NEogene Block TECTonics of Eastern Turkey
AND NORTHERN South America: CONTINental
APPLICATIONS OF THE FINITE DIFFERENCE
METHOD

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Abstract. Continental plate boundary
zones are, generally, wide diffuse zones
of deformation within which, in the upper
5 to 15 km, may be recognized blocks,
which are bounded by fault zones within
which strain is highly concentrated and
along which slip rates are fairly high (2-30 m Ma⁻¹). These blocks may be
irregular flakes, defined by older
crustal inhomogeneities of an upper
brittle crust below which strain occurs
in a ductile and more homogeneous lower
crust. With examples from the convergent
plate boundary zone of eastern Turkey and
the southern Caribbean plate boundary
zone of northern South America, we use
plate slip rates and trends and slip
rates of faults to construct block vector
diagrams to deduce the sums of relative
motion among block mosaics, slip rates
and trends of ill defined block
boundaries, and the extent to which
blocks are internally strained.

INTRODUCTION

Continental plate boundaries are wide
diffuse zones where relative plate dis-
placements are converted into complicated
and variable strain and smaller block-

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Bounding displacements, in contrast to
oceanic plate boundaries, which are gen-
erally narrow, relatively simple zones in
which only a small portion of relative
plate motion is converted into strain and
smaller displacements [McKenzie, 1972].
This contrast is probably due to the
relative weakness and buoyancy of quartz
and strength and negative buoyancy of
olivine in principal mineral phases in
the continents and oceans respectively
and to the great inhomogeneity and
anisotropy of the continental crust
riddled with zones of low strength
generated and modified by many varied
mechanisms contrasted with the relative
homogeneity of the oceanic lithosphere
generated by plate accretion with
fracture zone modifications [Dewey,
1982].

A critical question is, to what extent
is strain continuous or discontinuous in
space and time in continental plate
boundary zones and, where blocks bounded
by faults can be observed, to what extent
do the principles of plate tectonics
operate between such blocks, that is to
what extent are they internally rigid
with strain confined to narrow slip zones
at their boundaries. In theory, a great
range of possibilities exist and, in
zones of crustal thickening, have been
suggested from the low strength viscous
continuum model of England and McKenzie
[1982] to the discontinuum slip-line
field theory application of Molnar and
Tappone, 1975 and semicontinuous model of Dewey and Sengor, 1979. The kinematic theory of complex continental plate boundary zones has been addressed by McKenzie and Jackson, 1983. Evidence from field structural geology suggests that, with increasing metamorphic grade (depth), deformation becomes increasingly homogeneous on a smaller and smaller scale so that, at high structural levels, strain is well-scaled and concentrated in slip zones, while at deeper levels strain is increasingly penetrative. This is consistent with experimental data on quartz, seismic observations of hypocenters and stress and slip of an upper crustal brittle and semibrittle layer of high strength (Meissner and Boundary, 1979). In some zones below which strain is ductile, more penetrative and more homogeneous. Paleomagnetic data shows that rotations of areas up to about 30 km across occur without substantial internal distortion (Luyendyk et al., 1980). At the edge of rotated blocks, complex strains and displacements result from compatibility kinematics with substantial basins and thrust zones occurring on restricted geographic scale at block boundaries and triple junctions. It is likely that such blocks are the surface expression of thin upper crustal slabs above intracrustal decollements rather than small platelets sensu stricto because, if they were the latter, they would be mechanically difficult and unlikely narrow lithospheric spindles. However, whether the blocks are slabs or platelets, surface displacement and strain within the whole plate boundary zone should integrate to equal the plate slip vector. The continuum/discontinuum problem is of fundamental importance to the basic question of the vexing and difficult question of the relationship between plate tectonics and classical structural geology, that is, the extent to which and under what conditions relative plate slip vectors are directly expressed in structural geometry and fabric and, critically, how can plate slip vectors be deduced from integrated structural studies. In this paper, we show, using examples from eastern Turkey and the Caribbean boundary of northern South America, how block vector diagrams may be used to sum relative motions and make semi-quantitative statements about the extent to which blocks are internally strained during relative displacement, how inference may be drawn about slip rates on faults, and make paleotectonic and paleogeographic deductions.

EASTERN TURKEY

Eastern Anatolia consists of a 2 km high plateau bounded to the south by the southward-verging Bitlis Thrust Zone and to the north by the Pontide/Minor Caucasus Zone. It has developed as the surface expression of a zone of progressively thickening crust beginning about 14 Ma B.P. in the medial Miocene and has resulted from the squeezing and shortening of eastern Anatolia between the Arabian and European Plates following the Serravallian/Alpine collision and opening of the oceanic or quasi-oceanic tract between Arabia and Eurasia. Thickening of the crust to about 52 km has been accompanied by major strike-slip faulting on the right-lateral North Anatolian Fault (NAT) (Sengor, 1979) and the left-lateral East Anatolian Fault (EAT) (McKenzie, 1976) which approximately bound an Anatolian wedge that is being driven westward to override the oceanic lithosphere of the Mediterranean along subduction zones from Cephalonia to Crete, and Rhodes to Cyprus. Earthquake hypocenters are scattered throughout the region but earthquakes are concentrated mainly on the major faults and are mostly shallow (Jackson and McKenzie, 1984) supporting the idea of a brittle elastic lid with hypocenters concentrated toward its base with more ductile deformation in the middle and lower crust. Volcanic rocks are silicic/intermediate, calc-alkaline, high-potash suites of crustal origin and nepheline-hypersthene normative alkali basalts of mantle origin, both suites occurring in pull-apart basins in strike-slip regimes and along north-south extensional fissures.

We now address the questions of the relationship between shortening, crustal thickening, and strike-slip faults, and the scale at which deformation in eastern Anatolia is homogeneous/inhomogeneous. Continuous reference should be made to Figure 1 which summarizes the main tectonic features of eastern Anatolia, and Figure 2 which is a vector diagram that relates relative plate displacements, fault slip and strain in eastern Anatolia. The average convergence slip rate between the Arabian and European
Plates for the last 14 Ma has been 15.3 m Ma⁻¹, giving an average strain rate of about 2.0 x 10⁻¹⁵ s⁻¹ in the east Anatolian convergent zones, the slip rate deduced by adding the Dead Sea Transform slip rate (AF/AR, 5.3) to the Europe/Africa slip rate (EU/AP, 10). This Europe/Arabia rate may be too high for Anatolia because the average slip rate on the Dead Sea Transform north of the Antilebanon has been 4 m Ma⁻¹. This suggests motion between the Arabian Plate and a smaller Syrian Plate across the Antilebanon/Palmyran Zone, a zone of present day seismic activity and shortening (A. Quennell, verbal communication, 1984). If this is so, a Europe/Syrian (EU/SY) convergence rate of 14 m Ma⁻¹ is appropriate which, in turn, slightly reduces the average east Anatolian strain rate.

The Anatolian Block is bounded by the NAT and EAT and is being driven westward from the Europe/Syria collisional zone [McKenzie, 1972]. In Figure 2, a Europe/Syria/Anatolia (ANX) vector triangle is constructed from the length and trend of the Europe/Syria slip and the trends of the NAT and EAT. This construction indicates that, were the Europe/Syria convergence taken up solely by a horizontal plane strain by lateral wedging of a rigid Anatolian Block, the slip rates on the NAT and EAT would be 18.5 m Ma⁻¹ and 19.3 m Ma⁻¹ respectively. Average slip rates on the NAT and EAT over the last 9 Ma are well constrained. An 80 km offset of a Miocene suture along the NAT [Sengor, 1979] gives a slip rate of 8.9 m Ma⁻¹ and 15 km offsets of the antecedent Euphrates River and a crystalline block just southwest of Karliova give a slip rate of 1.7 m Ma⁻¹ along the EAT. Thus only a small part of the Europe/Syria convergent displacement is taken up by slip on the NAT and EAT. Slip on the NAT and EAT may be combined to give the slip direction and rate on the Varto Fault, a steeply northeast dipping thrust immediately east of the

Fig. 1. Summary map of the main tectonic features of eastern Anatolia and contiguous regions. First motion diagrams (solid, compressional quadrants; open, dilational quadrants) from J.F. Dewey, [1976] (Varto) and Cañizares and Ucer [1967] (Adana and Lice). Heavy line on first motions diagrams indicates azimuth of slip vector on suggested fault plane, dots, Adana Basin.
Earthquake
Europe/Syria
thrusting
of
azimuth
NAT,
southward-verging
fault-plane
Anatolian
possible
Anatolian
Zone,
taken
Karliova
taken
Varto
74
the
muths
and
joined
reasonably
SY,
faults
labelled
the
Varto
European
Syrian
slip
of
Figure
plane
plate
1.
slip
up
convergence
of
Karliova
and
up
convergence
given
NAT/EAT
Europe/Syria
AF,
Syrian
slip
Dewey,
ANX,
African
Plate;
AF,
Asian
plate
10.5
m
Ma
-1
representing
an
unknown
combination
of
slip
on
the
AF/AN
boundary
and
strain
within
the
Anatolian
Block.
If
no
internal
Anatolian
strain
is
occurring,
the
AF/AN
join
gives
the
AF/AN
slip
direction.
That
internal
Anatolian
Block
strain
has
occurred
both
east
and
west
of
line
AB
is
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by
the
2
km
high
plateau
which
indicates
a
crust
thickened
to
about
52
km,
assuming
approximate
isostatic
balance.
Thus,
in
addition
to
convergence
accommodated
by
strike-slip
motion,
which
can
allow
only
a
horizontal
plane
strain,
the
crustal
thickening
indicates
a
substantial
component
of
about
80%
vertical
stretching.
Now
this
vertical
component
is
structurally
accommodated
is
clear,
or
is
its
precise
temporal
relationship
with
strike-slip
faulting.
A
similar
tectonic
situation
exists
in
Tibet
where
a
5
km
high
plateau
caps
an
80
km
crust
thickened
by
vertical
stretching
[England
and
McKenzie,
1982].
The
major
strike-slip
fault
that
bounds
the
Tibetan
Plateau,
whether
or
not
related
to
strike-slip
fault
field
theory,
cannot
have
been
responsible
for
Tibetan
crustal
thickening
by
vertical
stretching
of
some
150%.
The
wedging
may
reflect
simply
a
late-stage
lateral
spread
of
a
crustal
buffered
at
80
km
by
stresses
generated
by
crustal
thickening
[England
and
McKenzie,
1982].
The
north-south
extensional
structures
of
Tibet
[Molnar
and
Tapponnier,
1975]
may
also
be
related
to
lateral
spreading.
The
positions
and
orientations
of
strike-slip
faults
in
the
brittle
upper
crust
of
both
Tibet
and
Anatolia
appear
to
be
controlled
principally
by
lines
of
older
structures.
The
Adana
Basin
(Figure
1)
is,
at
lateral
faults
all
of
which
may
be
flake
bounding
structures
at
a
variety
of
scales.
Thus,
east
of
a
drain
(Figure
1,
AB)
drawn
through
Maras,
about
a
third
of
the
convergence
between
Syria
and
Europe
is
taken
up
by
wedging
and
westward
slip
of
the
Anatolian
Block
while
the
rest
is
accommodated
by
thrusting
in
the
Bitlis
Zone
and
folding
and
thrusting
on
other
zones
of
shortening,
displacement
on
mainly
right-lateral
strike-slip
faults
and
internal
strain
within
the
Anatolian
Block.

West
of
line
AB
(Figure
1),
convergent
plate
motion
across
the
Anatolian
Block
is
constrained
by
the
Europe/Africa
motion
of
10
m
Ma
-1;
the
AF/AN
join
of
10.5
m
Ma
-1
represents
an
unknown
combination
of
slip
on
the
AF/AN
boundary
and
strain
within
the
Anatolian
Block.
If
no
internal
Anatolian
strain
is
occurring,
the
AF/AN
join
gives
the
AF/AN
slip
direction.
That
internal
Anatolian
Block
strain
has
occurred
both
east
and
west
of
line
AB
is
shown
by
the
2
km
high
plateau
which
indicates
a
crust
thickened
to
about
52
km,
assuming
approximate
isostatic
balance.
Thus,
in
addition
to
convergence
accommodated
by
strike-slip
motion,
which
can
allow
only
a
horizontal
plane
strain,
the
crustal
thickening
indicates
a
substantial
component
of
about
80%
vertical
stretching.
Now
this
vertical
component
is
structurally
accommodated
is
clear,
or
is
its
precise
temporal
relationship
with
strike-slip
faulting.
A
similar
tectonic
situation
exists
in
Tibet
where
a
5
km
high
plateau
caps
an
80
km
crust
thickened
by
vertical
stretching
[England
and
McKenzie,
1982].
The
major
strike-slip
fault
that
bounds
the
Tibetan
Plateau,
whether
or
not
related
to
strike-slip
fault
field
theory,
cannot
have
been
responsible
for
Tibetan
crustal
thickening
by
vertical
stretching
of
some
150%.
The
wedging
may
reflect
simply
a
late-stage
lateral
spread
of
a
crustal
buffered
at
80
km
by
stresses
generated
by
crustal
thickening
[England
and
McKenzie,
1982].
The
north-south
extensional
structures
of
Tibet
[Molnar
and
Tapponnier,
1975]
may
also
be
related
to
lateral
spreading.
The
positions
and
orientations
of
strike-slip
faults
in
the
brittle
upper
crust
of
both
Tibet
and
Anatolia
appear
to
be
controlled
principally
by
lines
of
older
structures.
The
Adana
Basin
(Figure
1)
is,
at

Karliova
NAT/EAT
junction;
the
coincidence
with
the
slip
direction
derived
from
the
fault
plane
solution
for
the
Varto
earthquake
[Dewey,1976]
is
reasonably
close.
The
portion
of
the
EU/SY
convergence
vector
that
is
not
taken
up
by
wedging
and
slip
on
the
Varto
Fault
is
given
by
the
SY/SY
join,
which
represents
difficult
to
differentiate
possible
combinations
of
strain
within
the
Anatolian
wedge
between
the
NAT
and
EAT
and
strain
between
the
Bitlis
Thrust
Zone
and
the
Minor
Caucasus.
The
SY/SY
join
is,
perhaps
significantly,
close
close
azimuth
to
the
slip
vector
on
the
north
east
dipping
Lice
Thrust
derived
from
the
fault-plane
solution
for
the
Lice
Earthquake
[Canitez
and
Ucer,
1962].
The
Europe/Syria
convergence
is
taken
up
east
of
the
Karliova
junction
of
the
NAT
and
EAT,
between
the
Syrian
Foreland
and
Minor
Caucasus
by
a
complex
array
of
southward-verging
thrusts
in
the
Bitlis
Zone,
several
zones
of
folding
and
thrusting
and
northwest-trending
right-

Dewey
and
Pindell:
Neogene
Block
Tectonics

Fig.
2.
Vector
diagram
illustrating
suggested
relationships
between
relative
plate
motion,
observed
slip
directions
and
slip
rates
on
major
"block-bounding"
faults
and
strain
in
eastern
Anatolia.
EU,
European
Plate;
AR,
Arabian
Plate;
SY,
Syrian
Plate;
AF,
African
Plate;
AN,
Anatolian
Block;
ANX,
Anatolian
Block
assuming
Europe/Syria
relative
motion
taken
up
by
lateral
wedging
of
Anatolia;
NAT,
North
Anatolian
Transform;
EAT,
East
Anatolian
Transform.
Slip
rates
in
millimeters
per
year.
Isolated
lines
labelled
Varto,
Lice
and
Adana
are
azimuths
of
slip
vectors
derived
from
fault
plane
solutions
of
these
earthquakes
indicated
in
Figure
1.
first sight, an apparent paradox in that it clearly represents a substantial lithospheric extension zone at the edge of the Anatolian Plateau. It could be a major pull-apart in a complex left-lateral transform zone that continues the EAT trend but its position at the Africa/Syria/Anatolia triple junction offers a better kinematic explanation (A. M. C. Sengor, verbal communication, 1984). A vector triangle derived from the known trends and slip rates of the EAT (1.7 m \( \text{Ma}^{-1} \)) and the Syrian segment of the Dead Sea Transform zone (4 m \( \text{Ma}^{-1} \)) yields an Africa/Anatolia slip vector of 3.4 m \( \text{Ma}^{-1} \), which gives north-northwest extension in the Adana region close to the Maras triple junction. A normal fault first motion derived northwest trending slip vector for an earthquake on the northern edge of the Adana Basin [Canitez and Ucer, 1967] is close to this extensional azimuth.

Although a Quaternary rate of 9 m \( \text{Ma}^{-1} \) along the western, east-west, segment of the NAT is close to the 8.9 m \( \text{Ma}^{-1} \) average rate deduced for the eastern northwest/southeast segment, the total slip on the western segment is only 25 km [Hancock and Barka, 1981] compared with 80 km on the eastern segment. Thus 55 km of right lateral motion has been taken up on other faults. Possibilities are that either or both the Kure [Bergougnan et al., 1978] and Sungurlu Faults took up the motion, that the Kure Fault was a precursor to the western segment of the NAT, or that the latter was a left-lateral structure during pre-Pleistocene times [Hancock and Barka, 1981] and formed the southern boundary to a west-moving wedge similar to but smaller than the present Anatolian block [Hempton, 1982].

An interesting contrast exists between pull-apart basins on the NAT and those on the EAT. From the slip rates of the NAT and EAT and the lengths of pull-apart basins along them, the Erzincan Basin has an extensional strain rate of \( 10^{-13} \text{ s}^{-1} \) while the Hazar Basin has one of 3.6 \( \times \) \( 10^{-15} \text{ s}^{-1} \); the Erzincan Basin contains volcanics whereas the Hazar Basin does not. Both pull-apart basins lie within the regionally thickened crust of Anatolia. Strain rate may be the governing difference; in regions of high extensional strain rate the lithosphere may be thinning faster than it thickens by regional shortening and by thermal re-equilibration thus allowing fertile mantle at 1330°C up to depths where partial melting is possible (<60 km).

**NORTHERN SOUTH AMERICA**

Since the early Late Miocene, considerable deformation has occurred within northern South America. This has led to the development of a South Caribbean plate boundary zone from the Gulf of Guayaquil to Trinidad, a wide zone of poorly defined seismicity, shear, extension and compression related to interactions between South America and the, relatively, eastward-migrating Caribbean Plate. Generally, rocks within the plate boundary zone have migrated northeast and east with respect to South America as indicated by seismic studies [Pennington, 1981; Aggarwal, 1983] and dextral offsets on many faults [Rod, 1956]. Because of the geological and topographical complexity of the zone, however, the offsets upon many of the fault zones have escaped direct assessment. Here, we indirectly assess some of these offsets by completing the vector sums of relative motions between plates, platelets of the circum-Caribbean region and blocks within the plate boundary zone, all with respect to a stable South America (Guyana Shield). Possible tectonic rotations of blocks about vertical poles as indicated by paleomagnetism [Skerlec and Hargreaves, 1980] are ignored because the rotations cannot be constrained to the Neogene, and because a clear understanding of these rotations has not yet emerged.

Quantifying the northeastward migration of blocks within the Andean Cordilleran and Venezuelan terranes from Guayaquil to Trinidad is achieved by construction of several velocity triangles between the blocks and platelets in question. Alternatively, if we can establish an age of initial motion along the faults separating the blocks and platelets, we need only construct vector triangles of fault offsets since that time.

For the present purposes, an initiation age of 9 Ma B.P. is assumed for several reasons. First, magnetic anomaly 5 has an age of 9 Ma B.P., and the North America-South America relative motion can be deduced by measuring the difference between the relative positions
of these continents at anomaly 5 and the Present. Second, Caribbean-North American offset for the last 8.3 million years has occurred across the Cayman Trough at a rate of 40 m Ma$^{-1}$ [MacDonald and Holcombe, 1978; Sykes et al., 1982], and very little error is involved in extrapolating the 40 m Ma$^{-1}$ rate to 9 Ma B.P. Third, and most important, is that the primary features of the southern Caribbean plate boundary zone, which collectively comprise the deformation with which we are concerned, have developed within this period. In the east, the opening of the Cariaco Basin (pull-apart) by motion on associated dextral transform faults (El Pilar and Morón) has occurred primarily during the Pleistocene [Schubert, 1982]. To the west, the uplift of the Cordillera Central, Oriental, Perija and Merida of Colombia and western Venezuela is well constrained to the Late Miocene and Pliocene (the last 9 to 10 million years). Structural and depositional studies indicate uplift, large-scale thrusting and strike-slip faulting, coarsening of terrigenous sediment, and general emergence during that time [Sharma, 1975; Irving, 1975; Bourgois et al., 1982; Kellogg and Bonini, 1982; Duque Caro, 1972; Campbell, 1968]. Furthermore, paleobathymetric studies of facies and fauna [Bandy and Casey, 1973; Keigwin, 1978] indicate coeval shallowing of the Panama Basin and eventual emergence of the Panamanian Isthmus. The cause of this uplift and deformation is, most likely, the progressive collision of the Panama arc with western Colombia [Pindell and Dewey, 1982; Wadge and Burke, 1983], and the attempted subduction of young, buoyant crust produced at the Galapagos Spreading Center, which includes the Carnegie and Cocos aseismic ridges.

With these considerations in mind, a vector triangle diagram for blocks of the southern Caribbean plate boundary zone may be constructed (Figure 3). Each block of the system is portrayed in Figure 3 as a point, with pairs of points being connected by tie lines representing the fault zones between the represented blocks. The trends of the tie lines (fault zones) are measured directly from geologic maps, and their lengths are defined by the amount of offset, where known, along each over the last 9 million years. Only those fault zones with proved offsets greater than 50 km have been used.

Both the trend and magnitude of relative motion of NoAm/SoAm and of NoAm/Columbia Basin for the last 9 million years are known fairly well. However, small circles defining the Cayman Trough and the North America/Columbia Basin relative motion [Jordan, 1975] cross cut the Puerto Rico Trench, which separates the North American Plate from the Venezuelan Basin, in such a way that one would expect extension. However, the Puerto Rico Trench is a transform fault with a compressional component [Schell and Tarr, 1978]. Furthermore, an unknown amount of convergence at the Puerto Rico Trench [Ladd and Watkins, 1978] suggests even greater disparity between the trends of Cayman Trough small circles and North America/Venezuelan Basin relative motion. It appears that the Venezuelan Basin is behaving independently of the Colombian Basin. Seismic studies [Sykes et al., 1982] indicate present overthrusting by the northern Lesser Antilles across the floor of the Atlantic at 70°E. This trend is more northerly than that of the Puerto Rico Trench, and may indicate considerable underthrusting at the Puerto Rico Trough, or may represent only a recently developed direction of relative motion. Assuming an average trend of relative motion between North America and the Venezuelan Basin over the last 9 million years that is approximately parallel with the Puerto Rico Trench (N83°E), a North America/Venezuelan Basin tie line of unknown length may be constructed whose trend differs from the North America/Columbia Basin tie line. The likely location for relative motion between the Colombian and Venezuelan Basins is the Beata Ridge. A tie line constructed from the point representing the Colombian Basin that is parallel to the Beata Ridge intersects the NoAm/Venezuelan Basin tie line at a point that theoretically defines the magnitude of both the Puerto Rico Trench and Beata Ridge offsets over the last 9 Ma B.P. By triangle completion with the North America/South America tie line, a NoAm/Venezuelan Basin tie line may be drawn that defines the trend (092°) and magnitude (445 km) of the SoAm/Venezuelan Basin offset. This motion has occurred
on the San Sebastian Fault zone off northern Venezuela, although, to the east and west, the motion has been spread across a number of faults such as the El Pilar and the fault along the northern margin of Arraya-Paria [Case and Holcombe, 1980], whose component motions are of lesser magnitude.

An Orchila/Venezuelan Basin tie line may be constructed with the trend of the Los Roques Canyon, defined by Case and Holcombe [1980] as a probable zone of dextral shear with questionable magnitude between the two. We suggest that the magnitude of the offset is 170 km as measured from the northern margin of the Caribco Basin (eastward continuation of the San Sebastian fault and southern edge of the Caribbean Plate proper) to the northern edge of the Orchila shelf, which is the distance by which the Venezuelan Borderlands have overthrust the Caribbean Plate. This is supported by seismic lines [Ladd and Watkins, 1978; Silver et al., 1975; Ladd et al., manuscript in preparation, 1984] which trace the Caribbean crust dipping beneath the accretionary complex just north of the islands, and also by the large negative gravity anomaly to the north of the islands [Bowin, 1976]. Furthermore, Neogene sediments are highly deformed to the west of Roques Canyon whereas to the east they are not [Silver et al., 1975].

At this point, further vector triangle construction may logically follow two different paths, depending upon the amount of shortening that has accompanied transcurrent motions within the Merida Andes. Method one assumes no compression

Fig. 3. Vector triangle diagrams showing trend and magnitude of relative offsets between blocks of northern South America and Caribbean region, following methods of construction outlined in text. Where appropriate, tie lines are chords to small circles of plate motions in the northern South American area. Figure 3a assumes no compression in the Merida Andes; Figure 3b assumes no dextral shear in basins separating Paraguana and Aruba-Ochila islands; Figure 3c is the preferred solution using values and trends interpolated between the end members of Figures 3a and 3b. Offset values in kilometers underlined values from published sources (below), others inferred from triangle construction. Only published values greater than 50 km are used, with an assumed east-west extension of 50 km within Neogene basins separating Paraguana and Aruba-Roques islands.

Dashed line in Figure 3a which connects Cordillera Central to South America-Maracaibo tie-line, is net compressional component in the Andean Cordilleras, largely seen in Eastern Andean thrusts. Sources: El Pilar, Schubert [1982]; Oca, Tschanz et al., [1974]; Santa Marta, Tschanz et al., [1974], Campbell [1968]; Cayman system, MacDonald and Holcombe [1978], Sykes et al., [1982]; Barracuda and related fractures, J. L. Pindell (manuscript in preparation, 1984); Roques Canyon, Silver et al. [1975], Case and Holcombe [1980].
so that the present trend of the range is the direction of transcurrent motion (Figure 3a), and method two leaves the trend of relative motion as an unknown, so that the amount of compression may be deduced from vector triangle construction (Figure 3b). In both methods, we have assumed an internal extension of 50 km within the basins between Paraguauna and the Aruba-Orchila islands, based upon their number, size and post-Late Miocene sedimentary thicknesses [Feo-Codecido, 1971; Silver et al., 1975; Edgar et al., 1971]. In method one, a SoAm/Maracaibo tie line of unknown length is drawn with the present trend of the Bocono-Merida system, and the trend of the Roques Canyon tie line is extended beyond the Orchila-Roques block. The eastward displacement of the Orchila-Roques block with respect to the Maracaibo block must equal the sum of the offset upon the Oca Fault and the inter island basin extension; hence, a tie line with a length of this sum and the trend of the Oca, is drawn in its singular position from the Merida tie line to the Roques Canyon tie line. Figure 3a shows that this tie line does not align with the point already defined for the Orchila-Roques block. Therefore, a dextral component of 46 km is inferred to have accompanied the extension within the inter island basins. Method two constructs the Maracaibo/Orchila-Roques tie line directly west from the previously defined Orchila-Roques point, thereby eliminating the dextral shear implied by method one. Its western end, therefore, defines the paleoposition of the Maracaibo block, and construction of a SoAm/Maracaibo tie line defines the offset of Maracaibo relative to South America. The transcurrent and compressional components within the Merida-Bocono system may then be deduced by measuring the difference between this constructed trend and the actual trend of the present day system, as shown in Figure 3b.

Once the main frameworks have been created, hypothetical tie lines may be drawn between any pair of points in either diagram to obtain the approximate trend and magnitude of the relative motion between the represented pair of blocks. For example, a tie line drawn from the Colombian Basin to the Maracaibo block defines the amount and trend of subduction during the last 9 Ma B.P. beneath the latter. The predicted average convergence trend over the last 9 m.y. of N44°W accords reasonably with the present convergence trend of N50°W ± 10° [Kellogg and Bonini, 1982]. Alternatively, the components of motion between blocks, i.e., transcurrent, extension and compression, may be approximated in other cases by comparing the constructed tie lines defining relative motion and the actual trends of the faults upon which the motion has occurred. This was done in method two (Figure 3b) to obtain theoretical transcurrent and compressional components of the Merida system. Similarly, the compressional component of the Eastern Andes Overthrust can be approximated by construction of a line normal to the Merida tie line that intersects the point representing the Central Cordillera block (Figures 3a, 3b, 3c). Sinistral motion along the Santa Marta Fault and dextral motion along the Merida Andes has allowed the Maracaibo block to escape much of the compression seen in the Colombian Andes.

Dextral slip within the five basins separating the Paraguauna Peninsula and the Aruba-Orchila islands is postulated due to their residence in the southern Caribbean dextral shear zone, which argues in favor of method one. However, a compressive component within the Merida Andes is well known [Shagam, 1975]. Thus, we suggest that the best vector triangle diagram for the southern Caribbean plate boundary zone is one that falls about half way between the end member constructions of methods one and two, which is depicted in Figure 3c. Figure 4, which depicts the pre-Andean paleogeography of the blocks in question, has been constructed from values and trends of Figure 3c.

The primary implication of this semi-quantitative analysis is that the Cordilleran terrane of Ecuador, Colombia and western Venezuela has migrated about 290 km to the northeast with respect to a stable cratonic South America in the last 9 million years. Dextral offsets of 250 meters have been measured in Quaternary sediments along the Bocono Fault [Giegengack et al., 1976], and 33 km has been measured at a dextral offset of Rio Bocono [Rod, 1956] but no total transcurrent offset within the Merida Andes, of which the Bocono is only a presently active, relatively minor fault, has been postulated before. Studies of relative motions between South America and the
Fig. 4. Pre-Andean (9 Ma B.P.) plate reconstruction of blocks comprising northern South America, derived by removing offsets, relative to South America, defined in Figure 3c. Shorelines of Panama and Sino-Atlantico Basins dashed because they are Pliocene-Recent additions. Proposed reconstruction produces a straight, continuous limit of Paleogene thrusting and metamorphism. Thrust sheets include sporadic remains of ophiolitic fragments, as shown. Because Blanquilla presently lies east of Roques Canyon fault zone, it is considered part of the Aves Ridge rather than part of the arc that collided with northern South America in Late Cretaceous-Eocene time. No obvious break between Margarita and the Lesser Antilles is indicated by geophysical data [Weeks et al., 1971]; rocks similar to those on Margarita may form the basement of the southern end of the Lesser Antilles arc. Ophiolite fragments in Margarita may have been tectonically extruded during shear between the Caribbean and South American plates prior to the plate boundary's jump to El Pilar Fault Zone in Pleistocene time. The Late Cretaceous plutons of Tobago at the leading edge of the Caribbean Plate indicate that a "Tobago block" has been obducted at some point during migration of the Caribbean Plate (G. K. Westbrook, personal communication, 1984). The vector triangle at the Gulf of Guayaquil defines strike-slip and compressional components of the Cordilleran terrane relative to Guyana Shield. Inset: Present outline of South America, defining blocks and fault zones used in this analysis. Heavy line defines pre-Andean (9 Ma B.P.) continental shape.

oceanic plates offshore to the west should recognize the independent motion of this intervening platelet.

Figure 5 outlines the complex interactions between the blocks of northern South America and the Caribbean Plate during the northeastward migration of the Cordilleran terrane. Simply put, the leading edge of the terrane has overridden the eastward migrating Caribbean Plate. However, because the Merida/Boconó fault zone changes trend so drastically as it merges with the San Sebastian fault zone, the Aruba-Orchila island arc has been internally deformed, resulting in the formation of the small basins lying between the islands. Dextral and extensional motion within these basins has prevented a gap from opening between the islands and northern Venezuela. Collectively, these motions have led to the obduction of the Aruba-
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Fig. 5. Schematic evolution of northern South America over the last 9 million years. Figures 5a, 5b and 5c are, respectively, paleogeographic reconstructions at 9 Ma B.P. (pre-Andean), 3 Ma B.P. (pre-Cariaco Basin/El Pilar fault development), and Present. Reconstructed offsets in Figure 5a are from Figure 3c, those in 5b are interpolated between Figures 5a and 5c. Caribbean/South America transform in 5a is the zone of incipient subduction, the site from which the Venezuelan Borderlands have been thrust onto the Caribbean Plate in Neogene time. Cordillera Central is treated as a rigid block, although much internal deformation has occurred which is beyond present quantitative analysis. Offset along the Oca Fault may die out to the east within decollement zones of the Falcon Basin. Progressive development of the Barbados, South Caribbean/Curacao and Panama accretionary complexes is inferred.
Orchila islands onto the Caribbean Plate by about 170 km. The term obduction is preferred to subduction, owing to the buoyant nature of the Caribbean Plate [Burke et al., 1978] and to the fact that no subduction-related volcanism has yet occurred. It has, however, caused the Plio-Pleistocene development of the extensive South Caribbean-Curacao Ridge accretionary complex. The complex is composed of continental slope and rise sediments derived from South America and deposited upon the Caribbean Plate during its Cenozoic eastward migration. The site upon which the Cordilleran obduction was initiated was the original transform fault separating the Caribbean and South American Plates (Figures 4 and 5). Obduction was facilitated by the fact that the Caribbean crust sits isostatically at 4 to 5 km below the adjacent margin. Hence, this transform, and evidence for its large offset since the Eocene, cannot be directly seen. Only the eastern, recently developed, relatively minor portion of the South America-Caribbean offset (Caribbean Basin, El Pilar and related faults) can be directly studied.

The prospects for petroleum discovery in the basins separating the Aruba-Orchila islands are poor. At the surface, these basins have an appearance similar to small productive basins offshore California. However, because the crust in which they have formed overlies the underthrusting Caribbean Plate rather than mantle, the basins may be expected to be quite cold, with little chance of their sediments having reached thermal maturation during their short lives of only 5 to 8 million years.

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Dewey and Pindell: Neogene Block Tectonics


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On the basis of construction of vector diagrams, Dewey and Pindell [1985] "indirectly assess" the displacement between plates and platelets of the circum-Caribbean region. One of their conclusions is that the "total transcurrent offset within the Merida Andes" of western Venezuela has been 290 km in a right-lateral direction during the last 9 million years. The existence of such large transcurrent offset is not supported by the stratigraphic and structural evidence recorded in the rocks of western Venezuela and reported in the comprehensive and readily available literature on the area. And it is in the rocks, after all, that the answers to most geological problems and the confirmation or disproval of geological postulates are found.

Dewey and Pindell state that the major displacement has not taken place along the Boconó fault, which they consider "only a presently active, relatively minor fault". They do not identify, however, the major fault or fault zone along which the postulated offset occurred. And yet, it should not be difficult to recognize a fault or fault zone which during the last 9 million years has experienced a continuous strike-slip movement of 290 km, particularly in a region with excellent outcrops, where a "relatively minor fault" like the Boconó fault has such a prominent geological and surface expression.

In order to try to demonstrate that no displacement of the magnitude postulated by Dewey and Pindell has taken place "within the Merida Andes" in the last 9 million years or, for that matter, at any time since at least the beginning of the Cretaceous, I will include in my discussion most of the Maracaibo and Caracas basins to the north and south, respectively, of the Merida Andes. I leave the discussion of the displacement along the Boconó fault to the many authors who have covered it so capably (Rod [1956], Schubert [1969, 1982], Schubert and Henneberg [1975], Shagas [1975], and many others). Few have postulated right-lateral displacement of more than 40 km along this fault. Most favor a smaller offset. Some even believe that there has been little or no transcurrent movement along the Boconó fault. Largest horizontal displacements have been reported from the northeastern part of the Merida Andes, where the Boconó Fault is plainly evident at the surface. The displacement apparently diminishes toward the southwest, and the fault splay into a
system of roughly parallel faults. The horizontal displacement of the Boconó Fault appears to be small as it crosses the Merida Arch.

There are numerous kinds of criteria which make Dewey and Pindell's "indirect assessment" untenable. I will restrict my discussion, however, to only two...
principal lines of evidence: (1) the lack of major displacement of the Merida Arch and (2) the distribution, lithofacies, and thickness of the Cretaceous rock sequence.

THE MERIDA ARCH

The presence of a pre-Cretaceous high arch, a projection of the Guayana Shield at right angles to the Merida Andes, the so-called Merida Arch, has been recognized for many years. It trends in a general NNW direction through the Barinas Basin, across the Merida Andes, and into the Maracaibo Basin. Figure 1 shows the position of the Merida Arch by means of contours on the top of the pre-Cretaceous "basement." The structure has been simplified by eliminating many of the lesser but complex Tertiary fault systems. In both basins the Merida Arch can distinctly be seen in spite of the considerable post-Cretaceous deformation and the deposition of a thick section of Tertiary sediments in deep troughs immediately north and south of the Merida Andes, particularly in the Maracaibo Basin. The Merida Arch is unmistakably manifested within the Merida Andes: A cross section parallel to the length of the mountain range reveals a broad arch with Precambrian in the central part, flanked successively by Paleozoic and Cretaceous rocks in northeastward and southwestward directions toward both ends of the range.

As Figure 1 shows, the Merida Arch crosses the Merida Andes with no major horizontal displacement.

CRETACEOUS STRATIGRAPHY

The stratigraphy of the Cretaceous rocks of western Venezuela distinctly reflects the position of the Merida Arch across the Merida Andes during the Cretaceous and further supports, therefore, the conclusion that no major transcurrent displacement has taken place within the Merida Andes since at least the beginning of the Cretaceous. Gonzalez de Juana et al. [1980] provide an excellent summary of the extensive literature on the many detailed studies of the Cretaceous rocks in this region. The Cretaceous section onlaps and thins over the Merida Arch, indicating that the arch is a pre-Cretaceous feature. Much of the thinning is due to the loss of section at the base of the sequence resulting from the progressive onlap. In the Maracaibo Basin the onlap and thinning is particularly well documented on the west side of the Merida Arch (sometimes called the Maracaibo Platform). Along the north flank of the Merida Andes the Cretaceous section thins over the Merida Arch from both sides. This is well documented by information from the many measured surface sections reported in the literature, the location of some of which is shown in Figures 1 and 2. The Cretaceous section is thinnest near the town of Torondoy, atop the crest of the Merida Arch [see Renz [1959], for instance]. Similar relations have been documented along the southern flank of the Merida Andes, in the Barinas Basin [Pierce, 1960; Kiser, 1961]. In the central part of the Barinas mountain front, in fact, the Cretaceous section seems to pinch out altogether over the Merida Arch [Gonzalez de Juana et al., 1980]. This pinchout may in part be due to erosion of a thin Cretaceous section as a result of post-Cretaceous uplift of the Merida Arch; the upper part of the Cretaceous section is known to be partly eroded and unconformably overlain by Tertiary sediments along the arch in the Barinas Basin and in the north flank of the Merida Andes [Renz, 1959; Zambrano et al., 1972; Feo Codecido, 1972].

The thickness distribution of the total Cretaceous section in western Venezuela shows the continuity of the Merida Arch across the Merida Andes. Particularly illustrative are the thickness maps of the intervals within the older part of the Cretaceous section, the pre-Genomanian units [Zambrano et al., 1972; Feo Codecido, 1972; Gonzalez de Juana et al., 1980]. A thickness map of the Aptian-Albian section, Figure 2, distinctly depicts the location of the Merida Arch at that time. By the beginning of the Campanian, most of the arch was covered with sediments, and the thinning of the upper part of the Cretaceous section over the arch is less evident.

Lack of large strike-slip displacement within the Merida Andes is also demonstrated by the lithology of the Cretaceous section. Excellent lithologic correlations within the Cretaceous section are possible throughout western
Venezuela, from the northern part of the Maracaibo Basin, across the Merida Andes, to the Barinas Basin. As mentioned above, the total section and most of its individual units thin over the Merida Arch. The Cretaceous, as should be expected, also thins and becomes more sandy toward the Guayana Shield to the south. But it is no problem to recognize and extend particular formations and members across the area where Dewey and Pindell postulate a horizontal displacement of 290 km in the last 9 million years. In the northeastern part of the Merida Andes, for instance, detailed correlations of the Cretaceous section can be carried out in surface sections from the northwestern flank, across the mountains to the southeastern flank, and then in the subsurface to the oil fields in the Barinas Basin.

Similarly, excellent surface and subsurface correlations can be carried out in the southwestern part of the Merida Andes (Renz, 1959). In this last area, a very distinctive but local siliceous lithofacies of the Coniacian-Santonian section has been recognized and mapped as either Tachira Chert, Quevedo Formation, or Navay Formation from the southwestern part of the Maracaibo Basin, across the Merida Andes, to the Barinas Basin (see Figure 1). It shows no horizontal displacement on crossing the Merida Andes.

The distribution, lithofacies, and thickness of the Paleocene-Eocene section of western Venezuela also demonstrate that there is no
transcurrent displacement of more than a few tens of kilometers within the Merida Andes. (See, for instance, Zambrano et al. [1972] and González de Juana et al. [1980]).

In summary, geological evidence in western Venezuela indicates that in order to postulate a horizontal displacement of 290 km during the last 9 million years within the region of the Merida Andes, it would be necessary to assume that during this time interval two pre-Cretaceous high arches, originally 290 km apart, flanked and covered by very similar Cretaceous and lower Tertiary rock sequences, were displaced along a yet unidentified fault or fault zone a horizontal distance that precisely positioned the two highs on trend with each other and made the overlying Cretaceous sections exactly correspond in thickness and lithologic composition. This does not seem probable.

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REPLY

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We thank Amos Salvador for his contribution to the complicated and difficult problem of reconstructing the Late Mesozoic/ Cenozoic paleogeography and tectonics of northern South America [Salvador, this issue]. However, we cannot accept that little or no strike-slip motion has occurred along the Bocono'- Merida system; the true question is, "How much strike-slip motion has occurred?" We agree that our calculated estimate of displacement for the last 9 or 10 Ma of 290 km on the Bocono' Fault and other faults in the Merida transpressional flower structure is too large. This is because it was based upon a vector nest that incorporated a 4-cm/yr slip rate [MacDonald and Holcombe, 1978; Sykes et al., 1982] between the Caribbean and North American Plates. A revised vector nest for the southern Caribbean is shown in Figure 1, that incorporates a 2-cm/yr Caribbean/South American slip rate. This rate is consistent, first, with earlier, lower estimates of motion across the Cayman Trough (1.94 cm/yr [Jordan, 1975; Minster and Jordan, 1978]), which now appear to be more correct (1.5-cm/yr [Ross et al., 1986]), and with recently estimated displacement between North and South America over the last 9 Ma [Pindell et al., 1986]. Second, our paleotectonic reconstructions of the southern Caribbean involve a transpressive South American/ Venezuelan Basin plate boundary zone that elongates as the Lesser Antilles arc sweeps eastward (Figure 2); to carry the arc from its Paleocene to its present position involves an average slip rate of 2 cm/yr. We see no way of further minimizing displacement on the Bocono' Fault. Our revised vector nest estimate of 100 km is supported by a dextral offset of the Lara Nappe front by almost that amount. Also, Schubert [1982, 1986] has shown that the Rio Bocono' drainage network is offset by 33 km, that the Bocono' has a Pleistocene slip rate of 6-10 mm/yr, and that 50-60 km of displacement is necessary to allow opening of the Yaracuy Basin, a small pull-apart along the Bocono' Fault. If any of these displacements are to be believed, then the concept of a "Merida Arch" falters, and the "Merida Arch" cannot be used as a paleogeographic criterion.

We believe that most, if not all, long, straight faults in the continental crust have substantial strike-slip displacements on them. On the question of the Merida Arch, we are not convinced, in working through the original data, that it existed as a single linear unbroken structure. Zambrano et al. [1972] questions its existence, and we do not believe that the
Fig. 1. Revised vector nest (finite difference) for displacements between some of the plates and blocks along the southern Caribbean plate boundary zone. Vector corners (Maracaibo, Guajira, etc.) represent blocks and plates. Tie lines (with displacements in kilometers and trends as shown) represent slip between blocks and plates for the last 9 to 10 million years. North America-South America relative motion is the translational displacement of the two plates (110 km) in the area of the Cayman Trough since anomaly 5 time (9 Ma); pole of rotation is 12.2°N, 52.1°W with an angular rotation of 1.86° [Pindell et al., 1986]. Note that the estimated offset of 170 km between North America and the Colombian Basin is primarily along the Cayman Trough (1.5 cm/yr for 10 Ma, or 150 km), but smaller offsets along other faults such as the Enriquillo-Plantain Garden fault zone have occurred as well (10 to 20 km, [Mann et al., 1984]).

Fig. 2. Sequential paleotectonic reconstructions of the Caribbean-South American borderlands, at (a) Upper Paleocene; (b) Middle Eocene; (c) Lower Oligocene; (d) Lower Miocene; (e) Upper Miocene; and (f) Present. Solid triangles, leading edge of accretionary prism; open triangles, thrusts; railroad tracks, sutures; V's, volcanic arc; heavy dots, nappes on continental crust; anticline symbol, axis of flexural bulge; fine dots, turbidites of Scotland Formation of Barbados prism.
stratigraphic data are sufficient in the Merida Andes to dispel the possibility of two quite separate Cretaceous highs or arches, one in the southeastern Lake Maracaibo region and one in the Barinas Basin.

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