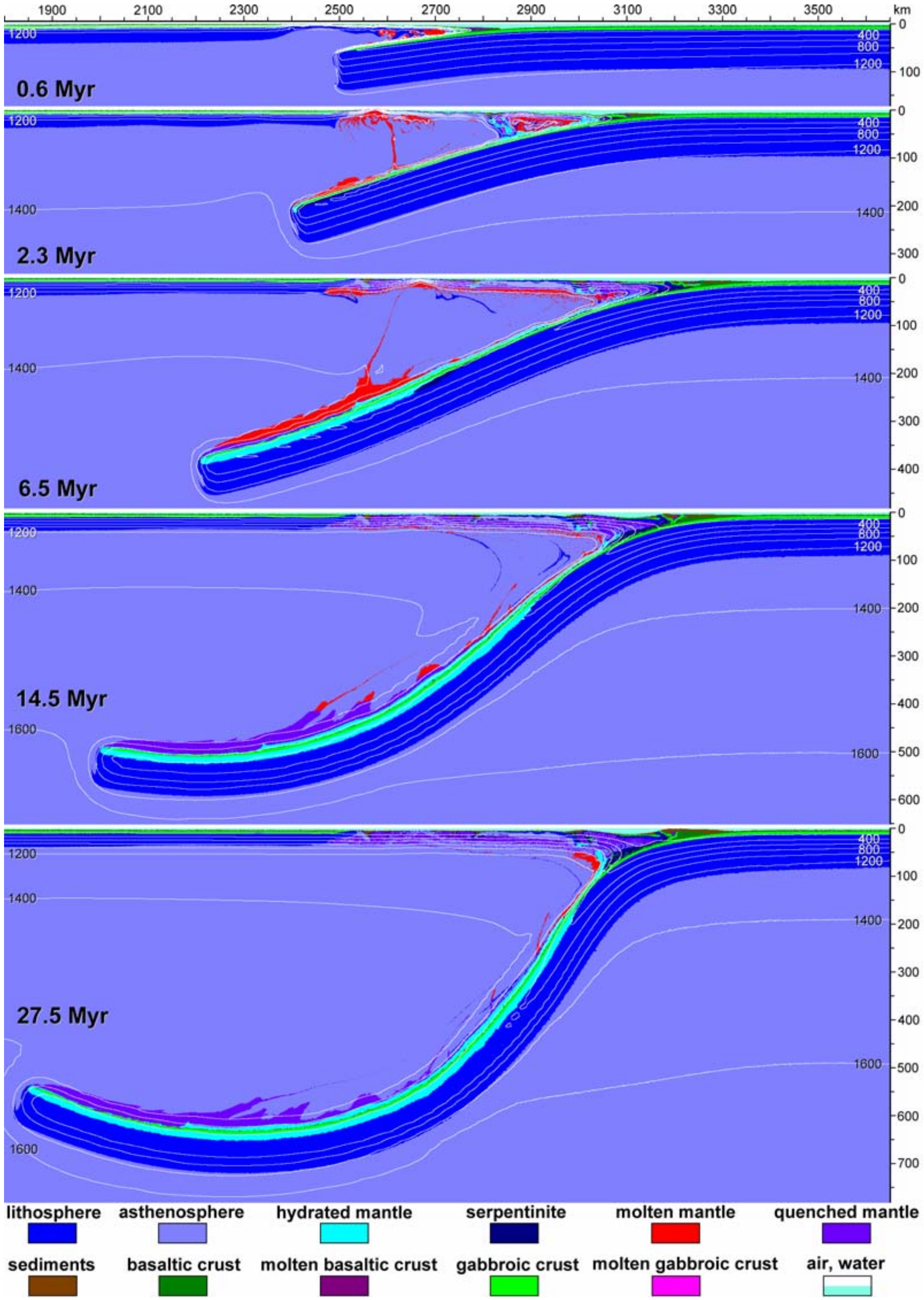

sles360.prn 33.497 Myr


sles370.prn 34.497 Myr

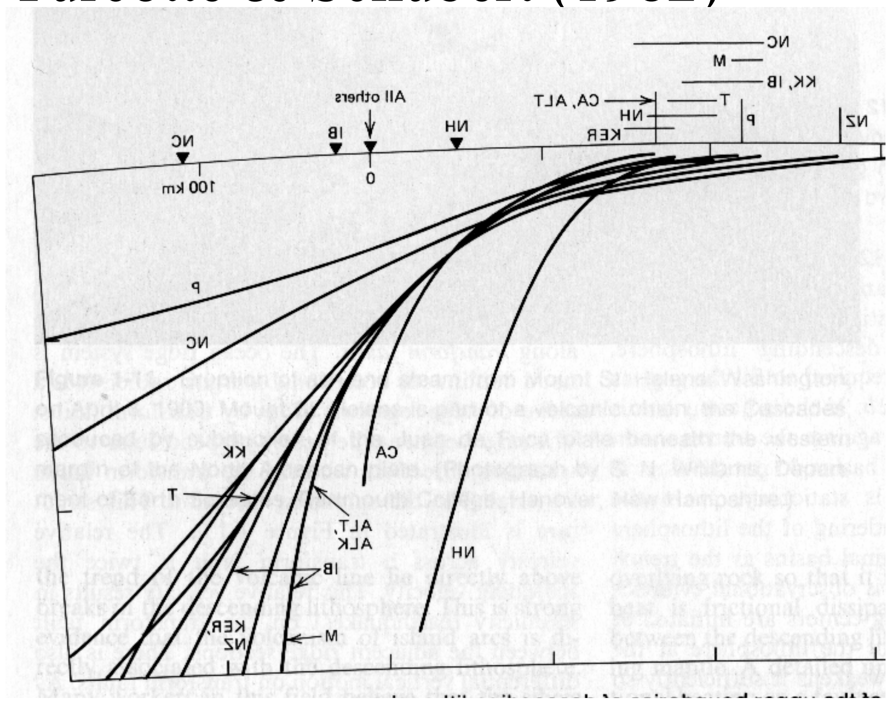

sles380.prn 35.306 Myr


sles388.prn 35.339 Myr

Intesity of slab bending changes with time

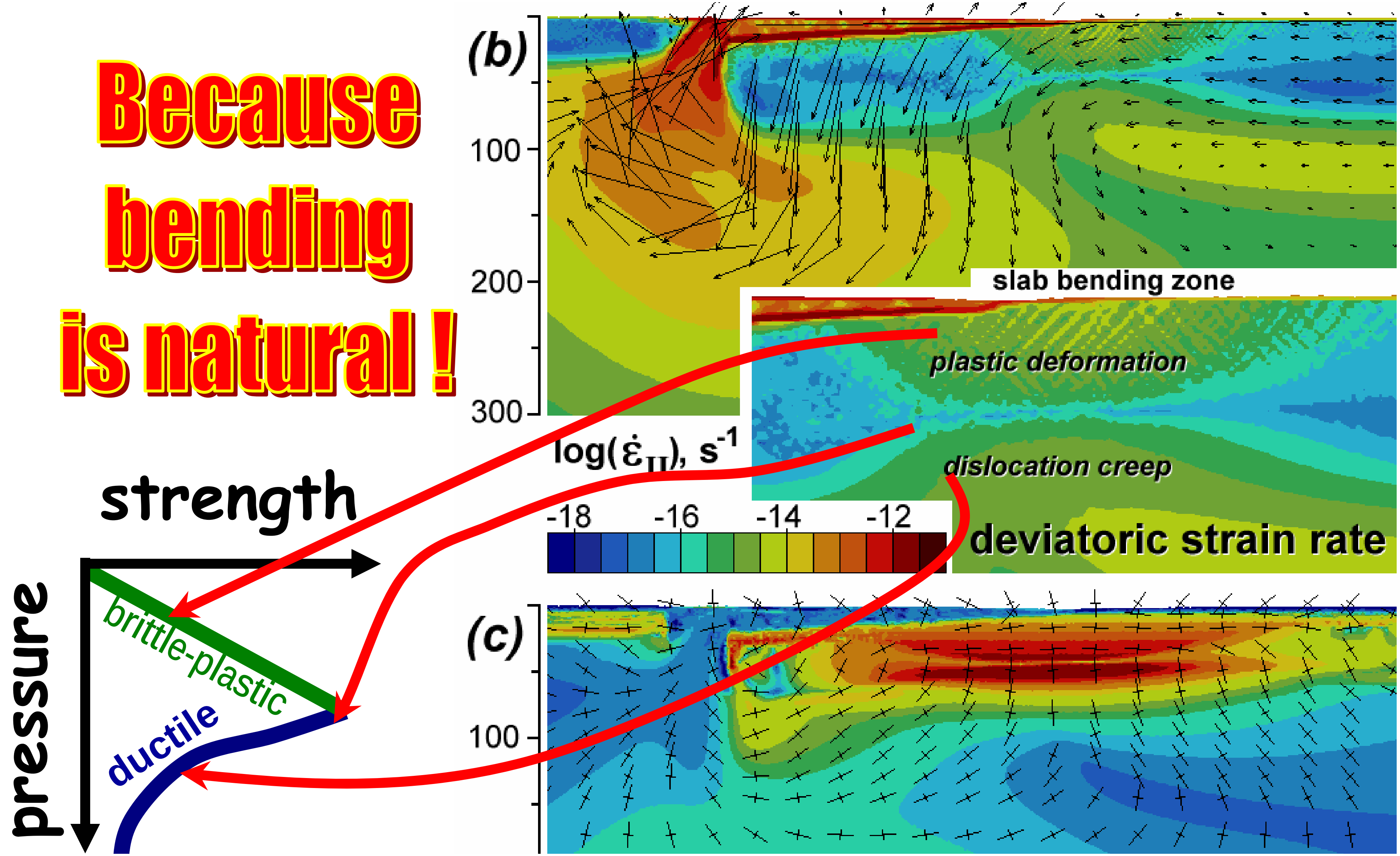


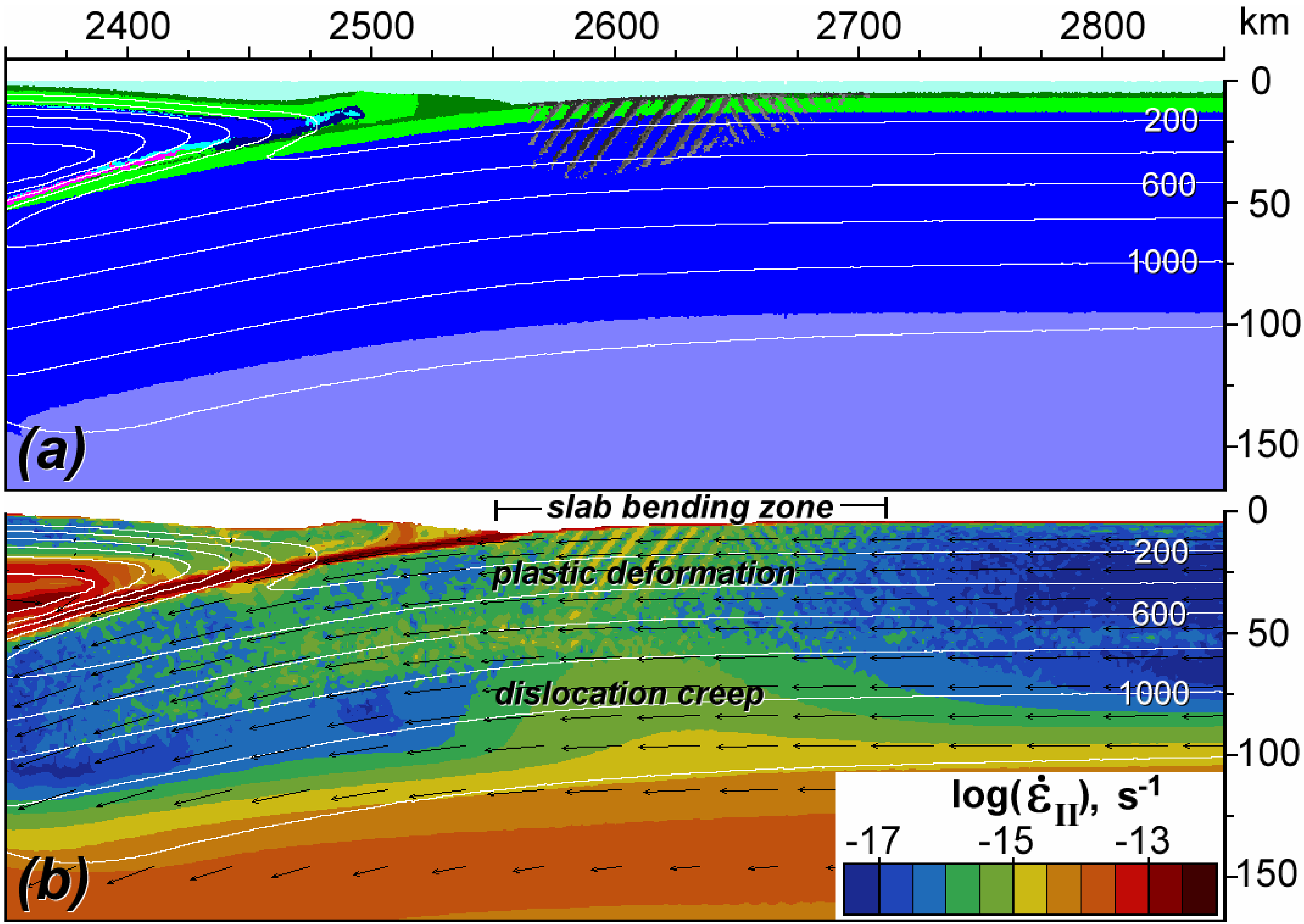
Turcotte & Schubert (1982)



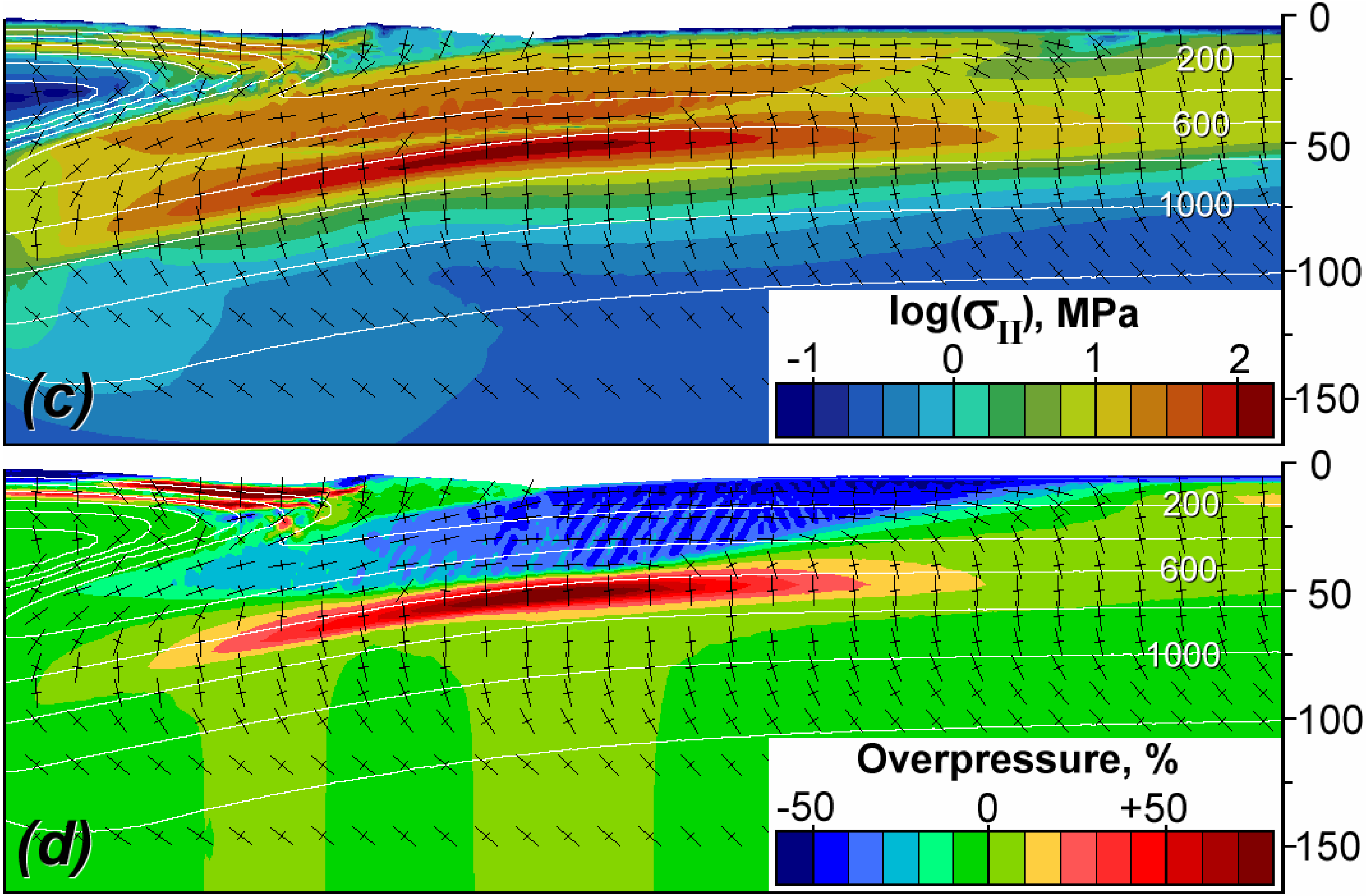
Why is it so easy to bend slabs?

Because bending is natural !



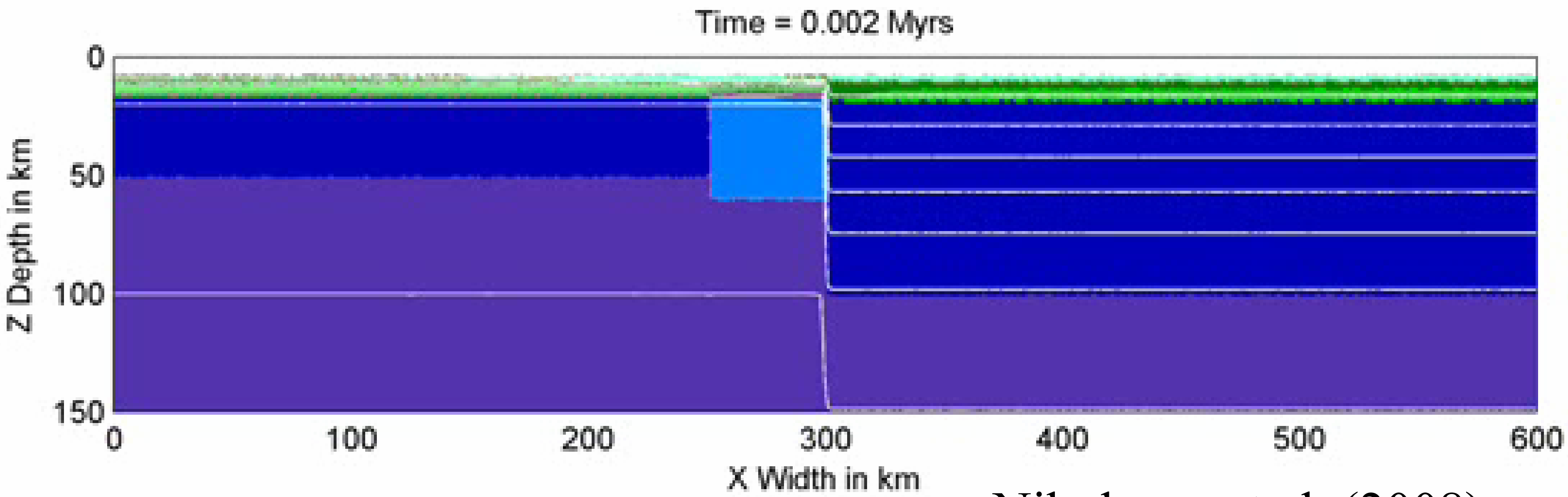


2400
2500
2600
2700
2800
km
0
200
600
50
1000
100
150
(a)
slab bending zone
0
200
plastic deformation
600
50
dislocation creep
1000
100
$\log(\dot{\varepsilon}_{II})$, s^{-1}
-17
-15
-13
150
(b)

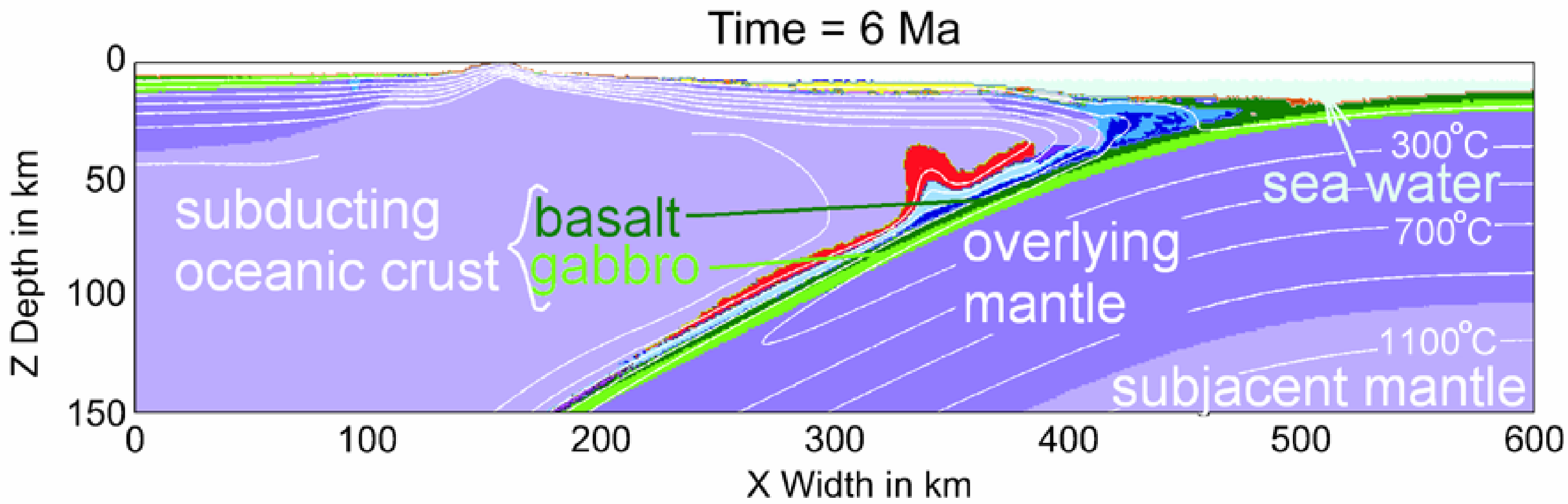


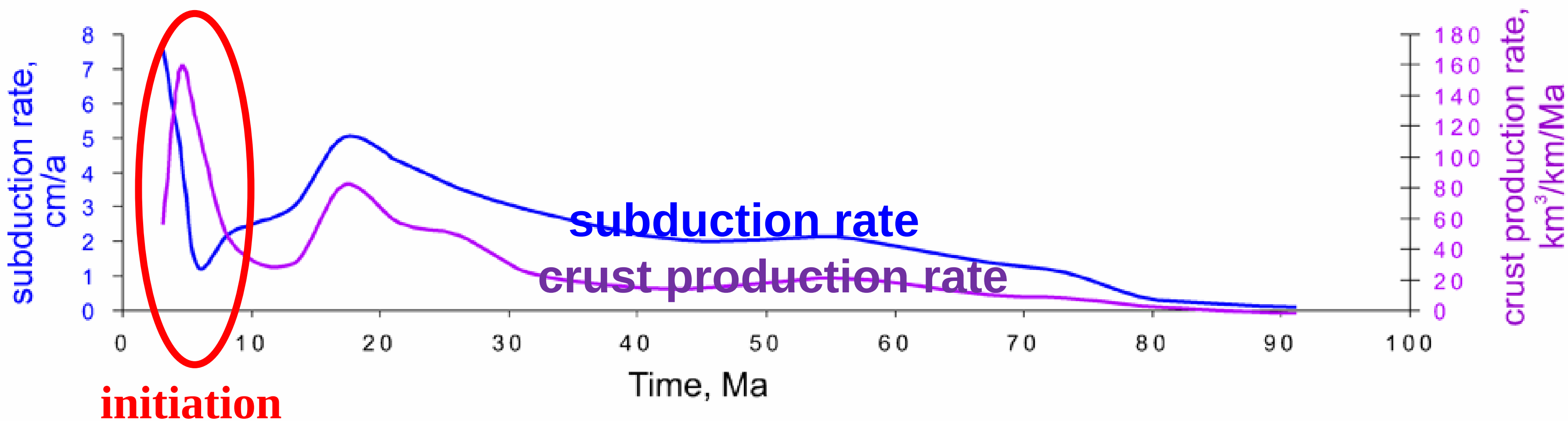
0
200
600
50
1000
100
150
log(σ_II), MPa
-1
0
1
2
(c)
0
200
600
50
1000
100
150
Overpressure, %
-50
0
+50
(d)

Spontaneous initiation across an oceanic fracture zone



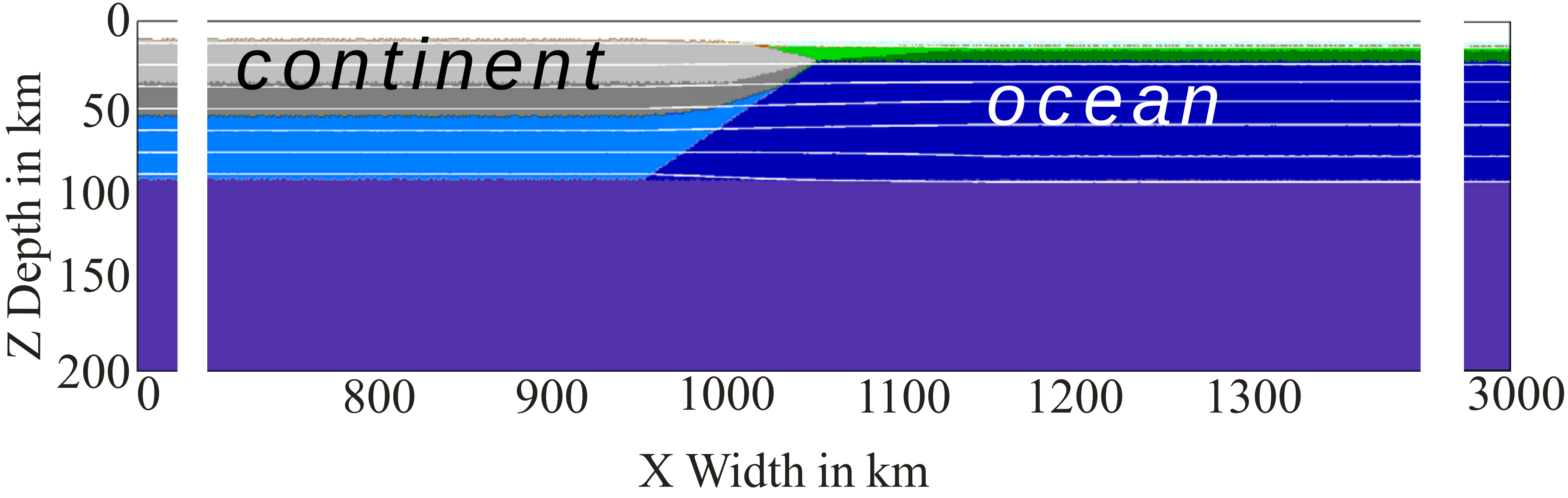
Nikolaeva et al. (2008)





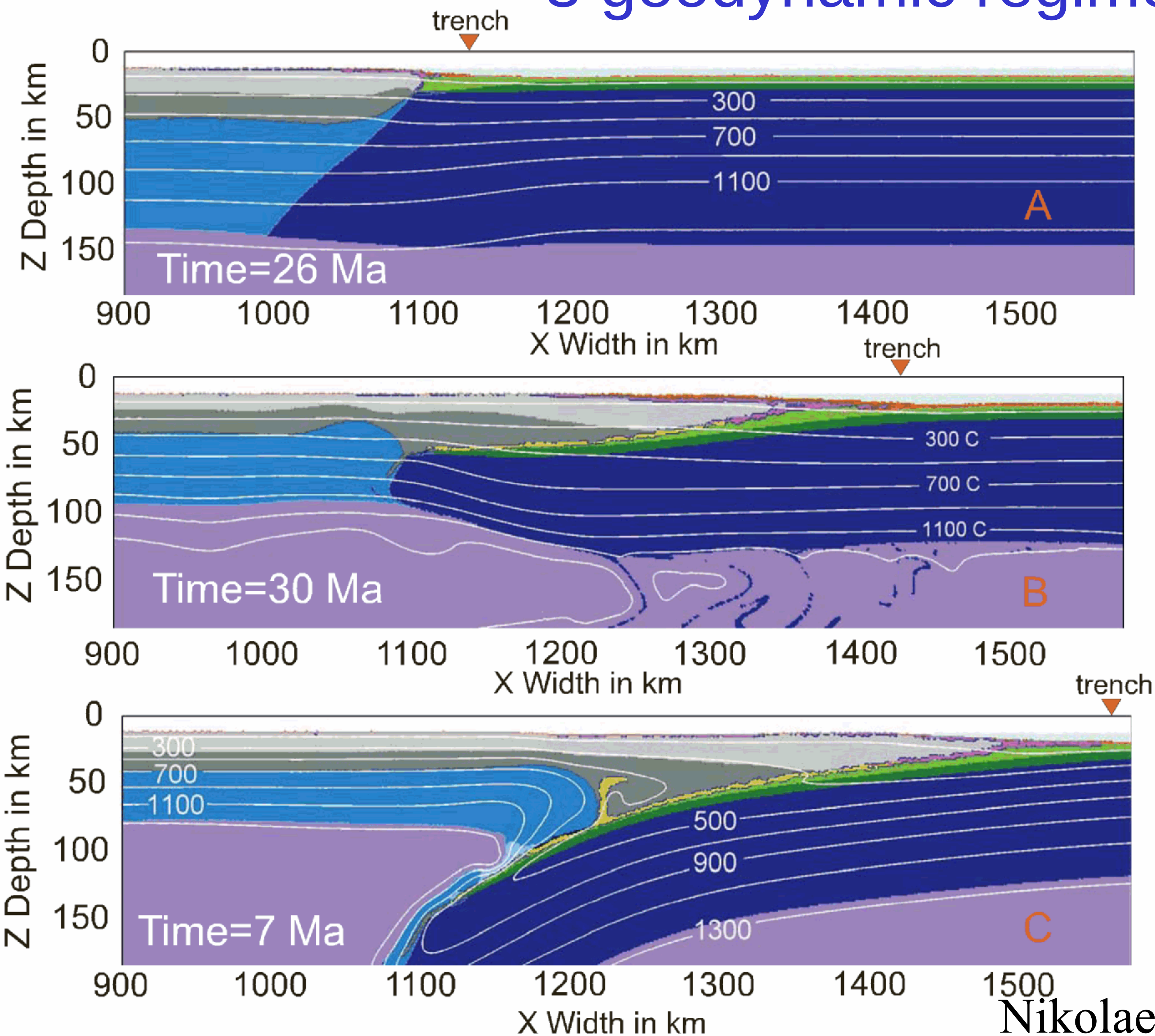
Nikolaeva et al. (2008)

Spontaneous initiation at a passive margin



Nikolaeva et al. (2010)

3 geodynamic regimes

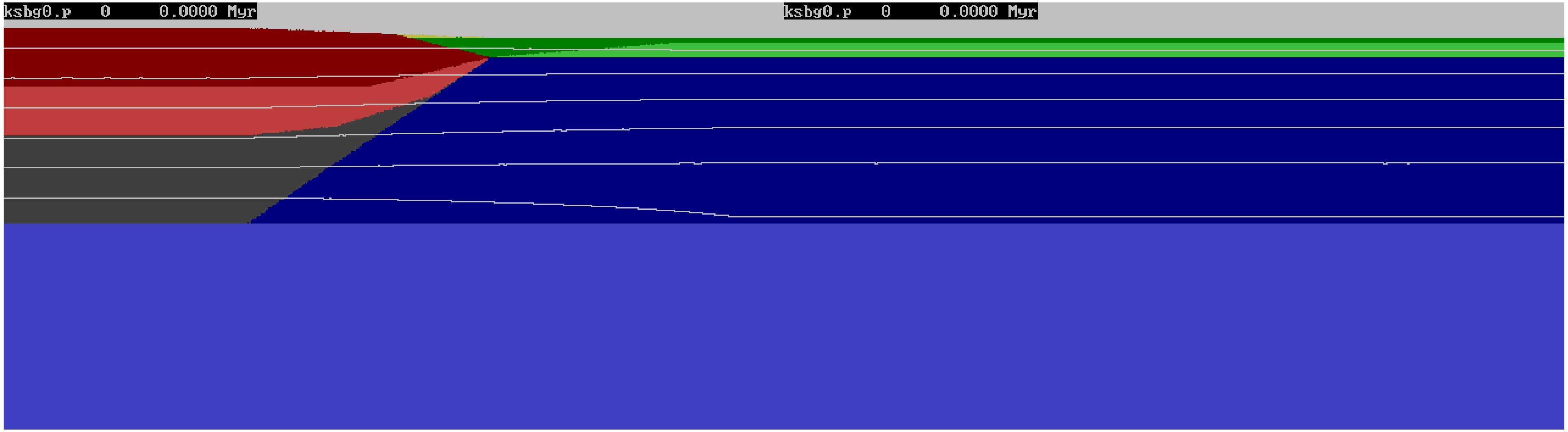


stable margin

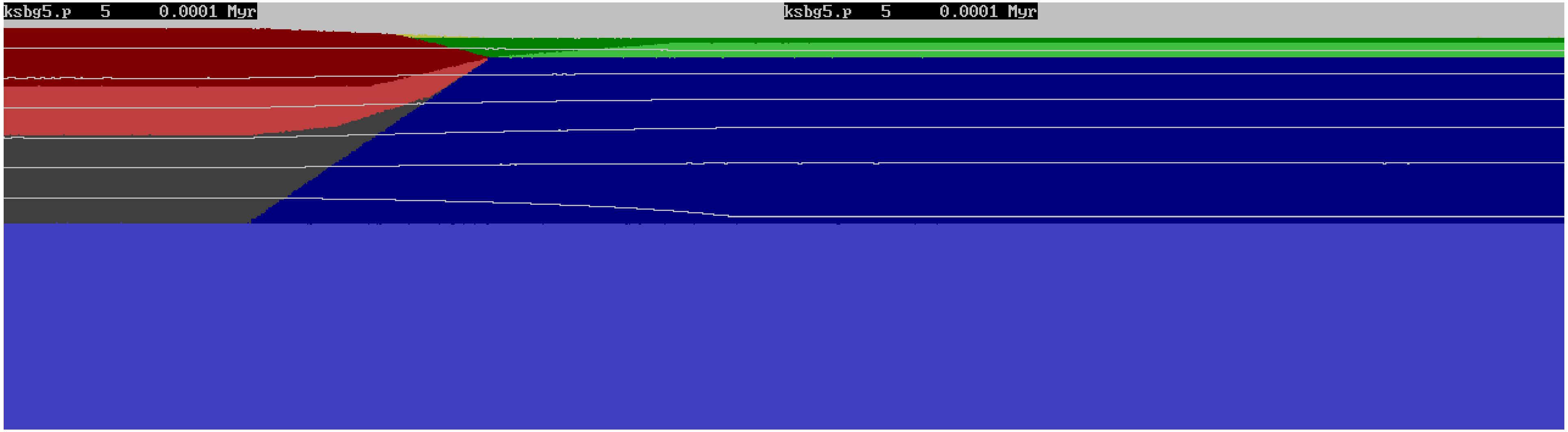
overthrusting

subduction

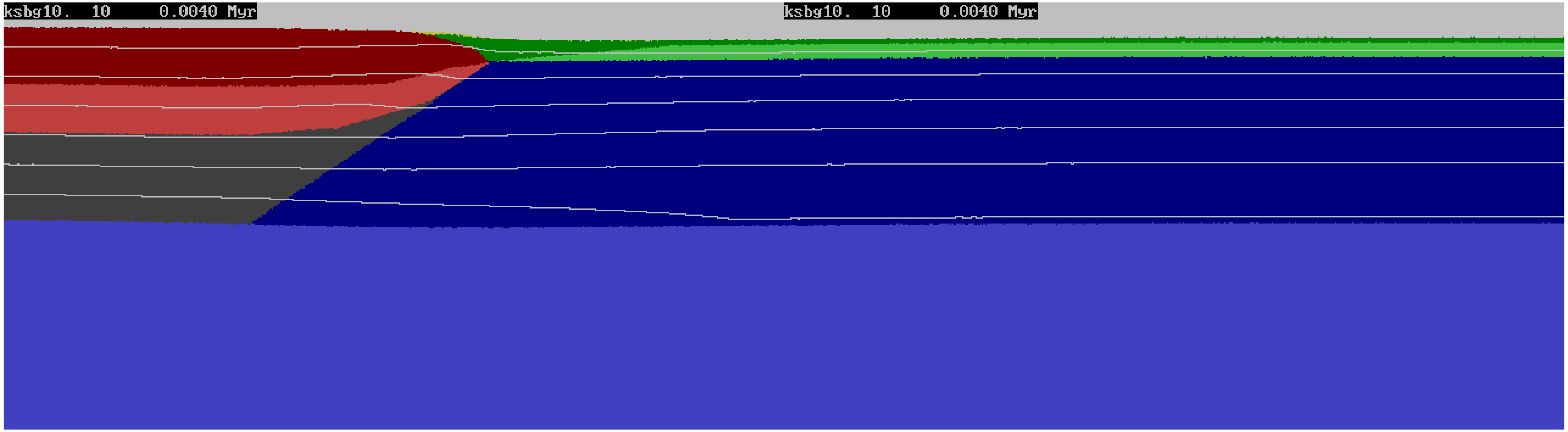
Nikolaeva et al. (2010)



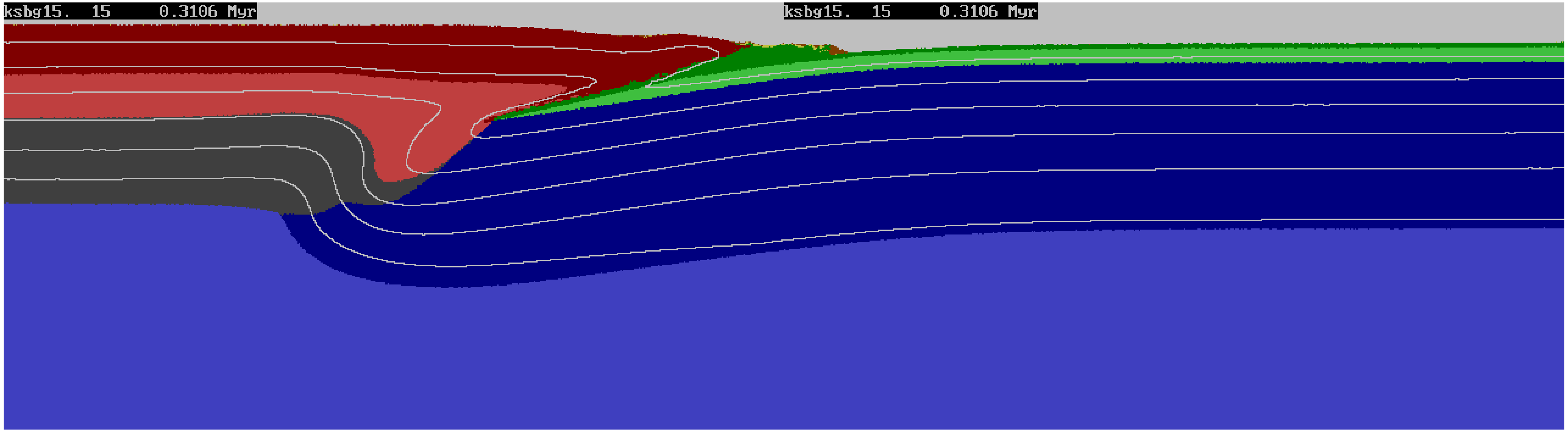
subduction regime



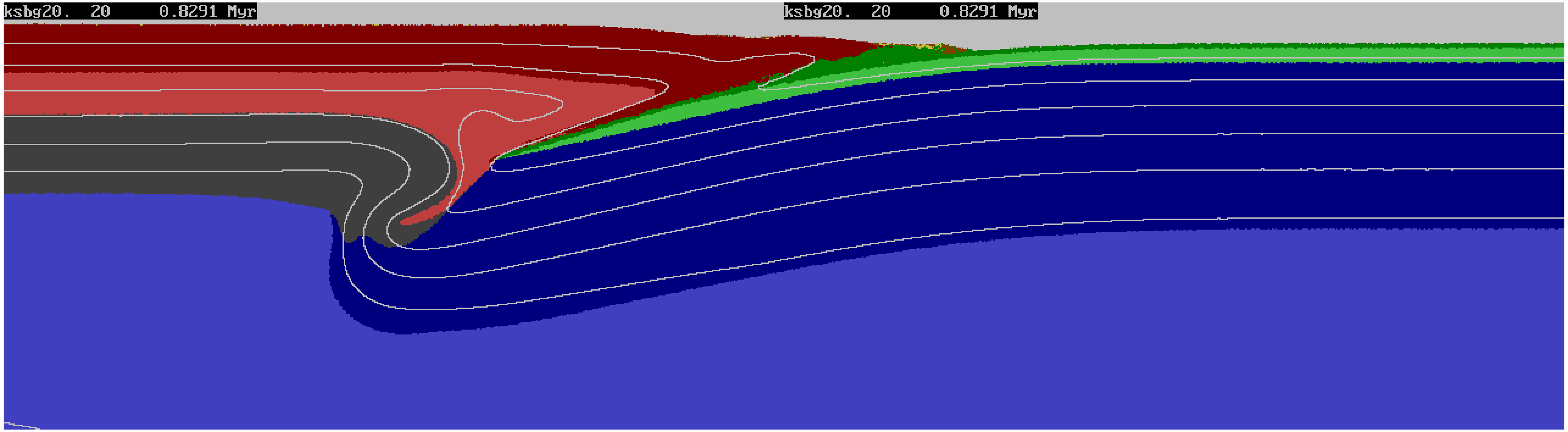
subduction regime



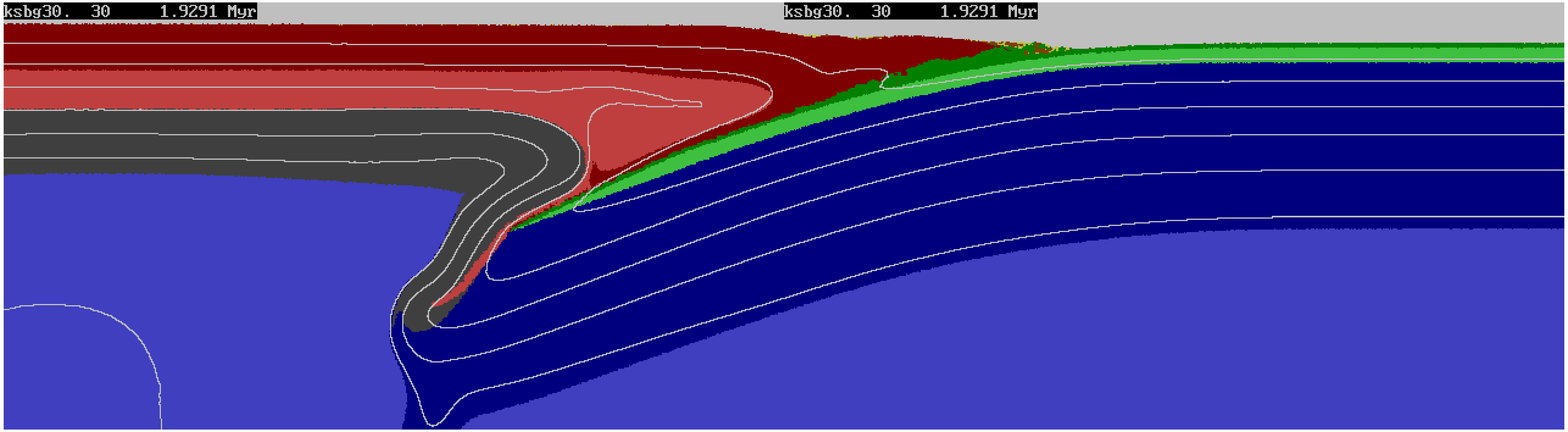
subduction regime



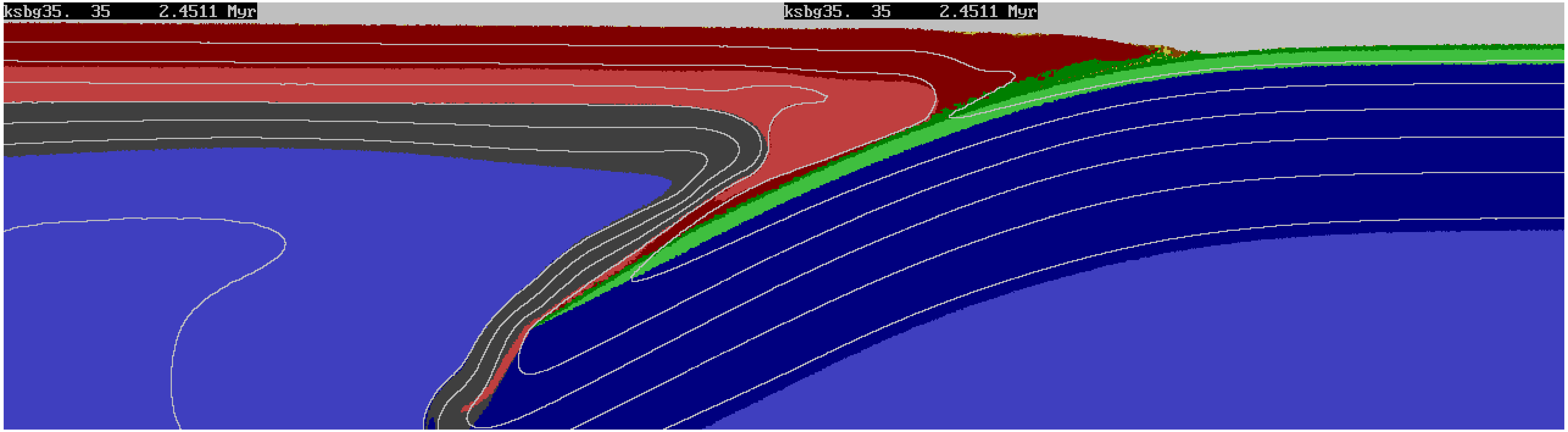
subduction regime



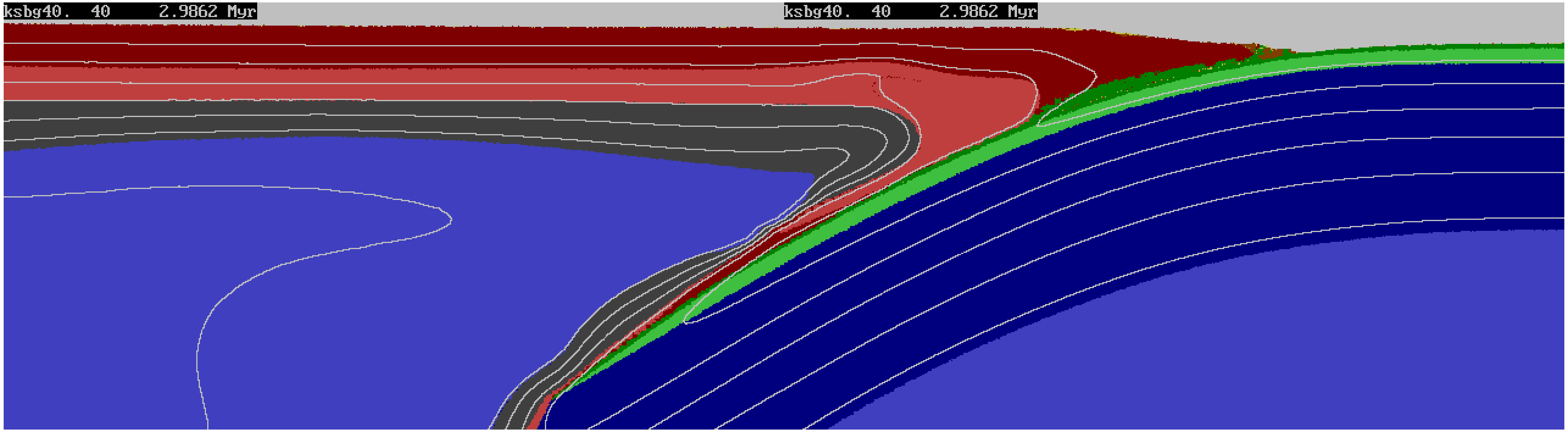
subduction regime



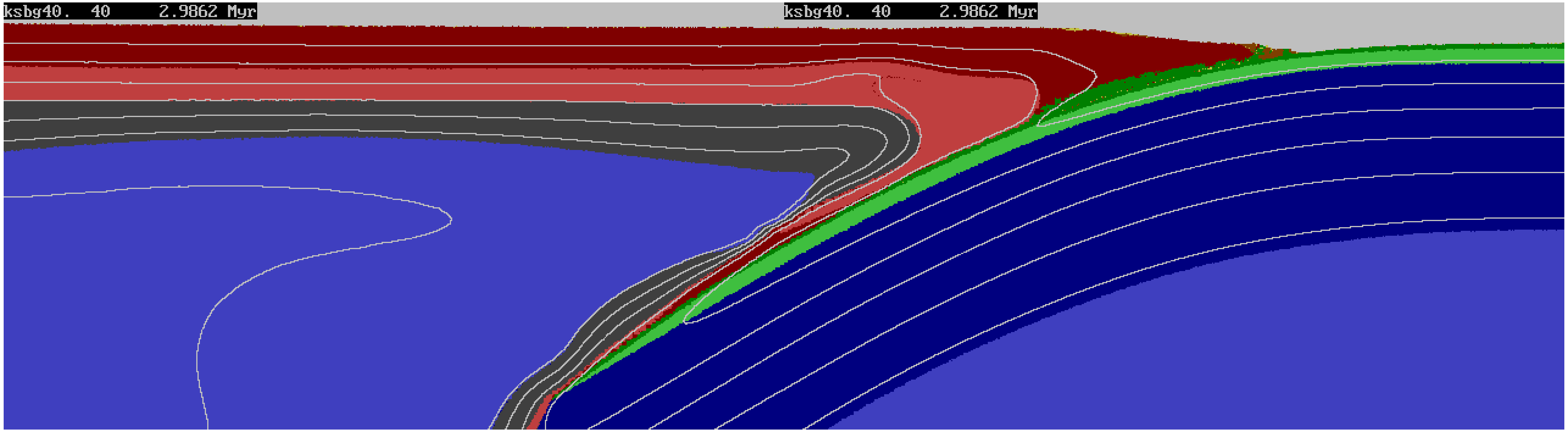
subduction regime



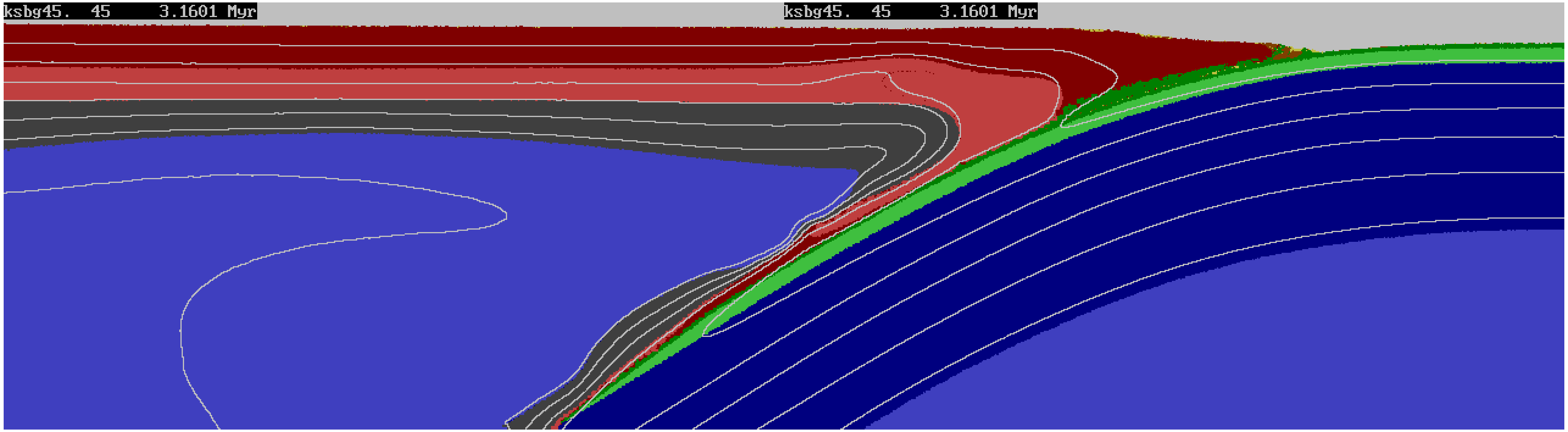
subduction regime



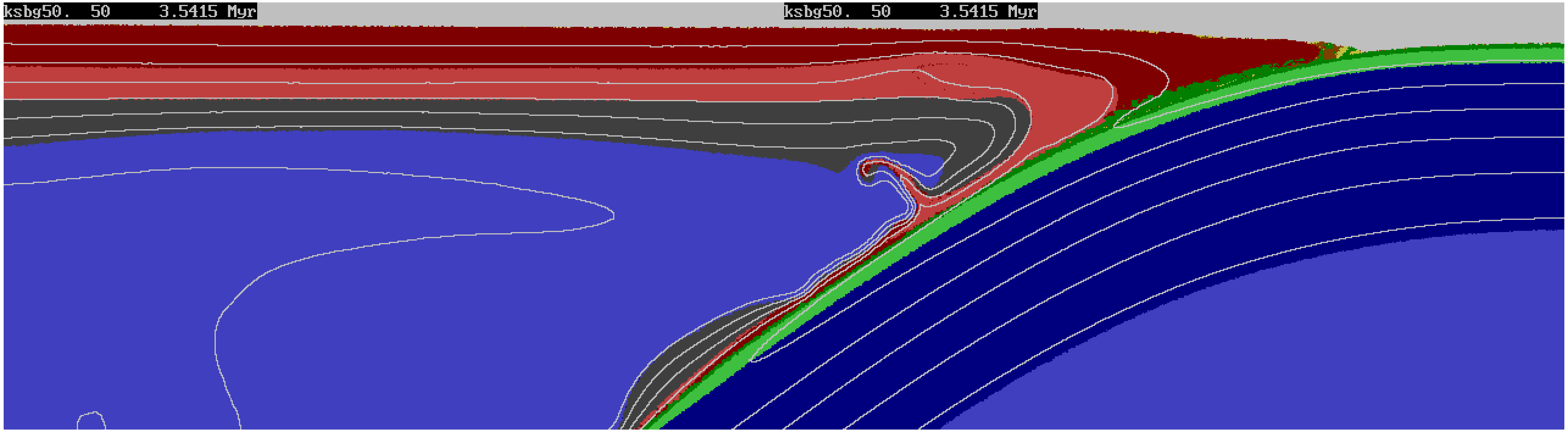
subduction regime



subduction regime

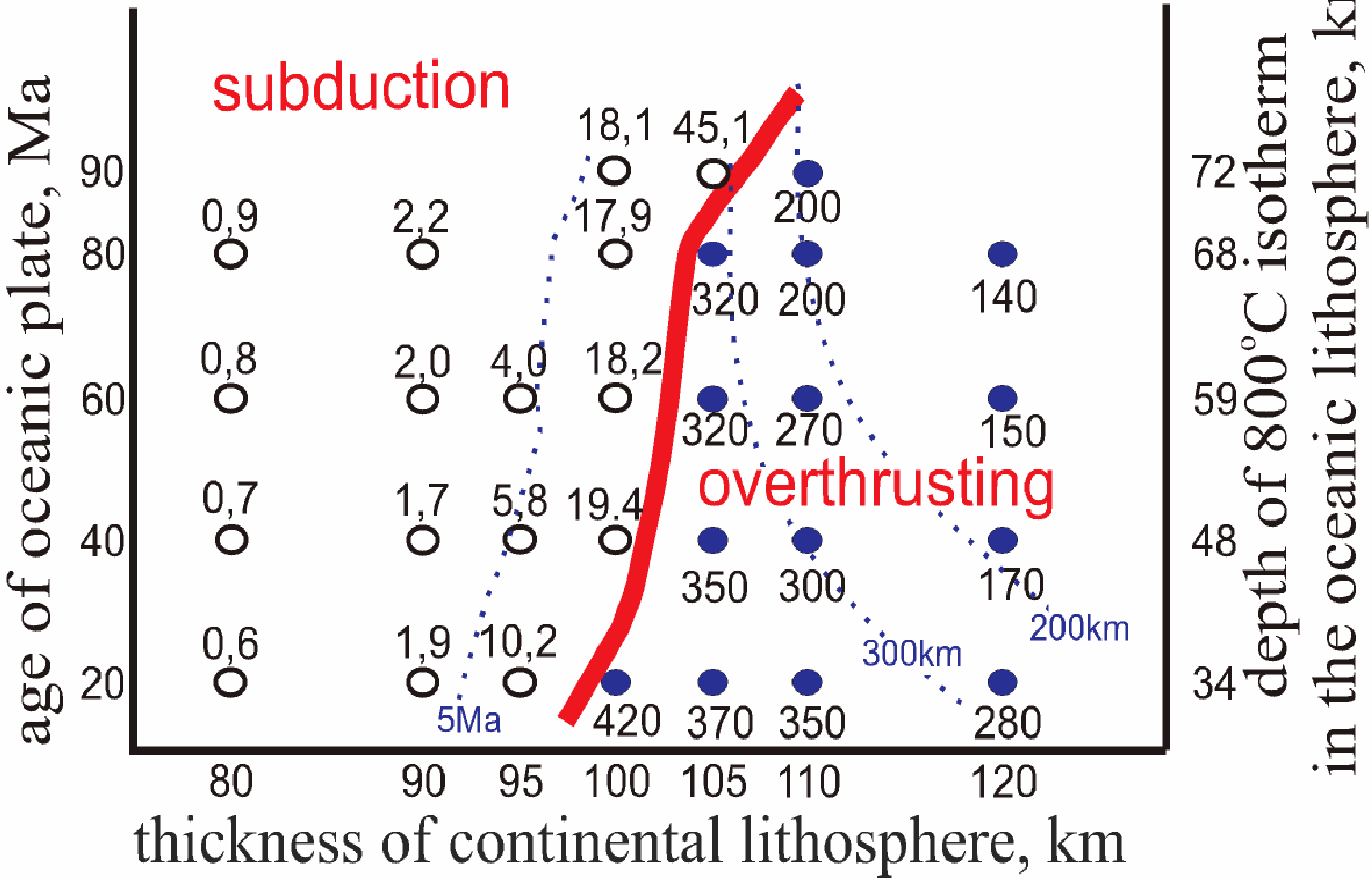


subduction regime



subduction regime

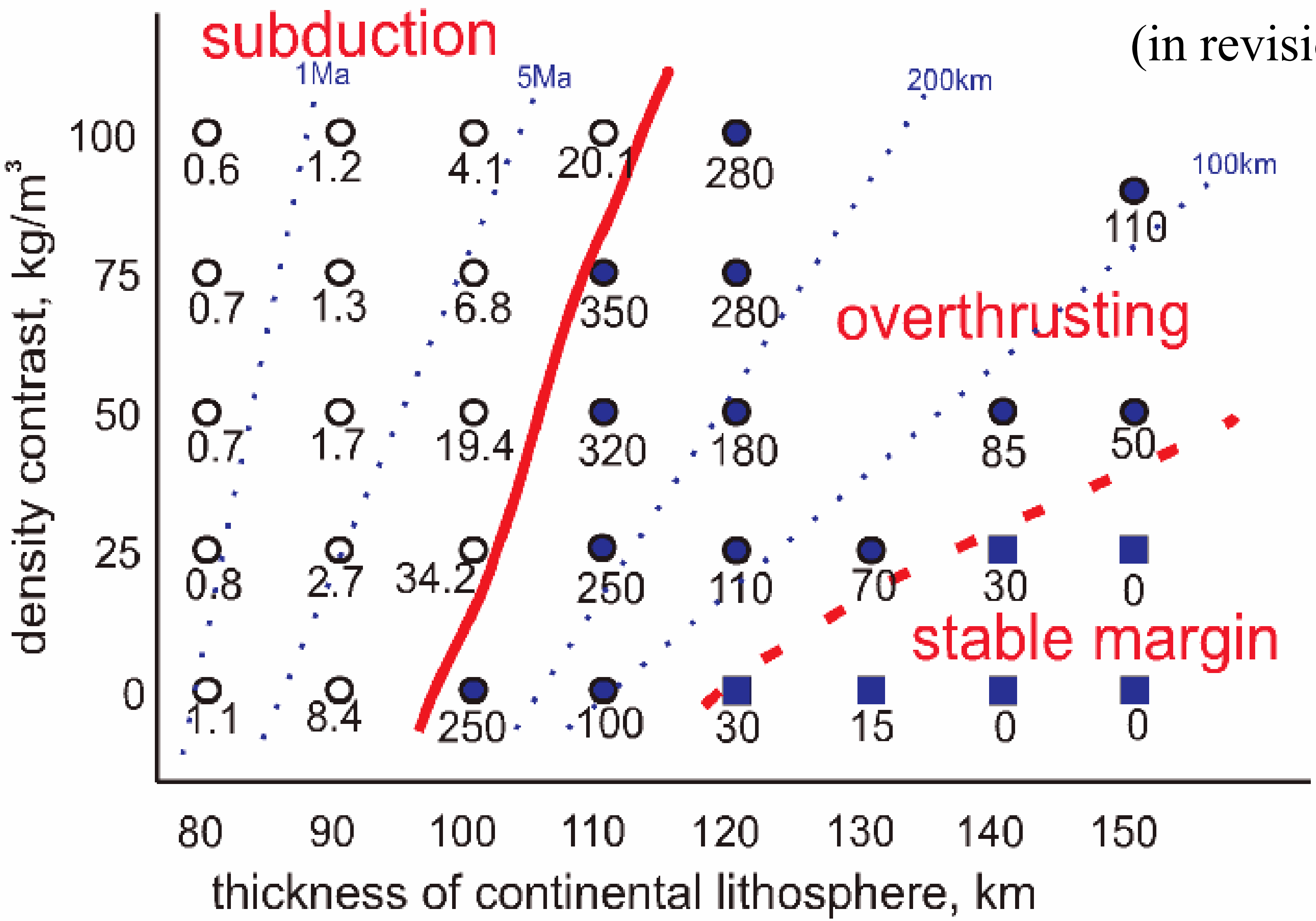
Nikolaeva et al.(in revision)



The age of the oceanic plate

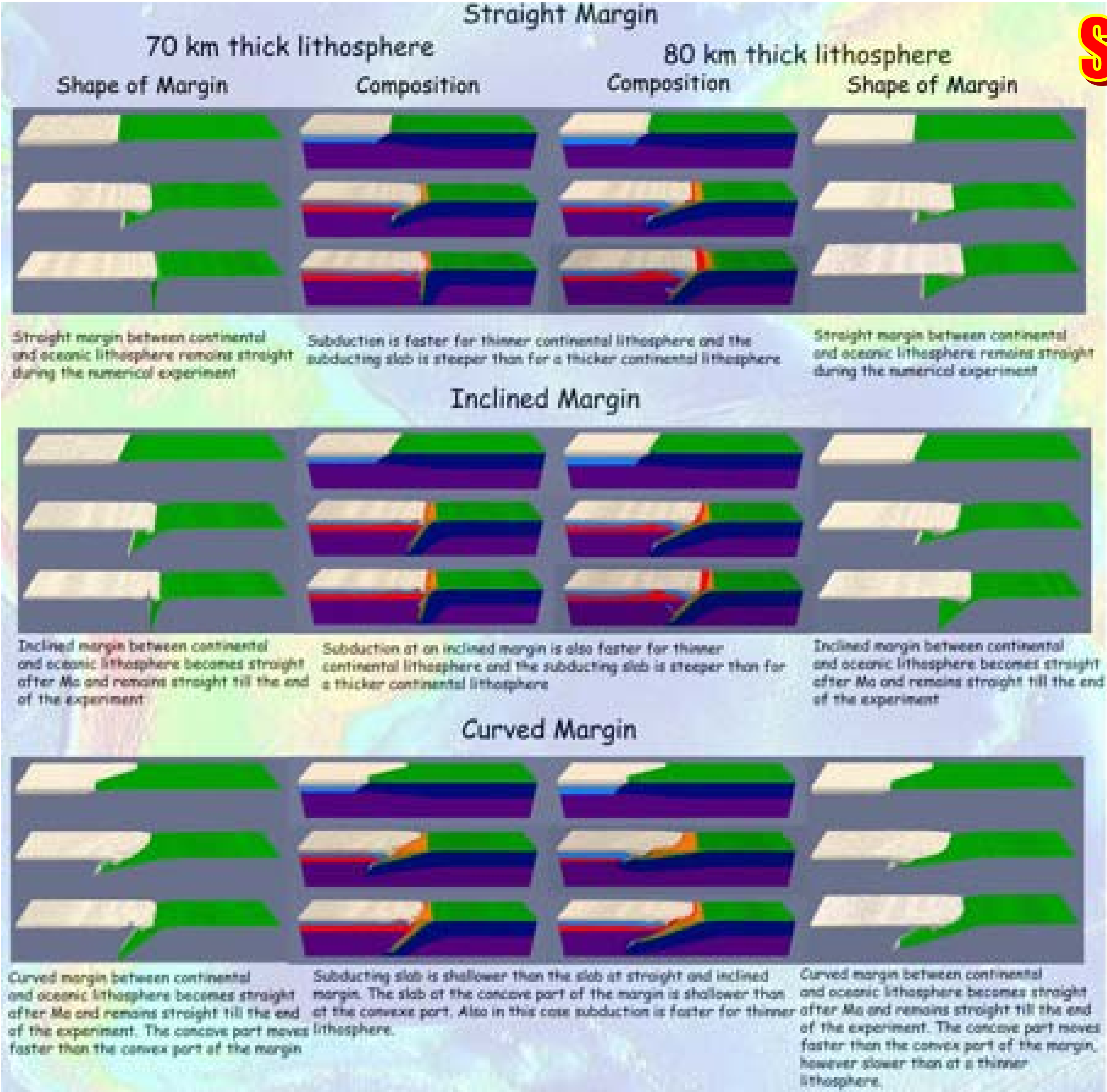
does not play a major role !

Nikolaeva et al.
(in revision)

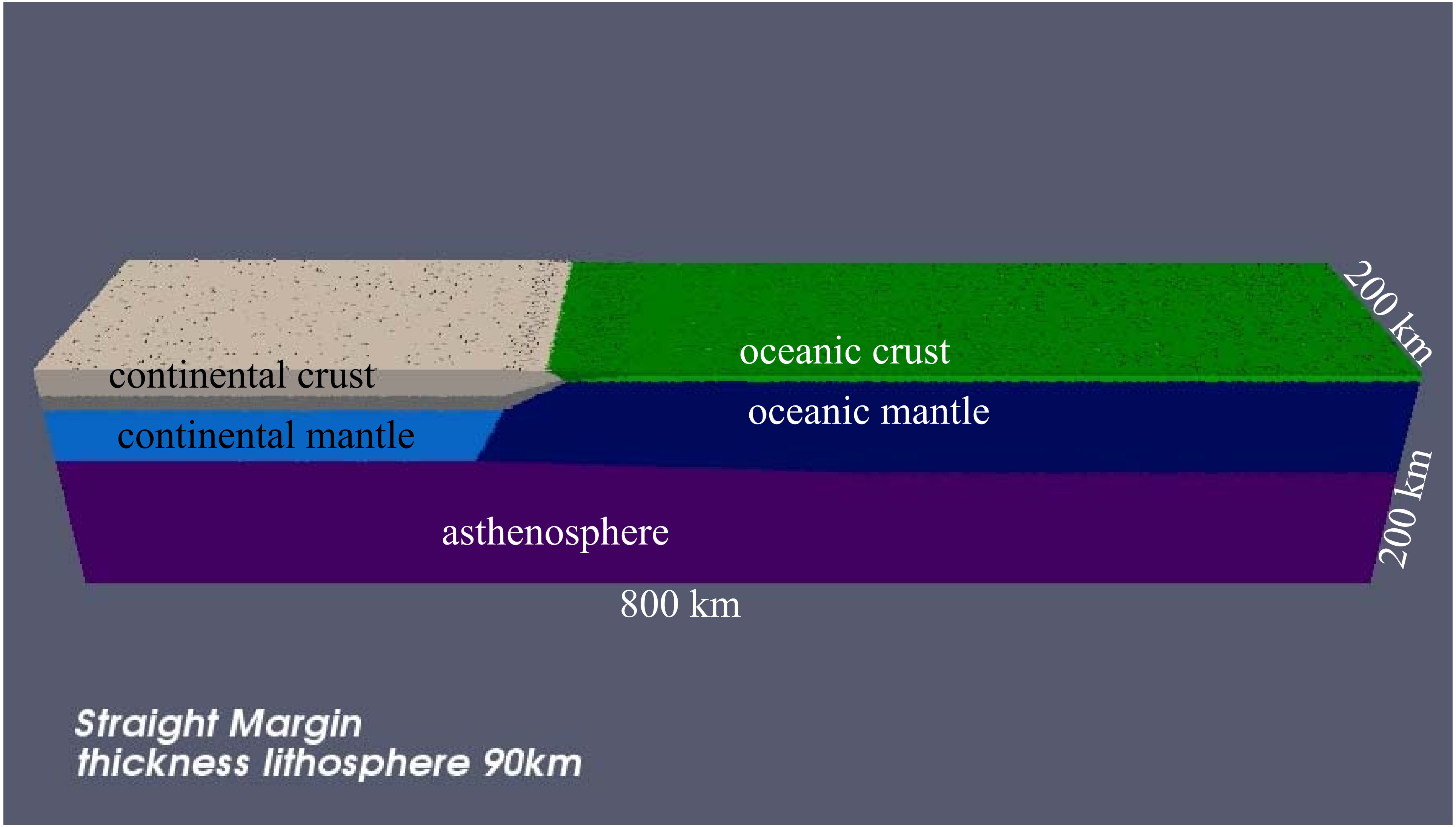


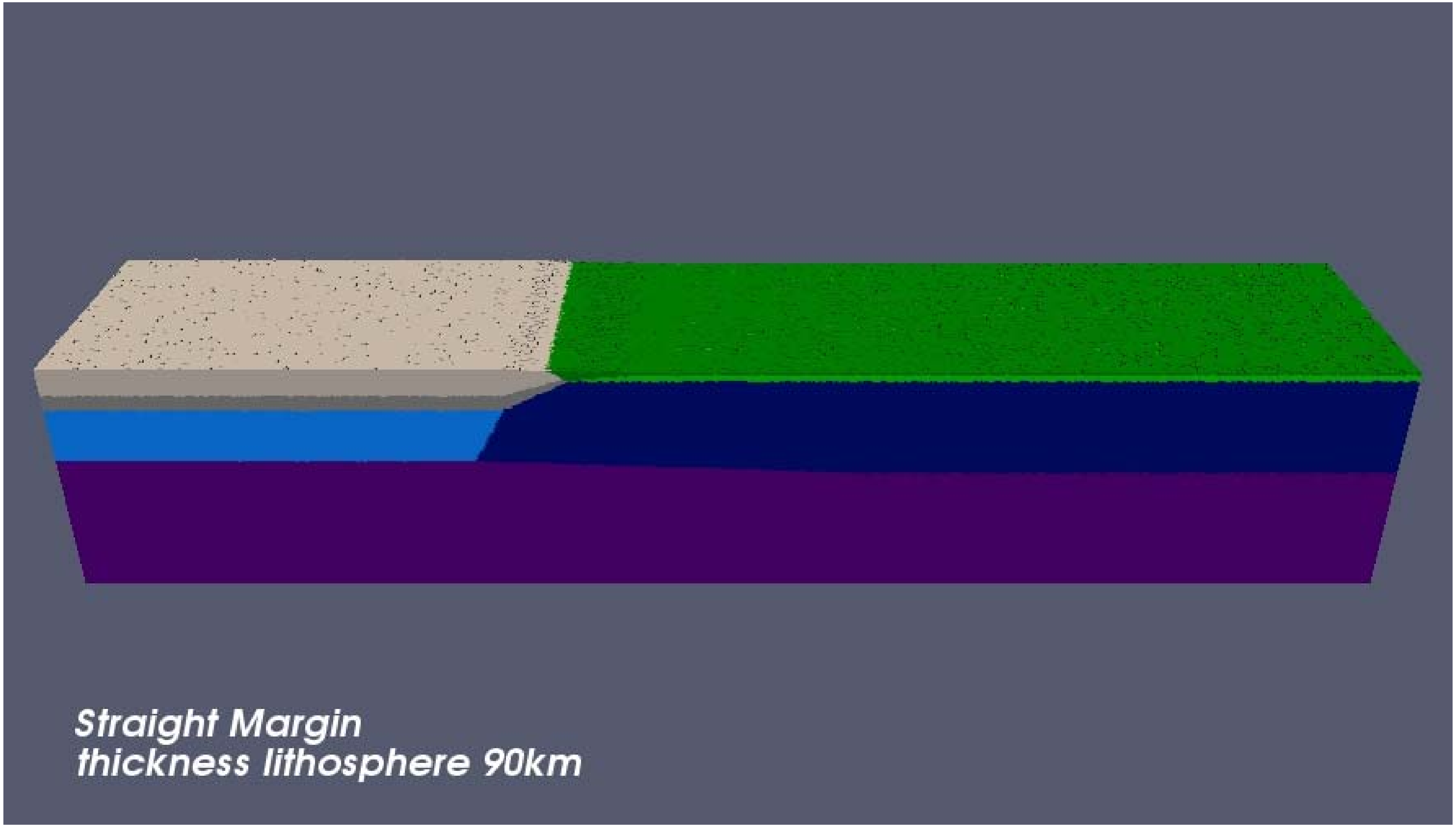
Thin continental lithosphere and
large chemical density contrast between oceanic and continental mantle
favor and speed-up subduction initiation

subduction initiation in 3D

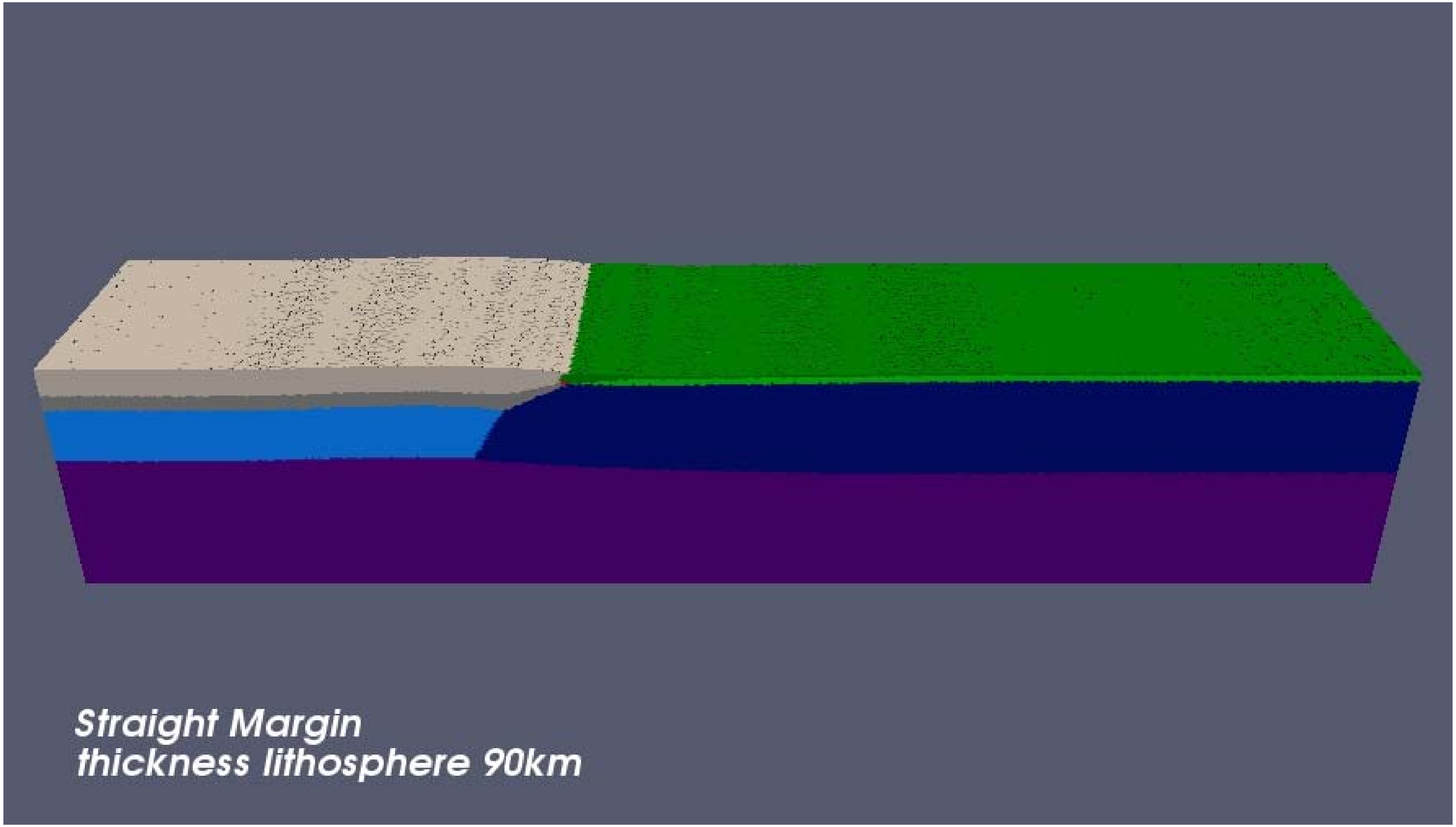


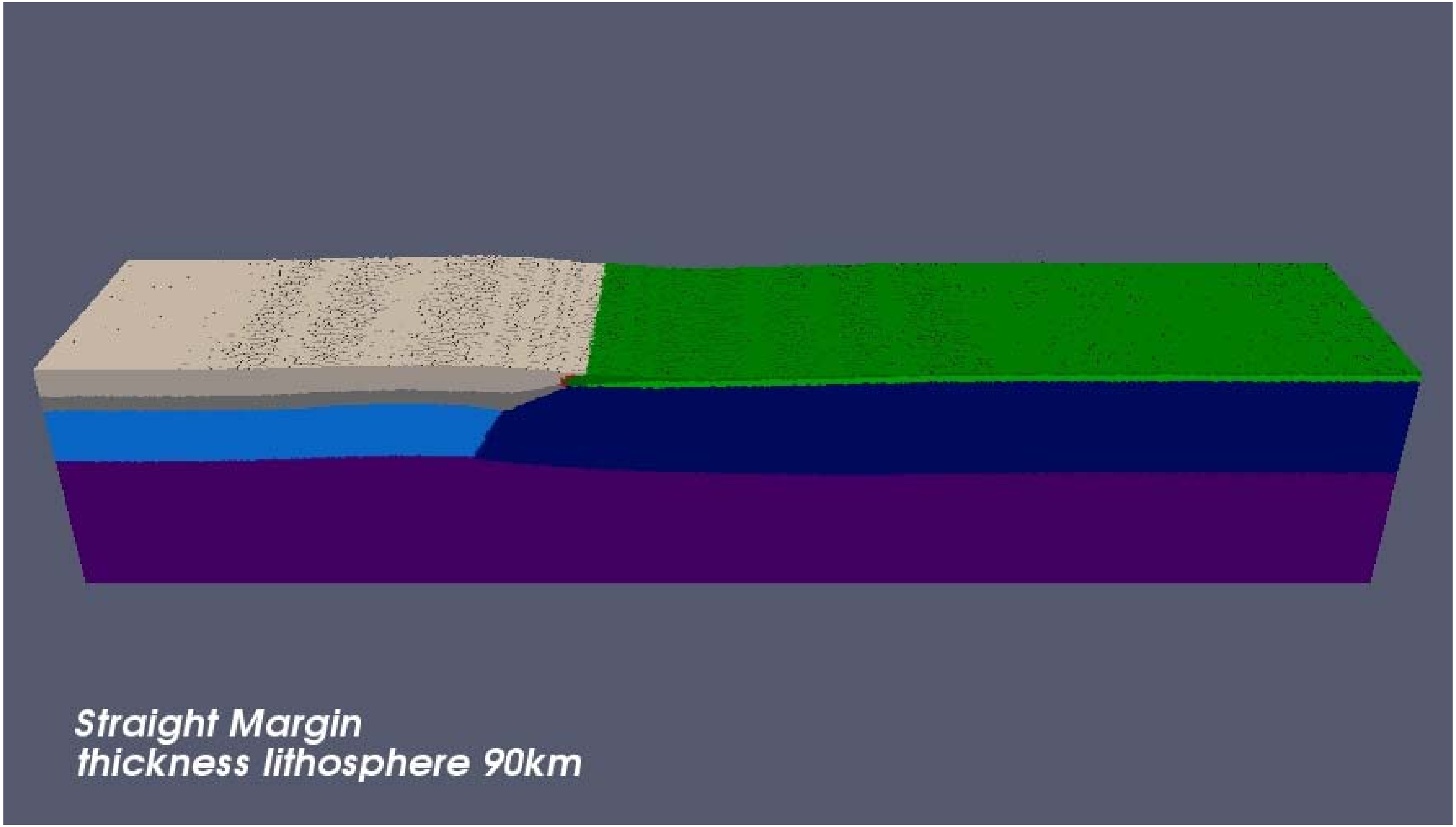
Armann et al.
(in preparation)

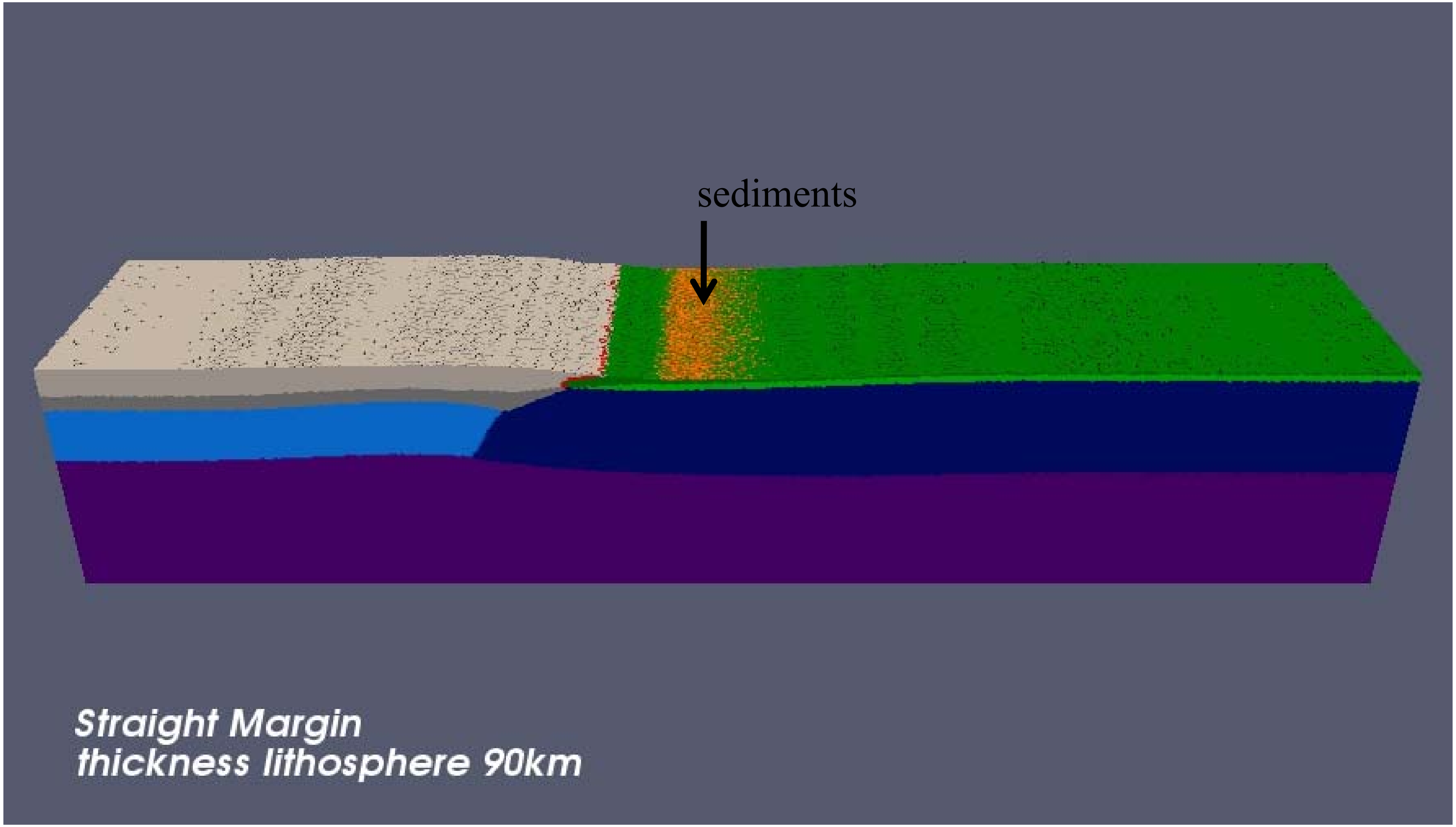

continental crust
continental mantle
oceanic crust
oceanic mantle
asthenosphere
200 km
200 km
800 km
Straight Margin
thickness lithosphere 90km

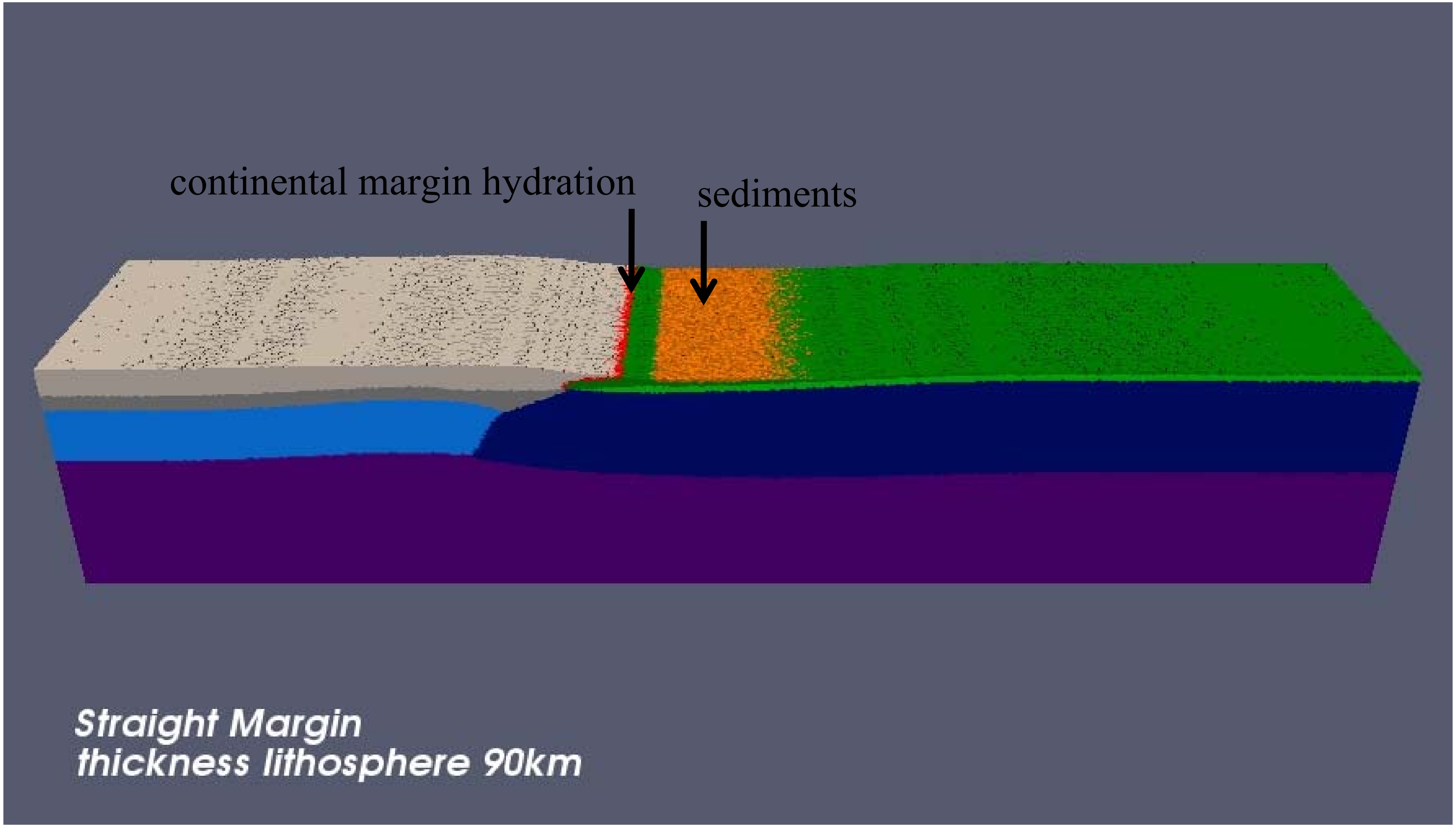

Straight Margin
thickness lithosphere 90km

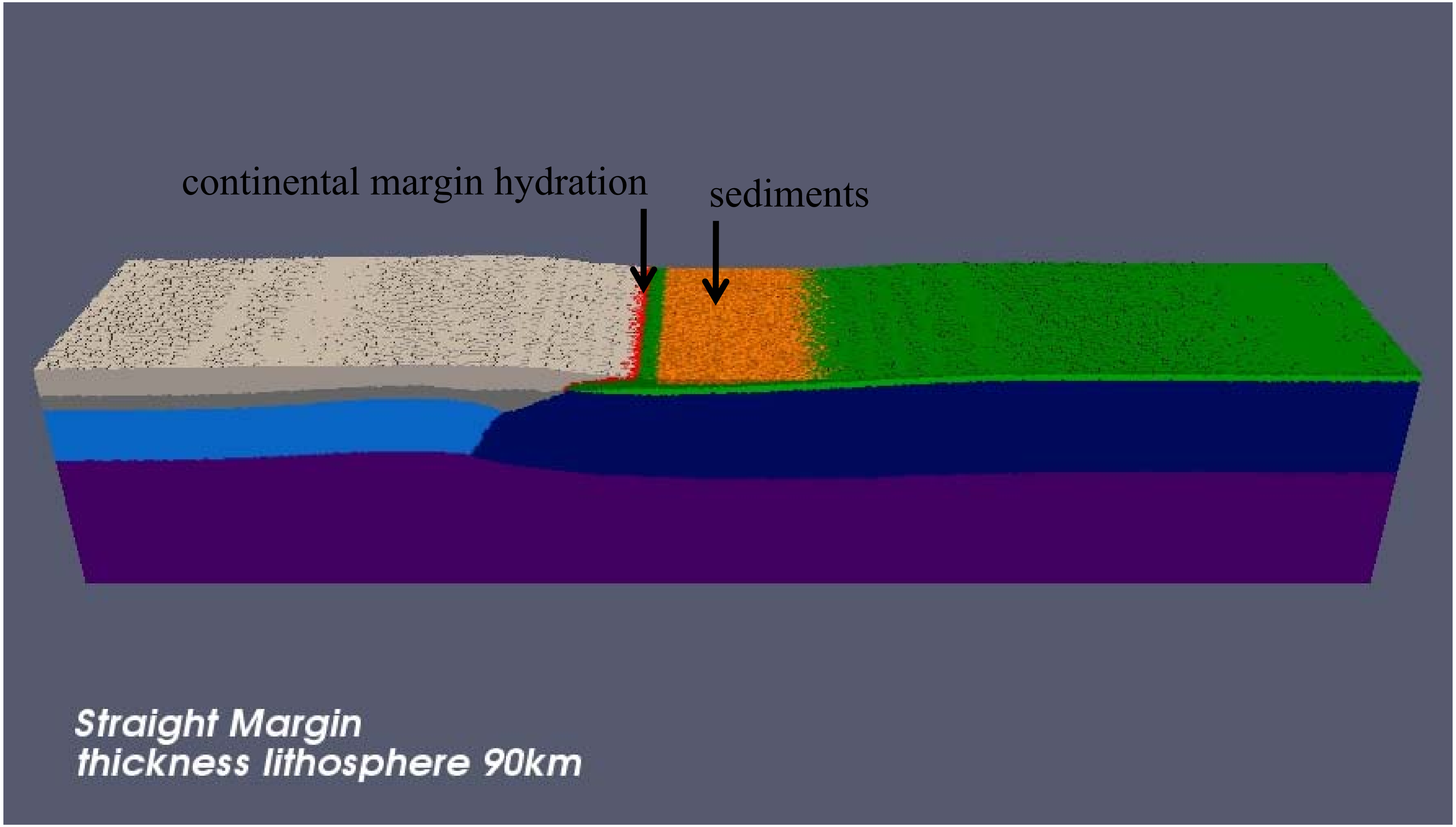
Straight Margin
thickness lithosphere 90km

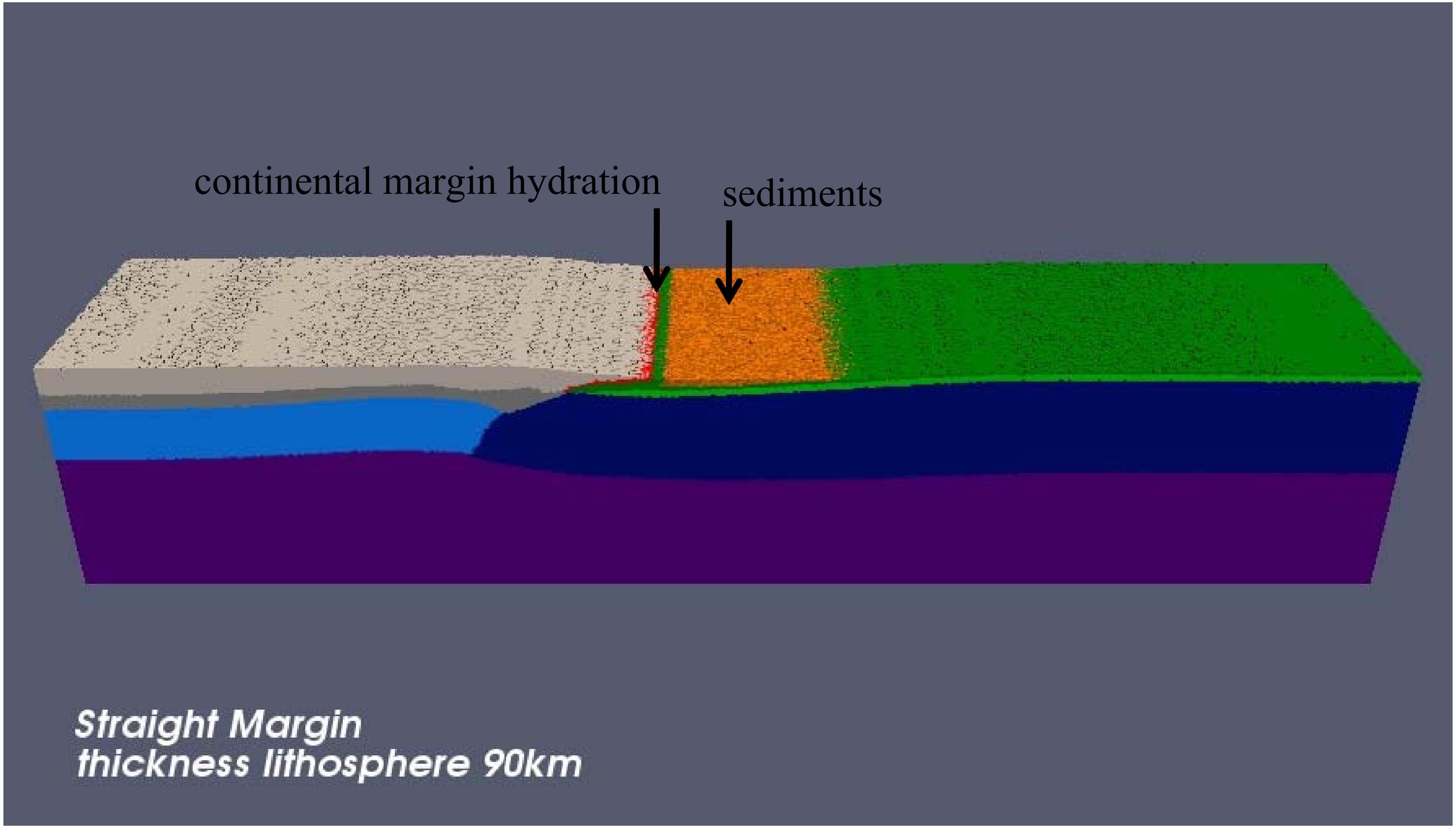

Straight Margin
thickness lithosphere 90km

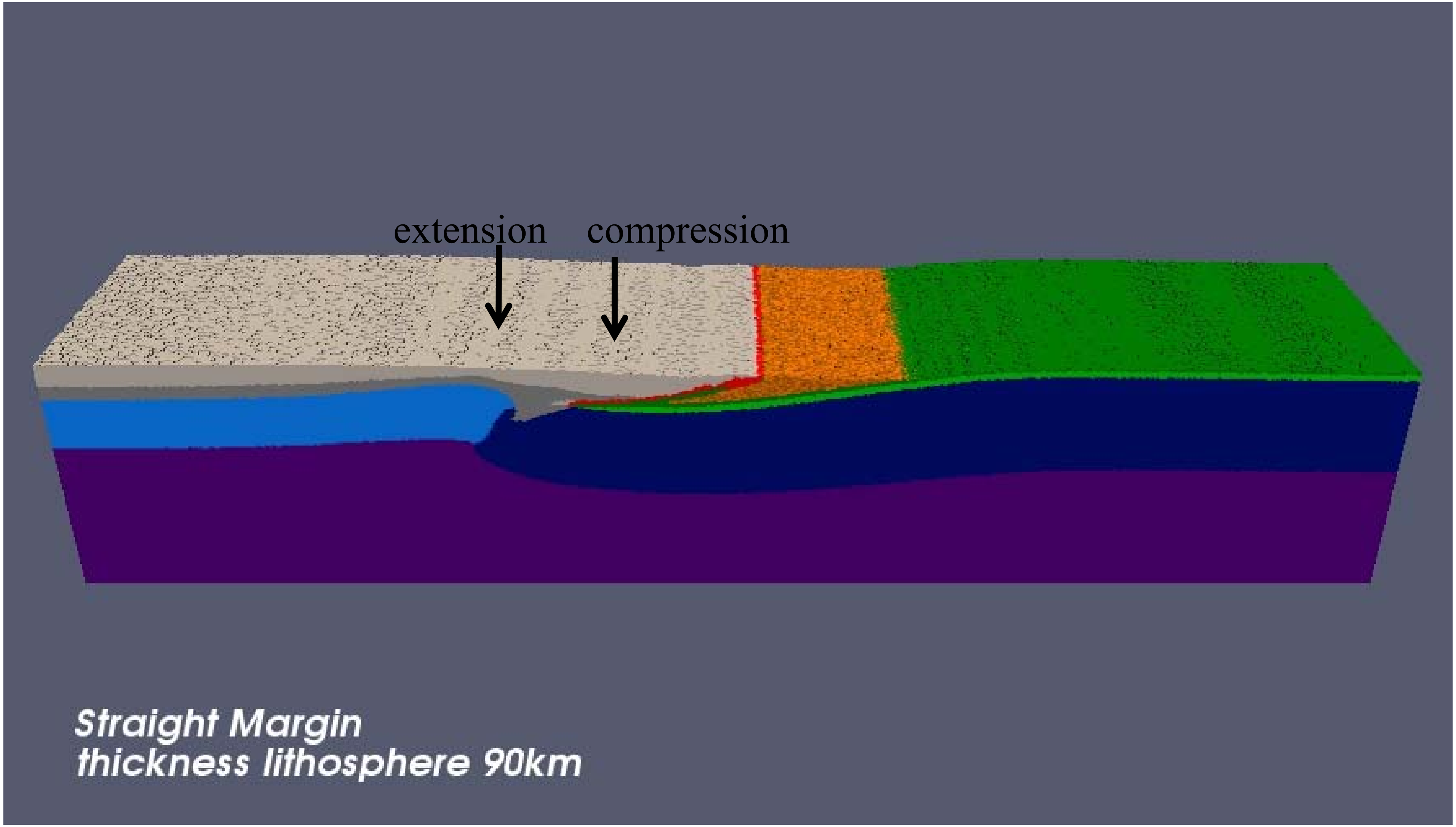

Straight Margin
thickness lithosphere 90km

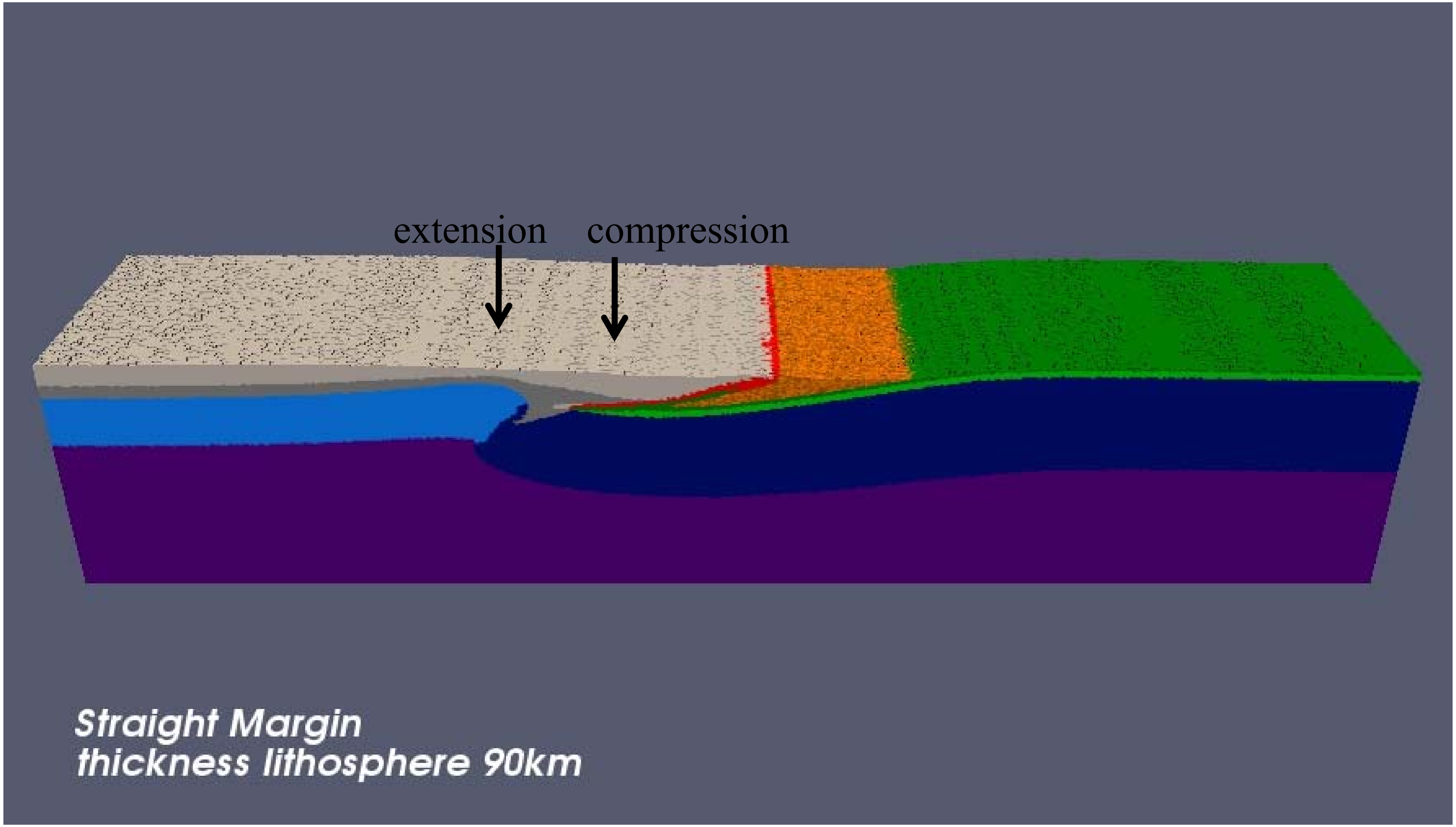

sediments
Straight Margin
thickness lithosphere 90km

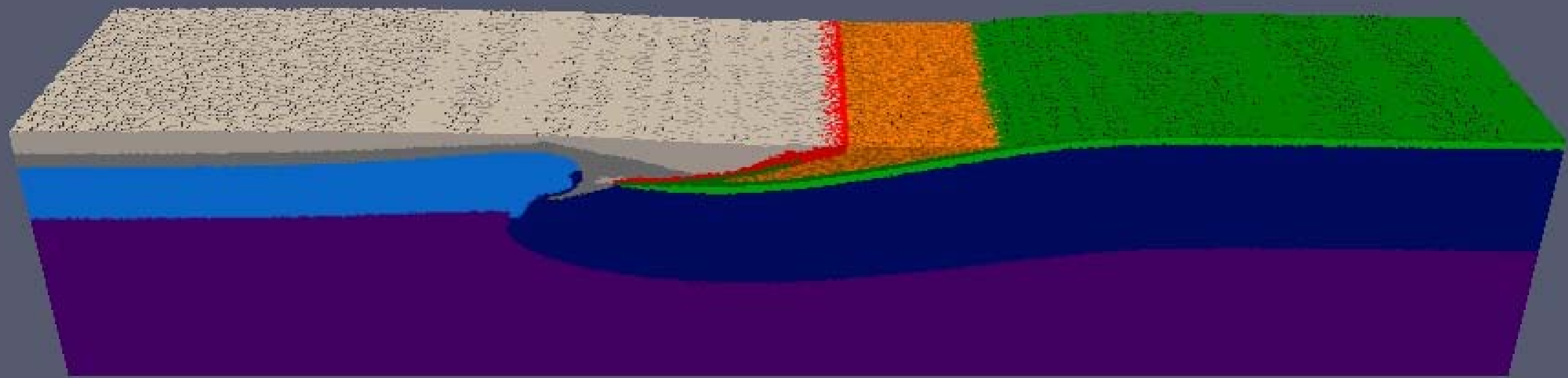

continental margin hydration
sediments
Straight Margin
thickness lithosphere 90km


continental margin hydration
sediments
Straight Margin
thickness lithosphere 90km

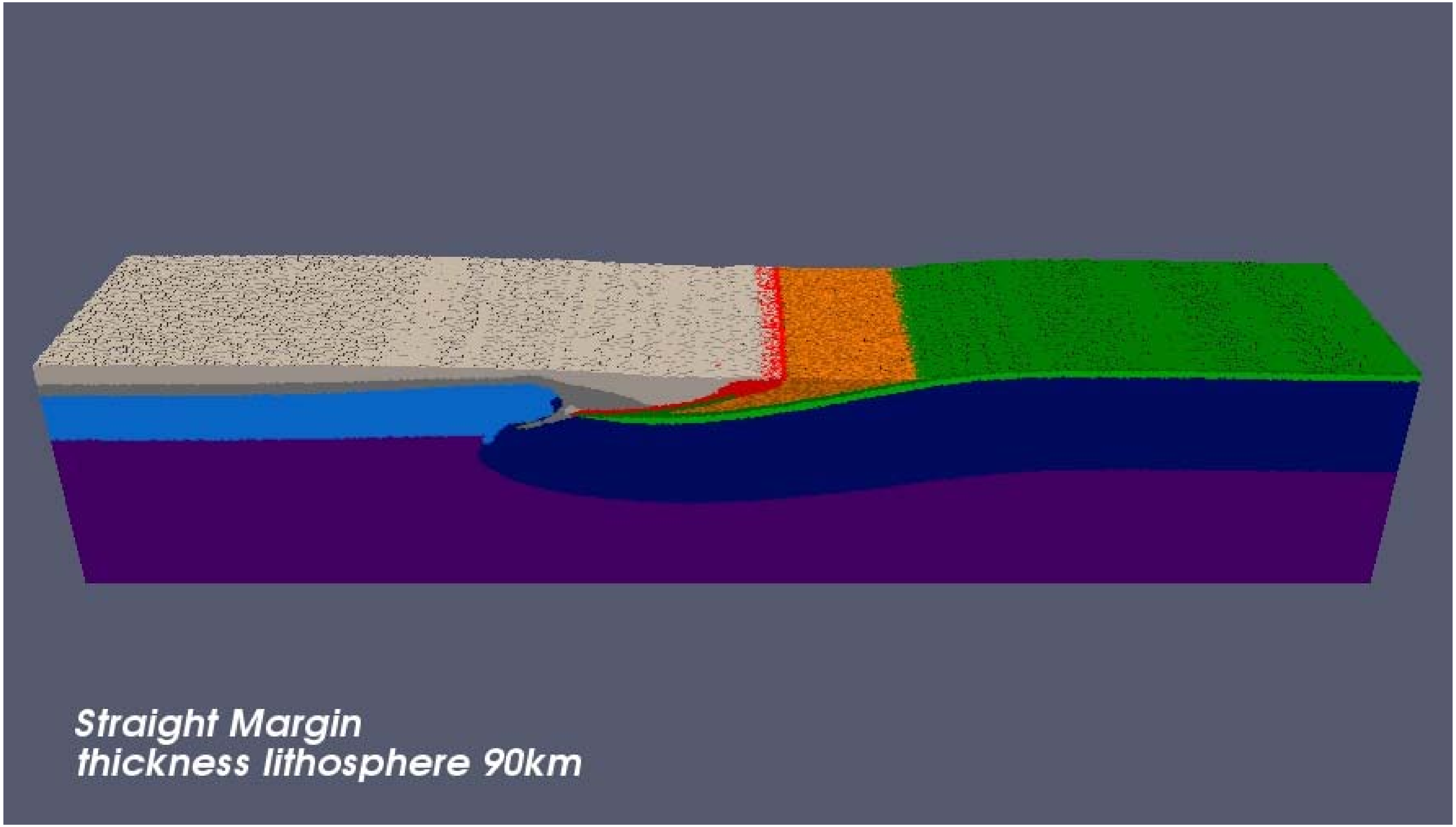

continental margin hydration
sediments
Straight Margin
thickness lithosphere 90km

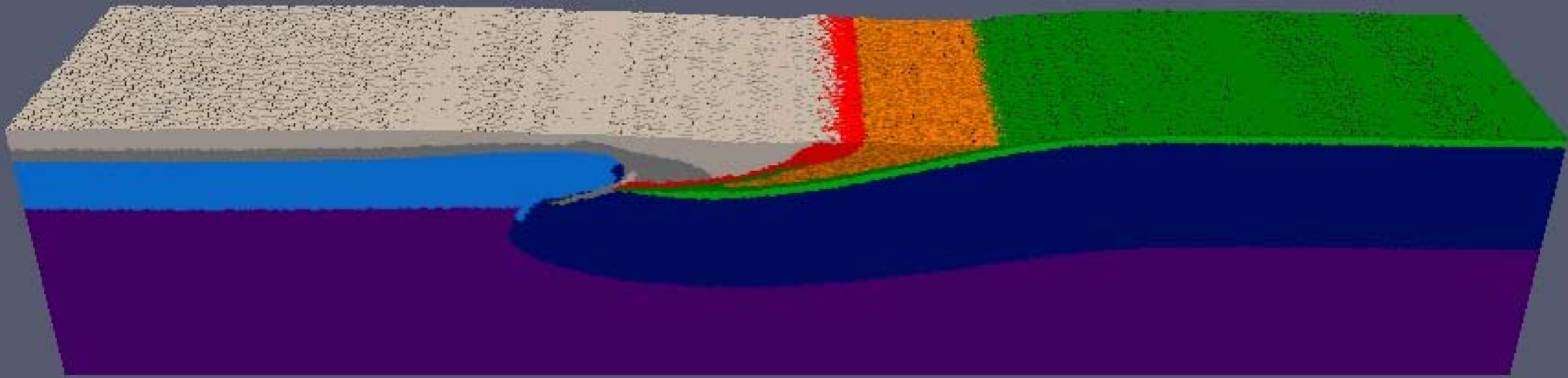

extension
compression
Straight Margin
thickness lithosphere 90km


extension
compression
Straight Margin
thickness lithosphere 90km

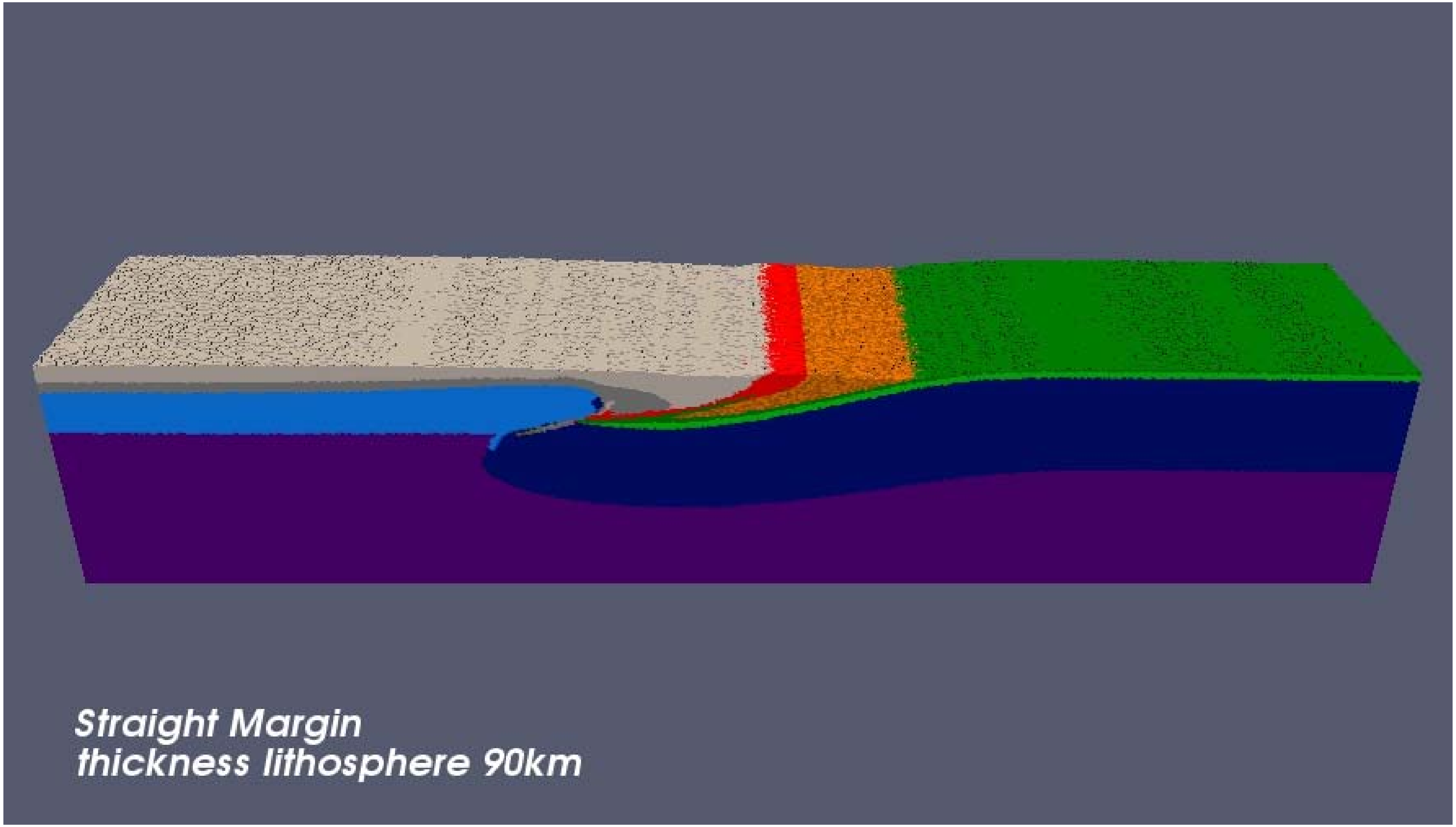


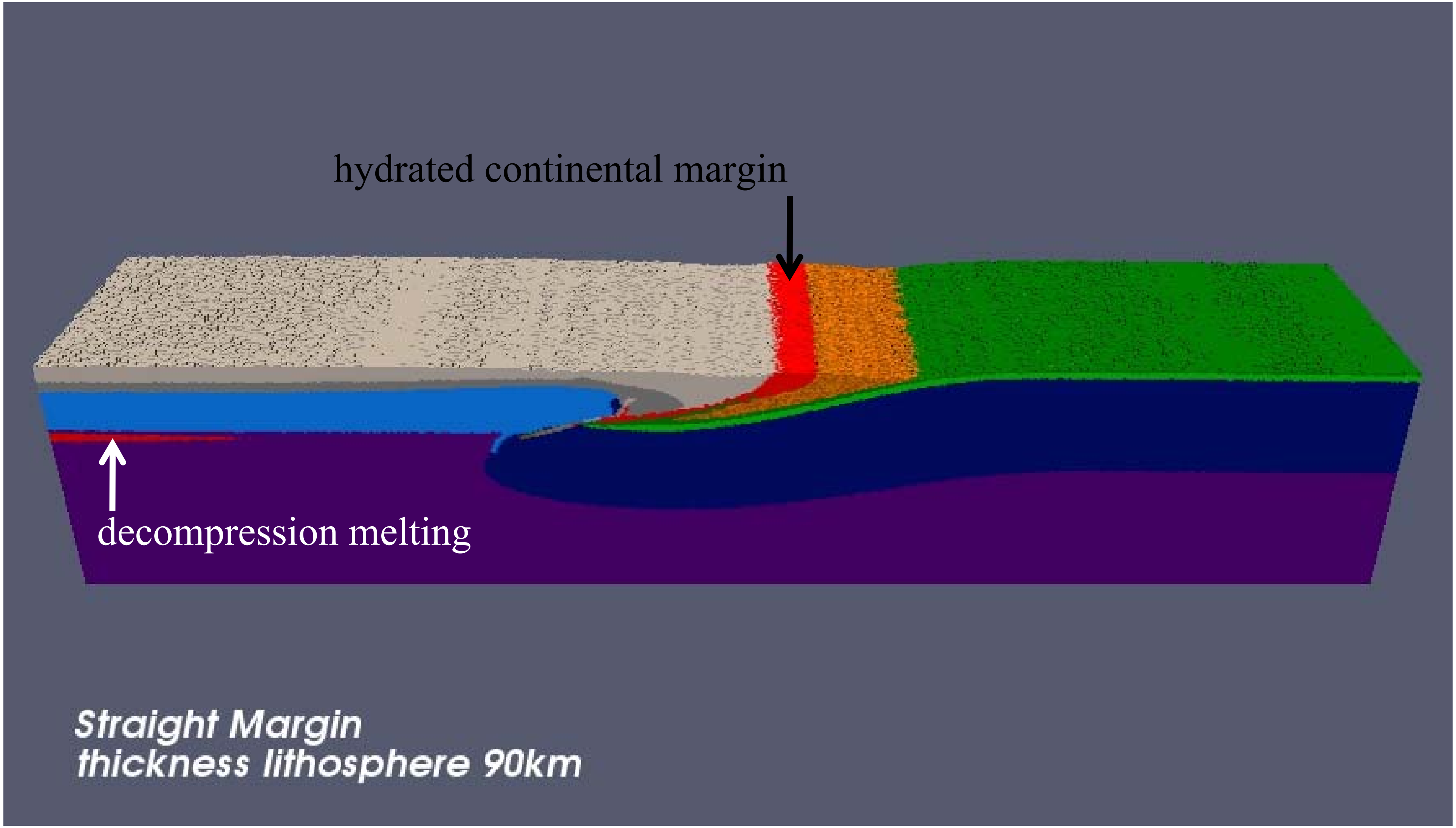
Straight Margin
thickness lithosphere 90km

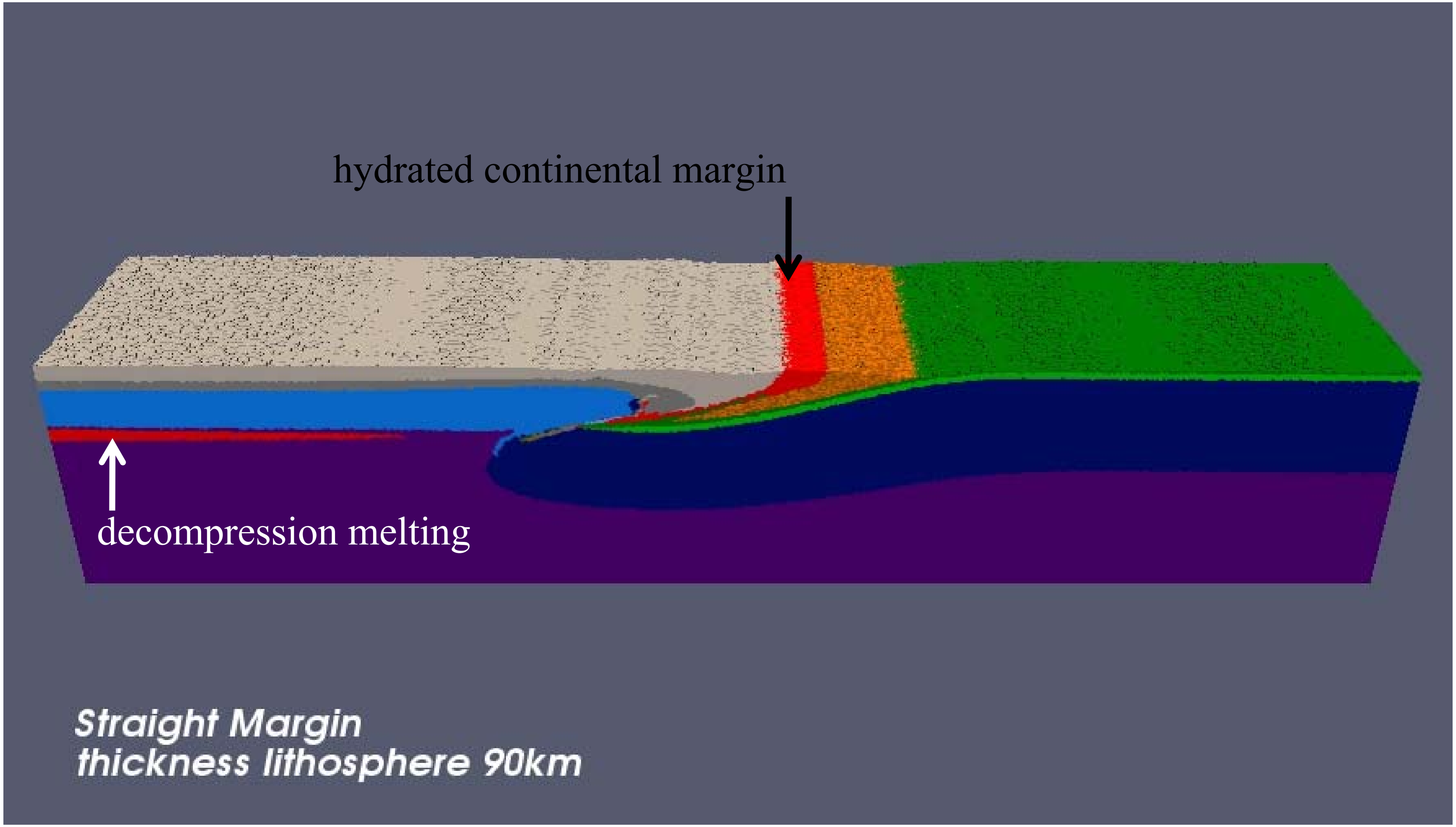

Straight Margin
thickness lithosphere 90km

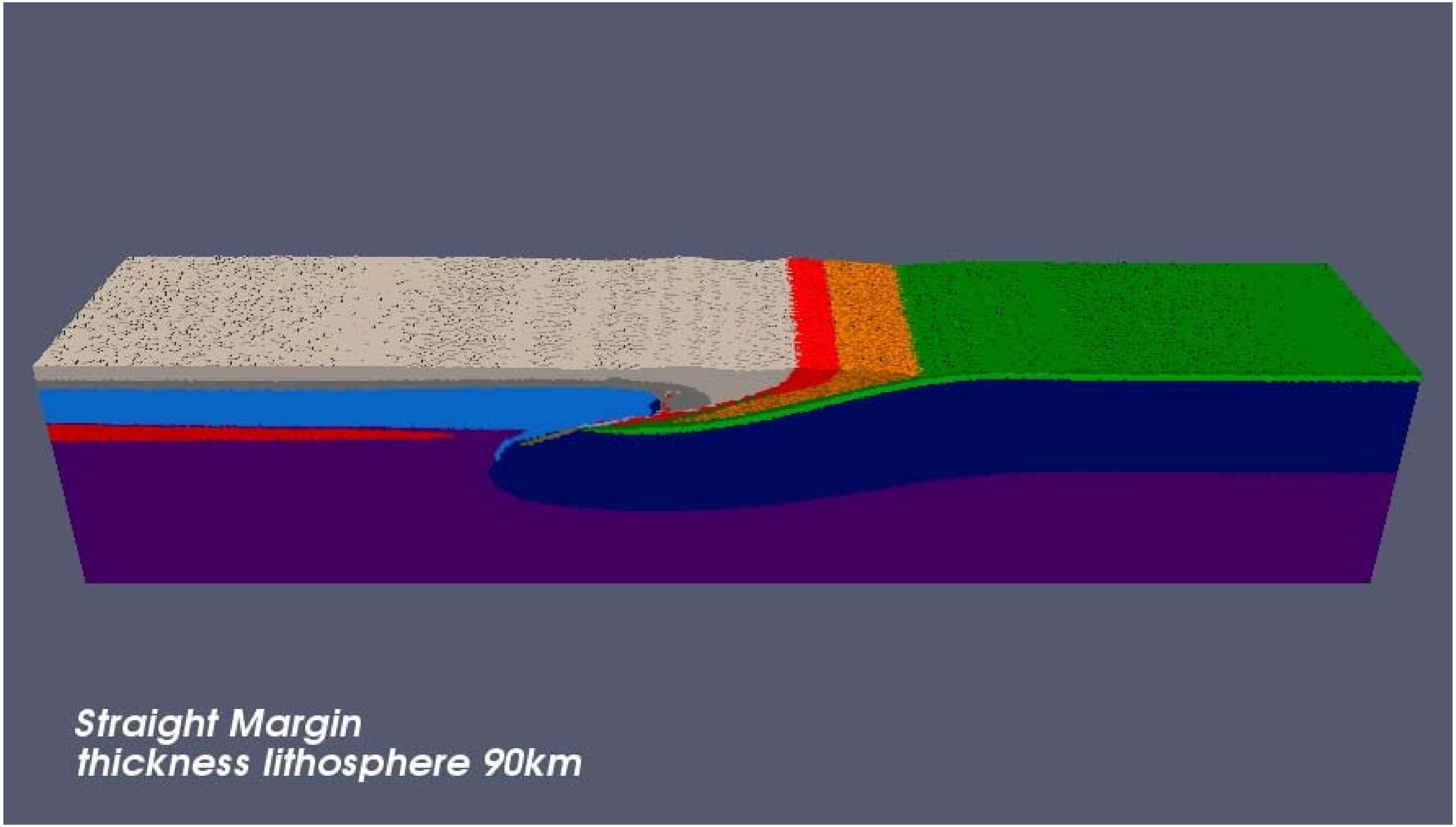


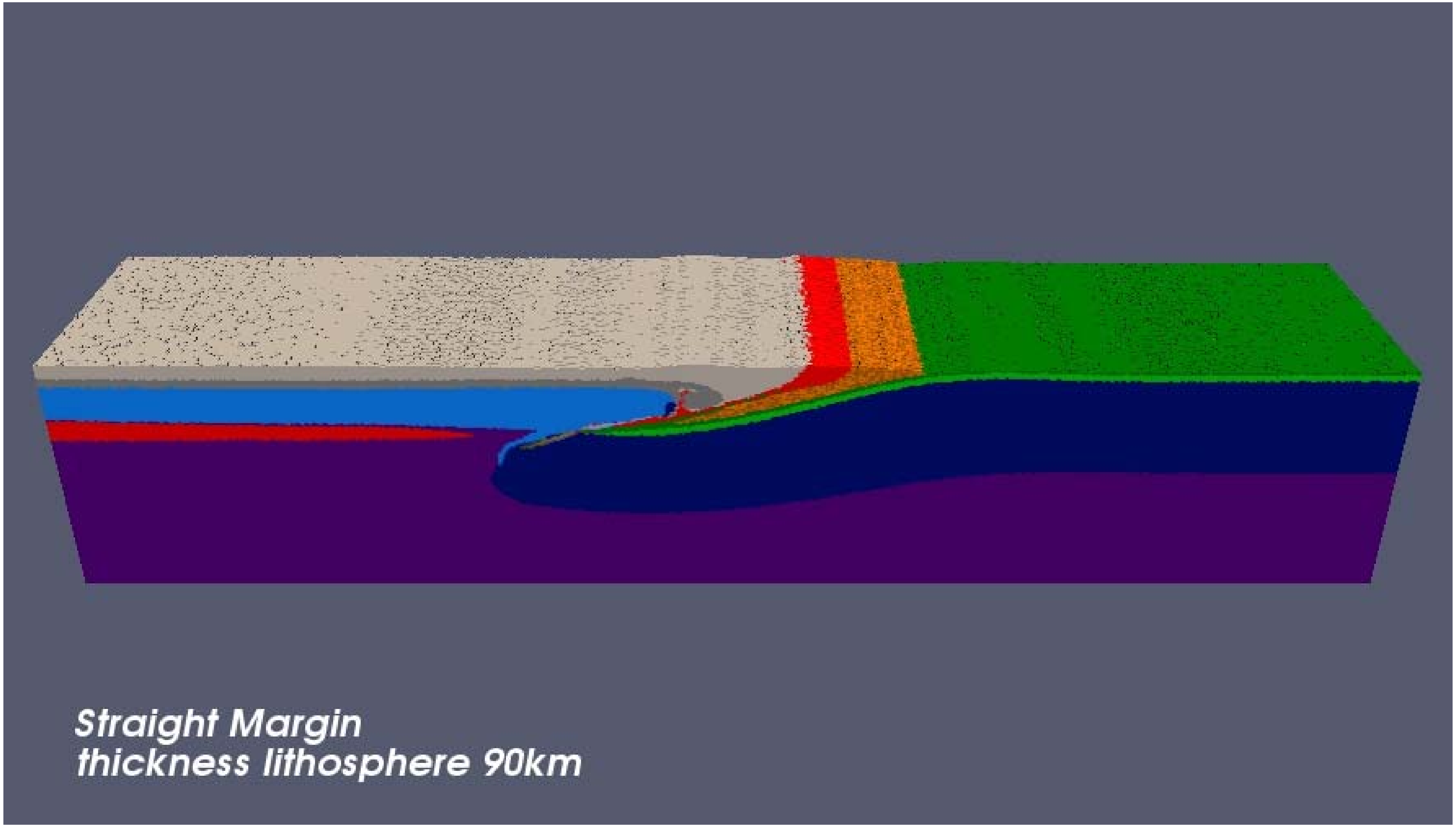
Straight Margin
thickness lithosphere 90km

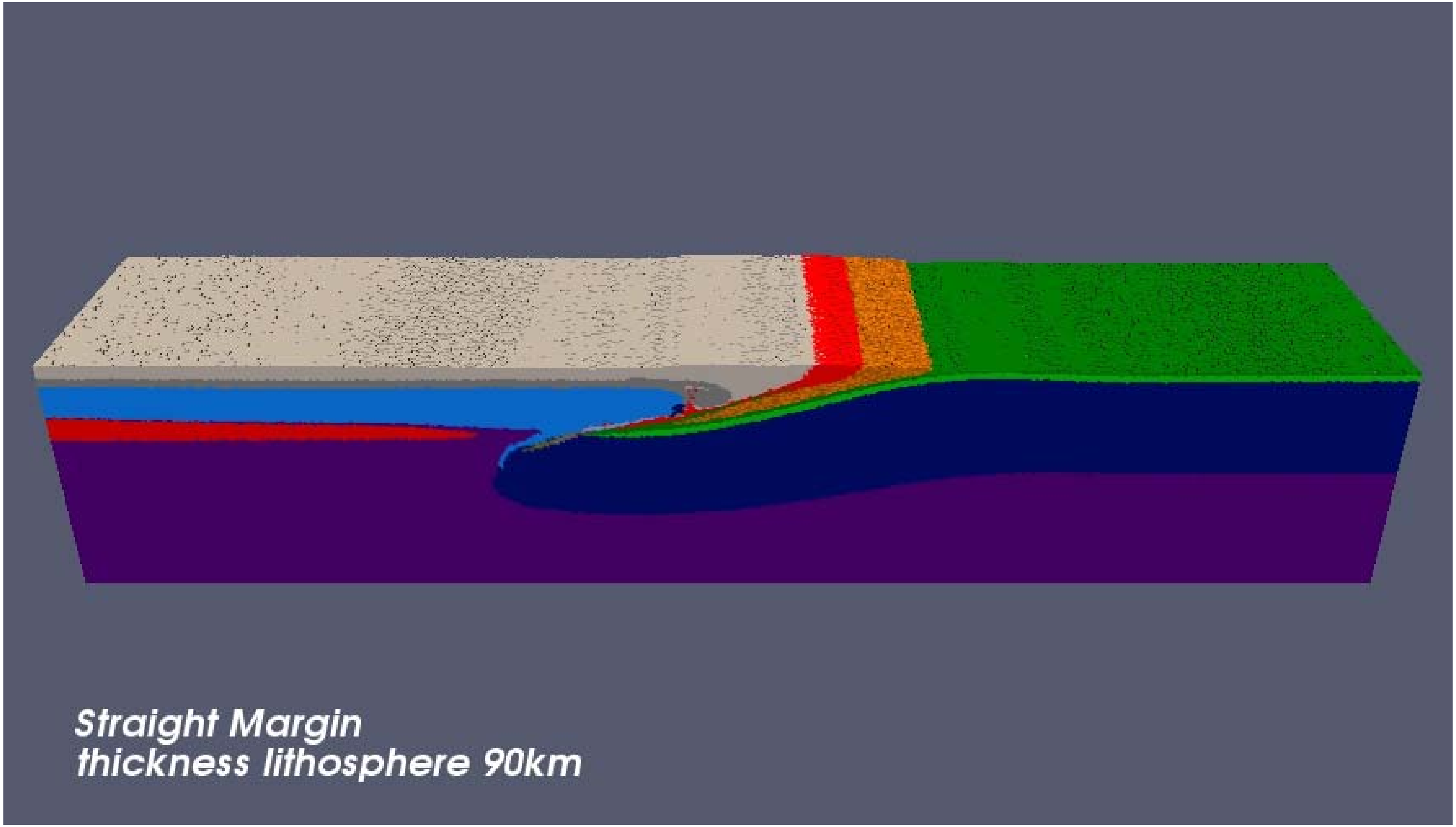

Straight Margin
thickness lithosphere 90km

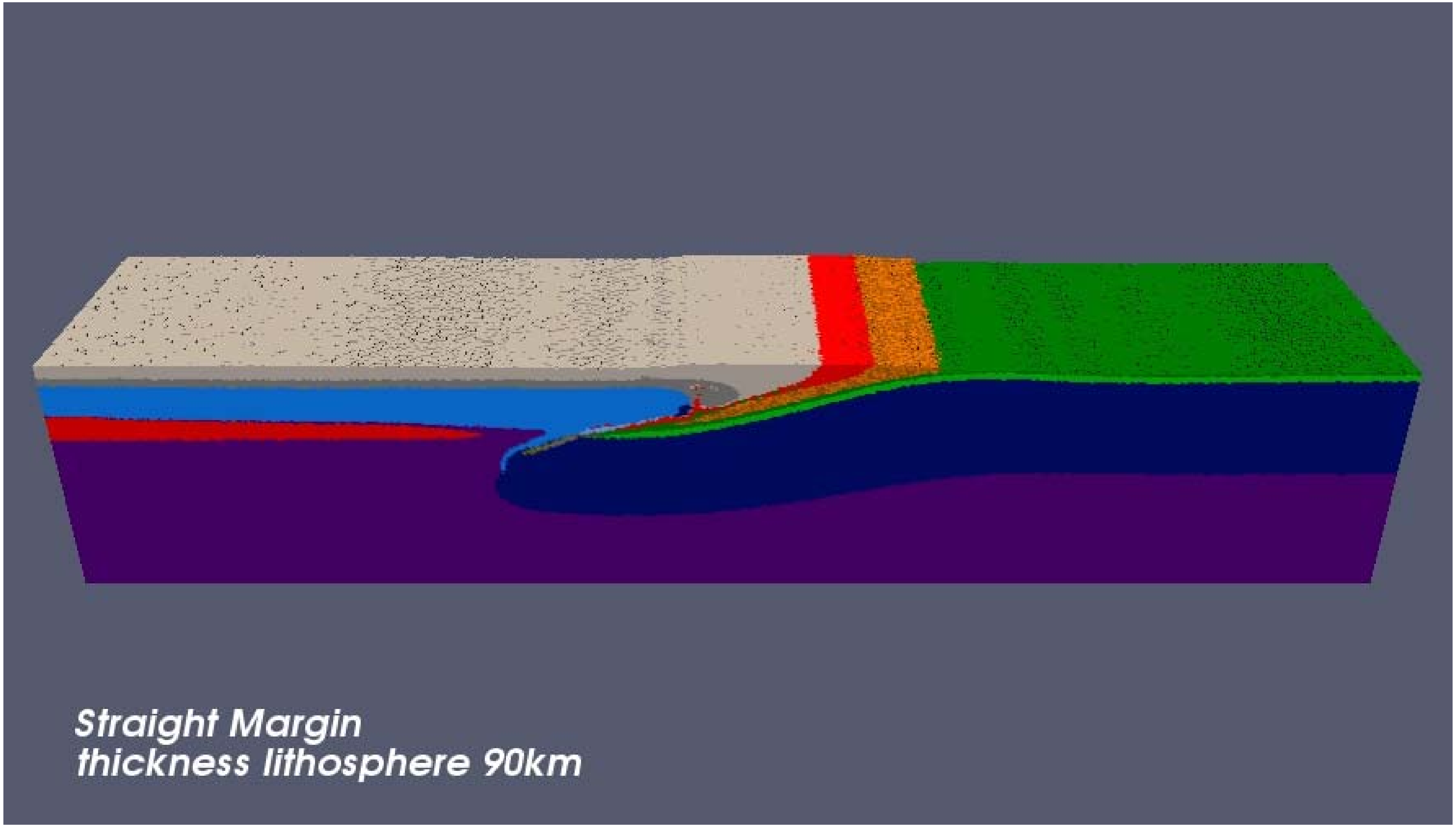

hydrated continental margin
decompression melting
Straight Margin
thickness lithosphere 90km

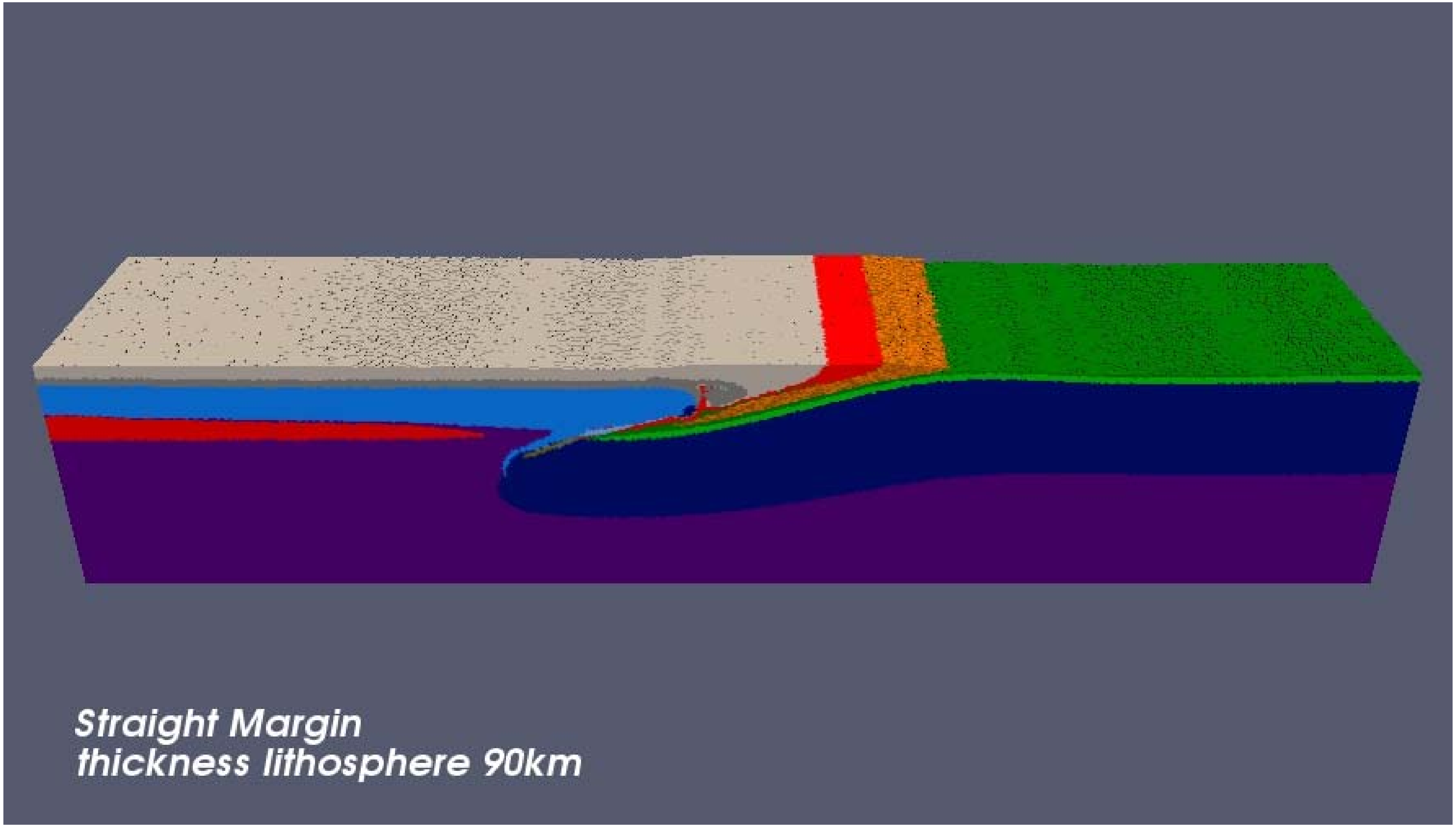

hydrated continental margin
decompression melting
Straight Margin
thickness lithosphere 90km

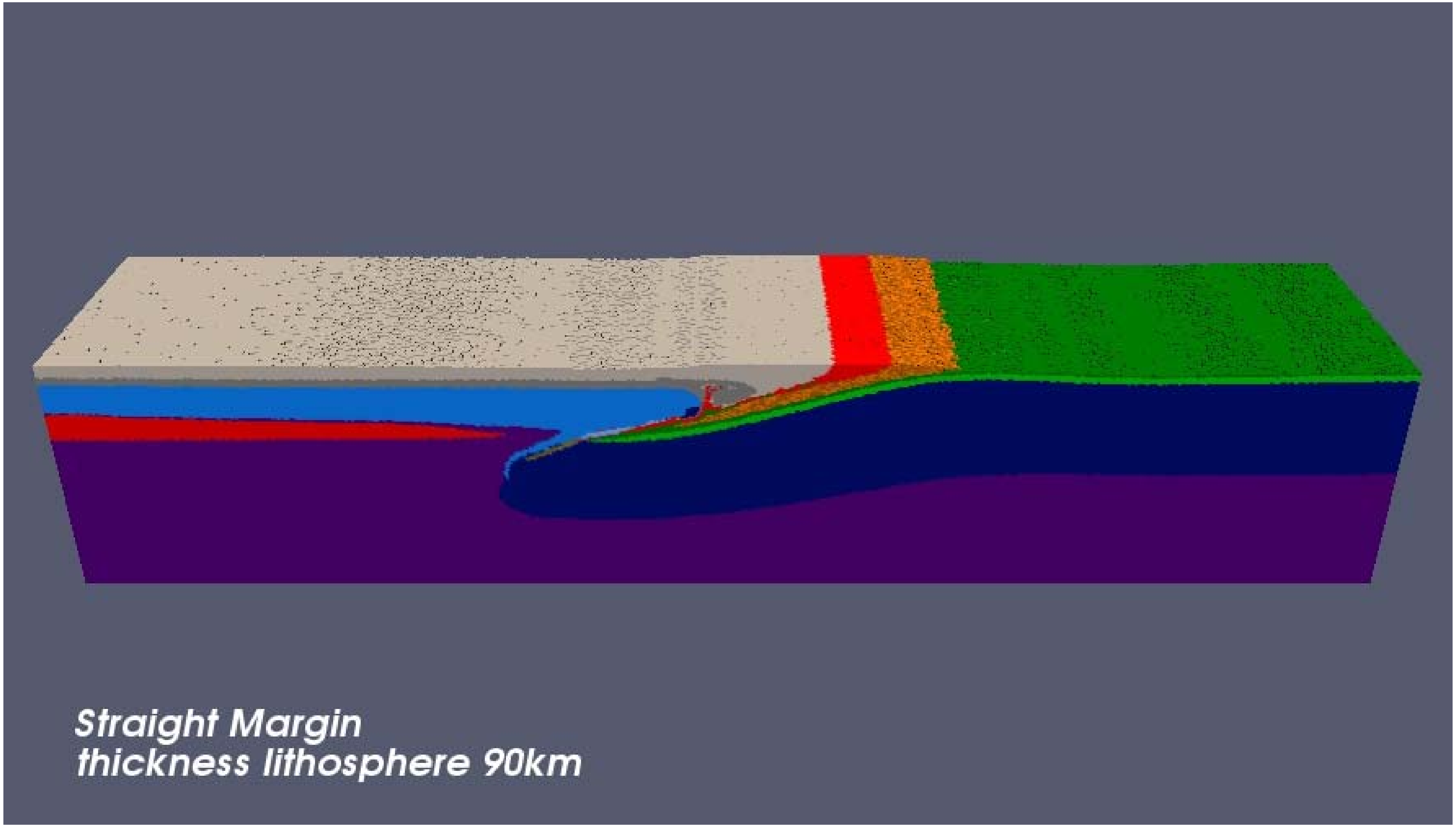

Straight Margin
thickness lithosphere 90km

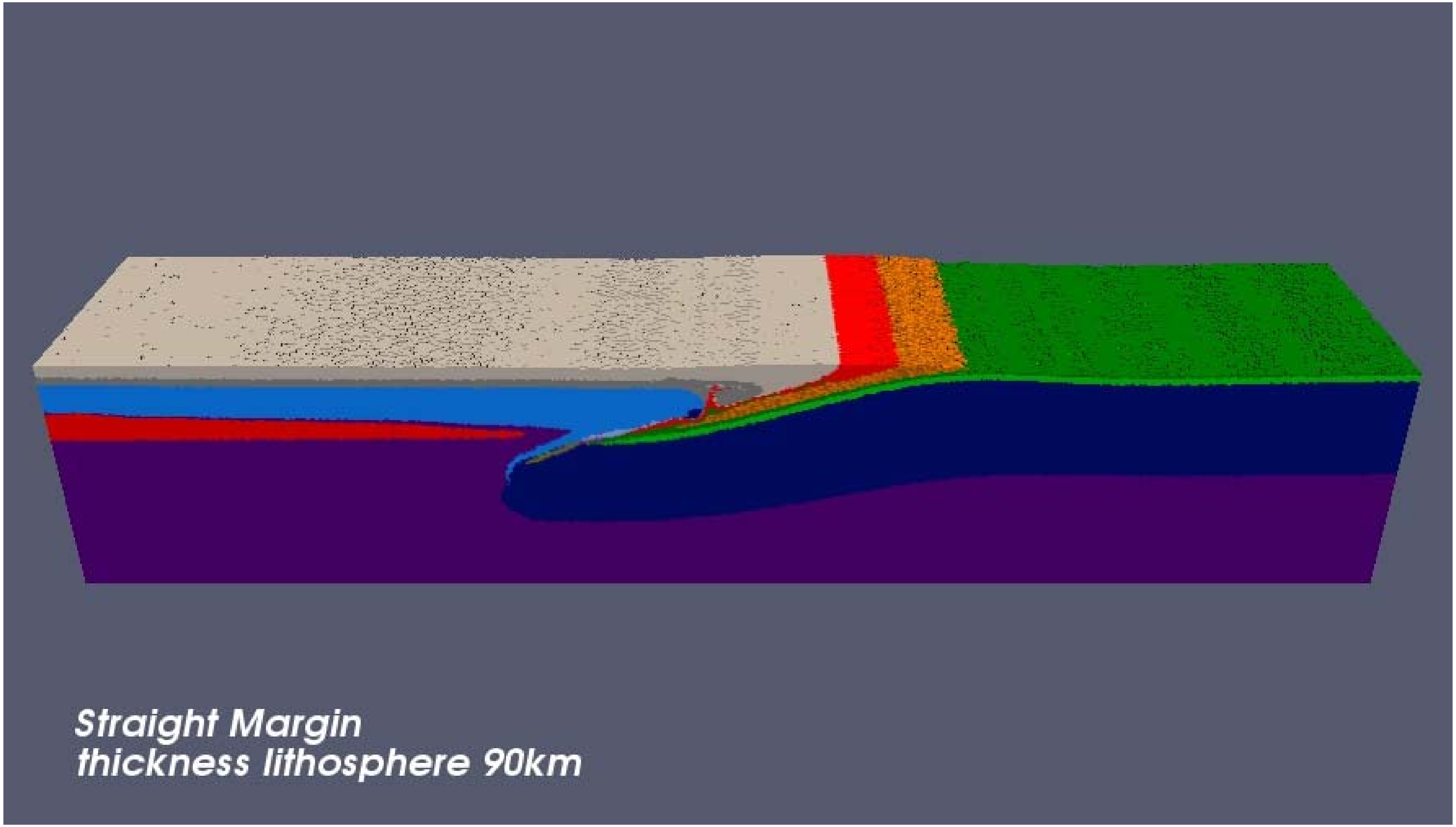

Straight Margin
thickness lithosphere 90km

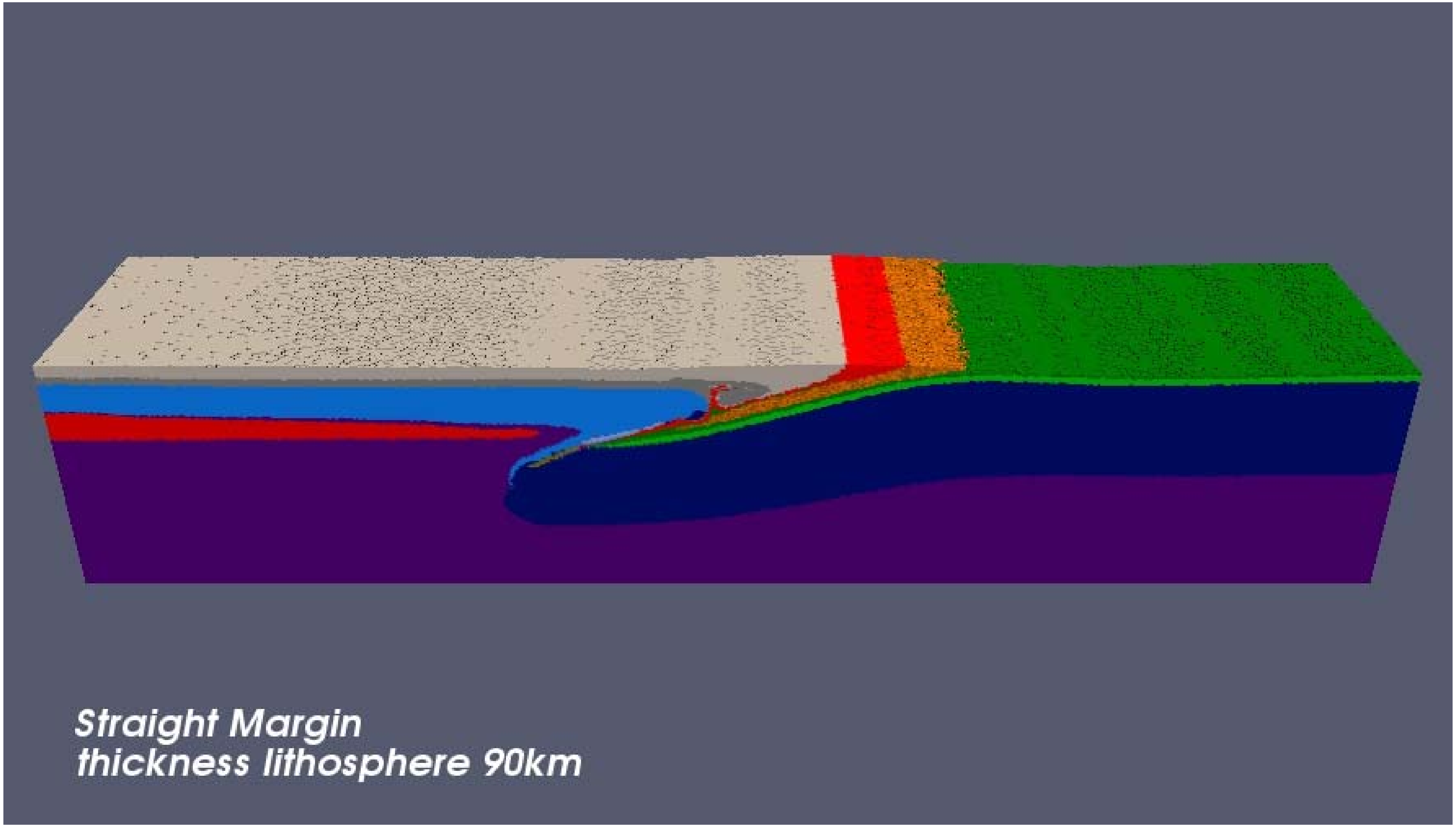

Straight Margin
thickness lithosphere 90km

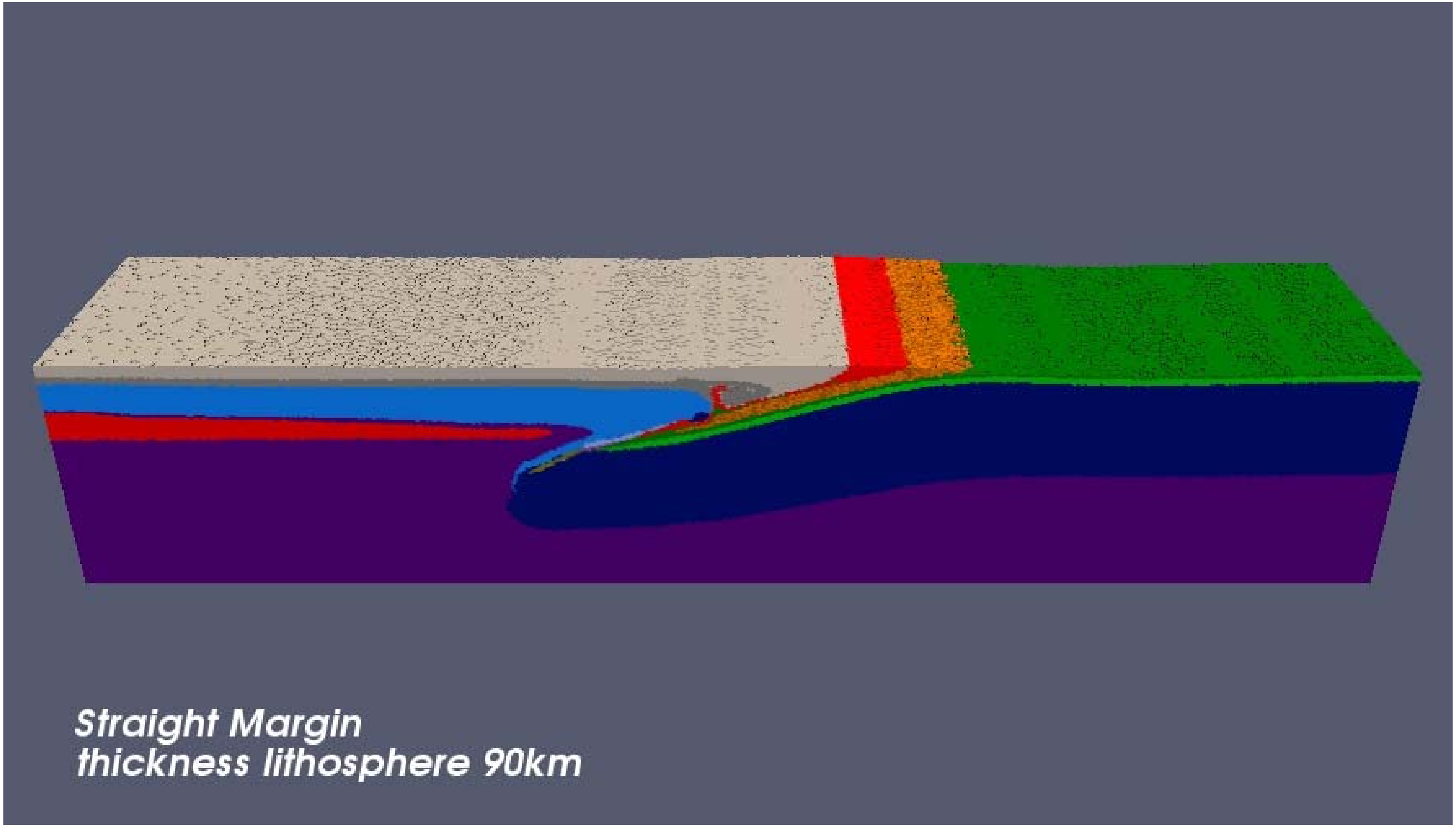

Straight Margin
thickness lithosphere 90km

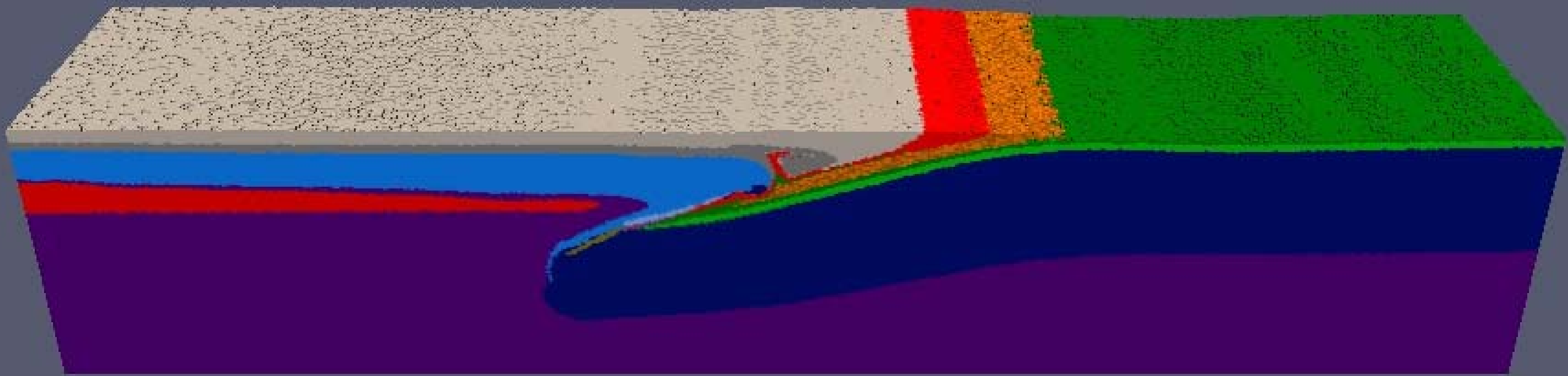

Straight Margin
thickness lithosphere 90km


Straight Margin
thickness lithosphere 90km

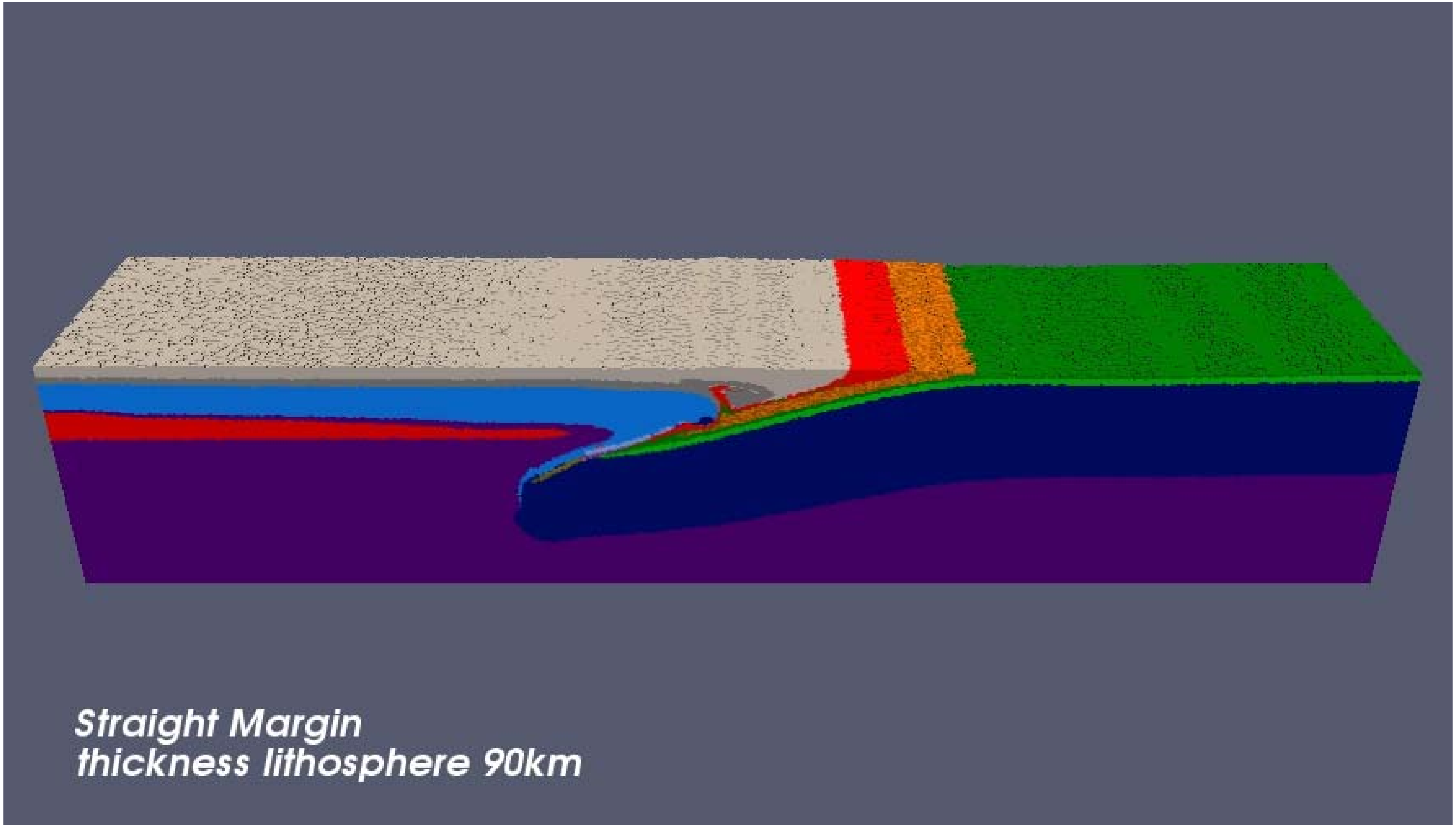

Straight Margin
thickness lithosphere 90km

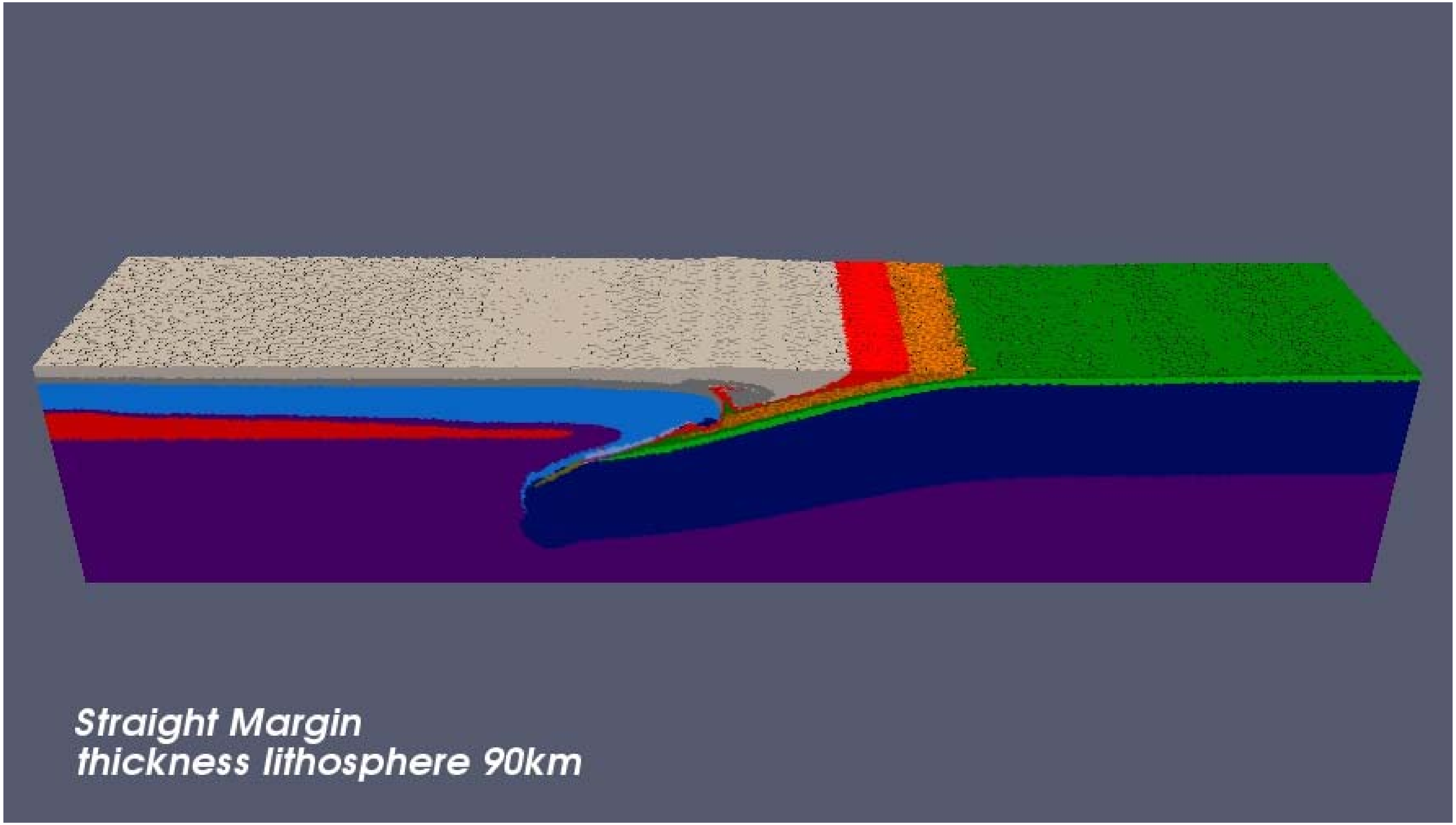

Straight Margin
thickness lithosphere 90km

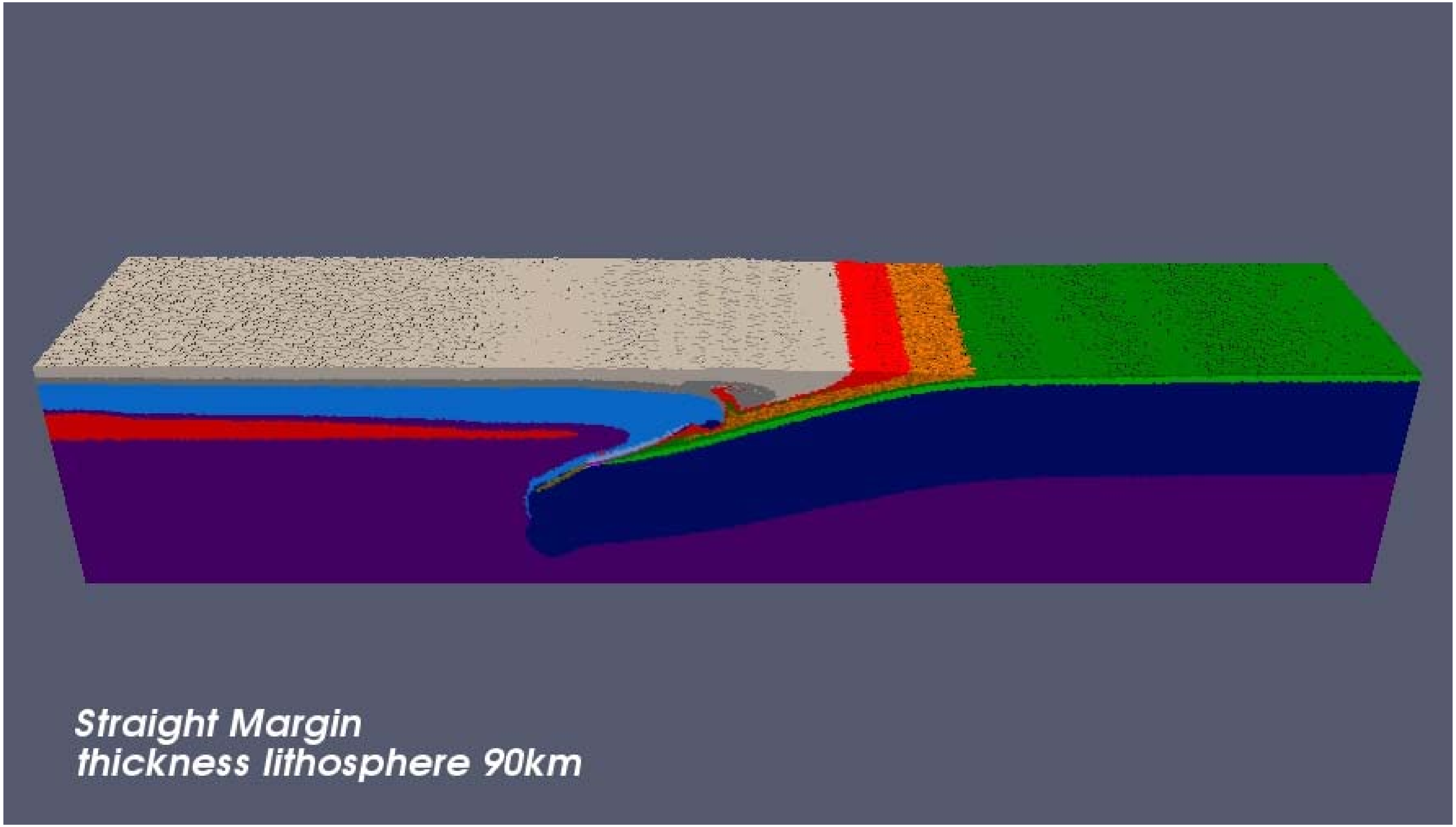

Straight Margin
thickness lithosphere 90km

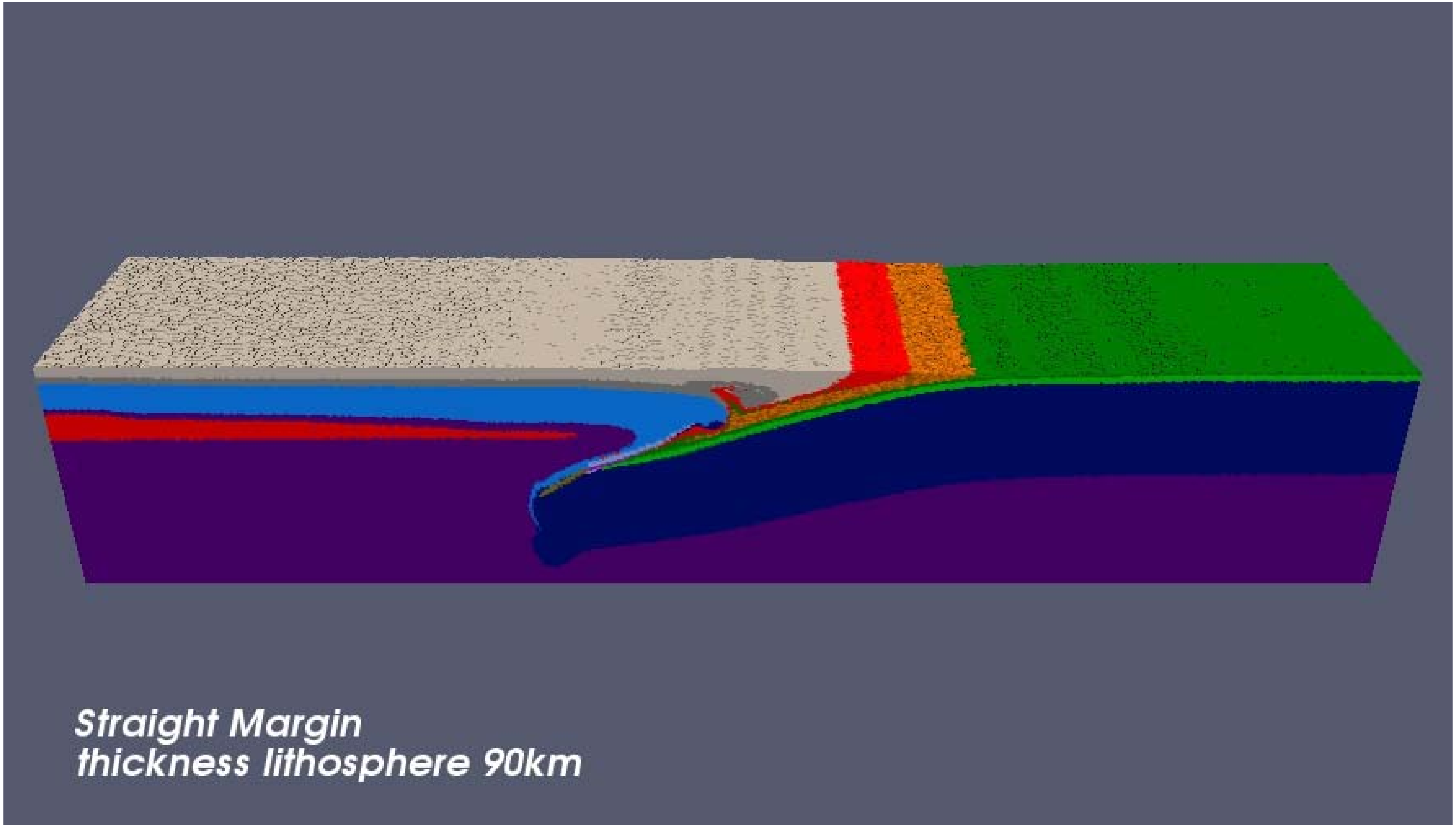


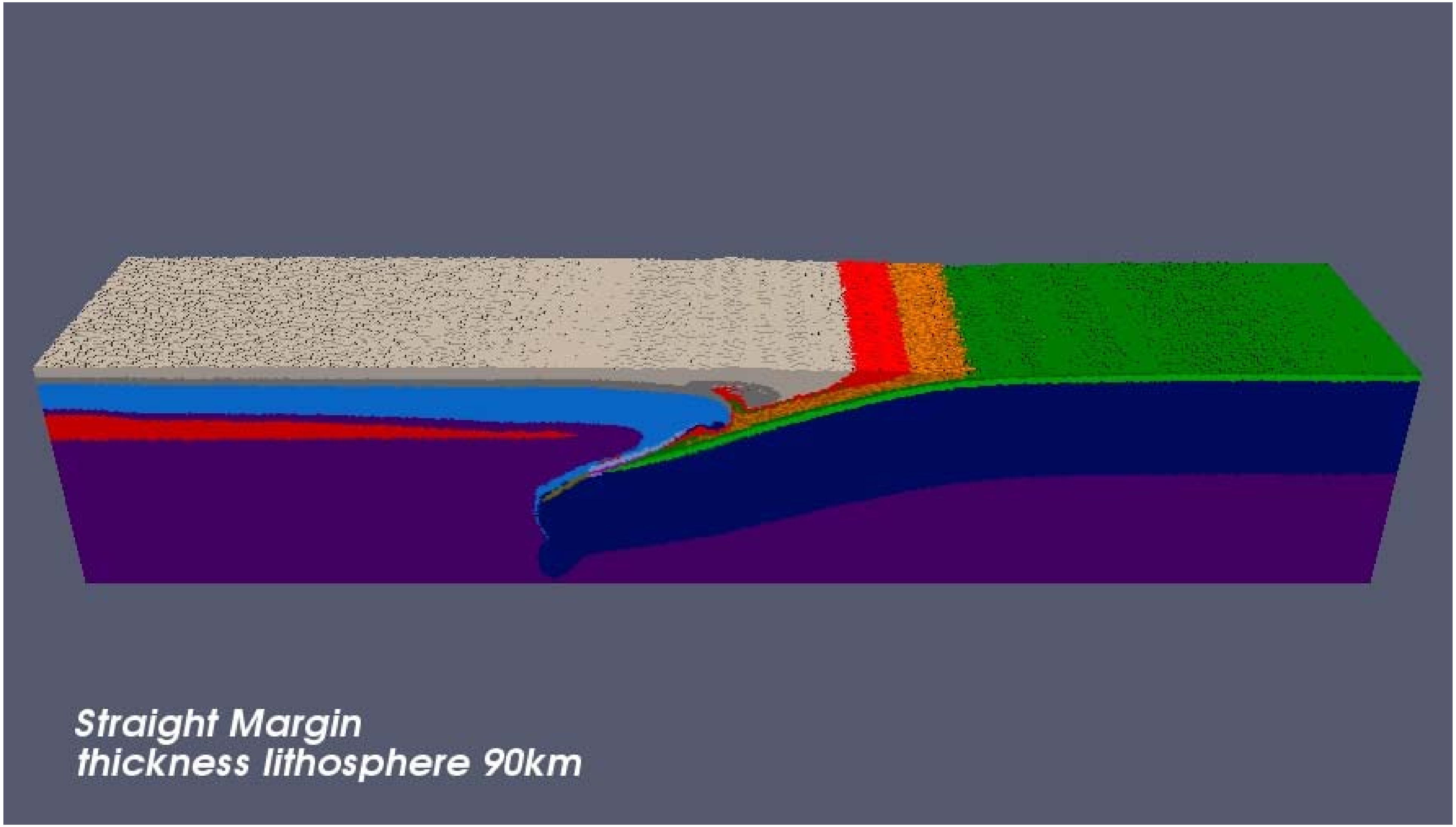
Straight Margin
thickness lithosphere 90km

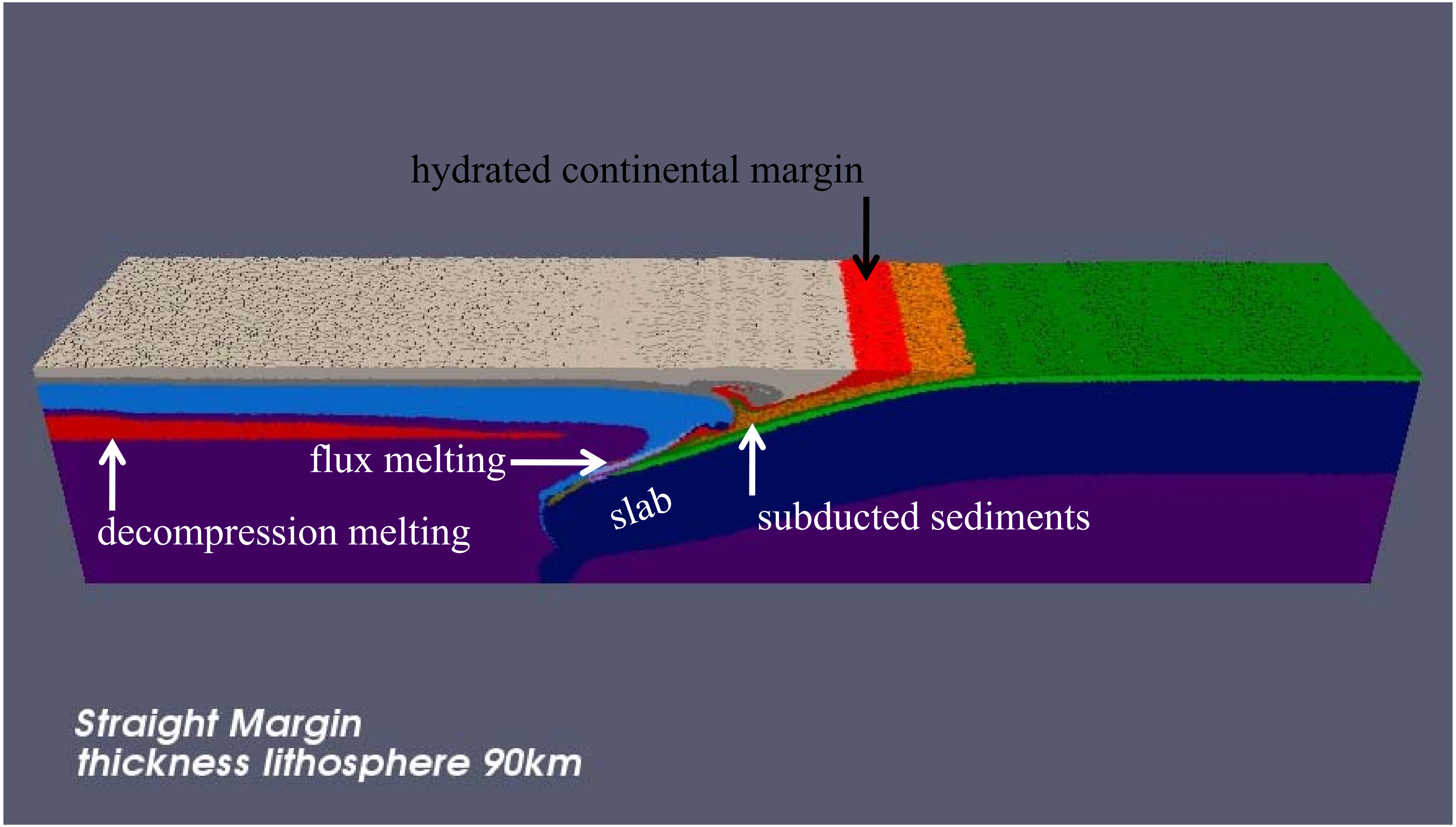

Straight Margin
thickness lithosphere 90km


Straight Margin
thickness lithosphere 90km

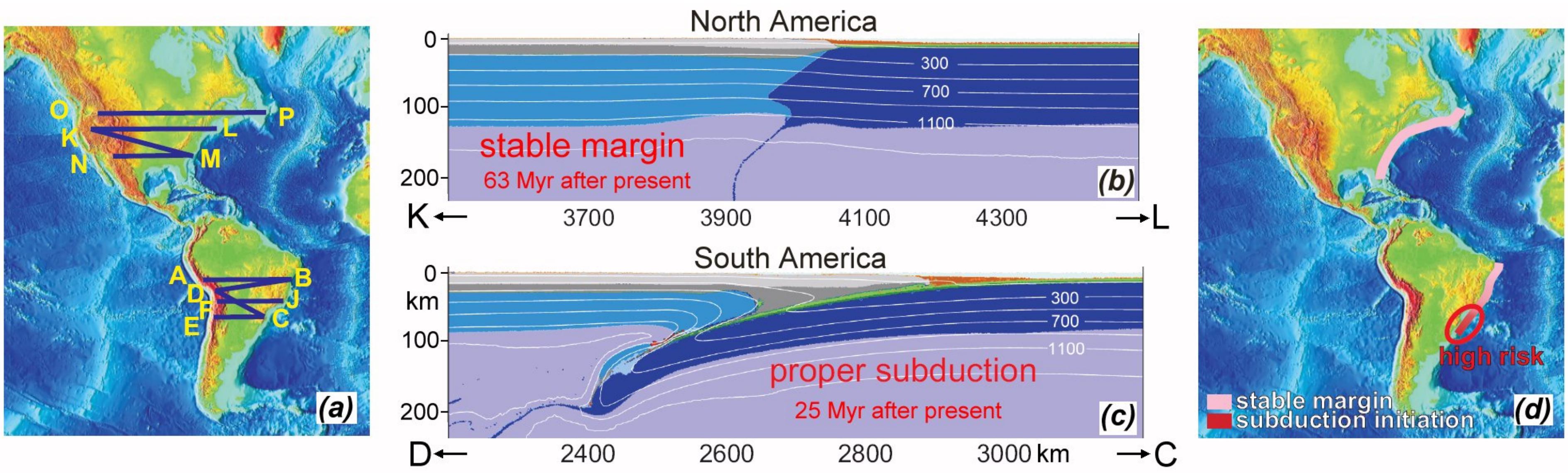

Straight Margin
thickness lithosphere 90km


Straight Margin
thickness lithosphere 90km


Straight Margin
thickness lithosphere 90km


hydrated continental margin
flux melting
slab
decompression melting
subducted sediments
Straight Margin
thickness lithosphere 90km

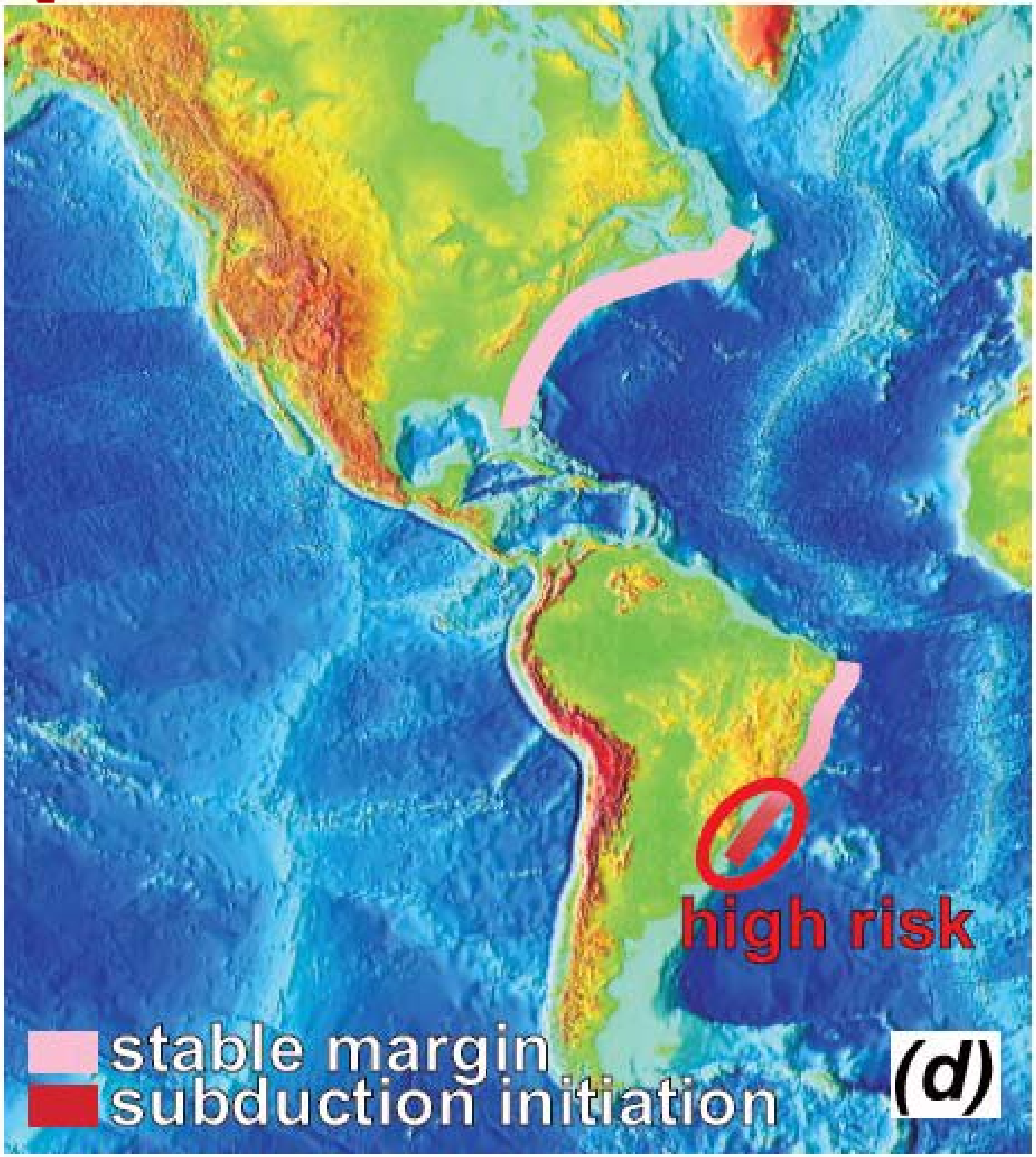
Where to look for spontaneous subduction initiation?



Nikolaeva et al. (2011)

Where to look for spontaneous subduction initiation?

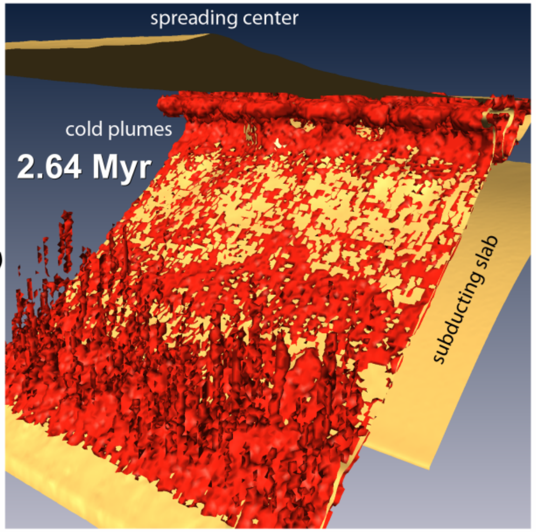
In Brasil !



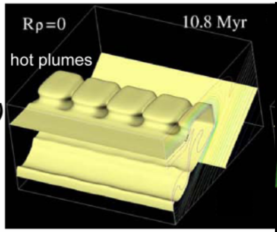
Nikolaeva et al. (2011)

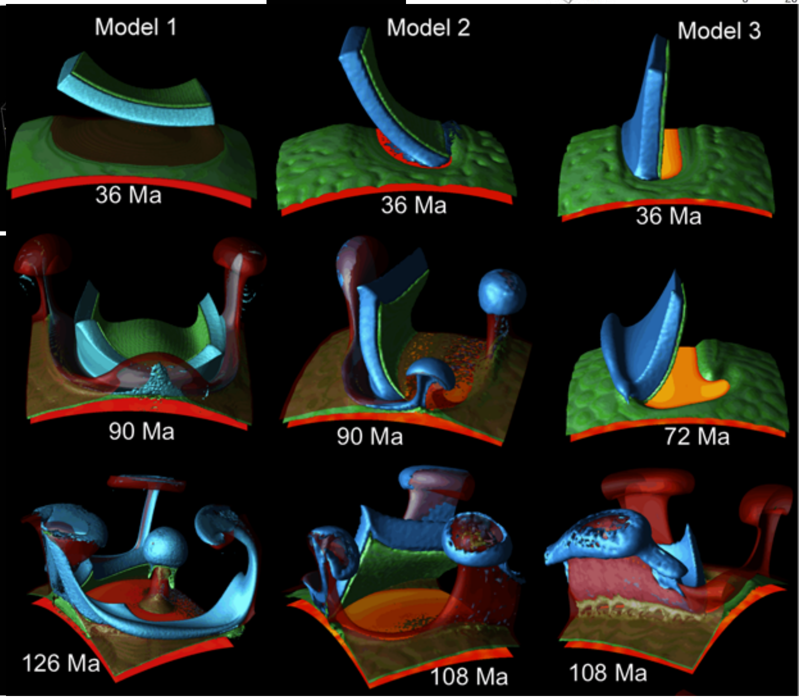
Review: Future directions in subduction modeling
Journal of Geodynamics
Gerya (2011)

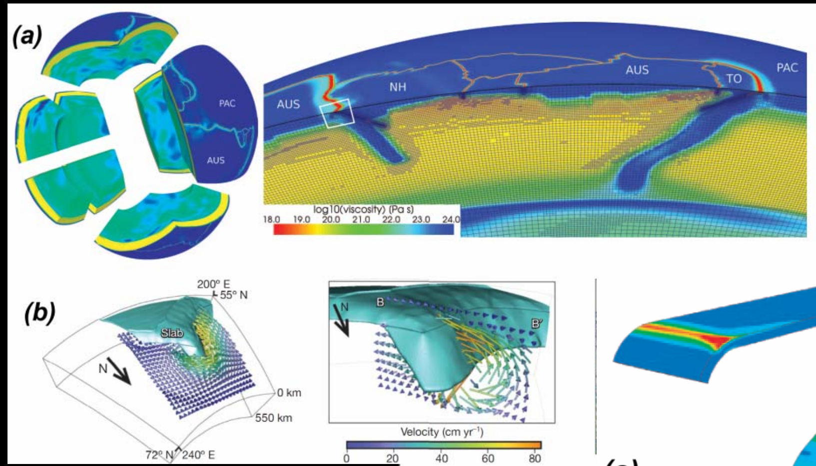
(a)

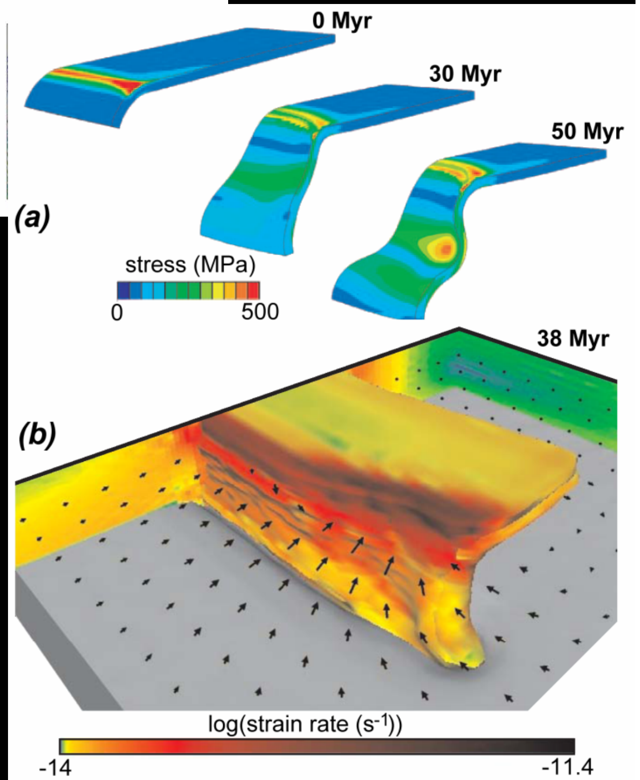


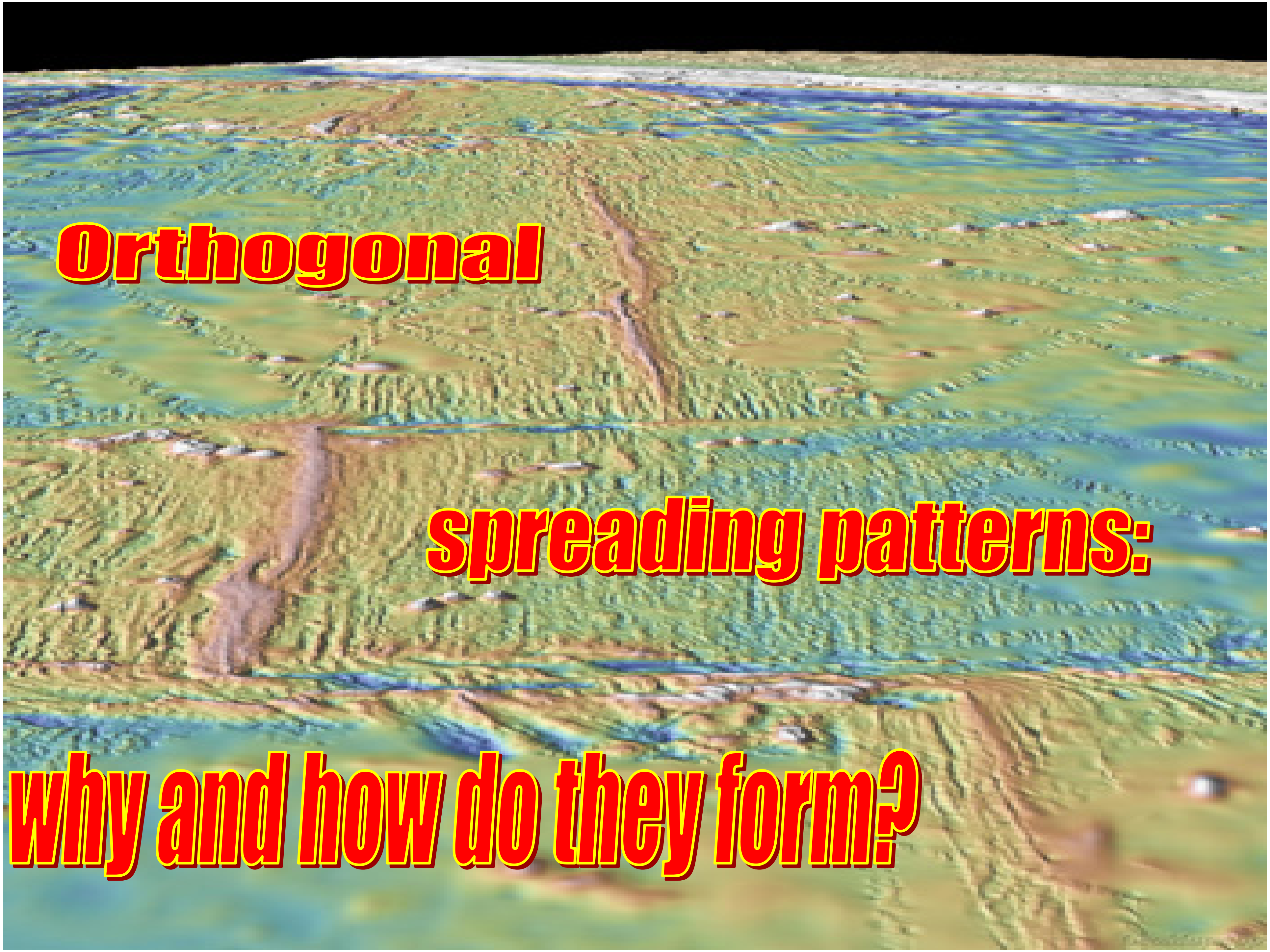
(b)



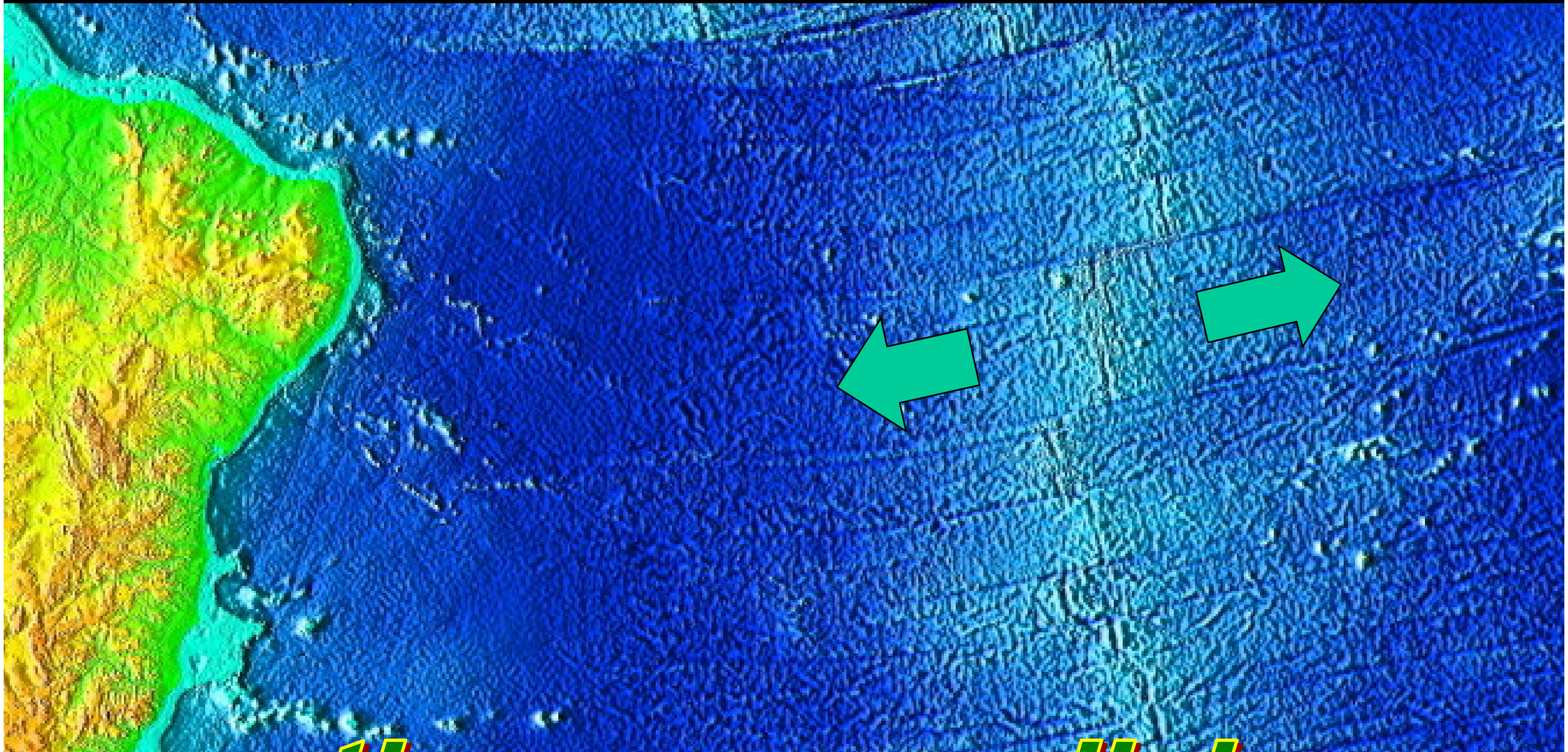






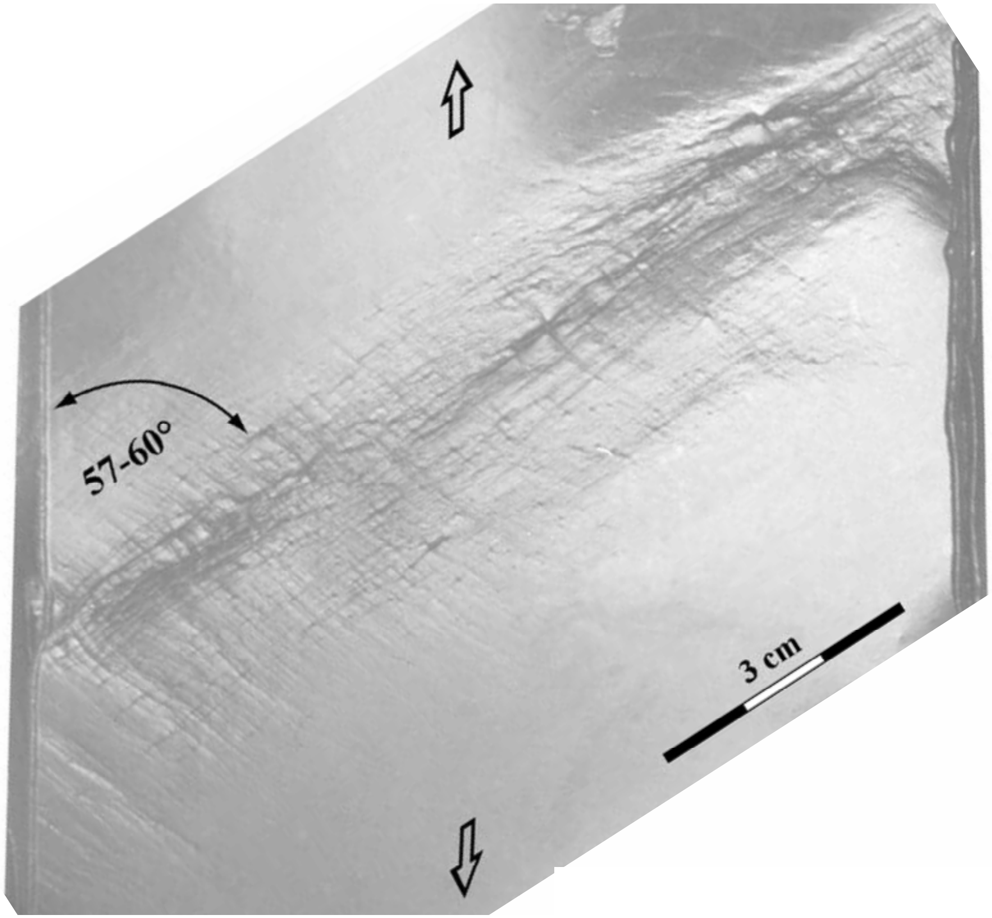

Orthogonal
spreading patterns:
why and how do they form?

Oceanic transform faults have wrong orientation

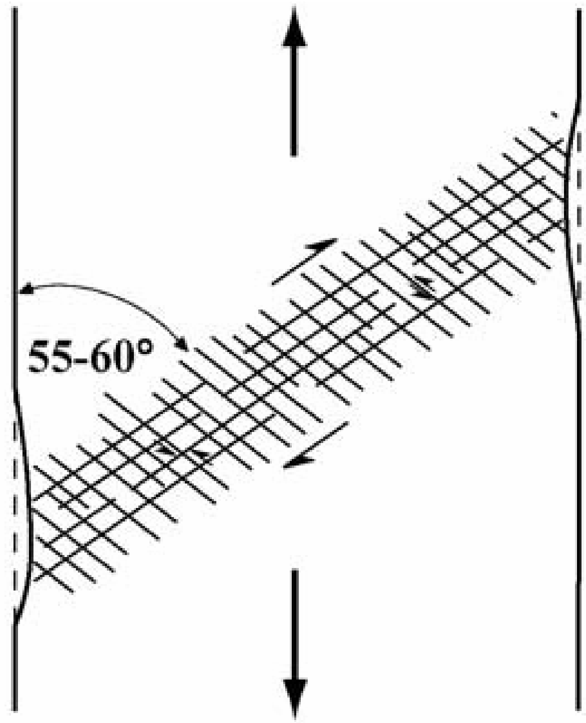


they are parallel to the extension direction

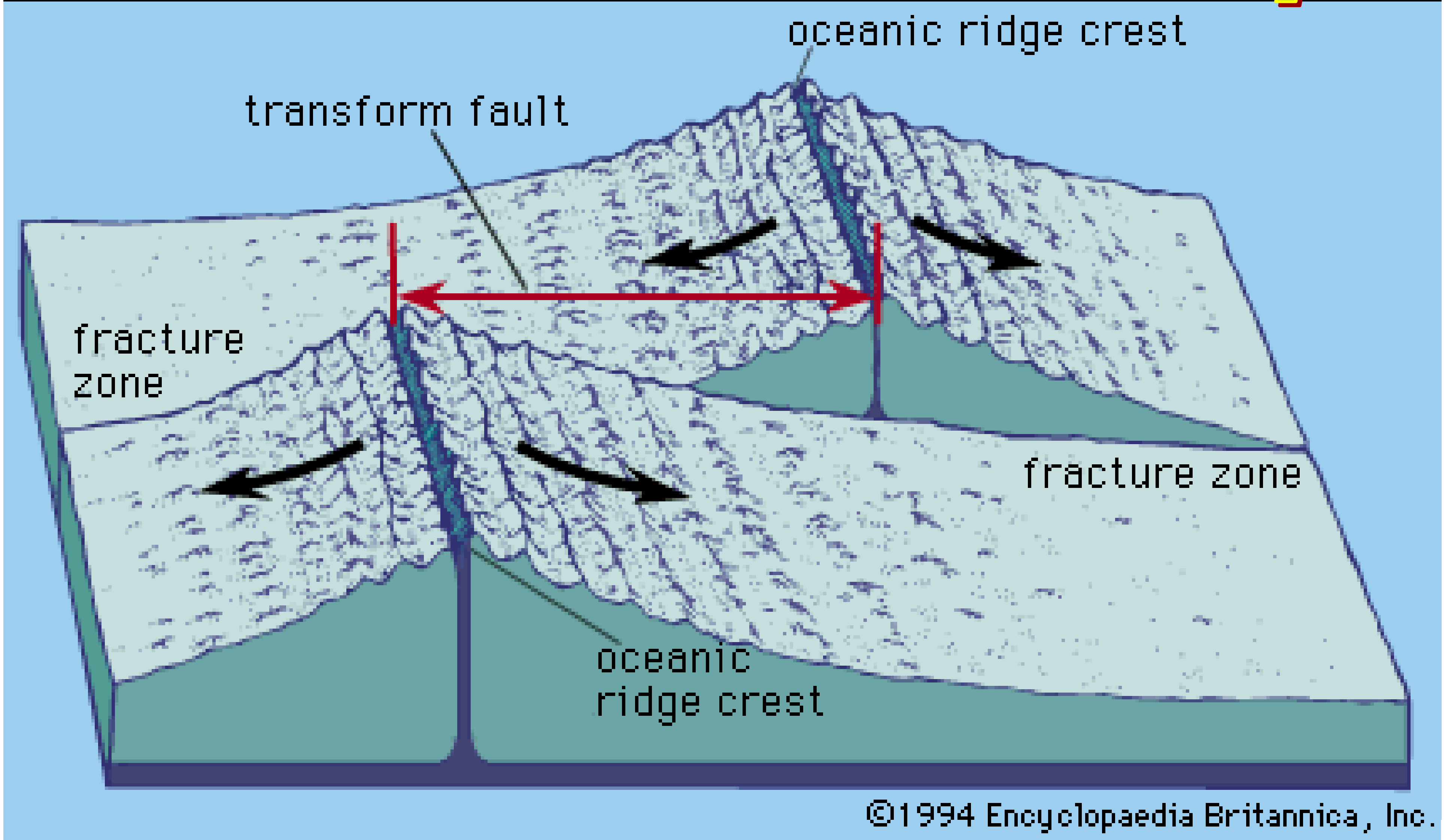
This is how faults should be oriented in extension

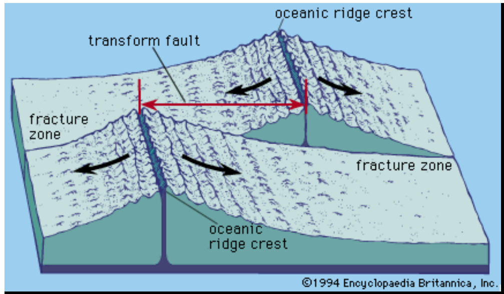


Chemenda et al. (2002)



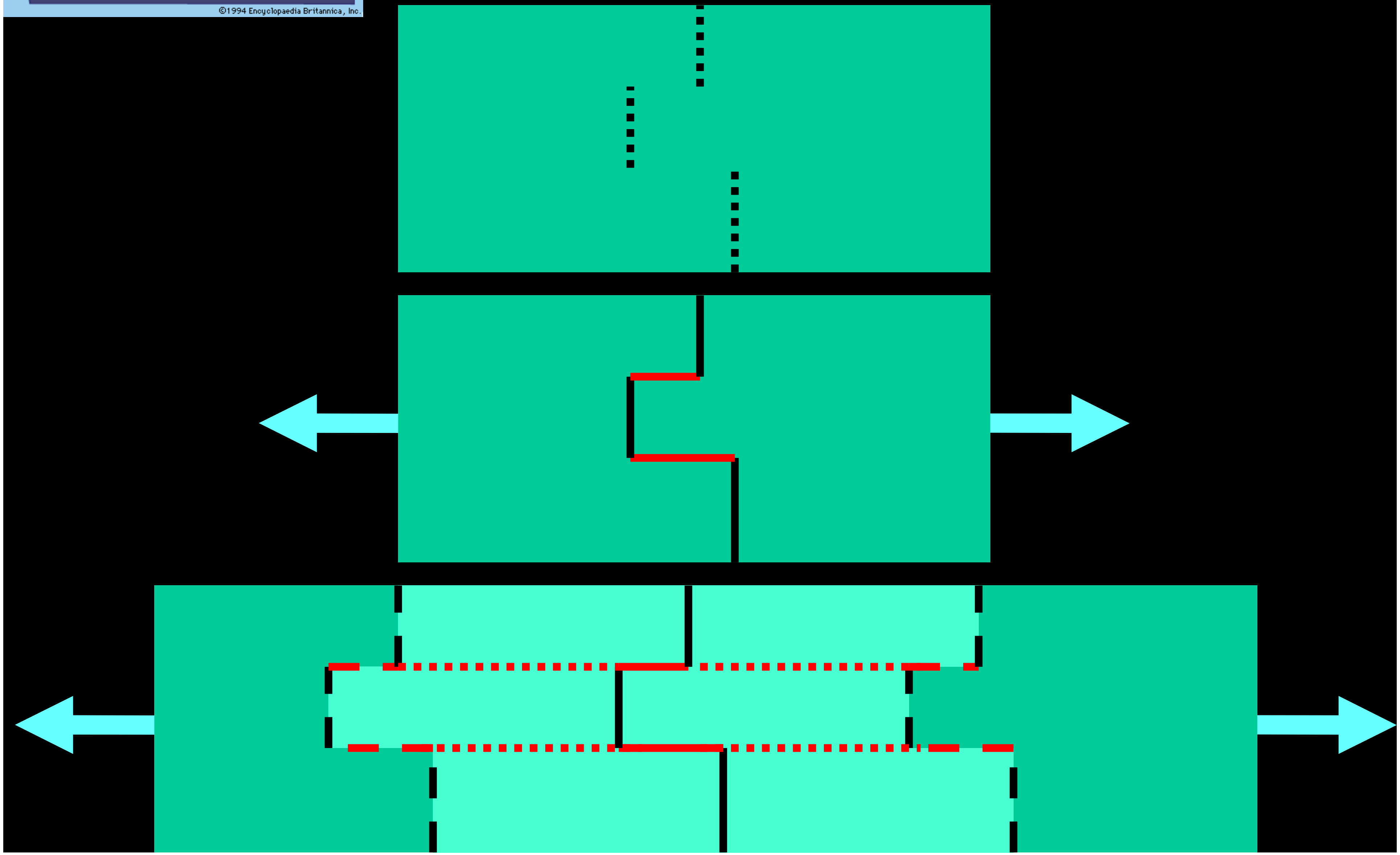
transform fault concept



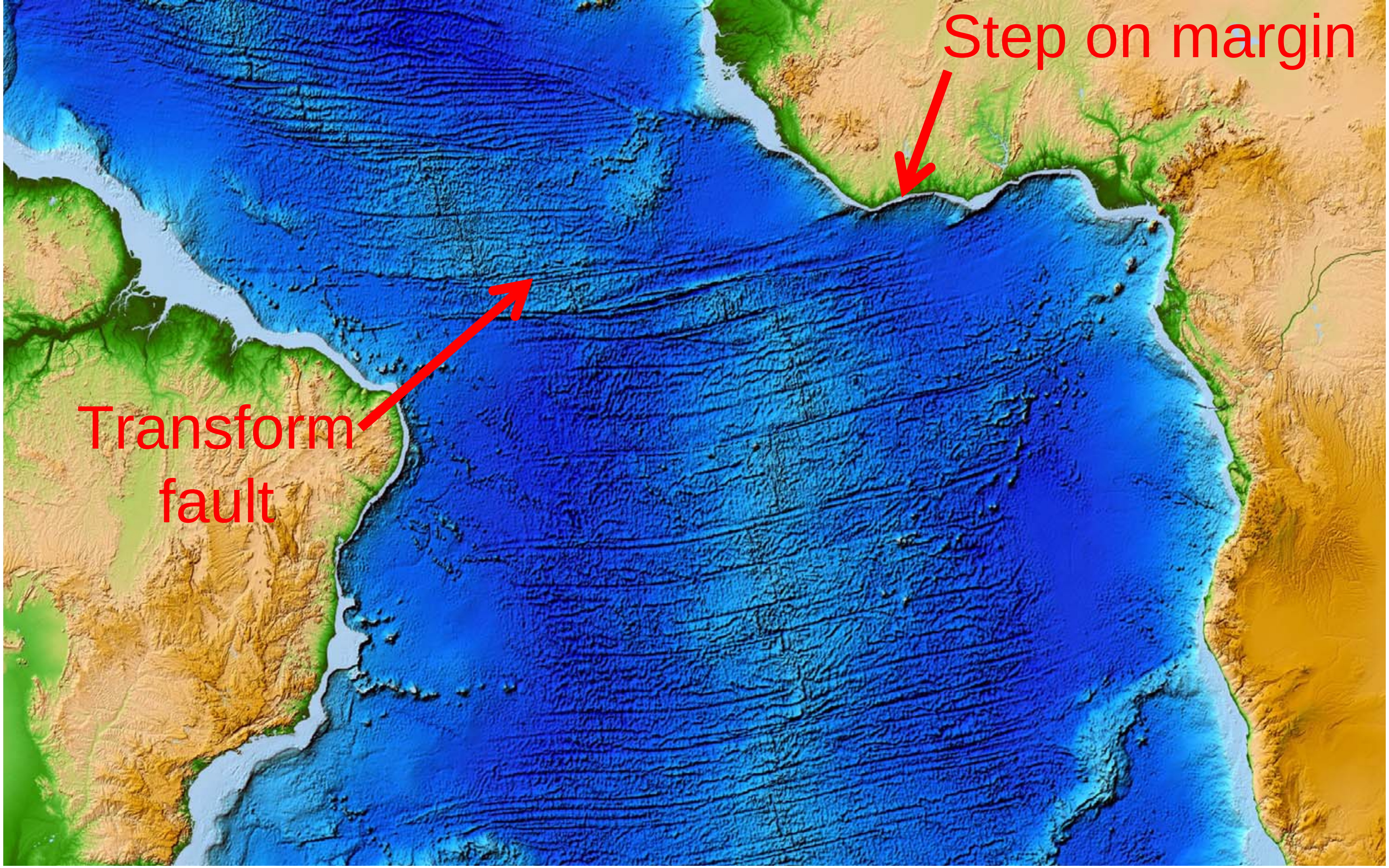


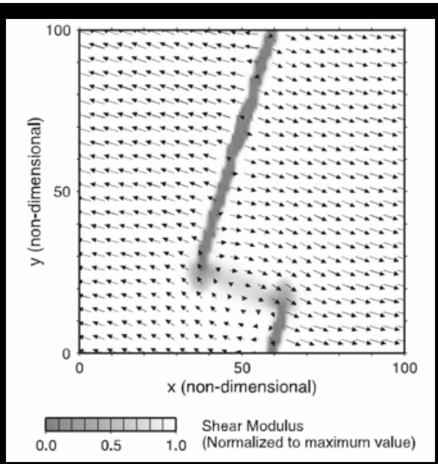
Common view:

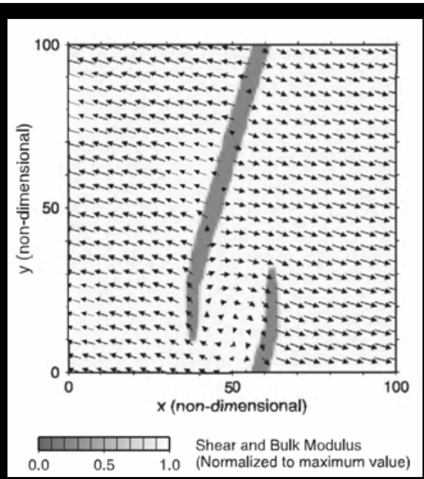
transform faults are **plate fragmentation structures** forming by fracturing of "fresh" plates as "connectors" between pre-existing ridge offsets that remain constant through time

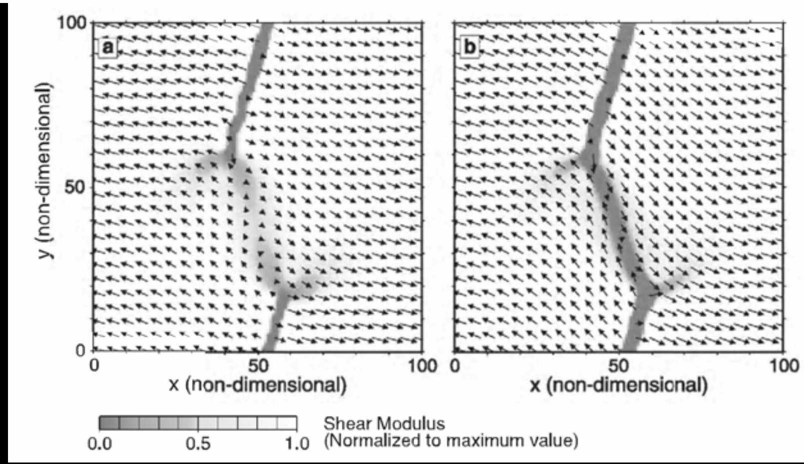


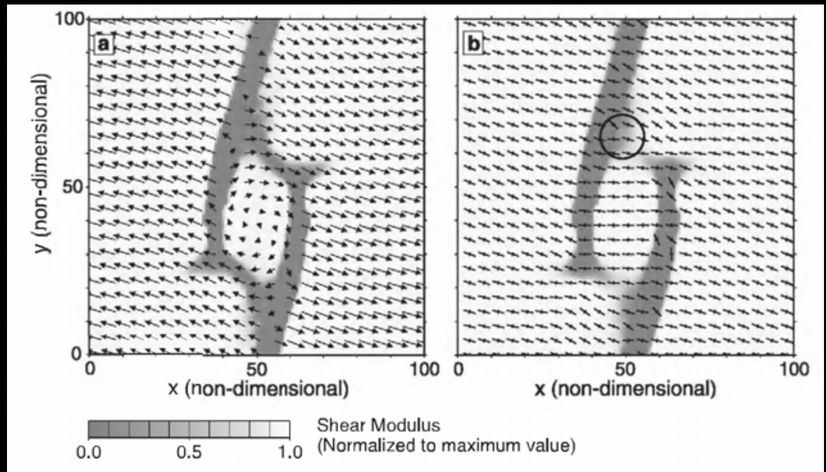
Concept of inherited transform faults

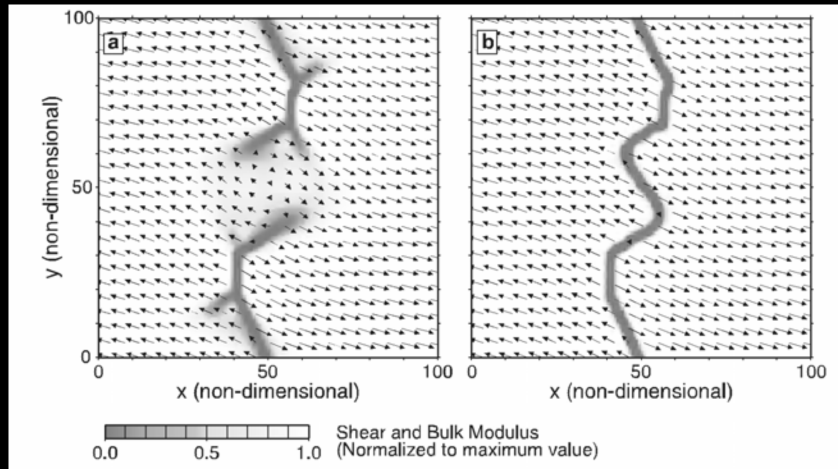


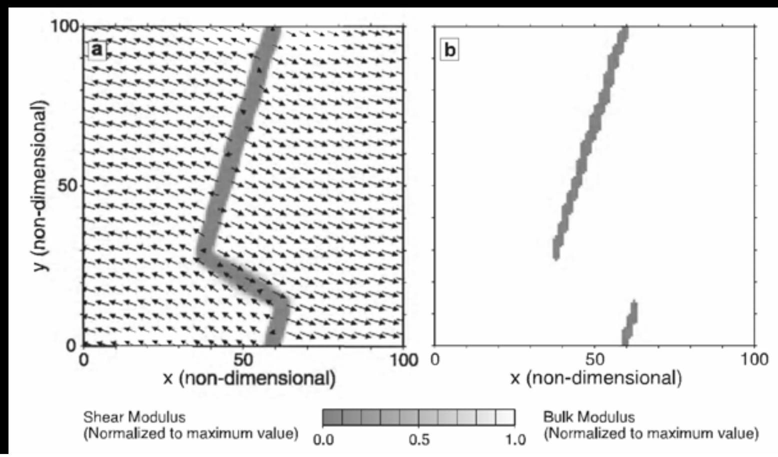












Hieronimus (2004)

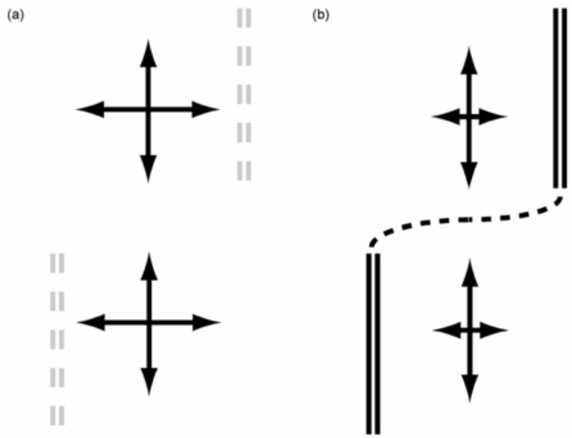


Fig. 1. Ridge segments and other ridge-parallel structures can release thermal stress in the ridge-normal direction, while leaving ridge-parallel residual stresses. Arrows represent the direction and the magnitude of components of thermal stresses aligned along ridge-perpendicular and ridge-parallel directions. (a) Before ridge segments are created, thermal stress is isotropic and its horizontal components are equal in magnitude. The future location of ridge segments are marked by the pairs of gray dashed lines. (b) The ridge-parallel component becomes dominant when the ridge-normal principal stress is released by the formation of ridge segments (pairs of solid lines). A possible trace of a structure connecting the ridge segments is denoted by a dased curve.

Choi et al. (2008)

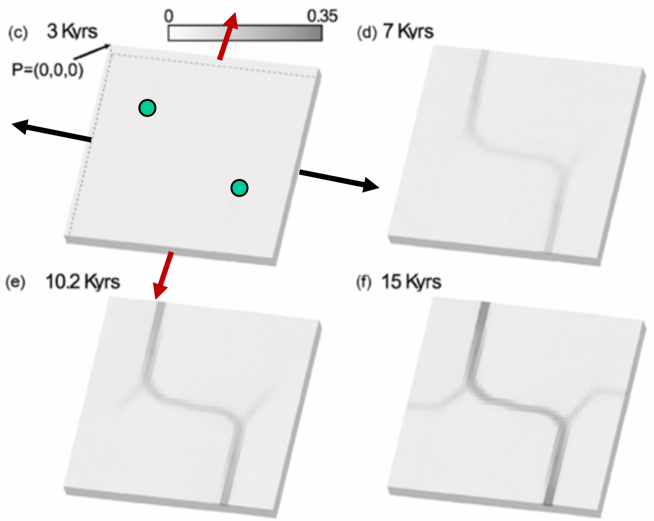
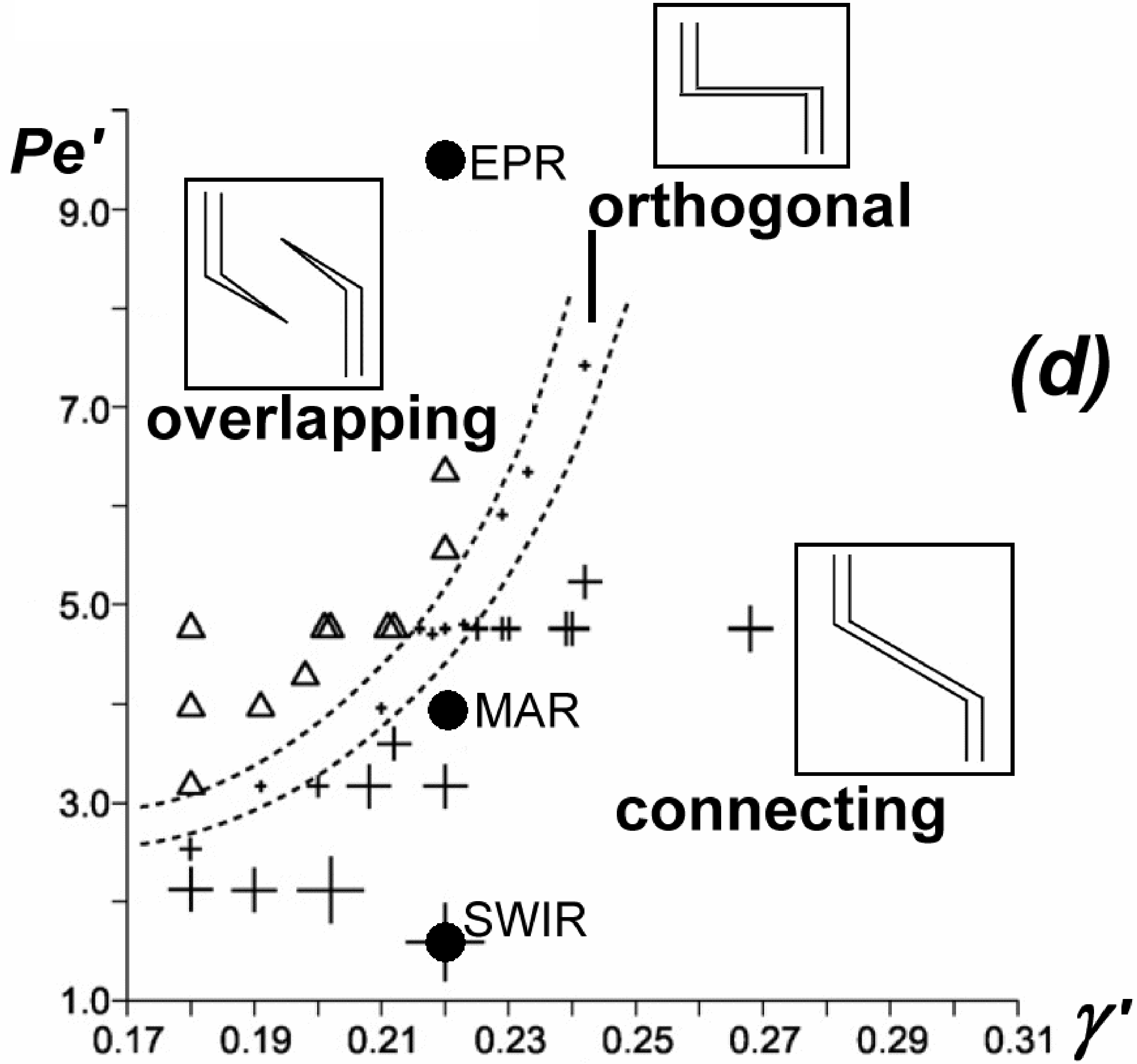
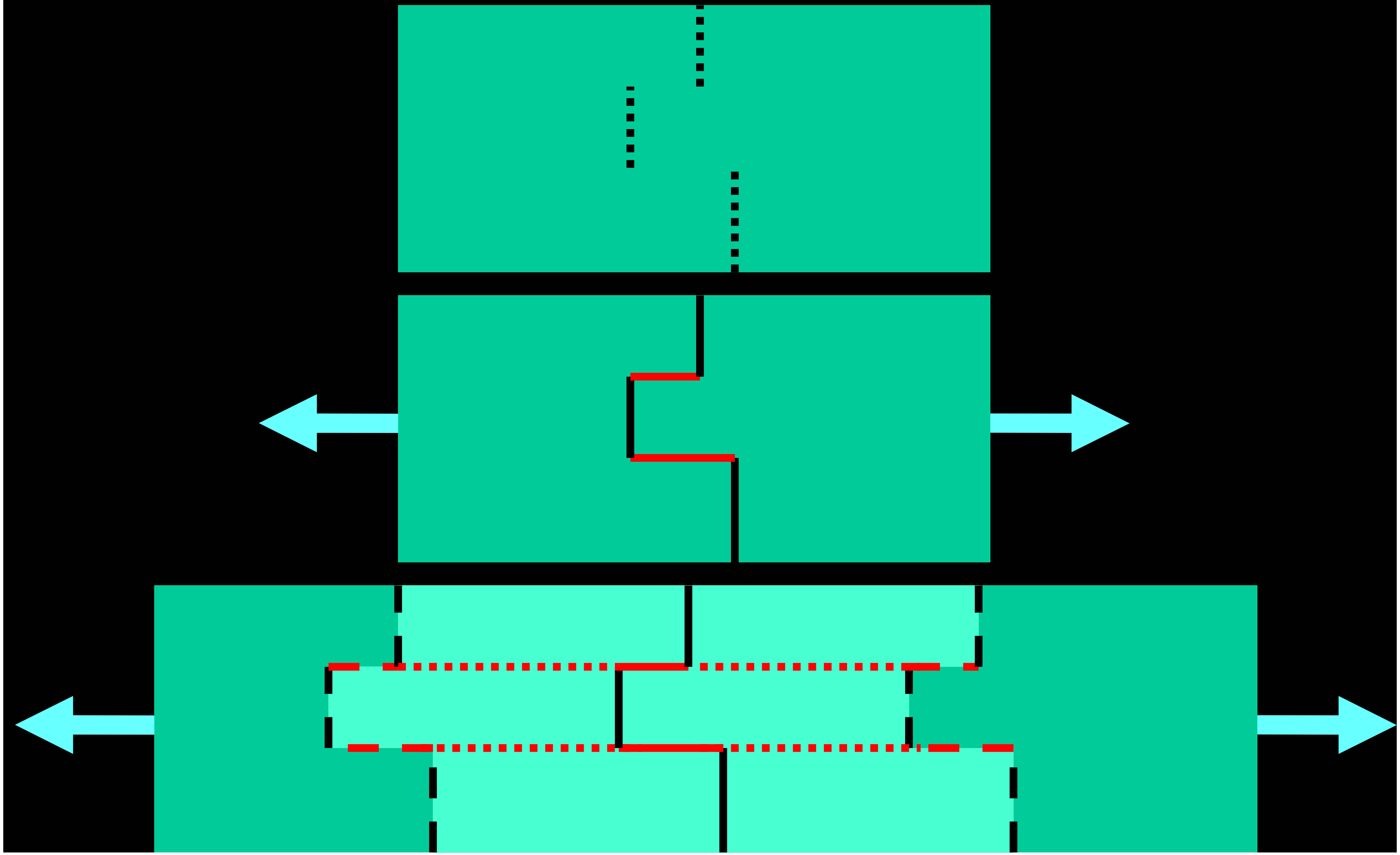


Fig. 3. (a) F_x, force required to extend the domain at the applied velocity in the *x*-direction as a function of time. (b) Depth profiles of temperature and viscosity are taken at the point *P* marked in (a) and compared at different time steps (0, 3, 7, 10.2, and 15 kyears). The rise in F_x at ~7 kyears coincides with the cooling and significant increase in viscosity of the subsurface (1–2 km deep) layer. 3D rendering of the second invariant of plastic strain at the same set of time steps: (c) 3 kyears, (d) 7 kyears, (e) 10.2 kyears, and (f) 15 kyears.

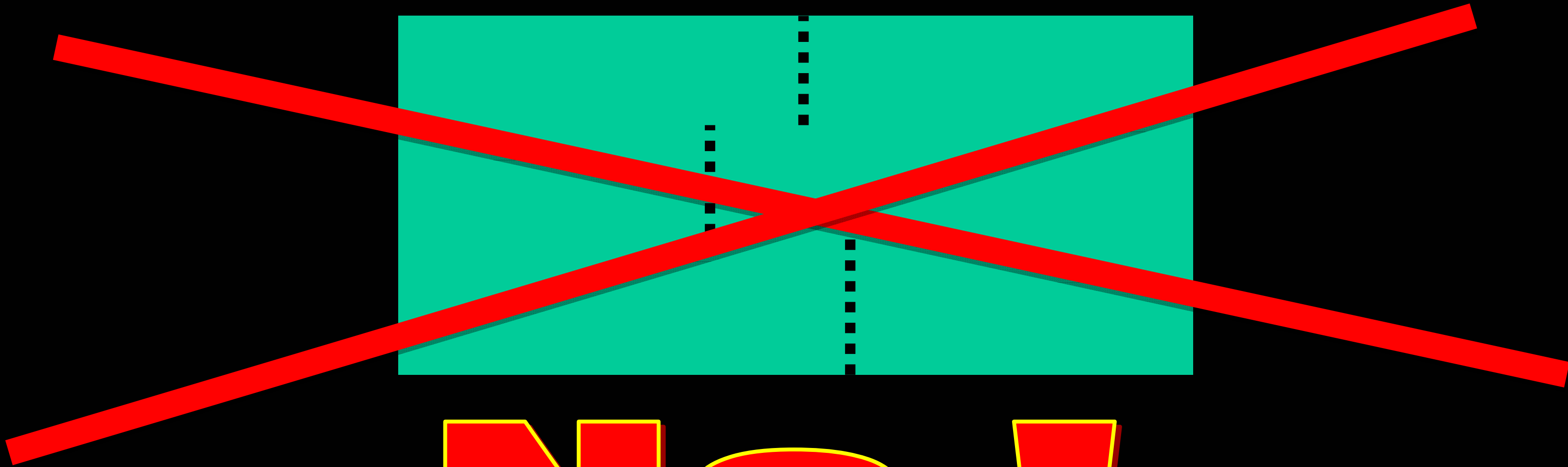


Choi et al. (2008)

Are transform faults allways inherited ?



Are transform faults allways inherited ?



No !

However, other observations support the hypothesis that the orthogonal ridge-transform system is emergent and not solely due to preexisting conditions:

(1) that single straight ridges can develop into an orthogonal pattern,

(2) the existence of zero offset fracture zones, and

(3) a positive correlation between ridge segment length and spreading rate

(4) transform faults are not inherited from transverse rift structures and nucleate while or after spreading starts

Transform faults can be emergent !

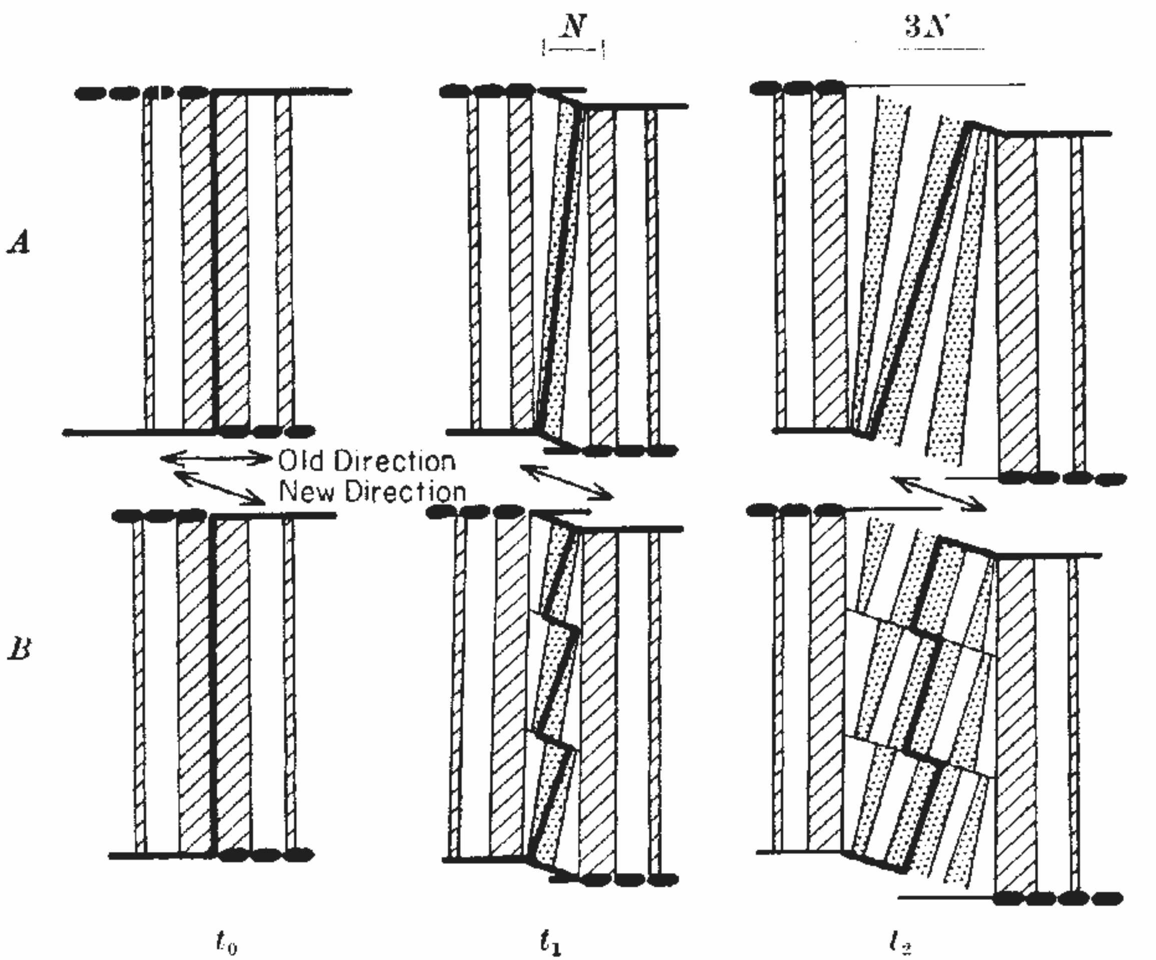
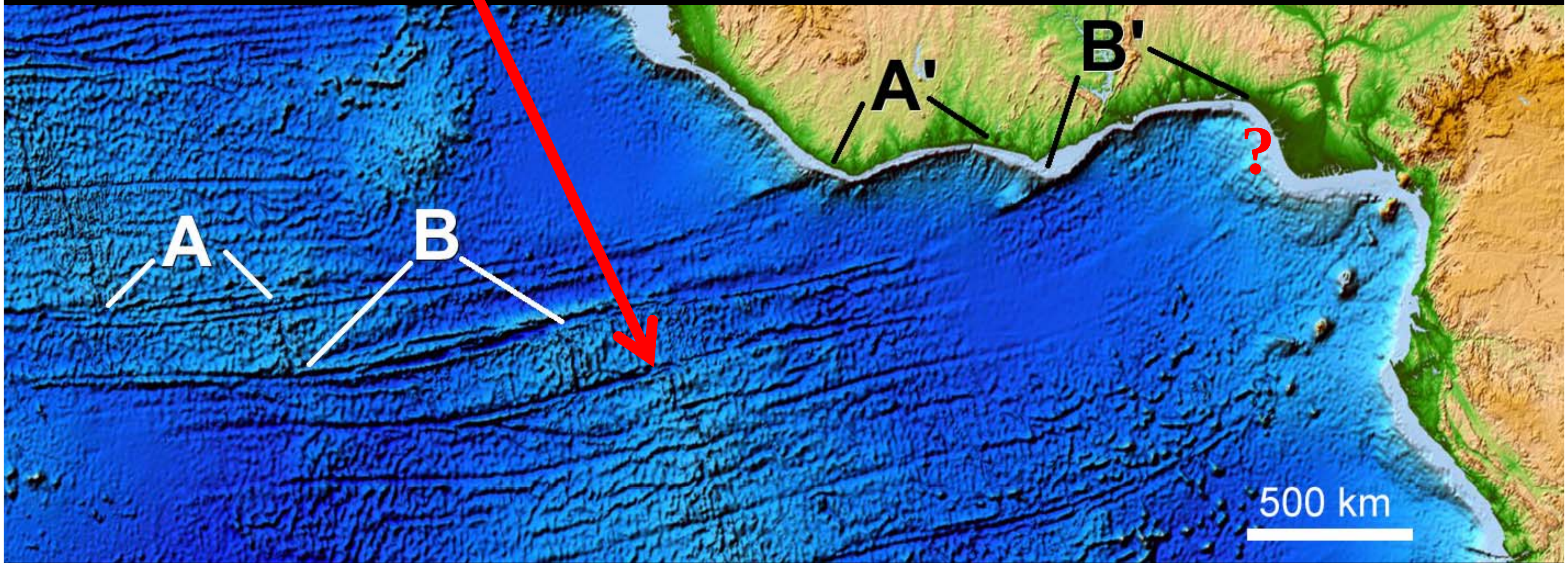


Fig. 5. Two possible modes for adjustment of a ridge to a change in spreading direction. *A*, The ridge readjusts as a unit taking on a new direction by time t_2 after $3N$ km of spreading has occurred. *B*, The ridge breaks into segments, each piece becoming realigned by time t_1 after N km of spreading.

Menard (1968)

Transform faults can be emergent !

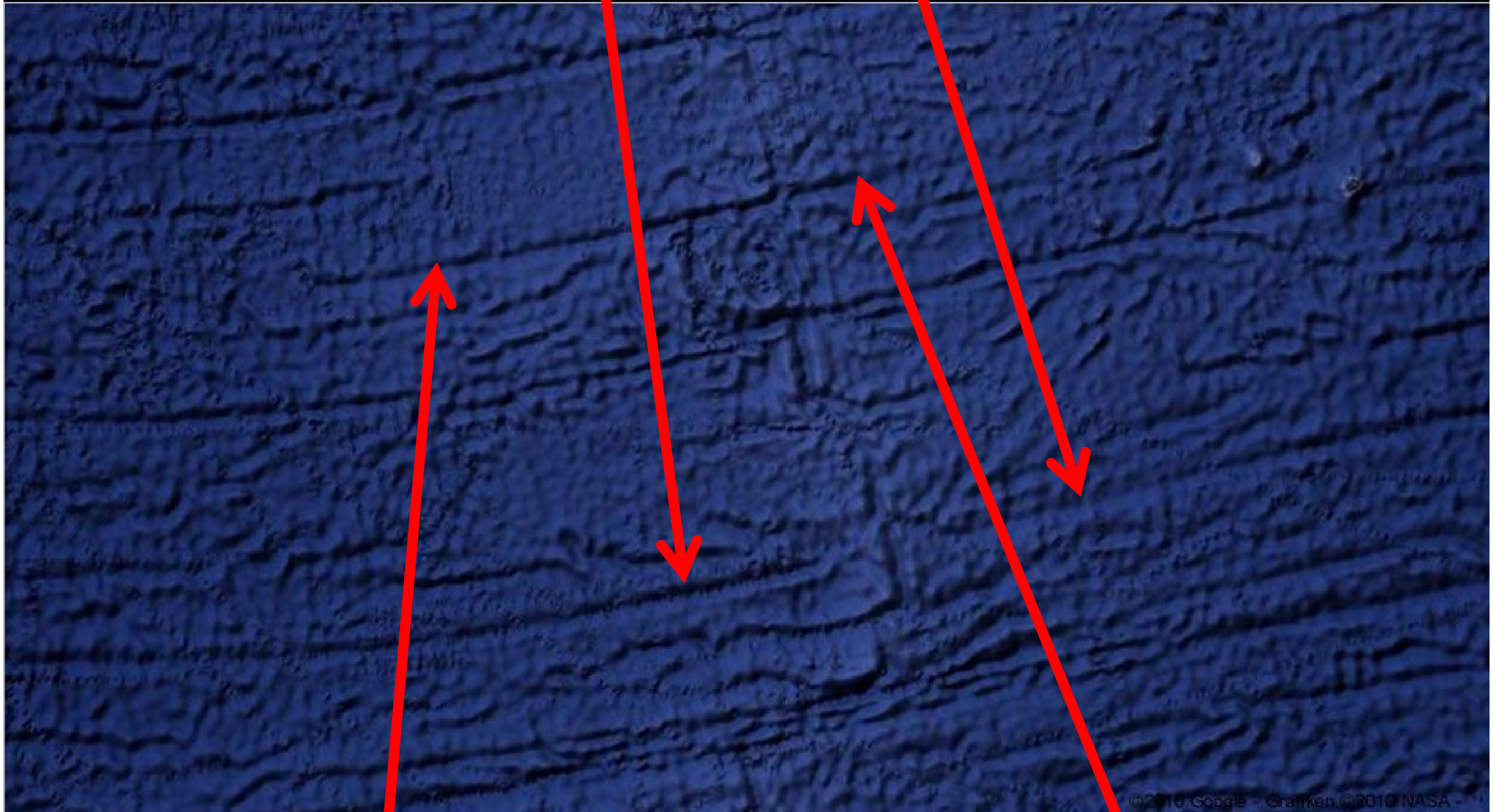


Emerging faults

Desuppearing faults

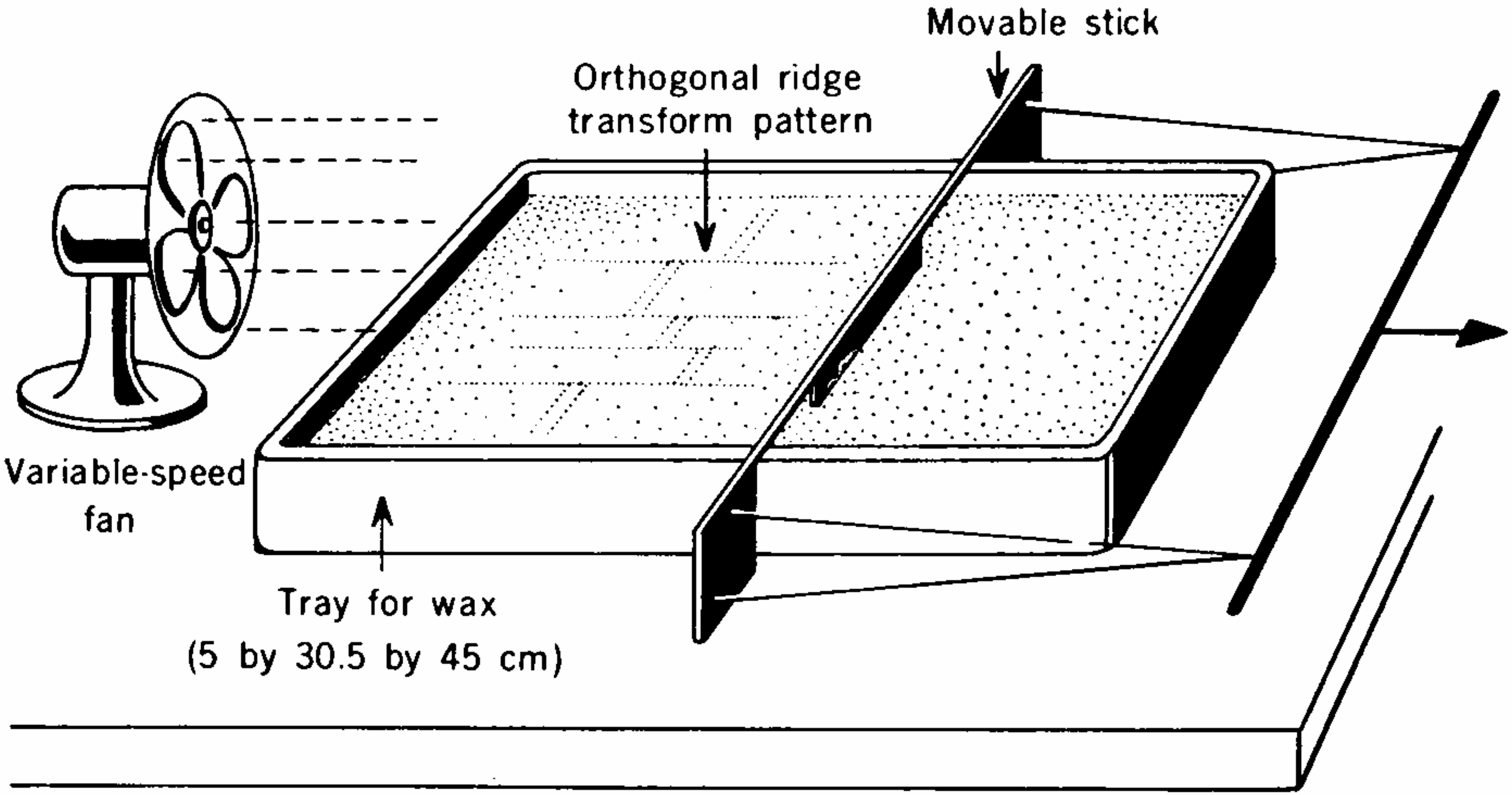
Emergent faults

Desuppearing faults



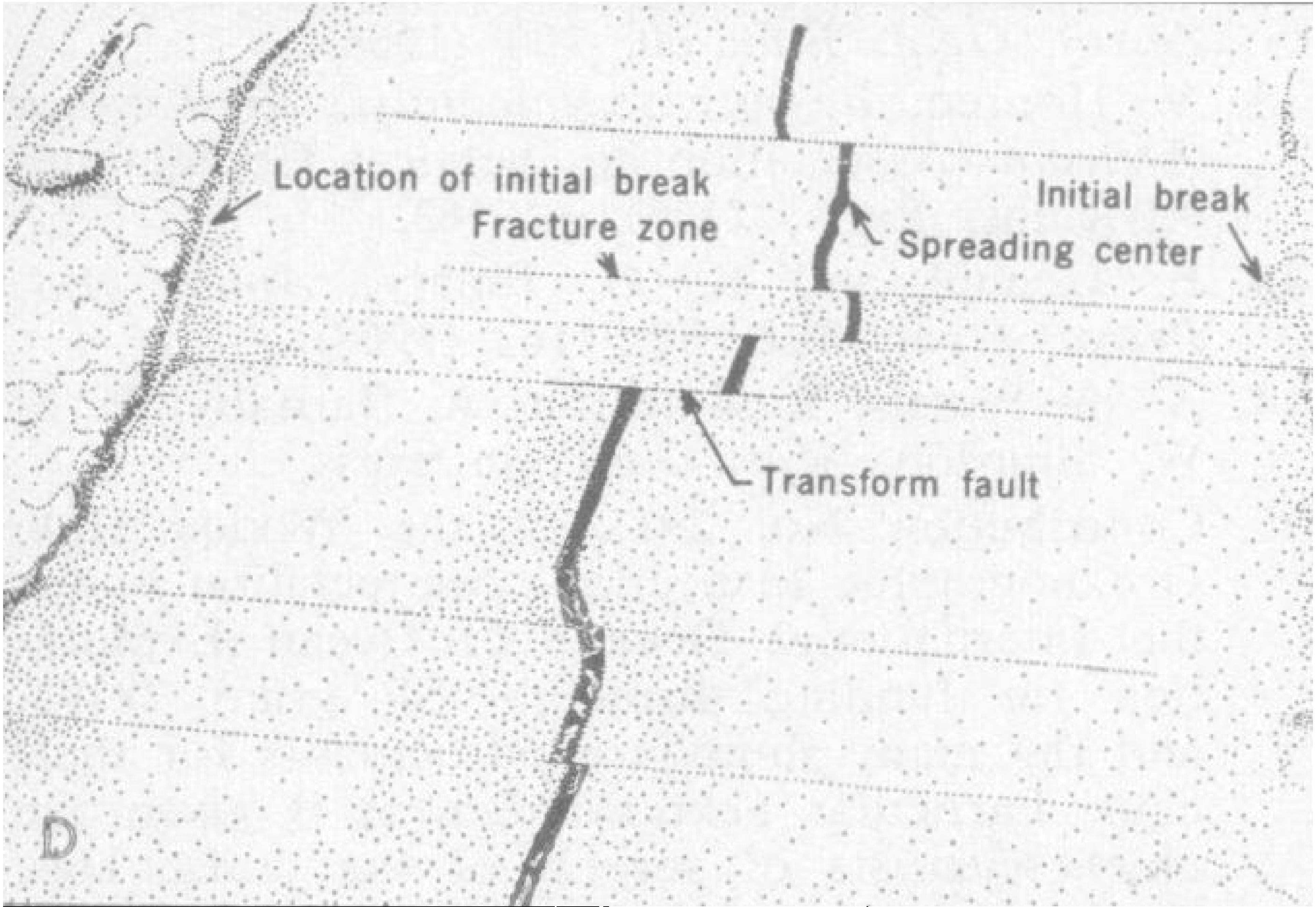
Emergent faults

freezing wax experiments



Oldenbburg and Brune (1972)

Oldenbburg and Brune (1972)



Oldenbburg and Brune (1972)

asymmetric accretion

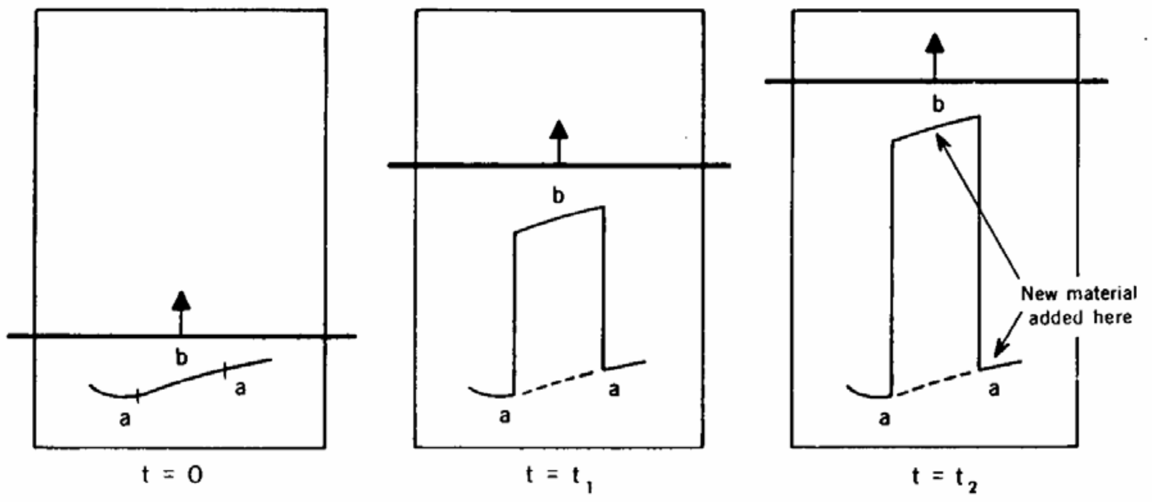


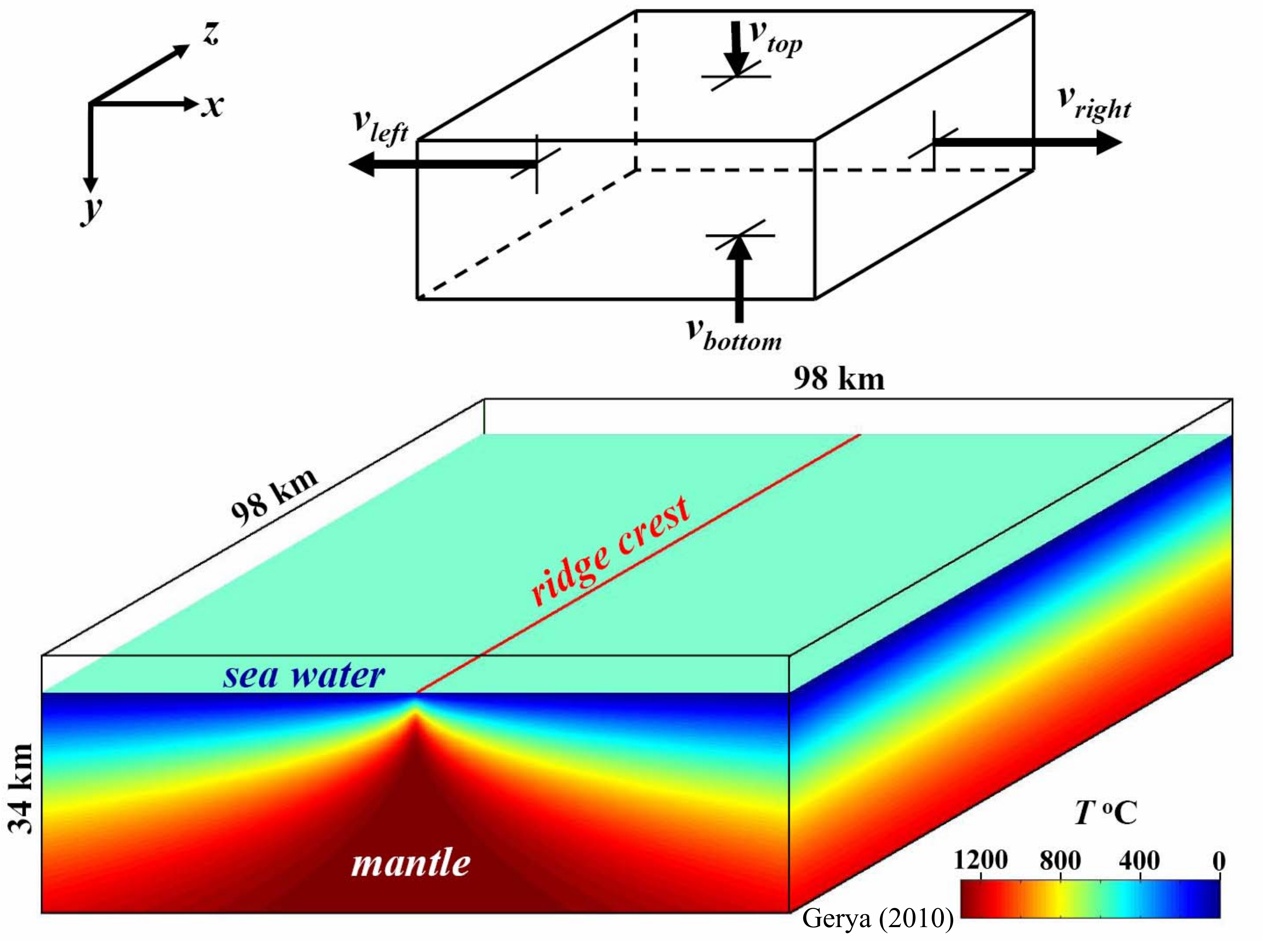
Fig. 3. Evolution of asymmetric spreading.

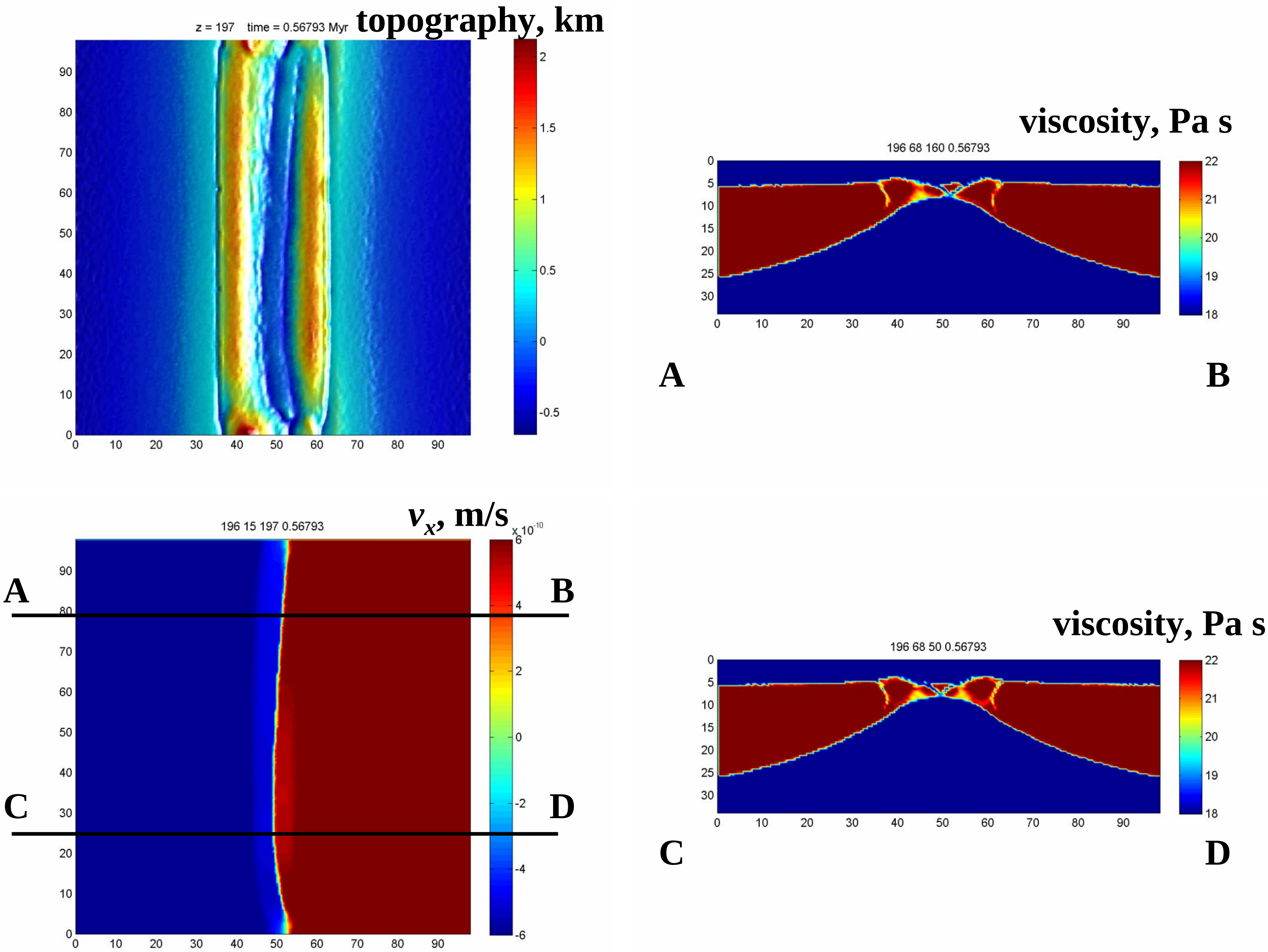
Oldenbburg and Brune (1972)

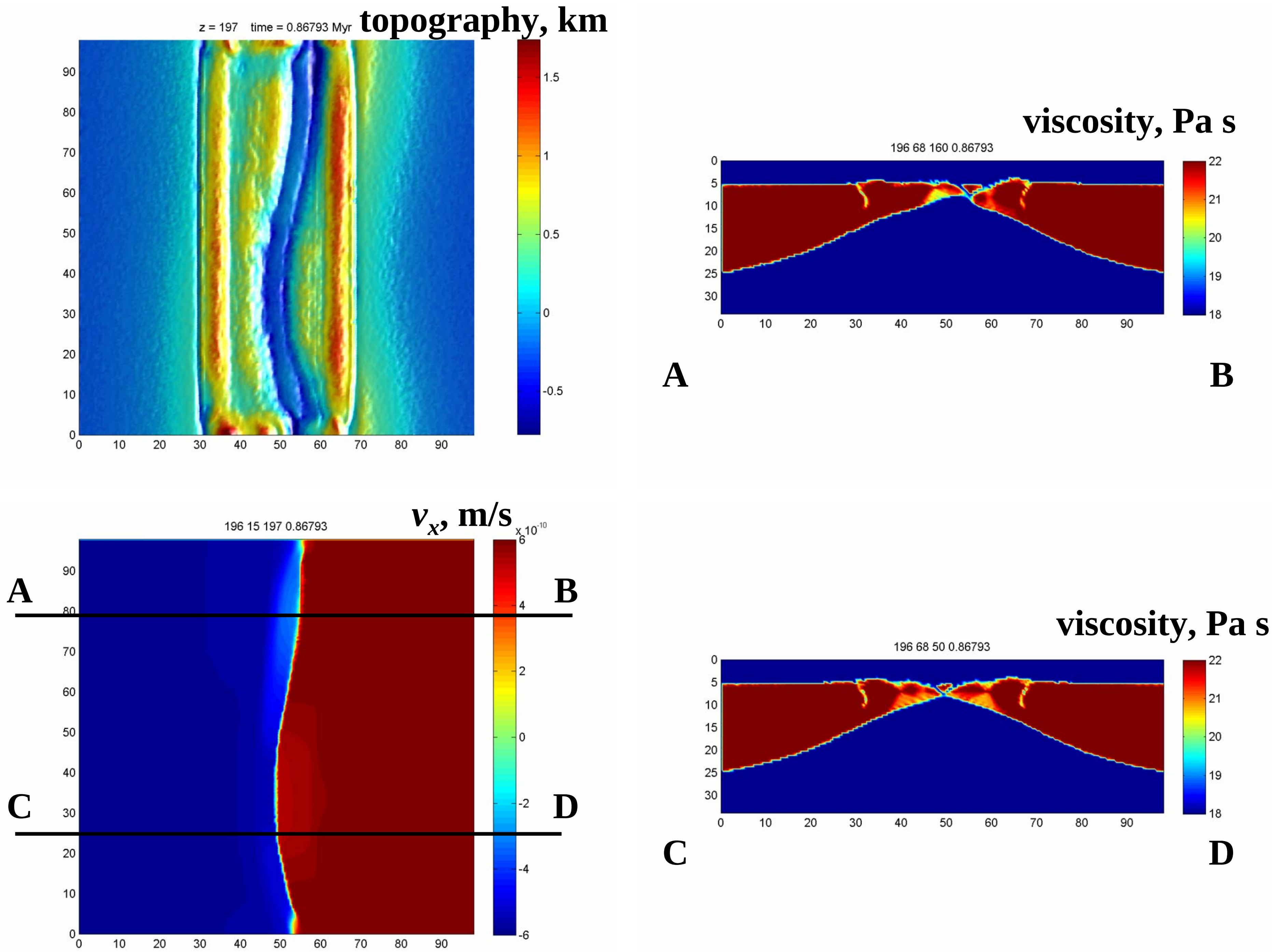
Separating the plates at rates significantly slower than the medium rate resulted in asymmetric spreading and occasional multiple breakup. The multiple breakup is evidently caused by the fact that the ridge crest freezes to a strength sufficient to cause the spreading center to jump, creating new fissures in one or more locations. Asymmetric spreading is characterized by an irregular ridge axis divided into a number of segments of random length, each spreading asymmetrically in an alternate direction. In each segment the ridge remains stationary with respect to either the moving or fixed plate. In this process the slow separation allows the wax to repeatedly freeze and break across the spreading center. For some unknown reason the solidified wax is bound less strongly to one side and, as separation continues, the solid material preferentially breaks away from this side, attaching itself entirely to other plate which therefore grows at a rate equal to the velocity of the moving stick. A schematic example of this evolution of asymmetric spreading is given in Fig. 3. The ridge segments labeled *a* do not move relative to the bottom of the diagram, and those labeled *b* do not move relative to the stick. A type of transform fault which continually increases in length is produced.

3D, high-resolution, and long-term mid-ocean ridge modeling required

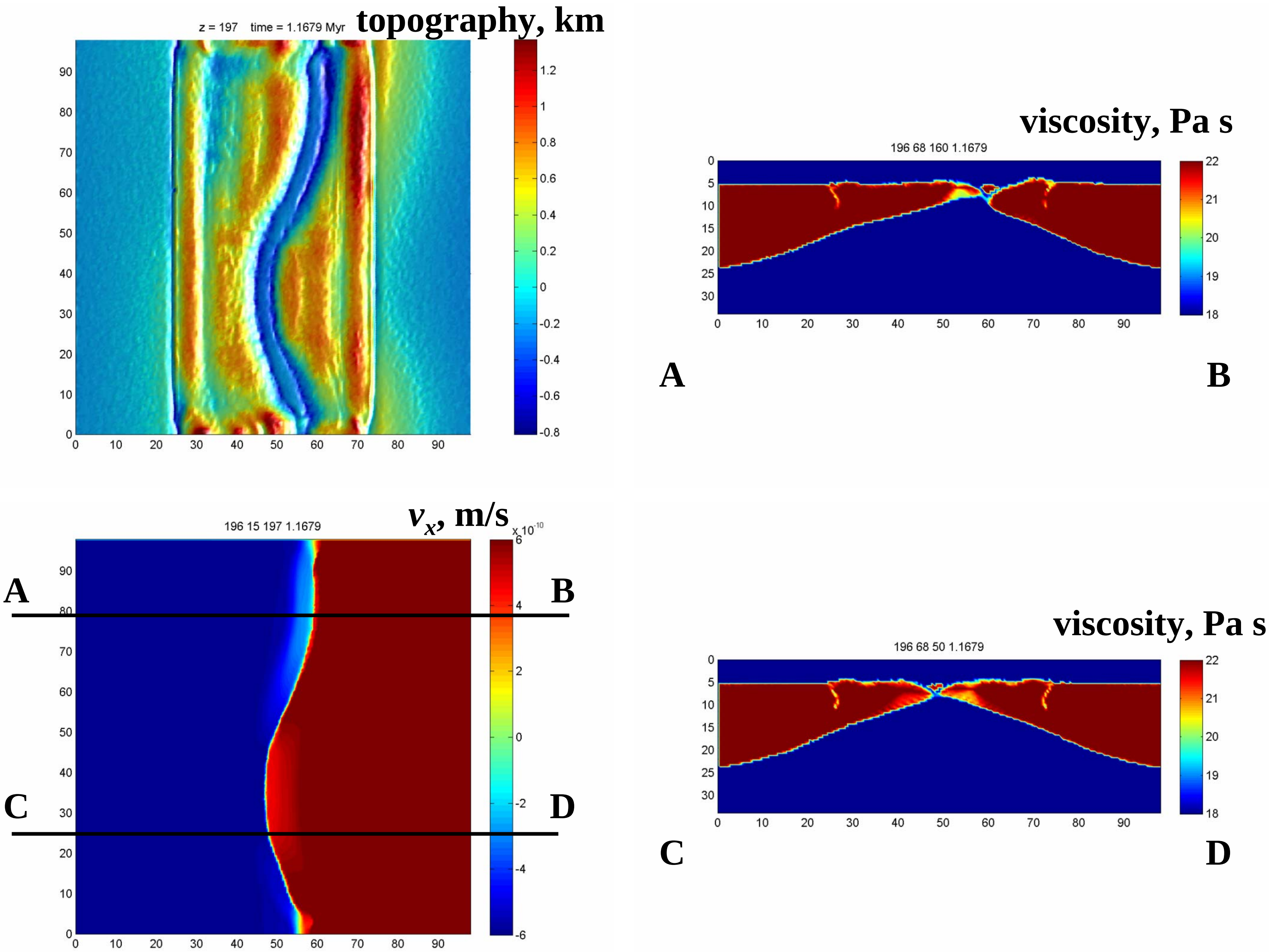
~300 experiments with I3ELVIS code were performed:
resolution up to 405x405x69 nodes (0.5x0.5x0.5 km)
and up to 100 million randomly distributed markers
viscous-brittle/plastic model with strain weakening

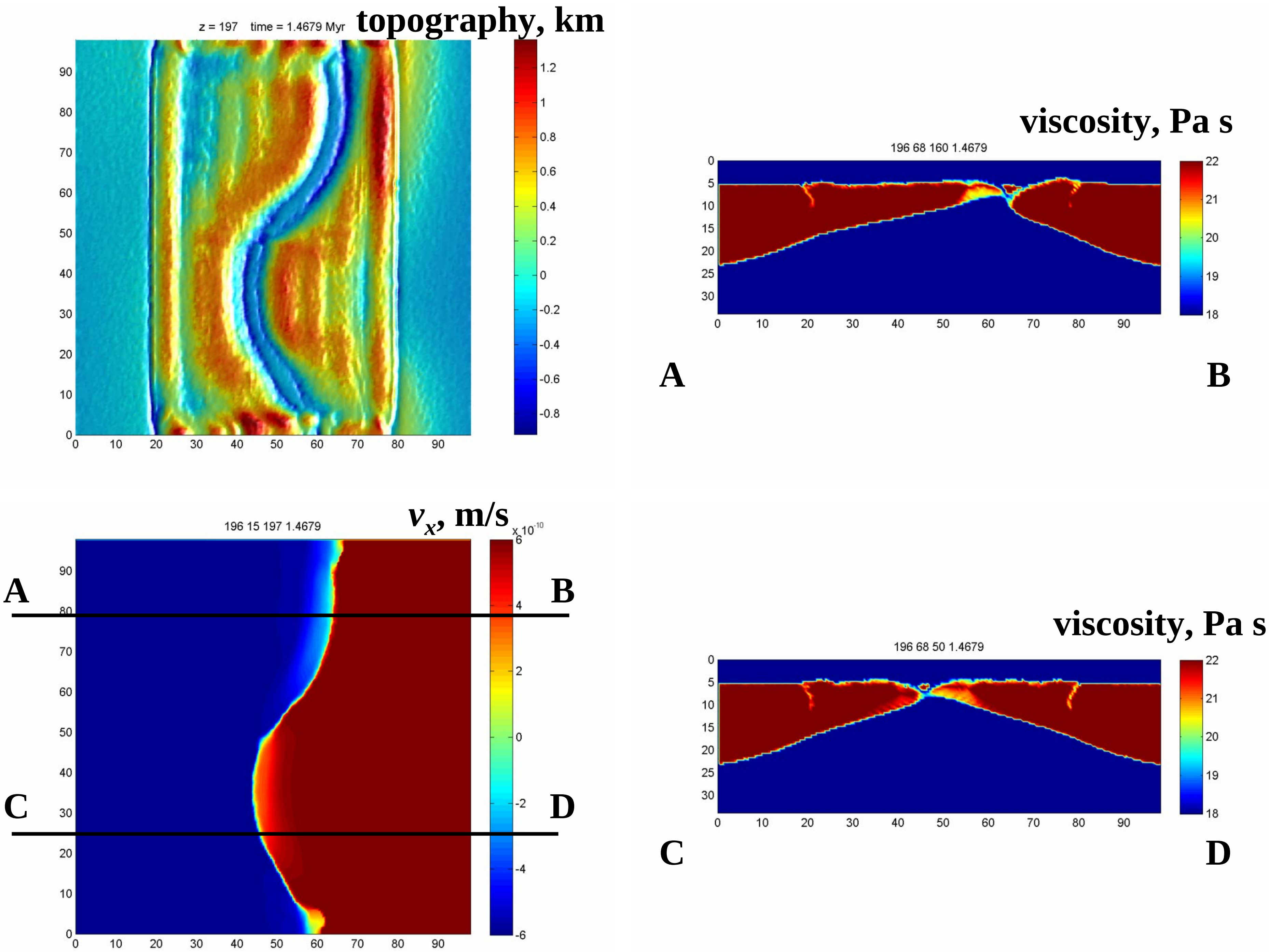

z
x
y
v_{top}
v_{left}
v_{right}
v_{bottom}
98 km
98 km
ridge crest
sea water
34 km
mantle
T °C
1200
800
400
0
Gerya (2010)


z = 197 time = 0.56793 Myr
topography, km
viscosity, Pa s
196 68 160 0.56793
A
B
v_x, m/s
196 15 197 0.56793
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 0.56793
C
D

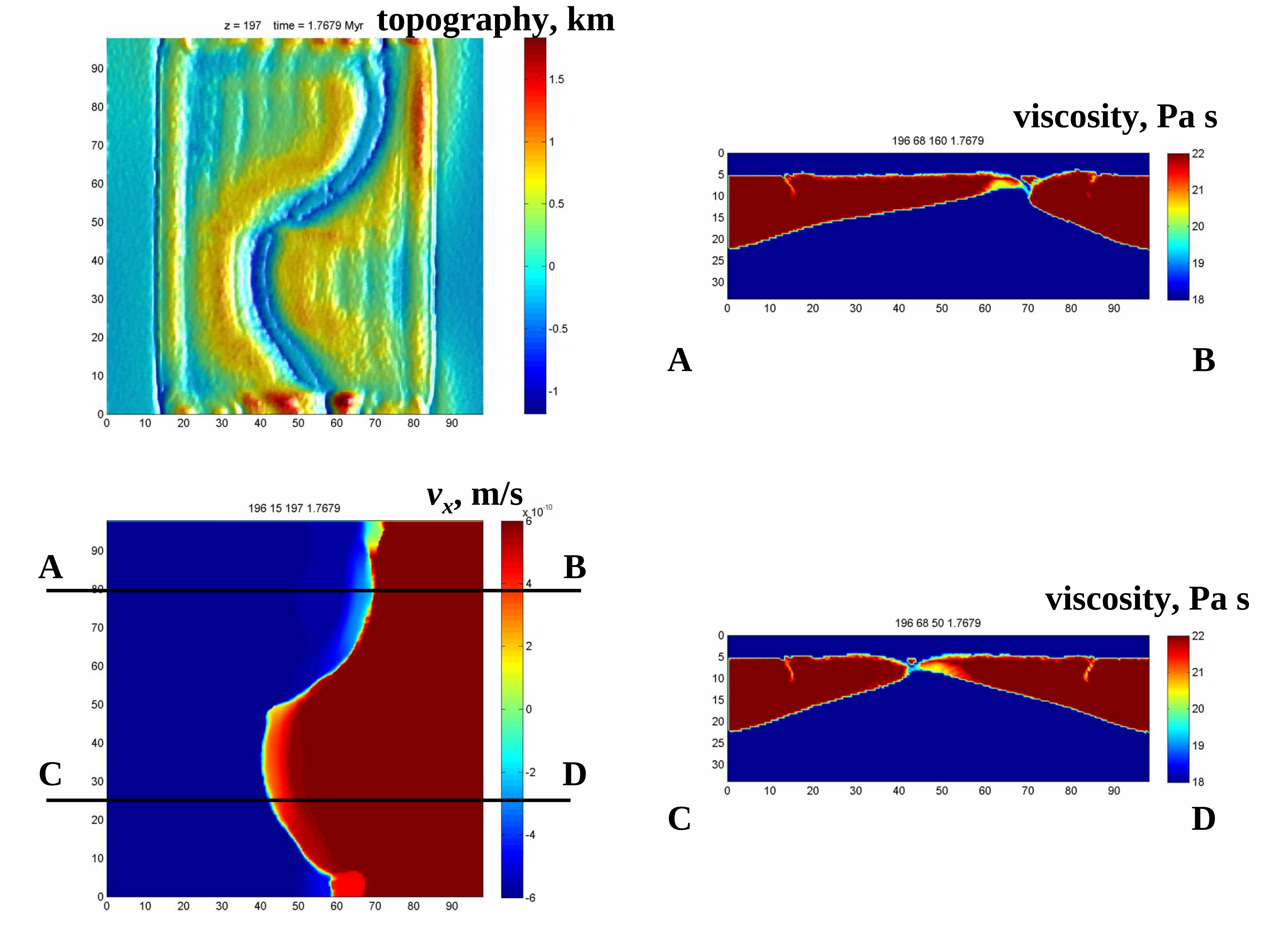


z = 197 time = 0.86793 Myr
topography, km
viscosity, Pa s
196 68 160 0.86793
A
B
v_x, m/s
196 15 197 0.86793
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 0.86793
C
D

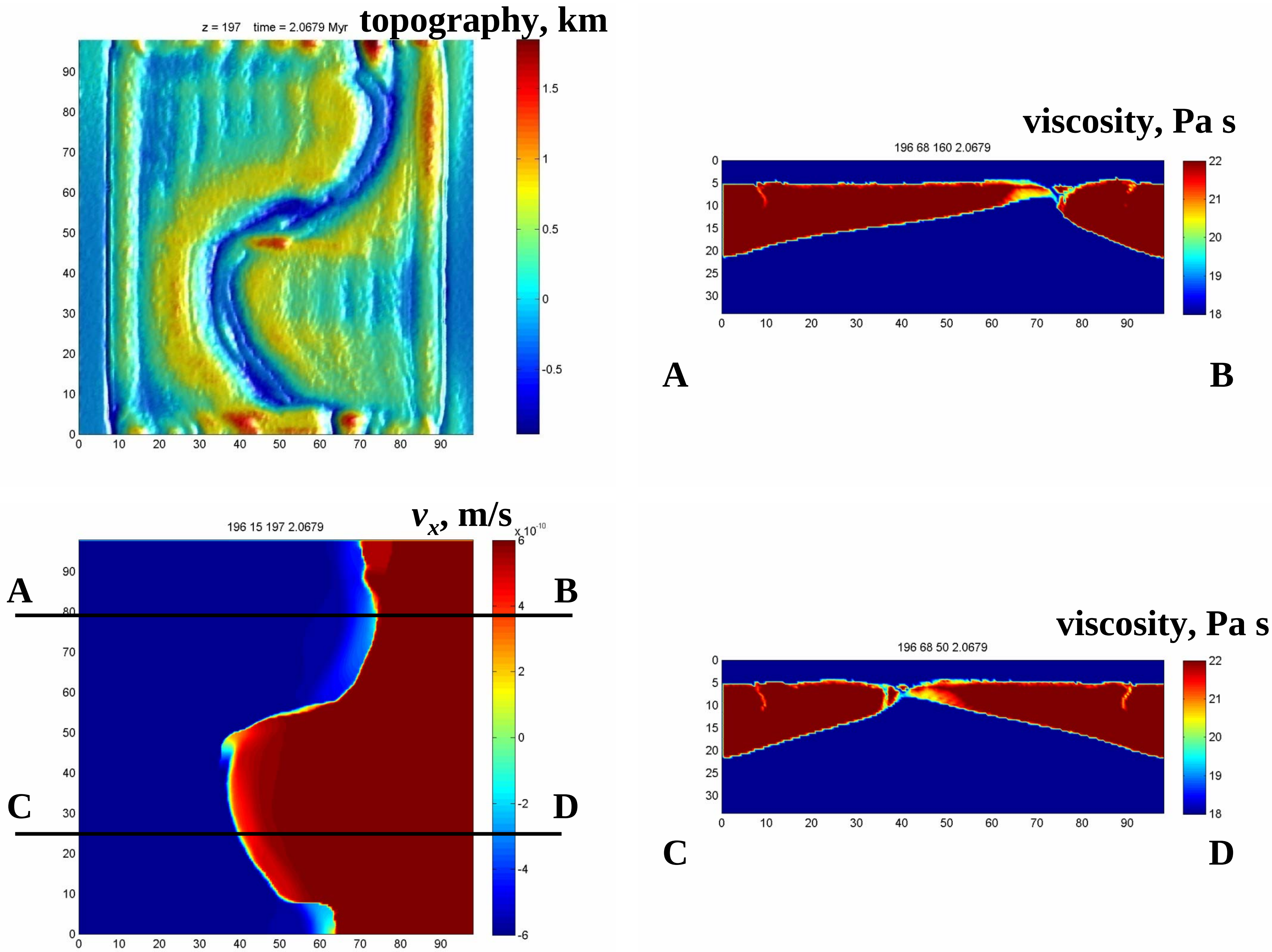

z = 197 time = 1.1679 Myr
topography, km
viscosity, Pa s
196 68 160 1.1679
A
B
v_x, m/s
196 15 197 1.1679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 1.1679
C
D



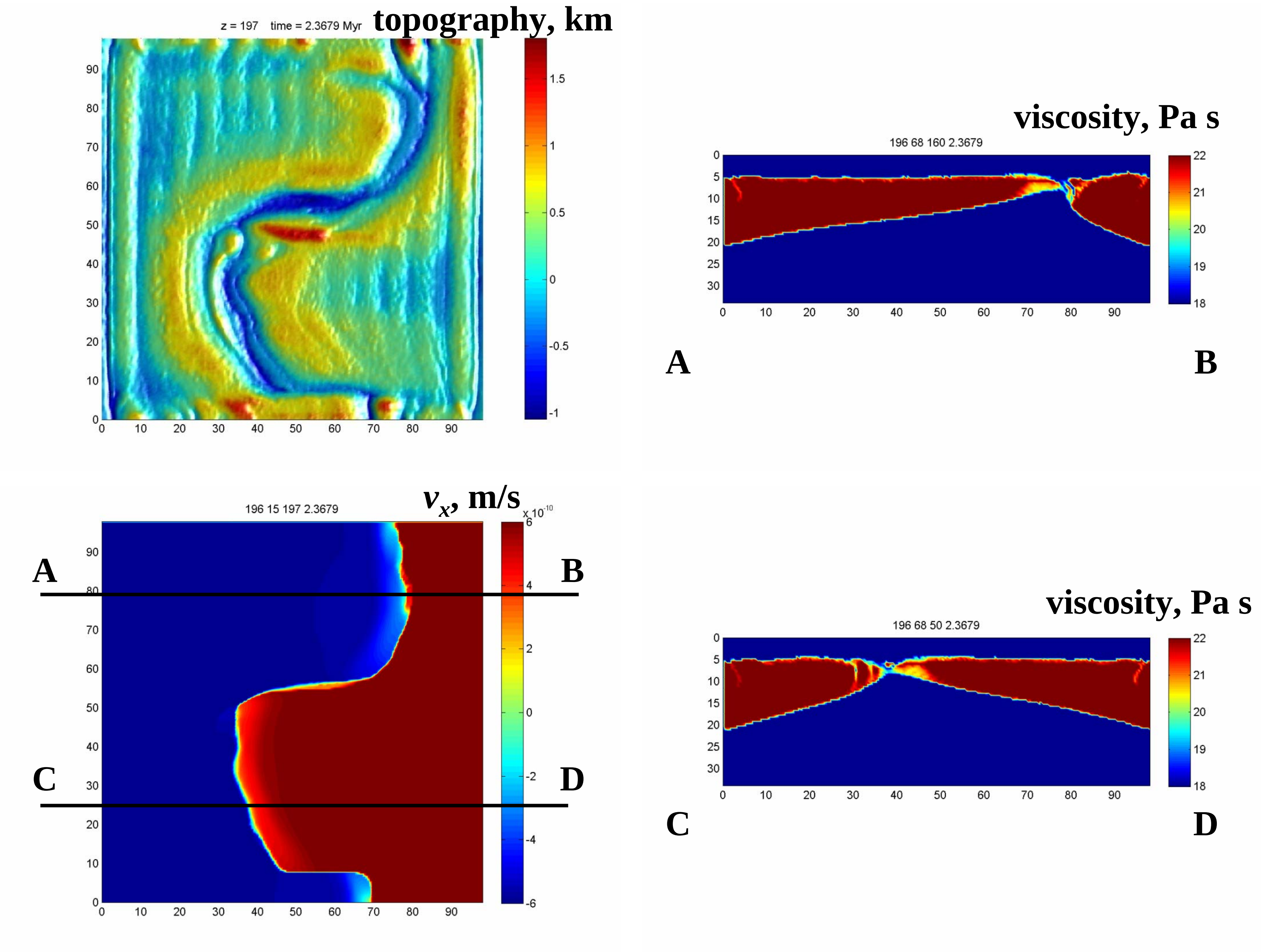
z = 197 time = 1.4679 Myr
topography, km
viscosity, Pa s
196 68 160 1.4679
A
B
v_x, m/s
196 15 197 1.4679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 1.4679
C
D



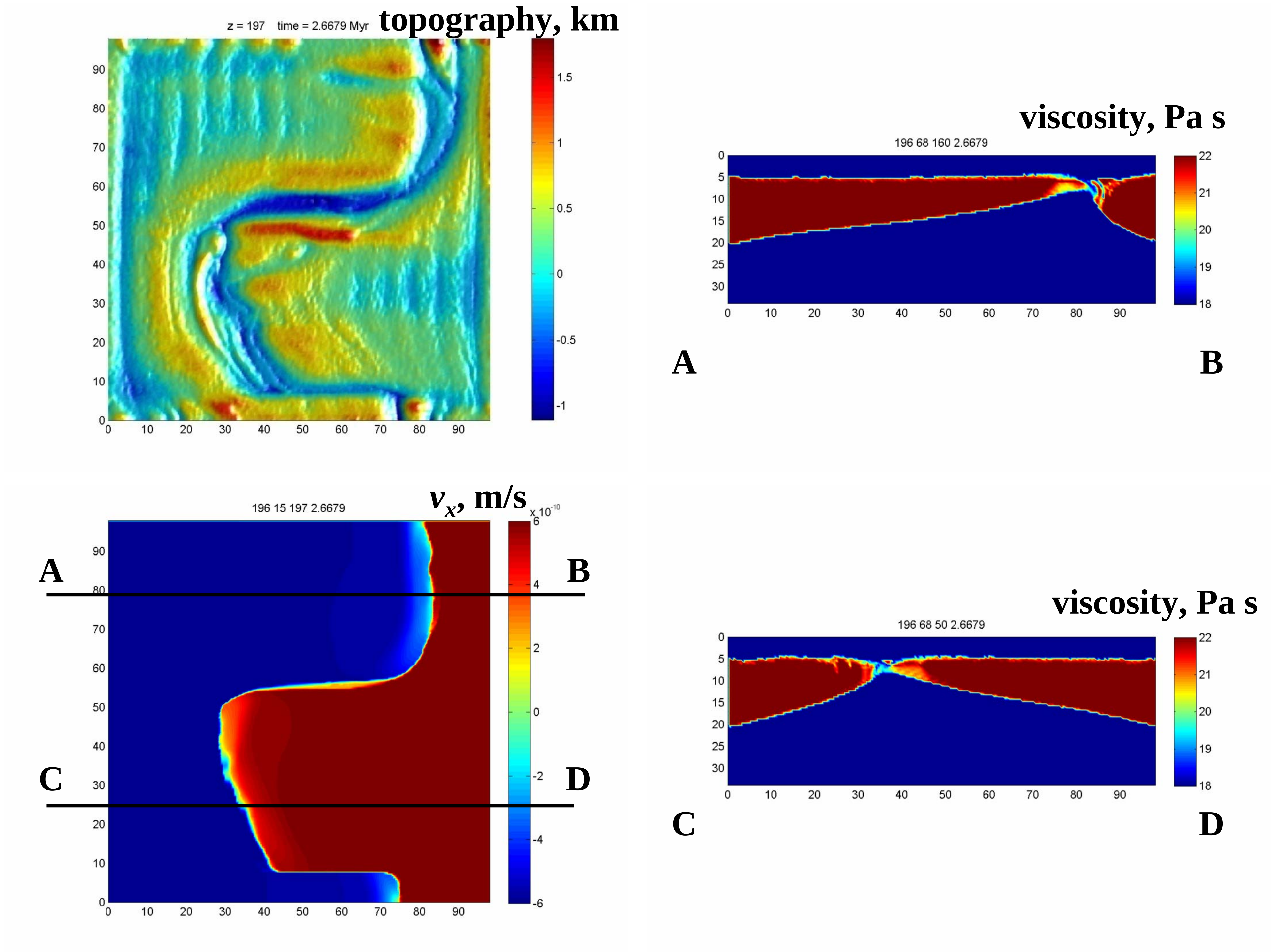
z = 197 time = 1.7679 Myr
topography, km
viscosity, Pa s
196 68 160 1.7679
A
B
vx, m/s
196 15 197 1.7679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 1.7679
C
D



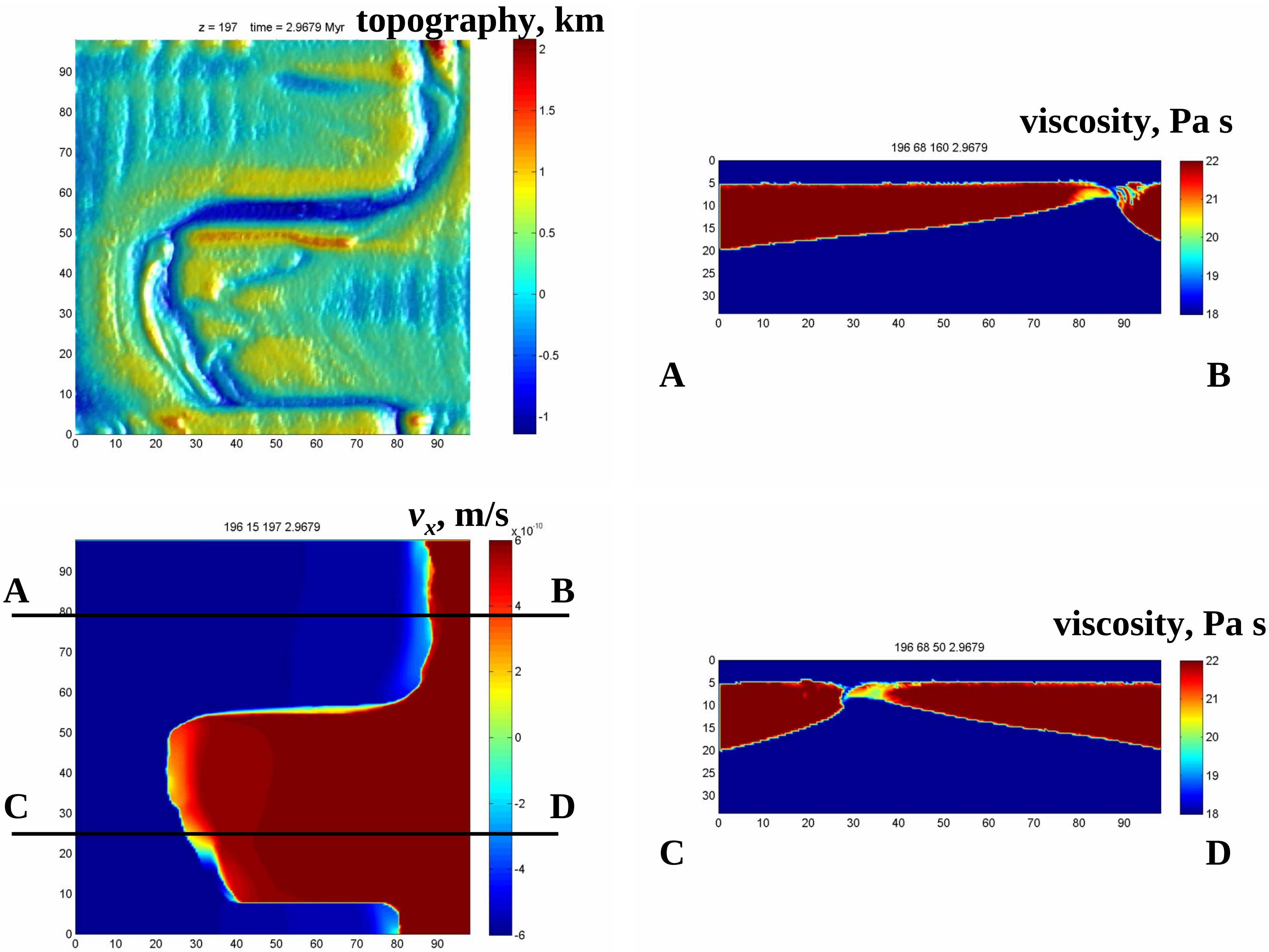
z = 197 time = 2.0679 Myr
topography, km
viscosity, Pa s
196 68 160 2.0679
A
B
v_x, m/s
196 15 197 2.0679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 2.0679
C
D



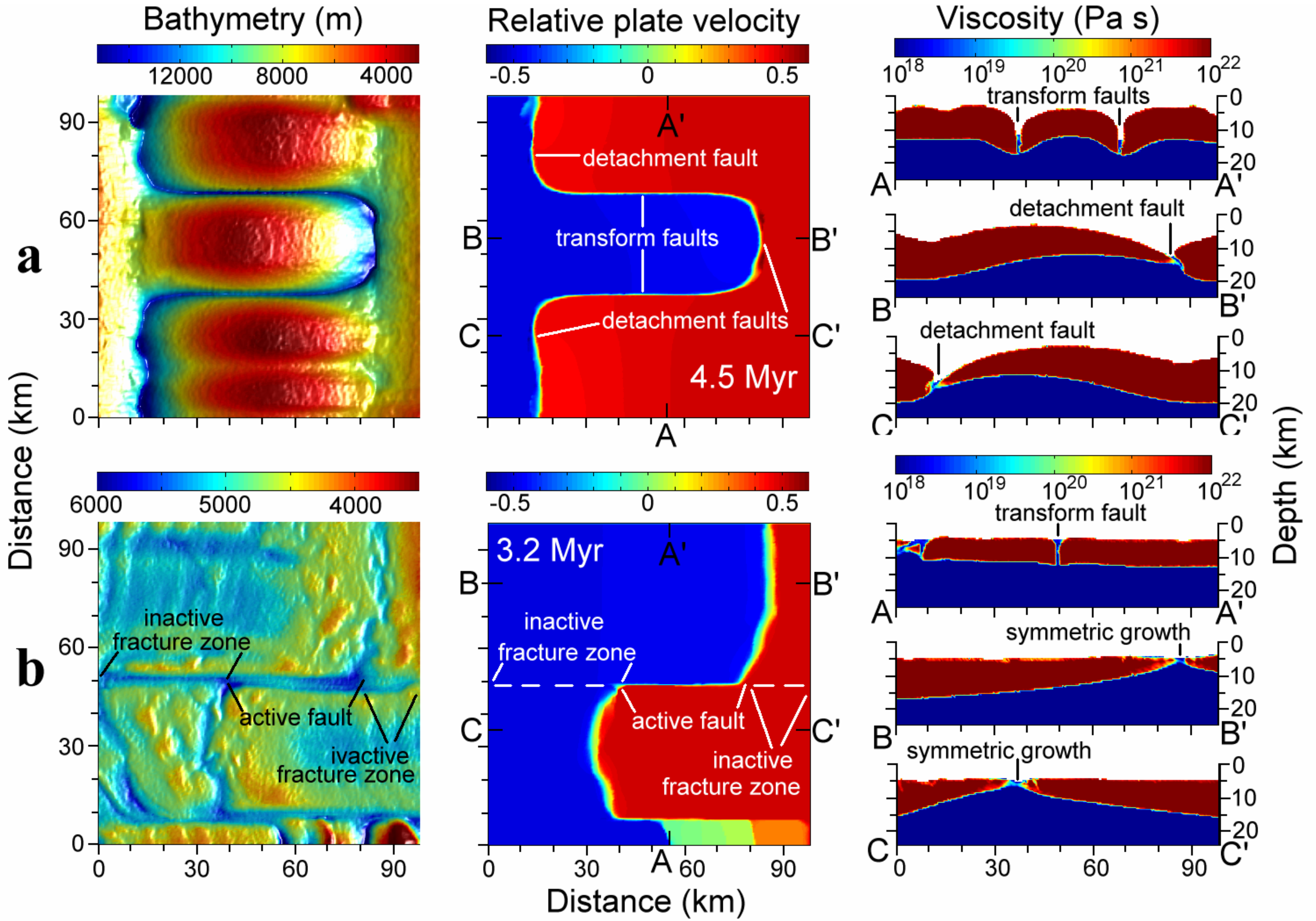
z = 197 time = 2.3679 Myr
topography, km
viscosity, Pa s
196 68 160 2.3679
A
B
v_x, m/s
196 15 197 2.3679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 2.3679
C
D



z = 197 time = 2.6679 Myr
topography, km
viscosity, Pa s
196 68 160 2.6679
A
B
v_x, m/s
196 15 197 2.6679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 2.6679
C
D


z = 197 time = 2.9679 Myr
topography, km
viscosity, Pa s
196 68 160 2.9679
A
B
v_x, m/s
196 15 197 2.9679
x 10^-10
A
B
C
D
viscosity, Pa s
196 68 50 2.9679
C
D

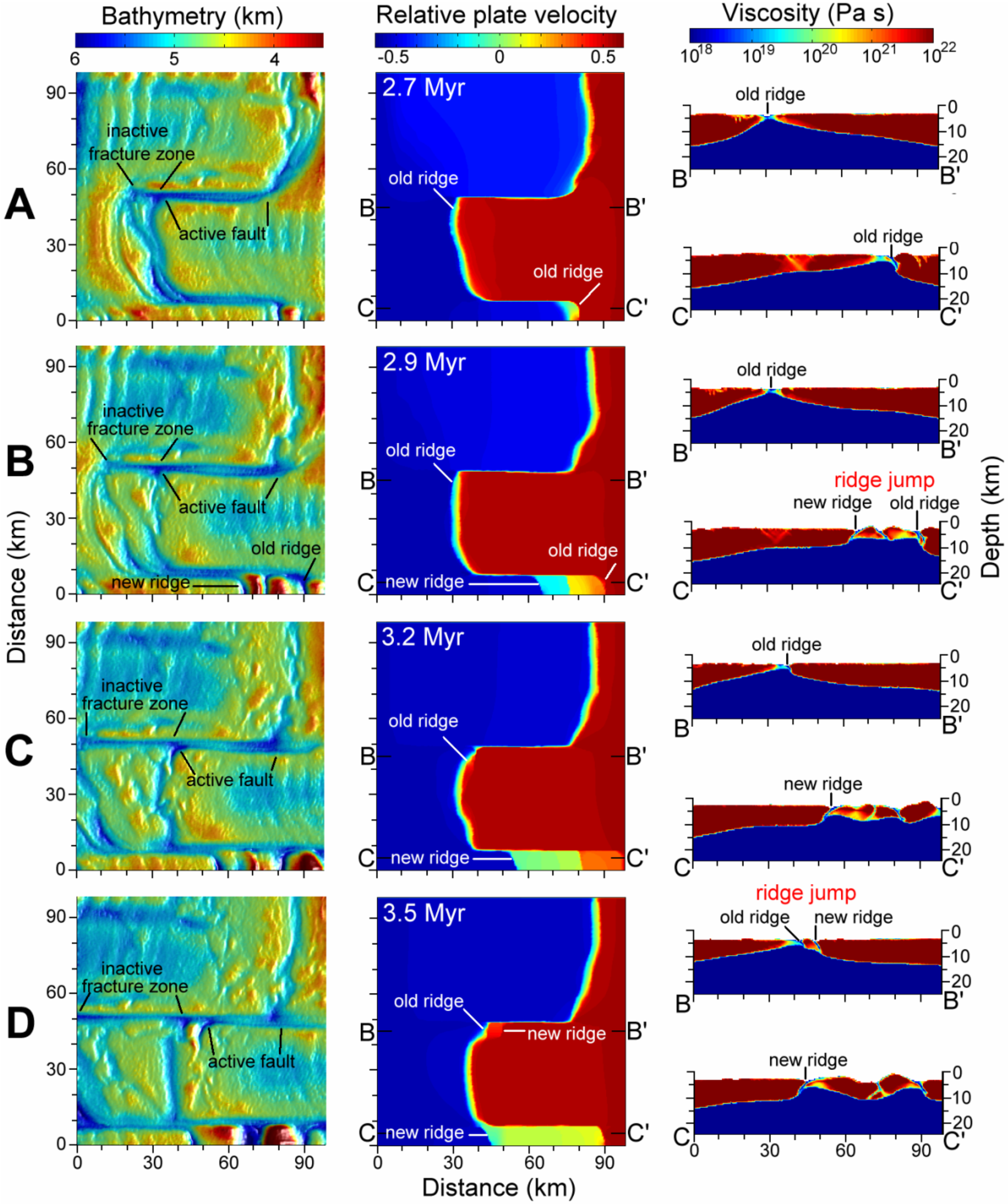
Model without gravitation



Model with doubling of spreading rate

Gerya (2010)

Inactive fracture zones and ridge jumps



Gerya (2010)

Accretion can be asymmetric => ridge offsets can change with time

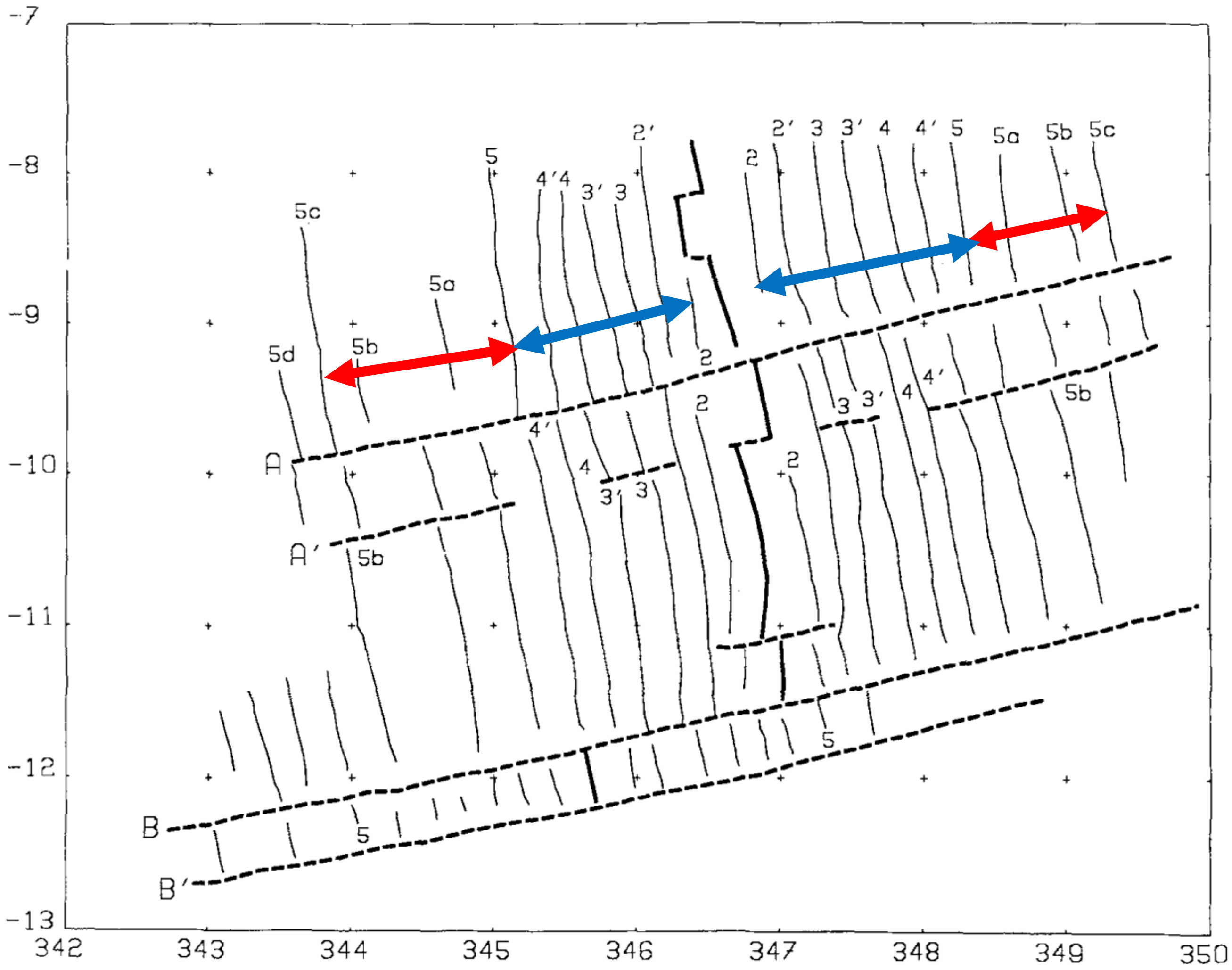


Fig. 1. The southern Mid-Atlantic Ridge (heavy line) and magnetic anomalies. Transform A′ reaches zero offset at anomaly 4 and 4′ time, and again at anomaly 2 and 2′ time. Offset along A′ is 15 km at anomaly 5b, 10 km at anomaly 3, and 20 km at present. 35% asymmetry in spreading is required to reach zero-offset (after Brozena, 1986).

asymmetric accretion

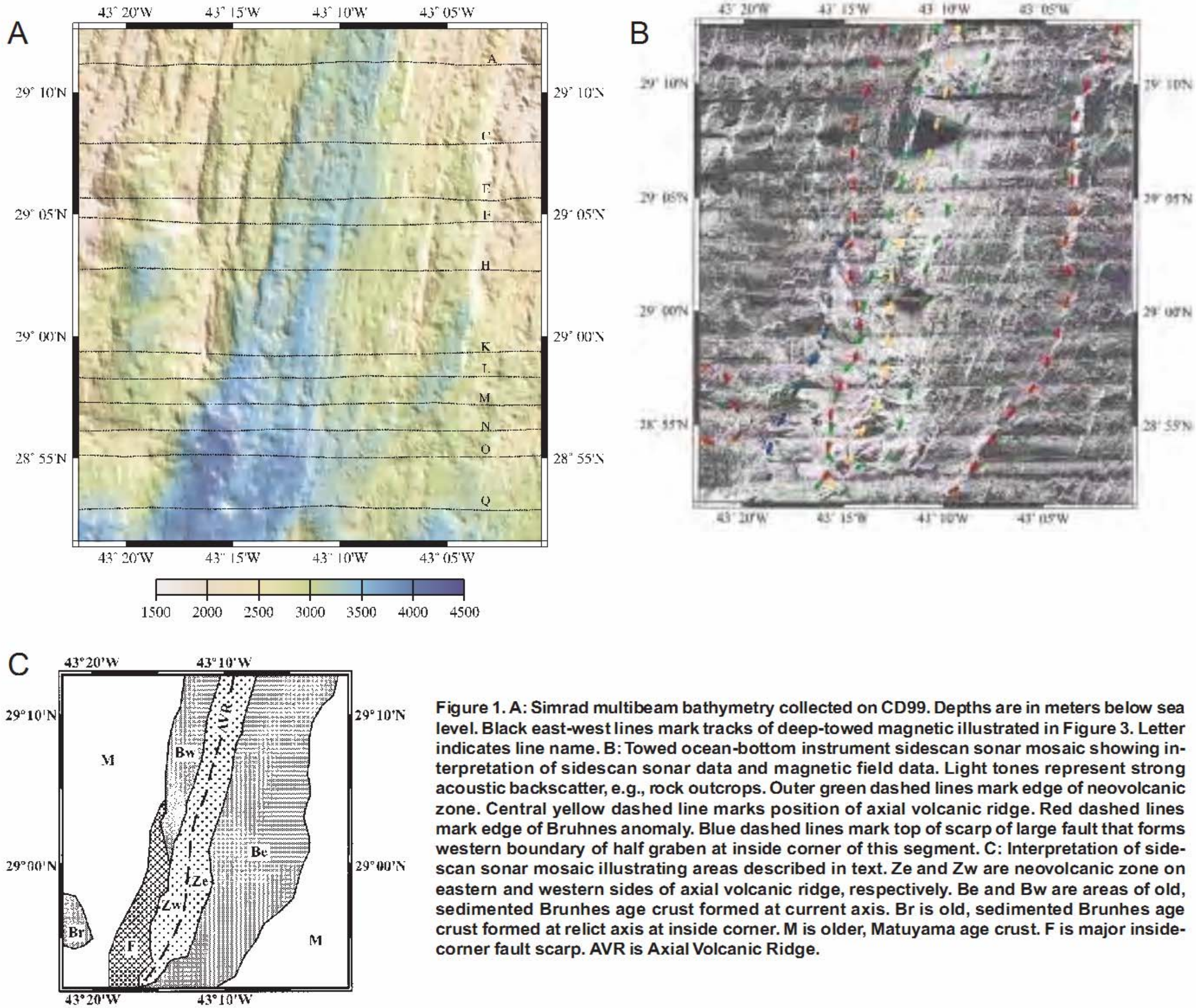


Figure 1. A: Simrad multibeam bathymetry collected on CD99. Depths are in meters below sea level. Black east-west lines mark tracks of deep-towed magnetic illustrated in Figure 3. Letter indicates line name. B: Towed ocean-bottom instrument sidescan sonar mosaic showing interpretation of sidescan sonar data and magnetic field data. Light tones represent strong acoustic backscatter, e.g., rock outcrops. Outer green dashed lines mark edge of neovolcanic zone. Central yellow dashed line marks position of axial volcanic ridge. Red dashed lines mark edge of Bruhnes anomaly. Blue dashed lines mark top of scarp of large fault that forms western boundary of half graben at inside corner of this segment. C: Interpretation of sidescan sonar mosaic illustrating areas described in text. Ze and Zw are neovolcanic zone on eastern and western sides of axial volcanic ridge, respectively. Be and Bw are areas of old, sedimented Brunhes age crust formed at current axis. Br is old, sedimented Brunhes age crust formed at relict axis at inside corner. M is older, Matuyama age crust. F is major inside-corner fault scarp. AVR is Axial Volcanic Ridge.

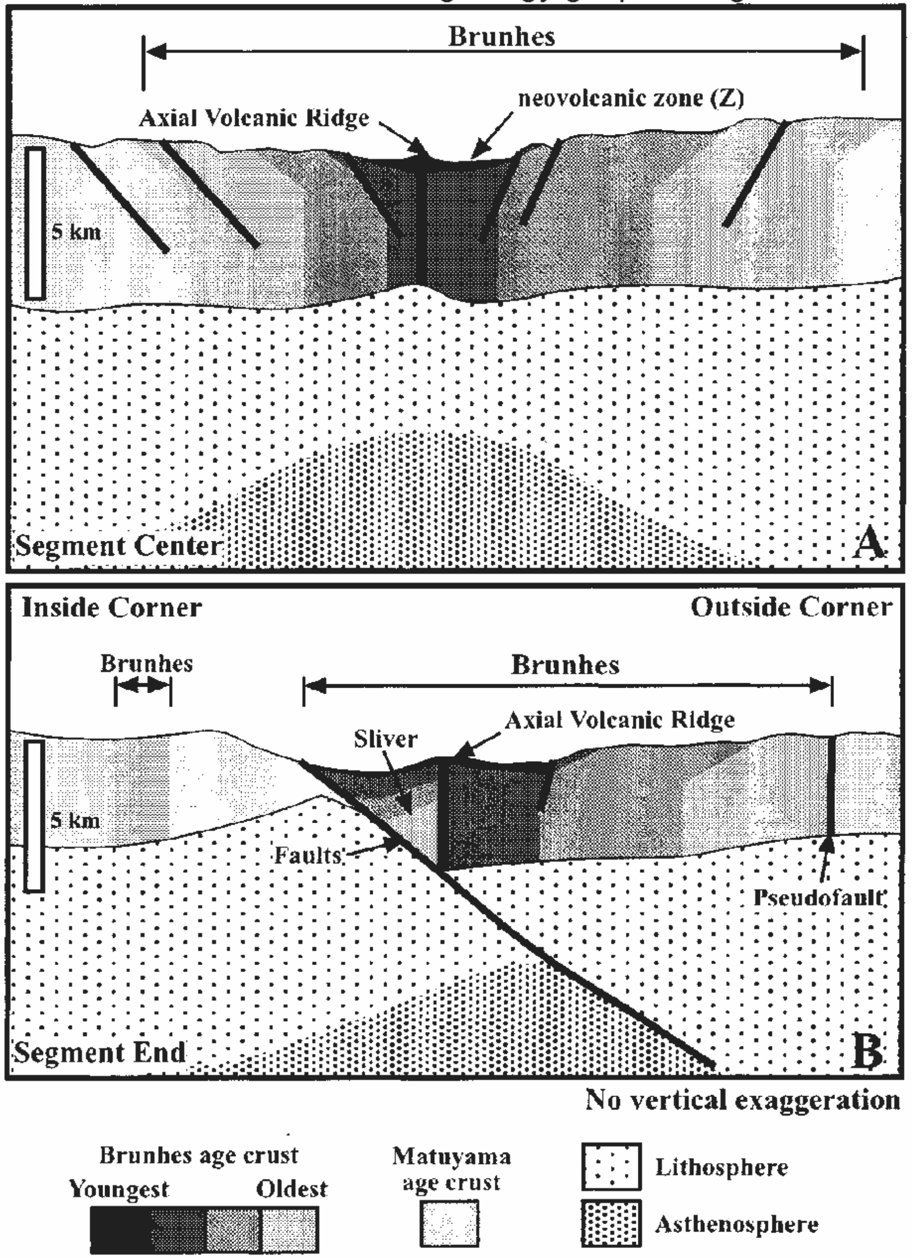
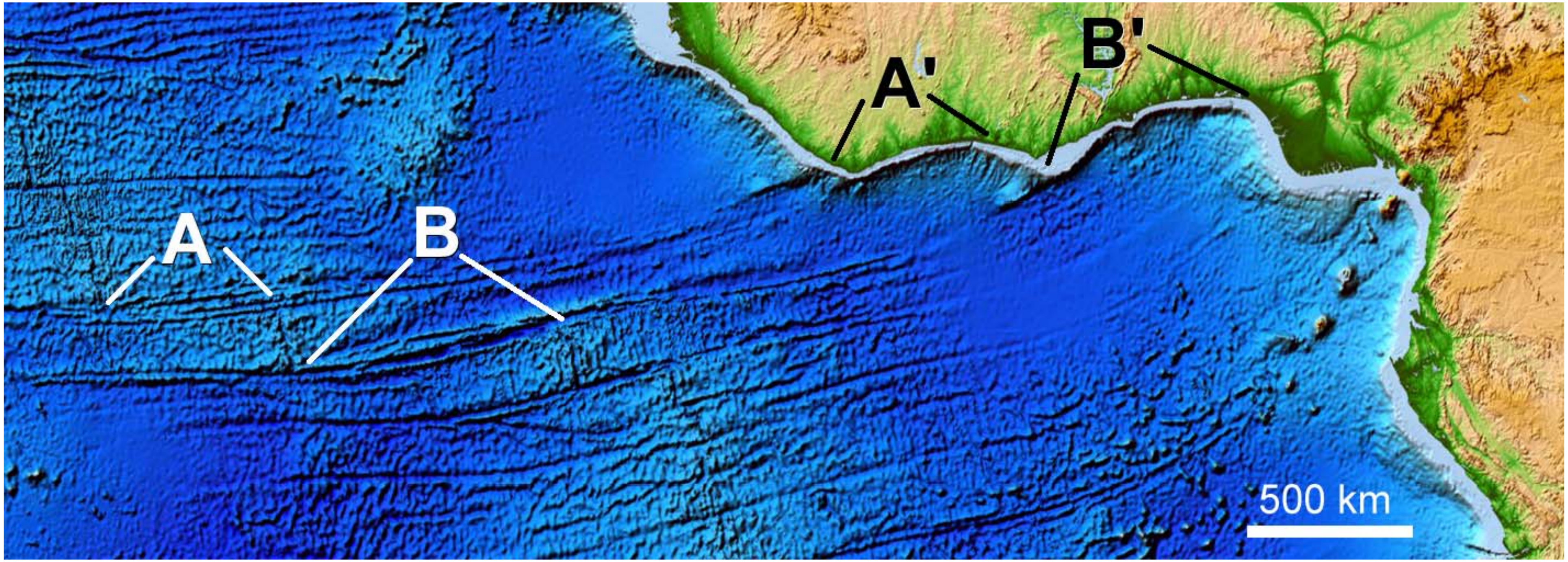
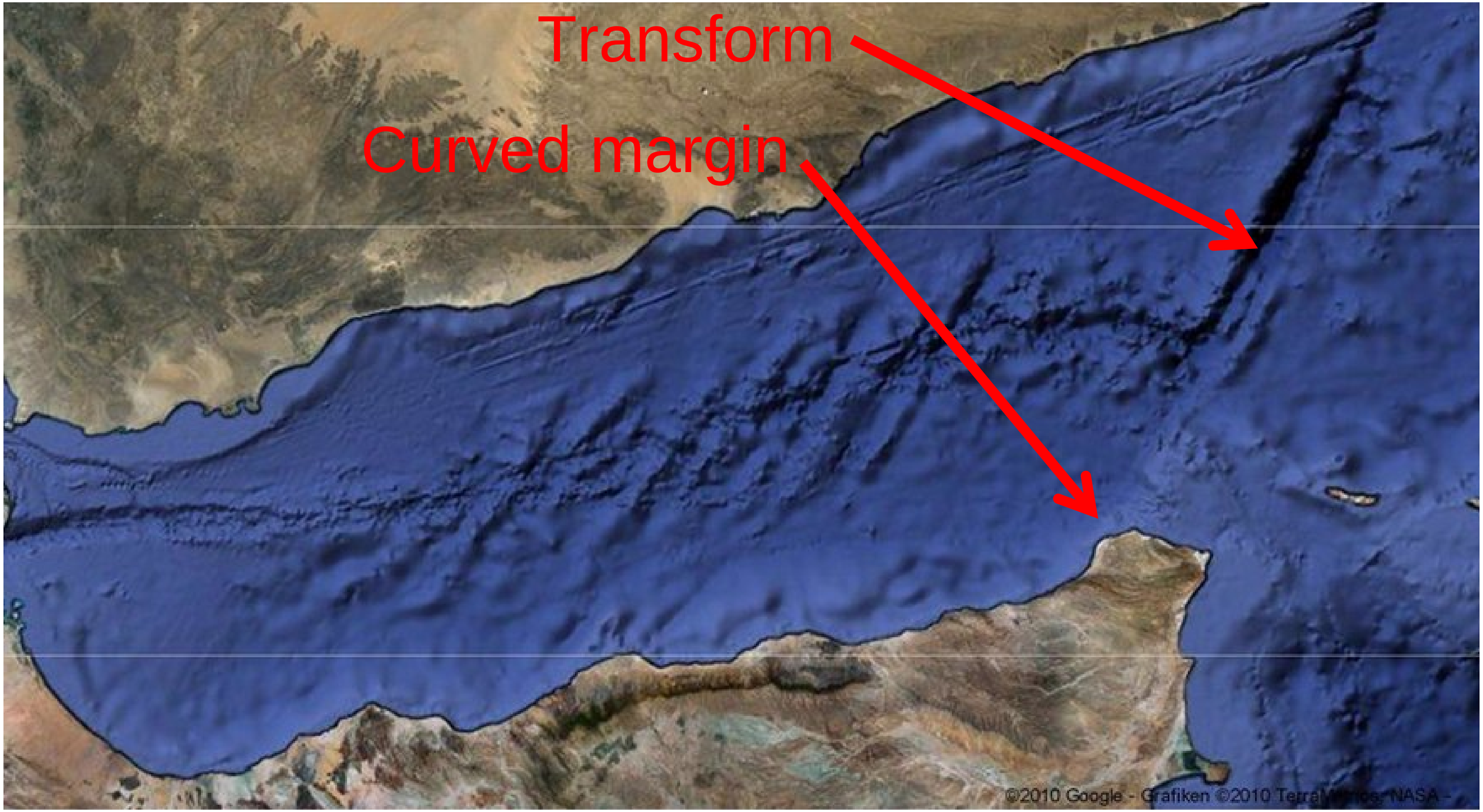


Figure 4. Models for accretion. A: Segment center: accretion is generally symmetric. B: Segment end: accretion is essentially one sided, with new crust being accreted on eastern side. On western side, new flows completely cover region to base of large fault scarp, but little magma is intruded beneath these flows. Flexure associated with development of half graben will produce tilting in hanging wall, which is progressively infilled. Triangular region bounded by large fault and fissures beneath axial volcanic ridge remains stationary at plate boundary.

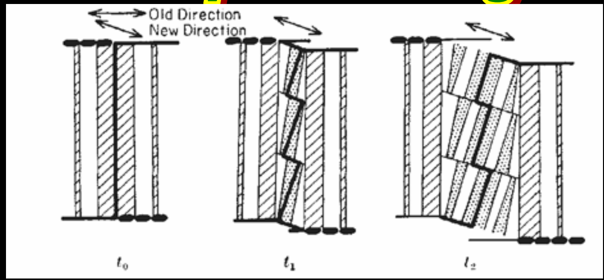
What about „inherited“ structures?!



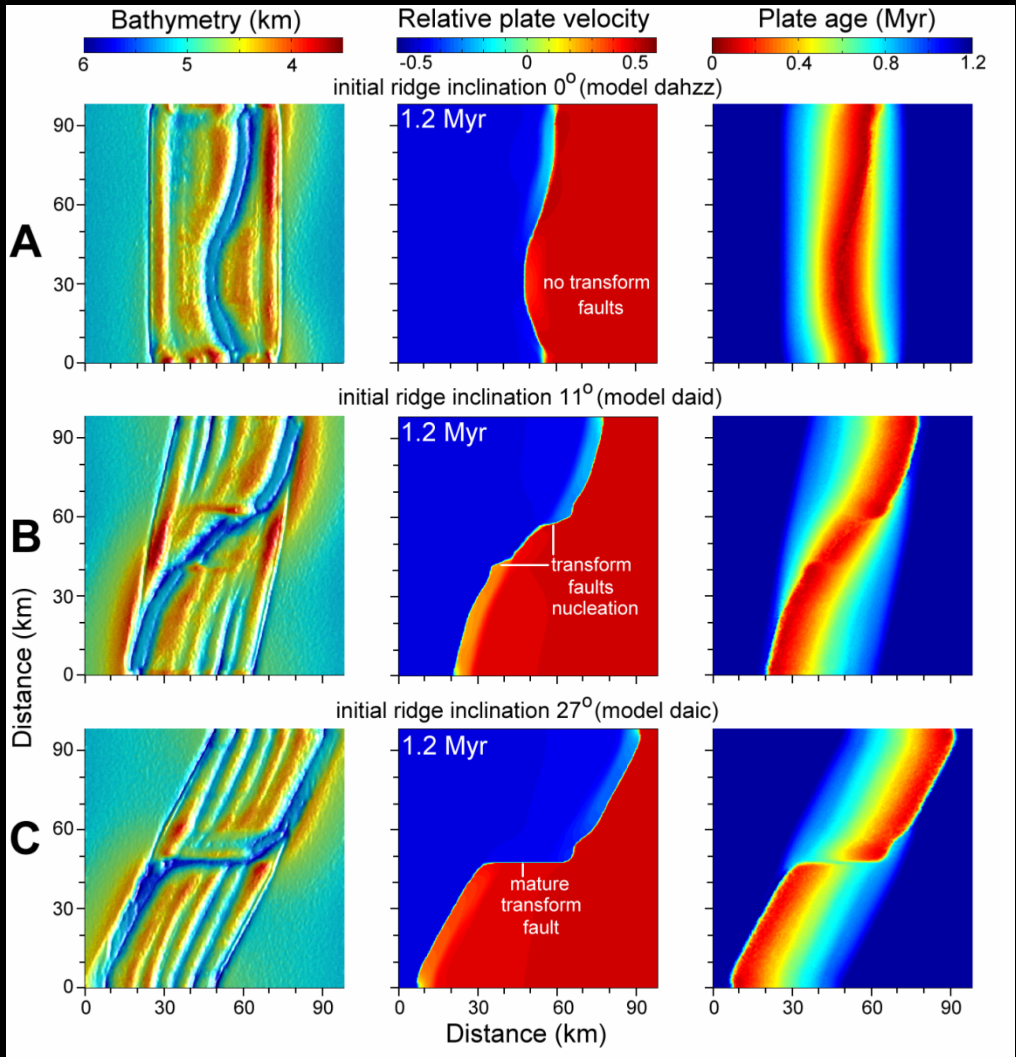
What about „inherited" structures?!



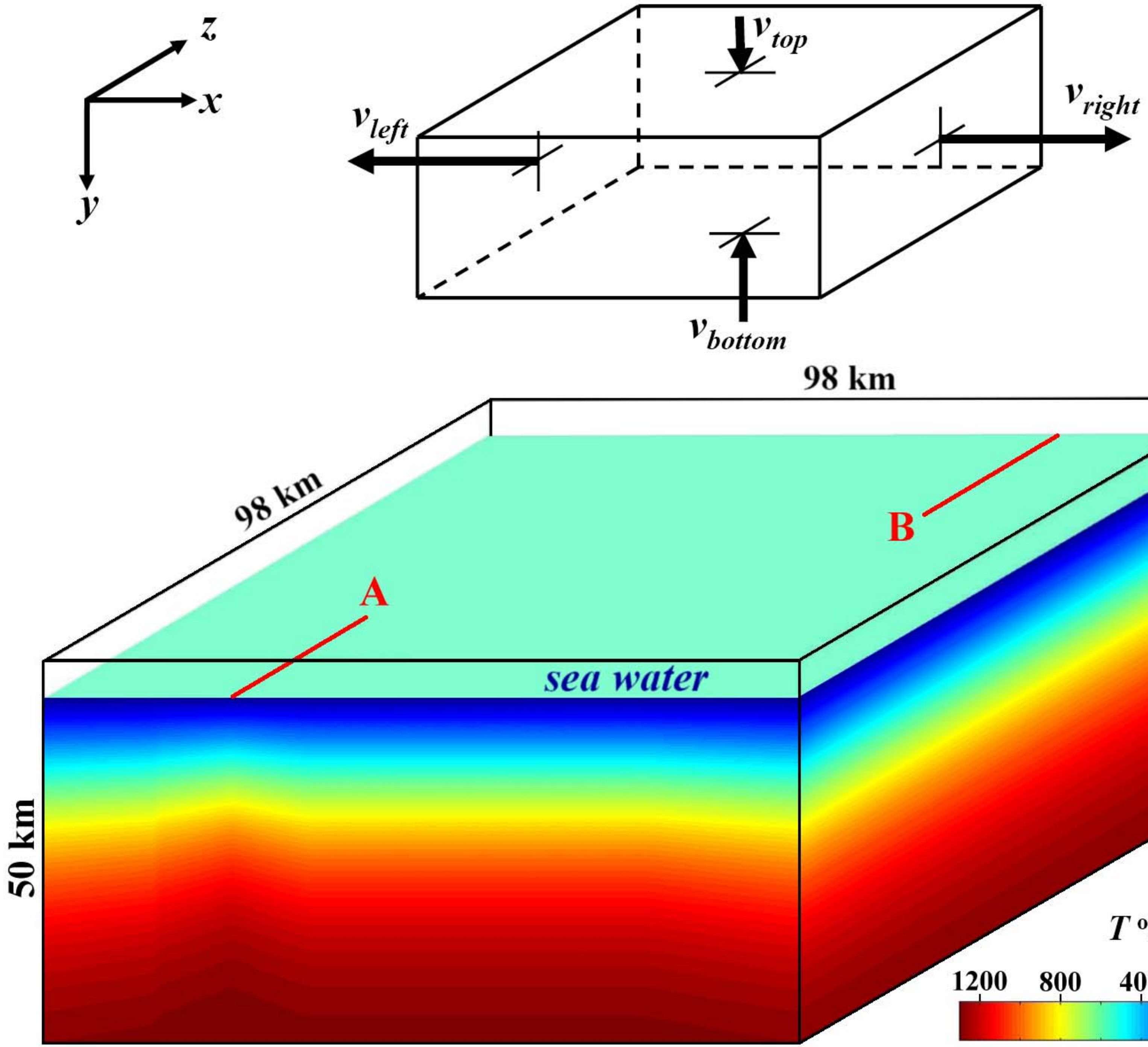
Changes in spreading direction



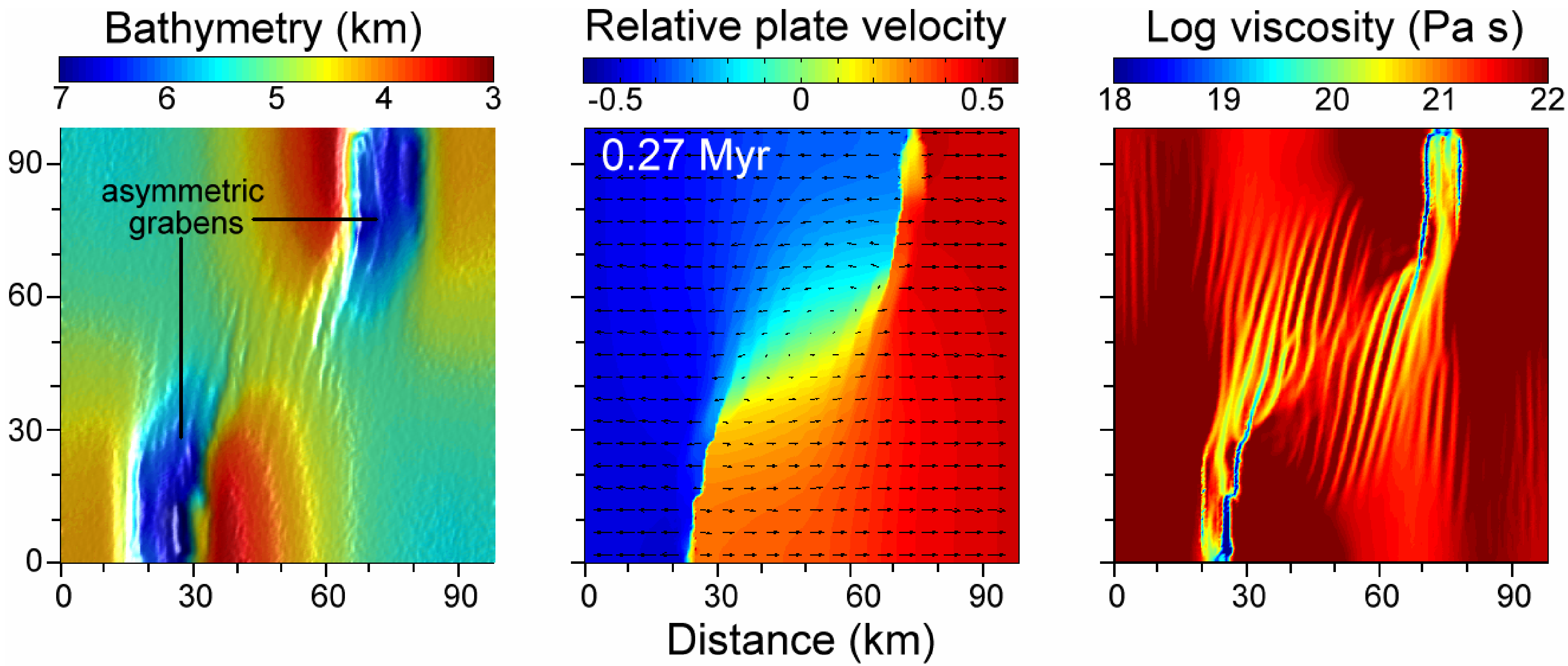
Menard (1968)



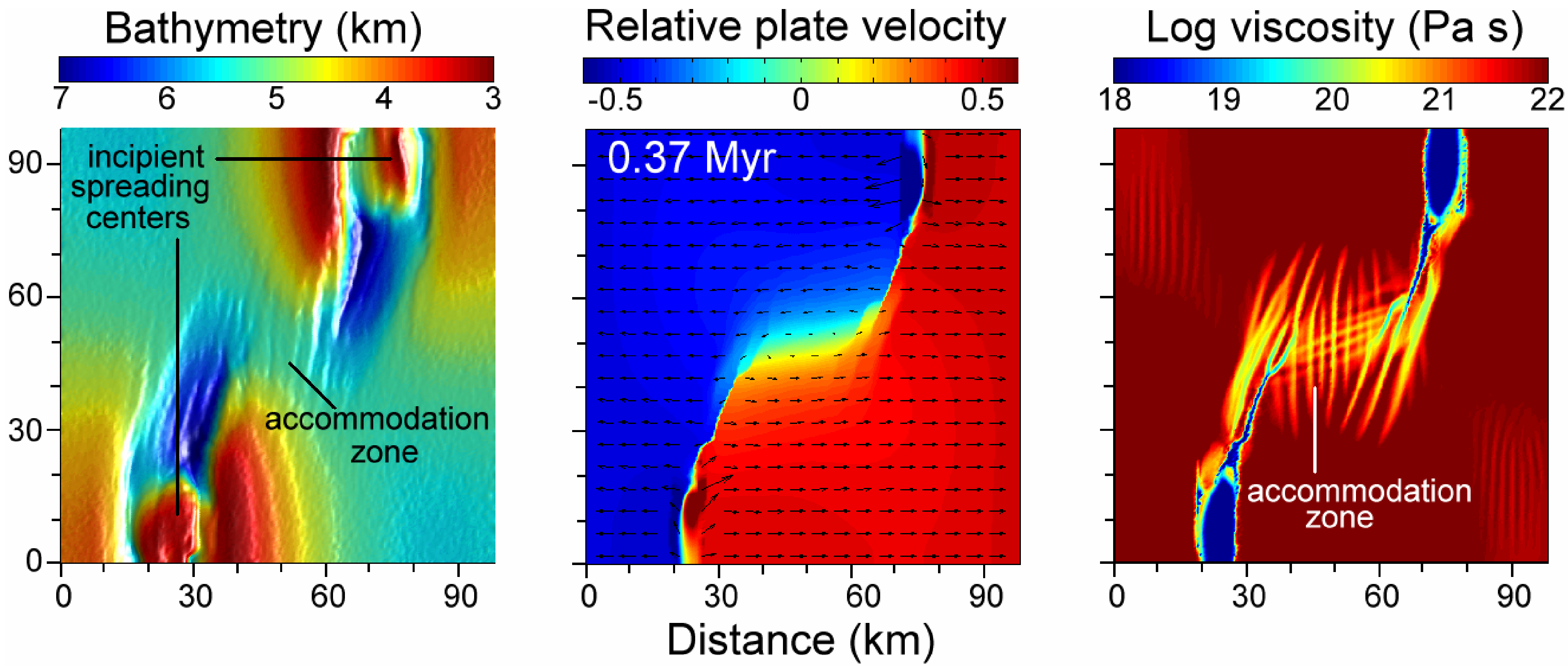
Gerya (2010)

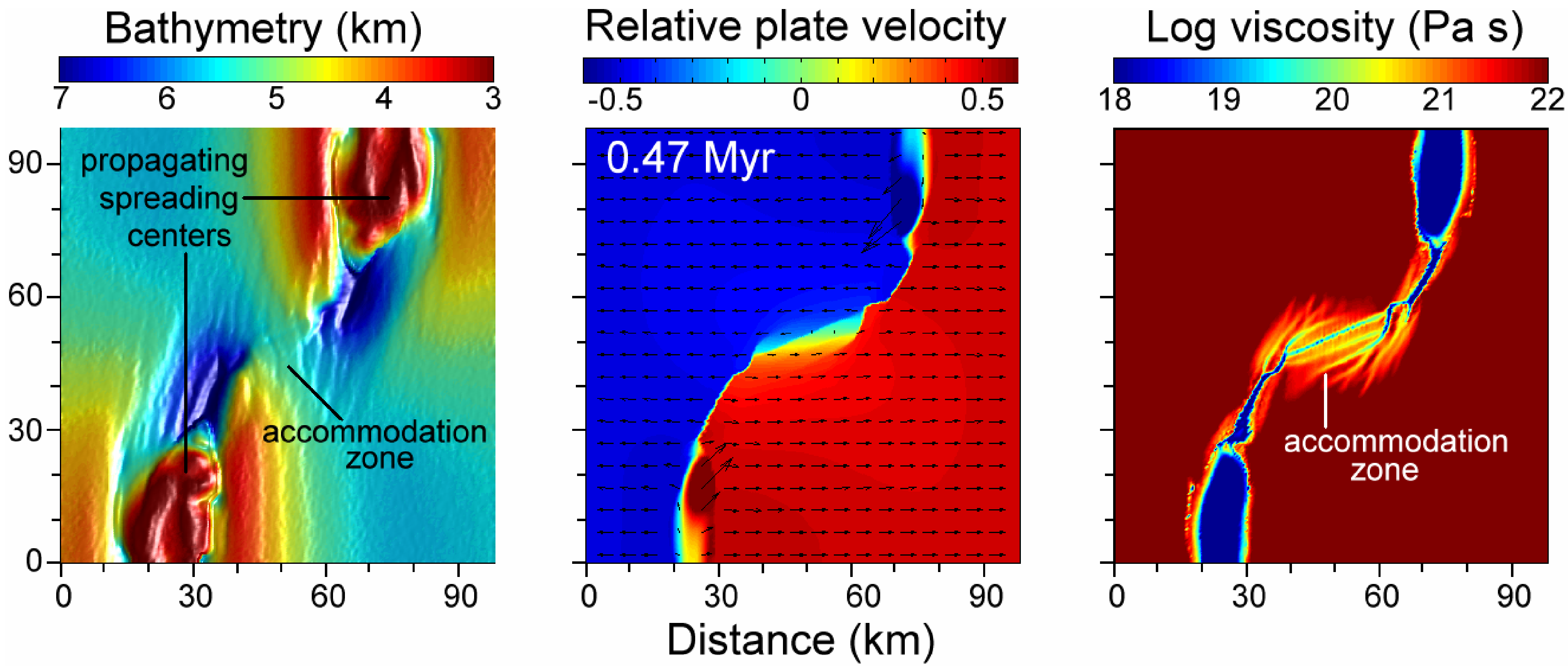


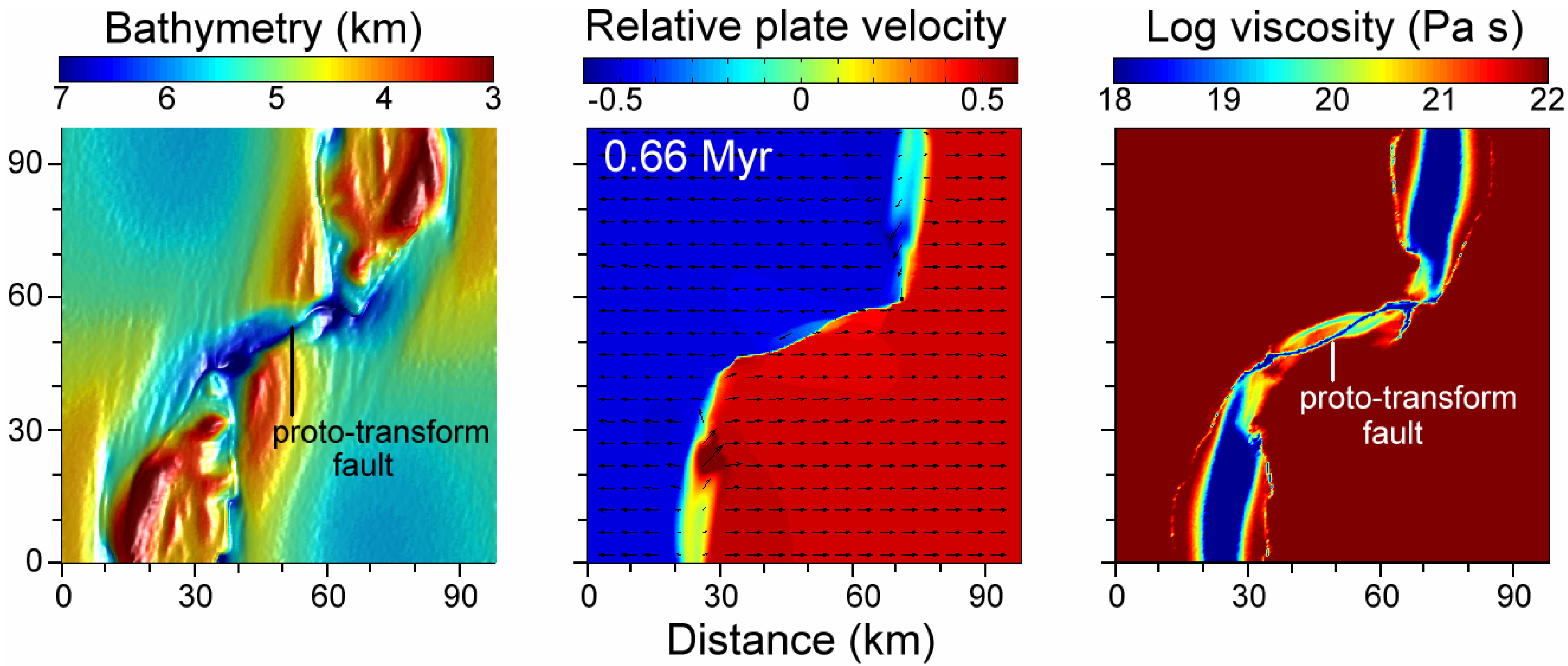
z
x
y
v_{top}
v_{left}
v_{right}
v_{bottom}
98 km
98 km
A
B
sea water
50 km
T °C
1200
800
400
0



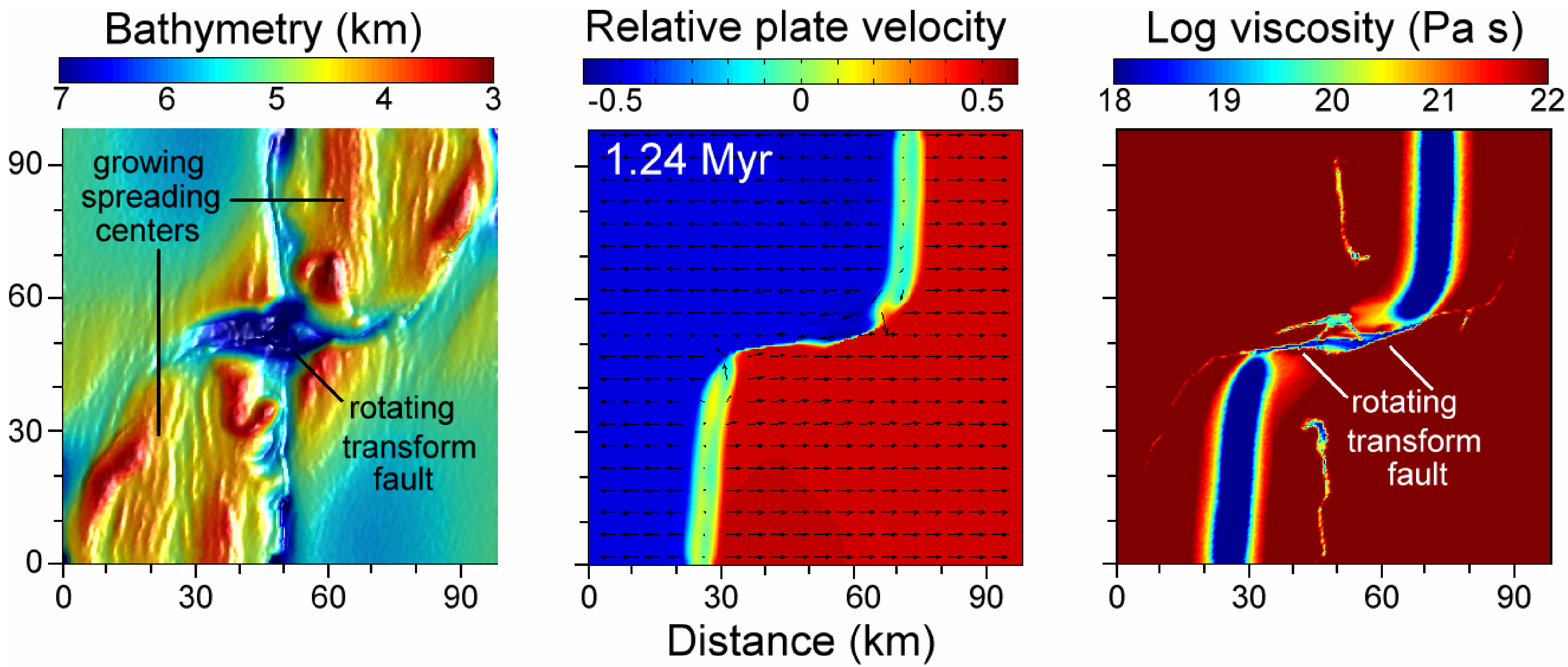
Bathymetry (km)
7 6 5 4 3
90
60
30
0
0 30 60 90
asymmetric
grabens
Relative plate velocity
-0.5 0 0.5
0.27 Myr
0 30 60 90
Distance (km)
Log viscosity (Pa s)
18 19 20 21 22
0 30 60 90


Bathymetry (km)
7
6
5
4
3
incipient
spreading
centers
accommodation
zone
90
60
30
0
0
30
60
90
Relative plate velocity
-0.5
0
0.5
0.37 Myr
0
30
60
90
Distance (km)
Log viscosity (Pa s)
18
19
20
21
22
accommodation
zone
0
30
60
90

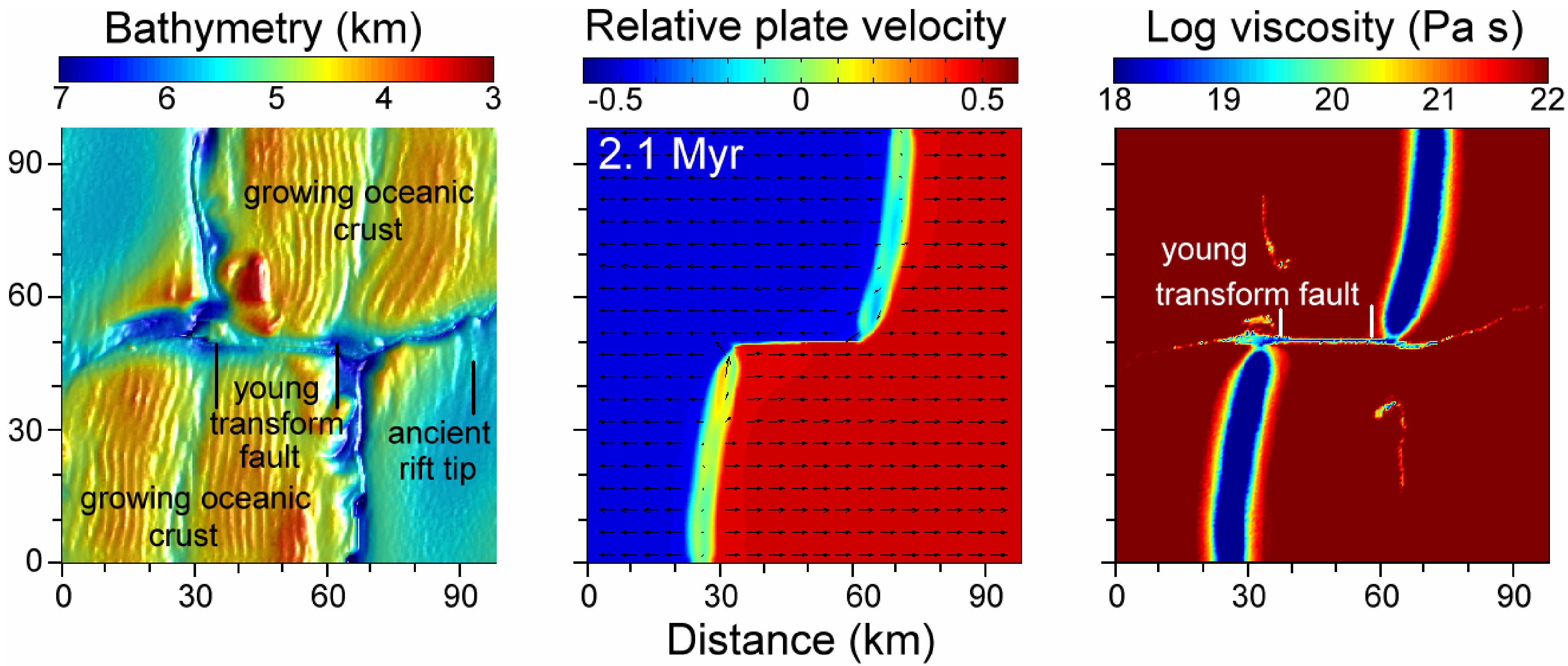

Bathymetry (km)
7 6 5 4 3
propagating spreading centers
accommodation zone
0 30 60 90
Relative plate velocity
-0.5 0 0.5
0.47 Myr
Distance (km)
Log viscosity (Pa s)
18 19 20 21 22
accommodation zone

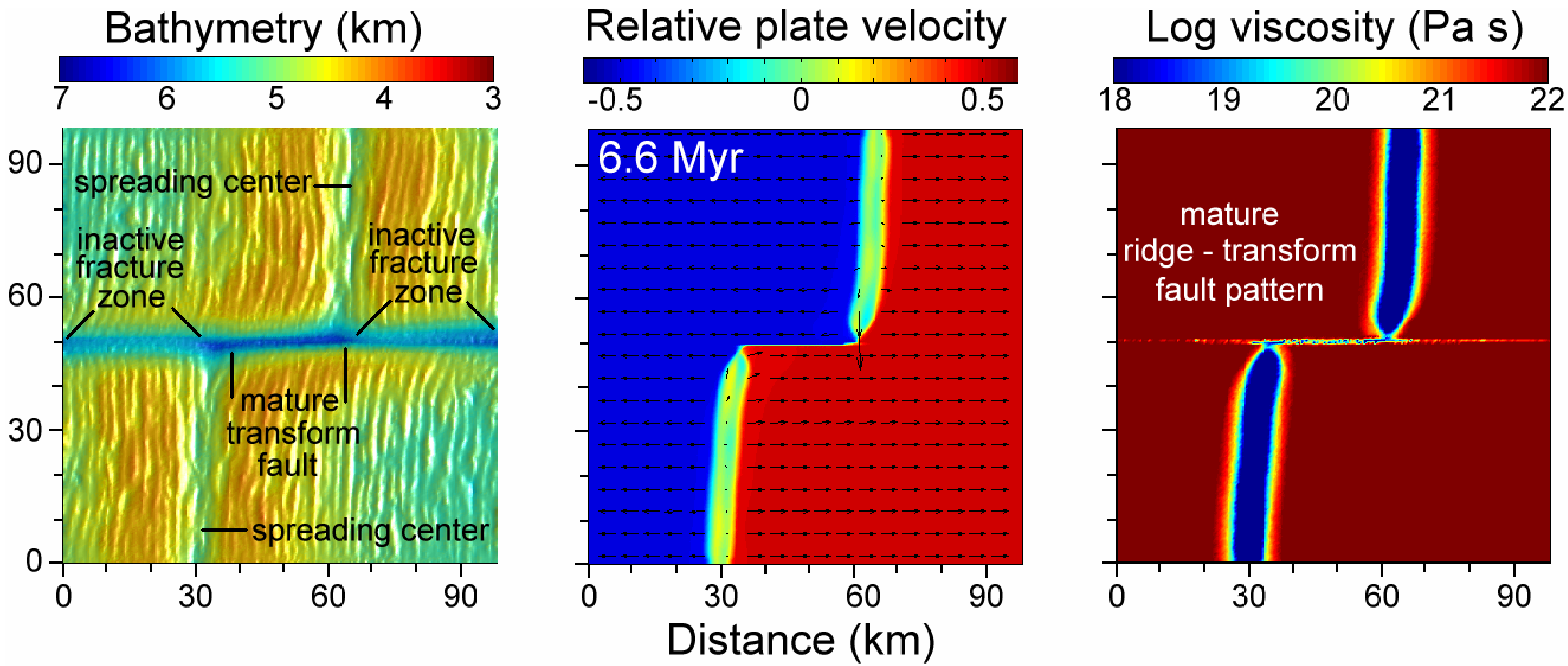


Bathymetry (km)
7
6
5
4
3
90
60
30
0
0
30
60
90
proto-transform
fault
Relative plate velocity
-0.5
0
0.5
0.66 Myr
0
30
60
90
Distance (km)
Log viscosity (Pa s)
18
19
20
21
22
0
30
60
90
proto-transform
fault



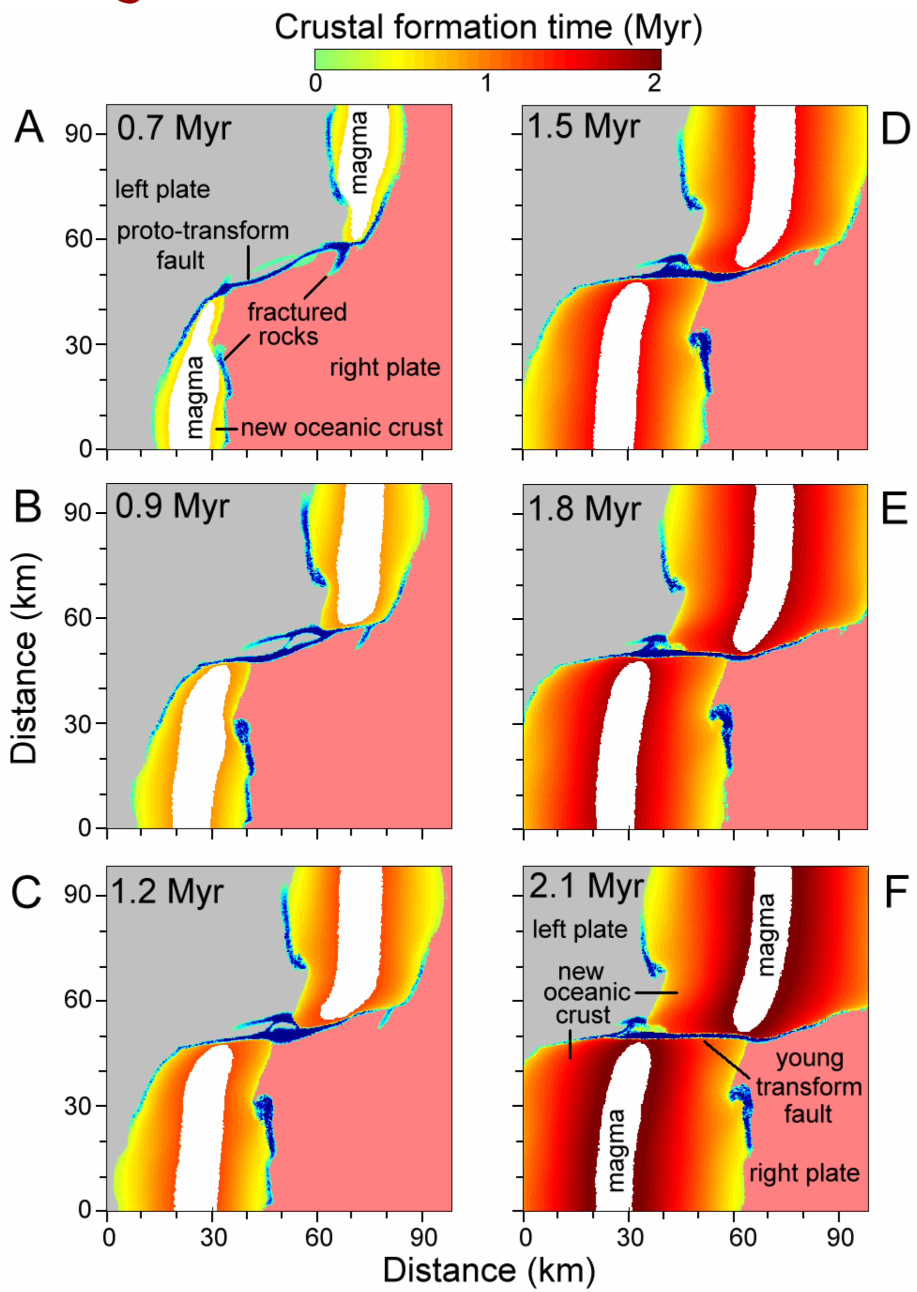
Bathymetry (km)
7
6
5
4
3
growing
spreading
centers
rotating
transform
fault
0
30
60
90
Relative plate velocity
-0.5
0
0.5
1.24 Myr
Distance (km)
Log viscosity (Pa s)
18
19
20
21
22
rotating
transform
fault


Bathymetry (km)
7
6
5
4
3
90
60
30
0
0
30
60
90
growing oceanic crust
young transform fault
ancient rift tip
growing oceanic crust
Relative plate velocity
-0.5
0
0.5
2.1 Myr
0
30
60
90
Distance (km)
Log viscosity (Pa s)
18
19
20
21
22
young transform fault
0
30
60
90

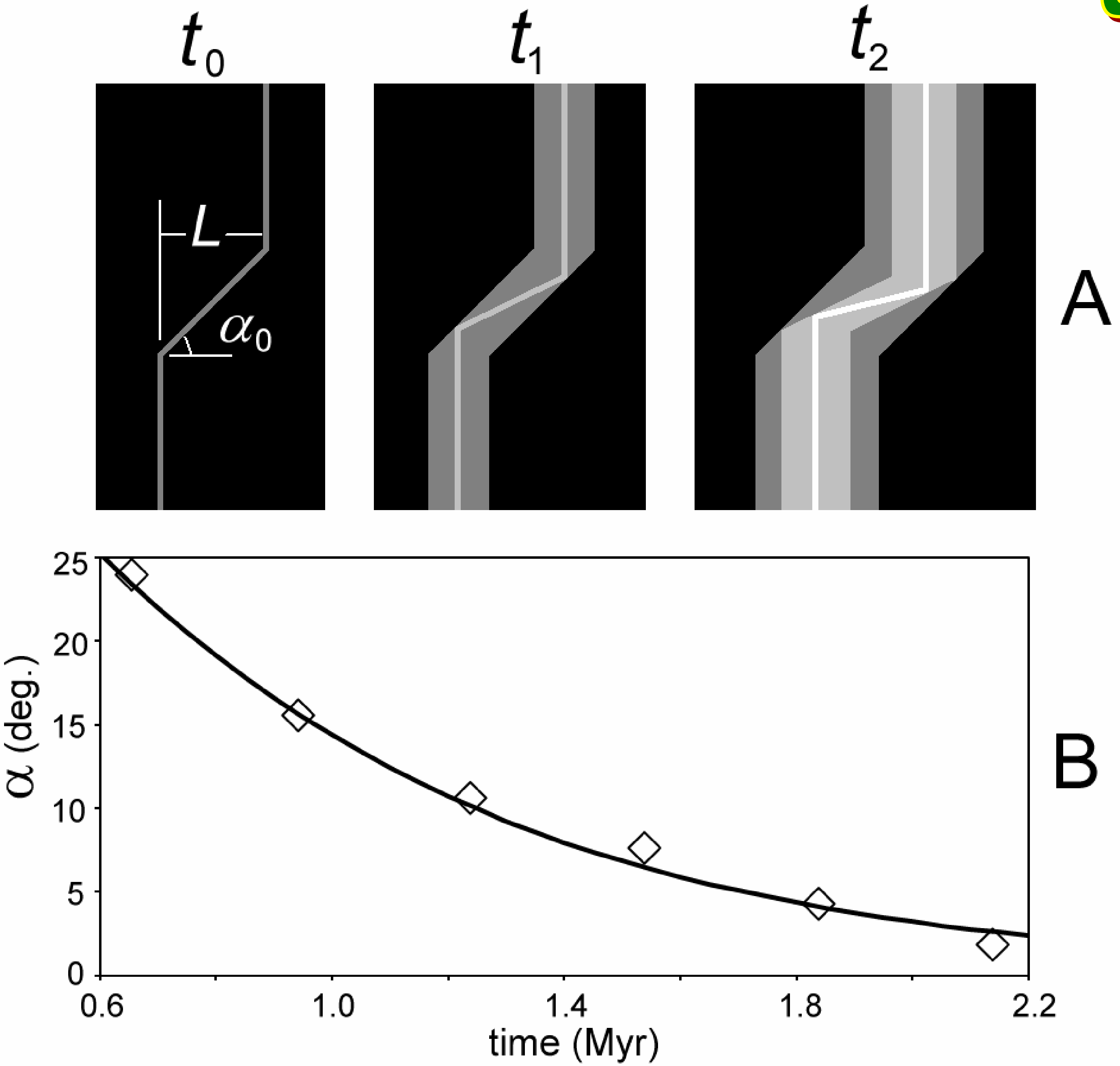


Bathymetry (km)
7
6
5
4
3
Relative plate velocity
-0.5
0
0.5
Log viscosity (Pa s)
18
19
20
21
22
6.6 Myr
spreading center
inactive fracture zone
inactive fracture zone
mature transform fault
spreading center
mature ridge - transform fault pattern
90
60
30
0
0
30
60
90
Distance (km)

How and why does orientation changes?



How does orientation changes



What about zero offset fracture zones?!

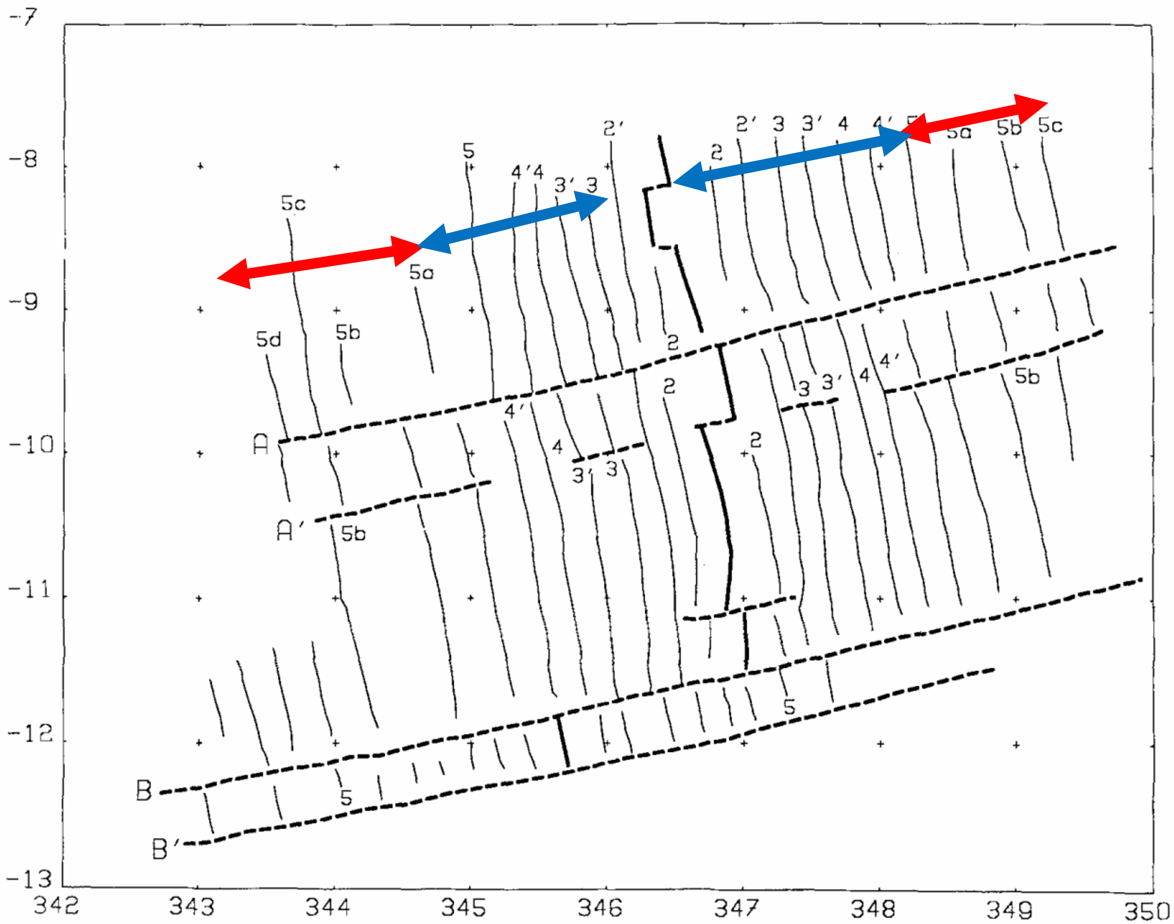


Fig. 1. The southern Mid-Atlantic Ridge (heavy line) and magnetic anomalies. Transform A′ reaches zero offset at anomaly 4 and 4′ time, and again at anomaly 2 and 2′ time. Offset along A′ is 15 km at anomaly 5b, 10 km at anomaly 3, and 20 km at present. 35% asymmetry in spreading is required to reach zero-offset (after Brozena, 1986).

Stoddard and Stein (1987)

Accretion can be asymmetric => ridge offsets can change with time

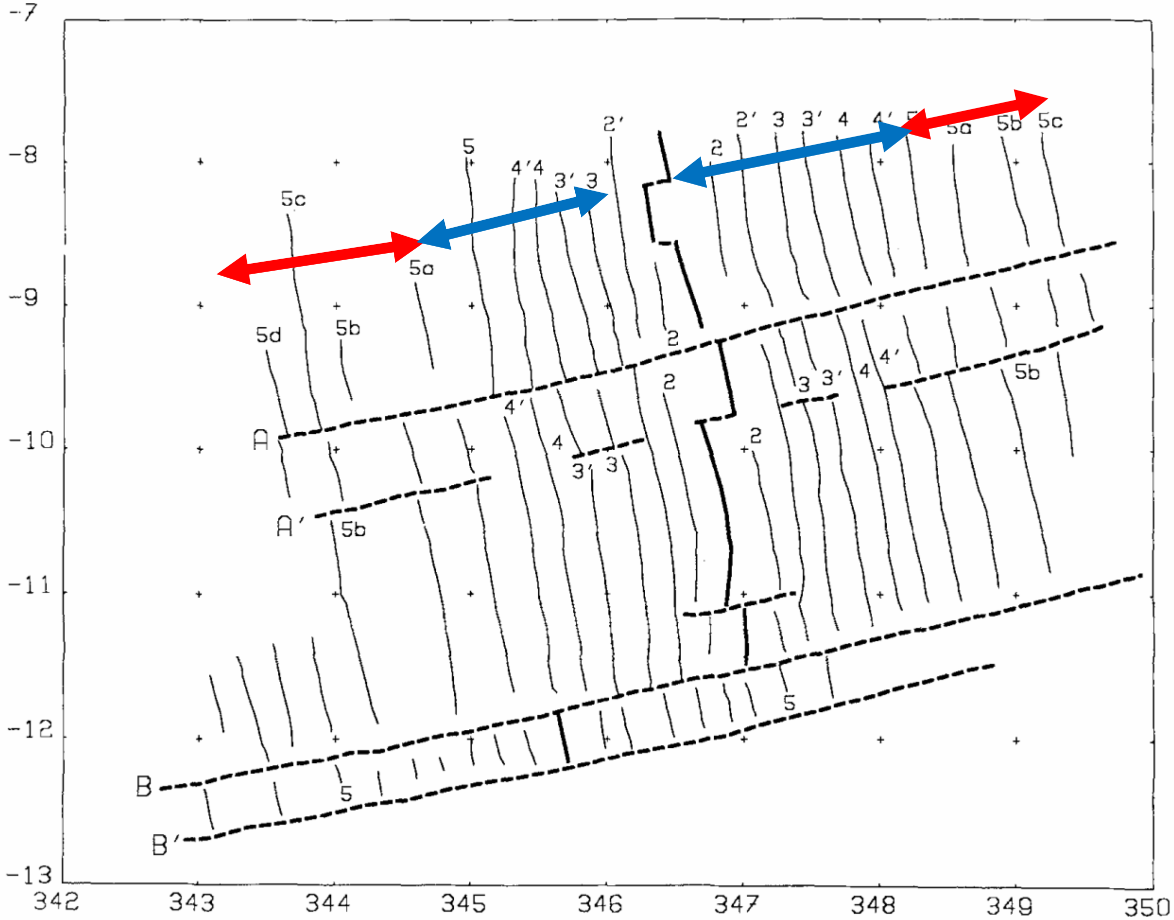
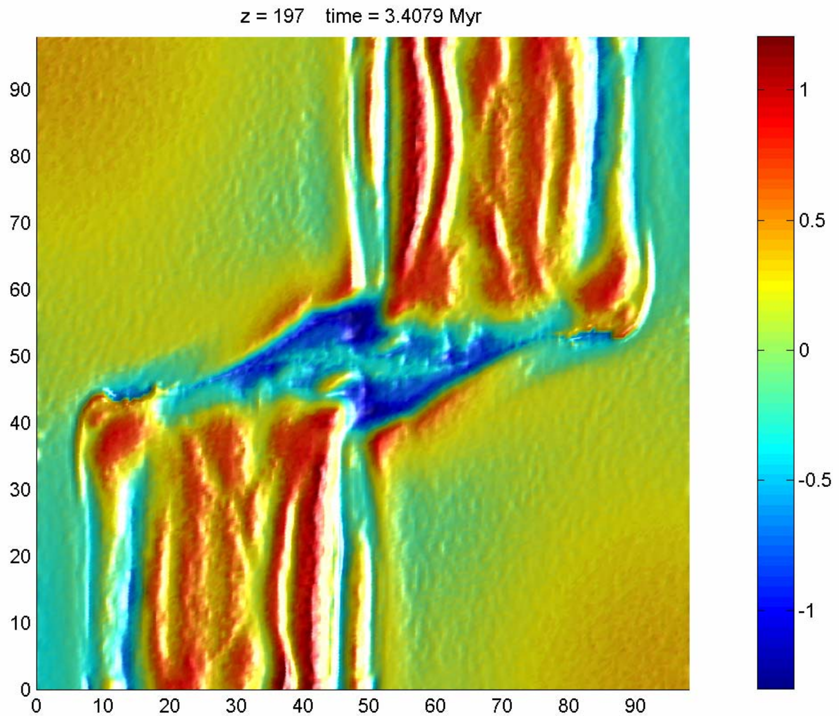
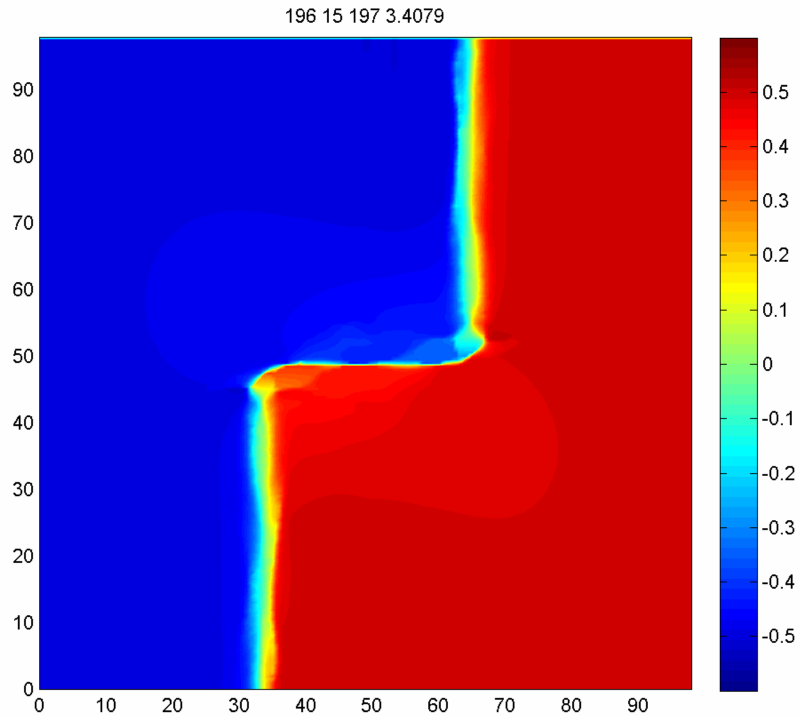


Fig. 1. The southern Mid-Atlantic Ridge (heavy line) and magnetic anomalies. Transform A′ reaches zero offset at anomaly 4 and 4′ time, and again at anomaly 2 and 2′ time. Offset along A′ is 15 km at anomaly 5b, 10 km at anomaly 3, and 20 km at present. 35% asymmetry in spreading is required to reach zero-offset (after Brozena, 1986).

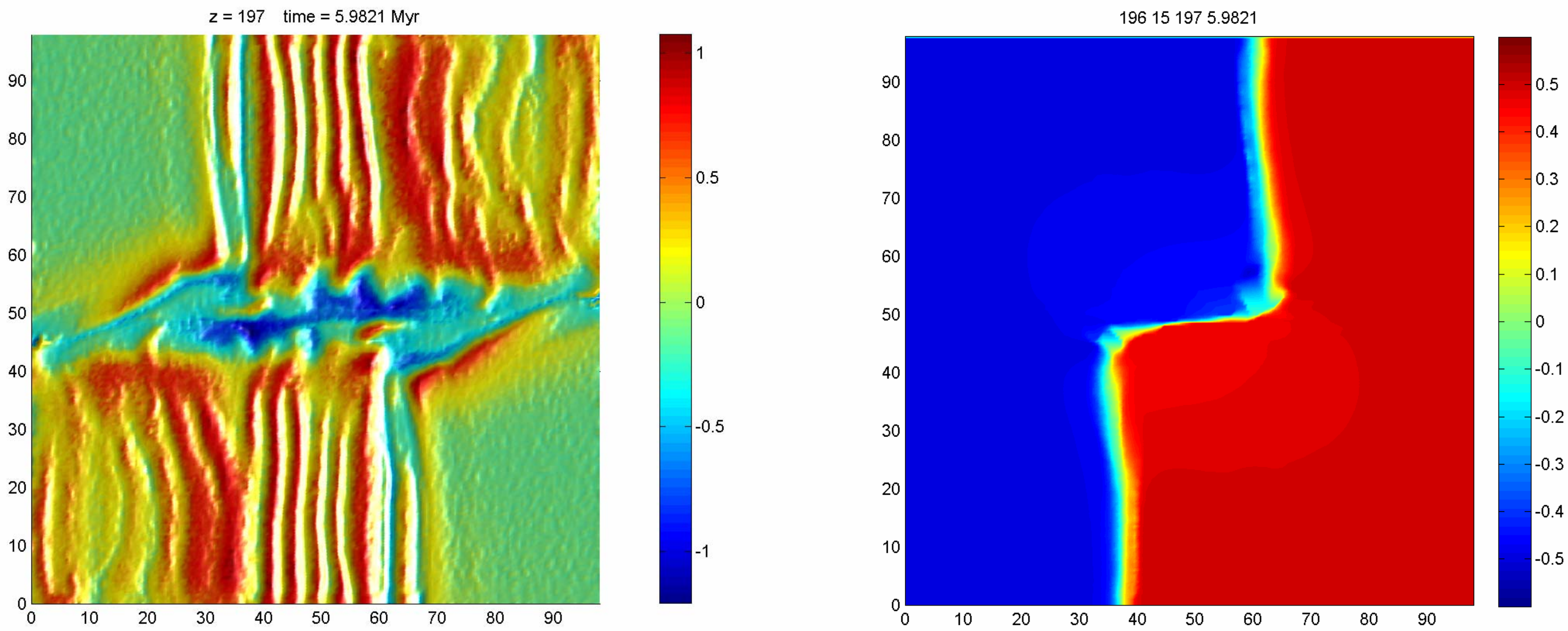
Stoddard and Stein (1987)



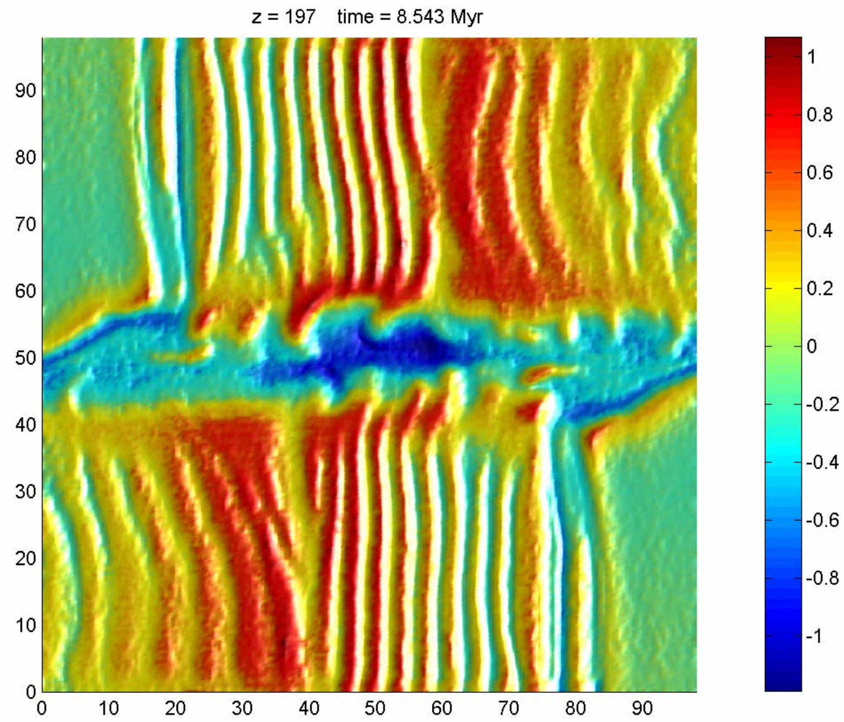
z = 197 time = 3.4079 Myr

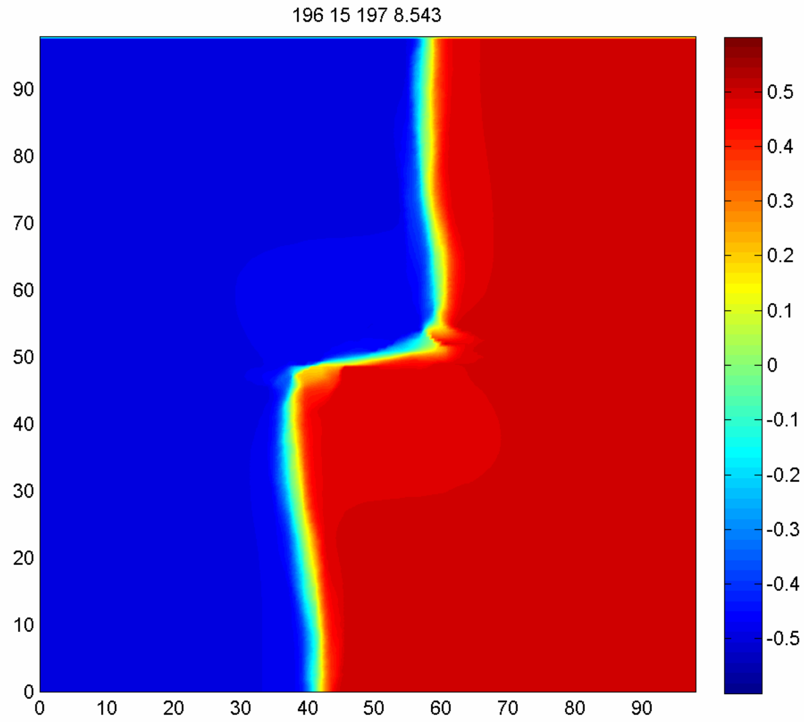


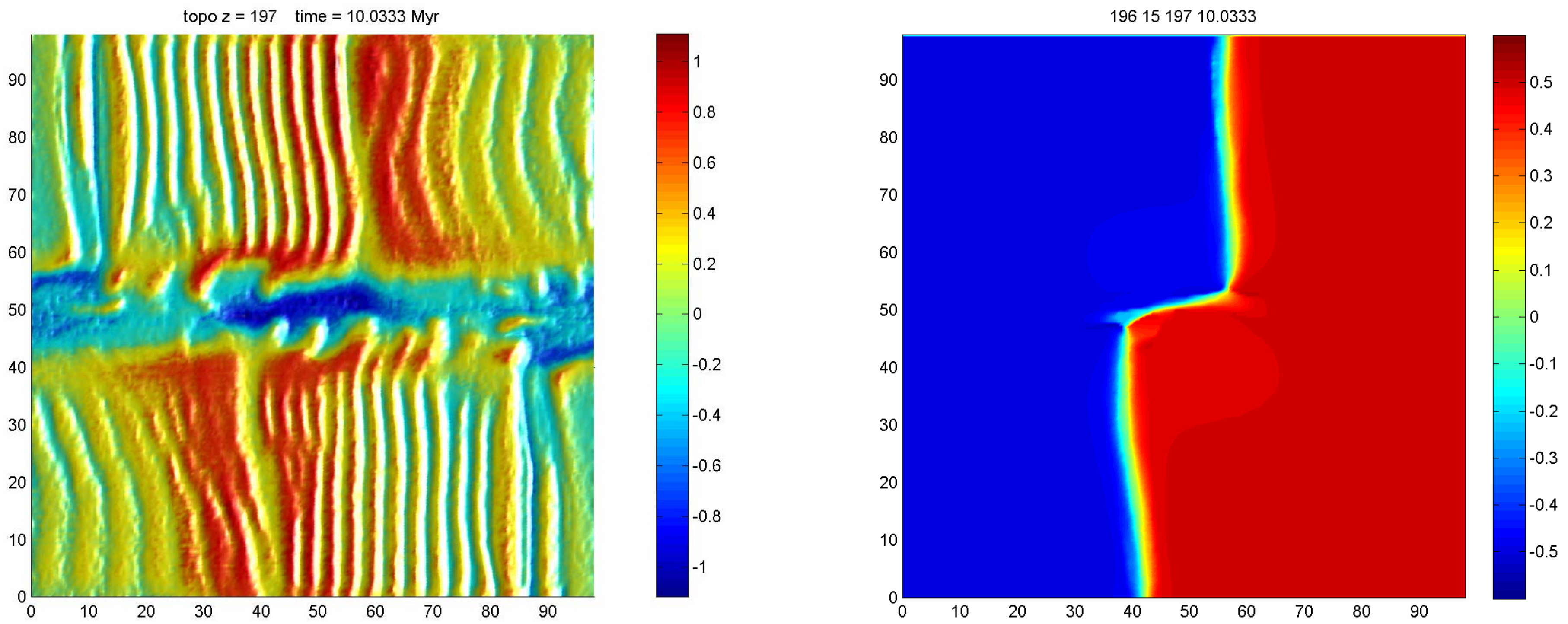
196 15 197 3.4079

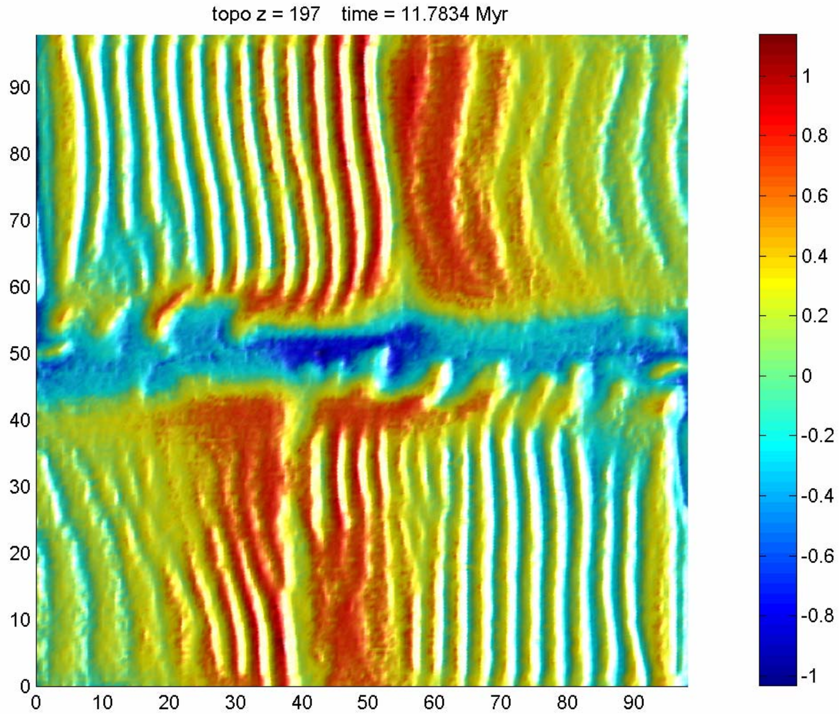


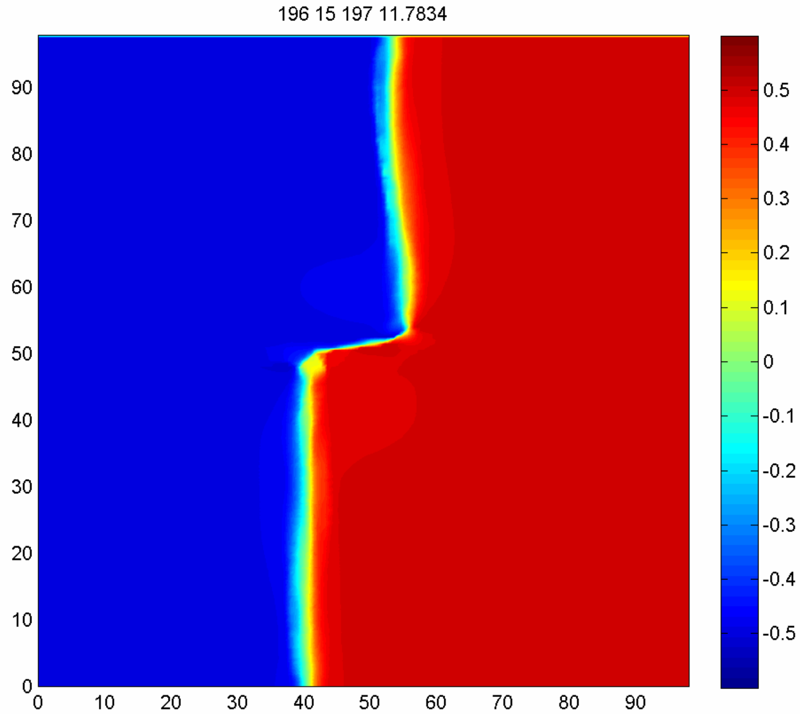
z = 197   time = 5.9821 Myr
196 15 197 5.9821

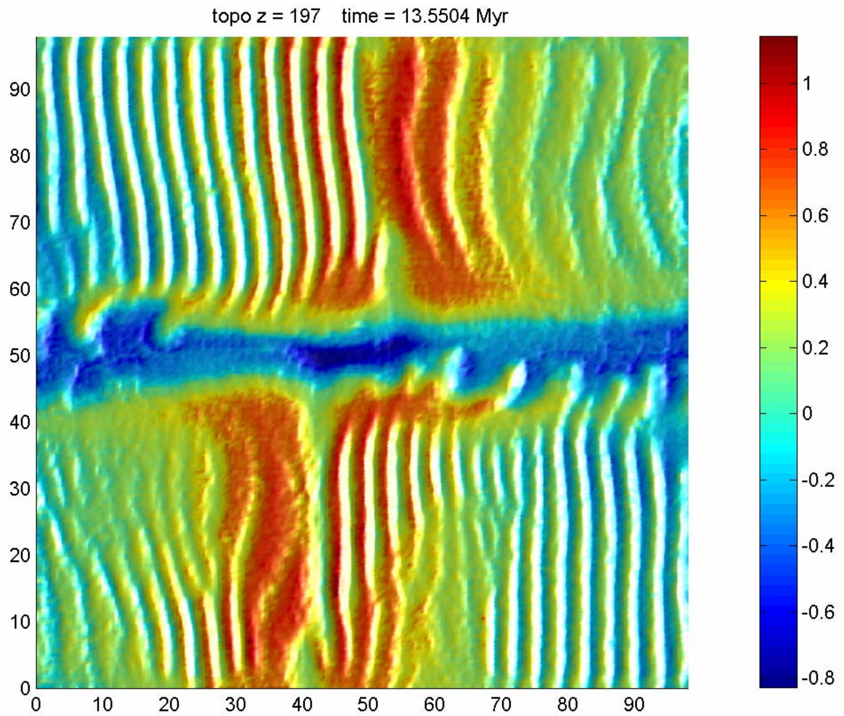

z = 197   time = 8.543 Myr
0
10
20
30
40
50
60
70
80
90
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1


196 15 197 8.543
0
10
20
30
40
50
60
70
80
90
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5

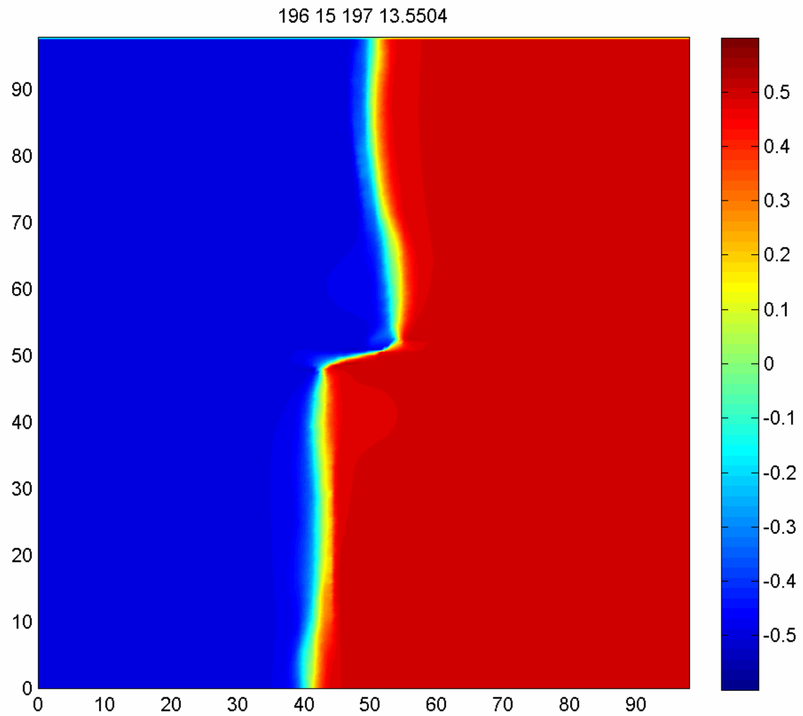

topo z = 197   time = 10.0333 Myr
196 15 197 10.0333


topo z = 197   time = 11.7834 Myr
0 10 20 30 40 50 60 70 80 90
1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1

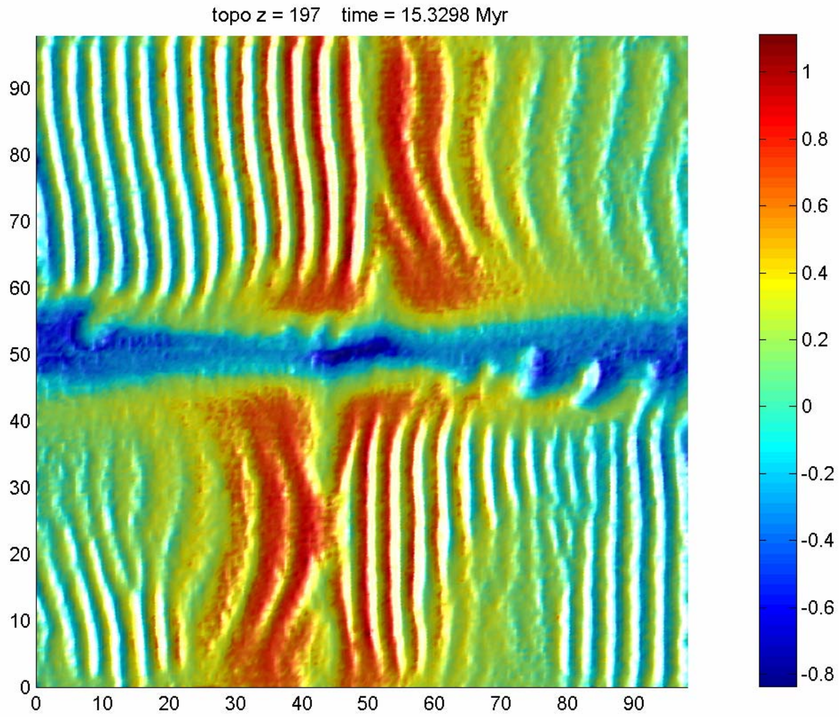

196 15 197 11.7834
0 10 20 30 40 50 60 70 80 90
0.5 0.4 0.3 0.2 0.1 0 -0.1 -0.2 -0.3 -0.4 -0.5

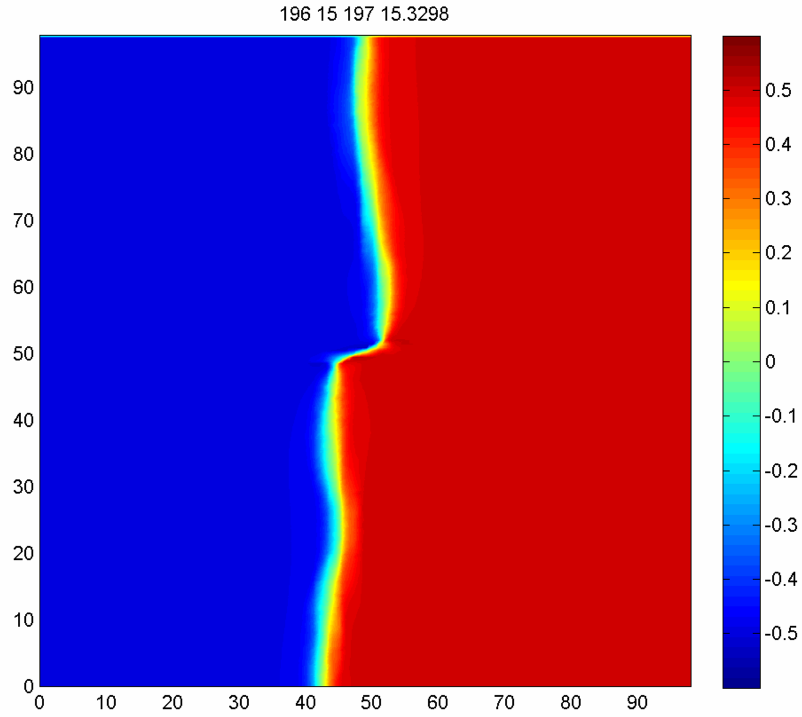


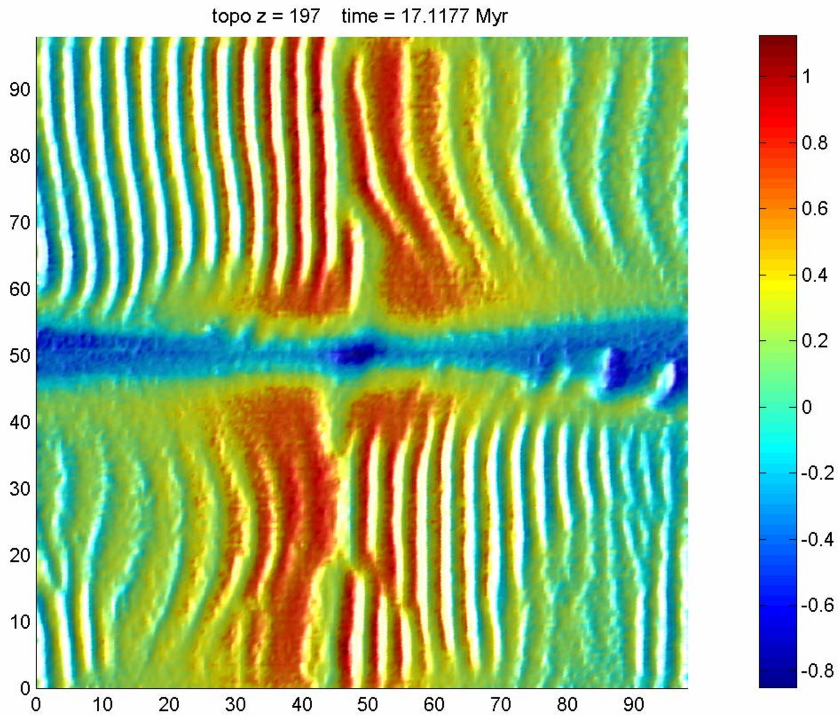
topo z = 197 time = 13.5504 Myr

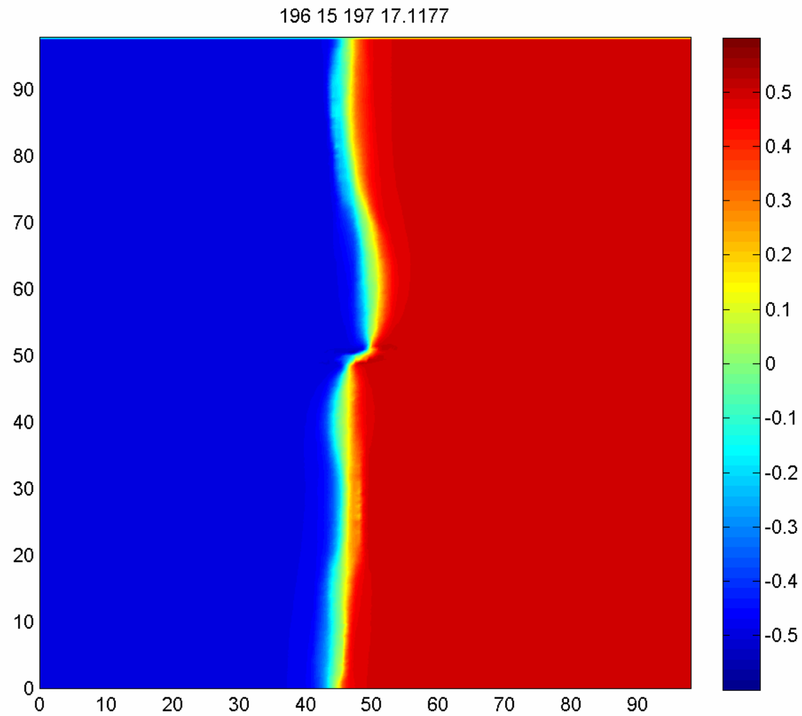


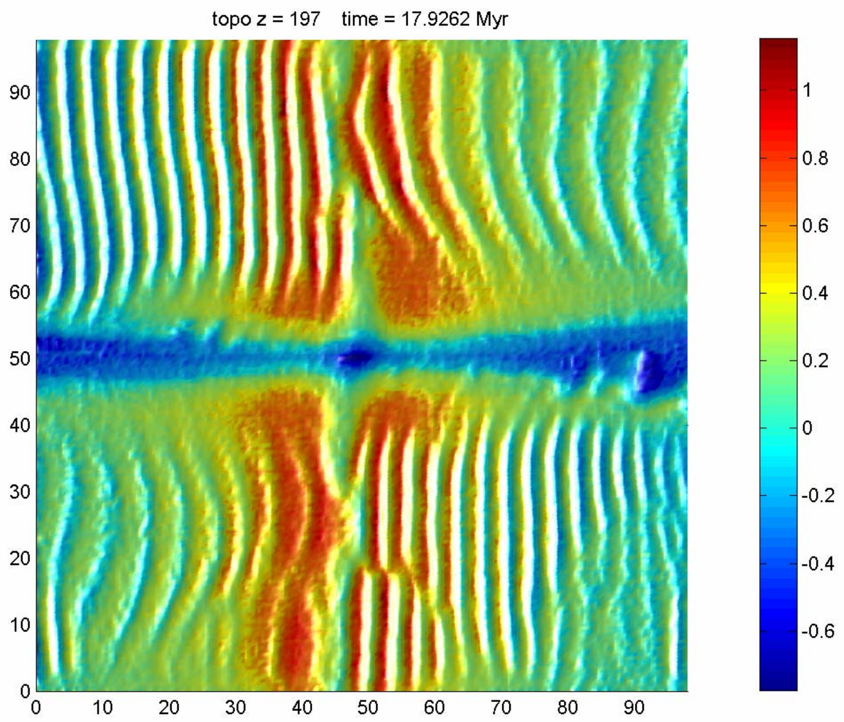
196 15 197 13.5504

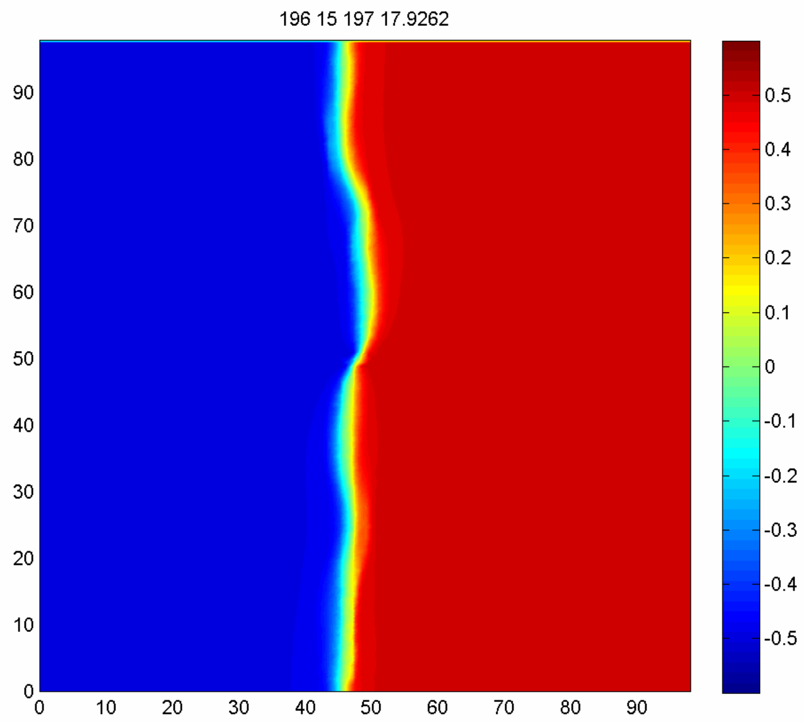

topo z = 197   time = 15.3298 Myr

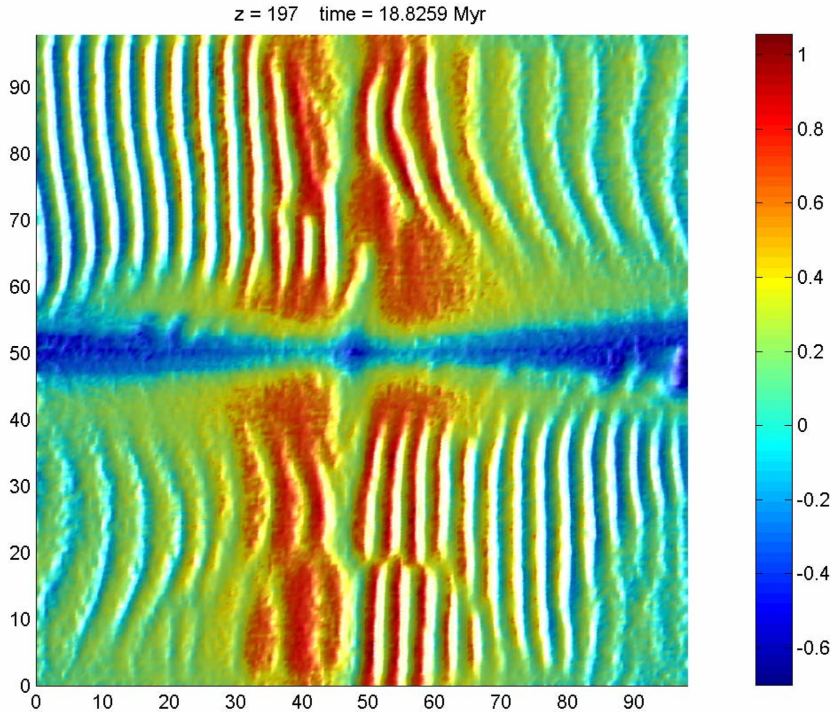

196 15 197 15.3298


topo z = 197   time = 17.1177 Myr
0
10
20
30
40
50
60
70
80
90
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

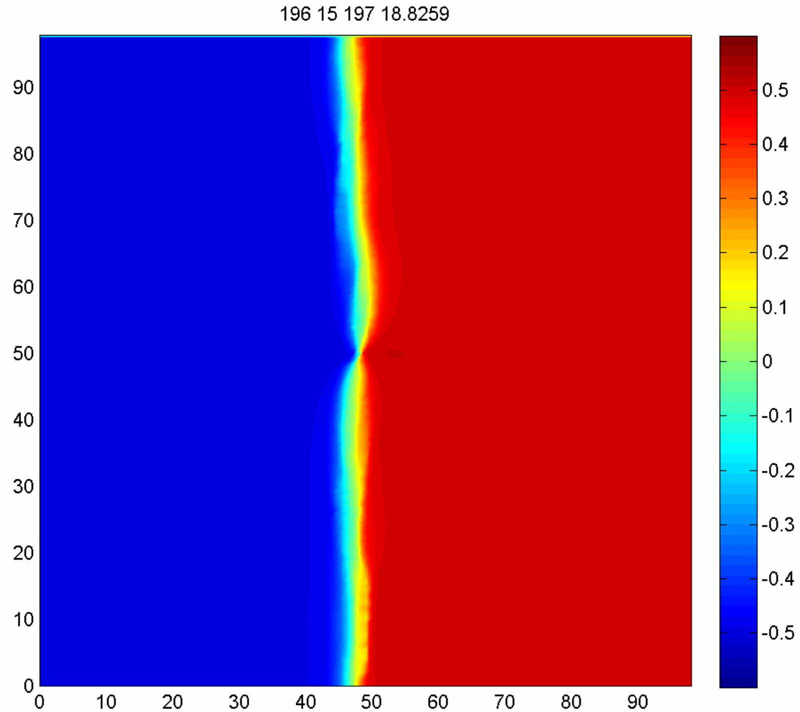

196 15 197 17.1177
0
10
20
30
40
50
60
70
80
90
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5


topo z = 197   time = 17.9262 Myr

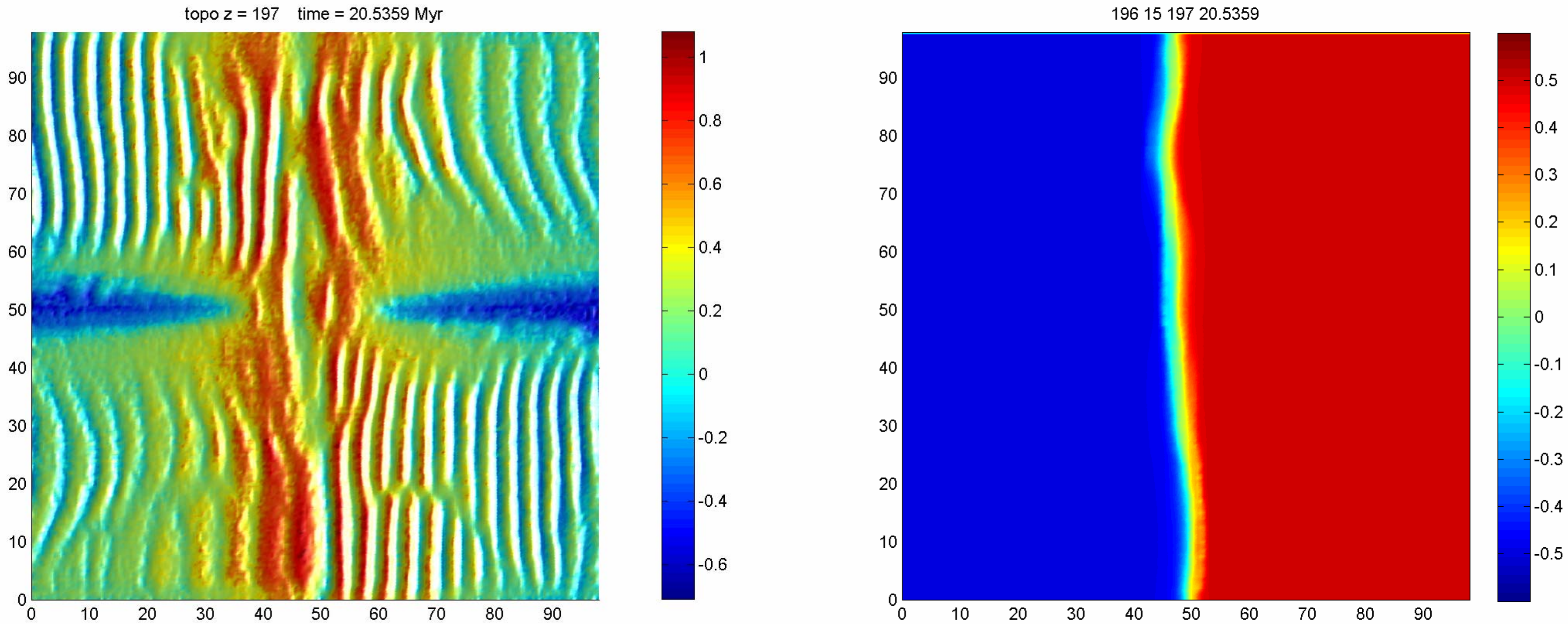

196 15 197 17.9262



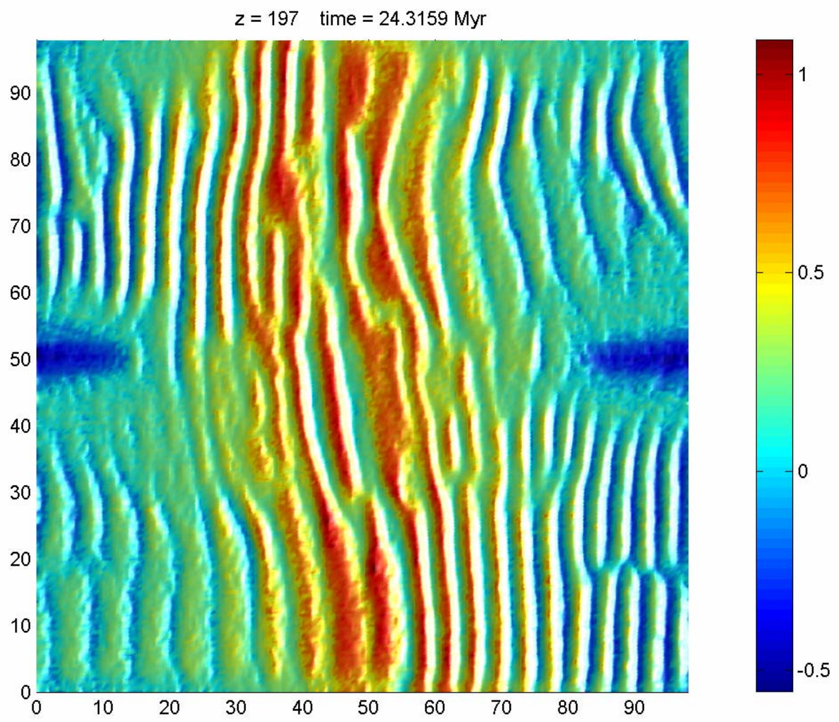
z = 197   time = 18.8259 Myr

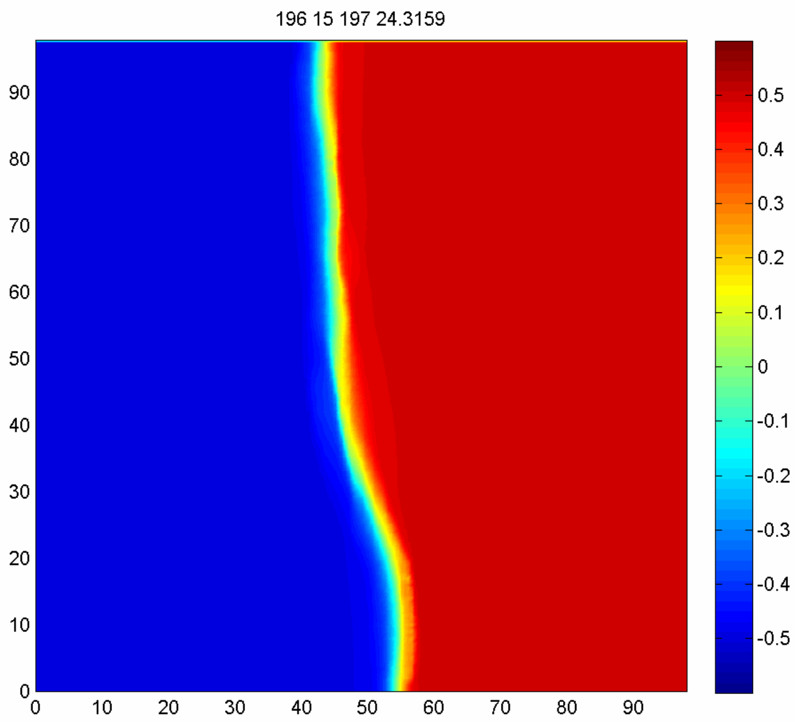


196 15 197 18.8259



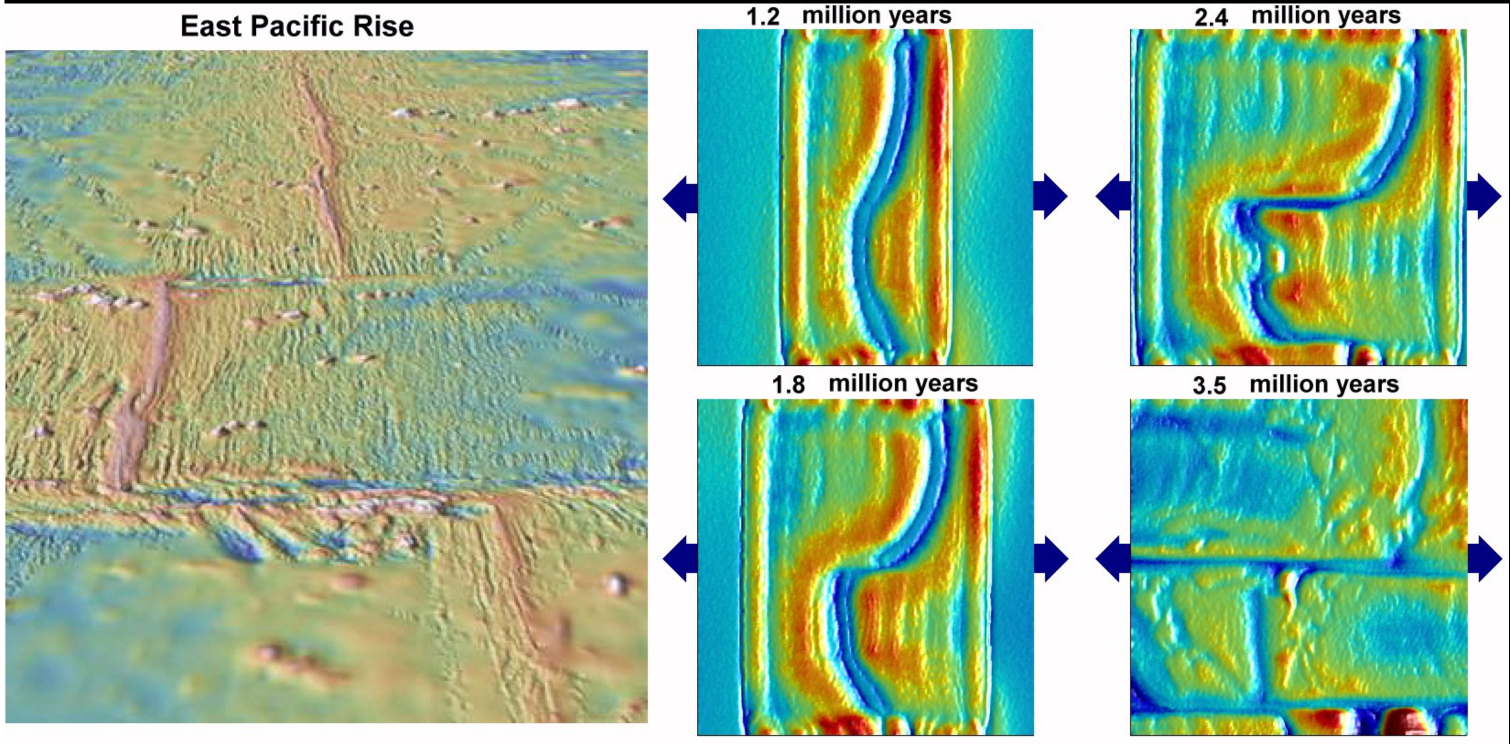
topo z = 197 time = 20.5359 Myr
196 15 197 20.5359


z = 197   time = 24.3159 Myr

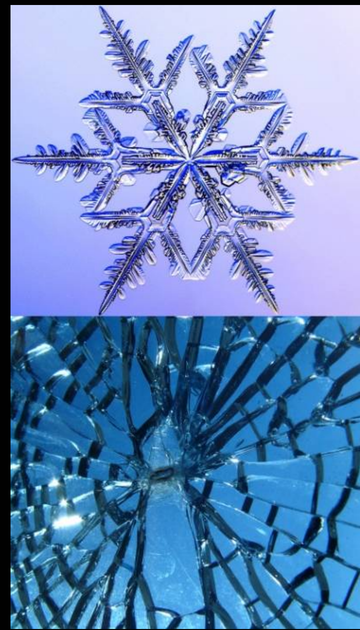

196 15 197 24.3159

Desuppearing fault

The truth about transform faults :



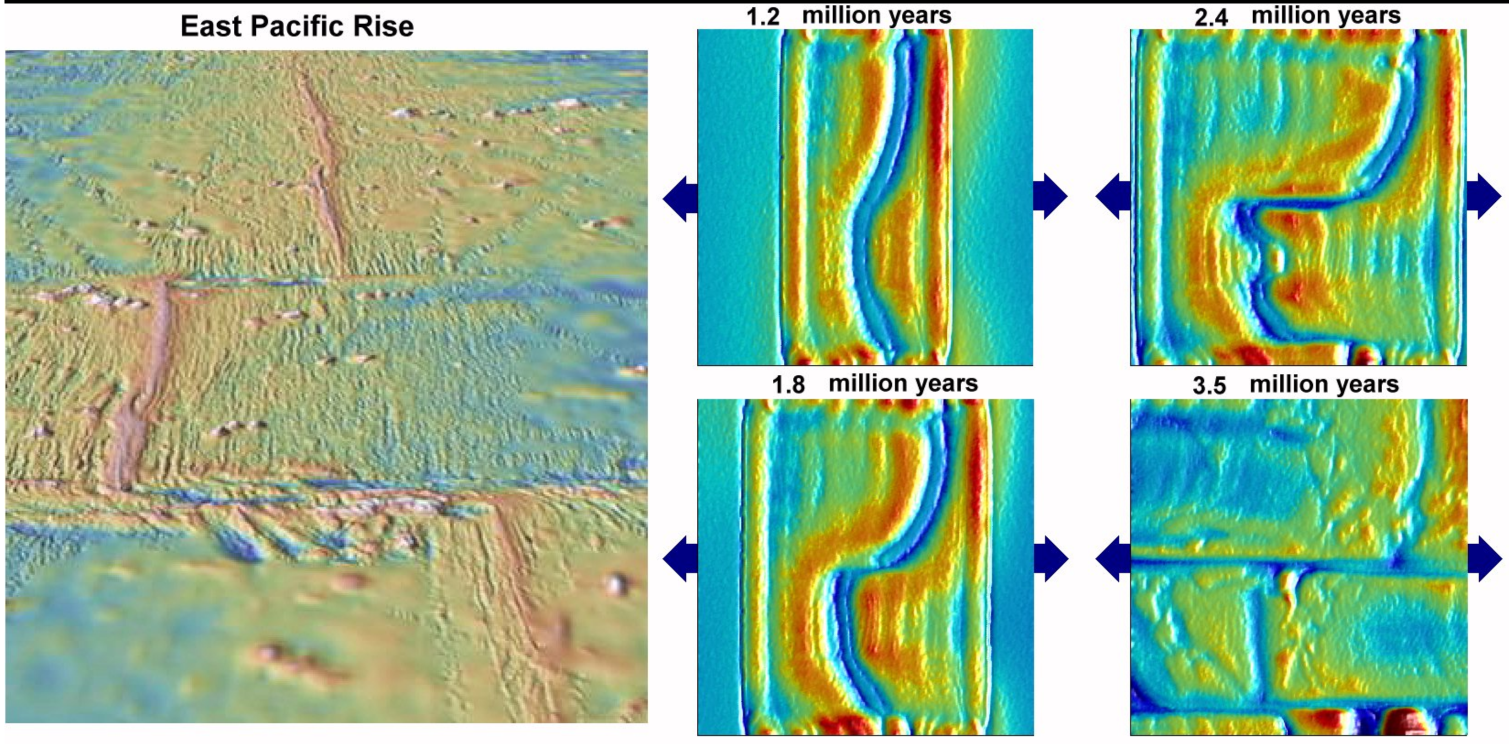
Yes



No

1. Transform are **plate-growth** structures and not **plate-fragmentation** structures: the difference is as in between **snowflakes** and **fragments of broken glass**.
2. Asymmetric plate accretion can spontaneously start in alternative directions along a single straight ridge
3. This causes dynamical instability of straight mid-ocean ridges promoting development of their curvature and finally leading to emergence of transform faults on the timescale of few millions years.

Oceanic transform faults : why and how do they form?



Yes

No

Why ? Because of dynamical plate growth instability .

How ? By rotation, and shearing of mid-ocean ridge sections .

Review: Origin and models of oceanic transform faults

Tectonophysics

Gerya (2011)