CONTINENTAL PLATE BOUNDARY ZONES

Plate boundaries initially viewed as narrow

Now recognize that many plate boundaries - especially continental - are deformation zones up to 1000 km wide, with motion spread beyond nominal boundary.

Continental crust is much thicker, less dense, and has different mechanical properties than oceanic crust. Thus plate boundaries in continental lithosphere are generally broader and more complicated than in oceanic lithosphere.
Studies of continental plate boundary zones provide important insights into fundamental geological processes controlling evolution of continents.

Study phases of the Wilson cycle in different places:

- Continental rifting
- Young ocean
- Ocean-continent convergence
- Closing ocean
- Continental collision

East African Rift
Gulf of Aden, Gulf of California
Andes
Southern Europe
Himalaya Zagros

Stein & Wysession, 2003
CHALLENGE: NUBIA - SOMALIA: EAST AFRICAN RIFT OPENING

Boundary geometry & motions unclear

Extension began 15-35 Ma and may be accelerating

Surprising given slowing of nearby plates

Geologic models infer opening from differences in Nubia-Arabia (Red Sea) & Somalia-Arabia (Gulf of Aden) or Nubia-Antarctica & Somalia-Antarctica (SW Indian Ridge) motion

Somalia GPS data from only 4 sites, one on volcano, one in rift zone

Not yet clear if models agree or disagree
East African rift is spreading center between the Nubian (West Africa) and Somalian (East Africa) plates.

Extension is so slow, \(< 10\) mm/yr, that it is hard to resolve in plate motion models, so two plates are often treated as one.

Topography, active faulting, and seismicity show a boundary zone broader, more diffuse, and more complex than at mid-ocean ridges.

For example, seismicity ends in southern Africa with no clear connection the Southwest Indian ridge, where the boundary must go...
Some of the complexity of continental extensional zones results from the fact that, unlike mid-ocean ridges, lithosphere starts off with reasonable thickness and then is stretched and thinned.

Rifting can progress far enough that new oceanic spreading center forms, as in Gulf of Aden and Red Sea, which are newly formed (and hence narrow) oceans separating Arabia from Somalia and Nubia.

Whether EAR will evolve this far is unclear: geologic record shows rifts that, though active for some time, failed to develop into oceanic spreading centers and died. Fossil rifts can be loci for intraplate earthquakes.
Figure 5.6-4: Cartoon for a diffuse transform plate boundary zone.

Stein, 1993
WESTERN NORTH AMERICA PLATE BOUNDARY ZONE - DEFORMATION INWARD OF NOMINAL BOUNDARY

Stein & Wysession, 2003

Hebgen Lake, Montana  1959 Ms 7.5

Owens Valley, California  1872 Mw ~7.5
Find Euler vector using GPS, earthquake slip vector, magnetic, geologic data

Motion described by Euler vector predictions (small circles about pole, rate increases as $\sin \Delta$)

Assess rigidity via fit of data to Euler vector predictions

Little (< 1 mm/yr rms) internal deformation

Deformation where fit to Euler vector prediction fails

Add Euler vectors for other plate motions

Stein & Sella, 2002
PACIFIC-NORTH AMERICA PLATE BOUNDARY ZONE: PLATE MOTION & ELASTIC STRAIN

~ 50 mm/yr plate motion spread over ~ 1000 km

~ 35 mm/yr elastic strain accumulation from locked San Andreas in region ~ 100 km wide

Locked strain will be released in earthquakes

Since last earthquake in 1857 ~ 5 m slip accumulated

Horizontal velocities of VLBI sites relative to the North American plate

Elastic strain

Broad PBZ

Stein & Wysession, 2003
GPS site velocities relative to North America

San Andreas Fault system

Stable Sierra Nevada block

Central Nevada seismic belt

Eastern California shear zone

Intermountain seismic belt

Great Basin

Colorado Plateau

PACIFIC - NORTH AMERICA PLATE BOUNDARY ZONE

NUVEL 1A

100 km

124°W  1  10mm/yr  110°W

Bennett et al., 1999
Complex interaction of subduction of Juan de Fuca plate and Pacific-North America strike slip

Paleomagnetic, geologic, and earthquake data suggested rigid Oregon and Sierra Nevada microplates

GPS data show this and resolve motion

Basin & Range may be rigid or diffuse extension zone - GPS data interpretations differ

Wells and Simpson, 2001
Removing elastic strain accumulation shows Oregon microplate rotation.

Velocity field from campaign and continuous GPS sites.

Reference frame is North America and ellipses are $1\sigma$.

Data dominated by elastic strain on locked subduction zone.

Use geodetic, earthquake, and geologic data to estimate simultaneously block angular velocities, coupling on block-bounding faults, and GPS reference frame.

Removing estimated elastic strain shows microplate rotation.

McCaffrey et al., 2003
CONTINENTAL CONVERGENCE ZONES
Of the three boundary types, continental convergence zones may be the most complicated compared to their oceanic counterparts.

One primary difference is that, because continental crust is much less dense than the upper mantle, it is not subducted and a Wadati-Benioff zone is not formed. As a result, continental convergence zones in general do not have intermediate and deep focus earthquakes.

However, the plate boundary tectonics occur over a broader and more complex region than in an oceanic case.

Ni and Barazangi, 1984
Large destructive thrust earthquakes reflect convergence on Himalayan frontal faults such as Main Central Thrust.

Normal faulting earthquakes occur behind convergent zone in the Tibetan Plateau, due to along strike extension from gravitational collapse.

Strike slip earthquakes occur further north.

Ni and Barazangi, 1984
Mountain building by continental collision produced boundary zone extending 1000's of km northward from the nominal plate boundary at the Himalayan front.

Total plate convergence taken up several ways. About half occurs across locked Himalayan frontal faults such as the Main Central Thrust.

These faults are part of the interface associated with the underthrusting Indian continental crust, which thickens crust under high Himalayas.

Larson et al., 1999
GPS data also show along-strike motion behind the convergent zone, in the Tibetan Plateau, presumably because the uplifted and thickened crust spreads under its own weight.

Extension is part of a large-scale process of crustal “escape” or “extrusion” in which large fragments of continental crust are displaced eastward by the collision along major strike-slip faults.

Larson et al., 1999
Collision process is thought to involve a complex interplay between forces due directly to the collision, gravitational forces due to the resulting uplift and crustal thickening, and forces from the resulting mantle flow.

Crustal "escape" or "extrusion" in which large fragments of continental crust displaced eastward by the collision along major strike-slip faults has been modeled assuming that India acts as a rigid block indenting a semi-infinite plastic medium (Asia), giving rise to a complicated faulting and slip pattern.

Also modelled numerically as thin viscous sheet flow.

Figure 5.6-7: Plasticine model for the deformation of Asia as a result of the collision with India.

Tapponnier et al., 1982
COMPARISON OF GEODE蒂IC AND SEISMOLOGICAL EVIDENCE FOR CRUSTAL SHORTENING IN THE TIEN SHAN

GPS data indicate that this intracontinental mountain belt, 1000-2000 km north of the Himalaya, accommodates about half the net convergence between India and Eurasia.

This shortening rate is approximately twice that inferred from seismic moments.

Focal mechanisms reflect local strike of structures, despite coherent shortening direction shown by GPS data.

Abdrakhmatov et al., 1996
Complicated situation involving African, Arabian, and Eurasian plates.

Northern portions of Arabia move approximately N40°W consistent with global plate motion models.

Eastern Turkey driven northward into Eurasia, causing compression & thrust fault earthquakes in Caucasus mountains.

McClusky et al., 2000  GPS site velocities relative to Eurasia
Anatolia (At) rotates as a rigid microplate about a pole near Sinai.

Motion across the North Anatolian fault, ~25 mm/yr, gives right-lateral strike-slip earthquakes like the 1999 M 7.4 Izmit event, about 100 km east of Istanbul that caused more than 30,000 deaths.

McClusky et al., 2000  GPS site velocities relative to Eurasia
W. Anatolia & Aegean interpreted as diffuse extension, shown by steadily increasing rates

Region may be "pulled" toward Hellenic arc, perhaps by an extensional process similar to oceanic back arc spreading

McClusky et al., 2000 GPS site velocities relative to Eurasia
Figure 5.6-8b: Focal mechanisms for a portion of the Africa-Arabia-Eurasia plate collision zone.
Figure 5.6-8c: Tectonic interpretation for a portion of the Africa-Arabia-Eurasia plate collision zone.
Anatolia (At) rotates as a rigid microplate, about pole near Sinai.

Aegean interpreted as diffuse extension, shown by steadily increasing rates.

McClusky et al., 2000

GPS site velocities relative to Eurasia.
Aegean also interpreted as microplate

Two other microplates proposed

Nyst & Thatcher, 2004 Velocities relative to Eurasia
ANDES:
NAZCA - SOUTH AMERICA
PBZ

ALTIPLANO
FTB
Integrate GPS, earthquake, plate motion & geologic data

Elastic strain from trench - primary boundary segment - & permanent deformation away from it

Altiplano acts as rigid block between forearc & thrust belt

Norabuena et al., 1998

GPS site vectors relative to stable South America
USING GPS VELOCITY PROFILE TO ESTIMATE LOCKING RATE AT TRENCH AND SHORTENING RATE IN FORELAND THRUST BELT

Norabuena et al., 1998
DEFORMATION IN PLATE BOUNDARY ZONE

Why is GPS velocity across orogen much higher than long-term crustal shortening?

\[ \text{V_{instanteous}} = \text{V_{elastic}} + \text{V_{permanent}} \]

\((\text{GPS})\) (earthquakes) (topography/shortening)

Chaco region, Foreland thrust belt
Predicted elevation (color background) and velocity field at the surface (arrows) for the two shortening models.

Lower crust assumed weak

In model A material flows from north & south, where strain rates are higher, to center

In model B material from center flows south first due to earlier shortening, reversed in past 10 Ma

Yang et al., 2003
REGIONAL TECTONICS OF THE MEDITERRANEAN

Nubia-Eurasia convergence causes complex geometry, many possible blocks/microplates, boundaries & motion directions often unclear

Major challenge to sort out

Oldow et al., 2002
CHALLENGE: ADRIATIC BOUNDARIES & MOTIONS

Is Adria a microplate?

What other blocks exist?

How do their motions relate to Nubia-Eurasia motion?

GPS, earthquake & geological data being integrated

Calais et al., 2003

Anderson & Jackson, 1987

Oldow et al., 2002
Geodetic and seismic data

Jenny, Hollenstein, et al., 2004
ADRIA MICROPLATE: NOW MOVES NORTHEAST WRT EURASIA

Focal mechanisms and GPS find Adria bounded by convergent boundaries in the Dinarides and the Venetian Alps, extensional boundary in the Apennines and moving northeast away from western Italy (Eurasia).
Adria subducted southwestward beneath Italy.

Apennines part of thrust belt extending south to Sicily.

Arc evolved in association with opening of Tyrrhenian sea since ~5 Ma, interpreted as back arc spreading associated with rollback of Adria slab.

As subduction migrated eastward, western Italy microplate rotated counterclockwise with respect to Eurasia.

After Rosenbaum & Lister, 2004
Subduction and back arc spreading ceased within past 2 Ma, making Italy west of the Apennines part of Eurasia.

Slab may be detaching (Wortel & Spakman, 2000)

Adria - Eurasia motion then caused shift from convergence to extension in the Apennines.

Stein & Sella (2004); modified from Malinverno and Ryan (1986)
SUMMARY

Continental boundary zone occurs where motion extends beyond elastic deformation associated with earthquake cycle at nominal plate boundary.

These zones may include discrete microplates and perhaps diffuse deformation zones.

Integrating plate motion, GPS, earthquake & geologic data can resolve geometry and rates of motion.

Differences between space geodesy & geologic plate motion models are increasingly able to resolve changes in plate motions.

Inferred changes often appear to be part of long-term trends.

Can be associated with changes in plate boundary geometry: mountain building (Andes, Zagros (?)), rifting (East Africa), slab breakoff (Adria), etc.

Better distribution of space geodetic sites and longer time series will improve ability to identify & confirm such changes.
Testing for significance of additional rigid plates
χ² TEST

Do data show a rigid microplate?

How well do the predictions of the Euler vector fit them?

Would a diffuse model be better?

Which data are poorly fit?

Use the misfit function that was minimized to find the Euler vector

\[ \chi^2 = \sum_i \frac{(d_i - d_i^m)^2}{\sigma_i^2}, \]

where \( d_i^m \) are the data predicted by the model, \( d_i \) are those observed, and \( \sigma_i \) are their uncertainties. Lower values of \( \chi^2 \) correspond to better fits.

Examine the reduced chi square

\[ \chi_v^2 = \frac{\chi^2}{\nu} \]

where \( \nu \), the number of degrees of freedom, equals \( n - p \), where \( n \) is the number of data and \( p \) is the number of model parameters estimated in the inversion.

If the model is a good fit to the data and estimates of the uncertainties are reasonable, then \( \chi_v^2 \) should be around one. However, if \( \chi_v^2 \) is much larger than one, something is likely wrong.

For example, the model may not include an important plate boundary, or the deformation is too diffuse to be well described by a rigid plate.
**F TEST**

Is the microplate necessary?

Do the data require it?

Is the model too complicated?

Separate North & South America, Nubia & Somalia, India & Australia pass test

In these cases, plate geometry inferred from other data

Modify test (more free parameters) if microplate inferred only from plate motion data

Because more plates can describe motions in an area better because the model has more parameters, test whether the improved fit (reduction in \( \chi^2 \)) is more than expected purely by chance due to the additional parameters.

An *F-ratio* test shows whether the fit to \( n \) GPS data of a model with \( p + 1 \) plates is significantly better than that of one with \( p \) plates. The \( p \) plate model has \( 3p \) parameters \( (n - 3p \) degrees of freedom) whereas the \( p + 1 \) plate model has \( 3p + 3 \) parameters \( (n - 3p - 3 \) degrees of freedom). We form

\[
F = \frac{[\chi^2(p \text{ plates}) - \chi^2(p + 1 \text{ plates})]}{\chi^2(p + 1 \text{ plates}) / (n - 3p - 3)}
\]

and examine the probability of observing an \( F \) value greater than for a random sample.

For example, if \( P_F \) is 0.01, there is only a 1% chance that the improved fit of the model is due purely to chance, so the additional plate seems distinct. Conversely, if the improved fit is likely simply from the additional parameters, the data do not strongly indicate an additional plate. However, the plate may be there - *just not resolvable with these data.*
IS RIVERA DISTINCT FROM NORTH AMERICA & COCOS PLATES?

Rates & directions from transform and earthquake slip vector azimuths along presumed Pacific-Rivera boundary misfit by Pacific-North America and Pacific-Cocos motion

Improved fit from a distinct Rivera plate passes F test, so plate can be resolved

DeMets & Stein, 1990