Assimilation of Plate Tectonic Reconstructions into Geodynamic Flow Models

Mark Turner, Mike Gurnis, Lydia Taylor, Vlad Manea, Sonja Kisin
Caltech, Tectonics Observatory

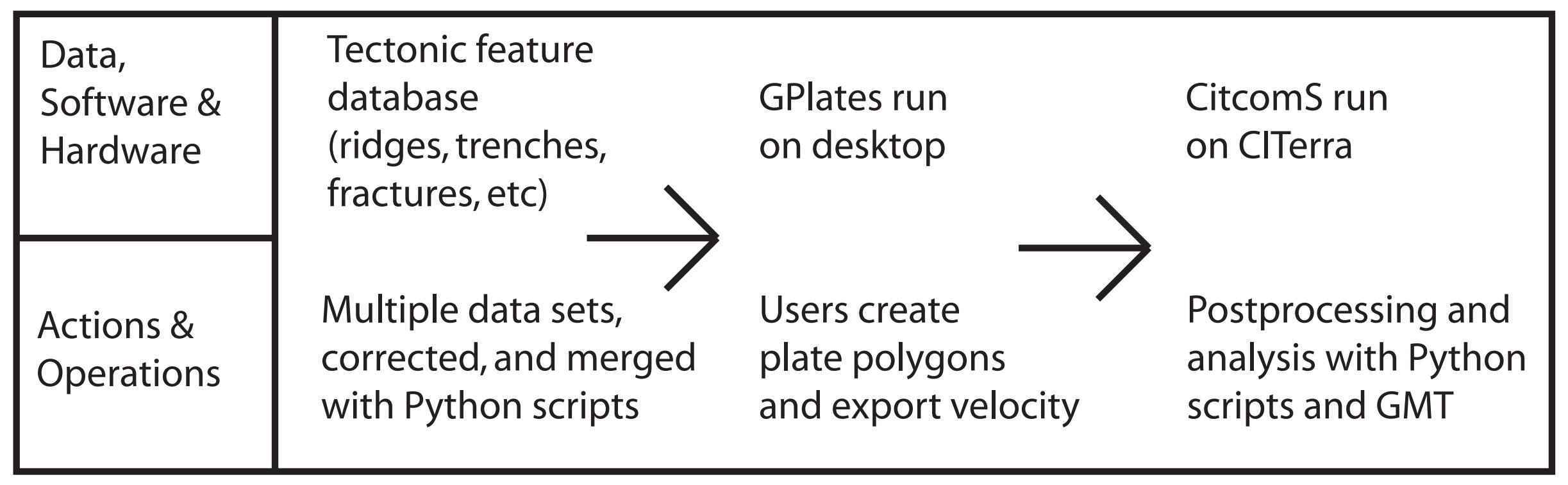
Dietmar Muller, Maria Sdrolias
University of Sydney, School of Geosciences

Introduction

One of our goals is to attempt to place the tectonics of individual boundaries within a global context and to understand the broader scale forces driving the deformation. There are a host of unsolved questions surrounding the causes for changes in plate motions, including the initiation of new subduction zones. In order to address these question, the CTO has been developing an entirely new generation of tools that are computationally advanced while being consistent with the actual structure and kinematics of plate boundaries. Thus far, we have made considerable progress in this direction. One goal is to assimilate plate tectonic reconstructions into global and regional geodynamic models. With the University of Sydney in Australia and the Geological Survey of Norway, the TO has been a key partner in the development of GPlates, a plate tectonic reconstruction software package. We are using GPlates as the preprocessing front end to global models of mantle convection using the CitcomS finite element code.

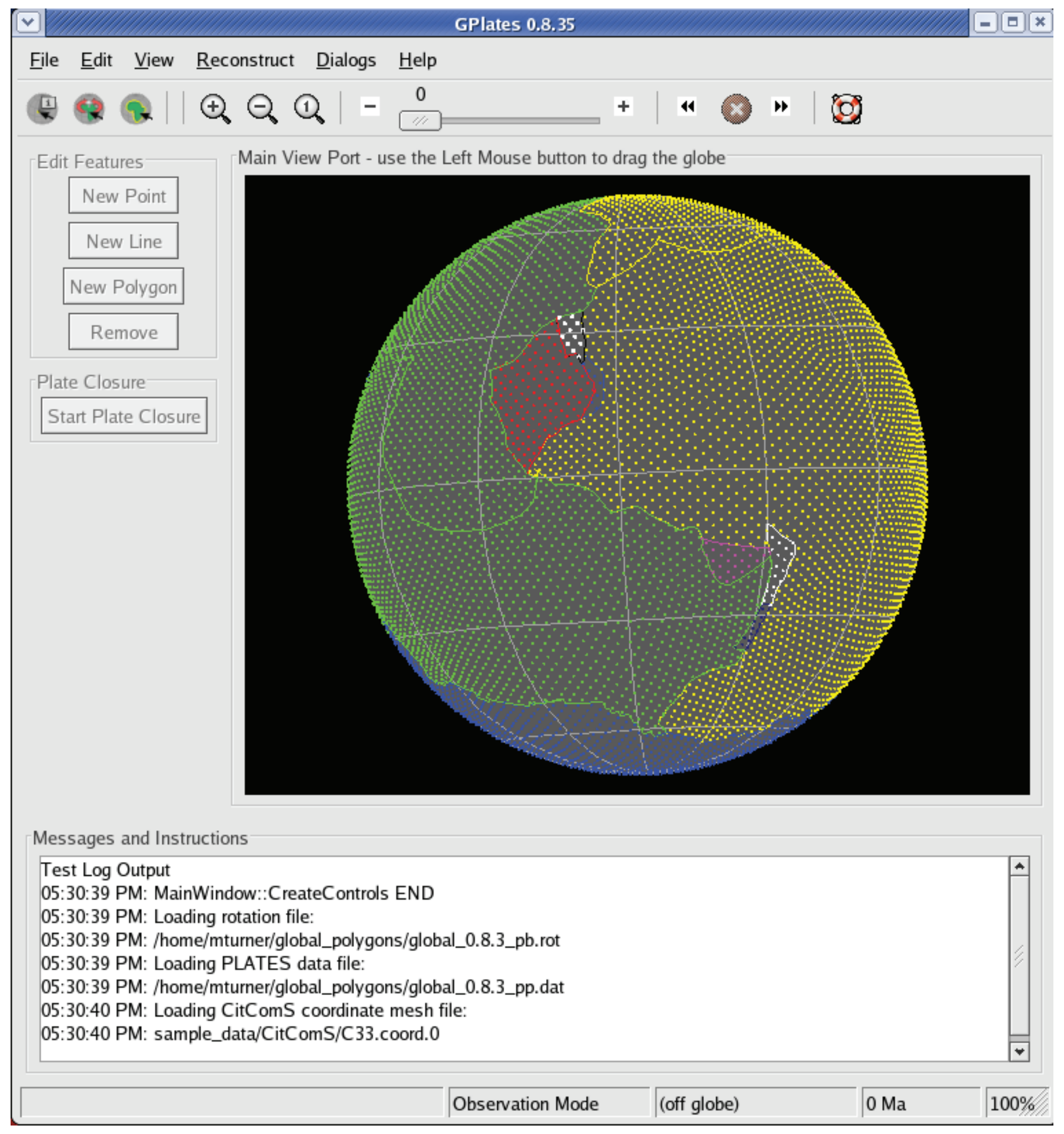
Using GPlates, we have developed a method for representing the evolving geometry of tectonic plates. A single plate is represented by all of the margins around the plate, reconstructed according to the euler pole of the margin, and an algorithm for computing the intersections of all of the margins. The end result is a complete evolving description of the surface of the earth without any blank spaces -- an essential prerequisite for merging dynamic models with paleo-reconstructions. We have used this software to build a global set of plates over the last 80 million years, to merge these "dynamic" plate polygons with paleo age grids, and to assimilate this data into global circulation models of the mantle. This work has given the CTO a new tool that allows us to explore the dynamics of changes in plate motions and shapes over the next several years. We are now routinely running this software on the CITerra supercomputer.

Typical Workflow Assimilating Data into Models



Data, Software & Hardware	Tectonic feature database (ridges, trenches, fractures, etc)	→	GPlates run on desktop	→	CitcomS run on CITerra
Actions & Operations	Multiple data sets, corrected, and merged with Python scripts		Users create plate polygons and export velocity		Postprocessing and analysis with Python scripts and GMT

GPlates: Software for Tectonic Reconstructions

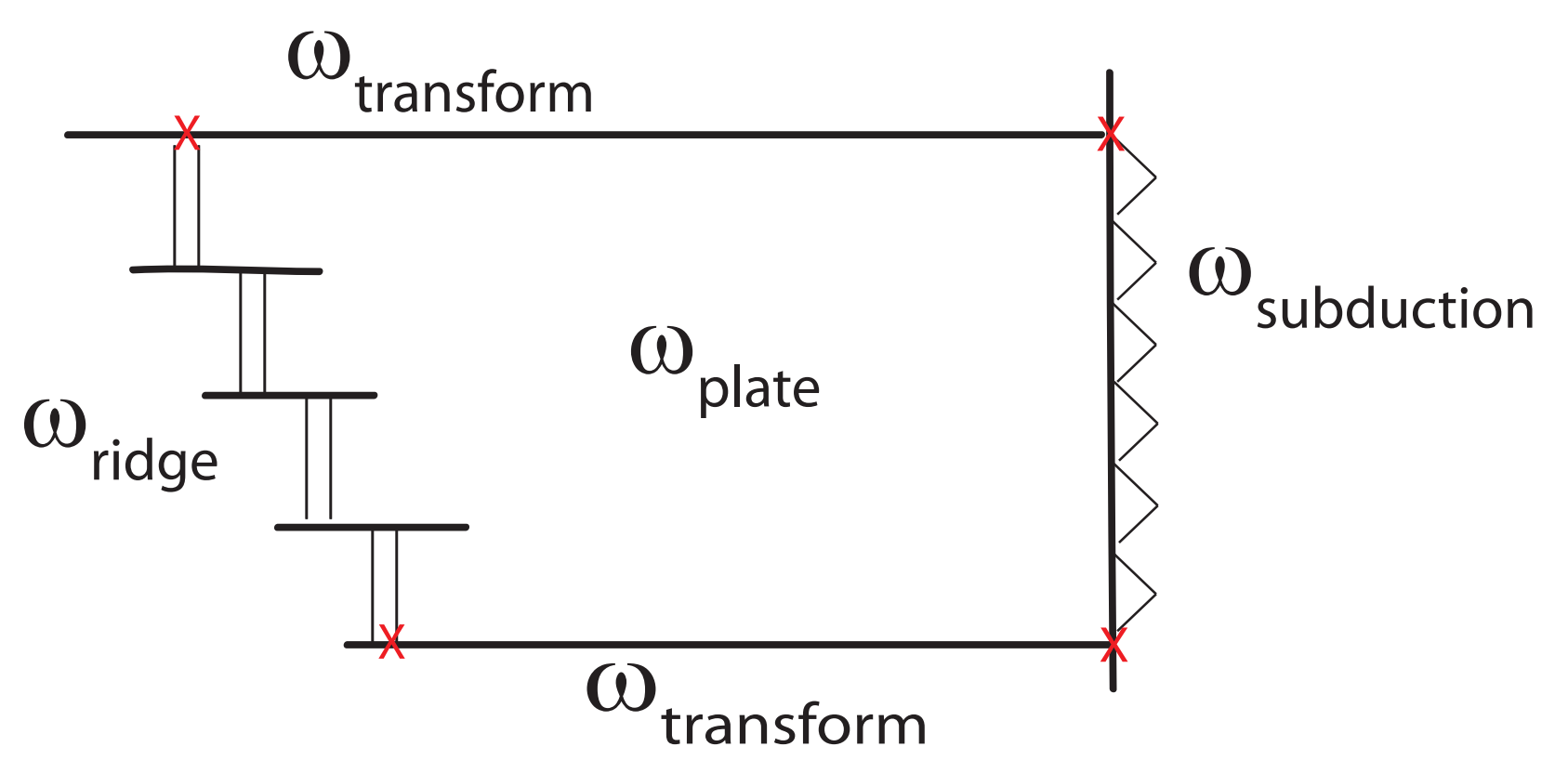


```
Test Log Output
05:30:39 PM: MainWindow::CreateControls END
05:30:39 PM: Loading rotation file:
05:30:39 PM: /home/mturner/global_polygons/global_0.8.3_pb.rot
05:30:39 PM: Loading PLATES data file:
05:30:39 PM: /home/mturner/global_polygons/global_0.8.3_pp.dat
05:30:40 PM: Loading CitComS coordinate mesh file:
05:30:40 PM: sample_data/CitComS/C33.coord.0
```

	Observation Mode	(off globe)	0 Ma	100%

The GPlates main window has a central globe for display, controls for creation and editing of tectonic feature data, and tools for performing reconstructions and animations. Most feature data may be exported as simple GMT xy files. When combined with a CitcomS mesh, GPlates can export surface velocity vectors for each mesh point.

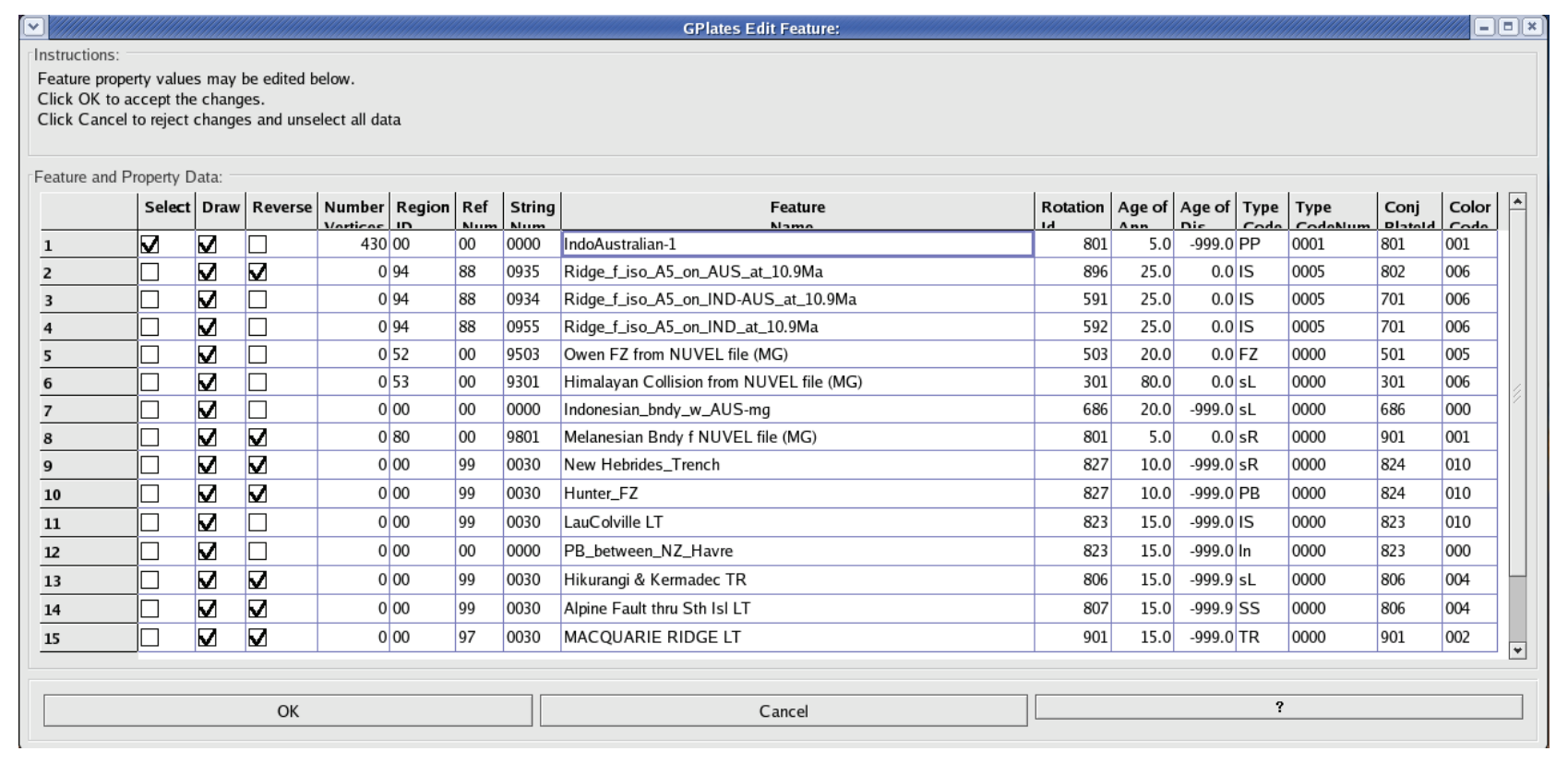
An idealized tectonic plate showing component margin line data features. Each line feature has its own euler pole and rotates according to the rules of plate tectonics.



The user selects line features to create a closed plate polygon. GPlates automatically calculates the intersection points (shown as red x's) to form the complete plate polygon boundary.

Upon each reconstruction all lines rotate independently, and GPlates automatically recomputes the new plate boundary to keep the polygon closed and consistent.

The table below shows a typical plate polygon with its component margins: the IndoAustralian plate from the present day back to five million years ago.



Instructions:
Feature property values may be edited below.
Click OK to accept the changes.
Click Cancel to reject changes and unselect all data

Feature and Property Data:

	Select	Draw	Reverse	Number	Region	Ref	String	Feature	Rotation	Age of	Age of	Type	Type	Conj	Color
1	☑	☑	☐	430	00	00	0000	IndoAustralian-1	801	5.0	-999.0	PP	0001	801	001
2	☐	☑	☑	0	94	88	0935	Ridge_f_iso_A5_on_AUS_at_10.9Ma	896	25.0	0.0	IS	0005	802	006
3	☐	☑	☐	0	94	88	0934	Ridge_f_iso_A5_on_IND-AUS_at_10.9Ma	591	25.0	0.0	IS	0005	701	006
4	☐	☑	☐	0	94	88	0955	Ridge_f_iso_A5_on_IND_at_10.9Ma	592	25.0	0.0	IS	0005	701	006
5	☐	☑	☐	0	52	00	9503	Owen FZ from NUVEL file (MG)	503	20.0	0.0	FZ	0000	501	005
6	☐	☑	☐	0	53	00	9301	Himalayan Collision from NUVEL file (MG)	301	80.0	0.0	sL	0000	301	006
7	☐	☑	☐	0	00	00	0000	Indonesian_bndy_w_AUS-mg	686	20.0	-999.0	sL	0000	686	000
8	☐	☑	☑	0	80	00	9801	Melanesian Bndy f NUVEL file (MG)	801	5.0	0.0	sR	0000	901	001
9	☐	☑	☑	0	00	99	0030	New Hebrides_Trench	827	10.0	-999.0	sR	0000	824	010
10	☐	☑	☑	0	00	99	0030	Hunter_FZ	827	10.0	-999.0	PB	0000	824	010
11	☐	☑	☐	0	00	99	0030	LauColville LT	823	15.0	-999.0	IS	0000	823	010
12	☐	☑	☐	0	00	00	0000	PB_between_NZ_Havre	823	15.0	-999.0	In	0000	823	000
13	☐	☑	☑	0	00	99	0030	Hikurangi & Kermadec TR	806	15.0	-999.9	sL	0000	806	004
14	☐	☑	☑	0	00	99	0030	Alpine Fault thru Sth Isl LT	807	15.0	-999.9	SS	0000	806	004
15	☐	☑	☑	0	00	97	0030	MACQUARIE RIDGE LT	901	15.0	-999.0	TR	0000	901	002

CitcomS: Mantle Convection Models

The plate tectonic reconstructions are assimilated into models of mantle convection solved with the finite element package CitcomS.py, developed at Caltech. CitcomS solves for conservation of mass, momentum and energy:

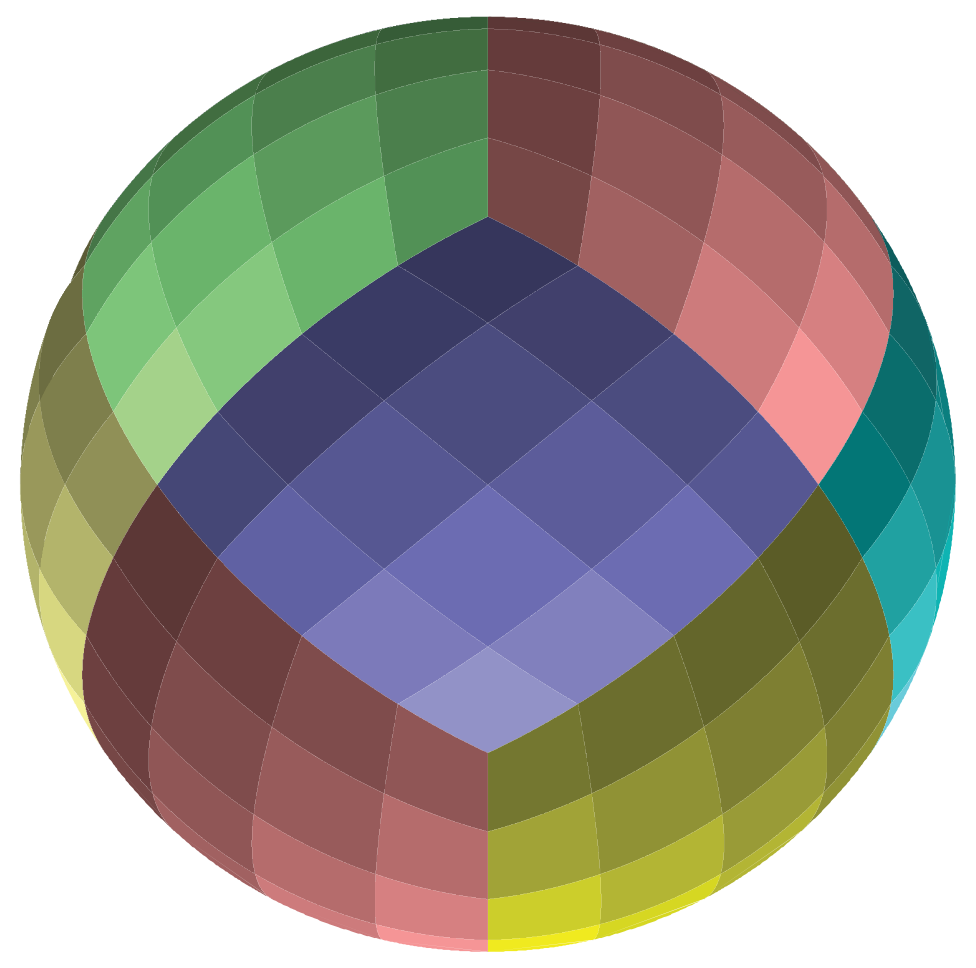
(1) $\nabla \cdot \vec{u} = 0$

(2) $\nabla \cdot \sigma = \rho_o \alpha (T - T_o)\vec{g}$

(3) $\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \kappa \nabla^2 T + H$

where *u* is velocity, σ is the stress tensor, *P* is dynamic pressure, η is dynamic viscosity, *T* is temperature, κ is thermal diffusivity, *H* internal heat and *g* is the gravitational acceleration.

These equations are solved with CitcomS.py [Tan et al., 2006] with the finite element. The model domain is a spherical shell representing the entire mantle and lithosphere. CitcomS.py uses a decomposition scheme such that the spherical shell is first decomposed into 12 caps so that in map view the elements are approximately equal area over the entire surface of the sphere. Then each cap is further divided such that the edges of the cap are equally divided.

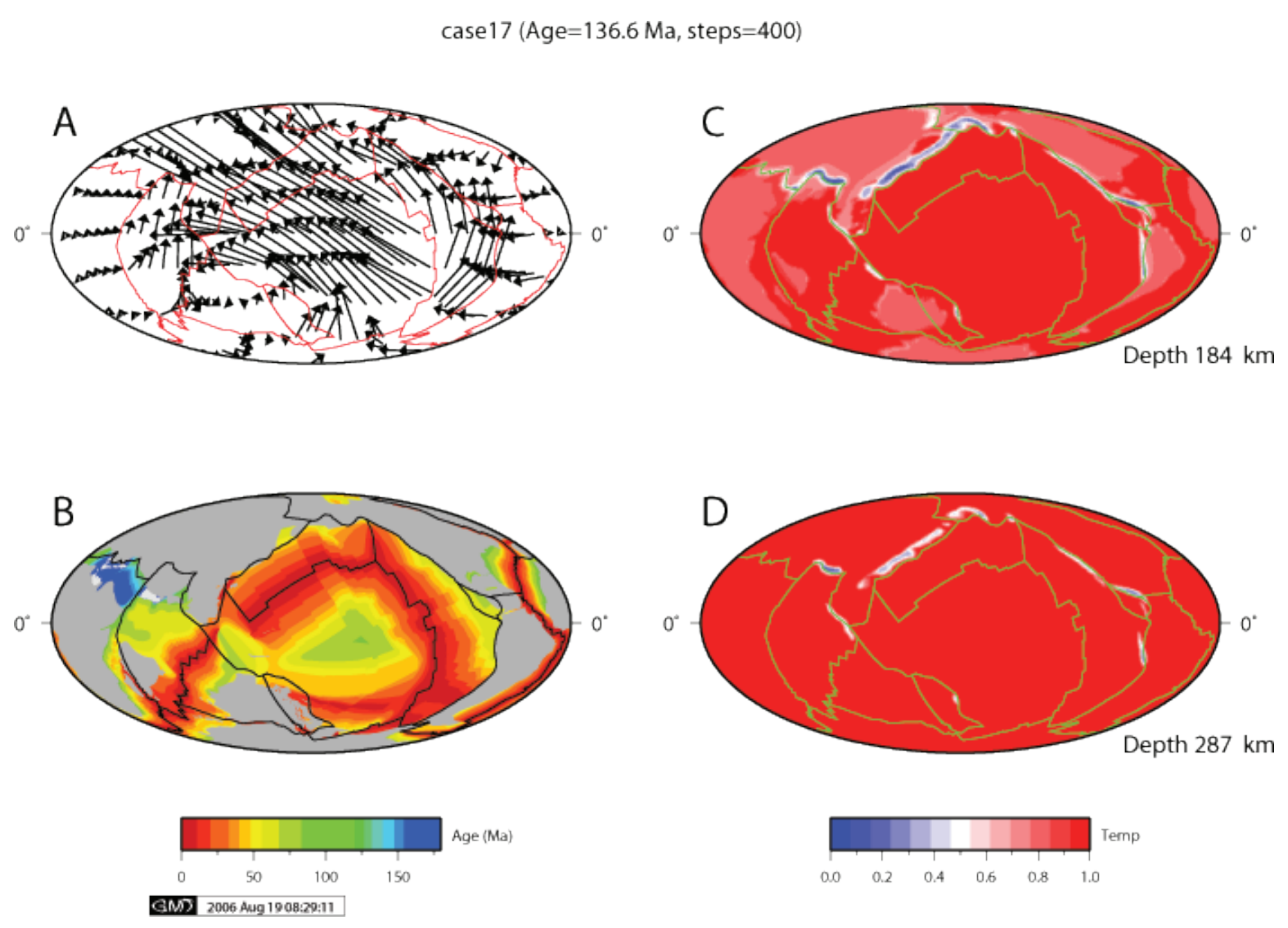


Orthographic projection of processors from a full CitcomS mesh in which there are 16 processors in map view for each cap. The CitcomS cap is shown as distinct colors while the processor domains within the caps are indicated by the intensity of the color.

This example was produced for a run with 2 processors in radius such that the total number of processors was 12x16x2=384. This is the largest model we have solved for on the CitTerra machine so far, and most of the cases have been solved with 96 processors with 128x128 elements in map view for each processor.

References:
Tan, E., E. Choi, P. Thoutireddy, M. Gurnis, and M. Aivazis, GeoFramework: Coupling multiple models of mantle convection within a computational framework, Geochemistry, Geophysics, Geosystems, 7, Q06001, doi:10.1029/2005GC001155, 14 pp., 2006.

Global Models with Polygons, Age Grids, and Convection

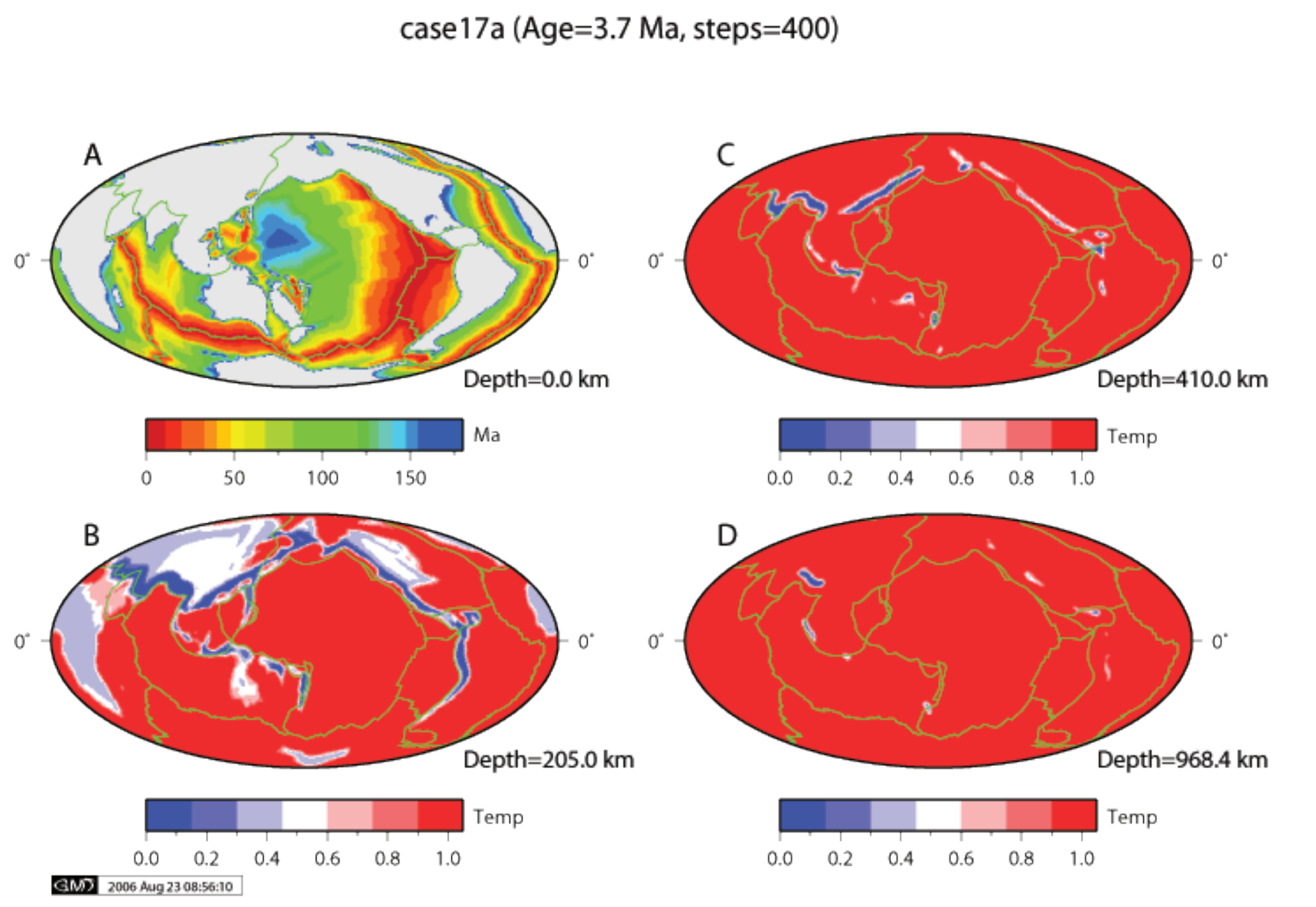


Model results incorporating the global closed plate polygons from 80 Ma to the present. The models are incorporated such that the 80 Ma reconstruction and age grid is imposed on the CitcomS model from 160 Ma to 80 Ma.

Results after 400 time steps, at '136 Ma', are shown on the left. Shown are (A) the imposed velocity field and closed polygons from GPlates, (B) the paleo-age grid, (C) the temperature field at 184 km, and (D) at 287 km.

We then show the results close to the present day (at 3 Ma) on the right. Shown are the (A) Paleoage grid, (B) temperature at 205 km depth, (C) at 410 km, and (D) at 964 km.

Early cases such as these have pointed toward the need for
(i) higher resolution, (ii) more realistic initial conditions,
(iii) closed plate polygons that extend to times earlier than 80 Ma,
(iv) more realistic rheological models for subduction boundaries.



Assimilation of Age Grids

We have been developing a new method by which the paleo age grids are assimilated into the flow models. We have explored a method by a thermal model for the conductive cooling of the oceanic lithosphere (a half-space model), is used

$$T_e(z,\tau) = T_s + (T_m - T_s) erf\left(\frac{z}{2\sqrt{\kappa\tau}}\right)$$

where Te is the expected temperature, Ts is the surface temperature, Tm is the mantle temperature, z is depth, K is the thermal diffusivity, and tau is the age of the oceanic lithosphere from the age grid. We attempt to conform the thermal structure within CitcomS to this thermal model for depths less than da, the assimilation depth. At each new time-step

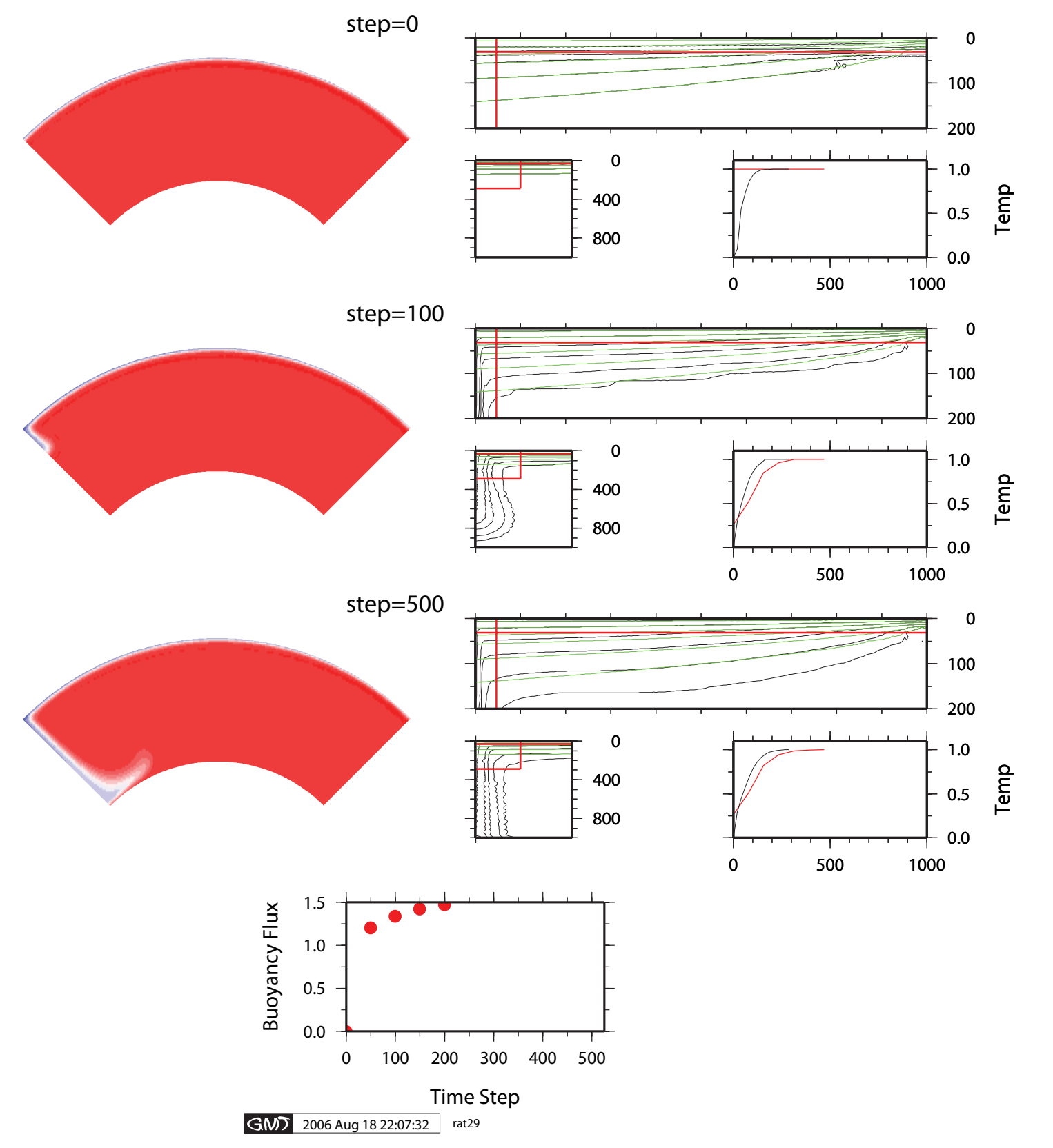
$\gamma = \frac{z}{2d_a}$ if $z < d_a$

$$T(z,t) = (1-\gamma)T'(z,t) + \gamma T_e(z,\tau)$$

where γ is the depth-dependent assimilation factor and T' is the temperature after the temperature is updated in the normal way by the solution of the energy equation.

In the figure on the right we show how this depth-dependent assimilation affects a simple model of cellular convection using the same set of parameters that we used in the global models, i.e. same Rayleigh number, d_a, age distribution, and resolution. What we find is that if d_a is too close to the thickness of the oceanic lithosphere for a given age, τ, then subduction is cut-off.

On the left is the temperature field for the entire model domain, while on the right we zoon in on the upper thermal boundary layer for three time steps, including the initial condition. In the contour plots on the right, we see the expected temperature contoured in green and the temperatures from CitcomS using d_a=0.005 (32 km).



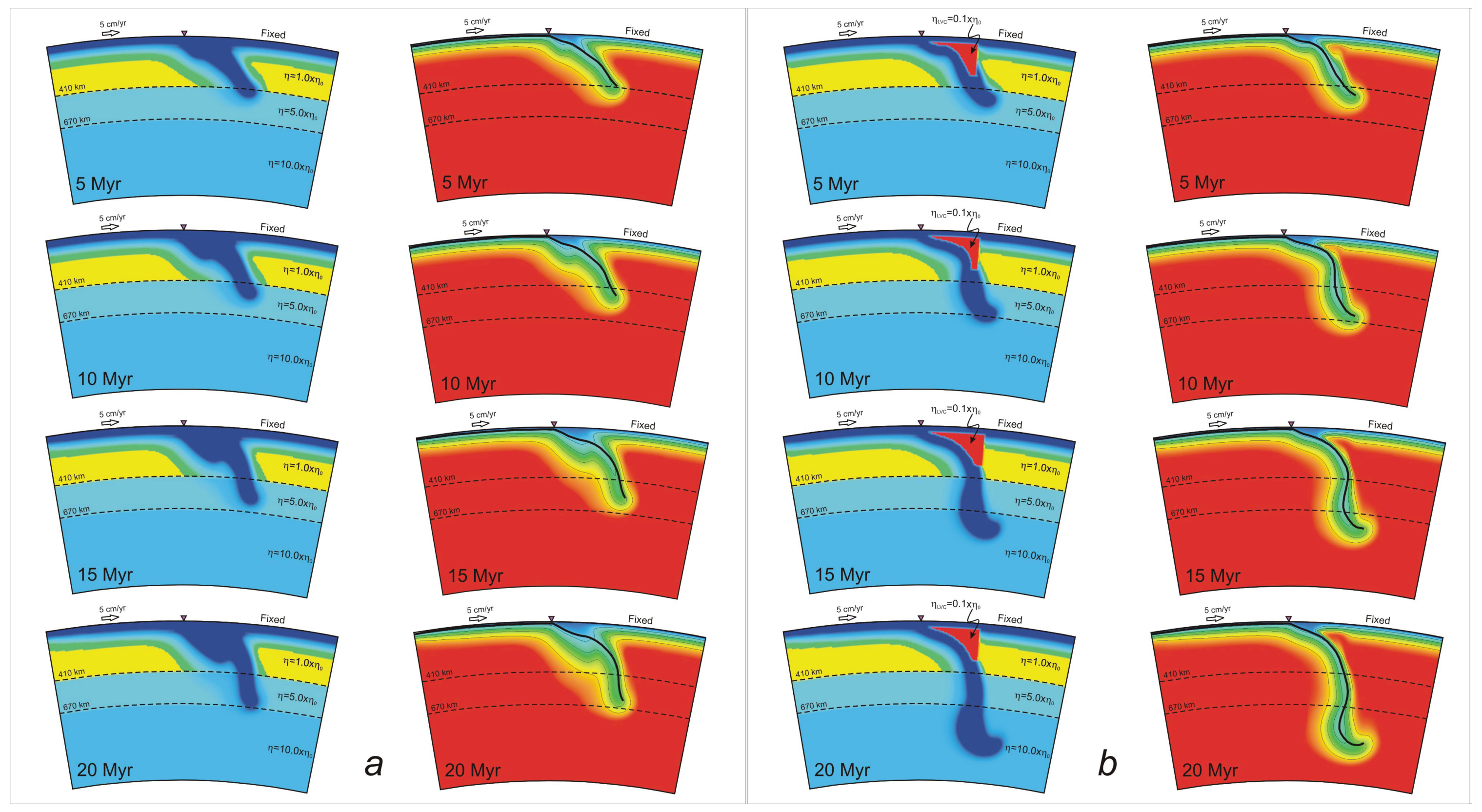
Low Viscosity Wedges

The details of plate margins, especially the introduction of low viscosity wedges (LVWs), can have a substantial influence on the dynamics of subduction zones.

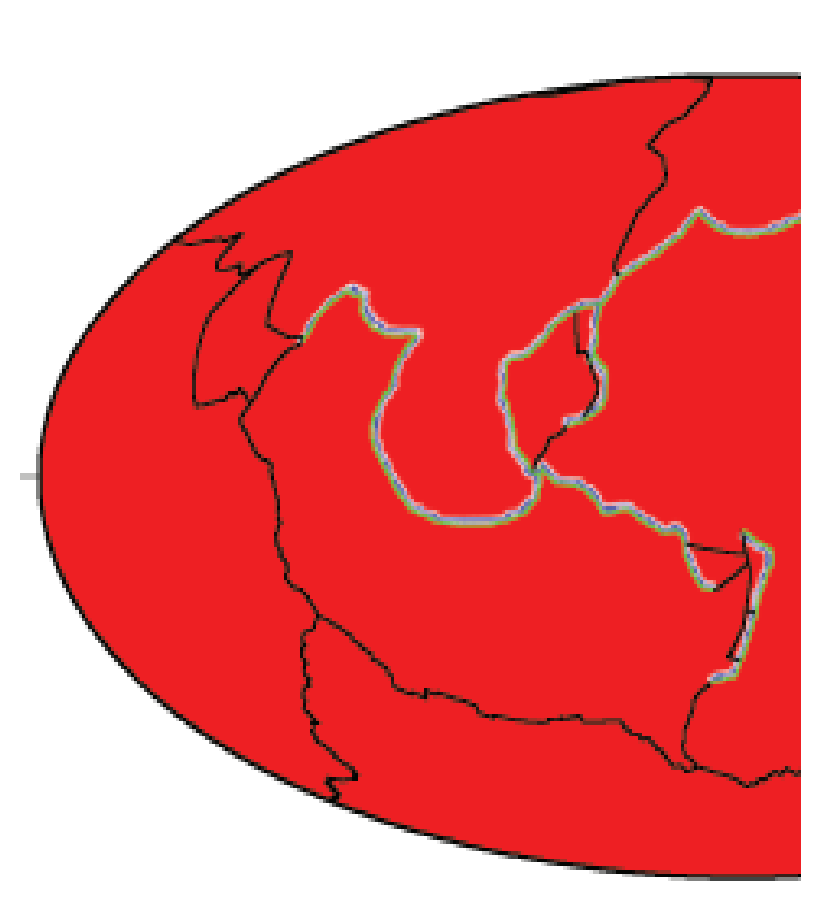
These models show a method we have developed to simulate the weakening of mantle wedge by way of the dehydration of subducted oceanic crust. It relies on tracking the oceanic crust after it has subducted by way of tracers and then lowering the viscosity of the mantle above the crust in terms of pressure and distance from the trench. The method has been incorporated into the regional version of CitcomS. The models shown are effectively 2-D but the method works in 3-D as well.

In the figures at right, the oceanic crust is shown in Blue on top of the temperature field. In the case shown in (a) there is no mantle wedge and the oceanic lithosphere has been advectively thickened below the over-riding plate.

The only difference in the model shown in (b) is the incorporation of a LVW such that the viscosity between a depth of about 40 km and 300 km has had its viscosity reduced by one order of magnitude. The excessive advective thickening has vanished, the slab dips at a steeper dip into the mantle, and the slab penetrates to a greater depth into the mantle for an equal interval of time.



Incorporation of Asymmetric Plate Boundaries from GPlates into CitcomS



We have been able to complete the workflow from subduction zones, including their polarity from the plate tectonic reconstruction (GPlates) and merged with CitcomS (shown at left). We are currently refining the procedure.

Shown at left is an image of the material type before incorporation into CitcomS as a raster image from red (normal) to blue (weak plate boundaries). GPlates distinguishes between the closed plate polygon (black lines) and the subduction boundaries (green lines).

These material types are then processed by CitcomS with the other controls on the viscosity (pressure and temperature) to create the viscosity shown at right, with the three cross-sections with the low viscosity wedges shown as the deepest red.