Continuous deformation in place of rigid plates for representing the kinematics of the Earth’s surface in geodetic applications

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Current status: Crustal kinematics based on plate tectonics

Plate tectonic models are based on geophysical data over geologic times.

Plate kinematics is derived geophysically from three observation types:
- Sea floor spreading rates (velocities),
- Transform faults azimuths (directions),
- Earthquake slip vectors (directions).

The result are plate rotation vectors on a sphere (Theorem of Euler)

Such a model of rigid plates is NUVEL-1A (DeMets et al. 1994). Station velocities of the ITRF are based on this model defining the kinematic datum.

NUVEL-1A does not include any non-rigid crustal deformation.
Considering more plates and crustal deformation zones

The plate model PB2002 (Bird 2003) includes 13 deformation zones within and between 52 plates, the 10 larger ones identical with NUVEL-1A.

The observation data cover a period of 3 Million years. Valid for today?

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Plate kinematics based on geodetic observations

- **Present day** plate kinematic models are only feasible since space geodetic observations allow **measuring global position changes** (velocities).
- Geodetic Actual Plate Kinematic Models (APKIM) are computed since 1988.

**Velocities used for APKIM 2014**
- only the latest periods in ITRF

**Techniques**
- GNSS 657
- Laser 46
- VLBI 54
- Doris 28

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**Total** 785

*Figure 11.* ITRF2014 horizontal site velocities with formal error less than 0.2 mm/yr. Major plate boundaries are shown according to *Bird* [2003].
Summary of the processing procedure

• ITRF includes point coordinates and velocities of consecutive periods (solutions). A new period starts at any discontinuity.

• Only the latest periods are taken for the estimation of the plate rotation vectors ($\Omega(\Phi,\Lambda,\omega)$).

• A two-dimensional adjustment is done (by spherical geometry) to avoid the effect of less precise vertical velocities.

• Iterative adjustments were done eliminating “non-fitting” ITRF velocities after the 3-sigma-criterion.
Available & eliminated velocities (outliers / deformations)

ITRF2014 latest period: 785 velocity vectors; used: 636; eliminated: 149;
Reasons: ITRF estimation uncertainties or intra-plate deformations

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Most velocities are given in the southern part that dominates the estimation. Northern velocities do obviously not correspond to the same rigid plate!
Deformable (non rigid) plates

Caribbean plate deformation (from the SIRGAS velocity model VEMOS2017)

The Caribbean plate is obviously not a rigid plate!
Deformable (non rigid) plates

South American plate deformation (from VEMOS2017)

The South American plate is not a rigid plate. There is deformation greater than the precision of the estimated velocities (< 1 mm/a), in particular in the south-eastern area (Patagonia).
Deformable (non rigid) plates

Eurasian plate deformation (from all the APKIM velocities since 2005)

The Eurasian plate is obviously not a rigid plate!
## Comparison of estimated plate rotation poles (Φ, Λ, ω)

*red* numbers are different to APKIM2014 after the 3-sigma-criterion

<table>
<thead>
<tr>
<th>Plate</th>
<th>APKIM2014</th>
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<th>NNR NUVEL-1A</th>
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<td>Φ [°]</td>
<td>Λ [°]</td>
<td>Ω [°/Ma]</td>
<td>Φ [°]</td>
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Alternative to plate models: continuous deformation model

An alternative to rigid plate kinematics for modeling global deformation is a continuous deformation model. We use a least squares collocation approach.

2D-vector prediction:

$$\mathbf{v}_{\text{pred}} = \mathbf{C}_{\text{new}}^T \mathbf{C}_{\text{obs}}^{-1} \mathbf{v}_{\text{obs}}$$

$$\mathbf{v}_{\text{pred}} = \text{predicted velocities} \ (v_N, v_E) \ \text{in a 1°} \times \ 1° \ \text{grid}$$

$$\mathbf{C}_{\text{obs}} = \text{correlation matrix between observed vectors} \ (C_{NN}, C_{EE}, C_{NE})$$

$$\mathbf{C}_{\text{new}} = \text{correlation matrix between predicted & observed vectors}$$

$$\mathbf{v}_{\text{obs}} = \text{observed velocities} \ (v_N, v_E) \ \text{in geodetic stations}$$

$$\mathbf{C} \text{ matrices are built from empirical isotropic, stationary covariance functions } c = E(x_i \cdot x_j).$$
The collocation approach includes station velocities up to 500 km from the grid point to be predicted. If a sufficient number of station velocities (> 3) is not available, the used plate model (APKIM2014) is considered.
Example of continuous deformation zones

The Persia-Tibet-Burma orogen (Bird 2003) between Eurasia and India plates
Example of extreme deformation zones

East Asia is a complicated tectonic area (extremely difficult for prediction)

Plates (e.g. PA) and orogens (deformation zone names) are according to Bird (2003)
Conclusions

• Plate tectonics is a good model for geology, in particular paleo geology.

• It can very well be used in geophysics for many modelling purposes.

• It may be used in geodesy as a basis for preliminary studies and models, but not for representing the global crustal deformation, which is needed in time-dependent global and continental reference frames (e.g. ITRF, AFREF, APREF, EUREF, NAREF, SIRGAS).

Thank you very much for your attention!