MODELING OF BLOCK-AND-FAULT SYSTEM DYNAMICS AND SEISMICITY

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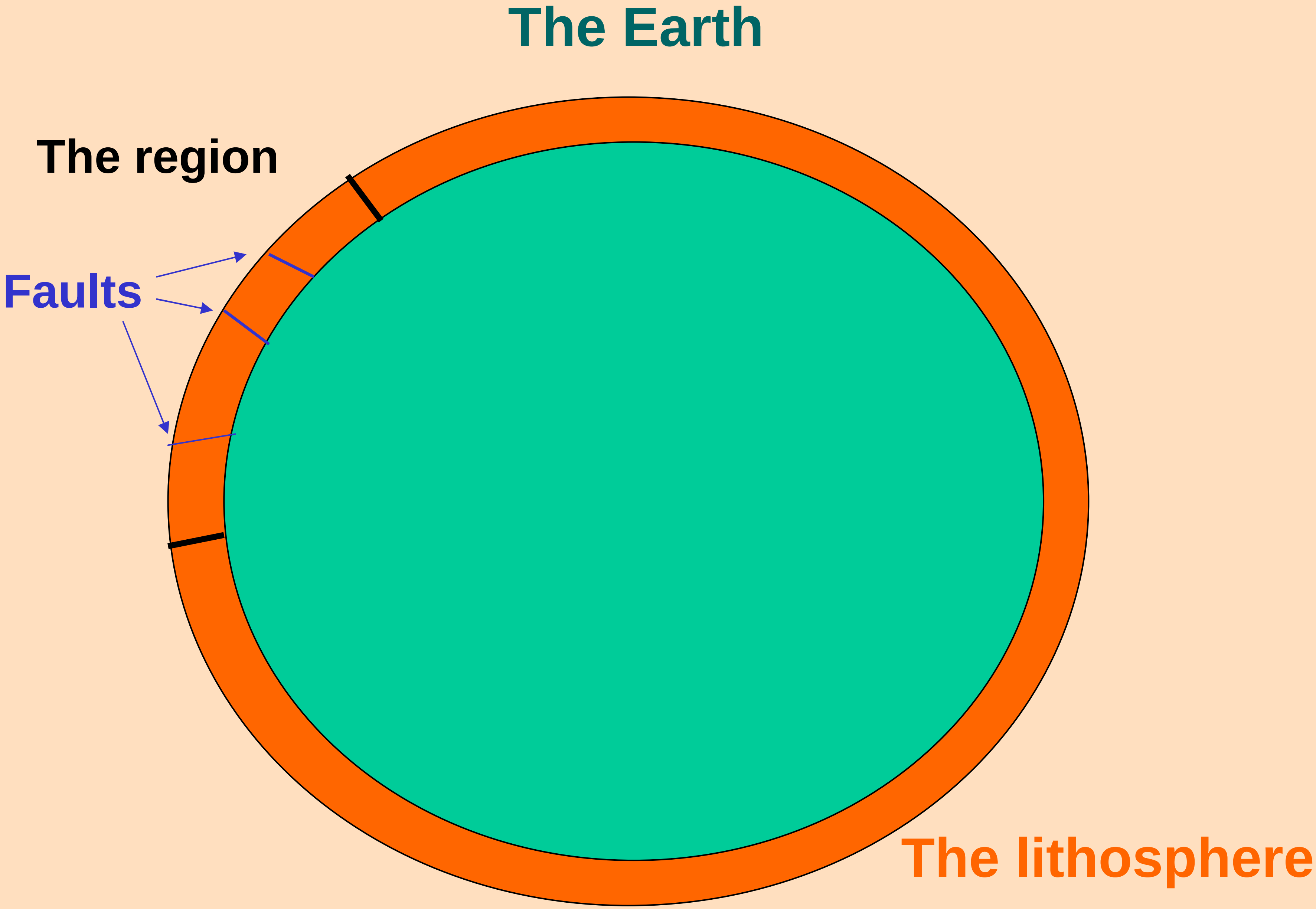
The Earth
The region
Faults
The lithosphere

BASIC PRINCIPLES OF THE MODEL

Lithosphere of a region is represented as a system of *perfectly rigid* blocks

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The blocks are separated by plane faults with arbitrary angles of dip

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All deformations and forces take place in the fault planes and the block bottoms

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Driving forces are applied to the lateral boundary of the structure and the block bottoms

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All displacements of the blocks are infinitely small, compared with the block size; the geometry of the block structure does not change during simulation

THE MODEL ENABLES

To reproduce the whole ensemble:

tectonic driving forces => geodetic movements => creep => earthquakes

To study:

(i) connection of seismicity and geodynamics;

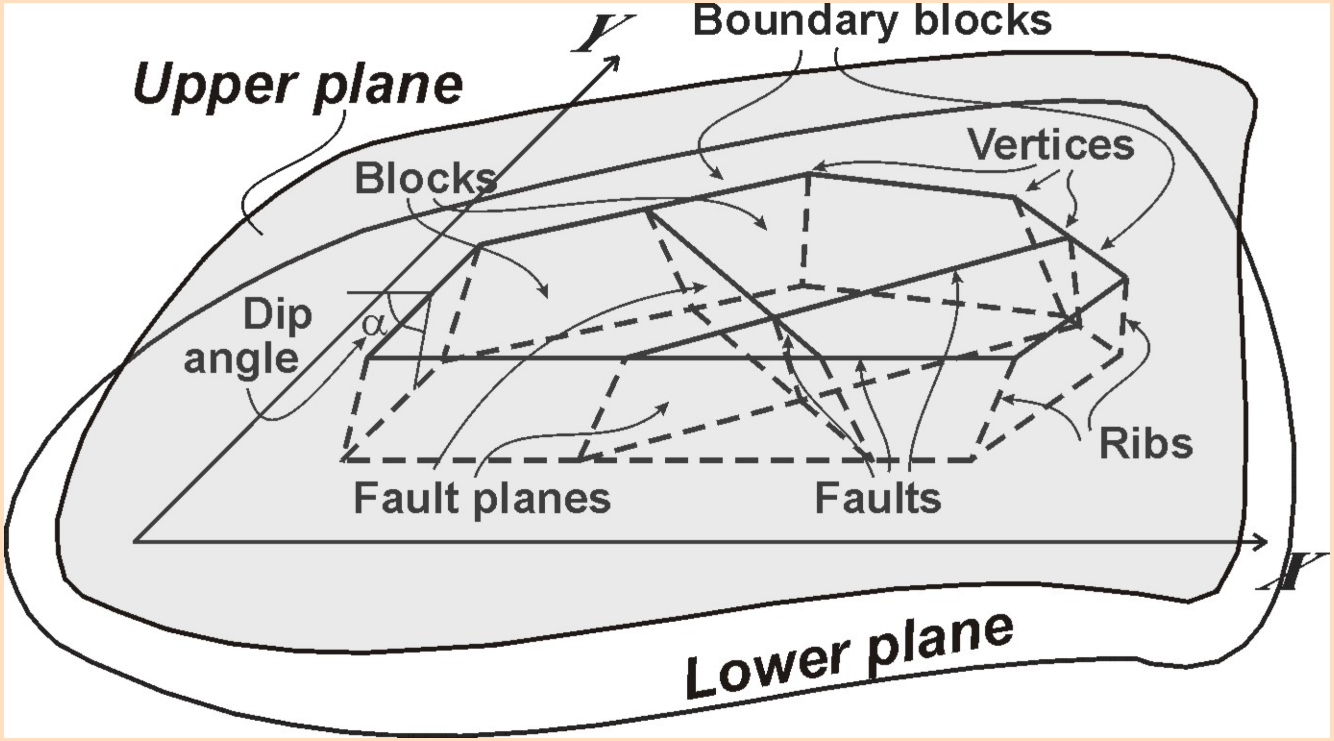
(ii) dependence of seismicity on general properties of fault networks; that is, fragmentation of structure, rotation of blocks, direction of driving forces etc;

(iii) the earthquake preparation process and earthquake prediction, moreover the model can be used to suggest new premonitory patterns that might exist in real catalogs;

(iv) dependence of block motions on driving forces.

To study, and to reproduce regional features of seismicity

A sketch of the block-and-fault dynamics model



SOURCE OF MOVEMENT

- **movement of the underlying medium;**
- **movement of structure boundaries (boundary blocks).**

NON-DIMENSIONAL TIME

All quantities that contain time in their dimensions are referred to one unit of the non-dimensional time.

Velocities in the model are measured in units of length. A velocity of 5 cm means 5 cm per one unit of the non-dimensional time.

When interpreting the results a realistic value is given to the unit of the non-dimensional time.

FORCES

Elastic stress $\mathbf{f} = K(\Delta\mathbf{r} - \delta\mathbf{r})$,

$\Delta\mathbf{r}$ – relative displacement,

$\delta\mathbf{r}$ – inelastic displacement,

$d\delta\mathbf{r}/dt = W\mathbf{f}$,

K and W – constant parameters.

Displacements of blocks are determined by the condition: ***For each block the total force and the total moment of forces acting on it are equal to zero.***

FORCES AT THE BLOCK BOTTOM

The elastic force per unit area $\mathbf{f}^u = (f_x{}^u, f_y{}^u)$ applied to the point with coordinates (X, Y)

$f_x{}^u = K_u(x - x_u - (Y - Y_c)(\varphi - \varphi_u) - x_a)$,

$f_y{}^u = K_u(y - y_u + (X - X_c)(\varphi - \varphi_u) - y_a)$.

X_c, Y_c - the coordinates of the geometrical center of the block bottom;

(x_u, y_u), φ_u, and (x, y), φ - the translation vector and the angle of rotation around the geometrical center of the block bottom, of the underlying medium and of the block respectively;

(x_a, y_a) is the inelastic displacement vector at the point (X, Y).

$$\frac{dx_a}{dt} = W_u f_x^u \qquad \frac{dy_a}{dt} = W_u f_y^u$$

K_u and W_u may be different for different blocks.

INTERACTION BETWEEN THE BLOCKS ALONG THE FAULT PLANES

The elastic force per unit area $\mathbf{f} = (f_t, f_l)$ applied to the point with coordinates (X, Y)

$$f_t = K(\Delta_t - \delta_t), \quad f_l = K(\Delta_l - \delta_l)$$

f_t is parallel, and f_l is normal to the fault line on the upper plane;

Δ_t and Δ_l are relative displacements of blocks along the fault plane in the same directions;

δ_t, δ_l are inelastic displacements along the fault plane at the point (X, Y);

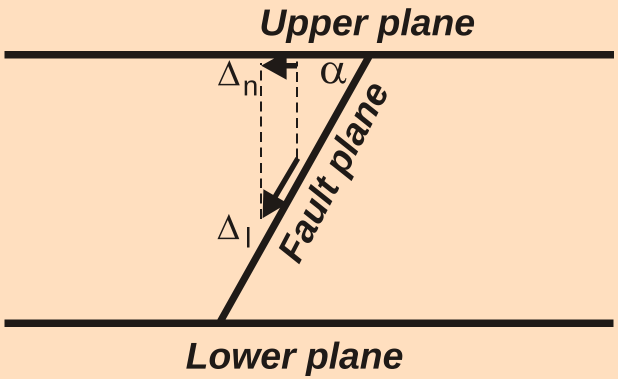
$$\frac{d\delta_t}{dt} = Wf_t \qquad \frac{d\delta_l}{dt} = Wf_l$$

K and W may be different for different faults.

RELATIONS BETWEEN DISPLACEMENTS

$$\Delta_t = e_x \Delta x + e_y \Delta y,\ \Delta_l = \Delta_n / \cos\alpha,\ \Delta_n = e_x \Delta y - e_y \Delta x$$

(e_x, e_y) is the unit vector along the fault line on the upper plane, α is the dip angle of the fault plane;



$\Delta x = x_i - x_j - (Y - Y_c^{\,i})\varphi_i + (Y - Y_c^{\,j})\varphi_j,$

$\Delta y = y_i - y_j + (X - X_c^{\,i})\varphi_i - (X - X_c^{\,j})\varphi j.$

$X_c^{\,i}, Y_c^{\,i}, X_c^{\,j}, Y_c^{\,j}$ - the coordinates of the geometrical centers of the block bottoms;

$(x_i, y_i), (x_j, y_j)$ - the translation vectors of the blocks;

φ_i, φ_j are the angles of rotation of the blocks around the geometrical centers of their bottoms;

the block numbered i is on the left and that numbered j on the right of the fault

REACTION FORCE

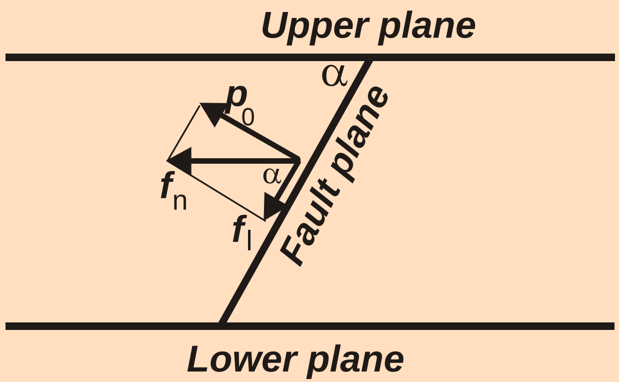
The elastic energy per unit area

$$e = (f_t(\Delta_t - \delta_t) + f_l(\Delta_l - \delta_l))/2$$

The horizontal component f_n of the elastic force per unit area normal to the fault line on the upper plane

$$f_n = \frac{\partial e}{\partial \Delta_n} = \frac{f_l}{\cos \alpha}$$

The reaction force per unit area $p_0 = f_l \operatorname{tg} \alpha$



DISCRETIZATION

A fault segment is divided into $n_1 n_2$ cells;

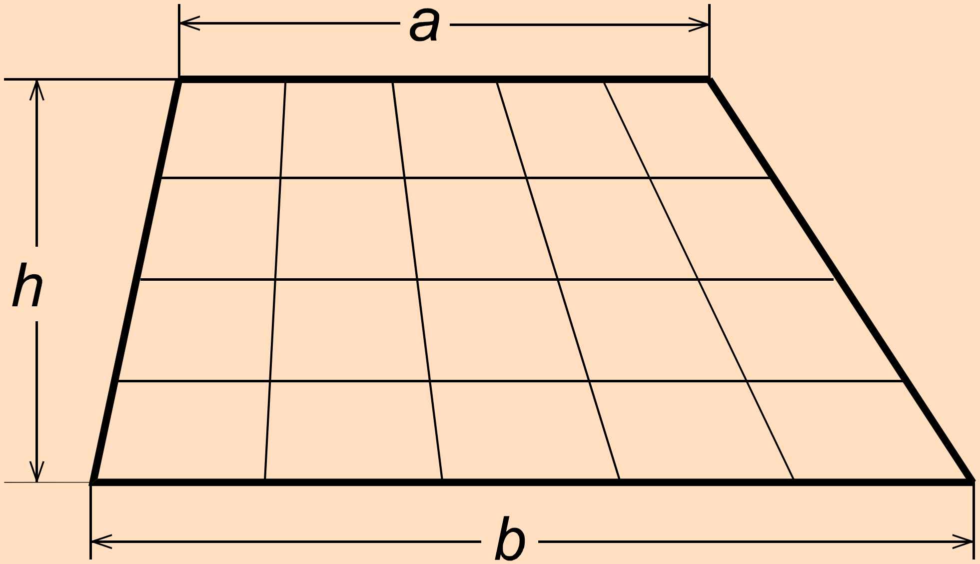
n_1 = ENTIRE(h/ε), n_2 = ENTIRE(max(a,b)/ε),

$h = H/\sin\alpha$, H - the depth of the structure,

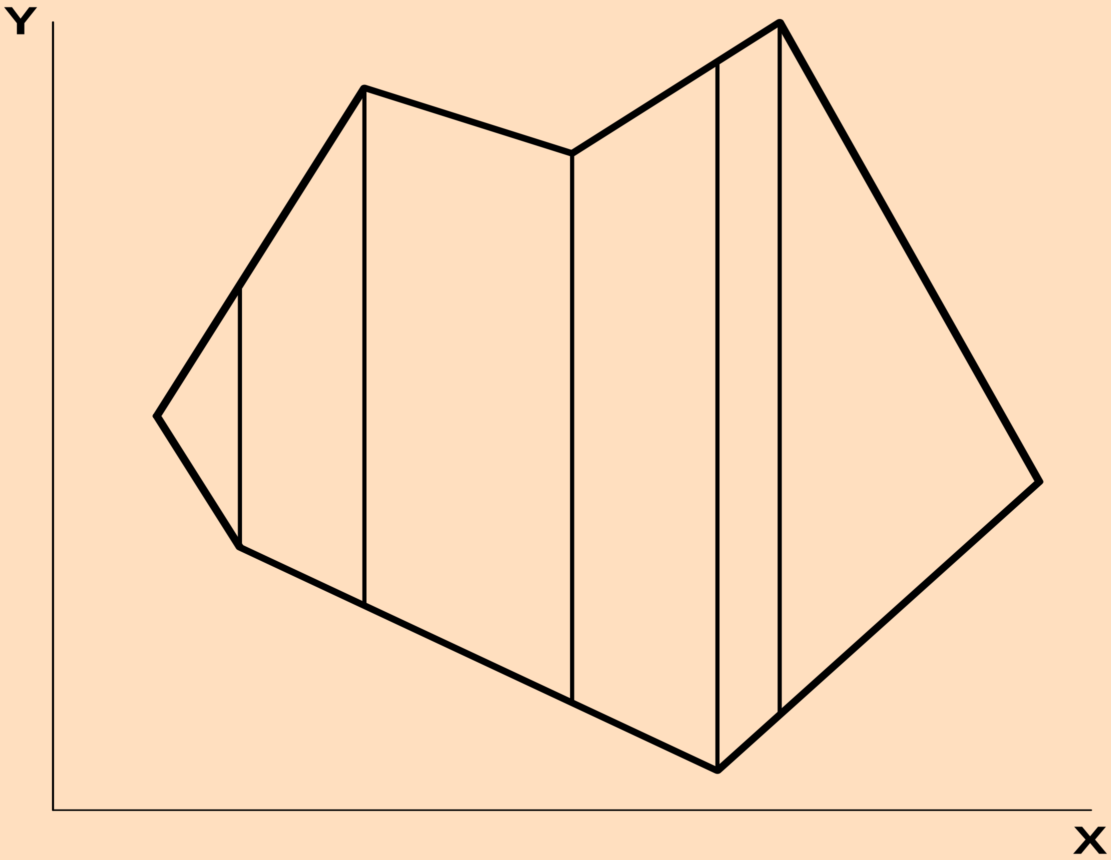
ε - a parameter, α - the dip angle of the fault plane.

Coordinates, inelastic displacements, and forces

per unit area are supposed to be the same for all points of a cell.



DIVISION OF THE BLOCK BOTTOM INTO TRAPEZIUMS AND TRIANGLES



EQUILIBRIUM EQUATIONS

Displacements of blocks are determined by the condition: ***For each block the total force and the total moment of forces acting on it are equal to zero.*** This is a condition of ***the quasi-static equilibrium*** of the system and at the same time ***the condition of the energy minimum.***

It is described by the system of linear equations for components of translation vectors of blocks and angles of their rotation.

For the block numbered m:

(x_m, y_m), φ_m, - the translation vector and the angle of rotation

$z_{3m-2} = x_m,\ z_{3m-1} = y_m,\ z_{3m} = \varphi_m$

$$\Sigma F_x = 0 \square \Sigma a_{3m-2,j}\, z_j = b_{3m-2}$$

$$\Sigma F_y = 0 \square \Sigma a_{3m-1,j}\, z_j = b_{3m-1}$$

$$\Sigma \mathrm{M}\boldsymbol{F} = 0 \square \Sigma a_{3m,j}\, z_j = b_{3m}$$

If blocks m and k have no common segments then

$$a_{3m-p,3k-r} = 0,\ \ p, r = 0, 1, 2$$

b_j depend on inelastic displacements and displacements of boundary blocks and the underlying medium.

SCHEME OF CALCULATIONS

(i) Calculation of inelastic displacements at t_i;

(ii) Calculation of displacements of boundary blocks and the underlying medium and the right parts of the system at t_{i+1};

(iii) Solving the system

$$\mathbf{Az} = \mathbf{b}$$

to obtain the translation vectors of blocks and angles of their rotation at t_{i+1}.

EARTHQUAKE AND CREEP

The levels $B > H_f > H_s$ are specified for each fault.

Value $\kappa = |\mathbf{f}|/(P - p_0)$ is calculated for each cell during simulation, P - parameter which is equal for all the faults and can be interpreted as the difference between lithostatic and hydrostatic pressure.

If at t_i $\kappa \geq B$ for any cell then in accordance with the dry friction model *a **failure ("earthquake")*** occurs:

$$\kappa \Rightarrow H_f : \boldsymbol{\delta}_t^{\mathrm{e}} = \boldsymbol{\delta}_t + \gamma f_t; \ \boldsymbol{\delta}_l^{\mathrm{e}} = \boldsymbol{\delta}_l + \gamma f_l$$

Parameters of the earthquake:

time t_i, magnitude $M = 0.98 \lg S + 3.93$ (S - the sum of areas (in km^2) of the cells included in the earthquake),

the epicentral coordinates and the depth are the weighted sums (weights are proportional to the areas of the cells) of the coordinates and depths of the cells included in the earthquake.

After the failures the cells are in ***the creep state***: W_s ($W_s > W$) is used instead of W.

Creep lasts while $\kappa > H_s$. After creep the cell returns to the ordinary state.

HIERARCHY OF FAULTS

The hierarchy of faults is controlled by the hierarchy of structures separated by them.

Larger faults separate larger structures.

The same elastic displacement leads to a smaller elastic force for the larger fault than for a smaller one:

the value of K has to be smaller for a larger fault.

The same force leads to larger slippage (inelastic displacement) for a larger fault than for a smaller one:

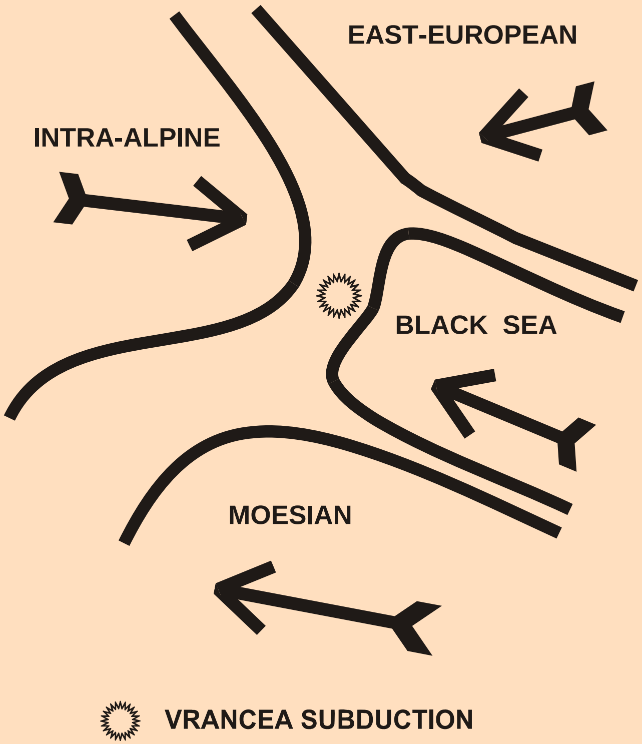
the values of W and W_s are larger for larger faults.

The earthquakes occur in the larger faults for smaller values of the parameter κ than in the smaller ones:

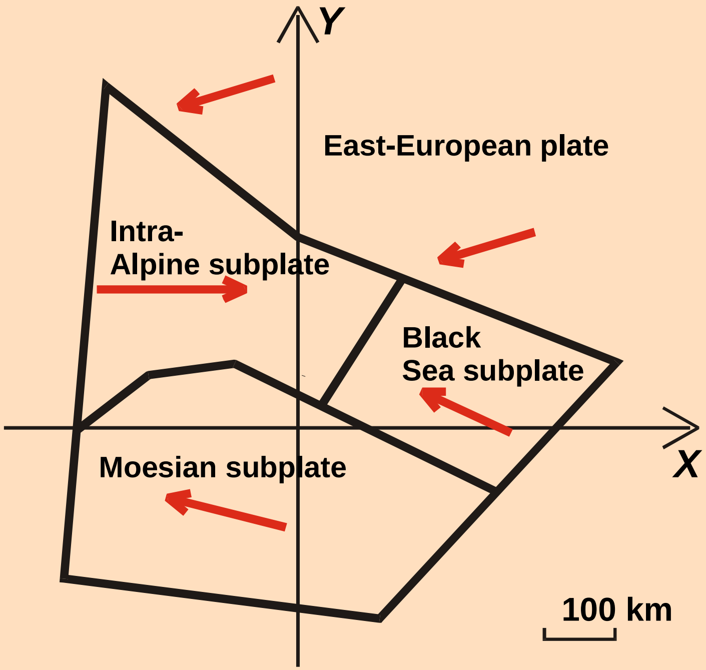
the levels B, H_f, H_s are smaller for the larger faults.

BLOCK MODEL OF THE VRANCEA REGION

KINEMATIC MODEL (after V.I.Mocanu)

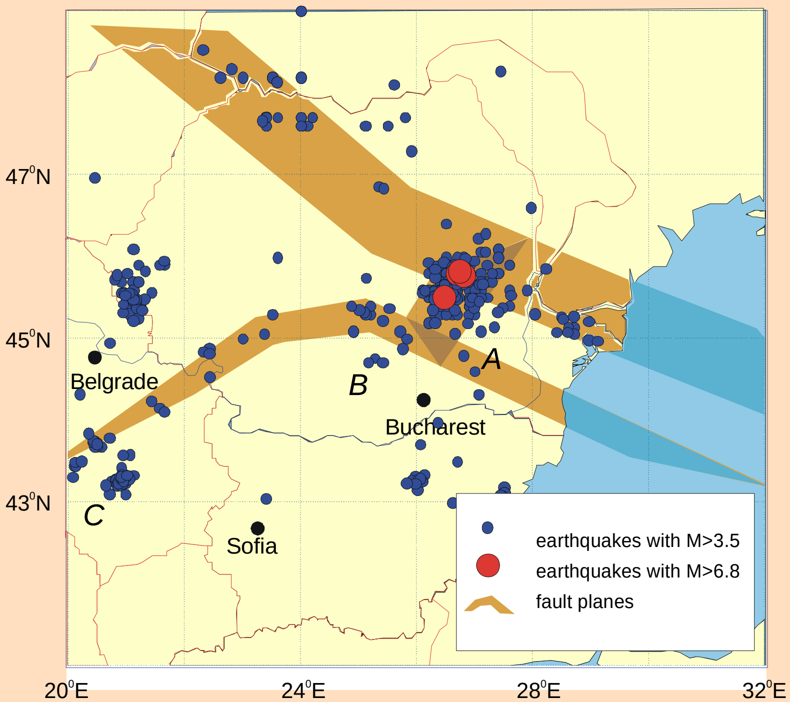


BLOCK STRUCTURE

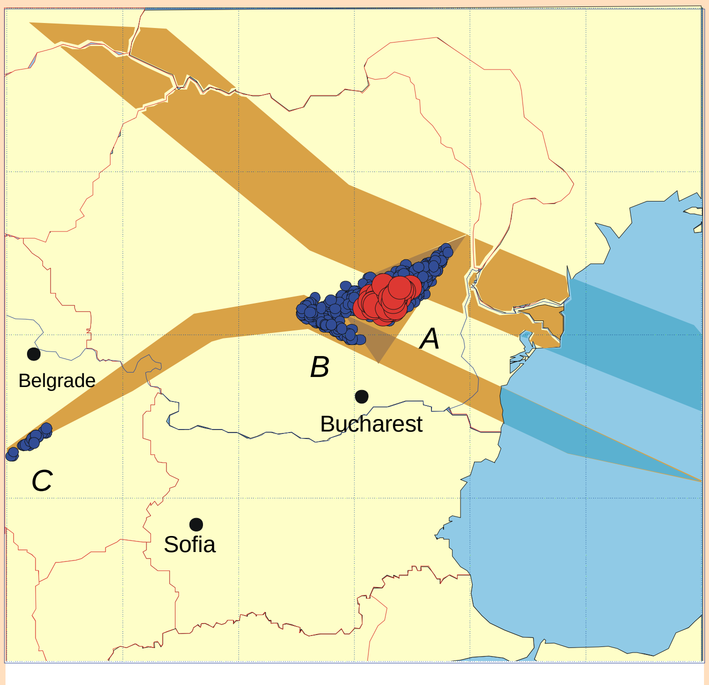


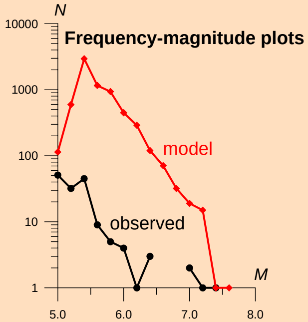
COMPARISON BETWEEN MODEL AND OBSERVED SEISMICITY

MAP OF VRANCEA SEISMICITY



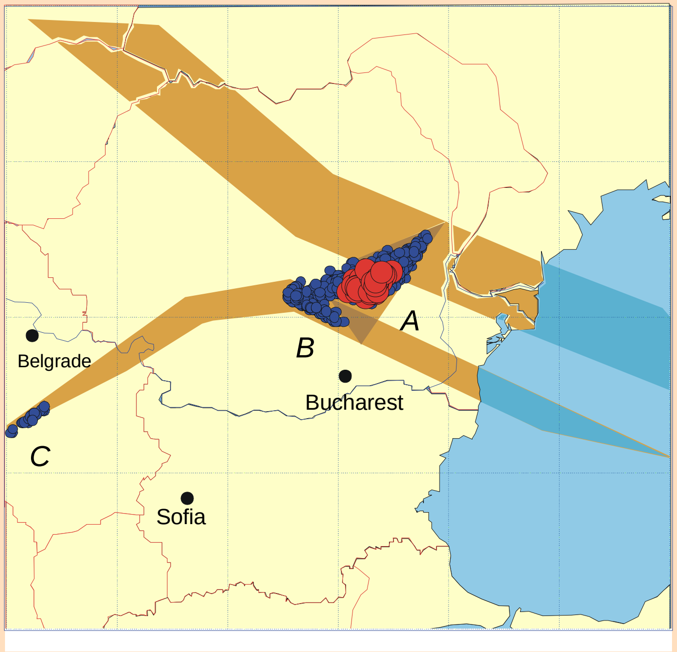
MODEL EPICENTERS



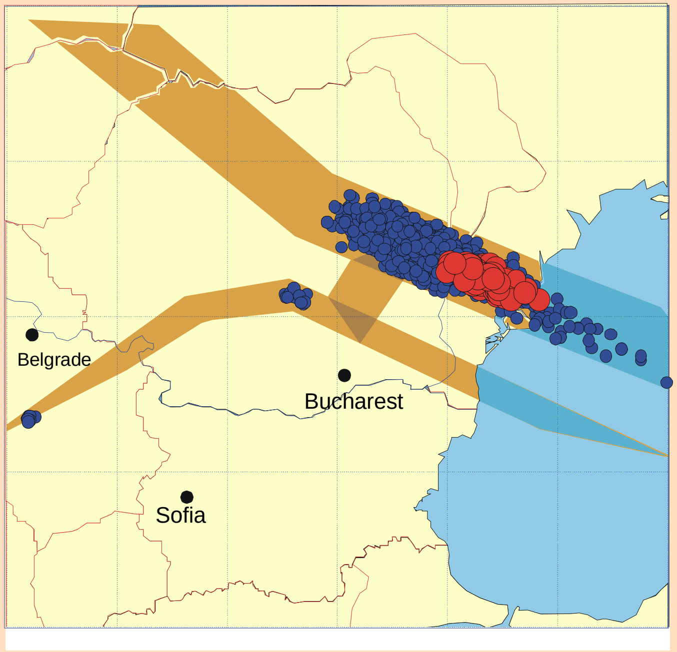


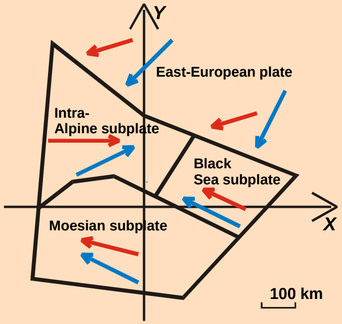
DEPENDENCE OF EPICENTER DISTRIBUTION ON MOVEMENTS SPECIFIED IN THE MODEL

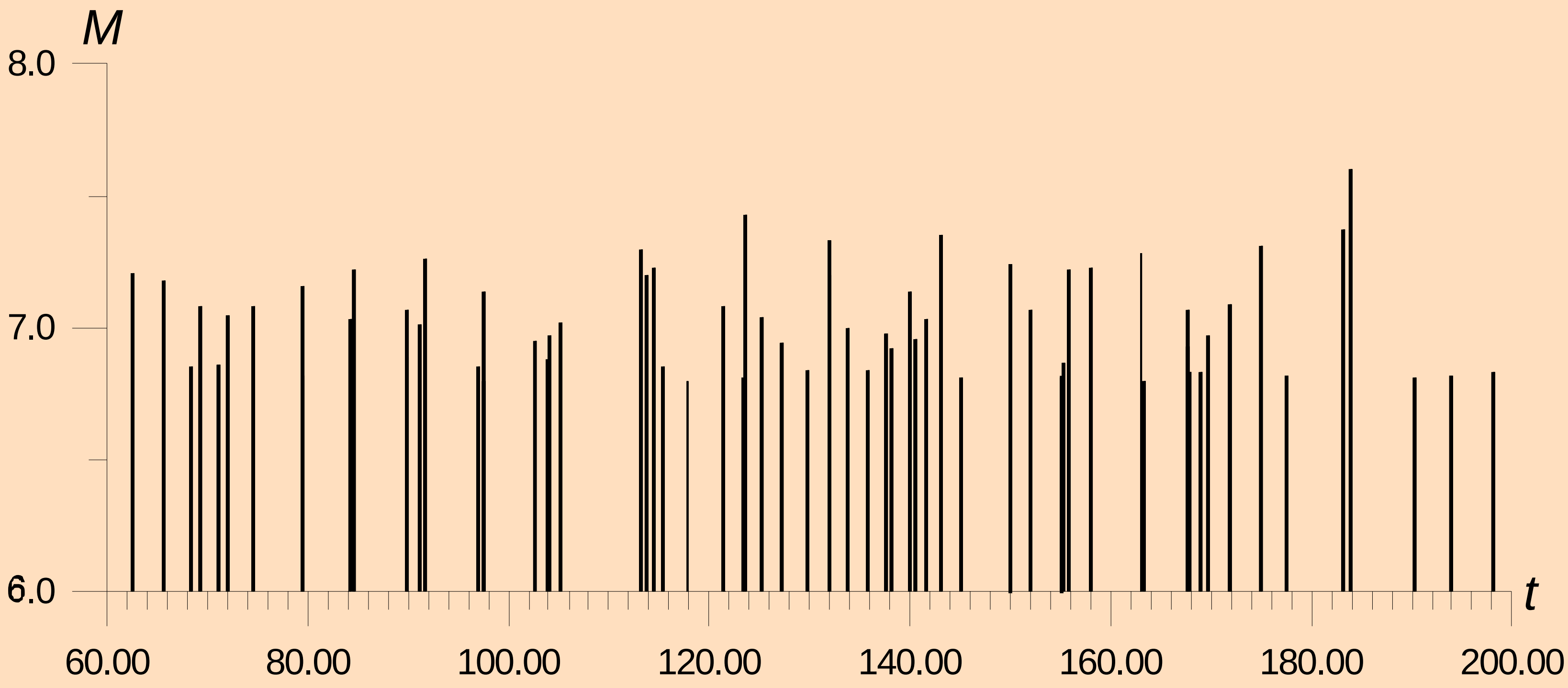
RED ARROWS



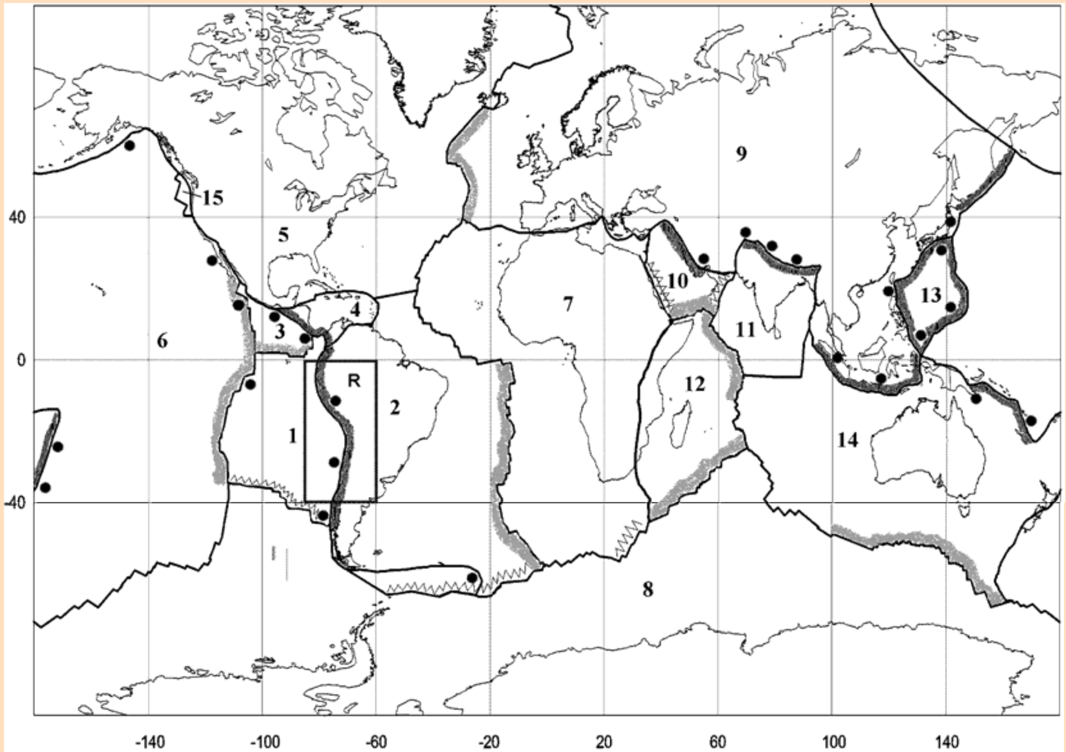
BLUE ARROWS






M
8.0
7.0
6.0
t
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00

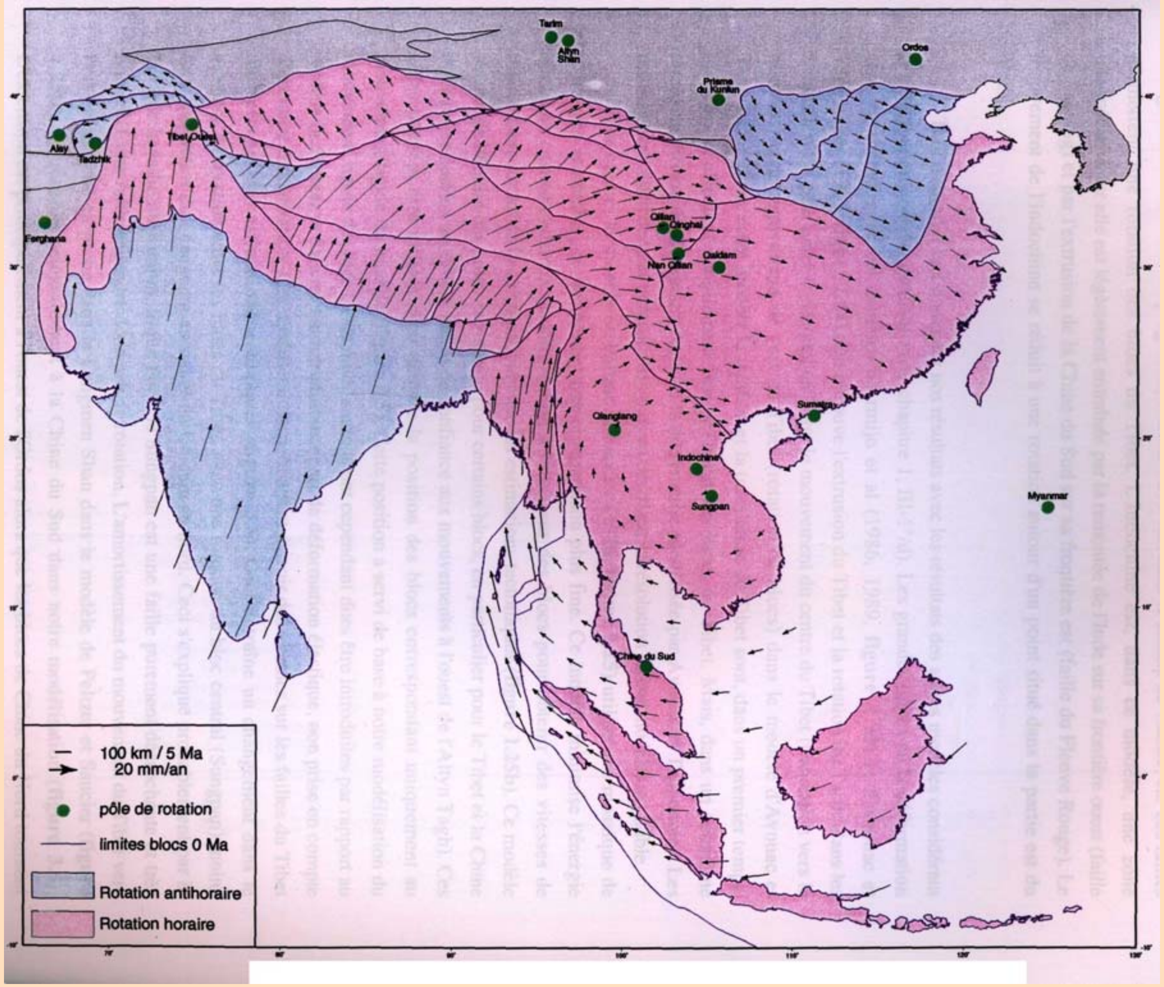
GLOBAL SPHERICAL MODEL OF TECTONIC PLATES



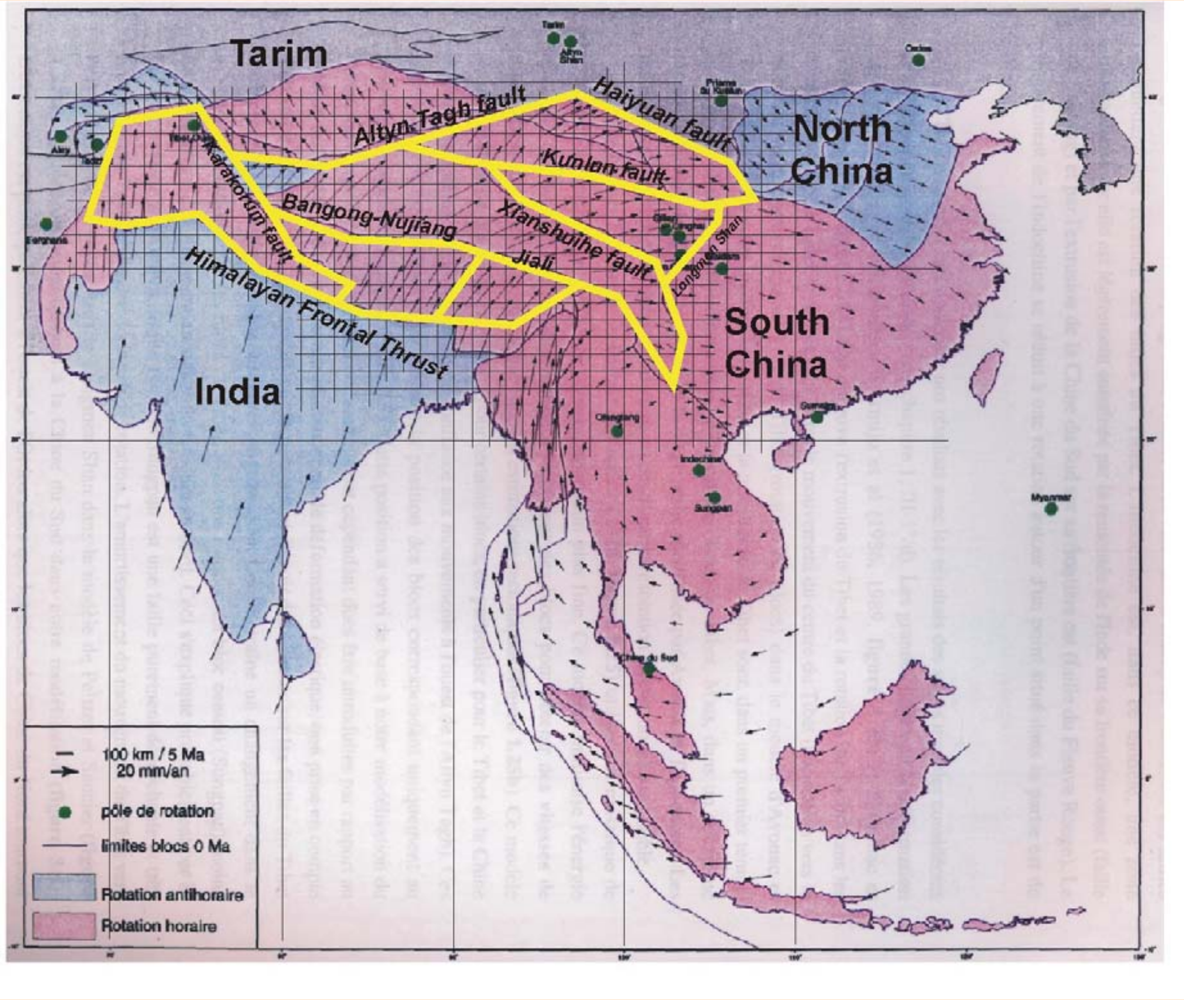
Results of simulation of the character of plate boundaries and spatial distribution of the strongest earthquakes: divergent plate boundaries (spreading, light shading), convergent plate boundaries (subduction, dark shading), transform plate boundaries (sliding, toothed shading), epicenters of model events occurred at boundaries (circles).

OBSERVED MOVEMENTS AND PRINCIPAL FAULTS OF TIBET AND ADJACENT REGIONS

(*A.Replumaz, P.Tapponnier, J. Geopys. Res. 108 (2003)*)



BLOCK STRUCTURE

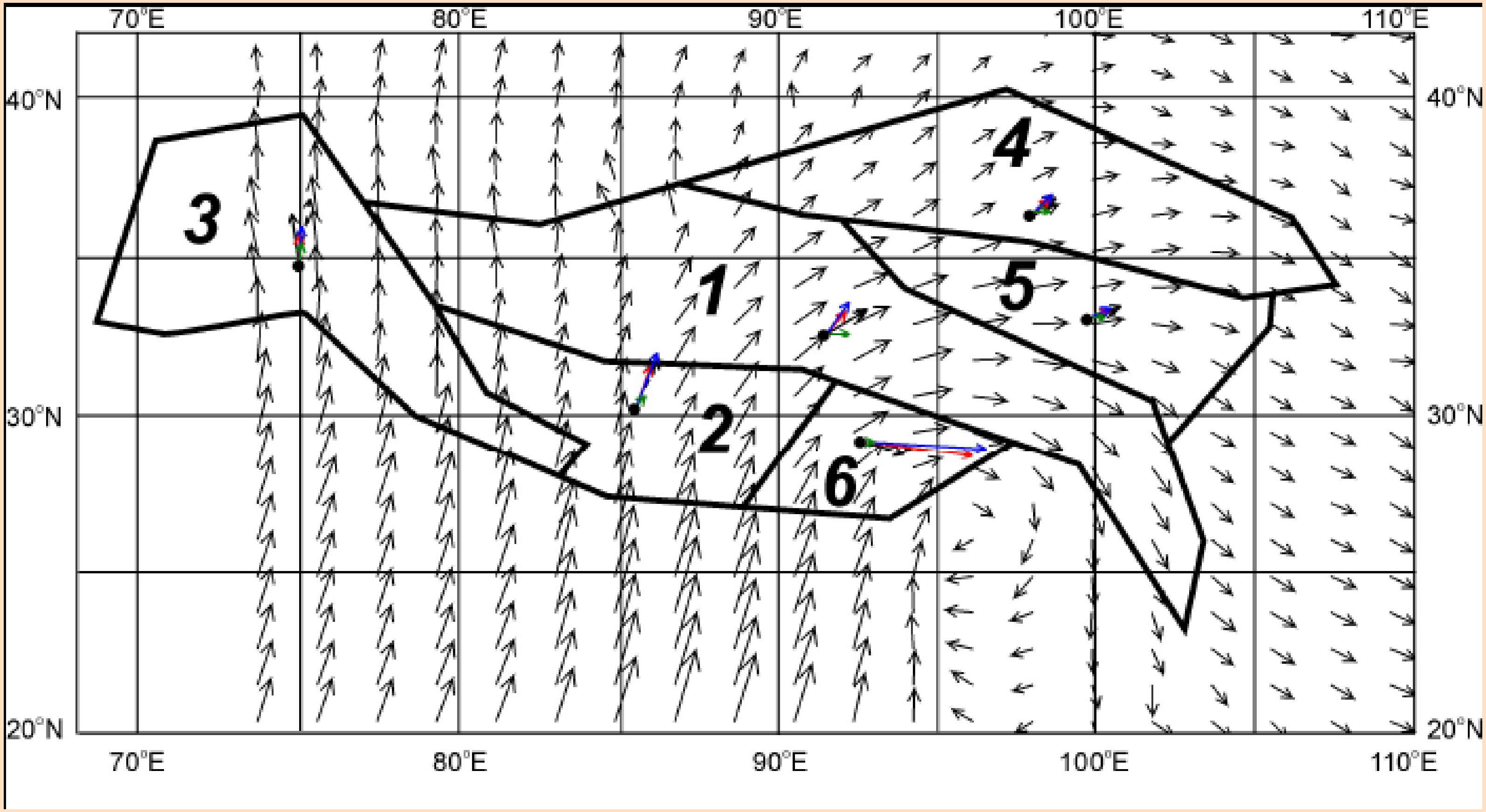


QUESTIONS UNDER CONSIDERATION FOR SIMULATING BLOCK STRUCTURE DYNAMICS

- How upper crustal blocks of the Tibetan plateau react on the Indian plate motion.
- How earthquakes cluster at the regional fault system.
- How rheological properties of the lower crust and fault zones influence the earthquake flow and fault slip rates.

GPS measurements and movements of blocks

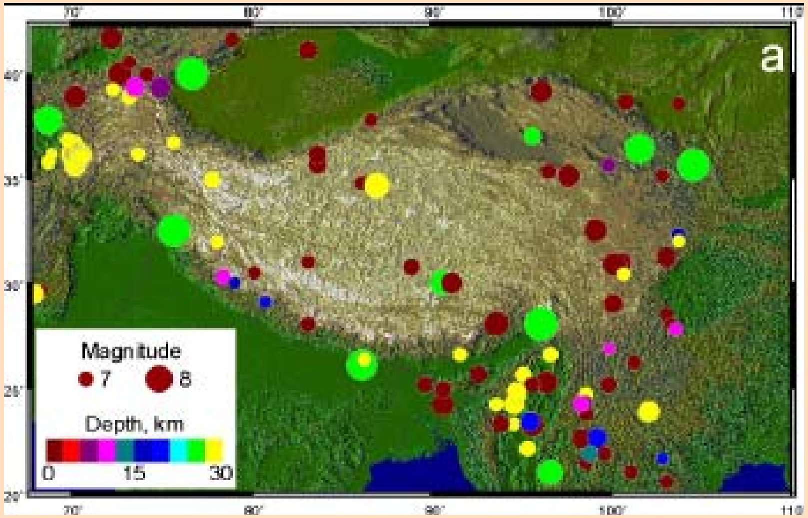
Black arrows present interpolated rates of observed horizontal movement (unpublished compilation of existing data by A. Yin and Z.-K. Shen) . Color arrows present modeled rates of horizontal movements.

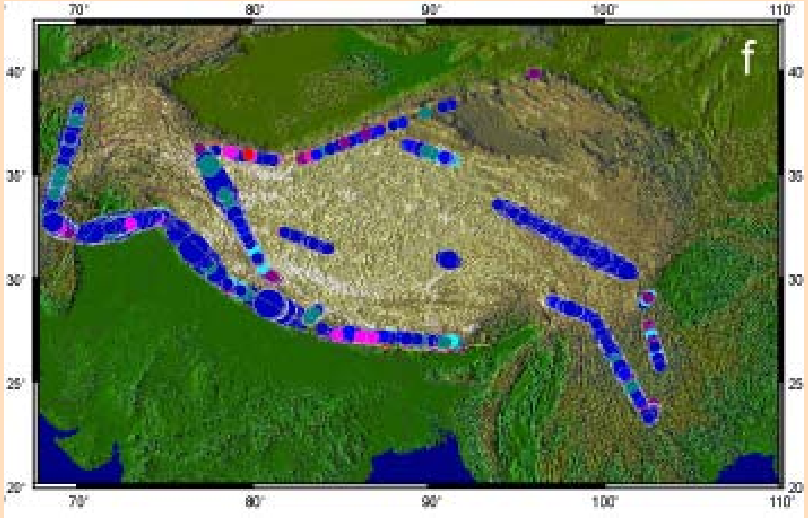


Spatial distribution of large (M>6.5) earthquakes in the Tibet-Himalayan region

(*a*) Observed seismicity since 1900.

(*f*) Synthetic seismicity obtained in one of experiments with the model.





DISCUSSION OF SIMULATION RESULTS

Slip rates

The results of our numerical experiments illustrate that variations in the rheological properties of fault plane zones and/or in the motion of the lower crust influence rates of the crustal block displacements and slips at the faults separating the blocks. This can explain the discrepancies in estimates of slip rates over short and long time scales at major faults in the region.

Earthquake flow

The slope of the FM plots and clustering of large earthquakes are sensitive to the changes in the movements of the lower crust and in the rheological properties of fault plane zones in the Tibetan plateau. Large events localize only on some of the faults, but not on all of the individual faults where the elastic and viscous coefficients were equally changed. This illustrates the fact that the BAFD model *does describe the dynamics of a network of crustal blocks and faults* rather than the dynamics of individual fault planes.

CONCLUSIONS

1. The contemporary crustal dynamics and seismicity pattern in the region are indeed characterized by the north-northeastern motion of India relative to Eurasia and the movement of the lower crust overlain by the upper crustal rigid blocks.
2. Variations in rheological properties of the fault zones and/or of the lower crust as well as in the motion of the lower crust influence the displacement rates of the crustal blocks and hence the slip rates at the faults separating the blocks. This may explain the discrepancies in the estimates of slip rates at major faults in the region based on different techniques.
3. Clustering of earthquakes is a consequence of dynamics of the crustal blocks and the faults in the region. The number and the maximum magnitude of synthetic earthquakes change with variations in the movement of the crustal blocks and in the rheological properties of the lower crust and the fault zones.