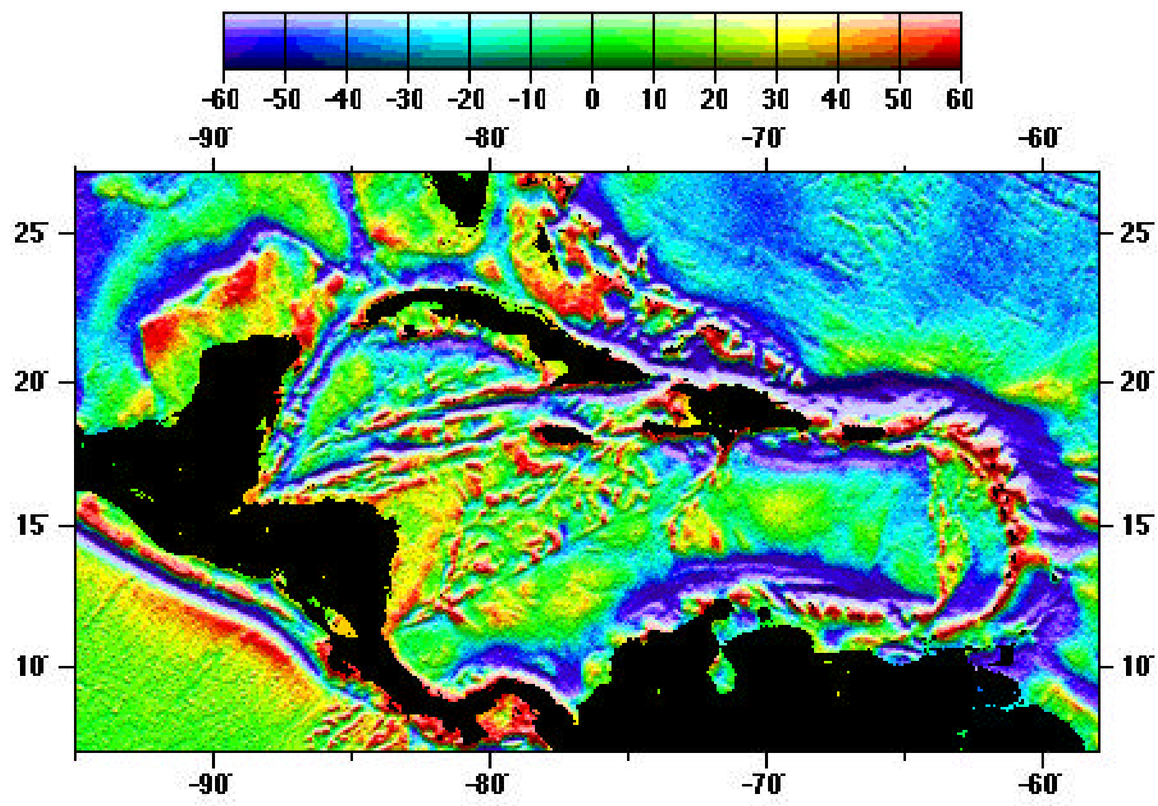
Penrose Conference

SUBDUCTION TO STRIKE-SLIP TRANSITIONS ON PLATE BOUNDARIES

Puerto Plata, Dominican Republic
January 18-24, 1999

ABSTRACT VOLUME



Conveners: Paul Mann, Nancy Grindlay and James Dolan

Sponsored by the Geological Society of America, Petroleum Research Fund, NSF and NASA

STRUCTURAL GEOLOGY AND SEDIMENTOLOGY OF A PLIOCENE INNER-TRENCH SLOPE SUCCESSION, NORTHWESTERN ECUADOR

K. R. AALTO

Dept. of Geology, Humboldt State Univ., Arcata, CA, USA 95521, kra1@axe.humboldt.edu

The Pliocene Upper Onzole Formation exposed in the vicinity of Punta Gorda, near Esmeraldas, Ecuador, is composed mainly of fine-grained mud turbidites, having regular vertical sequences of sedimentary structures associated with a positive grading, and bioturbation restricted mostly to the tops of beds. The remainder of beds measured consist of volcanic ash, mud pelagite, and glauconitic silt-sand turbidites. Vertical sequential analysis of stratigraphic sections for the most part show no pronounced trends in bed thickness or grain size. Volcanic ashes are crystal-vitric tuffs occurring in four bedding styles: A) normally-graded ashes with burrowed gradational tops and sharp wavy bases; B) ashes that form part of a complex microstratigraphy consisting of thinly-bedded mudstone, silt-sand turbidites, tuffaceous mudstone, and ash beds; C) less conspicuous ash laminae and ash-filled burrows; and D) a tuffaceous bed with ash and mud swirled together in convolute layers. Ash chemistry suggests an Andean high-K calc-alkaline provenance. Facies relations, paleontologic data and regional geologic setting suggest sediment accumulation on an inner trench slope in a basin situated oceanward of the Pliocene trench-slope break.

Faulting is extensive and reflects two deformational episodes, the youngest involving Holocene marine and fluvial terraces containing Pre-Columbian artifacts. Faults group into an older, northerly-trending, listric set, and a younger, WNW-trending high-angle set. Fault striations of both sets suggest dominantly dip-slip motion. Associated with the older set of faults is a spaced fracture cleavage defined by dark, curvilinear to sinuous S-surfaces that are less than 1 mm wide but tens-of-cm long, oriented subparallel to listric faults. Cleavage surfaces are spaced over distances as great as several meters from larger faults. Individual surfaces are defined in thin section by cataclastic deformation resulting in grain diminution, commonly characterized by small amounts of offset. The faults reflect an episode of Quaternary trench-normal extension in the forearc, followed by trench-parallel extension. Both sets of faults crosscut large NE-trending regional folds.

Daly (1989) documented east-west extensional deformation among late Oligocene-middle Miocene rocks in northwest Ecuador, but did not refer to similar strain recorded among Pliocene rocks. This deformation resulted in uplift of the southern and eastern margins of the Borbón Basin in the middle Miocene, which resulted in influx of coarse clastics into the basin from the east. Evans and Whittaker (1982) recognize successive episodes of uplift to the south that resulted in the influx of coarse turbidite clastics into the basin during the early Pliocene. Following deposition of these turbidites, mudstone deposition and basin deepening resumed, and the portion of the Upper Onzole exposed at Punta Gorda accumulated. It is possible that the episode of extensional deformation that produced the older, north-trending faults in the study area reflects reactivation of faults in the accretionary wedge that were responsible for the earlier episodes of Neogene basin inversion proposed by Evans and Whittaker (1982). Daly (1989) relates trench-normal extension in the forearc to decreasing plate-convergence rates, which resulted in collapse of the forearc wedge. Although he does not specifically relate a Neogene rate decrease to an episode of extensional deformation, this decrease may help to explain the genesis of the older, north-trending faults observed in the study.

During the Neogene the landward margin of the Ecuador trench may have also suffered net tectonic erosion, which is an alternative hypothesis to explain Neogene east-west extension recorded by the first generation of faults in the study area. If Neogene basin evolution in the Ecuadorian forearc reflects trench-normal extension, the resulting basins may be structurally and morphologically similar to those of the sediment-rich Central American forearc, a region also characterized by block-faulting reflecting extension orthogonal to the Middle America Trench. Another analog for the depositional setting of the Upper Onzole is the outer deep-marine basin portion of the terraced compound forearc basin of the Alaskan-Aleutian Arc, although these outer basins formed in response to transpressional and transtensional deformation associated with strike-slip faulting in the forearc (Ryan and Scholl, 1989). No concrete evidence of strike-slip faulting exists in either the study area. Daly (1989) invokes oblique convergence-induced strike-slip-related deformation in the Ecuadorian forearc during the late Miocene to Recent to explain a variety of regional structures. However, the stress vectors associated with his deformational fields (resulting in NE-SW crustal shortening and NW-SE extension) are incompatible with what is recorded in the Esmeraldas region, unless the structures reflect a complex partitioning of strain within a discrete block.

The younger WNW-trending high-angle normal faults reflect NNE-SSW extension, with faults oriented generally orthogonal to the modern Ecuadorian trench, a deformational field reflected in the orientation of some of the large faults on the regional map. Both these faults and the north-trending set of faults shown on the map truncate the large regional folds. Following Upper Onzole deposition, changes in stress regime, from generally NW-SE compression, to E-W tension, to NNE-SSW tension are difficult to explain. Perhaps this progressive deformation reflects stress rotation that resulted from the encroachment and collision of the leading edge of the continent with the thick crust of the Carnegie Ridge (Daly, 1989). This change in stress fields would have produced a final episode of “basin inversion” in the Esmeraldas region.

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Overview of structures associated with subduction to strike-slip transitions in New Zealand

P.M. Barnes[1], J-C. Audru[2,5], J-Y. Collot[3], B. Davy[4], J. Delteil[2], R. Herzer[4], G. Lamarche[3,1], J-F. Lebrun[3], B. Mercier de Lépinay[2], R. Sutherland[4], R. Wood[4].

[1]National Institute of Water and Atmospheric Research (NIWA), PO Box 14901, Kilbirnie, Wellington, New Zealand.
[2]UMR Géosciences Azur, UNSA-CNRS, Valbonne, 06050, Sophia Antipolis, France.
[3]UMR Géosciences Azur, ORSTOM, 06235, Villefranche sur Mer, France.
[4]Institute of Geological and Nuclear Sciences, PO Box 30368, New Zealand.
[5]Presently at Institut de Physique du Globe, 67084 Strasbourg cedex, France

The structure of the Pacific-Australian plate boundary in the New Zealand region varies along its length in response to changes in crustal structure, interplate coupling, and obliquity of relative motion between the plates. Two opposite-facing subduction to strike-slip transitions occur on the plate boundary, one at each end of the South Island of New Zealand, where oblique subduction of oceanic crust in the north and south merges with an oblique continental collision zone in central South Island (Fig. 1). The northern transition occurs from the west-dipping Hikurangi subduction zone, through the continental strike-slip Marlborough Fault System, to the oblique dextral Alpine Fault collision zone. The southern transition occurs from the alpine collision zone to the east-dipping Puysegur – Fiordland subduction system south of New Zealand.

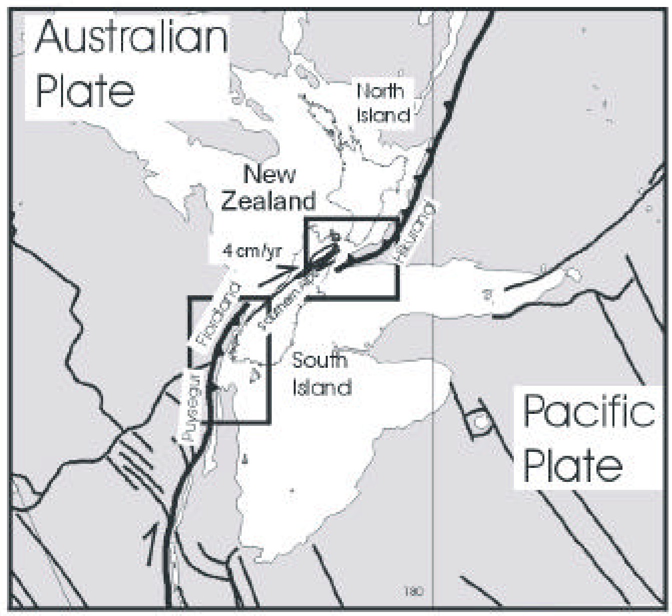

Fig. 1. Two subduction to strike-slip transitions in the New Zealand region.

Both regions of tectonic transition have existed as subduction to strike-slip transition plate boundaries since the Miocene. However, the geometry of the boundaries, the activity of geological structures, and the kinematics of faulting have changed through time as relative plate motion changed and as the northern part of the plate boundary rotated clockwise. The transition regions are presently undergoing oblique convergence at a relative plate motion rate of 3.5-4.0 cm per year.

During the last five years several complementary research teams have utilised deep-crustal and shallow-penetration seismic reflection data, shipborne gravity and magnetic data, EM12Dual multibeam swath imagery, MR1 side-scan sonar, 3.5 kHz profiles, seabed samples, and onland field data to reveal the active structures of both the northern [1,2,3] and southern [4,5,6] subduction to strike-slip transition areas.

The Hikurangi – Marlborough transition straddles an oceanic - continental boundary in the subducting Pacific Plate crust, and a consequent southward increase in interplate coupling across the southern end of the subduction zone. Thickened oceanic crust (12-15 km) is being subducted beneath North Island, where geological strain is being partitioned incompletely between an axial belt of strike-slip faults and a largely contractional forearc. To the south, where the edge of continental Pacific Plate has been subducted beneath northeastern South Island, almost all of the late Quaternary plate motion is recorded in the upper plate principally across a distributed zone of strike-slip faults that branch off the Alpine Fault and extend offshore from Marlborough into the southern end of the Hikurangi margin. Significant changes in the shallow crustal structure of the transition region during the last 2 million years may partially reflect the locking up of the southern end of the subduction zone.

The Fiordland – Puysegur transition straddles a change from a continental plate boundary in southwestern New Zealand to an intra-oceanic transform boundary on the Puysegur Ridge. The transition region evolved from a continental rift connected with an oceanic spreading system in the Eocene and Oligocene, to its present day strike-slip – trench – strike-slip character. The location of the Alpine Fault is well constrained on the Fiordland margin. The southern end of the fault terminates abruptly at the trench deformation front and is aligned with inherited structures on the rifted edge of a continental sliver on the Australian Plate. One possible model is that the abrupt transfer of plate motion from the Alpine Fault to the subduction zone may be facilitated by a tear in the subducted plate developing along an inherited tectonic structure. Contractional strain along the Fiordland margin is being partitioned west of the fault onto lower slope accretionary wedges that are developing under extremely oblique convergence. At a first order scale the Puysegur Trench subduction décollement together with a distributed zone of transpressive faults crossing the trench slope south of New Zealand transfer most of the plate motion across a mega-scale left step from the Alpine Fault to the oceanic strike-slip Puysegur Fault.

The most important difference between the two strike-slip to subduction transitions in New Zealand is the distribution of upper plate strike-slip deformation through the transfer region. In the northern transition the transfer of plate motion is accommodated across numerous strike-slip and oblique-slip structures, whereas in the south the margin parallel motion is more localised. This results largely from differences in the crustal structure and coupling of the plates, and in the geological evolution of each region. An important commonality to both transitions is the late Neogene capturing of parts of the Pacific Plate in response to changes in plate motion kinematics.

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Upper plate Quaternary strain rates, kinematics and paleoseismology in the transition from Hikurangi subduction to Southern Alps collision, New Zealand

Kelvin Berryman

New Zealand Institute of Geological & Nuclear Sciences, PO Box 30368, Lower Hutt. (k.berryman@gns.cri.nz)

To appreciate the present-day role of upper plate structures in the transition from the Hikurangi subduction margin to Southern Alps collision a synopsis of the late Neogene evolution of the region is useful. Key factors or observations that bear upon the present-day snapshot are:

- Total strike-slip motion on faults of the Marlborough system range from c. 2-34 km (Little & Jones, 1998), excluding the Wairau fault which has c. 140 km of total dextral slip (Mazengarb et al., 1993) - most of it presumably when it acted as the single northern continuation of the Alpine fault prior to the development of the Marlborough fault system.
- Total late Neogene dextral slip on the Wellington and Wairarapa faults in the North Island appears to be no more than a few kilometres (Begg & Mazengarb, 1996).
- The combination of total slip and current slip rate data imply that the Marlborough faults have accommodated dextral motion for much longer than the current dextral faults in southern North Island.
- In the late Miocene there was a broad forearc basin in southern North Island perhaps similar to that in present-day Sumatra (Cashman et al., 1992; Kelsey et al., 1995).
- Beginning in the early Pliocene (and perhaps earlier in the region of the present-day coastal ranges) there was broad regional uplift. This may coincide with the westward march of subduction of the overthick Hikurangi plateau (Kelsey et al., 1995).
- A marine strait existed at the western margin of the forearc basin until the early Pleistocene.
- The frontal ridge comprising the Tararua and Ruahine ranges did not become prominent features of the North Island until the last c. 1 Myr.
- The change from pure strike-slip motion on the Alpine fault to a component of convergence and resultant growth and erosion of the Southern Alps c. 5-7 Myr ago (Walcott, 1998) has had a dramatic impact on the volume of the sedimentary prism offshore of Marlborough and southern North Island. Changes in the internal dynamics of the subduction margin can therefore be expected, and may have resulted in a change in the location where the partitioned translational component of motion will be accommodated.

While the upper plate kinematics in the northern South Island may have been reasonably constant in the past few million years (apart from possible diminishing slip on the Wairau fault, and inception and development of the Porters Pass-Amberley fault system as the newest Marlborough fault), there have been rapid changes in the location, style, and rate of deformation in tectonic domains of southern North Island. About 80±20% of the translational component of plate motion is presently accommodated on 3-4 dextral strike-slip faults in southern North Island (Beanland, 1995). These have average dextral slip rates that range from 1-10 mm/yr, have single event displacements that range from c. 4-15 m, and average recurrence intervals for these maximum magnitude surface fault rupture events of c. 350-5000 yrs (Van Dissen & Berryman, 1996). The associated earthquake magnitudes are probably in the range M_W 7-8. Only the Wairarapa fault has ruptured in the 160 year historical period (in 1855 AD) in a M_W 8 event. The zone of dextral faulting is located 100-160 km from the trench.

At distances of 60-100 km from the trench there is a relatively stable region (currently, but there is evidence of significant late Miocene-Pliocene contraction in this region)(Kelsey et al., 1995), and then there are a system of coastal ranges which appear to be deforming rapidly by west-dipping reverse or oblique reverse faults immediately offshore of the coast. Coastal uplift of 1-4 m as a consequence of rupture of the coastal zone of faults has recurrence intervals of 500-2000 years

(Berryman et al., 1989; Berryman, 1994).

In Marlborough the orientation of the principal faults of the Marlborough fault belt are within a few degrees of the relative plate motion vector, and the sum of the 10-20 kyr averaged slip rates is within error of the NUVEL 1A plate motion rate (Holt & Haines, 1995). The majority of the slip is on the southern-most, well-developed fault - the Hope fault. Slip rates on this one fault are c. 20 mm/yr, about one-half of the relative plate motion (Van Dissen & Yeats, 1991; Cowan & McGlone, 1991).

Suggestions of an episodic clustering of upper plate large earthquakes in the coastal area of the Hikurangi margin (Berryman et al., 1989) appears to extend to northeastern South Island where a minor component of upper plate shortening is taken up by shortening on structures between the principal strike-slip faults (Ota et al., 1996; Miyauchi et al., in prep). Thus, upper plate clustering of large earthquake activity appears to extend across the transition from an active subduction zone to Marlborough where all of the relative plate motion is in the upper plate and the former subduction zone is regarded as fossil (Reyners & Cowan, 1993).

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Seismicity of Two Adjacent but Geometrically Different Subduction to Strike-Slip Transition Zones: San Cristobal and North New Hebrides Trenches, southwest Pacific

Andria Bilich[1,2], Cliff Frohlich[2], Paul Mann[2]

[1] Department of Geological Sciences; University of Texas at Austin; Austin, Texas 78712-1101
[2] Institute for Geophysics; 4412 Spicewood Springs Road #600; University of Texas at Austin; Austin, Texas 78759-8500

Overview

This study outlines the similarities and differences between two subduction to strike-slip transition zones possessing different plate intersection geometries (closed corner versus open corner trench orientation). We apply seismicity analyses to two transition zones of the southwest Pacific: the oblique subduction regime of the southern Solomon Islands and the classic subduction regime of Vanuatu. These two zones are geographically adjacent, as the San Cristobal Trench of the Solomon Islands becomes the North New Hebrides Trench near Santa Cruz (Vanuatu), and offer interesting points of contrast.

We employ four different data sources in this study, three earthquake seismicity catalogs and a compilation of local geologic data. The Harvard centroid moment tensor (CMT) catalog includes focal mechanisms over a 21-year period, giving short-term tectonic and moment information. The Engdahl catalog of relocated hypocenters covers 31 years and was used for information dependent on earthquake location, such as seismic frequency trends and depths. We also used the Abe historical catalog for M > 7.0 events between 1897 and 1976 to enhance moment calculations for these transition zones. The compilation of geologic data is a series of maps synthesizing onshore geology, faults, folds, and bathymetry.

Seismic trends: frequency, depth, and slip vectors

Two trends of hypocenter depth and frequency clearly delineate the two separate transition zones. Intermediate-depth seismicity (70 – 300 km) is present only in the subduction portions of the San Cristobal and North New Hebrides Trenches, and all events in the transform section connecting the two subduction zones is shallower than 50 km. Earthquake frequency follows similar trends, with 3 to 4 times more earthquakes occurring in the subduction zones than in the transform zone. We observe this frequency trend in both the Harvard CMT and Engdahl catalogs.

Drawing boundaries between the subduction, transform, and trench-orientation changeover areas, we created 4 geographic regions used for comparative analysis. Interestingly, these geographic regions closely correspond to abrupt changes in slip vector domains, i.e. primary slip vectors are perpendicular to the trench in subduction zones, parallel and curve with the trench at the closed corner of Santa Cruz, and are parallel to subparallel in the open corner (Solomon Islands) and transform regions.

With both slip vector domains and average seismicity trends, the secondary slip vector (the slip vector described above is the primary slip vector) is controlled by the plate motion vector, as demonstrated by roughly parallel strikes of the second slip vector and the local NUVEL-1 plate motion. Therefore, both trench orientation (dictating breaking stresses) and plate motion direction play important roles in determining earthquake type at different sections of the trench.

Seismic trends: mechanisms, moment, and consistency

We constructed ternary diagrams [see Cliff Frohlich's abstract for explanation] and moment-weighted average focal mechanisms to get a handle on the overall seismic trends in the four regions. The ternary diagrams clearly show a scarcity of strike-slip mechanisms throughout the study area, with strike-slip mechanisms conspicuously absent from the transform region. Average focal mechanisms (a moment-weighted summation of all Harvard CMTs for a region) show strong thrust character in the Solomon Islands and Vanuatu regions, but only a small strike-slip influence is added in for the transform and closed corner transitions. The ternary diagrams support this trend, as well as show the mixed nature of transform region seismicity (thrust, normal, and strike-slip earthquake types in relatively equal amounts).

Trends in seismically-expressed moment roughly parallel the consistency trends outlined above. The earthquake moment per kilometer per year in the subduction zones is 5 to 8 times greater than that of the transform region. The transform region’s shallow, infrequent seismicity does not energetically expresses the local tectonics.

Geologic data

We also compiled fault and fold orientation data from Hackman, Petterson, and the British Geological Society in order to relate the geology to stress orientations and seismic activity. An immediate clue to stress orientations are the two sets of perpendicular faults and folds predominantly on San Cristobal. Fold axis orientations trend WNW throughout the island, where these fold axes are paried with two main fault trends—one almost perpendicular and trending NNE, and one parallel set of fault orientations. Many of the synthetic faults stretch across the width of the island, while antithetic faults extend over much shorter distances.

Tying these observations to trench orientation, we draw a correlation between a high rate of seismic activity and a lack of faults, folds, convoluted topography, or bathymetric expression. Also, the main fault and fold trends of Guadalcanal and San Cristobal are much more consistent with local trench orientations, not with the fairly constant subduction direction.

AMS dating of sediment samples from the Dominican Republic

G.S. Burr[1], Carol Prentice[2], Paul Mann[3], Martitia Tuttle[4], andJ. McGeehin[5]

[1]NSF-Arizona AMS Facility, University of Arizona, Physics Department, Tucson, AZ 85721
[2]USGS, 345 Middlefield Road, MS 977, Menlo Park, CA 94025
[3]Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Rd. Bldg. 600, Austin, TX 78712
[4]University of Maryland, Department of Geology, College Park, MD 20742
[5]Radiocarbon Laboratory, USGS National Center, Reston, VA 22092

Radiocarbon dating is widely used in paleoseisomological studies to calculate the age of individual strata and determine rates of motion along faults. Such rate estimates depend on the identification of stratigraphic layers, their relative displacement in three dimensions, and on accurate age determinations for each sediment layer. In the optimal case one could collect coarse (>few mm) pieces of charcoal or wood from every stratigraphic layer of interest and analyze them for ^{14}C. In practice such cases do not normally occur.

Alternative candidates for ^{14}C dating include bulk sediments, terrestrial gastropods, pollen, and soil organic matter (SOM). All of these are inferior to wood or charcoal dates. It is well-known for example, that organics in soils move at different rates, which vary from annual to millennial timescales (Jenkinson and Raynor, 1977; Dörr and Münnich, 1986; Trumbore and Zheng, 1996). The problem with dating SOM is to identify an organic fraction in the soil which was introduced at the time the sediment was deposited and has not been chemically altered since deposition. To address this problem we have measured the radiocarbon content of a variety of different SOM fractions using both physical and chemical organic carbon separates. Methods employed include sieving, differential thermal combustion and combinations of acid and base pretreatments. The suite of dates from the SOM fractions allows us to assess the potential variability and uncertainties in the ^{14}C ages of the soils. A second potential problem for SOM dates stems from the likely occurrence of physical contamination in the tropical environment (Scharpenseel and Becker-Heidmann, 1992). Ultimately the usefulness of SOM dates depends on a thorough understanding of these processes, which are specific to each site and soil type. Our eventual goal is to use the radiocarbon results from the SOM fractions in conjunction with those measured from charcoal or wood samples collected from the same horizons to document the usefulness of the SOM dates on their own.

In addition to the bulk sediment and SOM results we have made measurements on several species of terrestrial gastropods. It is shown that these samples have a reservoir correction which is related to the species of gastropod. We have also observed a gradient in the amount of ^{14}C from the exterior to the interior of the gastropod shells, suggesting post-depositional exchange of carbon. We use a selective dissolution pretreatment developed for corals to remove this secondary contamination (Burr et al., 1992).

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Plate boundary zone deformation in the northern Caribbean: Observations, measurements and models

Eric Calais

CNRS Géosciences Azur – 250 Rue A. Einstein – 06560 Valbonne – France (calais@faille.unice.fr)

The Northern Caribbean plate boundary (NCPB) mostly consists of a system of left-lateral strike-slip faults connected to the west with the middle America subdction zone, to the east with the Lesser Antilles subduction zone. In its western part, the NCPB trace is the purely strike-slip Swan fault, marine extension of the Polochic-Motagua fault zone of Central America (Rosencrantz and Mann, 1991). The Swan fault connects to the east with the Oriente through the Mid-Cayman spreading center, a short oceanic spreading ridge that has been generating the oceanic crust of the Cayman trough since late Eocene (Rosencrantz et al., 1988). From the Mid-Cayman spreading center to the western edge of the Cuban margin, the geometry of the Oriente fault is poorly know but earthquake focal mechanisms indicate pure strike-slip motion. Along the western part of the Cuban margin, the Oriente fault is a system of sinistrally offset en échelon fault segments associated with pull-apart basins. In contrast, the central and eastern parts of the Cuban margin are characterized by active compressional structures (échelon folds, reverse faults and southverging thrusts) that form a 300 km long narrow zone of transpressive deformation along the Oriente fault (Calais and Mercier de Lépinay, 1991). It is associated with frequent moderate earthquakes, with focal mechanisms showing either pure thrust or a combination of thrust and strike-slip (Perrot et al., 1997; Calais et al., 1998). To the east, in the Windward Passage, the Oriente fault is associated with active en échelon folds and flower structures (Calais and Mercier de Lépinay, 1995). Further east, the Oriente fault follows the northern Haitian coastline and connects with the Septentrional fault in northern Hispaniola (Mann et al., 1984).

The Septentrional fault is responsible for the uplift of the Cordillera Septentrional in the northern Dominican Republic and for active folding and faulting at its contact with the Cibao valley (Edgar, 1989; De Zoeten and Mann, 1991; Calais et al., 1992; Prentice et al., 1993). Offsets in terraces dated by radiocarbon on gastropods shells suggest that the Holocene slip rate across the fault is less than 13 ± 4 mm/yr (Mann et al., 1998). Marine geophysical surveys north of Hispaniola (Dillon et al., 1992; Dolan et al., 1998) and Puerto Rico (Masson and Scanlon, 1991; Speed and Larue, 1991; Grindlay et al., 1997) indicate that the Septentrional fault zone extends to the east north of the island of Puerto Rico with seismic evidences for strike-slip motion in that area (McCann and Sykes, 1984; Calais et al., 1992). These surveys have also revealed active compressional tectonic structures along the northern Hispaniola margin (folds and north-verging thrusts), that might be associated with some of the largest earthquakes along that segment of the northern Carribean plate boundary (Russo and Villasenor, 1995; Dolan and Wald, 1998). These compressive structures connect to the east with the Puerto Rico trench, where the subduction of the Atlantic oceanic lithosphere is associated with a south-dipping Benioff zone and a very strong negative gravity anomaly (-400 mGals). North of the Puerto Rico trench, the available structural data show a significant subsidence of its inner wall along large normal faults (Le Pichon et al., 1985; Heezen et al., 1985; Masson and Scanlon, 1991; Speed and Larue, 1991). Finally, active faulting associated with a significant seismicity has also been identified along the Enriquillo fault zone in southern Hispaniola and along the Muertos acretionnary prism south of the Dominican Republic and Puerto Rico. At the longitude of the Dominican Republic anc Puerto Rico, the relative motion of the Caribbean plate with respect to the North American plate is therefore accomodated by a 200 km wide deformation zone undergoing left-lateral shear along the Septentrional and Enriquillo faults, limited to the north and to the south by two large thrusts with opposite vergence in the Muertos and Northern Hispaniola-Puerto Rico trenches.

This wealth of structural and seismotectonic data has prompted the development of a number of models to explain the present-day deformation along the NCPB. Among the most recent ones, Deng and Sykes (1995) emphasize the role of compressive structure and thrusts earthquakes and assume a highly convergent motion between the Caribbean and North American plates. Calais and Mercier de Lépinay (1993) and Russo and

Villasenor (1995) emphasize the role of strike-slip structures and earthquakes, and assume a mostly strike-slip motion between the Caribbean and North American plates. In such models, compressive structures are related to the geometry of the major strike-slip faults. Mann et al. (1995) and Lundgren and Russo (1996) emphasize the role of independant microplates within the plate boundary zone. Dolan and Wald and Mann et al. (1998) emphasize the role of strain partitioning of the mainly east-west interplate motion into onshore/nearshore strike-slip faults (Septentrional and Enriquillo faults) and thrust faults (Muertos trough and northern Hispaniola margin). In the absence of quantitative data and direct measurements of the strain distribution within the plate boundary zone, these models are difficult to test. Indeed, the strain distribution among the active structures of the NCPB is not yet quantified and the slip rate along the major active faults is not known. In addition, the relative motion of the Caribbean and north American plates is poorly defined in global plate motion models because of a lack of constraining data such as transform azimuths, ocean ridge spreading rates around the Caribbean plate. Moreover, slip vectors of earthquakes in its northeastern part are likely to be biased by strain partitioning in a kinematic setting where strike-slip and convergence coexist. Global Positioning System (GPS) measurements in the northeastern Caribbean (CANAPE project) are now starting to shed some light on these issues.

In 1986, a sparse network of geodetic sites was occupied by GPS in the northeastern Caribbean, as part of a NASA program to test and validate this new technology in a humid tropical environment (Dixon et al., 1991). In 1994, this network was reoccupied and a number of new sites were added, in particular in the Dominican Republic. Some of these sites have been reoccupied in 1995, 1996, and 1998. 27 new sites have been established in the Dominican Republic in September 1998, they will be occupied during a two-week campaign at the end of January 1999. The analysis of the GPS data collected in 86, 94, and 95 shows an eastward motion of the Caribbean plate at a rate of 17 mm/yr relative to North America, measured at Cabo Rojo, southern Dominican Republic (Dixon et al., 1998). Additional measurements performed at 4 sites in the Dominican Republic in September 1998 confirm this result, with slightly faster velocities (18 to 21 mm/yr in a N80E azimuth). Similar velocities have been found on Aves island, confirming a velocity of the Caribbean plate relative to North America about twice higher that the NUVEL-1A prediction of 11(3 mm/yr. We modeled the velocity field measured at six sites in the Dominican Republic and one on Grand Turk Island on the Bahama Platform using three-dimensional dislocations in an elastic half-space. The fault geometry and seismogenic depth were taken for geological and geophysical observations and imposed. Although this type of forward modelling by trial and error is non-unique, the tests that we have performed so far require a far-field NS convergent velocity field superimposed on the mostly eastward displacement of the Caribbean plate. This convergence is mainly accomodated on the northern Hispaniola fault zone, which ruptured in a series of magnitude 7-8 earthquakes in the 1940s and accomodates oblique slip at a rate of 5 mm/yr (4 mm/yr strike-slip and 3 mm/yr dip-slip for the best fit model). The models indicate that the Muertos thrust accomodates 3 to 1 mm/yr of pure NS convergence. They show a slip rate of 9 mm/yr on the Septentrional fault (8 mm/yr strike-slip and 2 mm/yr dip-slip for the best fit model), in agreement with the geologicaly-derived Holocene rate, and 13 mm/yr of pure strike-slip on the Enriquillo fault. Trenching across the Septentrional fault indicates that it last ruptured 730 years ago, slipping about 5 m horizontally and 2 m vertically (Prentice et al., 1993). At a slip rate of 9 mm/yr, this fault has accumulated about 6 m of potential slip since that last rupture, which could cause a M>7.5 earthquake if it was enterely released today (Wells and Coppersmith, 1994). In addition, we find that the extraction of rigid rotations from the GPS-derived velocity field does not support the idea of a counter-clockwise rotation of the Puerto Rico block as proposed in some models but indicate east-west extension between Hispaniola and Puerto Rico.

These recent but still preliminary GPS results, together with the most recent tectonic and seismotectonic data, seem therefore to favor a model with a Caribbean/North America plate motion slightly oblique to the plate boundary trace and partitioned into strike-slip faulting in Hispaniola and along the inner wall of the Puerto Rico trench and thrust faulting offshore north and south of Hispaniola and Puerto Rico.

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ANALISIS DE FOTOLINEAMIENTOS DE LA REPUBLICA DOMINICANA

Sergio Chiesa (*), Giovanna Civelli (°), Simone De Toni (+).

(*) CNR-Centro di Studio per la Geodinamica Alpina e Quaternaria, Milano, Italia. E-mail cnrbg@uninetcom.it
(°) Geotec arl - Via Artigiani, 1, Brusaporto (Bg), Italia. E-mail geotec@uninetcom.it
(+) Geoisa International S.A. - San Francisco Dos Rios, San Josè, Costa Rica. E-mail geos@habitat.co.cr.

In this poster we present the results of the study of one of the argument in the project "Proyecto D: Prevención de Riesgos Geológicos (Riesgos Sísmicos) del Programa de Desarrollo Geológico-Minero SYSMIN", financed by the European Union.

At the workplace, we performed the followings activities:

- An analysis of somes LANDSAT TM images (Thematic Mapper) at scale 1:250.000, covering all the national territory of the Dominican Republic.
- Some in sito surveys aimed to look for evidences of neotectonics.
- The drafting of one computerized map at scale 1:500.000 of all the national territory which shows all the lineaments identified by LANDSAT images.
- A statistical study of the radial distribution and the lineament persistence.

The term "lineament" corresponds to all the linear elements, rectilinear or curvilinear, which effects the topographic surface and which can be related to the geological and particulary tectonic phenomena. The study of LANDSAT images allows to draw attention to the deformation of rigid style, which is tipically caracterized by high angles, while deformations of plastic style, often with low angles, may not result too clear.

We have subdivided the Dominican Republic into 12 homogeneous zones, according to the "terranes" recognized in Hispañiola by Mann et al. (1991). The overall analysis has covered 17200 lineaments, with a total lenght of 26000 km.

Some linear elements have been prevalently identified, with an average lenght of 2-3 km and maximum lenght of 4-5 km. The spatial distribution of lineaments is naturally heterogeneous, with different density according to the various"terranes".

The mayor lineaments' density is shown on very important tectonics elements (fault zone) which in fact are formed by a field of minor elements with some fractures that follow the linear development of the fault zone; the width of this fault zone is related to mechanical caracteristics of crossed rocks.

The analysis of lineaments' distribution shows the presence of a high concentration along a belt with a N-S trend between San Josè Ocoa, Bonao and Jima Abajo. This belt cuts off, breaks off or deviates a great number of lineaments with orientation E-W, NW-SE and NNW-SSE, which are those prevalent in the whole Dominican Republic and in each "terrane"; the belt may represents a segment of the Gonave microplate margin.

Therefore, this structural element has an evident sense of neotectonic and might be the reason of sismicity in the Bonao-Azua area.

Dominican Republic (Hispañiola Island, north-eastern Caribbean): a map of morpho-structural units at a scale 1:500000 through LANDSAT TM image processing

Sergio Chiesa (*), Guido Mazzoleni (°)

(*) CNR–Centro di Studio per la Geodinamica Alpina e Quaternaria, Milano, Italia. Email cnrbg@uninetcom.it
(°) Geoisa Internacional S.A., San Francisco Dos Rios, S. José, Costa Rica. Email geos@habitat.co.cr

The territory of the Dominican Republic is located in an active plate margin area, at the boundary between the North American and the Caribbean plates. This area has been affected by catastrophic earthquakes, both recently and in the past. For this reason, and with the objective of designing an instrumental network for monitoring the microseismicity of the area, all the geological data available in the literature was collected and synthesised, and an original remote sensing study was carried out. The latter supplied results that agree well with the general morpho-structural framework described by different authors and confirmed some of their details; in addition, it highlighted some innovative elements. The morpho-structural units that were recognised by this study seem to be in good agreement with the morpho-tectonic zones proposed by Lewis (1980) and Lewis & Draper (1990).

The Northern Cordillera and the Samanà Peninsula are sharply interrupted to the south (towards Cibao Valley) by an evident boundary, which is probably both the most important tectonic element and a seismic source, the *Septentrional Fault Zone*. This boundary is formed by a set of closely spaced morphological steps, which become progressively more evident from west to east.

The Eastern Peninsula appears to be a separated physiographic element, with the little deformation present being mostly of the shear type, as no clear evidence of thrusting was observed. This area seems to be affected by a slight, progressive and homogeneous tectonic uplift. In the literature the peninsula is considered an area with minimal or null uplift if compared with the areas to the west of a structural line striking N-S and located 70°W to the west (Mann *et al.*, 1995). The remote sensing study presented in this paper detected a highly deformed belt, striking roughly N-S, which extends from Boca de Yàsica to the north to the Rìo Ocoa lower valley to the south. This is a slightly more western location than the structural element mentioned above.

By contrast, the Central Cordillera shows the morphological characteristics of an area that is affected by fast and significant recent tectonic uplift. This is evidenced by the widespread slope instability phenomena on the steep mountain-sides and by the deeply cut drainage network. This morpho-structural unit appears to be clearly separated from the neighbouring tectonic valleys, which, on the contrary, are strongly subsiding. The Central Cordillera and the Eastern Peninsula join together through the most complex and composite sector in the whole area studied. In this sector most of the transitional units identified are present. Some of these units show clear indications of extensive/transtensive tectonics, evidenced by NW-SE oriented morphological steps and horst/graben structures.

The eastern portion of the important lowland belt that contains Enriquillo Valley, the Laguna del Rincòn, appears to be more affected by extension/transtension tectonics. The shape and geometry of the morphological steps observed could indicate that this area is situated at the northern boundary of a pull-apart basin.

The Southern Penìnsula shows characteristics that partly recall the Eastern Península. However, it is clearly more deformed by both transtensive and thrusting tectonics, the latter in the northern sector. Ridges, valleys and general morphological patterns, mostly oriented N50°W were observed. They are parallel to or form a low angle with extension/transtension structures, averagely striking N40°W, such as morphological steps, normal faults and proper grabens, like the most evident one near Pelempito.

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TERTIARY TECTONICS OF THE HISPANIOLA FAULT ZONE IN THE NORTHWESTERN PIEDMONT OF THE CORDILLERA CENTRAL, DOMINICAN REPUBLIC

COLEMAN, Andrew Jay, (acoleman@ensr.com), WINSLOW, Margaret Anne (winslow@aol.com)

CITY COLLEGE OF NEW YORK
Department of Earth and Atmospheric Sciences, J-106
137th Street & Convent Avenue
New York, New York 10031

ABSTRACT

New road-cuts and dam projects create a unique opportunity to produce a new geologic map of the northwestern piedmont of the Cordillera Central (Figure 1). The Hispaniola Fault Zone ("HFZ") crosses the piedmont region north of the Cordillera Central in the map area. This study area is bounded by the coordinates 70°45'W to 71°15'W and 19°30'N to 19°20'N within the San José de las Matas and Moncíón quadrangles. Field evidence confirms that strike-slip faulting occurred along the HFZ during the middle to late Tertiary. Sinistral faults displace Oligocene conglomerates and Miocene sandy mudstones and limestones. Strike-slip fault movement along the HFZ created a pull-apart basin as early as the Oligocene. The faulting pattern within the rocks of the pull-apart basin can be explained by a Riedel model for left-slip movement. En-echelon folding and faulting within the pull-apart basin are consistent with regional deformation and the tectonic evolution of the Caribbean/North American plate boundary. New evidence from en-echelon faults on the north side of the HFZ suggests that fault movement continued through the Late Miocene and quite possibly into the Early Pliocene.

TECTONIC SETTING

The study area along the northwestern segment of the HFZ is bounded by the Cibao Valley to the north and by the Cordillera Central to the south (Figure 1). The HFZ displaces Tertiary clastic rocks deposited along the dissected plateau (Palmer, 1979). This study focuses on the structural geometry and evolution of the deformed Tertiary rocks. A Riedel model for left-slip movement and new structural and stereonet data aid in this interpretation.

The Tertiary rocks deposited in the pull-apart basin are folded and faulted in a structurally complex manner. Local structures in the field area include left-lateral strike slip faults, stretched pebbles and shear fractures. Tectonic breccias are also found along fault traces in the field area.

Data analyzed from these structures suggest that the pull-apart basin formed consistent with a Riedel model for left-slip movement. The Riedel model predicts that the pull apart basin evolved along the HFZ. Tectonic breccias found along the main faults of the HFZ evidence that movement occurred from at least the Early Oligocene through the Early Miocene. New tectonic breccias found along en echelon faults in the HFZ indicate that deformation occurred into the Late Miocene. The structural development and movement along the faults of the pull-apart basin are related to the predominant trend of motion along the on-shore Northern Caribbean Plate Boundary Zone given its current transpressional relative motion which combines transform slip as well as convergence (Molnar and Sykes, 1969; Sykes and others, 1982, Pindell and Barrett, 1990; Mann and others, 1991).

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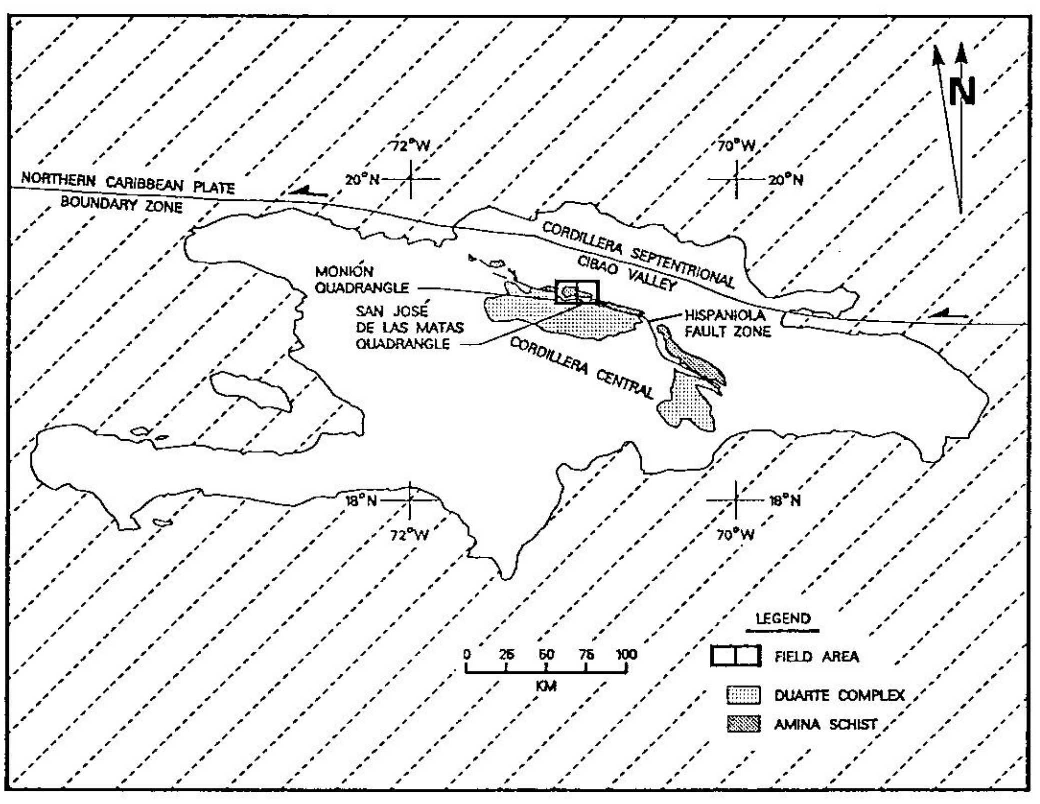

Figure 1 Location of the study area and general geologic features of the region.

Displacement partitioning and arc-parallel extension: Structural analysis of the Aleutian arc transitional margin.

John Comstock and Hans G. Avé Lallemant

Rice University, Department of Geology and Geophysics, 6100 S. Main St., Houston, TX 77005

The Aleutian volcanic arc is an ocean to ocean, concave, convergent margin between the North American and Pacific plates along which convergence obliquity ranges from perpendicular to the trench in the east to parallel to the trench in the west. Several authors (Jarrard, 1986; Geist et al., 1988; McCaffrey, 1991, 1992, 1996; Avé Lallemant, 1996) have developed the hypothesis that this increase in convergence obliquity produces strain in the fore-arc that is partitioned into trench normal and trench parallel components that correspond to the trench normal and parallel components of the convergence vector. Additionally, the margin is most accurately described by a system of the two plates and a portion of the overriding plate that is a quasi-independent of both plates, a trans-contractional terrane. The transcontractional terrane lies between the trench and back-arc bounding strike slip systems and is both translated west and internally extended as the convergence vector increases obliquity and rate. As this vector approaches parallelism with the Aleutian trench, an increasing percentage of the increasing convergence rate comprises the arc-parallel strike-slip component of the displacement. This differential displacement gradient necessarily produces internal extension of the terrane (Avé Lallemant and Guth, 1990; McCaffrey, 1996).

Structural geology studies on Unalaska, Adak, and Attu Islands in the Aleutian arc confirm that the deformational structures are not related directly to the relative plate convergence vector, but to trench normal and parallel components of the vector. All observed deformation was brittle, none ductile. Based on crosscutting and overprinting field relationships, data from Unalaska (53N, 167W) fall into five groups: reverse faults (F_1) related to NW-SE (arc-normal) contraction; conjugate strike-slip systems (F_2) and (F_3), related to the arc-parallel component of convergence and arc-parallel extension; normal faults (F_4) perpendicular to the arc resulting from arc-parallel extension; and veins and dikes (F_5), generally the youngest, showing arc-parallel stretching. Data from Adak (52N, 177W) show similar structures and arc-relative orientations, although the absolute attitudes are rotated from the Unalaska data (commensurate with the change in trench attitude.) Reverse and normal faults are less prominent, and therefore relative timing is not as well constrained as on Unalaska. Additionally, Adak has NE-SW trending, dextral splays between the arc-parallel dextral strike-slip systems, with individual fault blocks showing possible clockwise vertical-axis rotation. Data from Attu (53N, 173E) also show similar structures and arc-relative orientations, again with absolute attitudes rotated clockwise from the data on Unalaska and Adak.

Analysis of the brittle structures on three islands across almost the entire length of the Aleutian arc reveal a predominance of strike-slip and normal fault systems indicating arc-parallel extension and reverse fault structures indicating arc-normal contraction. Relative to the arc, the orientation of nearly all structures is constant. However, relative to the convergence vector of the North American and Pacific plates, the orientation of the structural elements of these Aleutian Islands varies considerably. The degree of penetrative deformation increases to the west as well, implying greater strain as more of the plate convergence vector is transferred to strike-slip and the commensurate internal extension.

Unfortunately, due to poor exposure and lack of stratigraphic control, the magnitude of displacement will be very difficult, if not impossible, to measure by conventional field geologic methods. Part of our continuing research into the Aleutian arc displacement is a three year GPS study, which should produce quantitative measurements after the 2000 field season.

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Evidence for subduction locking and strain partitioning from GPS measurements on the southern Hikurangi Margin, New Zealand

Desmond Darby and John Beavan

Institute of Geological & Nuclear Sciences, PO Box 30-368, Lower Hutt, New Zealand (d.darby@gns.cri.nz, j.beavan@gns.cri.nz)

The degree of locking of the Hikurangi subduction interface beneath the Wellington region of New Zealand is not well known. The Wellington and Wairarapa faults in the over-riding plate are the most important of many Quaternary transcurrent faults that are reactivated reverse faults. Interface locking has therefore occurred in the past, and would play a major part in determining the present interaction between the subduction interface and these crustal faults, and the potential for great earthquakes in the region.

A GPS project to address these problems started in 1992 with a small network crossing the Wellington fault. This network was re-surveyed and extended in 1994 to cross the entire southern North Island. The larger network has since been re-surveyed in 1995 and 1996. The average station spacing is about 12 km, and this is as great a density of GPS sites as has been established anywhere. There are about 50 points in common to at least two of these four surveys.

Results show that the relative velocity across the 80-km network width is about one half the NUVEL-1A prediction for the Pacific and Australian Plates. Inversion of the velocities and their full variance-covariance matrix can determine some of the elastic dislocation parameters that describe the source of the surface deformation as a locked segment on the subduction interface. The locking occurs between depths of 6±1 km and 22±1 km. This depth range coincides with a paucity of seismicity, and its limits correspond with low-angle thrust earthquake focal mechanisms that have recently been obtained by *Reyners et al.* [1997]. The fraction of plate motion presently locked is not very well determined, but probably lies between 75-100%. The width over which a great thrust earthquake may occur is constrained to be about 70 km down-dip.

As velocities have become better determined through time, a concentration of strain has become increasingly obvious across the Wellington fault trace. This is consistent with measurements obtained from a 5-m aperture rod strain-meter. Paleoseismic data indicate this fault has a mean recurrence interval of 500-800 yr for M=7.5 events, with the last being 300-400 yr ago [*Van Dissen and Berryman,* 1996]. There is no corresponding concentration of strain across the sub-parallel Wairarapa fault to the east. This fault has a 1-2 kyr mean recurrence interval for the last 4-5 events, and last ruptured in an M=8.2 earthquake in 1855, probably without slip on the plate interface [*Darby and Beanland,* 1992]. Forward modelling of slipping and locked patches on both the subduction interface and the Wellington fault can probably explain the GPS observations. However, algorithms to formally invert the data are being prepared, as our experience shows that inclusion of the covariance matrix is important.

It remains to be seen whether fault listricity can be determined from the closely spaced geodetic points that we have in this network. Although the deeper limit of locking lies vertically beneath the Wellington fault, the geometry of these reactivated reverse faults may show that this limit can be better associated with the junction of the Wairarapa fault and the subduction interface.

Multichannel seismic profiles showing deformation of the North American plate and plate boundary zone near the northeastern corner of the Caribbean plate

William P. Dillon[1], Elazar Uchupi[2], Uri S. ten Brink[1], Juan Acosta[3], Christopher H. Anton[1], Myung W. Lee[4]

[1]U.S. Geological Survey, Woods Hole MA, 02543, USA, bdillon@usgs.gov, utenbrink@usgs.gov, canton@usgs.gov
[2]Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA, euchupi@whoi.edu
[3]Instituto Español de Oceanografía, Corazon de Maria, #8 - 1°, 28002, Madrid, Spain, Juan.Acosta@md.ieo.es
[4]U.S. Geological Survey, Box 25046, Denver Federal Center, MS 960, Lakewood Colorado 80225, USA, mlee@usgs.gov

The North American plate (NOAM) is moving westward relative to the Caribbean plate (CARIB), with which it is in contact. NOAM is being subducted along the eastern boundary of CARIB, forming the Lesser Antilles island arc, and NOAM is moving past the northern side of CARIB with a dominantly transcurrent motion. At the northeastern corner of CARIB, the pattern is complicated by the presence of a plate boundary zone (PBZ) that extends along the northern side of CARIB, between CARIB and NOAM. The PBZ consists of one or more microplates that support eastern Hispaniola, Puerto Rico and the Virgin Islands. The contact between PBZ and NOAM occurs at the Puerto Rico Trench, north of the islands, and the contact between PBZ and CARIB occurs at the Muertos Trough, south of the islands. Where NOAM is overridden by the CARIB and PBZ, it is forced into a compound bend so that it dips westward to the east of the PBZ/CARIB and southward to the north of those plates. Thus complex stresses are being applied to contort the plate to its observed configuration.

Newly available multichannel seismic profiles are located on the deformed part of the NOAM and PBZ north of the Virgin Islands in an area of dominantly strike-slip motion. The data consist of a set of profiles collected jointly by the Instituto Español de Oceanografía and the U.S. Geological Survey in 1997 and newly-released seismic data that were collected by Shell International in 1974 (Dillon et al. 1998). Both sets of data were processed recently by the USGS seismic processing center.

Multibeam bathymetry, which was also collected during the 1997 cruise, discloses ~100-km-long, en echelon, WNW-oriented steps on the NOAM near its contact with the PBZ. Seismic profiles show these as fault blocks, including horsts and grabens. Such extensional features were presumably formed by the stretching that resulted from bending of the NOAM as it was overridden by PBZ lithosphere; segmentation of the steps also may be partially the result of the required extension caused by the compound warping of the North American plate. The seismic profiles show the continuation of NOAM crust that has been subducted and that dips beneath the PBZ. The subducted NOAM lithosphere also shows fault-block steps, apparently parallel to those exposed north of the trench. It seems unlikely that these steps would be preserved if significant subduction motion were normal to the plate boundary (normal to the Puerto Rico Trench axis), but their preservation is consistent with a dominantly transcurrent motion along the plate boundary, in which the subduction occurs to the east and motion between plates is basically strike-slip.

In the central part of the PBZ, shallow, flat-lying Tertiary limestone strata, as young as Pliocene age (Schneidermann et al., 1972; Moussa et al., 1987), form the Virgin Islands platform. However, on the north side of the PBZ, these strata have undergone major tilting (to 4°) and substantial subsidence. This post-mid-Pliocene collapse has resulted in more than 5 km of subsidence of platform rocks in the last ~3.3-3.6 my. Tilting of stratified limestone and active earthquake shaking have resulted in detachment and sliding of limestone slabs along the northern margin of Puerto Rico and the Virgin Islands (EEZ-SCAN 85 Scientific Staff, 1987; Schwab et al., 1991; Scanlon and Masson, 1996). Abrupt movement of these slabs may have generated some of the historical tsunamis near Puerto Rico and the Virgin Islands. Nondefinitive indications of small, offscraped tectonic accretionary wedges at the northern limit of the PBZ may suggest a minor component of shortening across the trench.

Two major tectonic movements have affected the region. The first is the westward movement of NOAM relative to CARIB (and the PBZ), which was initiated by a plate reorganization in Eocene time and still continues. This is the dominant plate motion that is well known and that accounts for the subduction at the Lesser Antilles island arc and the basic transcurrent motion along the northern Caribbean plate boundary. The second major tectonic movement that affects the northeastern Caribbean region is much younger, but it has resulted in major vertical movements. This is the post-mid-Pliocene set of movements that has resulted in more than 5 km of subsidence in some locations. This motion probably accounts for the present depth of the Puerto Rico Trench system, which therefore, must be very young, consistent with the very small amount of sediment accumulated there. The extremely large free-air gravity anomaly north of Puerto Rico (-380 mGal, the largest negative free-air gravity anomaly in the world) would logically be associated with the stresses that have resulted in downward crustal movements. The cause(s) of the catastrophic recent subsidence is not clear. However, analysis of seismicity patterns suggests that NOAM and CARIB, which are both bent down under the PBZ, may be in contact at depth (Dillon et al. 1996). One could speculate that some sort of restraining bend might exist at depth beneath the PBZ, such that the transcurrent motion between NOAM and CARIB is converted to vertical motions.

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Strike-Slip to Subduction Transition in South-Central Alaska

Diane Doser, Monique Velasquez, Annette Velleiux and Rodolfo Lomas

University of Texas at El Paso

South-central Alaska is located in an area of complex deformation between the Pacific and North American plates. Northwestard motion of the Pacific plate relative to North America results in subduction of the Pacific plate along the Aleutian trench west of 146 degrees W, and right-lateral strike-slip faulting along the Queen Charlotte/Fairweather fault system east of 136 degrees W. The plate boundary is complicated by the collision of the Yakutat block, an allochthonous terrane, with North America. Study of the source parameters of magnitude > 5.5 earthquakes occurring in this region since 1920 has been used to help determine how slip is partitioned along this boundary. Within the Sitka region, all events since 1927 show slip in the direction of plate motion. To the north in the Cross Sound/Fairweather region the larger events show slip in the direction of plate motion, but the smaller events (M<=6.0) show a clockwise rotation of slip direction relative to plate motion. In the St. Elias, Pamplona and Gulf of Alaska regions, about 40% of the earthquakes, regardless of size, show slip that deviated more than 15 degrees from plate motion, with no consistent direction of rotation relative to plate motion observed. In the Prince William Sound and Cook Inlet regions, the mismatch between slip vectors and plate motion increases to 60%. This mismatch does not appear to depend on whether the events occur above or below the plate interface. Most slip vectors for events located beneath Cook Inlet are rotated to the west (counterclockwise) of plate motion, while events east of Cook Inlet show greater variability. Events directly below the plate interface in Prince William Sound show east-west directed slip, while events above the plate interface in the same region have highly variable slip. These shallow events may reflect transitory stress changes following the 1964 great Alaskan earthquake.

The transition from Cretaceous convergence to Cenozoic strike-slip in Hispaniola and eastern Cuba

Grenville Draper

Department of Geology, Florida International University, Miami, FL 33199, USA

The presence of Late Cretaceous to lower Eocene magmatic arc rock suites and HP/LT metamorphic rocks in Hispaniola and Cuba indicate convergence. This convergence was interrupted by an oblique collision with the Bahama platform which caused the transition to late Paleogene and Neogene strike-slip dominated tectonics. This collision, as timed by the deposition of serpentinite deposits, seems to have begun in very latest Maasthrichtian time in Cuba, but is Paleocene in Hispaniola.

In (?mid) late Eocene time and possibly later, transpression was accommodated south of the present Cordillera Central by the formation of the south-verging Peralta/Ocoa fold and thrust belt. Offset is uncertain, but Pindell and Barrett, 1990 suggest strike-slip component of 350 km or more.

By latest Eocene/Oligocene, strike slip motion was transferred to the Hispaniola fault zone. Offset of the Amina-Maimon mylonite belt suggests at least 120km of motion, about 50km of which was involved in the formation of the Tavera basin. This motion may have continued into early Miocene time.

From late Miocene to Pliocene the locus of strike-slip motion jumped northward again to the fault systems of the Cordillera Septentrional. The exact sequence of faulting and the amount of offset are uncertain but seems to have been:

1. Rio Grande/ Rio Bajabonico faults; offset scaling relationships suggest approx >10km each,
2. Septentrional fault; offset of amber deposits suggests 85km ?scaling relationships suggest >30km,
3. Camu fault; observed offset 50-60km

It is not clear when Hispaniola began to separated from eastern Cuba, but consideration of the rate of motion of the Caribbean and North American plates (as given by the rates of opening of the Cayman Trough) it was probably in the Oligocene.

At the present time strike-slip motion in Hispaniola is taking place simultaneously in Hispaniola: offshore and on the Jacagua fault in the Cibao Valley in the north, and along the Enriquillo-Plantain Garden Fault in the south. In addition, north-south shortening is being accomodated by underthrusting in southern Hispaniola.

The example of Hispaniola suggests that the localization and partitioning of deformation in the wake of the transition from convergence to strike-slip does not follow any simple geometric or temporal pattern. Pre-existing structures and the geometry of the plate boundary are probably the most important controlling factors.

A Sedimentologic Signature in the Cibao Basin's Neogene Strata of Convergent Strike-Slip Motion on the Septentrional Fault, northern Hispaniola

Johan P. Erikson

Dept. of Earth Sciences, Dartmouth College, Hanover, NH 03755

Introduction

A sedimentologic signature of basement tectonism is identified within the upper Neogene Yaque Group, which accumulated on the asymmetrically subsiding basement of the Cibao basin, northern Hispaniola. Loading of the Cibao basement by south-vergent oblique thrusting along the Septentrional fault zone of the Cordillera Septentrional has been established through seismic, gravity studies, and structural studies. The sedimentary feature to be discussed is an incursion of conglomeratic sediment gravity flow deposits within an otherwise fine-grained section of calcareous siltstone at the base of the Mao Formation on the distal (i.e., southern) side of the Cibao basin. A critical aspect is that water depths increased at the time of conglomerate influx, which contrasts with the more common situation elsewhere of a water-depth decrease associated with progradation of coarse strandline and shoreface facies.

Background problem

The rates of relative sea-level (RSL) change and sediment supply control shoreline position and accommodation space within nearshore marine depositional systems. A high rate of RSL rise and a low sediment supply rate lead to transgression, while a low rate of RSL rise and high sediment supply lead to regression. In shelf and slope settings, transgression is typically interpreted as leading to the generation of thin sections of fine-grained sediment that accumulate over a long time period (cf. Transgressive Systems Tract). This model works just fine for passive margins and similar low-gradient settings with low rates of RSL rise and transgression. However, many active plate boundaries (convergent or strike-slip) have nearshore depositional settings with high-gradient depositional surfaces and occasionally rapid rates of RSL rise and transgression due to faulting. Based on sedimentary sections of the southern Cibao basin, I am working with a model in which isolated intervals of coarse sediment gravity flows break an otherwise continuously deepening and fine-grained shallow-marine sequence, and are the result of a rapid acceleration of transgression and RSL rise. Transgression and RSL rise accelerate due to contraction across the main, basin-bounding fault, the Septentrional fault.

Southern Cibao basin stratigraphy: the Yaque Group.

The Yaque Group comprises the vast majority of Neogene strata in the western Cibao Valley. The Upper Miocene to lower Middle Pliocene Yaque Group consists of the Cercado, Gurabo, and Mao formations. The following is a brief summary of my observations and interpretations of the southern Cibao basin (Erikson et al. 1998).

Sedimentologic and faunal evidence indicates that the entire Yaque Group preserves one single, continuous episode of transgression, deepening of the depositional surface, and subsidence. The notable break at the base of the Mao Formation in the generally upward-fining trend is <u>not</u> associated with a shallowing event.

(Step 1) Transgressive shoreline evolution was dominated by micro- to meso-tidal, wave dominated processes above a narrow, steep shelf or ramp. Brackish-water and shallow-marine deposits of the Cercado Formation were succeeded by calcareous siltstones and sandstones with a minor component of Central Cordillera-derived epiclasts within the Gurabo Formation. The depositional surface was continuously deepening during Cercado-Gurabo time, as inferred from sedimentary structures and the faunal assemblage.

(Step 2) The pebble- and cobble-conglomerate comprising a single, 10 to 20 m thick sequence of upward-fining and -thinning sediment gravity flow deposits at the base of the Mao Formation abruptly interrupt an otherwise fine-grained sequence. This occurred as water depths <u>increased</u> (based on sedimentary structures and faunal assemblages). Subsidence of the Cibao basement must have accelerated during deposition of the uppermost Gurabo and lower Mao Formations. Rapid subsidence was due to uplift of the Cordillera Septentrional along the Septentrional fault zone.

(Step 3) The enlarged sediment supply and possibly steepened depositional slope combined with normal storm activity and increased seismicity to generate a margin-wide pulse of coarse-grained, sediment gravity flows. Repeated flow events containing coarse, Central Cordillera-derived igneous and Tabera Group clasts created repetitive, stacked sequences of generally upward-fining and thinning conglomerates and sandstones at the base of the Mao Formation.

(Step 4) The supply of coarse clasts decreased after the initial influx, as seen in outcrops. Sedimentation returned to the pattern established during Gurabo deposition of fine-grained, deep-water, calcareous silt deposition contemporaneous with localized shallow-water carbonate buildups. Basement subsidence slowed and possibly reversed in middle and upper Mao-time as indicated by the deposition of the prograding shallow water facies within the clays of the upper Mao Formation.

Model: Episodic basinal influx of coarse, epiclastic shoreline sediments driven by accelerated transgression

(Step 1) A wave-dominated shoreline is transgressing above a moderately steep depositional surface due to relative sea level rise in excess of sediment supply. Much of the epiclastic sediments are retained landward of the offshore-transition zone by washover and normal intertidal processes. Those sediments that episodically pass onto the shelf and/or slope are deposited in upward-fining and thinning sequences possibly locally affected by reworking storm and geostrophic currents.

(Step 2) Acceleration of relative sea level rise occurs due to tectonic or eustatic causes. Transgression accelerates because sediment supply cannot immediately increase and compensate for the increased rate of relative sea level rise. Accelerated transgression, however accomplished, leaves a large volume of unconsolidated, coarse, upland-derived sediments below the shoreface zone. The faster the transgression, the greater the amount of the foreshore-backshore prism stranded on the shelf seaward of the shoreface.

(Step 3) Storms, seismic events, and possibly a steepened depositional surface (in the case of accelerated asymmetric basin subsidence) induce sediment gravity flows of the coarse, unconsolidated sediments, transporting them down the depositional slope under high energy conditions. Repeated sediment gravity flow events lead to deposition of repetitive sequences of graded conglomerates and sandstones. More sediment is produced during accelerating transgression than during steady-state because transgression is acting more quickly than sediment supply. The excess sediment is the mobile, unconsolidated sediment above storm wave base which was released from the strandline prism during acceleration of transgression. The stratigraphic record, as seen offshore, preserves coarser and thicker sediment gravity flows than were preserved prior to acceleration of transgression.

(Step 4) The rates of transgression and RSL rise stabilize. A constant rate of transgression leads to an equilibrium in which bars/beaches grow to a stable size. As this equilibrium is approached, the volume of sediments passing offshore is reduced until a steady state is reestablished. Storms and seismic events trigger sediment gravity flows which reduce the volume of the excess sediment until equilibrium is reestablished. Once the oversupply of relict sediment is exhausted there is only the smaller, background input of sediments that are transported beyond the intertidal zone, and sedimentation again becomes dominated by finer grained, probably hemipelagic, sediments.

Relevance to the Transitions from Subduction to Strike-Slip Plate Boundaries

Formation of the sedimentary feature addressed in this study is initiated by a very rapid RSL rise, which is most likely to occur due to rapid loading or extension of a basin's basement. The margin-wide incursion of conglomerate within fine-grained forereef slope deposits (or similar distal accumulations) is a feature that may function as an indicator of rapid basement subsidence. Correct interpretation of water depth changes is critical, because in the absence of reliable water-depth indicators, many relatively coarse-grained intervals are somewhat reasonably correlated with a decrease of water depth. However, for the model described here, an increase of water depth is required. One clue to the distinction between these contradictory modes of generation is the clear presence of a progradational, Highstand Systems Tract (HST) associated with a RSL fall or stillstand, versus the absence of all but the thinnest HST associated with a rapid RSL rise. To distinguish the proposed model from typical lateral migration of coarse, channelized debris flows, there must be multiple exposures along the paleo-shelf margin from which one may be able to deduce that channel migration has not occurred. If the rock record is reevaluated with an awareness of the possible tectonic significance of margin-wide, anomalously coarse intervals, then more sedimentary evidence of tectonic activity in subduction to strike-slip transitions may be found.

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Seismic Characteristics of Subduction/Strike-slip Transition Zones as Determined from Global Earthquake Catalogs

Cliff Frohlich[1], Andria Bilich[1,2], and Paul Mann[1]

[1]Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs #600, Austin, TX 78759
[2]Department of Geological Sciences, University of Texas at Austin, Austin, TX 78713

Earthquake catalogs provide an important source of information about the nature of tectonic activity along subduction/strike-slip transition zones. We present information on these zones selected from three global catalogs:

- The Harvard CMT catalog includes focal mechanisms from more than 10,000 earthquakes occurring between 1977 and 1998. Application of reliability criteria proposed by Frohlich and Davis (1999) eliminates about half of the mechanisms. The remaining mechanisms provide the principal data for this research.
- The EHB catalog presents carefully relocated hypocenters (Engdahl et al., 1998) for 100,000 earthquakes occurring between 1964 and 1995. Application of reliability standards for the number N and distribution (gap) of locating stations (typically, N ≥ 20; gap ≥ 200°; residual ≤ 2 sec) eliminates about a third of the hypocenters. The remainder provide the principal information about the geographic location of earthquakes used in this study.
- The Abe historical catalog presents locations for about 1500 large earthquakes occurring between 1898 and 1976 (Abe, 1981). It is globally complete for earthquakes with magnitudes of 7 and above. Because infrequent, large earthquakes are responsible for most of the seismically-expressed plate motion, the Abe and CMT catalogs provide the best available information about geologically significant earthquakes over the past century.

A geographic region meets our definition for a subduction/strike-slip transition zones if it possesses:

1) a plate-boundary segment with numerous thrust CMT mechanisms (P-axis dip ≥ 50°);
2) either a plate-boundary segment with numerous strike-slip CMT mechanisms (B-axis dip ≥ 60°) or a documented strike-slip fault; and
3) intermediate-depth (h ≥ 100 km) earthquakes in the EHB catalog situated within the zone.

Applying these criteria, there are approximately 26 qualifying geographic regions. Of these, 7 occur at triple junctions. The remaining 19 are regions of progressive transition along a continuous plate boundary; as explained in the previous presentation, we tentatively classify 14 as 'open' and 5 as 'closed' according to their geometery.

Several features of the seismicity in these 26 transition zones are remarkable:

- At the 19 zones of progressive transition, earthquakes with strike-slip mechanisms are absent or relatively rare, even in areas such as the western Aleutians where there are few thrust earthquakes and intermediate-focus earthquakes disappear. Cumulatively, at the transition the strike-slip CMTs are far less numerous and than the thrust CMTs; furthermore, taken as a group, the thrust CMTs generally contribute nearly all of the total moment (usually > 90%).
- If we compare the record of historical earthquakes to the CMT catalog, an important question is whether this moment deficit is taken up by very large but very rare strike-slip earthquakes, or instead by aseismic motion. Answering this question has significant implications for evaluating seismic hazard in densely populated transitions zones, including the eastern Caribbean and the Philippines.

- At the 7 triple junction transitions zones, strike-slip earthquakes are often numerous, especially if one triple-junction arm is a transform fault in oceanic crust. A typical example is the Antarctic-Nazca-South America triple junction in Chile.
- If we classify all CMT into four categories–thrust (P-axis dip ≥ 50°), strike-slip (B-axis dip ≥ 60°), normal (T-axis dip ≥ 60°), and 'other' (satisfying none of the above characteristics)–we find that CMT in the 'other' category are more common in the transition areas than along regular subduction or strike-slip plate boundaries (see figure below).
- In each transition zone we display the relative frequencies of different earthquake types using a ternary diagram with vertices corresponding to thrust, strike-slip, and normal mechanism (Frohlich, 1996). Often, the more complex patterns of focal mechanisms seem to occur where the a plate boundary encounters fragments of arc or continental crust. The complexity caused by these fragments complicates the classification of transitional boundaries. At present, we have been unable to identify any obvious differences between the patterns of focal mechanisms at 'open' or 'closed' boundaries.

There are mechanical reasons why 'other' mechanisms tend to be rare among shallow earthquakes in non-transitional tectonic environments. In particular, the stress conditions that hold at the Earth's surface produce strain releases which correspond to pure thrust, pure strike-slip, or pure normal focal mechanisms. Thus the presence of 'other'-type mechanism is notable. In some cases it may be indicative of stress conditions which are changing abruptly along a plate boundary; alternatively, it may simply reflect the complications introduced by the presence of arc or continental crust.

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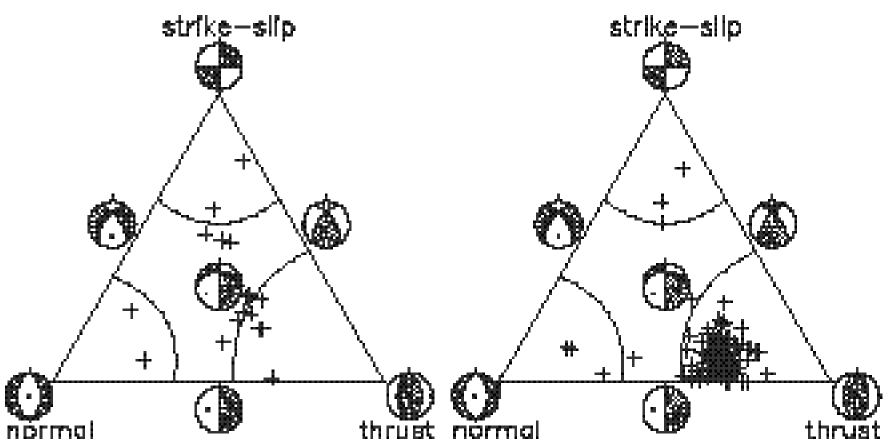

Ternary diagram showing distribution of shallow-focus CMT in the subduction/strike-slip transition zone in the western Aleutians (left diagram: 17 quakes, 165.5°E-173°E) and in the ordinary subduction region of the central Aleutians (right: 117 quakes, 178°E-174°W). Typically, earthquakes are less numerous and focal mechanism types are more variable in transition zones than in adjacent regions.

Rhyolitic arc-related volcanic corridors at subduction to strike-slip transitions: comparing North Wales and North Island, New Zealand.

Wes Gibbons

Department of Earth Sciences. Cardiff University. Cardiff CF1 3YE, Wales, UK.
e-mail: Gibbons@cardiff.ac.uk.

Some of the most voluminous eruptions of rhyolitic pyroclastics on Earth have occurred from linear clusters of calderas confined within fault-controlled corridors where an oceanic intra- or backarc basin impinges upon continental crust. The most spectacular modern example is the Taupo volcanic zone of North Island, New Zealand where over 10,000km^3 of ignimbritic ash flow tuff has been erupted over the last 1.6Ma. A similar, but much older, example of an arc-related rhyolitic volcanic corridor is partly preserved within late Ordovician rocks in the Snowdonian mountains of northwest Wales, UK.

The mid-Caradoc volcanic rocks of Snowdonia, produced by the subduction of Iapetus oceanic crust beneath Avalonia, provide a closely studied ancient analogue for modern arc-related rhyolitic magmatism. They represent the climax of some 35Ma of Ordovician (late Tremadoc to mid-Caradoc) subduction-related magmatism within a broadly elongate (c.120 x >200km) depocenter (the Welsh Basin). Snowdonian volcanicity was restricted in both space and time: eruptions took place over just a few (?2-4) million years inside the span of three mid-Caradoc stages (Soudleyan, Longvillian, Woolstonian) and two graptolite zones (*Dicranograptus clingani* and *Diplograptus multidens)* The tectonic setting invoked for the Welsh Basin at this time was one of subduction and sinistral transtension within an arc founded on continental crust.

Snowdonia volcanism was restricted to a NE-SW corridor, now c.20km wide (after Caledonian shortening), within which at least six major rhyolitic calderas, two andesitic stratovolcanoes, and several basaltic vents developed. Thick (locally >500m) rhyolitic ash flow tuff sequences were erupted from the calderas into a shallow marine and locally subaerial environment. These rhyolitic products are sometimes intercalated with, and were commonly followed by, basaltic effusions leaking up bounding faults and constructing transient Strombolian cones and trough-accumulations of submarine lavas. Significant andesite volcanism was confined to the northeast and southwest ends of the presently exposed corridor, although these eruptions were not exactly coeval because eruptions began later in the southwest. Abrupt cessation of magmatism occurred in Woolstonian times and black graptolitic mud covered the subsiding, extinct volcanic centres.

New Zealand currently lies on a transition from oceanic subduction to continental dextral transpression at the Australian-Pacific plate boundary. The two plates are both spreading away from Antarctica, but variations in the anticlockwise rotation of the Pacific plate has controlled the obliquity of its convergence with the Australian plate. Cenozoic subduction-related magmatism was initiated in earliest Miocene times in the north of North Island where andesites with associated basalts and minor rhyolites were erupted. Miocene arc volcanicity then focussed on the Coromandel Peninsula, a north-south belt (c. 35 x 200km) which terminates against the younger Taupo belt to the south. Early basalt-andesite eruptions in the Coromandel zone were later, in Pliocene times, joined by the first major rhyolitic ignimbrite eruptions. More recently, volcanism has reorganised into the NE-SW oriented Taupo volcanic zone the central part of which has become overwhelmingly dominated by Quaternary rhyolitic ignimbrite eruptions from a cluster of at least 8 caldera complexes.

The oldest volcanic centre (Mangakino Caldera) began erupting ash flow tuff around 1.62Ma but now lies west of the main focus of rhyolitic volcanism which over the last 0.64Ma has been the most productive site of rhyolitic volcanism in the world. This central zone today forms an actively extending (5-20mm/y) land corridor (120km by 40km) with an extremely high heat flow (c. 2600MW/100 km), and is filled with some 3km of mostly rhyolitic pyroclastics.

Major accumulations of rhyolite in continental crust require wholesale crustal or extreme fractional crystallisation of large quantities of ponded, mantle-derived (but preferably crustal contaminated) magma, or some combination of both. Although crustal fusion has been invoked to explain the Snowdonian rhyolites, most previous workers have favoured basalt fractionation as the major process at work. A similar petrogenetic debate has occurred over central Taupo where rhyolite is hugely dominant over basalts and intermediate fractionates: 95% rhyolite (12,000 km^3) as compared to 0.1% basalt (12 km^3). This fact, combined with an extraordinarily high heat flow, has led some authors to insist that the bulk of the Taupo rhyolites can only be a result of significant crustal melting.

Central Taupo lies at the southern end of the recently extinct Coromandel volcanic corridor, and heat flow is likely to have been elevated since at least Pliocene times. Quaternary magmatism in central Taupo therefore captured pre-heated crustal rocks, and perhaps also reservoirs of mantle melts produced by late Neogene subduction. Given the density contrast at the Moho, mantle-derived arc-related magma would tend to pond, an effect further promoted by the increased fracture toughness of a hot, partially molten crust. The petrogenetic pathway required to produce the central Taupo rhyolites is therefore considered to be one involving density-bound underplating beneath crust with an inherited high heat flow. Melting was perhaps aided by heat generated from intracrustal plastic deformation which would contribute synergistically to crustal anatexis which in turn would inhibit upward propagation of feeder dyke systems and thus reduce transmission to the surface of mantle-derived magma.

Despite the obvious differences of subduction direction, age, and sense of transcurrent movement, there remain several striking similarities in the tectonic settings of Taupo and Snowdonia. In both cases early volcanism was “normal” arc in character, and was heralded by a deformation phase associated with the onset of subduction (Tremadoc in Wales, Miocene in North Island). The first major rhyolitic tuffs were erupted after some 15-20Ma, and the latest phase of volcanism in New Zealand (latest Pliocene-present day), and the final phase in Wales (Soudleyan-Woolstonian) produced the greatest amounts of rhyolitic ash-flow.

The Hikurangi forearc has rotated from a WNW trend in the early Miocene to its present NE-SW orientation. During this rotation suprasubduction rollback-induced extension has propagated southwards for 2000km from the oceanic Lau Basin to the Havre Trough, and rhyolitic volcanism has transferred from the Coromandel zone to central Taupo. Initial spearheading of the North Island continental crust by the southward propagating suprasubduction extension produced the Neogene arc magmatism of North Island. Rollback then rotated the arc such that magmatism initially focussed within the Coromandel corridor but then became extinguished as continental margin-parallel shear was favoured over subduction. Continued rollback eventually resulted in a more orthogonal interaction between the axis of arc extension and the continental crust of North Island, favouring a return to arc magmatism accompanied by suprasubduction extension of the continental crust beneath Taupo. Continued rollback of the Hikurangi subducting slab is promoting clockwise rotations (measured at 7°/Ma in some areas) and extension of the Taupo corridor. It is suggested that the Snowdonian rhyolitic corridor was similarly produced by this combination of “spearheading” and rollback-induced rotation of an actively extending arc basin into Welsh continental crust.

There is not a simple continuum between the axes of the Havre Trough and the Taupo zone, but instead they show offset along a structure associated with (or at least coincident with) the Vening Meinesz fracture. Analogue modelling experiments illustrate how oblique impingement of the arc system on the continental margin, which is weaker than both oceanic and continental crust, could induce shear parallel to the margin and thus explaining the observed 50km offset along the VMFZ.

The apparently sudden extinction of Snowdonian volcanism in mid- to late Caradoc (Woolstonian) times is compatible with a model whereby magmatism is extinguished as subduction transfers to transcurrent movements. There is no evidence for collision having terminated subduction beneath Wales: regional compression of the Welsh area occurred over 50Ma later, during the Acadian phase of the Caledonian Orogeny. A projection of New Zealand geology 10 million years into the future illustrates how such a transition from subduction to strike-slip tectonics might take place. The Hikurangi subduction system, which currently terminates gradationally southwestwards into the transpressive Alpine fault system, is predicted to continue rolling back. If this promotes the eastward propagation of the present Alpine fault system and wholesale rotation of eastern North Island, then a future “Hawke Bay” displaced terrane will be dispersed along the Pacific-Australian plate margin. Another consequence of such movements would be the extinction of magmatism within the Taupo corridor which will be left stranded behind the future active subduction zone. What likely happened in Snowdonia 450Ma ago is thus predicted to repeat itself in North Island, New Zealand in the geologically near future.

Right-lateral Slip along the Southern Boundary of the Caribbean Plate, Northern Venezuela.

GIRALDO Carlos *, and Franck AUDEMARD

PDVSA Exploracion y Produccion, and FUNVISIS, Caracas, Venezuela.

Several geodynamic models proposed for the Caribbean region imply large-over a 1,000 km long right-lateral displacements along the southern margin of the Caribbean plate. In Northern Venezuela, such slip should be accommodated by the active Boconó, San Sebastián, El Pilar and Oca-Ancón faults. Nevertheless, this hypothesis seems hardly sustainable when the cumulative slip along every single of these major right-lateral strike-slip faults on Venezuelan onshore is assessed. Such amount of right-lateral displacement, as their geodynamic significance, is still matter of controversy in the geological community.

From both the revision of the existing literature and our own experience,this maximum right lateral displacement is much less than 150 km since the individual slip on these major faults are: (a) 30 to 35 km for the Boconó fault, (b) less than 65 km and probably close to 35 km for the Oca-Ancón fault system , and (c) around 60 km for the San Sebastián-El Pilar fault system. The Oca-Ancón and Boconó faults converge nearby Morón and prolong eastward as a single east-west striking right-lateral fault (San Sebastián-El Pilar fault), where kinematics of the former two faults is transferred on the latter one.

A general agreement regarding the activation of these major strike-slip faults seems to exist. A major middle Miocene-Pliocene compressional tectonic regime is responsible for their activation, However, such process has been slightly dyachronic as it started earlier on the west.

Oblique collision of the Bahama Platform in the Hispaniola-Puerto Rico area, northeastern Caribbean

N.R. Grindlay[1], P. Mann[2] and J. Dolan[3]

[1]Department of Earth Sciences, University of North Carolina at Wilmington, 601 S. College Road, Wilmington, NC 28403
[2]Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin TX, 78759
[3]Department of Earth Sciences, University of Southern California, University Park, Los Angeles, CA 90089-0740

The 3000 km-long North America-Caribbean (NOAM-CARB) plate boundary that stretches from Guatemala to the Lesser Antilles arc is dominantly a left-lateral strike-slip boundary that accommodates slow (1-2.6 cm/yr) eastward motion of the Caribbean plate relative to North America. The Puerto Rico-Hispaniola segment of the plate boundary is complicated by the presence of both strike-slip and subduction-related tectonics and the interaction of these structures with the obliquely colliding Bahama Platform. The main strike-slip feature is the Septentrional fault zone located in the Dominican Republic. Fault trenching studies of this fault segment in the Dominican Republic by Prentice et al., (1993) have shown that its last strike-slip, ground-breaking rupture occurred approximately 700 years ago. The main subduction-related feature is the Puerto Rico Trench located 65-70 km north of the Septentrional fault zone. The Puerto Rico Trench is the surface trace of a south-dipping Benioff Zone that most recently ruptured during the 1946 M8.0 northeast Hispaniola earthquake (Dolan and Wald, 1997; 1998).

The Puerto Rico-Hispaniola segment of the NOAM-CARIB plate boundary allows us to address several unanswered questions about the effects of obliquely colliding bathymetric highs on island arcs in strike-slip to subduction settings. In the case of collision, several questions arise: how does the collision affect the partitioning of strain along the plate boundary? What are the regional effects of tectonic erosion as the plateau is subducted beneath the arc? Tectonic escape is a well documented process in continental settings (Molnar and Tapponnier, 1975) but how important is this in intraoceanic arc systems?

To better understand the complex relation between strike-slip and subduction tectonics north of Puerto Rico, HMR1 bathymetric and backscatter data along with Hydrosweep bathymetry and single-channel seismic, gravity and magnetic data were acquired in June 1996 over the Puerto Rico Trench and northern Puerto Rico/Virgin Island margins (Grindlay et al., 1997). The major features observed include: 1) outer rise of the obliquely subducting Cretaceous-age Atlantic oceanic crust of the North America plate; 2) the 7-8.4-km-deep trace of this oblique subduction zone at the Puerto Rico Trench and the flanking North Puerto Rico Slope strike-slip fault, previously identified by Masson and Scanlon (1991); 3) a submerged “forearc” where we identified for the first time the South Puerto Rico Slope strike-slip fault (SPRSFZ) striking parallel to the GPS-derived plate vector (Dixon et al., 1998) and sub-parallel to the North Puerto Rico Slope fault 40-60 km to the north; 4) the northern Puerto Rico platform/slope area occupied by a drowned Oligocene to lower Pliocene carbonate platform, and 5) the Mona Passage, where we mapped in greater detail the Mona Rift and identified the Yuma Rift for the first time.

The new sidescan, bathymetric and single-channel seismic data indicate that two anomalous highs in the northern Puerto Rico and Hispaniola slopes are restraining bends formed between the sub-parallel North and South Puerto Rico Slope fault zones. Both restraining bends appear to be associated with the subduction of high standing ridges on the North American plate. The

Mona Block restraining bending exhibits more than 4 km of bathymetric relief and is bounded to the south by the Septentrional fault zone. Uplift of the block is attributed to both the bend in the South Puerto Rico Slope fault zone-Septentrional fault zone and underthrusting of the southeastern extension of the Bahama Platform (Dolan and Wald, 1997; 1998). The main geologic belts in the region: the outer sedimentary accretionary prism, the metamorphic belt that extends from the north coast of the Dominican Republic to beneath Mona block and the volcanic arc south of the Septentrional fault zone change orientation at the Mona Block. The Main Ridge restraining bend exhibits 2 km of bathymetric relief with thrust faults actively uplifting its southern margin. The Main Ridge is associated with a higher than average amount of crustal seismicity and is most likely associated with the underthrushing of a fracture zone high on the North American plate (McCann and Sykes, 1985; Muszala et al., in review).

The survey also revealed extensive normal faulting of the Oligocene to early Pliocene carbonate platform in the Mona Passage. Two fault populations are observed: 1) arcuate faults immediately south of the Mona Block, a pattern interpreted to be related to accentuated arching of the platform due to the collision and underthrusting of the southeastern section of the Bahama platform, and 2) NW trending faults which in some instances can be traced on land to lineaments in southwestern Puerto Rico. This localized extension of the platform strata is interpreted to reflect the recent differential northeastward relative motions of the Puerto Rico/Virgin Island and Hispaniola microplates.

On the basis of these findings we suggest that the Bahama platform is an “indenter” (Molnar and Tapponnier, 1975) which is presently colliding with the Greater Antilles intraoceanic arc along the north coast of Hispaniola. This collision has resulted in the change in trend of major strike-slip faults and development restraining bends in the forearc region. Another consequence of this collision is the “tectonic escape” of Puerto Rico/Virgin islands block to the ENE along the parallel trending strike-slip SPRSFZ and Anegada Fault Zones.

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SUMMARY OF THE DOMINICAN DISASTER MITIGATION COMMITTEE´S ACTIVITIES AND IMPACT: 1994-1998.

Christine M. Herridge, Coordinator of Dominican Disaster Mitigation Committee

The Dominican Disaster Mitigation Committee is a solid contribution of the Caribbean Disaster Mitigation Project to vulnerability reduction activities in the Dominican Republic. In late 1993, the CDMP began activities in the D.R., allowing local businesses and NGO´s the freedom to adapt project objectives to the country´s needs and circumstances. As of late 1995, the Dominican Disaster Mitigation Committee, became a legally established NGO to ensure the mid and long term continuation of the CDMP´s vulnerability reduction activities. The DDMC´s Board of Directors includes 5 NGO´s: Food for the Hungry, World Vision, SODOSISMICA, ADOZONA and ASONAHORES, as well as 4 companies: Codetel, Sea Land Service, Compañía Nacional de Seguros, and J. A. Abreu & Asociados. An independent office was established, equipped and organized to permit efficient and effective access to project-related information, materials, and activities. The poor response to products and services promotion, as well as the afiliation campaign, in general, has led to the design phase of an ADMD loss estimate for members based on their actual level of preparedness. The ADMD will develop and market this service and would appreciate any assistance and advice that the CDMP can provide. The ADMD has actively sought cooperative agreements with various agencies and submits proposals to national and international agencies interested in supporting vulnerability reduction activities. Already, the ADMD has been awarded with a three year contract with DIPECHO, the first year´s budget will be ECU$100,000 and should begin in December. An equal or greater value contract is needed to complete budgeting for activities and additional personnel in order to have coordinators for four of the five main activity streams. As a result of Hurricane Georges´ impact, there is a much greater interest in mitigation and various offers of joint activities and projects are being considered with NGO´s such as Plan International, World Vision, OXFAM, Esperanza International, IDAC, Cooperación para la Paz, and CIPROS.

We would like to take this opportunity to review the DDMC´s five areas of activity as well as the results achieved and the targets for 1999.

I Training of Trainers and Disaster Management Training:

The DDMC has been responsible for fourteen Disaster Management courses, since 1994, providing an opportunity to 329 professionals and technicians from the private, public and NGO sectors to participate in primarily the OFDA training series. Although other projects and institutions such as the UNDP Disaster Mitigation Project through the Secretary of State of Public Works contributed to the training effort, OFDA, CDMP, and the DDMC have made Disaster Management training in the D.R. possible. Due to the success of OFDA´s effort to train a Dominican team, the DDMC is able to schedule as many courses as desired due to the experience and capacity of the local team. Of the eight seminars offered by the DDMC in 1998, four successful courses were attended by important private company representatives. The seminars generate a modest income for the DDMC as well.

The DDMC has gathered multisectoral interest and support for the implementation of the UNDP´s APELL project for the Haina Port area and, hopefully, five other high risk locations. This project seeks to create a local response capacity among the industrial, official and community stake holders with support from PAHO/OPS, Red Cross, CEPREMID, Ministry of Public Health and other official, community and private organizations. The principal activity will consist of training at various levels as well as exercises and simulations. In early 1999 the DDMC will seek the commitment of the private sector and submit proposals to various agencies for assistance with this project.

The DDMC offered its training experience and capacity to the OFDA/USAID office in Costa Rica to facilitate courses in Spanish and English-speaking Caribbean countries and/or to support teams of instructors in Caribbean countries. OFDA did sponsor four Haitian instructors´ participation in the DDMC-organized Training for Instructor´s Course in 1997.

Eight hurricane simulations have been facilitated by the DDMC, reaching 293 representatives of major hotels, free enterprise zones, insurance brokers, businesses and communities. As a result, the DDMC has received formal requests for further simulations for individual companies and insurance firms. These activities are also self-sustaining and serve to generate some income for the DDMC. Another significant training activity included the Probable Maximum Loss Seminar held to provide orientation for insurers and reinsurers regarding exposure in case of disaster. The insurers, in most cases, are currently receiving a PML report for their portfolios from their reinsurers. Another factor influencing the lack of industry follow-up on the topic is that catastrophic coverage was still widely available at reasonable prices.

Regarding the CDMP´s interest in offering assistance to Dominican Insurers to implement a similar mitigation plan for home and business owners for a discount on policy rates such as the United Insurance Company program available in Barbados: the sector opinion was that the competition was so close that the prices were already cut as far as possible without regard to catastrophic exposure. However, some insurers do deny coverage to potential clients that they feel are high risks to catastrophic damage and loss. The region will undoubtedly experience some changes in this regards in response to Hurricanes Georges and Mitch.

II Coordination and Communication:

Since 1994, a total of 1,400 minutes (868 minutes in 1998 alone) of television time worth approximately US$868,965, and 590 minutes of radio time worth approximately US$12,280 have been donated to promote the DDMC´s activities, information and recommendations. An active television campaign was waged worth well over US$141,900, by the Compañía Nacional de Seguros to prepare the population for hurricane season. The 30 second spot was well promoted in July and August and gave equal credit to the DDMC. Additionally, radio stations nation-wide have donated time to run the DDMC´s radio spot on what to do before, during, and after hurricanes on a daily basis and at no cost. At least 39 newspaper and magazine articles have been published in donated space worth approximately US$23,251.

The DDMC has given 326 presentations to a total of 20,616 people nationwide to Dominican businesses, communities, schools and associations regarding the country´s natural hazards and necessary mitigative activities. A total of 124 presentations to 9,515 students and teachers in schools in over 20 cities nationwide is included in this awareness campaign. The DDMC received generous support from the Compañía Nacional de Seguros which designed colorful and informative materials (in excess of US$20,000) for students. During 1998, the DDMC gave 7 workshops to prepare 140 teachers and 26 Peace Corps volunteers to give the disaster preparedness and mitigation presentation to students and communities.

Presentations have also been given in Miami, Montserrat, Venezuela, and Panama to share the DDMC´s successful experiences. In addition, work meetings are held with heads of businesses, community and government organizations to raise awareness, garner support, obtain information and establish contacts to facilitate DDMC activities.

The DDMC coordinated with the NGO´s involved in its programming and with various international agencies in preparation for the passage of Hurricane Georges on September 22, 1998. The main focus was on facilitating information regarding damage and needs to assist coordination efforts and the distribution of aid. For this purpose, the DDMC participated in coordination meetings with the Red Cross and became an active member of the Comité de Emergencias Post-Huracán de Organizaciones de la Sociedad Civil organized by Participación Ciudadana, a USAID sponsored NGO which formed an alliance of more than 40 NGO´s to coordinate relief efforts regarding food, water, health, clothing and territorial reorganization (zoning). The DDMC emphasized the introduction of mitigative measures during repair and reconstruction of housing among other activities.

During the passage of Hurricane Hortense in 1996, the DDMC maintained contact with threatened communities and local authorities, providing damage estimates and lists of the items needed to organizations such as USAID and OXFAM.

Fulfilling a basic goal of the CDMP, the DDMC has structured coordination and communication mechanisms to address the needs of communities, private schools and companies, providing a forum in which they can share successful experiences, gain access to information, videos, books and other materials on disaster mitigation available in the DDMC´s office, as well as plan and carry out preparatory simulations before hurricane season begins.

III Information:

Over 80,000 brochures on what to do before, during and after hurricanes and earthquakes, as well as 5,000 1996 calendars detailing hurricane season, have been published and distributed.

Twelve informational bulletins on activities, the D.R.´s natural hazards and the most recommended measures to implement have been edited and distributed to at least 2,500 businesses, organizations and communities (each issue). A costal flooding map for the Santo Domingo-Haina area was prepared to show levels of flooding for each category of hurricane. This map, and others regarding hurricane trajectories, flood-prone areas, the deficient drainage system, geological faults, and other graphics have been included in the information bulletins circulated to date. The DDMC changed the bulletin´s format so that it could be sent by fax/modem and by e-mail every 3 months. This change has brought a very positive response from the readership and has cut the bulletin´s cost dramatically. Several recent editions have been published and/or features in newspapers and commented on radio programs.

The DDMC has built a video library documenting natural disasters, mitigative activities, project activities and televised interviews, DDMC presentations and visits to high risk communities to document the nature of their vulnerabilities. The video library now holds over 70 VHS tapes, all containing at least 2 hour's worth of material. The FEMA tapes with hurricane and fire prevention videos as well as the Puerto Rican Civil Defense´s video on earthquakes and the DDMC´s video with the Dominican Red Cross on how to handle accident victims are constantly in demand.

The DDMC holds Annual Meetings each November, and this year the Presentations by the Board Members of project activities were accompanied by video clips of the activities. The outstanding contributions made by individuals and organizations were recognized with plaques.

IV Community Education:

In 1995, the DDMC evaluated and selected a program designed by the Red Cross and has, to date, sponsored 6 courses to train 173 local facilitators from 44 NGO´s, 12 Project Development Areas (PDA´s) sponsored by World Vision, as well as from the Civil Defense and the Red Cross. Since October of 1995, 578 high risk communities have received the Community Disaster Preparedness Workshop. Over 17,340 community leaders have learned what a disaster is, how to identify vulnerability, how to identify the community's human and material resources, and - as a community - how to design a Community Emergency Plan. More could have been accomplished in 1998 if the facilitator training course had been given earlier in the year, which was not possible due to World Vision´s internal difficulties. Also, the active hurricane season made programming difficult and NGO´s fell behind in implementation.

In July of 1996, the workshop facilitators attended an evaluation seminar sponsored by the DDMC and the International Federation of Red Cross and Red Crescent Societies to discuss problems and solutions regarding the campaign. As a result, several improvements and changes have been implemented to standardize and assure the quality of the workshops and reduce the cost per workshop by at least a third. The goal for the 1998 campaign is to continue to increase local counterpart contribution, currently at 50% of the program´s value, to 90%. Thanks to an agreement with the World Food Program (UN) this significant cost reduction is possible. The DDMC focuses its resources on training facilitators in new regions and supports current participating NGO´s with miminal materials needed to give the workshops. This transition is already underway through NGO´s like World Vision which provides an operating budget to 13 NGO´s, each of which is required to dedicate a portion of its resources to disaster mitigation activities.

The DDMC hopes to integrate the Dominican Red Cross into its expansion efforts now that Dominican law protects its sovereignty as an NGO and the IFRC has moved its headquarters to Santo Domingo. The Red Cross is, in many cases, the only NGO with a strong presence in important areas surrounding La Vega, Santiago, Puerto Plata and other areas of the Cibao. Hopefully, past incapacities can be overcome to build up an effective community awareness program within the Red Cross´ sphere of activity.

V Community Initiatives:

The DDMC´s facilitation of Community Initiatives to implement vulnerability reduction projects was designed in consultation with NGO´s in the DDMC´s Board of Directors. The Community Initiative Facilitator was hired in August of 1996 and has actively oriented qualifying communities regarding the C.I. program and the application process. Given the requirement that the communities must provide - in local counterpart contributions such as manual labor, technical assistance, land, project permits, etc.- at least 50% of the total value of the project, fewer applications were received than initially anticipated.

During the period of August, 1996 through November, 1998, the DDMC has assisted a total of 17 rural and urban communities with various small infrastructure projects to reduce vulnerability regarding flooding and landslides. The investment made so far amounts to US$281,267.00, of which the local communities provided US$129,023; and other sponsors have contributed US$63,173; and the DDMC has invested US$89,070, only 32% of the entire value of the program. A total of 5,598 families representing 30,789 people have benefitted directly from these projects. In addition, 25,652 people from 4,664 families have benefitted indirectly. The total beneficiary population reaches 56,441 people in 10,262 families nationwide.

Twelve of the projects are drainage embankments leading to over 3,357 meters of channels to reduce flooding. One is a river containment dike. Two projects are a series of bridges over drainage channels. Another project built drainage wells and and the remaining project resulted in the construction of two containment walls to prevent landslides. Fifteen of the seventeen projects have been completed. Two should conclude within the first half of December and will be inaugurated in December, along with another that was just completed. Videos and pictures are available regarding each project.

In spite of periodic heavy rains since January and the passage of Hurricane Georges, 15 of the 17 projects have successfully fulfilled their objectives to the delight of the communities. Field reports show that the projects had a very significant effect in reducing the flooding expected due to the Hurricane. The two projects which failed did significantly reduce the impact of the Hurricane even though the failures did occur and have since been assessed and the modifications in design will be implemented when the reconstruction takes place.

SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Part 5: **Seismicity and Recent stress field of the Eastern Carpathian lithosphere: A Recent snapshot of terminal subduction retreat**

Stefan Hettel[1], Birgit Müller[1], Blanka Sperner[1], Friedemann Wenzel[1], Karl Fuchs[1]

[1] Geophysical Institute, University of Karlsruhe, Hertzstr. 16, 76187 Karlsruhe, Germany

Seismicity

Moderate crustal seismicity is recorded all over Romania (max. magnitude 5.6), but a far more intense subcrustal activity is restricted to a small seismogenic volume in the SE-bend of the Carpathian arc (Fig. 8), with about 30 x 70 km^2 lateral and 130 km vertical extent. This seismogenic volume correlates with the extent of the high-velocity body detected by seismic tomography (part 4). Northeastern and southwestern crustal bounds of the volume are the Trotus-Peceneaga-Camena fault zone and the Intramoesian fault, respectively. This focus of seismic events represents the most severe seismic hazard in Europe today: every century more than 20 earthquakes with magnitudes greater than 6.0 are recorded (max. magnitude 7.7 in 1940).

The moment release of the last seven large events is estimated to $1.0 \cdot 10^{21}$ Nm. Averaging over a large time interval and including earthquake reports of the pre-instrumental recording time, this results in a moment release rate of $8 \cdot 10^{18}$ Nm a^{-1}. This value is associated with a vertical extension of the Vrancea seimogenic volume at a rate of about $2.0 \cdot 10^{-7}$ a^{-1}.

Fault plane solutions

The crustal events (max. depth 35 km) show no uniform orientation of stress axes and no dominant tectonic regime. The stress axes orientations of the subcrustal events indicate a clear thrust-faulting regime, with the largest events having nearly identical orientations of fault planes. This has a direct impact on the seismic hazard in the region, because earthquakes with nearly uniform focal mechanisms should produce a similiar wavefield on the surface and thus constrain the distribution of the hazard.

Stress inversion

Stress inversion with all available focal mechanisms from the subcrustal seismogenic volume gives a best-fit stress-tensor of 079/19 (σ_1), 341/21 (σ_2), 207/61 (σ_3) with a misfit-angle of 22°. Inversion of datasets from depths between 40 and 140 km indicates E-W compression, whereas in depths below 140 km N-S compression dominates. The depth range in which the change in direction takes place correlates with the change in strike direction of the high-velocity body seen by seismic tomography.

Stress field

Besides earthquake focal mechanisms, crustal stress information can be obtained from borehole-breakout measurements (in the upper few kilometers) and from the analysis of geological structures. In the central Pannonian Basin the observed crustal stress field with maximum horizontal compression in NE-SW orientation can be related to the continental collision in the Dinarides. In contrast, the stress data from the Eastern Carpathians and adjacent foredeep basin show neither a uniform stress direction, nor a dominant tectonic regime (Fig. 9). Possible reason for this complexity is a superposition of different stress signals: stress reorientation along the major faults, pull of subducted slab, local basin formation and far-field tectonic stresses.

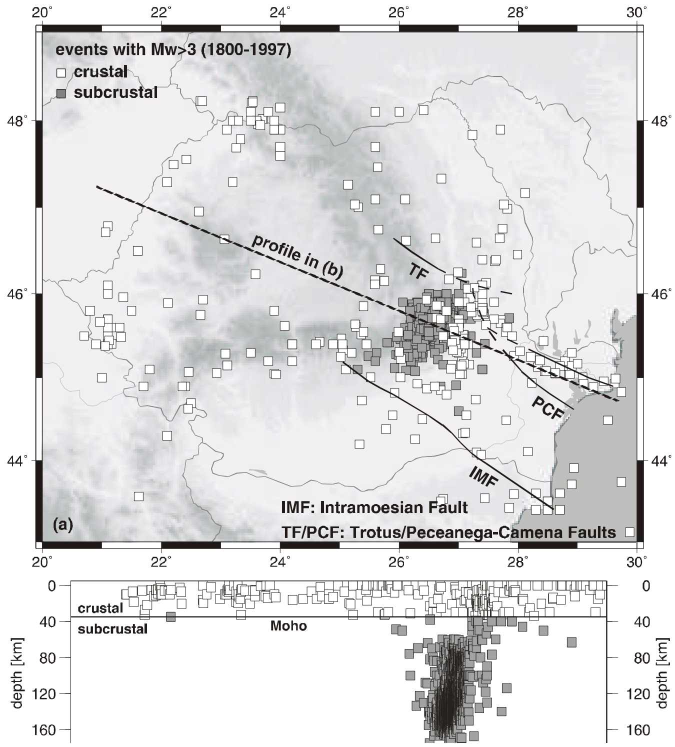

Fig. 8: Recent recorded earthquakes with magnitude greater than 3.0 in Romania. The moderate crustal activity (white squares) is more widespread, whereas the intense subcrustal seismicity (grey squares) is localized in the SE-bend of the Carpathian arc, indicating a subducted slab.

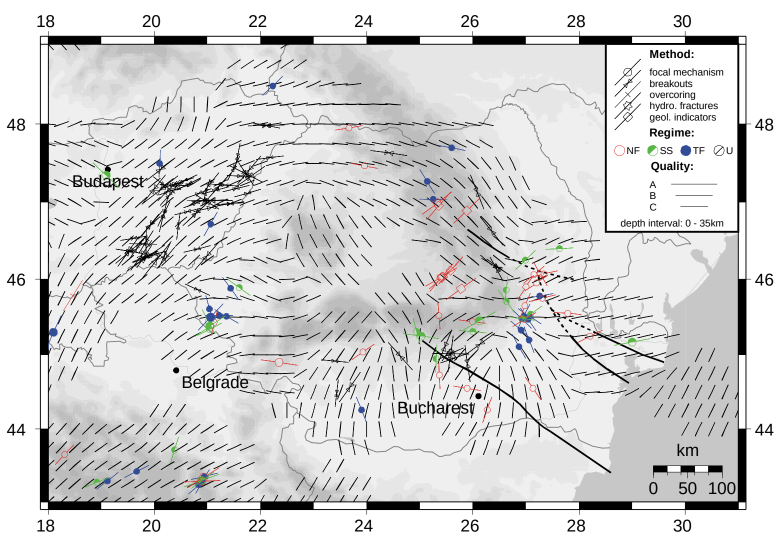

Fig. 9: Orientation of recent maximum horizontal compression in SE-Europe. The symbols are as indicated in the legend. Gridded black lines show the mean orientation of S_H. in the area. Whereas the observed stress field in the Central Pannonian Basin is uniform, is the observed stress pattern in the Eastern Carpathians very complex, due the superposition of various different stress signals.

KINEMATICS OF WRENCH ZONES

Catherine Hier and Christian Teyssier

Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA.
(e-mail: chier@geolab.geo.umn.edu and teyssier@tc.umn.edu)

The continental lithosphere is vertically stratified into three layers of contrasting rheology: the brittle upper crust, the ductile mid-lower crust, and the upper mantle. Wrench zones provide an ideal setting to study the difference in behavior of these rheological layers during deformation because the vertical structure of the lithosphere is not disturbed during deformation as it is along extensional and contractional zones.

The deformation in the brittle upper crust along wrench zones is accommodated by strike-slip partitioning. Rigid blocks are translated along strike-slip faults sub-parallel to the plate boundary. Deformation is concentrated along these strike-slip faults and the crust within the blocks remains essentially undeformed (Fig. 1).

Recent developments in seismology have allowed the resolution of mantle fabrics from seismic anisotropy data. This data has provided a glimpse of the structural geology of the upper mantle. Shear-wave splitting studies along wrench plate-boundaries have shown that a fast polarization direction lies parallel to the direction of wrenching. This zone of fast polarization has been well documented along the San Andreas plate boundary (Özalaybey and Savage, 1995) and both the North American and South American boundaries of the Caribbean Plate (Russo et al, 1996). The zone of fast polarization is interpreted by Teyssier and Tikoff (1998) as a zone of penetrative shearing in the upper mantle along the plate boundary (Fig. 1).

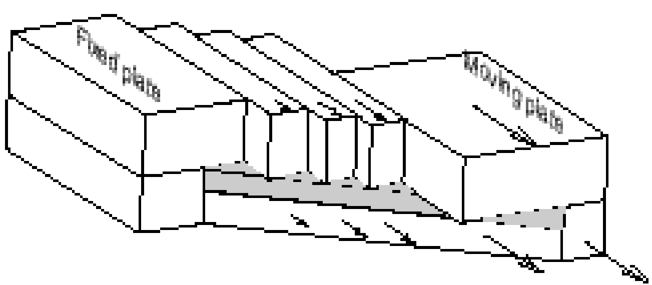

Fig. 1 Conceptual model of a three-layer lithosphere at a wide wrenching plate boundary (Bourne et al., 1998). Upper crustal blocks are translated above the shearing mantle. The grey zone is the ductile crust that transfers motion from mantle to upper crustal blocks. Arrows are velocity vectors.

The mechanics of the ductile crust sandwiched between the upper crust and upper mantle is not well understood. This layer, however, must accommodate the differential displacements between the strike-slip partitioned motion in the upper crust and the penetrative shearing in the upper mantle.

The kinematics of the ductile crust sandwiched between the rigid blocks of the upper crust and the upper mantle simple shear zone below can be modeled mathematically. This deformation zone combines a vertical shear zone where wrench is maximum at the base and 0 at the top with a horizontal shear zone where shearing is maximum at the top and 0 at the base. Although an analytical solution for the strain matrix in the ductile crust cannot be determined because deformation is inhomogeneous, solutions can be approached for a series of discrete thin layers superposed in the vertical direction. Within each of the thin layers, strain is produced by the two shear components mentioned above and corresponds to a simple shear for which instantaneous and finite strain quantities can be determined. This type of forward modeling predicts orientation of foliation, lineation, shear plane and direction within each thin layer, and the variation in fabric orientation from top to bottom of the deformation box. Any component of transpression can also be accounted for mathematically.

An alternative approach rooted in fluid mechanics can also be used to estimate strain within the ductile crust. If the rigid blocks are translated above a shearing lower lithosphere, and the ductile crust consists of a Newtonian fluid, then the thickness of the coupling zone is related to the width of the individual crustal blocks (Bourne et al. 1998). For example, for blocks 15-20 km wide, the transition zone in the ductile crust is calculated to be 5-7 km thick, from Laplace's equations. For a non-Newtonian fluid of power-law rheology, this thickness would decrease because deformation would be more localized. Therefore, it is critical to make geologic observations of the ductile crust in such settings and study the structures, microstructures, and deformation mechanisms of the deformed rocks in order to place mechanical bounds on rock rheology.

The Northern Range of Trinidad provides a unique opportunity to study an exhumed segment of ductile crust developed along a plate-scale wrench zone. The Northern Range of Trinidad preserves a cross-section from the upper crustal rocks in the eastern end of the range to ductilely deformed mid-crustal rocks at the western end of the range (Weber et al., in review).

The mantle shear zone north of Trinidad, documented from seismic anisotropy by Russo et al (1996) along with the transition from upright low temperature fabrics to higher grade flat lying fabrics exposed in the Northern Range of Trinidad preserve a complete vertical section of the lithosphere that was deformed during wrench motion along the Caribbean/South American Plate Boundary. Detailed studies of the ductile crust preserved in the Northern Range of Trinidad will allow us to address how the motion of the upper mantle is transferred vertically through the ductile crust into the brittle upper crust.

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Uplifted marine terraces on the east side of Bering basin along the shorelines of Bering and Karaginskiy islands: Indicators of large earthquakes in the Kamchatka/Aleutian region?

Kurbatov A.V.[1], Bursik M.I.[1], Melekestsev I.V.[2], Sulerzhitsky L.D.[3]

1. Department of Geology, SUNY at Buffalo, 876 NSM Complex, Buffalo NY, USA 14260
2. Institute of Volcanic Geology and Geochemistry, 9 Piip av., Petropavlovsk-Kamchatsky, Russia 683006
3. Geological Institute, 7 Pyizevskiy st., Moscow, Russia 109017

Tephrochronological dating (Braitseva et al., 1997) of co seismic-uplifted marine terraces on the east side of the Bering Basin allowed us to determine the age and extent of great earthquakes along the Kamchatka Peninsula for the late Holocene (Fig.1).

The radiocarbon ages of the first layers formed after terraces emerged from the sea followed the last sea-level transgression. For peat sampled in Karaginskiy Island the age is cal. BC 4470(4460,4410)4360 (GIn7778) (all samples were calibrated using Stuiver and Reimer (1993) for one standard deviation); for a peat layer at Uka site the age is cal. BC 5370(5280)5260 (GIn7794); and for a wood fragment, cal. BC 5060(5000)4940 (GIn6329), in the "Cherniy Yar" site. The different elevations (up to 10 m) of these layers in relation to present sea level support a co seismic mechanism of terrace formation.

The time range of terrace formation on Bering Island was determined based on radiocarbon ages for mollusc shells (cal. BC 1120 (980) 850 (GIn7750) and cal. BC 750 (510) 550 (GIn7751) and the peat layer above uplifted lake sediments cal. BC 370 (340, 320, 200) 170 (GIn7752). Another episode of uplift took place before deposition of a Shiveluch tephra layer dated by an overlying peat layer at cal. AD 1020(1070,1090,1120,1140,1150)1210 (IVAN 446). It is unclear when the lowest surface, 1.5 m above sea level, was formed because of the absence of any ash layers, which could be also due to many different factors such as tsunamis, storm-wave erosion or winds.

Two relatively well-preserved surfaces along the shoreline of Ossora settlement were formed before the deposition of the Ksudach (Ks_1) cal. AD 240 ash on a 4.5 m terrace, and Shiveluch cal. AD 1230(1260)1280 on a 2m surface (Melekestsev et al., 1997).

For Karaginskiy Island, the age of the best-developed 4.5-5 m–high terrace, is older than an ash fall from Shiveluch volcano of c. 1600 yr BP correlated based on a radiocarbon date of cal. AD 260(390)424 (GIn 7783) obtained from a peat layer above the tephra. Comparison of field observations made in 1993 with aerial photographs taken before the Ms=7.7 tsunamigenic earthquake on the eastern coast of Ozernoi Peninsula of November 23, 1969 57.8 N, 163.8 E shows that the channel of the Gnumvayam River changed after massive sand deposition blocked the river mouth, probably during tsunami propagation. A new terrace surface was not found as a result of this event which supports the hypothesis that only large seismic events generate uplift.

Clusters of marine terraces along the shoreline of Kamchatskiy cape show at least 4 episodes of co-seismic uplift (Melekestsev et al., 1994): 1) before deposition of the Ks_1 tephra layer of cal. AD 240, 2) before deposition of Shiveluch cal. AD 640(650)660 tephra, 3) before deposition of Shiveluch cal. AD 1230(1260)1280 tephra, and 4)one event before the Shiveluch eruption in 1964 AD, probably related to the largest known historical earthquake in November of 1737 (Zayakin and Luchinina, 1990).

Although more data have to be collected, some preliminary conclusions can be drawn. The highest tectonic activity occurred around AD 200 along Kamchatka's Pacific Pate boundary.

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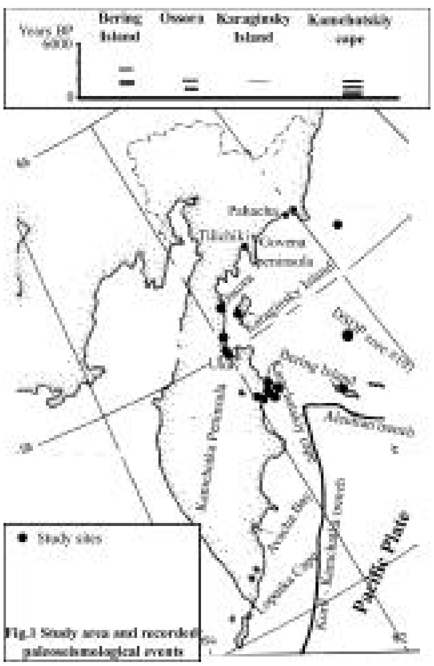

Fig.1 Study area and recorded paleoseismological events

Extracting Plate Kinematic Information from Mélange Fabrics

Timothy M. Kusky[1] and Dwight C. Bradley[2]

[1]Center for Remote Sensing, Boston University, Boston MA 02215 USA
[2]U.S. Geological Survey, Anchorage Alaska, 99508 USA

Analysis of early deformational fabrics in tectonic mélange may yield information about the kinematics of past plate interactions (e.g., Kano *et al.*, 1991; Onishi and Kimura, 1995; Kusky *et al.*, 1997a; Kusky and Bradley, in review). In this paper we develop a methodology for using kinematic data derived from tectonic mélanges in accretionary prisms to derive information about the slip vector directions within an accretionary wedge setting. This information may ultimately prove useful for reconstructing the kinematic history of plate interactions along ancient plate boundaries, and how this convergence was partitioned into belts of head-on and margin-parallel slip during oblique subduction, and for obtaining a better understanding of subduction - to strike-slip transitions.

As an illustration of the method, we analyze asymmetric fabrics from mélange of the McHugh Complex from the Seldovia Quadrangle on the southern part of the Kenai Peninsula, Alaska, with particular emphasis placed on relations from specific areas in which glacial retreat has created excellent 3-D exposure, permitting detailed mapping (Bradley and Kusky, 1991; Bradley *et al.*, 1999; Kusky and Bradley, in review). The McHugh Complex is a Mesozoic mélange comprising part of the Chugach terrane of southern Alaska, interpreted as an accretionary prism formed by offscraping (and/or underplating) outboard of the present seaward margin of the composite Peninsular - Wrangellia - Alexander superterrane. It is subdividable into subparallel internally complex belts of dominantly Triassic through Cretaceous chert, basalt, gabbro, graywacke, argillite, exotic Permian limestones, and other belts mappable macroscopically only as mélange, all of which wrap around dismembered ultramafic massifs, and intruded by a variety of igneous rocks (Bradley *et al.*, 1999). We have studied and mapped the McHugh Complex at scales ranging from 1:250,000 through 1:1,140, to 1:1, and mapped thin sections at magnifications of up to 250:1. A scale-invariance is reflected in the map patterns through the thin section scale, with individual belts varying from a fraction of a mm to a few km thick.

Structures within the mélange indicate a history including both contractional and extensional strains, formed at a variety of depths of deformation. A map-scale oceanic plate stratigraphy is repeated hundreds of times across the area, but structures at the outcrop-scale are dominantly extensional. Rheological units that were stronger than surrounding units during deformation now occur as blocks within a matrix that has flowed around the competent blocks, forming broken formation and mélange. Deformation was noncoaxial, and disruption of primary layering was a consequence of general strain driven by plate convergence, in a relatively narrow zone between the overriding lithified accretionary wedge and the downgoing, thinly-sedimented oceanic plate. Soft-sediment deformation processes did not play a major role in the formation of the mélange. We propose a model in which layers oriented at low angles to σ_1 are contracted in both the brittle and ductile regimes, layers at 30°-45° to σ_1 are extended in the brittle regime and contracted in the ductile regime, and layers at angles greater than 45° to σ_1 are extended in the brittle and ductile regimes.

Many of the structures within mélange of the McHugh Complex are asymmetric, and record kinematic information consistent with the inferred structural setting in an accretionary wedge. We develop a method for interpreting the kinematic significance of the fabric asymmetry in mélange, following in part earlier work by Kano *et al.* (1991). Slip vectors can be derived from many of the structural elements present in mélange, and analyzed in a manner similar to kinematic data from higher-grade mylonitic rocks. However, rocks in mélange like the McHugh Complex commonly do not have well developed slip lineations, so derivation of kinematic data is less direct. We have used the following asymmetric fabric elements for kinematic analysis: 1) intersection of planar elements, such as C (Y), S, P, and R1 surfaces, or between thrusts within duplex structures, with the slip vector lying at 90° to the intersection lineation, in the plane of slip (C); 2) slip or slickenline lineations on slip surfaces; and 3) fragment elongation lineations and bouden axes within S - surfaces of mesoscale mélange.

The most reliable data are plotted on the map as a series of lower-hemisphere, equal angle projections. For each of the stations great circles for C (Y) surfaces are plotted as solid lines, S- and R1 surfaces as dashed lines, and the slip vector direction in present coordinates is plotted as a solid dot with an arrow through it pointing in the direction of slip of the hangingwall. Because rocks of the McHugh Complex have been rotated since formation of the mélange, and folded about vertical axes (e.g., Kusky *et al.*, 1997b), several geometric corrections to the data were made to restore them to their presumed original attitude. First, a rotation about a vertical axis was performed on the data to bring the local strike into parallelism with the regional 035° strike. Second, the data were rotated about a horizontal axis to account for tilting and/or folding or the layering in the mélange. Since there is considerable uncertainty about the attitude at which the asymmetric fabrics formed, the rotated slip vectors are plotted for an attitude restored to a 30° NW dip for the main mélange foliation, and also in an attitude in which the slip vectors are restored to horizontal. Our assumptions in such rotations are accounted for by plotting this range of possible initial orientations for the slip vector orientations of the hangingwall blocks in the mélange.

Mélange of the McHugh Complex on the lower Kenai Peninsula can be divided into three sub-parallel belts with different slip vector orientations. The most inboard belt shows generally E-W directed slip vectors, with one exception coming from a chert unit that shows complex disharmonic folding on a regional scale (Kusky *et al.*, 1997b; Bradley *et al.*, 1999). A central belt preserves NNE-SSW directed slip vectors, and an outboard belt preserves SW-NE directed slip vectors. Together, these slip vectors can be interpreted as a displacement field associated with initial formation of the mélange.

The tectonic significance of the displacement field is less clear. In the simplest case, as the mélange grows progressively by successive offscraping events, each package will record the plate convergence direction at the time of accretion. By examining progressively younger (more seaward) mélange packages, a history of plate convergence directions may be reconstructed. In this sense, accretionary mélanges may record a kinematic history of convergence directions and plate interactions that occurred along a convergent margin during production of the mélange. Kinematic analysis of mélange fabrics may therefore yield kinematic information that is complimentary to, and extends the temporal limit of sea floor magnetic anomaly data that is commonly used for plate reconstructions. Systematic analysis of the kinematics of tectonic mélange belts formed at convergent margins may yield information about the convergence directions between the overriding and underriding plates, the mechanics of accretionary wedges, and the partitioning of deformation in zones of plate convergence. However, some complications in such an interpretation arise since accretionary wedges may not show such a simple direct response to plate convergence directions. Wedges may extend or contract in response to body forces and surface slopes (e.g., Platt, 1986), and strain may be partitioned into belts that show predominantly head - on convergence, and belts that show predominantly orogen-parallel displacements (e.g., Dolan and Mann, 1998). Further, more detailed kinematic analysis, coupled with well-controlled age-data and paleomagnetic poles may yield additional insight into the relationships between the kinematics of mélange in accretionary wedges and plate convergence directions.

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Strain partitioning and coupling between plates: Field observations and critical input from experimental modeling

Serge Lallemand [1] and Alexander Chemenda [2]

1 Laboratoire de Géophysique et Tectonique, CNRS, Université Montpellier 2, CC.60, place E. Bataillon, 34095 Montpellier, France – email: lallem@dstu.univ-montp2.fr

2 CNRS, Université de Nice - Sophia Antipolis, 06560 Valbonne, France – email: chem@faille.unice.fr

What are the forcing functions which govern strain partitioning in oblique subduction zones ? It can be (1) the convergence obliquity, (2) the strength of the overriding plate, (3) the degree of interplate coupling, (4) the tectonic regime of the overriding plate, or (5) the slab pull. One of the most difficult parameter to test is the interplate coupling, because there is not a single way to estimate it in nature (seismic coupling ?, kinematic coupling ?, viscous coupling ?, interplate pressure ?).

We have performed 40 experiments of 3-D analog modeling of oblique subduction to study the mechanism of strain partitioning. The model is two-layer and includes elasto-plastic convergent lithospheres and a low-viscosity liquid asthenosphere. The subduction is driven by the push force from a piston and the pull force when the density contrast between the subducting plate and the asthenosphere is positive. We vary both the slab pull and the interplate friction (frictional stresses), keeping the angle of obliquity constant and equal to 40°.

(1) Slip partitioning was only observed in the models with high interplate friction and when the overriding plate contained a weak zone (cut or thinned lithosphere).

(2) Back-arc extension and transcurrent faulting within the overriding plate appear to be non compatible processes.

The along-strike component of the friction force F_{ft} is balanced with the shear resistance along the transcurrent strike-slip fault F_{ss} and the boundary forces (driving or resistive) F_c and F_e. The horizontal component, normal to the trench, of the friction force F_{fh} is always negative (compression), whereas the horizontal component of the slab pull F_{ph} is either negative or positive. The sum of these two horizontal forces F_h governs the tectonic regime within the overriding plate.

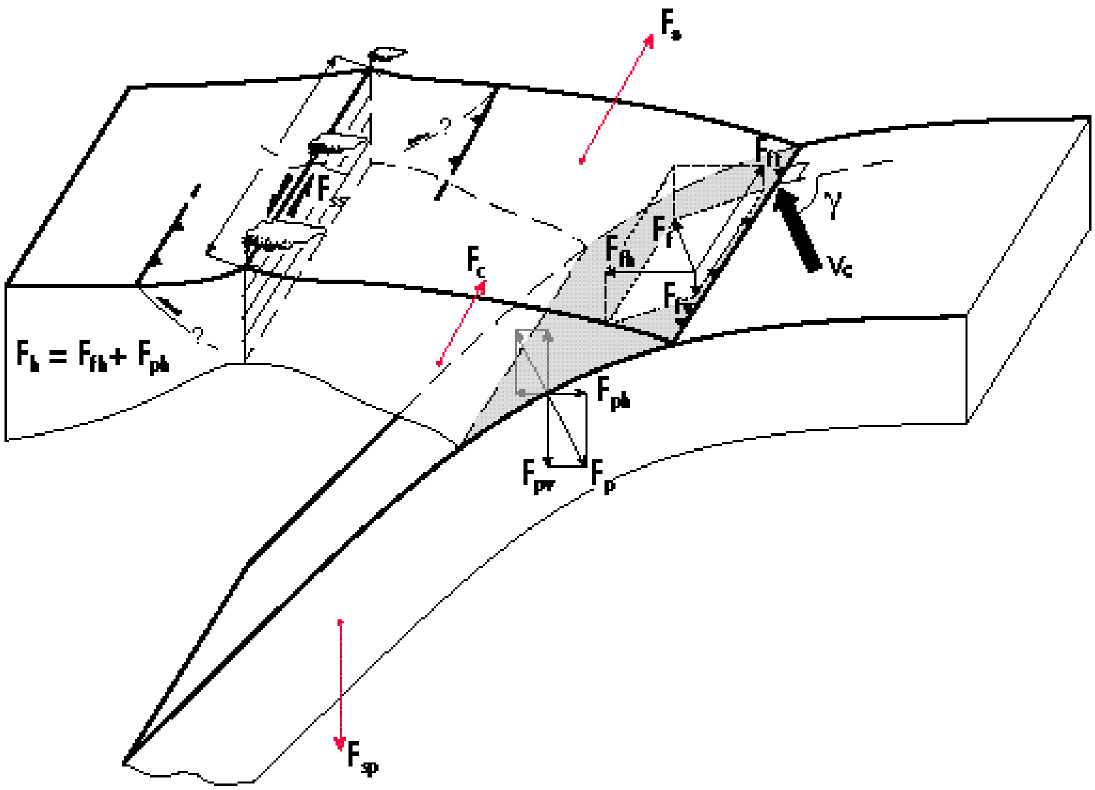

Figure 1: Balance of forces in oblique subduction zones. The interplate friction force F_f is the main force which has an along-strike component F_{ft} able to drive the forearc sliver. It may exist additional forces at both extremities of the sliver such as F_c and F_e.

The conclusion (2) is supported by the comparison of two oblique subduction zones whose geometry is comparable. The southern Kuril arc-trench system is compressional and undergoes strain partitioning with a convergence obliquity of only 27°, whereas the southern Ryukyu zone, with an obliquity of 50°, is extensional and no transcurrent faulting is observed in the basement of the arc.

Deflection of slip vectors in the southern Ryukyu subduction zone together with the absence of transcurrent faulting within the arc basement can be explained by a shear within the subducting slab. Indeed, strain partitioning may occur either in the overriding or the subducting plate if special conditions are met, such as the presence of a weakness zone within the lithosphere. Lateral forces are expected within the subducting slab in the southern Ryukyus as a consequence of the arc-continent collision occurring in Taiwan.

To summarize, existence of interplate friction and weakness zone in overriding plate are necessary conditions for strain partitioning in oblique subduction zones. The degree of slip partitioning will depend on the friction force and the boundary forces. The tectonic regime within the overriding plate depends on the interplate pressure which is slab pull and friction dependant. The friction force could be "slab pull" dependant, as suggested by the apparent inhibition of strain partitioning when the overriding plate undergoes extension.

Trench-parallel stretching and folding of forearc basins and lateral migration of the accretionary wedge in the southern Ryukyus: A case of strain partition caused by oblique convergence

Serge Lallemand [1], Char-Shine Liu [2], Stéphane Dominguez [1], Yvonne Font [2], Philippe Schnürle [2] and Jacques Malavieille [1]

1 Laboratoire de Géophysique et Tectonique, CNRS, Université Montpellier 2, CC.60, place E. Bataillon, 34095 Montpellier, France – email: lallem@dstu.univ-montp2.fr

2 Institute of Oceanography, National Taiwan University, P.O. Box 23-13, Taipei, Taiwan –email: csliu@ccms.ntu.edu.tw

Detailed seafloor mapping in the area east of Taiwan revealed trench-parallel stretching and folding of the Ryukyu forearc and lateral motion of the accretionary wedge under oblique convergence (Fig. 1).

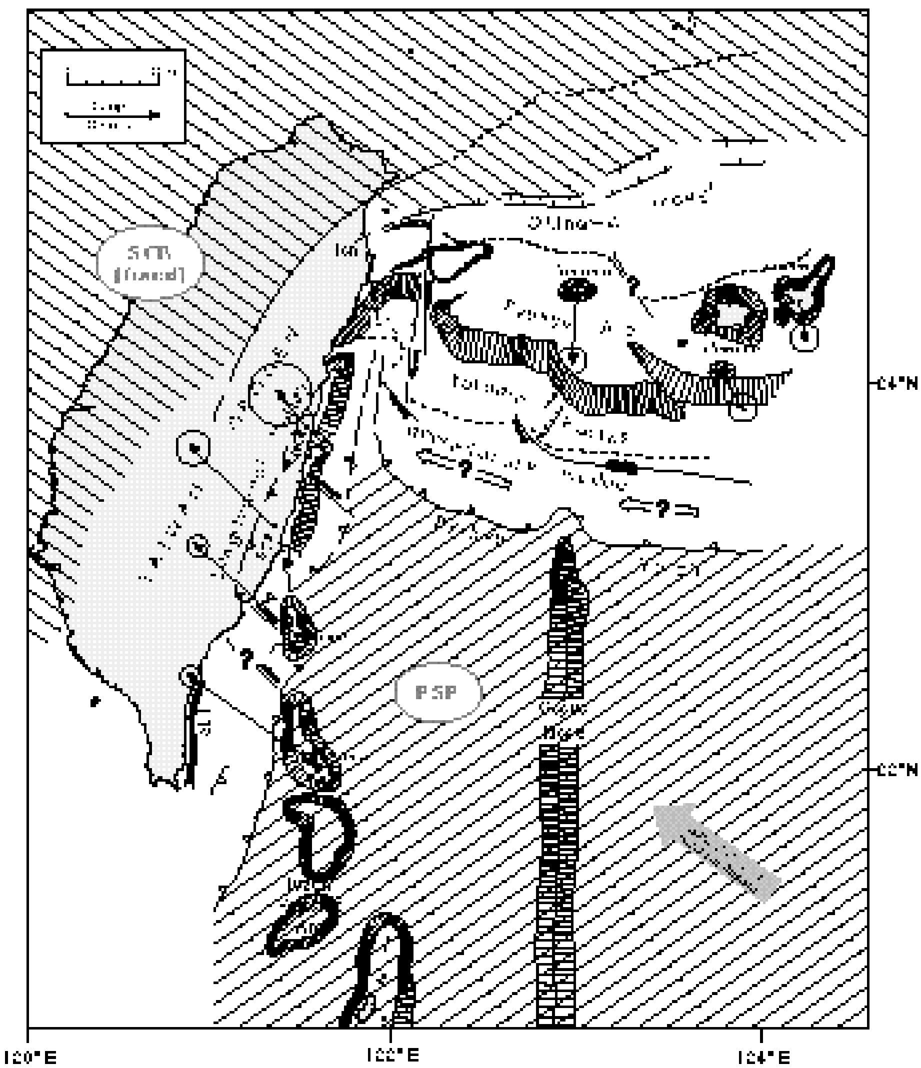

Fig.1: Present-day kinematics of the Taiwan region as given by GPS measurements. Arrows are displacement vectors of structural blocks with respect to the South China Block.

East of 122°40'E, a steep accretionary wedge is elongated in an E-W direction. A major transcurrent right-lateral strike-slip fault accommodates the strain partitioning caused by an oblique convergence of 40°. A spectacular out-of-sequence thrust may be related to the subduction of a structural high lying in the axis of the N-S trending Gagua Ridge. This asperity is likely responsible for the uplift of the accretionary wedge and forearc basement and may have augmented strain partitioning by increasing the coupling between the two plates. Morphological and structural considerations on wedge uplift and reentrant above and in the wake of subducting asperities have allowed us to estimate the azimuth of the relative motion between the subducting plate and the accretionary wedge. This azimuth is deflected by 20° with respect to the convergence between the converging plates as given by GPS measurements. Assuming that all the lateral component of the relative motion is accounted by the transcurrent fault, it gives a slip rate of about 3.7 cm/yr along the fault.

No major transcurrent fault has been mapped within the Ryukyu arc basement or back-arc basin (southern Okinawa Trough), despite the high convergence obliquity (40 to 60° depending on the sectors). Furthermore, GPS measurements indicate that the southern Ryukyu Arc is drifting toward the south-southeast with respect to the South China Block (including Chinese continental shelf), rather than toward the southwest as expected in case of strain partitioning along a fault located within the arc or the back-arc. A swarm of earthquakes occured close to the seismogenic interface near Taiwan that might indicate consistent slip vectors deflected by about 20° from the plate convergence vector. Because these earthquakes are located 40 km arcward of the mapped transcurrent fault, their deflection can not be simply explained by the motion along this fault. We propose to relate part of these events to the activity of an E-W trending tear fault within the subducting slab. Lateral together with vertical motion along the tear can be caused by the nearby arc-continent collision.

West of 122°40'E, the low-taper accretionary wedge is sheared in a direction subparallel to the convergence vector with respect to the Ryukyu Arc. The bayonet shape of the southern Ryukyu Arc slope partly results from the recent (re)opening of the southern Okinawa Trough at a rate of about 2 to 4 cm/yr. Right-lateral shearing of the sedimentary forearc with respect to the nonlinear Ryukyu backstop generates trench-parallel extension in the forearc sediment sequence at dilational jogs and trench-parallel folding at compressive jogs (Fig.2).

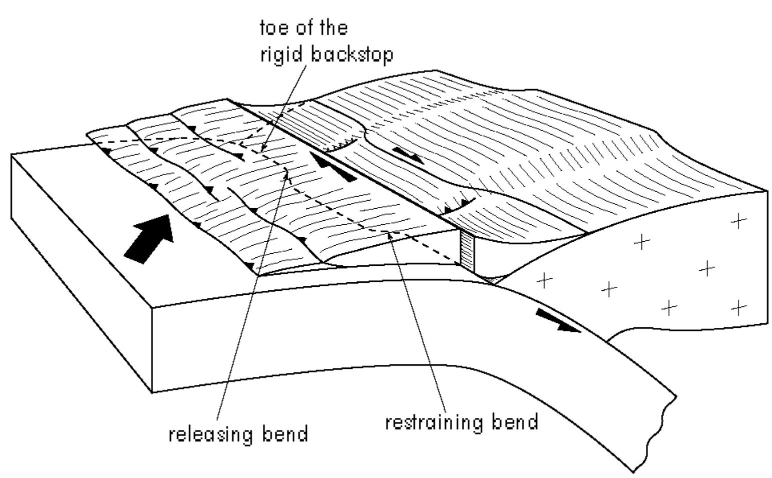

Fig.2: Perspective cartoon illustrating the geometry of releasing and restraining bends of the toe of the rigid backstop underlying the forearc basin sediments.

STRAIN PARTITIONING BEHIND THE TRENCH TO STRIKE-SLIP TRANSITION: ACTIVE INTRA-ARC DEFORMATION IN OREGON AND MEXICO

R.M. LANGRIDGE and R.J. WELDON II

Tectonic deformation in the region "behind" the trench to strike-slip transition adjacent to the Middle America (Mexico) and Cascadia (Oregon) margins is characterised by normal faulting. Seismic moment release is dominated by large (M ~7) earthquakes on faults which scale in length and displacement to these magnitudes. The latest Quaternary sedimentary records in these settings have a significant input from their nearby volcanic arcs.

The Trans-Mexican Volcanic Belt (TMVB) has experienced at least two of these M7 events in the last 450 years, including the 1912 Mw 7.0 Acambay Earthquake. We have investigated this event in the Acambay Graben (AG) and conclude that: i) this was a typical event for the Acambay-Tixmadeje Fault (ATF); (ii) the recurrence interval for earthquakes on the ATF is ~4000 years; (iii) extension across the AG is ~0.25 mm/year and is ~perpendicular to the ffabric of the TMVB; and (iv) when scaled to the entire TMVB the historic record for moderate to large events is near complete.

The Cascade and Central Oregon (COZ) Zones represent intra-arc and "behind-arc" extensional systems in Oregon. These zones have rates of deformation of 0.1-1.0 mm/year each and probably also release seismic strain through large (M ~7) events. Investigation of a tephra-rich lacustrine sequence at the Ana River Fault (ARF) in the COZ has revealed along paleoseismic record (<80 kyr) with: (i) earthquake recurrence of 10-20,000 years; (ii) a slip rate of 0.1-0.2 mm/year; and (iii) the recognition and understanding of sub-lacustrine event horizons for normal faults from near- and far-field localities.

Despite low slip rates and long recurrence times compared to subduction zones and strike-slip faults the "behind-arc" setting should be appreciated as a region of active tectonic deformation with significant seismic hazard potential. We believe that part of the reason for underestimation of hazard in these zones is related to the lack of microseismic to moderate-sized events, which may be a function of a higher heat flow regime in arc-adjacent settings.

Fast Subduction, Slow Subduction, and Strike-Slip Faulting, Chile Margin Triple Junction

Stephen D. Lewis

Geology Department, California State University, Fresno
slewis@csufresno.edu

The Chile Ridge, an active spreading center between the Antarctic and Nazca plates, is being subducted beneath South America at 46° S, forming the northward-migrating Chile Margin triple junction. A comprehensive suite of marine geophysical observations, including scientific drilling during ODP Leg 141, has shown that the forearc of Southern Chile is undergoing subduction erosion where the active Chile Ridge spreading center is presently being subducted. These data also show that Pleistocene-aged sediment is still being accreted at the base of the trench slope only 30 km north of the site of ridge subduction, indicating that this region of the forearc remains unaffected by the triple junction.

South of the triple junction, where the spreading ridge was subducted about 6 my. ago, large folds and landward-dipping thrust faults characterize the structure of the margin. This indicates that subduction accretion is now dominating the tectonics of the forearc. If Late Miocene/Pliocene ridge subduction resulted in forearc subduction erosion here, then the well-developed accretionary structures present must have formed in the last 6 my. Thus, the transition from the dominance of subduction erosion at the triple junction to subduction accretion following ridge subduction along the Chile Trench occurs over an along-strike distance of about 50 km, and within time periods of no more than 6 my.

The Linquine-Ofqui fault (LOF) is present landward of the Chile Trench, trending roughly parallel to the continental margin. Geological and geophysical data suggest that the LOF is a right-lateral strike-slip fault, with deformation beginning in the Oligocene, when the convergence between the Nazca and South American plates was highly oblique. There is evidence for recent activity on the southern LOF. The LOF appears to be characterized by splays from the main fault zone that curve seaward into at least two prominent embayments underlain by extensional sedimentary basins in the Chile margin in the vicinity of the triple junction. The present-day plate convergence direction between the Nazca and South American plates north of the triple junction is oblique to the margin, while the convergence direction between the South American and Antarctic plates south of the triple junction is nearly orthogonal to the margin. The northward-migrating triple junction, and hence the northward-migrating transition between oblique and orthogonal subduction, may be related to recent activity on the LOF and the extensional deformation along its seaward terminations. The southern termination of the LOF is comprised of fault splays that accommodate localized extensional deformation within the Chile Trench forearc in the Golfo de Penas and other embayments. Hence, the extensional and subsidence histories of these shelf "forearc" basins may provide quantitative constraints on the timing and rates of strike-slip offset along the LOF. As the Chile Triple Junction migrates northward along the South American margin, the southern end of active strike-slip faulting that accommodates the oblique component of subduction should also terminate.

GPS Preliminary results on Northeastern Caribbean plate boundary zone.

A.López (1), P.Jansma (1,2), E.Calais (2), C.Demets (3), P.Mann (4), T. Dixon (5), G.Mattioli (1,2)

1:Department of Geology-University of Puerto Rico-Mayaguez
2: CNRS-Geosciences Azur, Sophia Antipolis, France
3: University of Wisconsin-Madison
4: Institute for Geophysics-University of Texas-Austin
5: Rosenttiel School for Marine and Atmospheric Sciences, University of Miami

The North American-Caribbean plate boundary near Hispaniola, Puerto Rico and the Virgin Island is characterized by a complex deformation zone, whose NS width ranges between 200 and 250 km. Data from GPS (Global Positioning System) geodetic networks in the northeastern Caribbean point to differences in strain accommodation in Hispaniola and Puerto Rico, which are broadly consistent with geologic and geophysical observations. Explanations for the transition in deformation style along the boundary from west to east focus on collision of the northeastern Caribbean plate boundary with the Bahamas Platform (e.g. McCann and Sykes, 1984; Mann et al., 1995). Measurements obtained from campaigns beginning in 1994 with the funding of NSF and NASA to create CANAPE (Caribbean-North American Plate Experiment) have been essential for the on-going densification of the Caribbean plate motion.

Dixon et al. (1998) presented initial results from CANAPE, which showed a complexly deforming zone across the Caribbean, as represented by a site at southern Dominican Republic (which is assumed to have velocities of stable Caribbean plate), with 24 ± 3.6 mm/yr in a roughly east-west direction relative to stable North America. Although the azimuth is similar, the velocity is twice as fast in comparison with the NUVEL-1 model (Demets et al., 1990). Although the data was processed in ITRF '94 (International Terrestrial Reference Frame), new measurements from 1998 that were obtained in late 1998 were processed with two different softwares and with ITRF'96, which yielded results with more accuracy in a span of eight years (1990-1998). These updated velocities of all sites in the Dominican Republic still decreases from south to north, but the azimuths now consistently show a component of convergence across the major strike-slip both onshore an offshore. With respect to Puerto Rico, a site in the north has similar motion to the southern station in the Dominican Republic at a little more than 16 mm/yr with respect to fixed Turk island of the Bahamas, and to fixed North American plate. However, these results does have a statistically significant northward velocity of a few mm/yr with respect to the southern Dominican Republic, implying increased convergence along the boundary north of Puerto Rico and a component of left-lateral displacement between northern Puerto Rico site and Dominican Republic southermost station.

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SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Part 4: **Gravity data and seismic tomography from the southeastern Carpathians: Imaging the terminal phase of subduction**

Frank P. Lorenz[1], Michael Martin[1], Blanka Sperner[1], Friedemann Wenzel[1], Victor Mocanu[2]

[1] Geophysical Institute, University of Karlsruhe, Hertzstr. 16, 76187 Karlsruhe, Germany
[2] Geophysical Institute, University of Bucharest, 6 Traian Vuia Street, 70139 Bucharest 1, Romania

Gravity

A zone of negative Bouguer anomaly parallels the southeastern Carpathian arc (Fig. 6). Lowest values (-110 mgal) are recorded from the Getic depression (for loc. s. Fig. 4) where overthrusting of the Tisia-Dacia block onto the northern margin of the Moesian platform caused formation of deep sedimentary basins. In contrast to this upper-crustal feature, an offset in the Bouguer anomaly just north of the SE-bend of the Carpathian arc seems to be caused by „deeper processes“: the offset separates the region of thickened crust in the N from the region of basin formation and fast foredeep subsidence in the S (Fig. 4 & 6). Additionally, it represents the northern border of the high-velocity body outlined by seismic tomography.

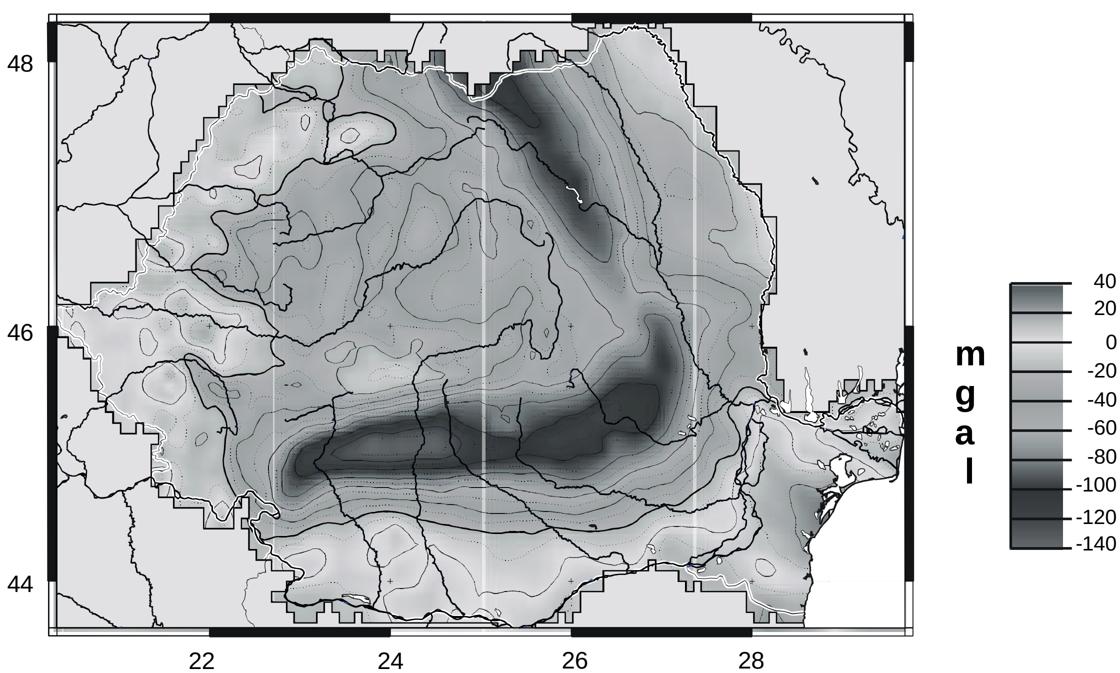


Fig. 6: Bouguer anomaly of Romania / southeastern Carpathians

Seismic tomography

A 3-D model of the velocity-depth structure for the SE-bend of the Carpathian arc was calculated by inverting teleseismic P-wave travel-time residuals. The digitally recorded waveforms for 125 events were picked, travel-time residuals were calculated with the IASP91 reference tables and the inversion was done with the ACH-method. The weighted relative residual, which are more or less independent of hypocenter localisation errors, were minimized using a standard least squares algorithm. Our current best fit model with a variance improvement of 70% reveals a local high-velocity body with maximum perturbations of about 3% which is totally embedded in a low velocity medium with negative peak perturbations of about 5%. All intermediate depth earthquakes lie within the high-velocity body. The seismically quiet depth range (40 to 70 km) is (within the limits of resolution) not associated with a velocity anomaly. On a global scale, all images of active subduction zones are characterized by high P-wave velocities. We interpret this as strong evidence for remnants of a slab of oceanic lithosphere beneath the southeastern Carpathians.

The high-velocities body displays a peculiar structure, the main feature of which is a change of strike from top to bottom. The uppermost high velocity material strikes roughly SW-NE (Fig. 7). This is consistent with subduction to the NW or delamination and rollback to the SE. Deeper portions of the high velocity material, however, are oriented more N-S, close to the strike of the Eastern Carpathians. Presumably this was also the strike orientation of subduction before the last slab segment was totally incorporated into the mantle (Fig. 2c). Thus the directional change of subduction during the last phases of collision in the Eastern Carpathians may be preserved in the tomographic image. N-S oriented high-velocity material would represent older westward subducted material that is detached from the foreland lithosphere, but still attached to the upper SW-NE trending part of the slab. This deeper (N-S striking) portion of dense oceanic lithosphere generates a downward force which increases shear stresses in this passive slab.

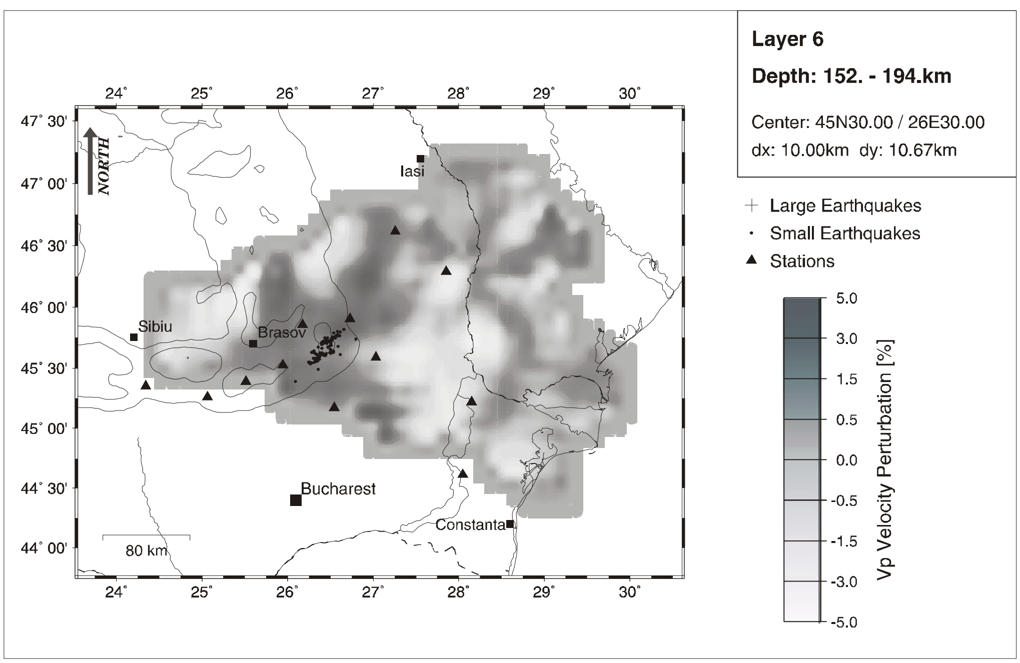


Fig. 7: Seismic tomography of the upper mantle between 112 and 152 km in depth. For 1999 a large tomographic experiment with 143 stations and a reasonable resolution towards depths of 400 km is planned (CALIXTO = Carpathian Arc Lithosphere Cross-Tomography Project).

Lithospheric-Scale Modeling of Transpressional Regimes: Application to the South Island, New Zealand

R.Malservisi and K.P.Furlong

Geodynamics Research Group, Department of Geosciences, Penn State University, University Park, PA, USA.
e-mail rocco@geodyn.psu.edu

The pole of rotation of the Indo-Australian and Pacific Plates is close to the plate boundary in the area of New Zealand; this makes the dynamics of the region very sensitive to any change in plate motion.

A migration of the pole of rotation westward characterizes the history of the Indo-Australian/Pacific plate in the last 6(10?) Ma. This leads to an increasing compressional component in the relative motion along the Alpine and Puysegur faults and a change from a translational to a transpressional regime.

The effects of this change are very pronounced in the Fiordland region where the lithospheric interactions have led to a subduction like regime manifested by deep earthquakes (deeper than 150 km), large gravitational anomalies and rapid uplift.

The response of the lithosphere to this evolution in plate kinematics is the principal feature we are testing in our 3d-FEM model (TECTON). In particular we have tested the conditions that influenced the early stage of the transition to generate the present situation of a localized region of deep earthquakes and significant bouguer gravity anomaly.

The model is focused on the area of Fiordland and it is parametrized to evaluate the response of the lithosphere to different geometries, rheologies and thermal states, to verify how these parameters can affect geophysical observable such gravity, topography and seismicity providing an important constraint on dynamics of the area.

Classification and tectonic comparison of subduction to strike-slip transitions on active plate boundaries

Paul Mann and Cliff Frohlich

Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin, TX 78759

Strike-slip to subduction transitions on active boundaries occur where Benioff zones abruptly or gradually terminate on crustal strike-slip zones. In ancient rocks, these transitions are recorded in island arc rocks that are superimposed by strike-slip faults and related rocks with no evidence for continued arc activity. In this meeting, we will discuss the active and ancient examples together with the aim of identifying the main tectonic, seismogenic, and geologic elements of subduction to strike-slip transitions.

To initiate this five day discussion, we classify transitions on the world's active plate boundaries into three types:

Open corner type: This type of transitional boundary is characterized by plate boundaries describing obtuse "open" angles when viewed from the downgoing plate (Figure A). Characteristics of open corner transitions include: 1) the trench and Benioff zone vary smoothly along strike; 2) the trench is anomalously deep with depths of 6-9 km; 3) the Benioff zone steepens to vertical as the strike-slip boundary is approached; 4) discontinuous pieces of subducted slabs are present in the area of the oversteepened Benioff zone; 5) strike-slip faults are present above the area of detached slabs and lengthen in a trenchward direction; and 6) a common tectonic setting of open corner transitions is a closing "loop" or strongly arcuate island arc constrained between two continents; inactive arc segments mark already collided areas now converted to strike-slip faults and active arc segments mark actively subducting areas (Figure A). The tectonic process responsible for open corner transitions appears linked to collision of an unsubductable bathymetric high at an adjacent closed corner (continental parts of North and South America plates in Figure A). Collision of the high and the arc detaches the already subducted oceanic slab from the high and allows the slab to sink into the mantle at a steep to vertical angle. Strike-slip faults mark the suture between the unsubductable high and the collided arc and lengthen trenchward with continued progressive collision (Figure A).

Discussed examples of open corner transitions: Northeastern and southeastern Caribbean (Figure A), northeastern and southeastern Scotia, central Aleutians, northern and southern Marianas, Philippines, Taiwan, San Cristobal trench of Solomon Islands, southern Vanuatu, northern Tonga, North and South Islands of New Zealand, southern Carpathian Mountains, Aegean, and Sumatra-Andaman.

Closed corner type: This type of transitional boundary is characterized by plate boundaries describing acute "closed" angles when viewed from the downgoing plate (Figure B). Characteristics of closed corner transitions include: 1) a narrow seafloor bathymetric high or continental block adjacent to the closed corner on the downgoing plate (e.g., Hawaii-Emperor seamount chain-Obrutchev Rise in Kamchatka - Figure B); 2) the trench and Benioff zone conforms to the shape of the incoming colliding feature; 3) the Benioff zone is locally contorted into a sharp angle but is not necessarily vertical in dip or associated with detached pieces of slab; and 4) strike-slip faults may not be present on both sides of the closed corner. The tectonic process responsible for the transition appears linked to the subduction of the narrow, bathymetric high that continues to subduct despite the formation of the prominent corner or cusp in the subduction geometry (Figure B). Because subduction of the high continues, detachment and sinking of an oceanic slab from the high may not occur.

Discussed examples of closed corner transitions and associated colliding features: Kamchatka (Hawaii-Emperor seamount chain - Figure B), western Himalayas (Indian sub-continent), southeastern Alaska (Yakutat block)

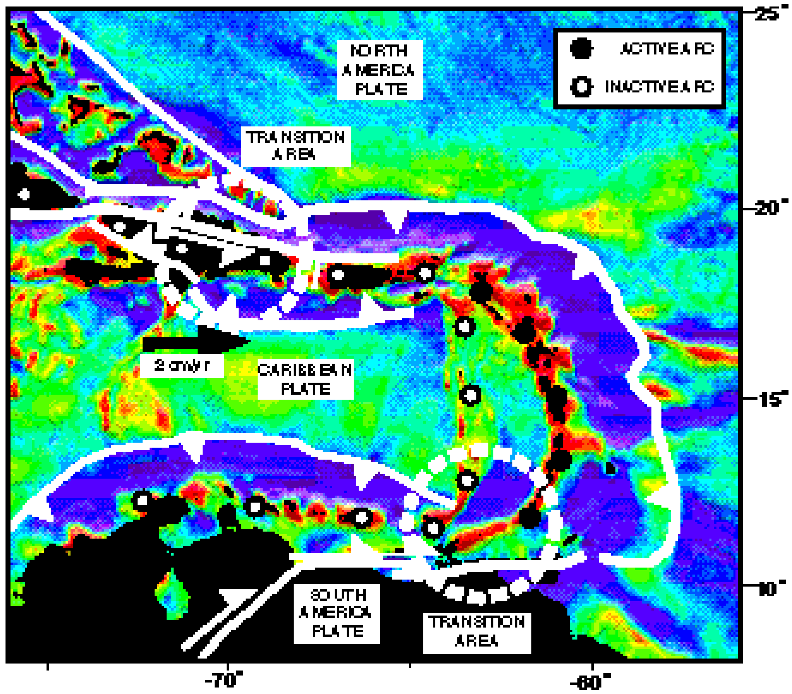
Possible relation between open and closed corner transitions. Collision of the bathymetric high and the arc forms a prominent cusp in the subduction zone (Figure B). Continued interaction of the high, the arc, and lengthening strike-slip zones could produce an open corner adjacent to a closed corner (e. g., open corner transition of central Aleutians is adjacent to closed corner transition of Kamchatka). Therefore, the collision process at closed corner transitions may initiate the eventual formation of adjacent open corner transitions.

Discussed examples of adjacent open and closed corner transitions. Kamchatka and central Aleutians; northern Marianas and Ogasawara Plateau; southern Marianas and Caroline Ridge; western Himalayas and western Indian sub-continent; northeastern Scotia and Northeast Georgia Rise; northeastern Caribbean and Bahama-Greater Antilles collision zone; southeastern Caribbean and northern South America collision zone.

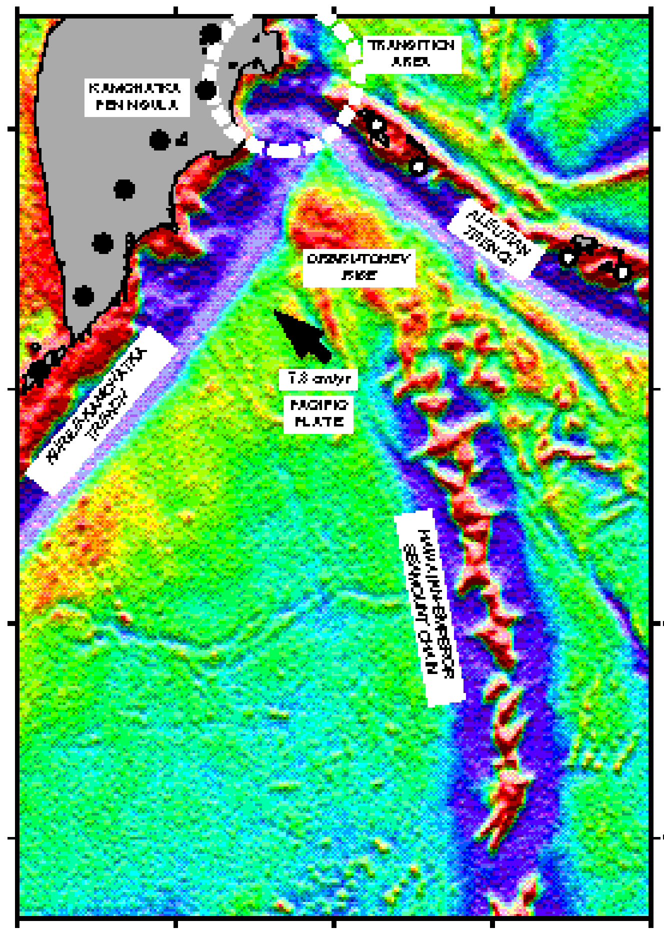
Triple junction type. This is the most abrupt type of strike-slip to subduction transition and consists of a fault-fault-trench (FFT) or fault-trench-trench (FTT) triple junctions as described by McKenzie and Morgan (1969) (Figure C). FFT junctions are stable if the trench and one fault are colinear. As plate motions proceed, the junction maintains its geometry and boundary types. When the trench and one fault are not colinear, the junction is unstable and a triangular gap appears at the junction that must be accommodated by surrounding regions (Figure C). Ridge-trench-trench (RTT) junctions appear shortlived in most cases because ridges often cease spreading on entering the trench and convert to strike-slip faults and FTT junctions.

Discussed examples of triple junction transitions: Gautemala (FTT); Panama (FTT); Chile (RTT where ridge appears to continue spreading on subduction), Mendocino (FTT - Figure C), Woodlark (RTT to FTT because ridge appears to have converted to a strike-slip zone on subduction); New Ireland (TTF): New Guinea (FTT).

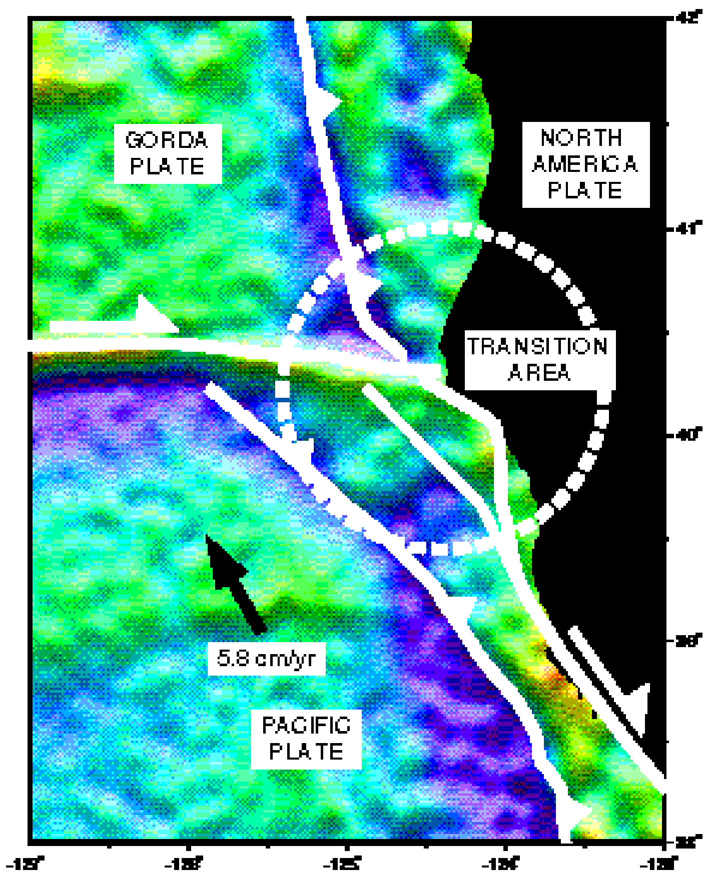
A. OPEN CORNER TYPE



B. CLOSED CORNER TYPE



C. TRIPLE JUNCTION TYPE



The role of Paleogene volcanism in the evolution of the northern Caribbean margin

Giuseppina Mattietti-Kysar

The George Washington University, 2029 G St. NW, Washington D.C. 20052, USA

Since Cretaceous time, the northern Caribbean margin has evolved from subduction controlled plate boundary to the present day strike-slip tectonic regime. This process has probably involved different, contemporaneous tectonic settings along the strike.

This study focuses on the Paleogene age magmatism of the Sierra Maestra (southeastern Cuba), a 250 km long, east-west striking structure, that represent the axial part of a former volcanic arc with northward subduction (Lewis and Draper, 1986). The Sierra Maestra is in alignment with the submerged Cayman Ridge to the west, and it is bounded to the south by the Oriente deep and on land by two tectonic depressions (Cauto valley and Guantanamo basin).

The Sierra Maestra exposes a thick, relatively undeformed succession of volcanic and volcaniclastic rocks, intercalated with marine sediments. Several sets of dikes cut trough this succession, and small plutonic bodies crop out along the southern flank of the Sierra and on the highest peaks. The Paleogene volcanic rocks rest with discordance on reworked, moderately metamorphosed material most probably from the weathering of the Cretaceous volcanoes to the north (Iturralde-Vinent, 1996). This study supports the idea that the Sierra Maestra was part of the Cayman arc structure, as suggested by Perfit and Heezen (1978) who pointed out the similarities between lithologies observed in the Sierra Maestra and those dredged on the Cayman Ridge.

During three field seasons (1996-1998) sampling of magmatic rocks was carried out for petrological and geochemical studies. New analytical results show that the Paleogene arc volcanism followed a tholeiitic differentiation trend. Discrimination diagrams for the volcanic rocks based on Zr, Ti, Y, Ta, Th, Yb, etc ... indicate a primitive, oceanic arc signature. REE plots reveal depletion of the magmatic source with respect to N-MORB. In addition the data for the intrusive rocks show the existence of two distinct groups with depleted patterns. These two groups correspond with the western and the eastern plutonic bodies respectively (Kysar et al.).

U-Pb zircon ages determined on seven samples from the Sierra Maestra span a 10 Ma interval (from 56 to 46 Ma). The oldest intrusion, located toward the western end of the Sierra Maestra, is separated by a 6 Ma hiatus from the younger intrusions to the east. This suggests the existence of two magmatic episodes in the studied area. These absolute age determinations confirm the existence of a 20 Ma hiatus from the last dated Cretaceous volcanism in Cuba at the end of the Campanian (Kysar et al., 1998b). None of the analyzed fractions show any inheritance from older zircons, thus confirming the juvenile character of the Sierra Maestra arc activity. The primitive, depleted geochemistry and the absolute age dating indicate that the Sierra Maestra magmatism was not simply the final stages of the Cretaceous arc activity, although it was probably built on the remains of the Cretaceous forearc (the metasediments mentioned above).

This study also shows that the Sierra Maestra arc was short-lived and with at least two magmatic episodes, each from a chemically different source. Although it is not yet possible to constrain the older magmatism (56 Ma) to a specific tectonic episode, it is concluded that since 56 Ma (Late Paleocene) the western part of the active margin of the northern Caribbean was situated along the east-west striking Cayman-Sierra Maestra arc. This arc was striking at about 45 degrees from the northwest-southeast Cretaceous arc. Probably such counterclockwise rotation began as soon as the Yucatan continental block collided against the western edge of the Cretaceous arc. This event must have terminated the Cretaceous volcanism in Cuba, opened the Yucatan back-arc basin (Wadge et al., 1984) and triggered the onset of Cayman-Sierra Maestra arc.

The younger magmatism (Eocene, 50-46 Ma) was active until the culmination of collision with the Bahamas continental platform. This second collision event most probably changed the stress configuration of this area, transferring to tangential stress in order to accomodate the Caribbean crust which was now moving eastward. This event also resulted in the emplacement of the Mayari-Baracoa ophiolite complex in the mid-late Eocene (as confirmed by the age of the olistostromes to the north of the Sierra). As a consequence, uplift of the Sierra Maestra (a submarine arc) occurred, and the Cauto and Guantanamo basins were formed. The present data give no clear information on the time of the opening of the Cayman Trough.

Acknowledgements

This presentation has been made possible thanks to a grant-in-aid for junior scholars offered by the Cosmos Club Foundation of Washington D.C.

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Strain partitioning and development of upper plate strike-slip faults during oblique convergence: An example from Sumatra

Robert McCaffrey

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy NY 12180-3590, Phone: (518) 276-8521 Fax: 276-8627, Email: mccafr@rpi.edu, Web: www.rpi.edu/~mccafr

Margin-parallel strike-slip faults are frequently found inboard of oblique convergent margins and there is little doubt that a direct mechanical relationship exists between the shear faulting and the shear stress along the dipping thrust fault. We seek to understand the details of the mechanics because the resulting geology, such as the location of the strike-slip fault, will reveal in some fashion the forces involved. In this talk we will focus on the question of where and how strike-slip faults develop in the overriding plate and what this tells us about the interplate forces.

At the subduction zone of northern Sumatra, GPS measurements reveal that the strain associated with the oblique plate motion is fully partitioned between trench-normal convergence within the forearc and arc-parallel shear strain within 30 km of the Sumatra fault. The strain partitioning is consistent with kinematic inferences made from earthquake slip vectors although the slip vectors indicate slightly less partitioning. GPS measurements at several other plate boundaries are used to estimate the degree to which strain is partitioned during oblique convergence. Principal strains within the leading edge of the upper plate are compared to the azimuths of earthquake slip vectors, plate convergence vectors, and the orientations of the deformation fronts. At some margins, such the Himalayas (Nepal), Nankai, and Sumatra, the contractional principal strain direction is perpendicular to the deformation front even though plate convergence is very oblique. Margin-parallel shear strain is then localized landward of the strongest contractional strain. In other places, such as the large bend in the Peru-Chile trench from 15°S to 18°S, where the obliquity is 35°, in Alaska (Prince William Sound) where obliquity is 20°, and in Ecuador where obliquity is 25°, the contractional strain aligns with the plate convergence vector.

Finite element modeling is being used to try to understand the conditions under which strain is partitioned or not. In particular, we are addressing the factors that can cause the principal strain directions rotate by up to 45° between the forearc and the arc regions of convergent margins. In some cases, such as Sumatra, the presence of an arc-parallel strike-slip fault may promote the strain partitioning but in general, we find that a strike-slip fault need not exist for partitioning to occur. Moreover, the models suggest that the strike-slip faults develop because of strain partitioning within the upper plate but they need not develop at the volcanic arc.

Space and Time Variance Among Large Earthquake Ruptures Inferred From a Worldwide Data Set

JAMES P. McCALPIN

GEO-HAZ Consulting, Inc., P.O. Box 1377, Estes Park, Colorado, 80517, USA

Time Variance

In 1997-98 McCalpin, Slemmons, and Nishenko inventoried the published and "gray" literature for paleoearthquake chronologies in which 3 or more consecutive paleoearthquakes were dated by numerical means. We found 41 chronologies containing a sum of 161 paleoearthquakes; most of these local sequences contained 3 or 4 dated paleo-earthquakes, i.e. 2 to 3 dated recurrence intervals (RIs). The variability in recurrence was assessed by normalizing the individual recurrence times (T) in a local sequence to the average recurrence (Tavg) of that sequence. The frequency distributions all have a mean=1 (since the data were all normalized), and thus the sigma value is also the Coefficient of Variation (COV).

Table 1. COV of T/Tavg for Various Types of Faults

Fault Type	No. of RIs	COV of T/Tavg
Strike-slip	44	0.39
Subduction	45	0.39
Normal	56	0.32
Reverse	16	0.37
ALL TYPES	161	0.36

All Fault Types

Grouping all the 161 normalized RIs together, the frequency distribution is slightly asymmetric, with a mode of 1.0- 1.1, and more RIs smaller than Tavg than larger. The extremes are T/Tavg= 0.2 and 2.0. Thus, if a fault had a long term mean RI of 1000 years, and it obeyed the grouped frequency distribution, its RIs over time would range from 200 years to 2000 years, with RIs shorter than the mode being slightly more common than the larger intervals. This latter tendency implies weak clustering of earthquakes in time. Clustering results in more short (intra-cluster) RIs and fewer long (inter-cluster) RIs

Reduction of Variance with More Paleoearthquakes

The 13 local sequences containing only three dated paleoearthquakes (two RIs) had COVs ranging from 0.02 to 0.96, but as the number of RIs in the sequences increases, the spread of COV values decreases, converging on a value of ca. 0.3. One interpretation of this pattern is that all the sampled faults have a long term COV of recurrence of ca. 0.3, and that the larger a portion of their complete recurrence history has been sampled by the paleoseismic investigation, the closer the estimated COV is to the real COV. If seismogenic faults all share a fundamental property of generating earthquake time-series with a recurrence COV=0.3-0.4, this fact would have critical implications for seismic hazard forecasting.

Spatial Variance

We also inventoried 56 historic surface ruptures where post-faulting investigations had yielded at least 15 high-quality measurements of one or more components of slip. Ruptures with 15-30 slip measurements were most common, with a decreasing frequency for more measurements. The largest number of slip measurements (269) was made on the 1920 Haiyun, China earthquake.

One way to characterize the frequency distribution of slip along strike is to compare the average displacement (AD) to the maximum displacement (MD). This ratio ranges from 0.30 to 0.42 for various fault types, with an overall average of about 0.35. Thus, the average displacement tends to be about 35% of the maximum displacement, or put another way, the maximum displacement tends to be about 2.9 times larger than the average displacement. This finding contrasts with the conclusion of Wells and Coppersmith (1994), who concluded that AD averaged about 50% of MD. Our results indicate that the maximum displacement on a rupture is even more anomalous than previously suspected.

Table 1. Ratio of Length-Weighted Average Surface Displacement (AD) to Maximum Surface Displacement (MD), for Various Fault Types

	AD/MD		
	Component of Displacement		
Fault Type	Dvert (N)	Dss (N)	Dnet (N)
Strike-slip	-	0.38±0.08 (18)	-
Normal	0.33±0.09 (11)	-	-
Normal-oblique	0.31±0.07 (6)	0.37±0.11 (2)	0.42±0.11 (2)
Reverse	0.38±0.09 (6)	-	-
Reverse-oblique	0.33±0.12 (16)	0.30±0.11 (14)	0.35±0.10 (11)

Based on measurements of displacement in historic surface ruptures, it appears that normal faults have the largest proportion of small displacements relative to the maximum (i.e., <10% Dmax). Strike-slip ruptures, in contrast, have the highest proportion of larger displacements relative to the maximum. Reverse fault ruptures show intermediate tendencies between these two extremes. The high proportion of small displacements in normal faulting events means that such ruptures are the most affected by erosional modification obscuring smaller displacements. This may explain why paleoseismic evidence for normal faults often indicates anomalously short rupture lengths for the amount of displacement measured. The most reasonable explanation is that post-faulting weathering has obscured a significant part of the original rupture length. This phenomenon would not affect reverse or strike-slip ruptures as strongly.

Using the frequency distributions, one can make a statistical prediction of Dmax given one or more random measurements of displacement during a paleoearthquake. If the measurement site was not randomly located with respect to visible displacements from the studied event, it is possible to use only part of the frequency curve. Using such statistical methods , it is no longer necessary to assume that displacements measured in trenches were the largest (Dmax) for each recognized paleoearthquake.

Global overview of earthquake hazards at transition zones

James P. McCalpin

GEO-HAZ Consulting, Inc., P.O. Box 1377, Estes Park, CO 80517 USA

Historic earthquakes in transition zones have caused damage from both direct, on-land strike-slip style tectonics and indirect, offshore subduction-style tectonics. In a way, transition zones are vulnerable to a wider suite of earthquake hazards than transcurrent or subduction plate boundaries alone.

Surface Rupture: Some of the largest historic surface displacements on strike-slip faults have occurred in transition zones. For example, the 1855 West Wairarapa, New Zealand earthquake may have been accompanied by as much as 12-15 m of dextral offset, or twice the maximum offset in the 1906 San Francisco, California earthquake. However, even decimeter surface displacements have caused collapse of buildings. In the 1972 Managua, Nicaragua earthquake, the 3-story reinforced concrete Customs House was totally collapsed by sinistral displacement of 28 cm. Sub-decimeter offsets caused widespread collapse of wood frame/adobe houses along the fault traces.

The most destructive effects of surface rupture are often on lifelines and utilities. Following the 1972 Nicaragua earthquake fires raged for weeks, because water mains had been broken by surface faulting.

Ground Shaking/ Amplification: Ground shaking from on-land strike-slip earthquakes tends to have more energy concentrated in the high-frequency bands than shaking from more distant, offshore subduction earthquakes. Because transition zones experience both types of events, a wider spectrum of building types may have resonant frequencies that match those of the seismic wave train. Thus, high-rise buildings in transition zones may experience severe damage due to long-period waves coming from great distances (e.g., 1985 Mexico City earthquake), as well as due to short-period waves from smaller but closer strike-slip earthquakes.

Liquefaction: The strength of ground shaking in transition zones is certainly sufficient to cause liquefaction, if the local materials are susceptible. Liquefaction in the 1692 Jamaica earthquake destroyed the city of Port Royal and led to the founding of modern Kingston. Liquefaction and building settlement during the 1960 Niigata, Japan earthquake is an often-cited classic case of bearing load failures. In the Caribbean, liquefaction occurred during the 1976 Guatemala earthquake and the 1997 Venezuela earthquake. Both prehistoric and historic liquefaction has been documented for the Septentrional fault, Dominican Republic, by recent studies of Tuttle, Prentice, and Pena. However, the 1972 Nicaragua earthquake was not accompanied by significant liquefaction, due to water table depths of 10-30 m in Managua and the coarse, angular nature of pyroclastic deposits there. As in most areas, liquefaction susceptibility is controlled by local sedimentary environments, and microzonation maps can only be produced from detailed Quaternary geologic mapping combined with analysis of borehole data.

Landslides: The topography in many transition zones is rugged, and near-angle-of-repose slopes are susceptible to earthquake-induced landsliding. For example, the 1958 Fairweather, Alaska earthquake (Mw=7.7) caused landslides over an area of ca. 70,000 sq. km. The Mw 7.5 Guatemala earthquake of 1976 caused slides over about 18,000 sq. km. These landslides typically obstruct roads and railroads, hampering relief efforts, and sometimes contributing the largest share of monetary earthquake damage. Although the low-relief terrain of cities in transition zones are not hit particularly hard by landslides, substandard housing on hills surrounding metropolitan areas is becoming increasingly vulnerable to landslide damage.

Lateral-spread landslides form a special case associated with subsurface liquefaction, and have occurred on gently-sloping terrain in metro areas. Much of the damage to the docks at Kobe, Japan in 1995 was caused by lateral spreading of man-made land in the harbor. This type of damage may be expected in any urban harbor area where bays were filled with hydraulic slurry material or nonstructural fill placed at low densities.

Geodetic Changes: Subduction earthquakes are typically accompanied by permanent changes in coastal elevations, with landward belts of subsidence and seaward belts of uplift paralleling the subduction zone. In the 1931 Napier, New Zealand earthquake maximum uplift along the coast was 2.5 m; the 1994 Petrolia, California earthquake experienced coastal uplift up to 1.4 m. In areas of low tidal ranges, meter-scale uplifts can render harbor facilities unusable.

Tsumanis: Two catastrophic tsunamis occurred in 1992 in or near transition zones, and highlight this hazard. The 1 Sept. 1992 Nicaragua earthquake (M 7.0) generated waves 8-15 m high that struck 26 towns along 250 km of Nicaragua's Pacific coast. The waves penetrated as much as 1 km inland, killing 116, with 63 missing, 489 injured, and 40,000 homeless. Total losses were US$ 25 million. The 12 Dec. 1992 Indonesia earthquake (Ms 7.8) created waves with a maximum runup height of 26.2 m with a landward penetration up to 300 m, which severely scoured some coastal areas and deposited up to 1 m of sediment elsewhere. About 1000 people were killed, 500 injured, and 90,000 left homeless.

Slip Partitioning and the Earthquake Cycle

For hazard forecasting it would be helpful to know whether subduction and strike-slip earthquakes alternate in a transition zone, or whether sequences of gap-filling subduction events follow sequences of gap-filling strike-slip events. The historic record in Hispaniola includes two consecutive strike-slip (?) events in 1842 and 1887 in western Hispaniola, followed by two consecutive subduction events in 1946 and 1953 in eastern Hispaniola. Thus, at present there are two gaps, one on the eastern Septentrional fault, another on the western North Hispaniola Deformed Belt. Which of these zones will fail next? This question could be addressed by boundary-element modeling, which predicts the increase of static stresses (and thus, time-to-failure) on fault-bounded crustal blocks caused by slip on adjacent fault blocks.

Collisional Tectonics of the Bahama Bank along the Northern Margin of the Caribbean Plate: Cause and Effects

William R. McCann

Earth Scientific Consultants, 6860 West 99th Avenue, Westminster, Colorado 80021

Several Late-Miocene to Recent tectonic events along the northern margin of the Caribbean - North American Plate Boundary are related to the entrance of the Bahama Bank into Northern Lesser Antilles or Puerto Rico subduction zone. The reaction to the collision of this buoyant feature with the subduction zone depends upon the obliqueness of subduction, and the buoyancy of the interacting Bank.

In the Northern Lesser Antilles, the Bank enters the subduction zone about Middle Miocene, coinciding with a period of magmatic quiescence along the northern part of the subduction zone. Magmatism appears again in earliest Pliocene time, but with its locus shifted westward away from the Lesser Antilles Trench. This shift occurs because of erosion of the forearc of the Northern Lesser Antilles, or by a shallowing in the dip of the subducted plate caused by a more buoyant slab or both. The event affects about 300 km of arc.

Along the more oblique margin to the North and West, the effects occur later and are of a different form. Puerto Rico suffered a major tectonic event in Late Miocene- Pliocene Time. The Bahama Bank lay just north of Puerto Rico during this time. Shallow water limestones of Pliocene and older age are now found at 4 km depth along the northern flank of the Puerto Rico Platform. The rapid subsidence of this forearc was probably due to accelerated tectonic erosion.

Also, Puerto Rico experienced a period of accelerated rotation when it rotated counterclockwise 24^{o} starting about 11 MA and ceasing about 4-5 Ma. This event was contemporaneous with: 1- Development a rotating microplate along the Caribbean-North American margin, containing all of the Puerto Rico Virgin Islands Platform and perhaps a significant part of Hispaniola; 2- Rotation induced extension (N30W) along the SE edge of the microplate i.e. Anegada Passage; 3- Rotation induced compression (subduction) along the SW edge of the microplate i.e. Muertos Trough; 4- Development of a separate microplate westward of the immediate collision zone (Gonave Microplate), including the initiation of the Jamaican zone of deformation. This event affects at least 1500 km along the northern margin of the Caribbean Plate and is best characterized as collision induced rotational back-arc thrusting, shifting a segment of the Greater Antilles island arc onto the crust that lay in its back arc region.

In the last 5 Ma, 1- Rotation of the Puerto Rico Microplate ceases and corresponding extension and compression induced by that rotation also ceases around Puerto Rico; 2- A new region of extension (N45E) develops between the Puerto Rico and Hispaniola. This new area of extension reflects *continuing* subduction along the Western Muertos Trough induced by continuing collision of the Bahama Bank with Hispaniola, associated lateral arc extension caused by the geometry of subduction zones of opposing dips, and docking of Puerto Rico with the buoyant Caribbean Plate.

If Hispaniola in fact rotated in tandem with Puerto Rico during the 11-4 Ma period mentioned above, then a significant segment of "Caribbean Plate" that lay to the SW of the microplate would have been subducted along the Muertos Trough and its extension to the NW. A pole of rotation for the opening of the Anegada Passage was probably located about 100km south off the western coast of Puerto Rico (17N, 67W). If that were in fact a fixed pole for rotation of the Puerto Rico-Hispaniola Microplate, then convergence of 200-300km would be required along the westernmost portion of the microplate in Haiti, and 100-200km in the Dominican Republic. In the Eastern Dominican Republic there is a 100-200km downdip section of seismic activity generally believed to be North American Plate that preceeded the Bahama Bank into the Puerto Rico Trench.

We suggest that another possibility exists for the origin of that cluster of intermediate depth seismicity. Perhaps that earthquake activity represents lithosphere of the Caribbean Plate subducted at the Muertos Trough by the collision induced rotation of the extended Puerto Rico Microplate. This concept is consistent with deformation observed in Central Hispaniola and the extensive accretionary prism just south of the Dominican Republic. It may also explain the enigmatic gap in seismcity between shallow events, clearly related to present day subduction at the westernmost portion of the Puerto Rico Trench, and the intermediate depth events beneath Eastern Hispaniola. We suggest that perhaps the latter events should instead be related to shallower seismicity near the Muertos Trough. This concept would also predict the existence of an easterly narrowing strip of the Caribbean Plate lies underthrust beneath the Mona Passage and westernmost Puerto Rico.

If Hispaniola did not rotate along with the Puerto Rico-Virgin Islands Platform, then the seismicity gap mentioned above may represent a real break in the subducted North American lithosphere. However, this model suggests that 10's if not 100 kilometers of deformation occurred somewhere between Western Puerto Rico and Eastern Hispaniola as the Puerto Rico Microplate rotated. No such deformation zone has yet been identified.

Crustal Evolution of the Cascadia Subduction Margin in the Vicinity of the Mendocino Triple Junction

Patricia A McCrory[1], Douglas S Wilson[2], and Mark H Murray[3]

[1]US Geological Survey, Menlo Park, CA 94025, [2]Geological Sciences Department, University of California, Santa Barbara, CA 93106, and [3]Geophysics Department, Stanford University, Stanford, CA 94305

The Mendocino triple junction occupies a transitional zone between the Cascadia subduction regime to the north and the San Andreas transform regime to the south. The continental margin at the southern end of the Cascadia subduction zone is composed of a 15-km-wide deformation front backed by the Franciscan complex—a 100-km-wide belt of Cenozoic and Mesozoic subduction-complex terranes juxtaposed against the Mesozoic and Paleozoic Klamath Mountain terrane on the east. The strata that fill the Humboldt basin, a 40-km-wide and 200-km-long synclinorium overlying the subduction-complex basement, represent a record of the margin behavior. This record of subduction-related tectonism—when compared with the style of modern tectonism—yields insight into the ongoing transition from a subduction regime to a transform regime in the vicinity of the northward-migrating triple junction.

Humboldt basin consists of a series of coalesced sub-basins. The southernmost sub-basin is the Eel River basin which contains a marine stratigraphic sequence that documents a restricted deep-water depocenter in the Miocene, shoaling as the depocenter filled with turbidite facies in the Pliocene, and a widespread slope and shelf environment that developed as adjacent sub-basins coalesced in the Pleistocene. This sequence is consistent with continuum models explaining the evolution of accretionary margin basins, yet the vertical tectonic signal preserved within this sequence reveals several significant deviations (McCrory, 1989; 1995): (1) Humboldt basin strata overlie Paleogene and older Franciscan Complex rocks, implying a hiatus of about 15 My between accretion of basement rocks and deposition of overlap strata; (2) deep-water conditions during deposition of overlap strata persisted for at least 10 My (*ca.* 14-4 Ma); and (3) rapid uplift began along what is now the southern basin margin late in basin history (*ca.* 3.5 Ma) followed by onset of folding (*ca.* 2.0-1.5 Ma). This ongoing phase of uplift and shortening may be driven by the increased coupling between the subducted oceanic slab and overlying subduction-complex rocks, inferred to result from the strongly oblique convergence between the Juan de Fuca plate and northern California that began at about the same time (Wilson, 1993).

Thrust faulting began *ca.* 1 Ma. North of 40.8°N, thrust faults trend north-northwest consistent with subduction-related shortening within the upper plate. This structural pattern is disrupted in the Cape Mendocino region where active thrust faults developed in the Yager and Coastal Franciscan terranes (and their offshore equivalents) trend west-northwest. A comprehensive survey of active thrust faults within onshore Franciscan terranes (McCrory, 1996) indicates permanent contraction of about 10 mm/y directed 55±10°. The contraction associated with these young faults is oblique to the relative motion between the southern Juan de Fuca plate and northern California, suggesting that the strain may be distorted by a Pacific plate buttress propagating northward with the migrating triple junction. However, few widespread age markers occur in the onshore Quaternary strata, hampering efforts to determine whether the onset of crustal faulting in the Humboldt region was synchronous, diachronous, or progressed from south to north as might be expected from the northward migration of the Mendocino triple junction.

Modern strain accumulation across the Humboldt region (1981-1989) indicates interseismic contraction of about 15 mm/y directed 35±8° (Murray and Lisowski, 1995). Motion between the southern Juan de Fuca plate and the northern California margin is about 40-50 mm/y directed 47±7° (McCrory, Wilson, and Murray, 1995). The discrepancy of 12±11° between the direction of interseismic contraction and the direction of subduction-related convergence, although not very statistically significant, suggests that a component of modern deformation may be unrelated to strain accumulation on the megathrust. This component may be driven by convergence between the easternmost Pacific plate and the Eel River basin area at about 38 mm/y directed 340° (McCrory, Wilson, and Murray, 1995). The onshore Pacific plate buttress may have formed recently by an inland jump in the local plate boundary, or alternatively, the buttress may have translated northward along the margin for some time. In either case, the skewed contraction direction likely results from both localized anomalies in Juan de Fuca motion adjacent to the Pacific plate and from direct convergence between the Pacific and North America plates.

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The Transition From Subduction To Transform Regime: Structural And Stratigraphic Signatures Associated With Triple Junction Migration Offshore Northern California

Anne Meltzer and Sean Gulick

Dept. of Earth & Environmental Science, 31 Williams Dr., Lehigh University, Bethlehem, PA 18015, asm3@lehigh.edu

In northern California, the North American, Gorda, and Pacific plates come in contact forming the Mendocino Triple Junction. The triple junction itself is a broad zone extending over several hundred square kilometers laterally and includes the crust and upper mantle at depth. North of the triple junction the Gorda plate is subducting beneath North America forming the southern end of Cascadia subduction zone. South of the triple junction, the Pacific and North American plates form a transform boundary with strike-slip motion occurring along a series of faults associated with the San Andreas Fault system. West of the triple junction, the Pacific and Gorda plates form a transform boundary along the Mendocino Fracture Zone. Seismicity and structural and stratigraphic data indicate that the triple junction is centered onshore near Petrolia, however, the tectonic processes and strain related to plate boundary interaction radiate outward and influence crustal deformation of coastal California between Clear Lake and Crescent City and extend offshore well west of the deformation front of the Cascadia subduction zone.

The canonical view is that the triple junction has been steadily marching northward along the western margin of North America since the Pacific-Farallon spreading ridge intersected the margin approximately 28 million years ago. As the triple junction migrates northward arc magmatism shuts off and convergence yields to strike-slip with local extension and shortening accommodating any oblique component of motion between the Pacific and North American plates. In the wake of the triple junction, a slab-free zone develops where there is no oceanic plate subducting beneath the margin and hot asthenosphere wells up toward the base of the crust. Thermo-mechanical models incorporating spatial and temporal heating of the crust due to the asthenospheric window predict localized weakening in the lower crust leading to deformation related to transform tectonics in the upper crust.

In detail, the transition from subduction to transform motion has been complicated by the irregular boundary between the Pacific and Farallon plates, a series of ridge segments offset by fracture zones, that progressively interacted with the margin of western North America. A complex pattern of magnetic anomalies offshore California tell a tale of slowed spreading, plate fragmentation, stalled subduction, and eventual micro-plate capture as young, hot, negatively buoyant oceanic slabs east of the spreading ridge stall beneath the overriding plate then are subsequently ceded to the Pacific plate. As this happens, the main locus of strike-slip shifts eastward farther into the North American continent and transform motion propagates rapidly northward lengthening the transform margin on relatively short time scales.

A series of seismic reflection profiles from the Mendocino Triple Junction seismic experiment augmented with industry data sets provides an interesting view of the structural and stratigraphic development offshore Northern California during this period and provide a current snapshot capturing the plate boundaries in transition from subduction to transform motion.

The Vizcaino block and overlying Neogene Pt. Arena basin sit immediately south of the triple junction between the Mendocino and Pioneer fracture zones. The Vizcaino block is bound on the east by a well-defined 3-5 km wide shear zone mapped as the San Andreas Fault zone. The western boundary is the Oconostota Ridge which is underlain by 25-26 Ma Pacific oceanic crust. In the most simple plate model, this entire region has been passively riding above the Pacific plate for its entire history, its northeastern corner coinciding with the triple junction. In this position the Vizcaino block would have been shielded from deformation taking place north of the migrating triple junction and would sit west of the main transform plate boundary. While interpretation of the reflection data is generally consistent with this model, the Vizcaino block can be broken into three distinct structural domains based on the character of basement reflections and thickness/deformation of the overlying Neogene sedimentary section. The region shows a remarkable amount of young deformation (shortening) well south of the triple junction and west of the main locus of strike-slip associated with the transform plate boundary. An older, high angle, through going fault is observed west of the shear zone associated with the San Andreas Fault. This fault offsets basement ~1.5-2 km in places (up to the east) and deforms overlying sediments as young as Pliocene. The fault merges with the San Andreas approximately 50 km south of Pt. Delgada. The shear zone associated with the San Andreas trends onshore at Pt. Delgada. If the San Andreas curves northwest and trends offshore again as suggested in previous maps, it does so within the three-mile state waters. There is no evidence of the fault trending offshore north of Pt. Delgada within the available seismic data.

Directly northwest of Pt. Arena, the southern end of the offshore Pt. Arena basin is characterized by a thick (>3.0 km), highly deformed sedimentary section including fault cored anticlines and anticline/syncline pairs above faulted/folded basement. At least 2 distinct phases of deformation are observed. An early phase (pre 5 Ma) and a younger, predominantly Plio-Pleistocene phase which continues today, in places folding sediments near the seafloor on the western edge of the basin. Upper Miocene and younger sediments were largely funneled into local depocenters between growing anticlines and syntectonic deformation of these sediments dates fold growth. A major erosional unconformity separates the deformed sediments from westward prograding Pleistocene and younger sediments. North of this region the degree of deformation diminishes. Sediments and basement are still folded and faulted, but the folds are broader and less frequent. In the far northern end of the basin, just south of the Mendocino Ridge, strong, coherent, flat to gently northward dipping basement reflections are observed. A thick, essentially undeformed sedimentary section overlies basement. Sediments are thickest immediately south and west of the triple junction (northeast corner of the basin). The Pt. Arena basin terminates at the Mendocino ridge. Sediments on the flank of the ridge are uplifted and tilted southward. There is a strong angular unconformity at the seafloor indicating the ridge crest was at one time at sea-level and has subsided over 1200 meters.

The Mendocino Fracture Zone passes on the north side of the Mendocino Ridge. In this region the Mendocino Transform Fault juxtaposes 25-26 my old oceanic crust of the Pacific Plate to the south against 6-7 my old oceanic crust of the Gorda Plate to the north. Structural development of this region is affected by the age transition across the Mendocino Fracture Zone; the young, hot, Gorda plate absorbs most of the deformation. The Eel River forearc basin overlies the subduction zone complex north of the Mendocino Fracture Zone. The southern end of the Eel River basin is extremely deformed, shortened, uplifted, and in the process of being cannibalized. The Southern end of the forearc lies beneath only 100 m of water and folded and faulted sediment are truncated at the seafloor. The presence of the triple junction in the Eel River basin is currently felt at least 60 km to the north as a broad region of uplift. As a result of this uplift, Upper Pleistocene and younger sediments bypass the southern end of the basin and are either deposited in a depocenter on the lower shelf or are transported through the Eel Canyon to be deposited along the toe of the accretionary prism. The northern portion of the basin shows primarily dip-slip low angle faulting on the western edge of the basin and high-angle faults suggestive of strike-slip deformation beneath the continental shelf. There is an intervening little deformed 30 km wide marginal plateau (the Klamath Plateau), and the main forearc basin is in essence a single large synclinorium. In the Southern portion of the basin, low-angle primarily dip-slip faults on the western edge of the forearc curve east-southeast towards the triple junction and change dip to become high-angle faults that resemble positive flower structures suggestive of youthful strike-slip motion. Near the triple junction the original forearc basin is subdivided into a series of smaller sub-basins.

From the toe of slope to the continental shelf deformation changes from convergence related low-angle thrusts to near-vertical faults suggesting a component of strike-slip. As the triple junction moves northward, faults originally accommodating shortening in the convergent plate setting north of the triple junction, rotate and steepen, serving as sites for strike-slip motion during and after passage of the triple junction. Strike-slip activity on these eastern faults suggests that the transition to transform motion associated with the Pacific-North American plate boundary is propagating northward.

A gravity study of the Puerto Rico Trench and surrounding region: Implications for the origin and tectonics of the Puerto Rico Trench

A. Miller[1], N.R. Grindlay[1], P. Mann[2] and J. Dolan[3]

[1]Department of Earth Sciences, University of North Carolina at Wilmington, 601 S. College Road, Wilmington, NC 28403
[2]Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin TX, 78759
[3]Department of Earth Sciences, University of Southern California, University Park, Los Angeles, CA 90089-0740

The worlds' large free-air a gravity minima (-380 mGal) and the Atlantic Ocean's deepest locality are found at the Puerto Rico Trench (8450m). The trench lies to the north of the island of Puerto Rico within a wide area of deformation associated with the oblique convergence of the North American plate beneath the Caribbean plate. Motion along this plate boundary is dominantly left-lateral strike slip. A puzzling feature of the Puerto Rico Trench gravity anomaly is that there are other deep trenches and oblique convergent plate boundaries around the world that do not exhibit such a large amplitude anomaly. Several tectonic models have been proposed to explain the origin of the trench, it's associated gravity anomaly and the rapid subsidence of the Pliocene shallow-water carbonate platform on the northern insular margin of Puerto Rico about 3.3 Ma. These models include: 1) extreme tectonic erosion associated with the oblique underthrusting of aseismic ridges (Birch, 1986), 2) regional transtension (Speed and Larue, 1991), 3) and the favored model, loading of the North American by the Caribbean plate, presently subducting northward along the Muertos Trough, beneath the island of Puerto Rico (Dillon et al., 1996, Dolan et al., 1998)

Recently collected bathymetry and single-channel seismic data together with existing multi-channel seismic data have been used determine realistic crustal and upper mantle structure for the region. Two-dimensional forward modeling of gravity anomalies associated with the plate boundary have been performed in an effort to test the viability of these proposed models. Three roughly N-S trending profiles across the eastern, central and western portions of the trench and Puerto Rico/ Virgin Islands arc have been modeled. Only the easternmost model profile that crosses the Virgin Islands platform appears to closely to match the observed data. Modeled profiles over the central and westernmost portions of the trench predict higher gravity values than observed. Since the 2-D models assume isostatic equilibrium, the differences between modeled and observed data can best be explained by a dynamic component. Loading of the North American plate at depth by the Caribbean plate, as proposed by Dillon et al., (1996) would cause the plate to flex downward thus introducing a dynamic component that would cause the region not to be in isostatic equilibrium. Future plans include testing this hypothesis by modeling the expected flexural shape of a loaded North American plate and comparing that with the shape of the Puerto Rico trench.

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Three-dimensional structure of the Cordillera Oriental of Colombia: A segment of the southern Caribbean plate boundary

Camilo Montes

306 G&G Building, Structural Geology and Tectonics, The University of Tennessee, Knoxville TN, 37996-1410 , fax: (423)974-9326, office phone: (423)974-0701, e-mail: cmontes@utkux.utk.edu

Current palinspastic reconstructions of the Cordillera Oriental of Colombia assume deformation paths perpendicular to the trend of the Cordillera (NW-SE dip-slip), ignoring strike-slip deformation. Kinematic plate tectonic reconstructions (Ladd, 1976) predict that the Cordillera Oriental of Colombia experienced oblique NE-SW convergence and transpression throughout the Cenozoic. Despite its regional setting, a doubly vergent fold-thrust belt geometry (driven by subduction) has been suggested for the Cordillera Oriental, and about 150 km of NW-SE horizontal shortening has been estimated using standard two-dimensional reconstruction techniques.

Deformation in the Cordillera Oriental must be related to transpression produced by oblique convergence, and dextral motion of the Caribbean Plate along the NW corner of South America since the Eocene. The overall structure of the Cordillera Oriental might resemble a dextral "palm tree"structure (Lowell, 1972; Sylvester, 1988) where the double vergence is the expression of a room problem created as two blocks obliquely converge, and the material in between is thrust up. These upthrusts may flatten upwards and cause passive uplift, and mild deformation on the thick layer of Upper Cretaceous and Tertiary sediments along the axis of the Cordillera. Oblique convergence may have been accommodated by thrust sheets moving out of the NW-SE plane usually chosen to model the two-dimensional structure. Therefore, prominent strike-slip faulting should not necessarily be present.

We complied a comprehensive geologic database to test competing hypotheses regarding the tectonic evolution of the Cordillera Oriental (subduction vs. transpression). This database served as starting point to build a three-dimensional computer model where forward modeling was performed. This model illustrates the viability of transpression, instead of subduction, as the driving mechanism for deformation of the northern Andes. Although this dataset is limited, and some of the underlying assumptions are open to question, this model highlights the need and the viability to study the structure of the Cordillera in three dimensions. Currently, field studies are being carried out in the western flank of the Cordillera with the goal of measuring the relative contributions of strike- and dip-slip to deformation.

Tectonics of the Ibero-African margin.

Teresa Moreno & Wes Gibbons

Department of Earth Sciences. Cardiff University. Cardiff CF1 3YE, Wales, UK.
e-mail: MorenoT@Cardiff.ac.uk

The Iberian Peninsula lies at the western end of the Alpine-Himalayan orogen, caught between the two continents of Africa and Europe, the widening Atlantic Ocean, and Neotethyan subduction systems in the western Mediterranean. Iberian tectonism over the last 100Ma reflects this unique position, with deformation occurring on both the northern (Pyrenees) and southern (Betic) margins of the Peninsula as it moved broadly eastward and rotated anticlockwise, sometimes as an independent plate, sometimes linked to Africa or Europe. Since early Miocene times (c.24Ma) Alpine deformation in Iberia has focused along the southern margin which became the African-European plate boundary. The late Mesozoic to Recent tectonic history of the Betic orogen provides a record of Ibero-African interactions, but the geology is complex and controversial. Successive events have interleaved mantle lherzolites with crustal rocks, emplaced blueschists over the Iberian margin, and induced massive extensional collapse which was partly synchronous with thrusting, strike-slip faulting, oroclinal rotations, and calc-alkaline magmatism.

During the Early Cretaceous Iberia, mainly linked to Africa, had rotated 30º anticlockwise with respect to Europe. Continuing eastward drift during the mid-Cretaceous was achieved independently of both Africa and Europe, with the Azores-Albor·n tectonic line (AATL) acting as a southern transform plate boundary. Late Cretaceous Iberian movements once again closely paralleled those of northwest Africa, and movement on the AATL declined. Thick, deep marine, late Mesozoic to Palaeogene siliciclastic sediments (later to become the Flysch Nappes) were deposited in transcurrent basins between Iberia and Africa. Mesozoic transtensional thinning and upwelling of lower lithospheric continental mantle along the Ibero-African margin has been invoked to help explain the later introduction of fertile lherzolite to the Tertiary Betic nappe stack. Africa and Iberia continued to move ENE across the K-T boundary and during the early Palaeogene. These movements were accommodated further east by the subduction of oceanic crust in the western Mediterranean. The late Cretaceous to Palaeogene blueschists and eclogites produced by this subduction were destined to be stacked over the continental basement of Europe and are currently exposed in the Western Alps, Corsica, and the Betics.

As the rotation pole of Africa moved progressively northwards during the Eocene and Oligocene, Iberia increasingly once again behaved as a separate plate, bounded by the Pyrenees and the Azores-Albor·n tectonic line (AATL). Africa moved ENE with respect to Europe, sliding transpressionally against Iberia which also continued to drift eastward. HP-LT accretionary prism rocks were thrust over continental basement as the western Mediterranean subduction system collided with western Europe. Most authors envisage a SE-dipping slab (as shown here: this is more in accord with Corsican geology), although a NW dip has been suggested. The age of internal Betic nappe stacking is poorly constrained but generally attributed to the Palaeogene. More controversial is the timing of lherzolite exhumation: although one of the largest known masses of orogenic fertile mantle rocks, whether they were exhumed after oblique Palaeogene collision or by Neogene extension remains unproven. Also uncertain is the number of Palaeogene deformation events recorded in the Betics, with some authors preferring alternating compressional and extensional phases rather than only one major compression. A major problem inhibiting understanding of Palaeogene events is a later widespread overprint of Neogene extension.

In early Miocene times Iberia became attached to Europe as Pyrenean movements ceased and Africa continued its ENE drift. In the previously thrust-stacked internal zones of the Betic orogen, lithospheric extension commenced and led to the (Aquitanian) onset of sedimentation in the Alboran Sea. The Betic Cordillera became an archipelago similar to the modern Aegean Sea. Regional extension ran NE-SW from the Provencal-Ligurian basin NW of Corsica through the Valencian Trough to the Alboran Sea, transecting the earlier arc-continent collisional front and migrating eastward with time. The extension in Corso-Sardinia and Italy was, and in places still is, associated with calc-alkaline to shoshonitic magmatism, and has been linked to SE retreat of the modern

Calabrian subduction zone. Lower Miocene magmatism in SE Iberia began in the western Betics, initially producing arc tholeiite dyke swarms (Aquitanian), then became more organised by the mid-Miocene when major andesitic caldera complexes erupted in the eastern Alboran Sea. Volcanism in the eastern Alboran region continued into the late Neogene, locally erupting more evolved (dacite to rhyolite) magmas from calderas, and becoming generally more K-enriched with time to produce Late Miocene to Pliocene shoshonites, alkali basalts, and lamproites.

Currently competing hypotheses presented to explain the dramatic Miocene extension in the Alboran Sea area emphasise one of the following models:

1 *Convective removal of a thickened lithospheric root*: initial rise of hot asthenosphere produces uplift at the Earth's surface followed by collapse to produce a basin with a fixed depocentre. The Betics are commonly viewed as a world classic example of this kind of radially directed "extensional collapse" as vertical stresses caused by elevated crust surpass the horizontal stresses induced by plate convergence.

2 *SE-directed delamination of thickened subcrustal lithosphere*: initial rise of hot asthenosphere produces uplift at the Earth's surface followed by extension as the lithosphere peels away and moves laterally to produce a basin with a migrating depocentre. This model is used to explain the eastward migration of sedimentation in the Alboran Sea.

3 Collision with NW-dipping subduction zone then slab detachment: Palaeogene oblique convergence between Iberia and a NW-dipping Mediterranean subduction zone is followed by Neogene detachment and rapid sinking of the lithospheric slab. Release of slab-pull force beneath the thickened Betic orogen, combined with lateral inflow of hot asthenosphere, induces uplift and subsequent extension, with elevated isotherms and decompression melting driving calc-alkaline volcanism.

4 Collision with SE-dipping subduction zone then polarity reversal and slab rollback: Late Mesozoic- Palaeogene convergence between Europe and a SE-dipping subduction zone produces collision from the W Alps to the Betics. A new, late Oligocene to Quaternary, orogenic system with an opposite sense of polarity then cuts obliquely through the earlier thrust-stacked orogen. NW-dipping subduction retreats SE to induce intra-arc extension from Provence to the Alboran Sea. This is also consistent with eastward migration of sedimentation in the Alboran Sea.

Convergence along the Ibero-African margin became more compressive in the mid-Miocene (16Ma) when Africa turned northwards and initiated the transcurrent trans-Alboran/Eastern Betics shear zone running from Morocco through SE Spain. Another anticlockwise plate rotation took place in the late Miocene, turning Africa more northwestwards into Iberia and reducing the size of the Alboran Sea. A similar intensification of NW-directed convergence in the late Pliocene induced further uplift and inversion of late Neogene sedimentary basins. A return towards more NNW-directed convergence during the early to mid-Pleistocene reorganised fault and basin kinematics and began the development of the present day landscape. Many Quaternary Ibero-African movements have focussed around the sigmoidal Eastern Betics shear zone which is transpressive in the NE (Alhama de Murcia fault system), transcurrent in the centre (Palomares fault system) and transtensional in the SE (Carboneras fault system). This tectonic lineament is the modern expression of a long-active Neogene strike-slip boundary separating a transtensional western Alboran sector from a transpressive eastern Alboran sector. The boundary probably roots into a low-angle mid-crustal detachment beneath the Betics (8-10km depth) that has presumably been reactivated many times since Palaeogene collision. Combined deep (>600km) earthquake data in southern Spain and seismic tomography studies indicate the current presence of a vertical slab of seismically faster material between 200-700km below the Betics and Alboran Sea. Other modern seismic activity occurs at shallow or intermediate (<180km) depths and is attributed to current oblique convergence between Africa and Europe.

Thus the late Mesozoic-Cenozoic tectonic evolution of the Betic orogen reflects interactions between two Mediterranean subduction events and oblique Ibero-African plate movements. Neogene extension in the Alboran Sea was probably mainly, or wholly, driven by subduction processes rather than convective removal or delamination of a thickened lithospheric root. This interpretation is the most consistent with an overview of Mediterranean tectonics and especially emphasises: 1. The linkage in space and time between the Alboran Sea and the opening of the suprasubduction Ligurian-Valencian basins. 2. Calc-alkaline to high-K magmatism throughout Neogene time in the Alboran region: comparison is drawn with the still-active volcanicity in the Calabrian arc of S Italy. 3. The presence of a dense vertical slab at depth beneath the Betics and Alboran sea: this is interpreted as a detached remnant of subducted oceanic lithosphere.

Results from the Neotectonics studies in Western Puerto Rico.

Juan Carlos Moya[1].

[1]3114 Broadway # 3. Boulder, CO 80304. jcmoya@hotmail.com

Puerto Rico is located in a tectonic environment associated with the oblique subduction of a buoyant marine ridge, the Bahama Bank. A reconstruction of the tectonic history of Puerto Rico shows that the effects of this oblique subduction have been complex. In the Eocene to the Middle Oligocene, compression created a suture zone between island blocks and strike-slip faults were also developed in the island. The Late Oligocene to Middle Miocene was a period of quiescence. After this period, from the Late Miocene to the Pliocene, the passage of the Bahama Bank underneath the Puerto Rico Microplate induced the island to rotate. It is suggested that during this time, from the Miocene through the Pliocene, Puerto Rico and eastern and central Hispaniola were part of the same microplate. Rotation of this microplate around a single rotation pole, located in the Caribbean Plate south of western Puerto Rico, generated the opening of the Anegada Passage together with a zone of extension in southern Puerto Rico, the formation of the Muertos Trough, and a zone of compression in central Hispaniola. Geomorphologic, geologic, and structural data suggest that somewhere in the Pliocene maybe Late Pliocene and Early Quaternary, southwestern Puerto Rico presented an environment of strike-slip faults with transtensive and transpressive faults. Information from two faults located in western Puerto Rico, the Cordillera-Mayaguez Fault System and the Joyuda Fault, suggest that after the rotation, Plio-Quaternary strike-slip fault movements the regional geomorphology of western Puerto Rico. A minimum of 50 m of uplifting has been suggested for southwestern Puerto Rico.

Recent GPS vectors show that Puerto Rico and Hispaniola are now moving apart at about 4-5 mm/yr. This separation has created an extensional seismotectonic regime affecting the eastern portion of Hispaniola, the Mona Passage, and western Puerto Rico, within a boundary zone between the North American and Caribbean Plates. The zone of extension between Puerto Rico and Hispaniola suggested by the GPS data can be explained by the recent attachment of Puerto Rico to the Caribbean Plate, which is moving to the east. Thus, the former Puerto Rico microplate has partitioned into two smaller microplates; the new Puerto Rico microplate (Puerto Rico) and the El Seibo microplate (eastern Hispaniola). Their separation has been generated by the release of the Puerto Rico microplate by the Bahama Bank and the recent locking of Hispaniola by this buoyant feature. The zone of extension then includes eastern Hispaniola, the Mona Passage and Western Puerto Rico (Figure 1). This extension can be explained as a new seismotectonic regime for Western Puerto Rico which changed from strike-slip to extension.

Paleoseismic information on tsunami deposits and paleoliquefaction show the importance of the seismic hazards in western Puerto Rico associated with this extension. Some of the normal faults as suggested by recent focal mechanisms, could be reactivated faults, which were originally strike-slip faults. These normal faults and the others in the Mona Passage and Eastern Hispaniola represent an important seismic risk for western Puerto Rico having potential magnitudes up to M7.5. The recent paleoseismic information on tsunami deposits and on liquefaction injections suggests that there was one important event between 1300 and 1511. The most recent event generating tsunami deposits was in 1918. The 1300-1500 event is the first pre-historic event defined in western Puerto Rico. Many areas in Western Puerto Rico present soft deposits with high potential to some earthquake induced hazards such as: liquefaction, ground motion amplification, lateral spreads, landslides, and tsunamis.

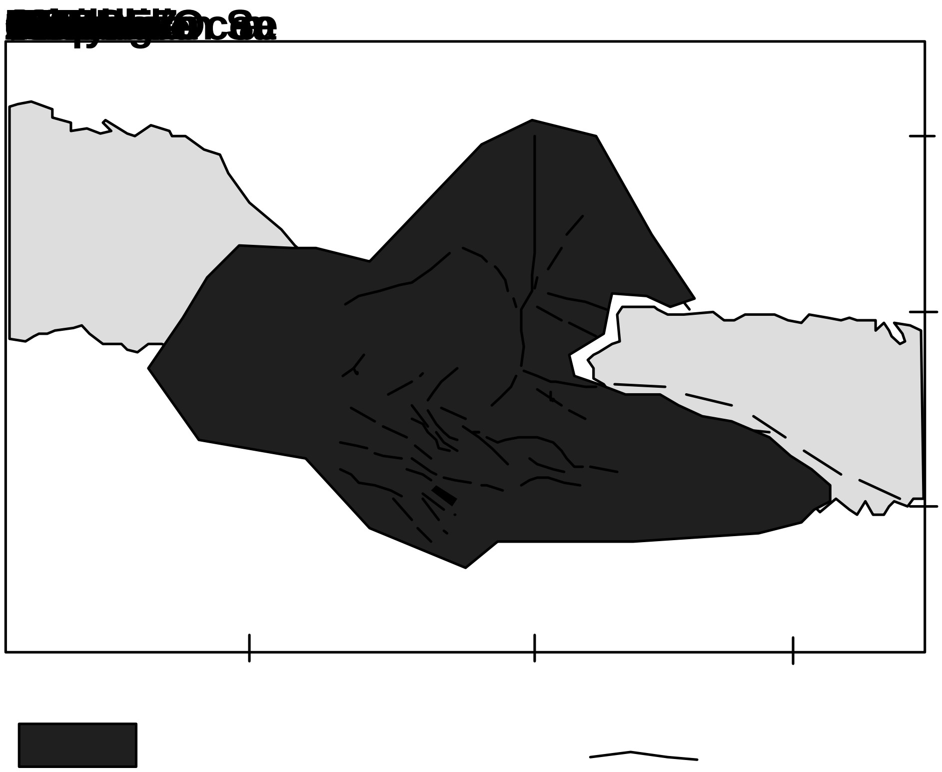

Figure 1. Areas under extension between Puerto Rico, Mona Passage, and Eastern Dominican Republic showing some important faults as suggested by structural, geomorphologic, seismic, and marine data.

Transpressional History of the Serrania del Interior Foreland Fold and Thrust Belt, North-Central Venezuela: New Evidence from Apatite Fission-Track Modeling and 2D Seismic Reflection Analysis.

Jaime Perez De Armas

Rice University, 6100 South Main St., Department of Geology and Geophysics, MS-126, Houston, TX 77005-1892, USA.

The Caribbean-South American plate boundary along north-central Venezuela is a megasuture which consists of three east-west trending belts: 1) Cretaceous metavolcanic rocks of the Dutch and Venezuelan Leeward Antilles, 2) Jurassic-Cretaceous meta-sedimentary and metavolcanic rocks of the Caribbean Mountain System, and 3) Mesozoic-Cenozoic sedimentary rocks of the Serrania del Interior foreland fold and thrust belt and Guarico sub-basin. Deformational structures in the plate boundary zone indicate partitioning of the right-oblique convergence-rate vector into two components resulting in south-vergent thrusting and dextral displacements along E-W trending faults. Within the Caribbean Mountain System, the post-Miocene La Victoria fault zone is the southernmost expression of dextral strike-slip motion in continental north-central Venezuela. Southward, deformation is taken up solely by the plate boundary perpendicular shortening component.

The western Serrania del Interior foreland fold and thrust belt and the Guarico sub-basin are the southernmost units of the diffuse transpressional Caribbean-South American plate boundary. This fold and thrust belt involves Upper Cretaceous passive-margin deposits, Maastrichtian-Lower Eocene flysch, and Oligo-Miocene foredeep deposits. Within the Guarico basin, the sequence consists of Paleozoic pre-rift and Jurassic syn-rift sedimentary rocks of the Espino graben, both of which rest unconformably either on Paleozoic metamorphic rocks or on crystalline basement of the Guyana craton. Unconformably overlying the economic basement, are Cretaceous passive margin siliciclastic and carbonate rocks. The foredeep consists of Lower to Middle Oligocene transgressive litoral sandstones, Middle to Upper open-marine shales, and a regressive Miocene siliciclastic sequence.

Fission-track modeling of Maastrichtian-Lower Eocene rocks from the Serrania suggests that two important cooling events occurred in the study area in 1) Middle Eocene and 2) Late Oligocene-Early Miocene. These apatite fission track ages do not seem to fit the model of younging of Caribbean-South American plate collisional events from west to east during the Cenozoic. The Middle Eocene cooling event has been found near the Ensenada de Barcelona. This Middle Eocene cooling event has also been observed in apatite fission-track analyses of core samples from the Lake Maracaibo basin. The Late Oligocene-Early Miocene fission-track ages occur in the Cretaceous-Paleogene rocks in the entire area. Fission-track modeling of Oligo-Miocene samples from the Serrania and the Guarico sub-basin suggests as well that these rocks were not heated above ~ 110 °C.

Interpretation of seismic reflection profiles (1500 km) allows to constrain the tectonic model for the area. Four stratigraphic sequences have been recognized in the Guarico sub-basin. These sequences rest on top of an economic basement. The latter includes igneous-metamorphic basement of the Guyana craton and pre-Cretaceous pre-rift and syn-rift sedimentary deposits. The recognized sequences are: Sequence 1) Cretaceous transgressive siliciclastic and carbonate rocks; Sequence 2) Lower Oligocene to Upper Oligocene-Lower Miocene foredeep deposits; Sequence 3) Miocene siliciclastic rocks, and Sequence 4) Miocene and younger deposits.

On the basis of apatite-fission track modeling and interpretation of seismic reflection profiles it is suggested that the tectonic evolution of the western Serrania del Interior and Guarico foredeep involves seven phases of deformation: 1) Triassic-Jurassic inception of the Espino Graben, 2) Generation of a Late Cretaceous-Early Eocene foredeep along northern Venezuela, 3) Middle Eocene southward accretion and destruction of the Late Cretaceous-Early Eocene foredeep, 4) Early Oligocene inception of the foredeep, 5) Early Oligocene NW-SE extension in the basin, 6) Neogene thrusting, 7) Pliocene to Recent regional uplift.

The Paleozoic and Cretaceous autochthonous sedimentary rocks and non-decoupled Lower Oligocene foredeep sequences may extend below the Serrania del Interior and possibly underneath the accreted terranes to the north.

DIAPIR-FED MUDFLOWS AND SERPENTINITES: STRIKE-SLIP RECYCLING OF BUOYANT MATERIAL IN HISPANIOLA'S OBLIQUE-SLIP FOREARC

James Pindell

Dept. Earth Sci, Oxford U., Oxford OX1 3PR England; also Dept. Geology, Rice University, Houston, Tx.

INTRODUCTION AND REGIONAL SETTING

In northern Dominican Republic, the fault-bounded (10-30km) "Puerto Plata Inlier" (PPI) is flanked by the coastline (north), the Camu Fault and Neogene carbonate rocks (south), and Neogene carbonate rocks (east and west). The PPI exposes rocks belonging to a Cretaceous-Eocene forearc/subduction complex from beneath a Neogene carbonate cover (see Fig., field guide). The linear E-W Camu Ft bounding the PPI's south side is sinistral and stratigraphically N-side up at the PPI contact, but the Neogene carbonates on the fault's S flank sit higher (C. Septentrional), suggesting relatively faster erosion within the PPI. Projecting NE from Camu Ft and occurring within in PPI, the alluvial Maimon Valley separates two structurally distinct parts of the PPI. To the west, Basement Complex rocks form a morphologically mature landscape, whilst equivalent/other rocks east of the Valley comprise a relatively high relief, immature morphology.

This morphological difference indicates recent/active diapirism of relatively buoyant/mobile lithologies and mélanges of the subduction complex east of the Valley. This is further suggested by the occurrence of the Franciscan-like San Marcos mud-diapir/flow unit which extrudes and "flows" N-ward across all strata in the PPI from a portion of Camu Ft which was/is a conduit for mud diapirs. Diapirism, or faulting associated with it, has also disrupted the formerly continuous Neogene carbonate cover.

The isolated occurrence of Neogene carbonates of Pico Isabela, which rests on the Basement Complex, appears to have been tectonically dislocated from the Neogene carbonate section outside the PPI. The buoyant and mobile San Marcos unit (and several serpentinite bodies) fills the void created by this dislocation (see Fig., field guide). Field relations prevent a clear understanding of that dislocation, but a half graben (master E-dipping fault surfacing at Maimon Bay "graben"?) has probably formed along the north side of the sinistral Camu Ft (see Fig., field guide), suggesting extensional breakup within the PPI.

Although San Marcos derives from the Cretaceous-Eocene subduction complex below, it has also picked up knockers as young as Middle Miocene during diapirism and subsequent sub-horizontal gravitational flow. The unit today maps as a Late Miocene-Pleistocene lobate wedge. This 2-part history has caused confusion, namely that San Marcos might represent a Miocene subduction mélange (e.g., Bourgois et al., 1982).

GEOLOGY AND GEOLOGICAL HISTORY

Puerto Plata Basement Complex (PPBC) of the PPI comprises Lower Cretaceous-Eocene serpentinites, tectonized harzburgite, cumulate gabbroic rock, and mafic/intermediate volcanic rock sometimes with red interpillow cherts, interpreted as remnants of an ophiolite. The non-Tethyan cherts (Montgomery, 1992/4) suggest pieces of far-travelled Caribbean forearc rather than obducted slivers of Proto-Caribbean (Tethyan).

The PPBC is overlain by two units of similar age: 1, Paleocene-Early Eocene Imbert Fm off-white crystal tuffs, vari-colored cherts, and sandy to pebbly turbiditic rocks. Coarse clastic beds are more common low in this formation, and contain sand and pebbles of serpentinite, volcanic and metamorphic rock, and limestone; and 2, sedimentary serpentinite conglomerates and algal-limestone buildups or patch reefs of the ?early Paleogene shallow-water La Isla Fm. La Isla limestone buildups and serpentinite conglomerates contain fragments of one another, and corals were observed in growth attachment to serpentinite cobbles, indicating coeval, shallow-water deposition of the conglomerate and limestone. Imbert Fm is believed to be older than La Isla because it is more deformed and because Imbert deposition occurred in deeper water than La Isla deposition, possibly prior to or during uplift from forearc platform to photic water depths. The period of La Isla deposition and probably longer thereafter was a time of erosion across much of the PPI, leading to an angular unconformity between Imbert and younger units. The Eocene uplift and erosional hiatus is interpreted as recording convergence/collision between Greater Antillesarc and Bahamas.

In Late Eocene-Oligocene, shelf deposition is indicated by conglomerates and terrigenous, mica-bearing sands/marine shales of Luperon Fm. Tectonism at this time was apparently minor. Deformation and erosion (emergence?) occurred again in Early Miocene, but deposition was renewed in Mid to Late Miocene with Villa Trina Fm carbonates (terrigenous input reduced). Early Miocene deformation/change in sedimentation may pertain to strike-slip separation of Hispaniola from SE Cuba along Oriente Transform Ft.

Regional uplift occurred again since Pliocene, elevating the Pliocene reefal cap of Villa Trina Fm to several hundred meters, and exposing ?Pleistocene reefal limestones/beachrock along the coast. This uplift is due to oblique convergence of Hispaniola with easternmost Bahamas Bank along the Oriente transform. Finally, since ?Pliocene and probably associated with the Pliocene-Recent uplift, the San Marcos mud unit carrying mm to 100 m sized blocks of all the above mentioned lithologies (and others) diapirically rose to the surface and flowed horizontally across areas of the Imbert, Luperon and Villa Trina Fms.

THE CAMU FAULT AND MAIMON VALLEY

Camu Ft defines the PPI's southern limit. Fault gouge, breccias and steep dips in Villa Trina Fm (with sinistral indicators) are common in the fault zone. No definitive strike-slip offset markers are known, but the PPBC may correlate with Río San Juan Complex across Camu Ft to the east, possibly suggesting 50-60 km of mainly late Neogene displacement. Villa Trina Fm of C. Septentrional is topographically higher than the PPI north of Camu Ft. but along the PPI's length the Camu juxtaposes older (north) with younger rocks (south). Thus, the Camu is post-Miocene north side up as well here. The north side's relative uplift is superposed upon the regional uplift of C. Septentrional. The fault's linearity for ~100 km suggests a steep dip near the surface. Vertical displacement is up to 300m (thickness of Villa Trina flanking the PPI).

Maimon Valley is also fault controlled, a graben along an E-W sinistral shear (Mann et al. 1984). Vertical offset is ~200 m as indicated by elevation differences of La Isla Fm outcrops within vs to the west of Maimon Valley. Fault breccias occur along the valley's W flank and on the S-ward extension of the east flank. The E flank separates immature, diapirically-generated topography to the east, from more mature morphologies to the west. Maimon Valley defines the western limit of most active tectonism in PPI.

The east flank of the valley appears to be the hanging wall of a NE-trending half graben whose master fault dips E from the trace of Maimon Valley. Further, the diapirically-generated topography within this hanging wall may extrude along collapse faults within the hanging wall, thereby creating locally high, immature relief. North of Imbert, and east of the west boundary fault of Maimon Valley, the Luperon and Imbert formations dip homoclinally west, possibly indicating rotation of the half-graben's hanging wall.

SAN MARCOS UNIT

San Marcos unit occurs in 2 or 3 N-projecting lobes from Camu Ft and comprises blocks of the PPBC plus metamorphic rocks (marbles, greenschists, blueschists, amphibolites) chaotically contained within a non-lithified sheared mud matrix with Eocene fauna (Nagle, 1979). Middle Miocene Villa Trina marls/limes are also common, indicating a post-Middle Miocene age for its emplacement or deposition, even though the matrix is dominantly composed of Eocene material (Nagle, 1966). Mud diapirism and subsequent lateral flow (post-Miocene) is responsible for San Marcos unit as it maps today, as suggested by: 1, San Marcos muds are associated with brecciated serpentinites, locally intruding as well as resting upon the serpentinites and other PPBC constituents; 2, diapirism provides a mechanism for emplacing San Marcos in shallow water and/or subaereal conditions; 3, diapirism/lateral flow explains N-wardly thinning lobes of San Marcos unit; 4, diapirism explains the pervasive shear stria, or slickensides, of the matrix. Diapirism was post- Villa Trina time, as there is no interstratification or contamination between/by the two, and probably relates to post-Miocene tectonism on Camu and Maimon faults, and regional uplift of C. Septentrional. San Marcos matrix sources from Imbert Fm tuffs plus PPBC serpentines (Nagle, 1966). The Eocene San Marcos fauna are Imbert equivalent, but do not date final emplacement. San Marcos blocks may have been incorporated into the mobile matrix either during subduction or during diapirism and lateral flow.

IMPLICATIONS FOR FOREARC GEOLOGY

The ability of buoyant lithologies and mélanges to mobilize diapirically to the surface and, in so doing, to incorporate cover rocks that are far younger than the true age of subduction, is a process which must be considered when interpreting the period of subduction from the rock assemblages of subduction mélanges. Further, such reworking of buoyant materials should be expected especially in zones of highly oblique convergence, where the strike-slip component of motion often occurs at trench-parallel faults (such as Camu Ft) which can easily serve as migration conduits for buoyant materials from depth to the surface.

FIGURES AND REFERENCES (see field guide)

Paleoseismic studies along the Septentrional fault, Dominican Republic

Carol S. Prentice[1], Paul Mann[2], Luis R. Peña[3], G. Burr[4]

[1]U.S. Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025
[2] Institute for Geophysics, 4412 Spicewood Springs Road, University of Texas, Austin, TX, 78713
[3]Avenida Cuesta Colorado Esquina Calle no. 9, Las Colinas, Santiago, Dominican Republic
[4] NSF Accelerator Facility, University of Arizona, Tucson, AZ 85721

Along most of the North American-Caribbean plate boundary, active faults are offshore and unavailable for study using typical paleoseismic techniques. However, the Septentrional fault zone (SFZ) is the major, strike-slip, North American-Caribbean plate-boundary structure at the longitude of Hispaniola, and it traverses the densely populated Cibao Valley of the Dominican Republic, forming a prominent scarp in alluvium (Prentice et al., 1993; Mann et al., 1998). Study of the SFZ provides an opportunity to understand and quantify the late Quaternary behavior of this part of the plate boundary, and the seismic hazard it represents for the islands of Puerto Rico and Hispaniola. Recent GPS-based geodetic studies show high rates of motion between the North American and Caribbean plates (21 mm/yr) suggesting the potential for large accumulated elastic strain across the SFZ (Dixon et al., 1998). Our investigations show that the most recent ground-rupturing earthquake along this fault in the north-central Dominican Republic occurred about 800 years ago, and involved a minimum of about 4 m of left-lateral slip. Our studies of offset stream terrace risers at two locations, Rio Juan Lopez and Rio Licey, provide late Holocene slip-rate estimates of 6-9 mm/yr, and a maximum of 11-12 mm/yr, respectively, across the Septentrional fault. Three excavations, two near Tenares and one at the Rio Licey site, yielded evidence for the occurrence of several prehistoric earthquakes. Dates of strata associated with the penultimate event suggest that it occurred post 30 AD. These studies indicate that the SFZ has likely accumulated elastic strain equivalent to a significant earthquake during the approximately 800 years since it last slipped, and should be considered likely to produce a destructive future earthquake. These data also indicate that several large earthquakes in the historical record were not produced by the Septentrional fault, and most likely occurred within the offshore thrust belt described by Dolan et al. (1998).

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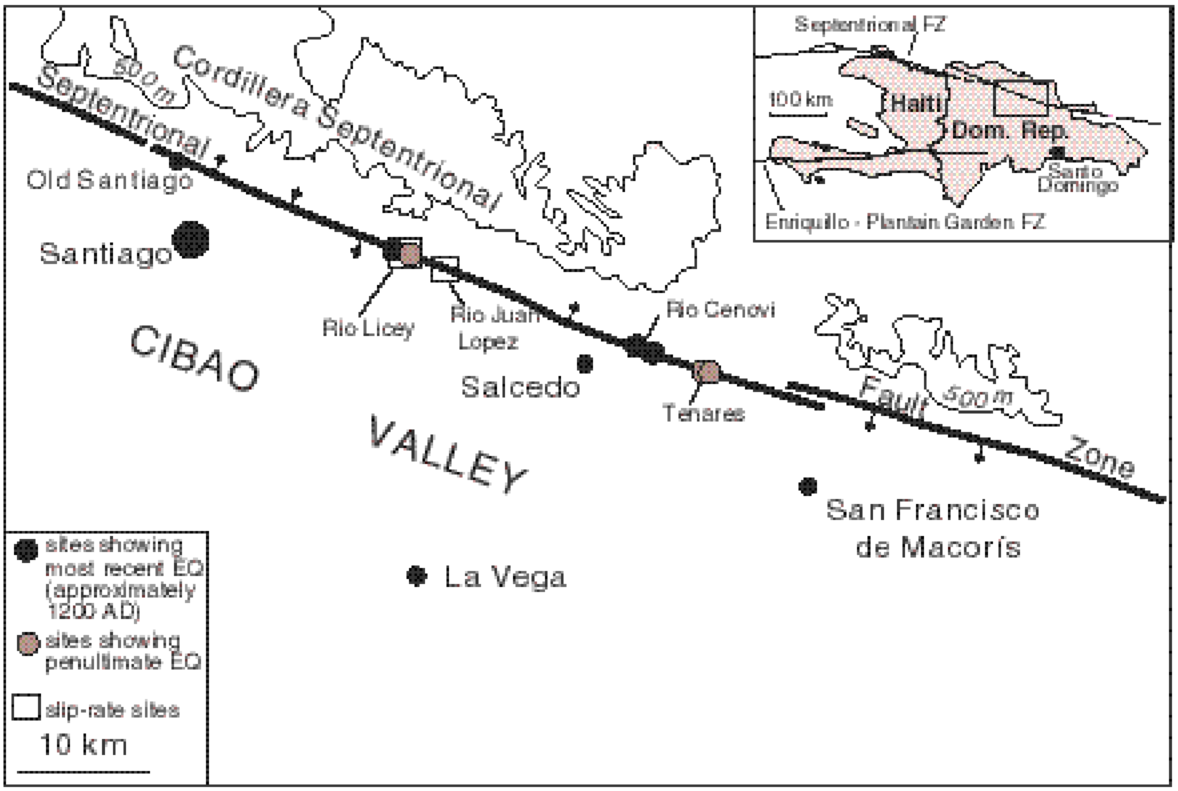

Figure 1: Map showing locations of paleoseismic excavation sites along the Septentrional fault, Dominican Republic. Rectangle in inset shows area of larger map.

The northernmost San Andreas fault near Shelter Cove, California: New data regarding an old debate

Carol S. Prentice[1], Dorothy J. Merritts[2], Edward C. Beutner[2], Paul Bodin[3], Allison Schill[2]*, Jordan R. Muller[2]**

[1]U.S. Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025
[2]Geosciences Department, Franklin & Marshall College, Lancaster, PA 17604-3003
[3]CERI, Memphis State University, Memphis, TN
* Present address: North American Publishing Co, 401 North Broad Street, Philadelphia, PA
** Present address: Department of Geology and Geophysics, University of Hawaii, 1680 East-West Road, Honolulu, HI 96822

The location of the San Andreas fault in the Shelter Cove area of northern California has been the subject of long-standing controversy within the geological community (e.g., McLaughlin et al., 1983; Wald et al., 1993; McLaughlin et al., 1994; Brown, 1995). Surface faulting associated with the 1906 San Francisco earthquake was reported for a distance of approximately 435 km along the San Andreas fault (Lawson, 1908). For most of this distance the fault is on land, but north of Point Arena the fault lies offshore. Near Shelter Cove, about 120 km north of Point Arena, 1906 fault rupture was reported onshore for a distance of about 3 km (Lawson, 1908). However, interpretation of the Shelter Cove surface rupture as a continuation of 1906 slip along the San Andreas fault has been questioned in several publications that discuss results of regional geologic mapping (McLaughlin et al., 1983; 1994; Underwood et al., in press). McLaughlin et al. (1983, 1994) interpret their mapping to show no large-scale, post-middle Miocene offset across faults in the area where the 1906 ruptures were observed. They propose instead that the San Andreas fault is either offshore or inland from Shelter Cove, and that the observed 1906 ruptures were the result of shaking-related and gravity-driven deformation, rather than San Andreas fault slip.

Other workers, however, interpret the 1906 reports, along with geomorphic and geologic features in the area, as evidence of an onshore continuation of the San Andreas fault near Shelter Cove (Brown and Wolfe, 1972; Slosson, 1974; Brown, 1995; and Hart, 1996). Recent analysis of geodetic data supports the interpretation that fault slip occurred this far north in 1906 (Thatcher et al., 1997), but analysis of teleseismic waveforms in 1906 seismograms finds nothing that requires slip along the fault north of Point Arena (Wald et al., 1993). Wald et al. (1993) conclude that seismic data from the 1906 earthquake do not provide evidence to support fault slip north of Point Arena.

Our study (Prentice et al., *in press*) uses historical research, excavation across the 1906 rupture, and independent geologic and geomorphic mapping to provide additional data bearing on whether or not a Quaternary fault is present onshore near Shelter Cove, and whether the surface ruptures reported in the region in 1906 were the result of faulting. We conclude that the surface ruptures reported in 1906 were the result of strike-slip faulting, and that a significant, Quaternary fault is located onshore near Shelter Cove. The apparent offset of Telegraph Creek (180 m), combined with a minimum radiocarbon age of about 13,000 years, suggest the Holocene slip rate of this fault is greater than about 14 mm/yr, indicating that it plays an important role within the modern plate boundary system. The onshore trace of the fault zone is well expressed as far north as Telegraph Hill, about 3 km north of Shelter Cove; north of Telegraph Hill, its location is less well constrained, but we propose that a splay of the fault may continue onshore northward for at least 9 km to the vicinity of Saddle Mountain.

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Figure 1: Map showing location of Shelter Cove and San Andreas fault.

SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Part 2: **Slab break-off and lateral extrusion in the Eastern Alps and Western Carpathians: Kinematics and analogue material modeling**

Lothar Ratschbacher[1], Blanka Sperner[2]

[1] Geological Institute, University of Würzburg, Pleicherwall 1, 97070 Würzburg, Germany
[2] Geophysical Institute, University of Karlsruhe, Hertzstr. 16, 76187 Karlsruhe, Germany

Here we describe the collision - strike-slip subduction transition of the Alpine-Carpathian region and explore the effects of a weakly confined lateral boundary, imposed by subduction, on the orogenic architecture of the Eastern Alps.

1. Why did the collision to subduction transition originate at all?

East of the Alps, along which the European foreland has an ~ E-W trend, the foreland recedes, giving way to an embayment along which the ì230° orogenic arc of the Carpathians was built (Fig. 2). About S-ward subduction and overall N-ward drift of Adria led to discontinuous collision along the strike of the Alps-Carpathians and to the coupled system of continental collision along the Alps and subduction along the Carpathians.

2. Why did a strike-slip transition originate between the collision and subduction segments?

Slab break-off at about the transition between continental and oceanic crust in the Alps frees the ocean slab in the Carpathians for further subduction. The Carpathian oceanic slab steepens due to its reduced along-strike-length and sets up back-arc extension which is migrating from the Alpine/Carpathian transition E-wards with the back rolling slab. The strike-slip boundary is established due to:

a) Rollback of the slab along the continental margin establishing a lateral transfer zone (Fig. 3a & b);
b) Lateral tectonic escape of crustal wedges from the now intra-continental indentation site in the Eastern Alps towards the subduction zone in the Carpathians (Fig. 3b & c);
c) Lateral (along strike) flow of gravitationally instable material from the collision site in the Eastern Alps towards the Carpathians.

3. How does the collision to strike-slip transition manifest itself in the upper crust?

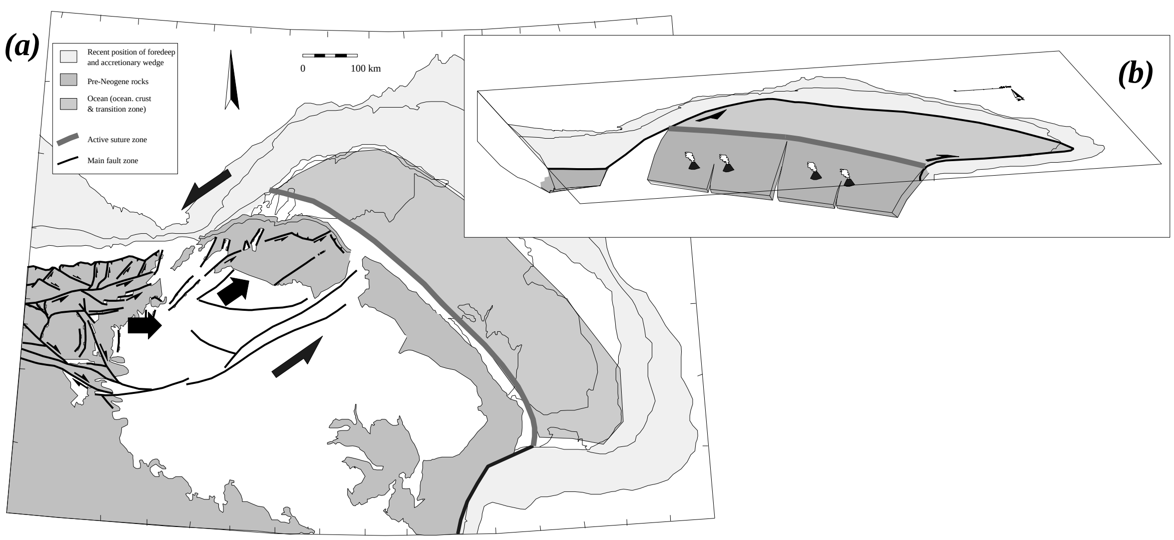
Slab break-off in the Alps at ~ 40-35 Ma is manifested by the about coeval closure of isotopic systems in HP eclogitic oceanic crust and adjacent HP European continental margin basement all along the strike-of the Alps; this might reflect the onset of exhumation. Slab break-off is further manifested by the linear E-W trend of magmatites of ~ 35-25 Ma age along the strike of the Alps; magmatism carries a crust contaminated mantle signature (tonalites). Slab break-off may also be one reason for gravitational orogenic collapse of the thickened and continuously thickening crust under ongoing intracontinental N-S indentation in the Eastern Alps. Coeval with the collapse the Alpine crust fragments and a lateral tectonic escape fault pattern is set up, along which crust blocks are expelled towards the weakly confined lateral boundary, the Carpathian subduction. We define the interaction of collapse and tectonic escape as lateral extrusion, which thus encompasses plane strain horizontal motion of tectonic wedges driven by forces applied to their boundaries and spreading away from overthickened, rheological weak crust in a orogenic belt towards a weakly confined lateral boundary.

4. What is the structural record of the collision to subduction transition?

The lateral extrusion process, i.e. the collision - subduction transition, governs the late Oligocene-Miocene tectonic style of the Eastern Alps and Western Carpathians. In the Eastern Alps from W to E a contractional province passes into a contractional wrench province, which in turn passes into a wrench-extension province (Fig. 3a & c). Structures related to lateral mass flow from the Eastern Alps towards the Carpathian subduction characterize the western part of the Carpathian domain. The area where the foreland steps towards north, the Western Carpathians, acted as a displacement transfer zone of the extruding mass; the transfer zone is characterized by a lack of crustal thickening. Thickening in the eastern Western Carpathians is localized along en-echelon, right-(N)-stepping thrust segments connected by sinistral strike-slip faults; it is localized where the foreland assumes a NW-trend and the extruding mass collided with the foreland.

5. Which boundary conditions are most important in the establishment of the collision to subduction transition?

Experimental models using rock analogues predict the significance of lateral extrusion structures in the Eastern Alps in terms of gravity spreading (due to thickening in the Alps and back-arc thinning in the Carpathian area) or indentation/escape (due to indentation in the Eastern Alps) (Fig. 3c). They also classify the importance of the boundary conditions which govern the structural architecture of the Eastern Alps. Ranking from more to less important, these boundary conditions are: weak lateral confinement in the E (i.e. the transition from a collision site to an orthogonally oriented low-stress subduction boundary), low strength of crust in the Eastern Alps, high strength of the foreland, shape of the indenter in the Eastern Alps, and indentation velocity.



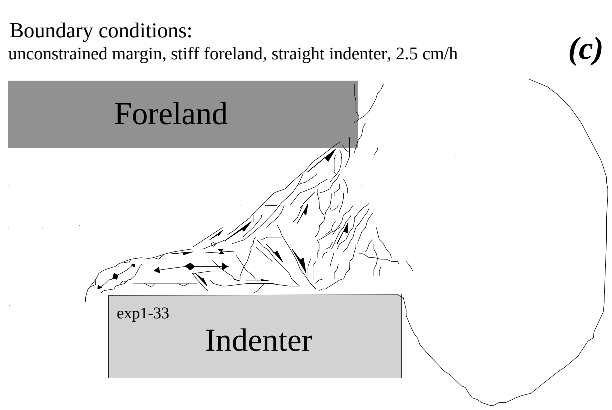


Fig. 3: (a) Deformation structures in the Eastern Alps and Western Carpathians during lateral extrusion; (b) Plate-tectonic situation during early Miocene (16-17 Ma); (c) Analogue modelling of lateral extrusion.

Stress directions in the shallow part of the Hikurangi subduction zone, New Zealand, from the inversion of earthquake first motions

Peter McGinty, Martin Reyners & Russell Robinson

Institute of Geological & Nuclear Sciences, PO Box 30-368, Lower Hutt, New Zealand
(p.mcginty@gns.cri.nz, m.reyners@gns.cri.nz, r.robinson@gns.cri.nz)

The Hikurangi subduction zone along the east coasts of the North Island and northern South Island of New Zealand is unusual amongst subduction zones worldwide, in that the plate interface is only about 15 km deep at the coastline. We thus have an opportunity to study the shallow part of the plate boundary, including the seismogenic zone which is capable of producing large subduction thrust earthquakes, using land-based observations. In recent years we have exploited this opportunity by deploying a number of dense portable seismograph networks along the subduction zone. The numerous earthquakes recorded during these seismograph deployments provide an opportunity to investigate stress directions in the shallow part of the subduction zone. Here we invert for the stress tensor orientation for various parts of both the overlying and subducted plates at both ends of the Hikurangi subduction zone - the northern South Island and southernmost North Island in the southwest, and the Raukumara Peninsula in the northeast.

To determine stress tensor orientations, we consider all first-motion polarity observations of selected groups of earthquakes together, regardless of whether or not they are sufficient to define single event focal mechanisms. It is essentially a grid search over a range of stress axes orientations defined by the greatest principal stress (($_1$) azimuth and dip, and the least principal stress (($_3$) azimuth. These parameters are sufficient to define two planes with maximum Coulomb failure stress, and the direction of maximum shear stress on them, assuming a coefficient of friction. For all earthquakes in a selected group, we simply count the number of polarities for which observation and prediction are the same, and take the best stress orientation which maximizes this count. Error estimates in the stress axes (95% confidence limits) are obtained by the resampling method. The stress inversion suggests which of the two planes with maximum Coulomb failure stress is the preferred fault plane, as generally more first motions will fit one plane than the other. We group hypocentres based on known tectonic boundaries and provinces, while ensuring that there are sufficient polarity observations in each grouping to give stable estimates of stress directions. Hypocentres and raypaths have been determined using three-dimensional seismic velocity models.

Analysis of over 12,500 first motions has provided the following insights into stress directions in the shallow part of the subduction zone:

- In the crust of the subducted plate beneath the southernmost North Island and Raukumara Peninsula regions, ($_3$ is closely aligned with the dip of the plate. The subducted plate is acting as an efficient stress guide, with slab pull from the deeper part of the plate being transmitted to shallow depth.
- Beneath the northern South Island, ($_3$, while still in the plane of the subducted crust, is rotated clockwise out of the downdip direction. This can be related to stronger coupling at the plate interface in this region.
- Normal faulting on steeply dipping fault planes is favoured in the crust of the subducted plate, suggesting that bending of this crust is accomplished through bulk simple shear (akin to shuffling a vertical deck of cards). Such a bending mechanism has been suggested by studies of large earthquakes in other subduction zones, and avoids the curling of the subducted plate inherent in pure bending mechanisms.

- In the overlying plate in the northeastern South Island, $(_1$ and $(_3$ are horizontal, thus favouring strike-slip faulting. The orientation of $(_1$ is close to that expected if the overlying plate is contracting in response to coupling at the underlying plate interface. However, sinistral motion on NW faults is favoured, whereas motion on the major NE-ENE surface faults is predominantly dextral.
- In the Raukumara Peninsula, thrust faulting on steeply dipping planes is favoured in the lower part of the overlying plate and near the plate interface. The stress regime at the plate interface does not favour interplate thrusting, and a weak interface is required for this to occur.
- It appears that strain in the overlying plate in both the northeastern South Island and Raukumara Peninsula is partitioned in time - conjugate faults may be active in taking up strain in the interseismic period between large events on the major faults.

The coupled zone of the plate interface at the Hikurangi subduction zone, New Zealand, and its relationship to structure in both the subducted and overlying plates

Martin Reyners

Institute of Geological & Nuclear Sciences, PO Box 30-368, Lower Hutt, New Zealand (m.reyners@gns.cri.nz)

The Hikurangi subduction zone along the east coasts of the North Island and northern South Island of New Zealand is geometrically uniform, and there is little variation in the oblique relative plate motion along its length. However, there are strong lateral variations in the way plate motion is accommodated along the subduction zone, with back arc spreading in the north changing to continental collision 600 km to the south. Much of this change results from subduction of the volcanic Hikurangi Plateau on the Pacific plate. The crust of this plateau thickens from about 10 km in the north to about 15 km adjacent to the Chatham Rise in the south, and it is thus much more buoyant than the ~7 km thick oceanic crust typically found at other subduction zones.

This additional buoyancy has resulted in exposure of the forearc above the shallow part of the plate interface. We thus have an unusual opportunity to study the seismogenic zone of the plate interface in detail, using land-based observations. In recent years we have exploited this opportunity by deploying a number of dense portable seismograph networks along the subduction zone. These have provided insights into the structure and seismic strain regime of the subducted and overlying plates, and the nature of plate coupling at the shallow part of the plate interface.

At the southern end of the subduction zone in the northern South Island, an earthquake arrival-time inversion for three-dimensional structure images the subducted plate as a relatively low-velocity feature in the uppermost mantle, reflecting the thick crust which is being subducted. Seismic velocity variations within the subducted and overlying plates appear to be spatially correlated. This suggests an interaction between the plates which extends well beyond the plate interface, and is consistent with other evidence that the plate interface in the northern South Island may be permanently locked. We do not see any low-angle thrust earthquakes near the plate interface in this region.

There is an abrupt decrease in the thickness of the crust (and hence buoyancy) of the subducted plate northwards across Cook Strait, between the North and South Islands. In the southern North Island, we do see low-angle thrust events near the plate interface. These concentrate in two areas: 22-25 km deep beneath Wellington, and about 15 km deep near the east coast. Through comparison with elastostatic dislocation modelling of GPS measurements, we interpret these thrust events as marking the downdip and updip edges of a locked zone at the plate interface. The plates appear to be strongly coupled over a downdip width of about 70 km, and subduction thrust earthquakes of about M_w 8.0 are estimated for this region.

By tracking the distribution of small low-angle thrust events northward along the subduction zone, we find that the width of the inferred locked portion of the plate interface progressively decreases, to be only about 20 km wide in the northern part of the Raukumara Peninsula. Subduction thrust events of only M_w 6.9 are estimated for this region. Also, earthquake arrival-time inversions for 3-D crustal structure indicate a northward increase in the thickness of sediment carried down by the subducted plate, which in turn can be related to a northward decrease in coupling at the plate interface. While changes in coupling in the south of the subduction zone arise principally from changes in the thickness in the subducted plate, in the north they are mainly due to changes in thickness of the overlying plate. When this overlying plate crust is thin, subducted sediment ponds against relatively strong uppermost mantle, while when it is thicker, the relatively weak lower crust allows sediment subduction to greater depths.

So we move from a permanently coupled plate interface in the northern South Island, through a 70 km-wide, strongly coupled zone in the southernmost North Island, to a 20-km wide, weakly coupled zone in the northern part of the Raukumara Peninsula, over a distance of only 600 km. This transition is reflected in strike-slip deformation of the overlying plate, with the intensity of this strike-slip faulting being directly related to plate coupling. In the northern South Island, the dextral Marlborough fault system takes up all the margin-parallel plate motion. In the southernmost North Island, the North Island dextral fault belt takes up 75% of this motion, and this percentage decreases northwards to be less than 5% in the northern part of the subduction zone. The resulting deficit in margin-parallel motion in the north is accommodated by clockwise rotation associated with back arc spreading. Such spreading is itself promoted by the weak coupling of the plate interface in the north. Because of the rapid lateral changes in plate coupling, the concept of partitioning of oblique relative plate motion is not particularly applicable to the Hikurangi subduction zone.

The eastern strand of the North Island dextral fault belt parallels the downdip edge of the locked zone determined seismologically. Also, dislocation modelling indicates that the large earthquakes on this strand in 1855 (M 8.1-8.2), 1931 (M_s 7.8) and 1932 (M_s 6.9) all occurred on faults which meet the plate interface close to the downdip edge of the inferred locked zone. The geometrical relationship between these faults in the overlying plate and the locked zone is no coincidence. Modelling of Coulomb failure stress changes indicates that thrusting on the plate interface will promote the slip observed on the eastern strand of the North Island dextral fault belt.

EAST TO WEST TRANSITION FROM ORTHOGONAL, TO OBLIQUE, TO STRIKE-SLIP, TO ORTHOGONAL SUBDUCTION ALONG THE NORTHERN RIM OF THE PACIFIC BASIN

David W. Scholl

Department of Geophysics, Stanford University, Stanford, CA 94305

From east (Gulf of Alaska) to west (Kamchatka) along the Alaska-Aleutian subduction zone, the relative direction of convergence between the Pacific plate and the leading edge of the North America plate changes progressively from orthogonal, to oblique, to strike slip, to orthogonal (Figure 1). The principal plate-boundary processes that effect regional-scale tectonism are, from east to west, (1) continental terrane collision of the Yakutat block in eastern Gulf of Alaska, (2) disruption of the Aleutian Arc into clockwise rotating and westward translating blocks of arc massif, (3) arc-parallel splintering of the arc massif, and (4) collision of these elongated fragments with the Kamchatka subduction zone. Block rotation and length-shearing occur in response to the westward increase in the right-lateral, plate-boundary shear couple and strain partitioning. Westward shuttling of arc fragments takes place because they are free to move in this direction toward the "free surface" of the Kamchatka subduction zone. Arc-continental collision takes place because the NAM-PAC plate boundary has jumped behind (north) of the far western or Komandorsky sector of the arc (Figure 1). In effect, this section of the arc is moving toward Kamchatka with much of the speed of the Pacific plate. The fragmentation style and displacement geometry of block movements imply that the speed of westward translation increases in this direction.

The critical transition from oblique to strike-slip tectonism takes place along the central and western sectors of the Aleutian Arc (Figure 2; Geist et al 1988, 1992 and Geist and Scholl, 1994). The process of arc break up and westward translation of blocks and arc splinters has been underway for at least the past 55 my, when the geometry of the present plate boundary setting was established. However, arc fragmentation and translation appear to have accelerated during the past 5-7 my, coincident with the progressing collision of the Yakutat block with the northeastern margin of the Gulf of Alaska. The modern or late Neogene episode of arc volcanism along the Aleutian Ridge also got underway at this time.

As shown diagrammatically on Figure 2, rotating blocks of arc massif tear away from the arc-magmatic front, leaving trailing-edge basins in their wake. Collision of the Yakutat block, which rapidly elevated and glaciated Alaskan coastal ranges, flushed large volumes of clastic debris westward along the Aleutian Trench to the front of the arc massif. This resulted in the growth of a large accretion wedge and the subduction of thick masses of sediment. Speculatively, the late Cenozoic outbreak of arc volcanisms and accelerated fragmentation and mobilization along the transition zone from oblique to strike-slip plate boundary contact are co-linked to a consequent improved plate-boundary coupling and enhanced injection of subducted fluids into the mantle beneath the magmatic front.

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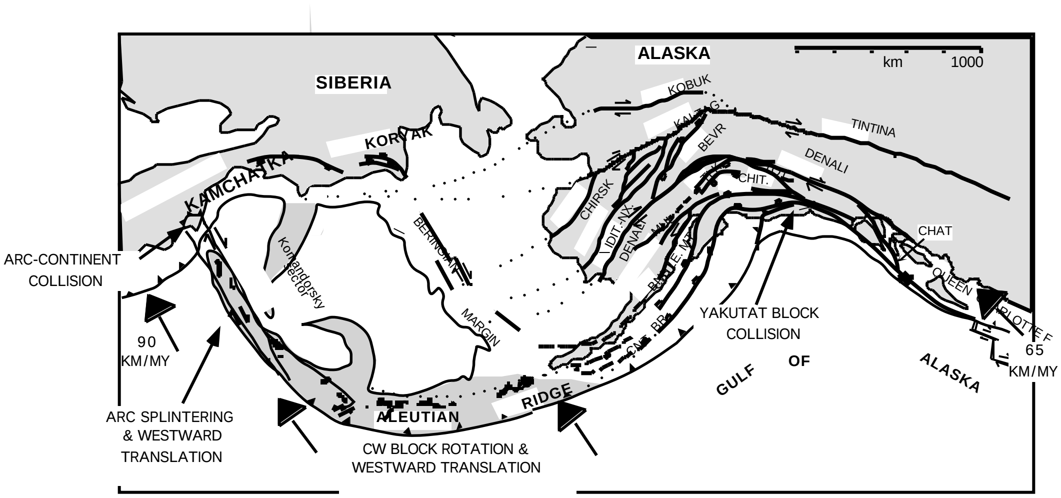

FIGURE 1: PLATE TECTONIC SETTING FOR NORTHERN RIM OF PACIFIC BASIN. FROM EAST TO WEST, PROGRESSIVELY FROM ORTHOGONAL TO OBLIQUE TO STRIKE SLIP TO ORTHOGONAL PLATE-BOUNDARY CONTACT. ARROWS SHOW RELATIVE CONVERGENCE DIRECTION AND RATE

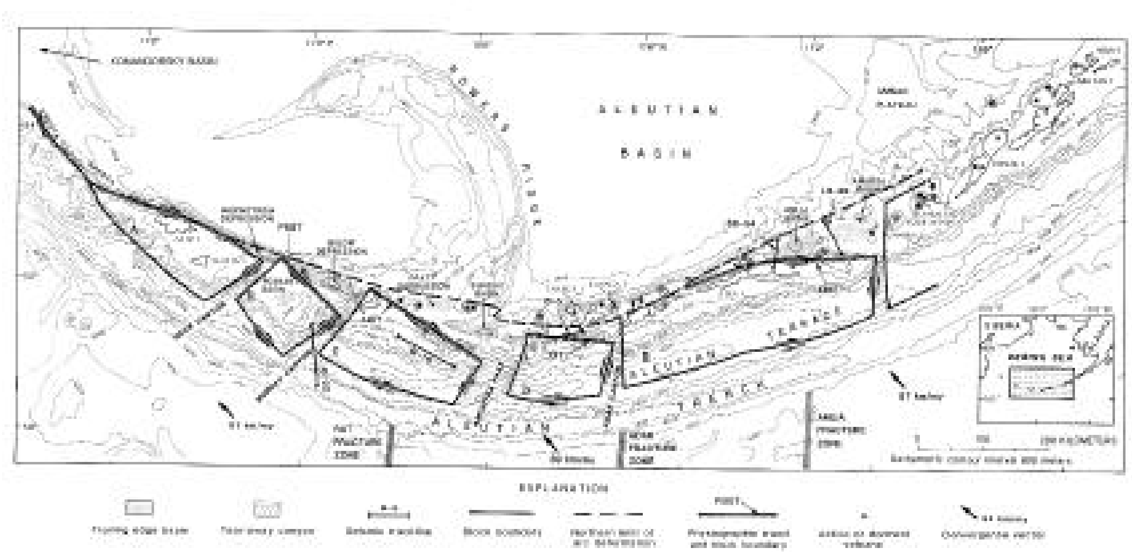

FIGURE 2 : TRANSITION FROM LEFT-OBLIQUE CONVERGENCE CAUSING CW ROTATION AND WESTWARD TRANSLATION OF ARC BLOCK TO RIGHT-LATERAL, ARE-PARALLEL SHEARING AND WESTWARD TRANSLATION OF ARC CRUSTAL SLICES

Tectonic transitions in Papua New Guinea and adjacent seas

Eli A. Silver, Laura Wallace, and Colleen Stevens

Earth Sciences Dept. and Institute of Tectonics, University of California, Santa Cruz, CA 95064

The northern margin of Australia is undergoing complex tectogenesis as a result of arc-continent collision and oblique convergence of the Pacific plate relative to Australia. In the eastern part of the New Britain/Solomon arc system, the Ontong-Java plateau collision has resulted in reversal of subduction polarity and tearing of the arc, leading to the development of rapid backarc spreading in the Bismarck Sea (Taylor, 1978). The latter spreads obliquely as well, in the manner of a leaky transform fault system. Where this transform fault intersects the margin of Papua New Guinea, near the town of Wewak, the tectonics of PNG changes dramatically. To the west, much less detailed study has been carried out, but a new burst of activity has accompanied the July 17, 1998 earthquake and tsunami. West of Wewak oblique convergence is partitioned into convergence along a narrow trench slope with low sediment input, and strike slip faulting onshore (Hutchinson and Norvick, 1978). The July 17 earthquake apparently broke along a low angle thrust surface and its slip vector is much more normal to the coastline than is the plate convergence direction (Harvard and USGS PDE, 1998). The large tsunami may have been generated by a large landslide, for which evidence is being evaluated at present. Farther west in Irian Jaya, slip also appears partitioned between large strike-slip earthquakes within the mountain range (Abers and McCaffrey, 1988) and subduction along the north margin of the range (the north New Guinea trench). No convergence is measured with GPS at the south margin of the range (Puntodewo et al., 1994).

East of Wewak, thrusting dominates and strike-slip faulting is largely restricted to faults normal to the range (Abers, 1989; Abers and McCaffrey, 1994). Transitions occur across the collision front from oceanic subduction with evidence of subduction erosion in the Solomon Sea to rapid accretion, collision and uplift of the mountains as continental crust is overridden (Abbott et al., 1994). GPS studies show rates of convergence of 90-120 km/My across the Solomon Sea, decreasing rapidly eastward into the collision zone (Tregoning et al., 1998). Earthquake locations, GPS observations, and gravity modeling attest to the fact that thick-skinned deformation governs the accretion of the Finisterre Range terrane to the Australian continent (Abbott et al., 1994; Stevens et al., 1998; Wallace et al., 1998). During October, 1993, a set of large earthquakes occurred at 18-20 km depth and GPS measurements document that co-seismic slip occurred very near the ground surface along a steep thrust ramp. GPS measurements taken before and after these earthquakes have captured the inter-, co-, and post-seismic slip rates across the frontal thrust (Stevens et al., 1998).

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SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Alpine-Carpathian working groups from the Geological and the Geophysical Institutes at the Universities of Karlsruhe, Tübingen and Würzburg (Germany)

The Alpine-Carpathian orogenic belt offers an outstanding opportunity to study two subduction to strike-slip transition zones which both have been active during Tertiary time. In order to give a coherent picture of the data and models available for this region (Fig. 1), we decided to combine our abstracts in one paper with different sections for the different presentations. In detail these are: (1) an overview about the Tertiary tectonic evolution of the Alpine-Carpathian orogenic belt, (2) & (3) the kinematics of the two subduction to strike-slip transition zones, one in the Eastern Alps-Western Carpathians, the other in the Southern and Eastern Carpathians, (4) & (5) geophysical data available from the southeastern transition zone including gravity, seismic tomography, recent stress field and seismicity.

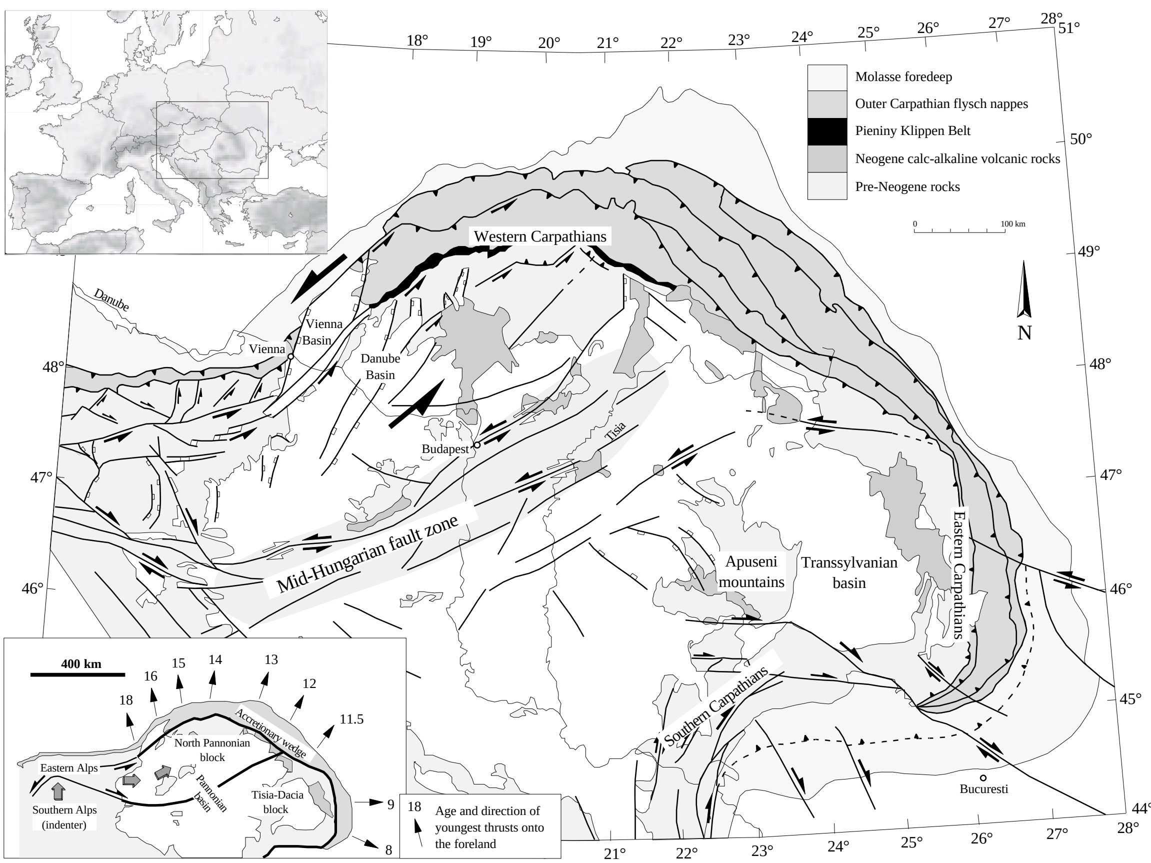

Fig. 1: Tectonic overview of the Eastern Alpine-Carpathian region

SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Part 1: **Lateral extrusion, slab-break-off and subduction retreat: the Oligocene-Recent collision-subduction transition in the Alps and Carpathians**

Blanka Sperner[1 (now 2)], Lothar Ratschbacher[3], Peter Zweigel[1 (now 4)], Franz Moser[1], Stefan Hettel[2], Frank P. Lorenz[2], Radu Girbacea[1 (now 5)], Friedemann Wenzel[2]

[1] Geological Institute, University of Tübingen, Sigwartstr. 10, 72076 Tübingen, Germany
[2] Geophysical Institute, University of Karlsruhe, Hertzstr. 16, 76187 Karlsruhe, Germany
[3] Geological Institute, University of Würzburg, Pleicherwall 1, 97070 Würzburg, Germany
[4] IKU Petroleum Research, S. P. Andersens Vei 15 B, 7034 Trondheim, Norway
[5] Rock Fracture Project, Geol. and Environ. Sciences, Stanford University, CA 94305-2115, USA

New structural, sedimentological, paleomagnetic, and seismological data and analogue material modeling outline a geodynamic model for the Neogene tectonic evolution of the Alpine-Carpathian-Pannonian region encompassing two subduction to strike-slip transition zones. Driving mechanisms for the Miocene movements of the Alpine and Carpathian plates were the lateral extrusion in the Eastern Alps and the subduction retreat along the Carpathian arc. Major driving forces for lateral extrusion in the Eastern Alps are the convergence between the European continent and the Adriatic microplate which caused the indentation of the Southern Alps and subduction rollback in the central and eastern Carpathians which exerted a tensional stress on the eastern boundary of the Alps. The particular tectonic architecture of the Eastern Alps is further influenced by a rigid foreland, a strength minimum in the eastern Alpine lithosphere due to thermal relaxation after the Alpine stacking and a rotating intender.

Subduction retreat started during Oligocene continental collision in the Alps and slab break-off beneath the Alps lead to the reduction in the width of the remaining slab. Resulting sideways asthenospheric flow around the edges of the slab reduced the hydrodynamic suction between upper and lower plate, so that the slab started to steepen and roll back. Due to the northeasterly convex embayment in the orogenic foreland, collision of African continental fragments with Europe migrated from the Alps towards the NE and finally SE (Fig. 2). Those parts of the subducting slab which were blocked by continental collision detached. The very last stage is well documented by seismicity and seismic tomography outlining the youngest slab segment beneath the SE bend of the Carpathian arc.

In our contributions we review the structures related to lateral mass flow from the Alps towards the Carpathians, which emphasize a transition from lithospheric thickening to strike-slip transfer and lithospheric extension in the Eastern Alps (part 2). The Western Carpathians acted as a displacement transfer zone of the extruding mass, which is characterised by a lack of crustal thickening. The Eastern Carpathians are unaffected by the mass extruding from the Alps and show frontal sediment accretion coeval with strong back-arc extension in the Pannonian realm. Simultaneously, dextral strike-slip movements along the Southern Carpathians accompanied the rotation and translation of the Tisia-Dacia-block (Fig. 1 & 2; part 3). The (former) subduction to strike-slip transition zone at the southeastern bend of the Carpathian arc is identical with the area of recent subcrustal seismicity. Newest seismic tomography in this region outlines the current position of the last remaining slab segment and its ongoing break-off (part 4). Strong seismicity outlines the dynamics of this process: during the last 60 years four earthquakes with magnitudes between 6.9 and 7.7 occurred at depths of 70-180 km. Focal mechanisms, also from smaller earthquakes, prove a strong vertical extension within the subducted slab (part 5).

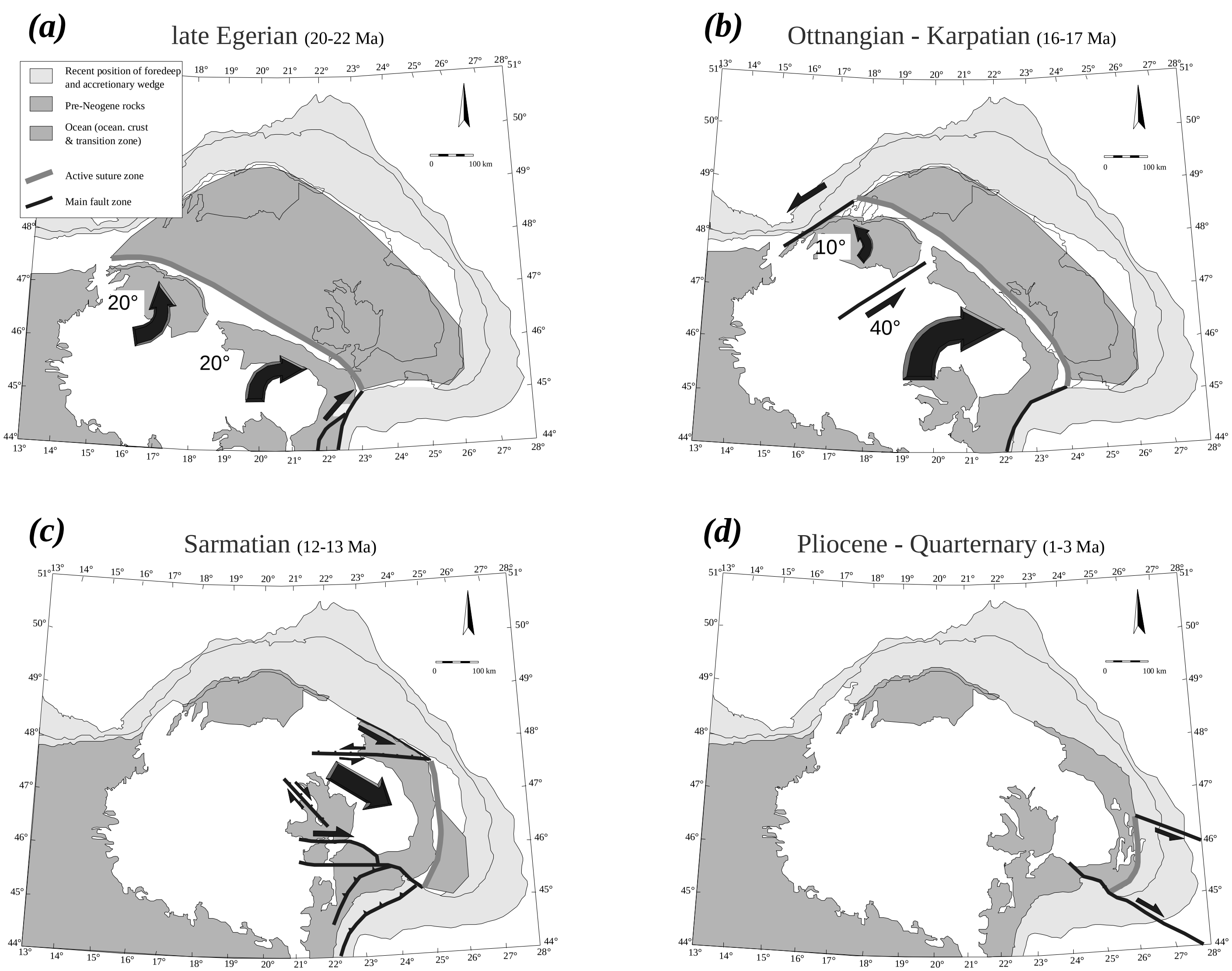

Fig. 2: Geodynamic evolution of the Eastern Alpine - Carpathian region

SUBDUCTION, STRIKE-SLIP AND COLLISION IN THE ALPINE-CARPATHIAN REGION

Part 3: **The subduction to strike-slip transition in the SE Carpathians: structural, sedimentary, and surface uplift response to subduction retreat and slab break-off**

Blanka Sperner[1], Franz Moser[2], Peter Zweigel[3], Radu Girbacea[4], Lothar Ratschbacher[5]

[1] Geophysical Institute, University of Karlsruhe, Hertzstr. 16, 76187 Karlsruhe, Germany
[2] Geological Institute, University of Tübingen, Sigwartstr. 10, 72076 Tübingen, Germany
[3] IKU Petroleum Research, S. P. Andersens Vei 15 B, 7034 Trondheim, Norway
[4] Rock Fracture Project, Geol. and Environ. Sciences, Stanford University, CA 94305-2115, USA
[5] Geological Institute, University of Würzburg, Pleicherwall 1, 97070 Würzburg, Germany

Plate tectonics

During Miocene subduction the two intra-Carpathian blocks moved independently with different directions and velocities, only confined by the geometry of the continental embayment into which they moved and which was bordered by the European continent in the north and the east, and the Moesian platform in the south (Fig. 1 & 2). Rotations of the blocks are proved by paleomagnetic data which reveal a 30° counterclockwise rotation of the North Pannonian block (NPB) and 60° clockwise rotation of the Tisia-Dacia block (TDB) since the beginning of Miocene. Continental collision with following slab break-off occurred first in the northernmost part of the arc and later on shifted towards the SE and S leading to a corresponding shift of foreland basin depocenters and of volcanic activity.

Deformation structures at the frontal part of the TDB

A typical accretionary wedge evolved during subduction at the frontal parts of the intra-Carpathian blocks. Oblique collision of the TDB with the European foreland resulted in differing post-collisional deformation styles in the northern and southern part of this fold-and-thrust belt. Overthrusting of the northeastern edge of the TDB onto the foreland led to shortening and crustal thickening in this part of the collision zone (Fig. 2c). Simultaneously, thinned continental crust was still available in the southern part, i.e. in the corner between Moesian platform and European continent, thus enabling gravitational collapse and basin formation in this part of the accretionary wedge (Fig. 2d). This process was additionally supported by delamination of the lower lithosphere followed by asthenospheric rise and surface uplift of this area.

Deformation structures at the southern border of the TDB

Dextral strike-slip movements dominated the Miocene deformation along the contact between TDB and Moesian platform. Timing of this deformation comes from the subsidence of sedimentary basins caused by bendings and offsets along the main strike-slip faults (Fig. 4). Later on, basin inversion and thrusting onto the northern margin of the Moesian platform demonstrate the transpressive character of this strike-slip zone.

Subduction to strike-slip transition zone

Foredeep basins evolved around the whole Carpathian arc, but a special situation is given in its southeastern corner where about 9 km of sediments were deposited during middle Miocene to Pleistocene time. Additionally, this region is characterized by strong subcrustal seismicity indicating the presence of a remnant of the subducted slab. Surprisingly, this slab is located 80-100 km SE of the Miocene suture zone - an additional indication for delamination and rollback of the lower lithosphere (Fig. 5).

Recent surface uplift

Large uplift rates are recorded from the northern part of the Eastern Carpathians where the TDB overthrusted the European foreland and thus caused crustal thickening. Smaller, but still remarkable uplift rates occur in the southern part where no crustal thickening took place, so that additional processes have to be considered. Slab break-off which started in the N and migrated towards the S can serve as such an additional mechanism.

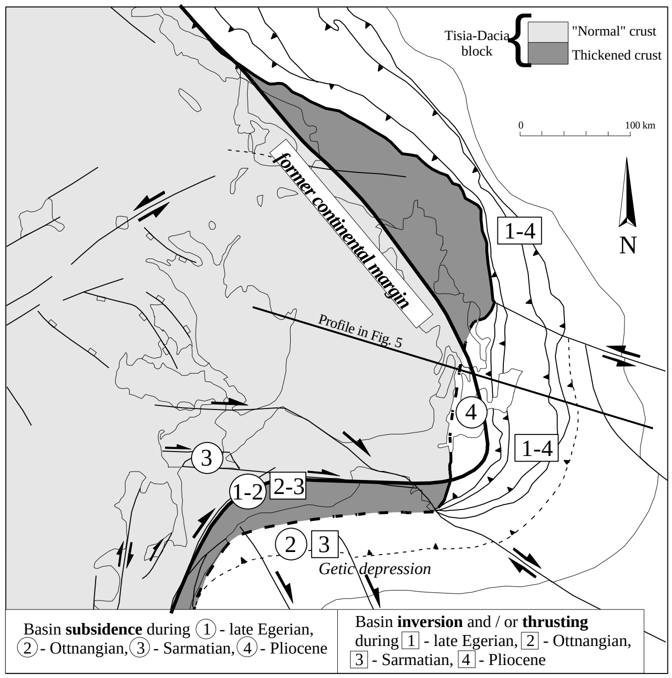

Fig. 4: Overthrusting of the Tisia-Dacia block onto the European foreland in the NE and onto the Moesian platform in the S resulting in crustal thickening. Timing of basin subsidence, followed by inversion and overthrusting.

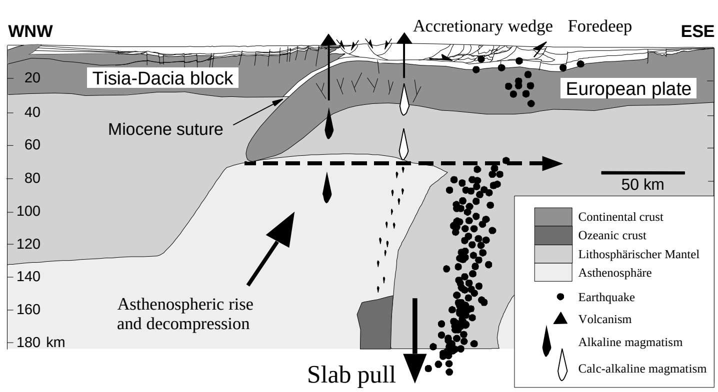

Fig. 5: Profile through the Eastern Carpathians (s. Fig. 4) showing delamination of the lower lithopshere

Plate deformation at depth under northern California

Uri S. ten Brink[1], Nobumichi Shimizu[2] and Philipp C. Molzer[3]

[1]US Geological Survey, Woods Hole, MA 02543 USA. Tel. 508-457-2396. Fax: 508-457-2310. E-mail: utenbrink@usgs.gov
[2]Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA
[3]US Geological Survey, Woods Hole, MA 02543 USA

The prevailing view of asthenospheric upwelling (a slab gap) under coastal California stems from the assumption that plate boundaries at depth behave rigidly and are of zero width. For northern California plate kinematics predict a gap in the underlying subducted slab caused by the northward migration of the unstable Pacific-North America-Juan de Fuca Triple Junction. Large scale decompression melting and asthenospheric upwelling to the base of the former forearc are not supported however, by geophysical and geochemical observations. We suggest that perhaps a more realistic view of the interaction between the Pacific, Juan de Fuca and North American plates is one where the Juan de Fuca and Pacific plates under coastal northern California deform continuously to fill the geometrical gap in the wake of the northward migrating Mendocino Triple Junction. We explain the minor Neogene volcanic activity, its chemical composition and the observed heat flow by thermal re-equilibration of a 20-30 km thick forearc underlain by a thinned young Juan de Fuca slab. This view is consistent with the region being underlain by a fossil oceanic crust and by an upper mantle lithosphere of young thermal age. It is also consistent with the pervasive deformation of the southern Juan de Fuca plate and the Mendocino Triple Junction region onshore. In contrast, the consequences of a “true” slab gap in the forearc region can be examined in the Inner California Borderland offshore Los Angeles where local asthenospheric upwelling took place during the Miocene as a result of horizontal extension and rotation and is manifested by high heat flow, voluminous magmatism, primitive melt composition, and the absence of a fossil crust.

Liquefaction Features: A Potentially Powerful Paleoseismic Tool in the Dominican Republic

Martitia Tuttle[1], Carol Prentice[2], Luis Pena[3], and Kathleen Dyer-Williams[4]

[1]Department of Geology, University of Maryland, College Park, Maryland, USA 20742, mtuttle@geol.umd.edu
[2]U. S. Geological Survey, 345 Middlefield Rd MS 977, Menlo Park, California, USA 94025, cprentice@usgs.gov
[3]Avenida Cuesta Colorado Esquina Calle No. 9, Las Colinas, Santiago, Dominican Republic
[4]Department of Geology, University of Maryland, College Park, Maryland, USA 20742, kder@geol.umd.edu

Earthquake-induced liquefaction features, including sand blows and sand dikes, occur in the eastern, central, and western parts of the structurally controlled Cibao valley in northern Dominican Republic. This region is traversed by the Septentrional fault, an onshore portion of the North American-Caribbean plate boundary. Our observations of liquefaction features in this region are significant because paleoliquefaction features can be used to estimate the timing, source areas, and magnitudes of prehistoric earthquakes and are particularly useful in areas where active faults cannot be studied directly.

Accounts of historic earthquakes in 1842, 1897, and 1946 described ground failure typical of liquefaction. Scherer (1912) reported that springs and ground cracks formed along the Rio Yaque in the vicinity of Santiago (central Cibao valley) during the 1842 earthquake. He also reported that cracks formed and the ground subsided near Guayubin (western Cibao valley) during the 1897 earthquake. Following the 1946 earthquakes, Lynch and Bodle (1948) reported that high silt banks along the Rio Yuna near Arenoso (eastern Cibao valley) settled in terraces paralleling the river and that sand and water spouts occurred up to 100 m from the river bank. Because liquefaction typically recurs where susceptible deposits are present, sites of historic liquefaction are prime targets for paleoliquefaction studies.

In the central Cibao valley, Prentice et al. (1993, 1994) found liquefaction features in a trench across the Septentrional fault, where a sand dike apparently intruded along a fault plane. Radiocarbon dating suggests that these features formed during rupture of the Septentrional fault circa A.D. 1200. In the eastern and western Cibao valley, where the active trace of the Septentrional fault is buried by Holocene alluvial deposits, we conducted reconnaissance for liquefaction features along 13 km of the Rio Yuna near Arenoso and along 20 km of the Rio Yaque between Guayubin and Castanuela. We selected these areas for reconnaissance based on the likely presence of liquefiable sediments and availability of cutbank exposure of Holocene deposits. We documented liquefaction features at seven sites along the Rio Yuna and at ten sites along the Rio Yaque. Multiple features occur at almost every site and we found evidence of recurrent liquefaction at five of the sites.

At a site along the Rio Yaque near Castanuela in the western Cibao valley, we documented at least two, and possibly three, generations of liquefaction features, including sand blows and related sand dikes. Sand blows range up to 6 cm in thickness and most sand dikes range from 1 to 18 cm in width. A 42-cm-wide compound sand dike apparently was utilized by venting sand and water during more than one event. The youngest generation of liquefaction features occurs high in the section and may have formed during the 1897 earthquake. Unfortunately, we found no material suitable for radiocarbon dating at this site. Sand dikes at other sites along the Rio Yaque range from 2 to 15 cm in width. Sand blows may occur at several of these sites but additional excavation is needed to verify this. At one of these liquefaction sites, charcoal was collected near the base of the cutbank from the host deposit. It yielded a calibrated age of 6490 to 5930 years B.P. and provides a maximum age of liquefaction features observed along the Rio Yaque.

Near Arenoso, along the Rio Yuna in the eastern Cibao valley, we logged prehistoric sand blows and related sand dikes at three sites. The sand blows range from 30 to 105 cm in thickness and the sand dikes range up to 24 cm in width. The two thicker sand blows are compound structures and probably formed during two or more events in an earthquake sequence. Sand blows at the three sites have similar stratigraphic positions to each other and may have formed during the same earthquake sequence. Radiocarbon dating of charcoal within one of the sand blows and of soil clasts within two feeder dikes yielded similar results and indicate that the sand blows formed after A.D. 690. Radiocarbon dating of clayey soil horizons overlying the sand blows yielded ambiguous older dates. Burr (this volume) attributes these older dates to carbonates held by clay particles within the samples. Although not conclusive, radiocarbon dating of these sand blows allows for the interpretation that they formed during the A.D. 1200 rupture of the Septentrional fault in the central Cibao valley. In comparison, relatively young sand dikes that may have formed during the 1946 earthquakes are smaller ($\leq$ 7 cm) than prehistoric sand dikes in the area. Furthermore, historic sand blows appear to be less prevalent than the prehistoric sand blows. These observations suggest that the prehistoric earthquakes were larger than or located closer to Arenoso than the historic earthquakes.

Additional study is needed to map the age and size distribution of liquefaction features in the eastern and western Cibao valley. Age estimates of paleoliquefaction features must be narrowly constrained in order to differentiate earthquake sequences and to correlate features across a region (Tuttle et al., 1996). Regional correlations of liquefaction features are important because they establish the area affected by high levels of strong ground shaking, which can, in turn, help constrain models of source areas. In general, the largest features in a regional distribution of paleoliquefaction features reflect the source area of a prehistoric earthquake. A better understanding of the age and size distribution of liquefaction features in the Cibao valley would help to define the source area and magnitude of the A.D. 1200 event, to identify other prehistoric earthquakes that struck the region, and possibly to differentiate earthquakes produced by thrusting from strike-slip events.

Liquefaction features provide a tool to help reconstruct the prehistoric earthquake record of the Dominican Republic, and thus to assess the earthquake hazard of this seismically active region. In addition, our observations indicate that liquefaction and lateral spreading is likely to occur during future large earthquakes. Defining areas underlain by liquefiable sediment would be an important step towards mitigating this hazard.

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Tectonic Activity in the Mona Passage Area during the three Cretaceous-Holocene tectonic phases of the Puerto Rico-Virgin Islands platform.

Jean-Paul van Gestel[1], Paul Mann[2], James F. Dolan[3], and Nancy R. Grindlay[4]

[1]Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712, jpges@utig.ig.utexas.edu;
[2]Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin, TX 78759-8500, paulm@utig.ig.utexas.edu;
[3]Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, dolan@coda.usc.com,
[4]Department of Earth Sciences, University of North Carolina at Wilmington, Wilmington, NC 28403-3297, grindlayn@uncwil.edu

Introduction:

In the summer of 1996 single-channel seismic reflection, sidescan, bathymetry, gravity, and magnetic data were collected during cruise EW 96-05 on board of R/V *Maurice Ewing* in which all authors participated. These newly acquired data have been integrated with and correlated to onland outcrops and well information and have been used to re-examine the proposed regional geologic and tectonic models. The depositional history of the different sequences of the platform North of Puerto Rico has been studied and three different tectonic phases have been distinguished.

Setting:

Puerto Rico occupies the northeastern segment of a lower Cretaceous to Holocene island arc chain that extends from western Cuba to the north coast of South America. The core of the island is formed by Cretaceous arc basement rocks. Both in the north and in the south Oligocene-Early Pliocene carbonate platform sediments can be found. In the north the platform covers a small portion of the island but extents under a smooth continuous 4 degree dip offshore to a depth of 4 km deep. In the south the platform has a steeper dip and it extends less far offshore. The whole shallow submarine area in between the islands of Hispaniola, Puerto Rico and the Virgin Islands is also covered with Oligocene-Pliocene carbonate rocks. The Puerto Rico-Virgin Islands platform overlies the Puerto Rico-Virgin Islands microplate that has been defined on the basis of earthquake data and marine geophysical sidescan surveys of offshore areas. To the north, the microplate is bounded by the Puerto Rico trench. To the east of Puerto Rico, the platform trends to the east-northeast and covers most of the area of the Virgin Islands. The eastern and southeastern edge of the platform and the Puerto Rico-Virgin Islands microplate are sharply bounded by the Anegada fault zone. This fault zone runs trough the deepwater Anegada Passage between Puerto Rico and St. Croix and connects the Sombrero and Virgin Islands basins. These two fault-bounded deeps are pull-apart basins along the right-lateral Anegada fault zone. The southern edge of the Puerto Rico-Virgin Islands microplate is defined by the Muertos Trough where the Caribbean plate is subducted beneath the microplate. To the west of Puerto Rico, the carbonate platform extends across the Mona Passage and onto the island of Hispaniola. Bathymetric deeps in the Mona Passage correspond to rifts that locally extend and fragment the platform between Puerto Rico and Hispaniola. The origin and age of this rifting in the Mona Passage area is unclear and will be the focus of this presentation.

Three tectonic phases of the northern margin of Puerto Rico:

In a regional study of the offshore seismic reflection profiles surrounding Puerto Rico, we have documented three distinct, Cenozoic tectonic phases that occurred during development of the northern margin of Puerto Rico.

Tectonic phase 1: Late Cretaceous to Middle Eocene formation and sedimentary infilling from the south of a forearc basin. This basin was formed between down-to-the-north normal faults near the present day coast of Puerto Rico and an outer-arc ridge near the present day shelf break. Tectonic phase 1 contained the last volcanic arc activity in Puerto Rico that was produced by the subduction of oceanic crust of the North America plate beneath the Caribbean arc system. The end of tectonic phase 1 is related to an initial collision between the Caribbean arc and the Bahama carbonate platform.

Tectonic phase 2: Latest Eocene to early Pliocene formation of a 1578 m thick, northward-thickening Puerto Rico-Virgin Islands platform, predominately formed of carbonate sediments. Depositional thicknesses of sedimentary layers deposited during phase 2 are controlled by two large arches: 1) The NNW-trending Guajataca arch appears to have formed as the elevated flank of the north-south striking Mona rift, which forms the western boundary of the present day Puerto Rico-Virgin Islands microplate, 2) the northeast-trending San Juan arch can not be related to any adjacent structure or plate boundary feature. The results of paleomagnetic studies of the carbonate sediments show that Puerto Rico experienced a counterclockwise rotation during tectonic phase 2.

Tectonic phase 3: Early Pliocene to Holocene northward tilting of the Puerto Rico-Virgin Islands platform, submerged the northern edge of the platform to a depth of 4 km and elevated the southern edge of the platform to several hundred meters above sea level on Puerto Rico. Northward tilting of this area occurred on the northern limb of a large arch or anticline formed parallel to the long axis of the island of Puerto Rico and its shelf areas. The arch probably formed in response to a post early Pliocene convergence between the North America and Caribbean plates.

Reconstruction measurements in the Mona Passage:

Three lines with seismic reflection data have been collected in the Mona Passage area during cruise EW96-05. Two longer NE-SW lines that cross the Mona and Yuma Rift areas and one east-west line that only crosses the Mona Rift. These three lines have been interpreted and reduced to their original length using reconstruction software packages in an effort to calculate their extension. For the East-West trending line 31 the extension has been estimated to be 6.35 km. In the two other lines crossing the Mona Rift, being line 32 and 35, the estimate is only 4.5 and 3.1 km. However one has to take into consideration that the orientation of these two lines is not parallel to the estimated main direction of extension which will cause the calculated amount to be smaller than the real extension. One has to take into consideration that these numbers contain a fairly large interpretation uncertainty. Extension of 6.35 km between the two islands of Hispaniola and Puerto Rico combined with the 2 mm/yr of difference in the eastward movement of the two islands observed in the GPS measurements would lead to a 3.2 million year old Mona and Yuma Rift extension.

Comparisons between the carbonate platform on both sides of the Mona Rift:

In our study of the well, seismic reflection and outcrop data there was a considerable thickness difference noted in the two sequences of the carbonate platform on both sides of the Mona Rift. In the north coast basin the maximum thickness of the platform is 1578 m. However towards the Mona Rift it appears that the platform is thinning to a minimum of only 600 m on the east-slope of the Mona Rift. When studying the isochron maps of the different sequences within the platform this thinning can be found to appear in the lower and older sequences, while the upper and youngest sections of the platform have a more uniform distribution. The thinning of the lower sequences onto the edge of the Mona Rift can be explained by activity of the NNW-trending Guajataca Arch. This arch appears to have formed as the elevated flank of the north-south striking Mona rift, which forms the western boundary of the present day Puerto Rico-Virgin Islands microplate.

Conclusions:

In conclusion, we believe that the Mona Rift has evolved in two different periods. The rifting was first active in the second tectonic phase, when the area in between Hispaniola and Puerto Rico functioned as the pivoting point of the counterclockwise rotation of Puerto Rico. Compared to the homogeneous, constant thickness platform in the north coast basin of Puerto Rico the isochron map of the carbonate platform and the seismic reflection profiles show a large amount of variation in the Mona Passage area. This is the result of seismic activity during the formation of the carbonate platform. After the formation of the platform in tectonic phase 1, the rotation stopped and the arching phase began. During this third tectonic phase, the Mona Rift started opening, which seems to agree well with the calculated age of the origin of the extension.

TECTONICS OF THE ALBORAN SEA BASIN: A TRANSTENSIONAL BASIN IN A TRANSPRESSIONAL REGIME

J.T. Vázquez (1) and R. Vegas (2)

(1) Dpto. Geología, Fac. Ciencias del Mar, Univ. Cádiz, Campus Rio San Pedro, 11510-Puerto Real. Spain.- juan.vazquez@uca.es

(2) Dpto. Geodinámica. Fac. Ciencias Geológicas. Univ. Complutense. 28040 - Madrid. Spain.

The Alboran Sea Basin is located at the western edge of the Mediterranean Sea between the Iberian Peninsula and northern Africa. It extends westwards of the South Balearic Basin and it is surrounded by the Betic-Rif Arc which represents a collisional orogen and it is included in the westernmost chains of the Mediterranean Alpine belt. The basin has been originated during the Miocene and its formation and later evolution are closely related to the Betic-Rif orogen development and to the oceanic spreading of the Western Mediterranean Basin.

A set of structures associated with different stages are superimposed. The main structural trends, indicated by the bathymetry, basement structure and volcanic buildings display the following directions ENE-WSW to NE-SW and WNW-ESE. The oldest structures are related to normal faults that have been active until the Lower Tortonian. The structures that affect the Upper Miocene to Quaternary units have been interpreted as oblique strike-slip faults. The development of some transpressional (ramp anticlines and ridges) and transtensional (pull-apart basin and local collapses) features which determine the physiography have been identified.

The aeromagnetic studies and drills show a continental basement. The gravimmetric, heat flow, refraction and deep reflection data show a thinned crust, about 17 km, which thickness decreases eastwards of the Alboran island meanwhile southwards the crust reaches to 23 km which is a consequence of the African margin wide in the eastern part of the basin. A detached slab below the Betic-Alboran region, between 200-670 km of depth, characterise the mantle structure. The seismicity is characterised by a continuous activity of moderate to low magnitude. It is remarkable the occurrence of intermediate depth events (45-150 km) that draw a narrow arc in the western part of the basin.

Several aspects should be pointed out in the tectonic setting of the Alboran Sea Basin:

1) It is located on the plate boundary between Eurasia and Africa and its Cenozoic evolution is controlled mainly by a convergent regime from the Late Cretaceous to Tortonian times and a transpressive regime from that time to present (Dewey et al., 1989). In this context, a continental lithospheric block (Alboran Domain) would have collided, simultaneously and laterally, against the two largest plates in the Mediterranean area, Eurasia and Africa, in the location of the main plate boundary. It can not be rejected that previously to the current collision a limited subduction of oceanic lithosphere would have developed.

2) It overlies a thinned continental crust segment that mainly belongs to the Alboran crustal domain (Vegas et al., 1995)

3) Nowadays the Alboran Sea Basin is an extensional basin located in a backarc position in relation to the Betic-Rif Arc. However, it does not display all the backarc basins characteristics. It does not exist a B-subduction, either exists volcanic processes related with this subduction, neither oceanic crust floored this basin. There are some calcoalkaline volcanic buildings of Miocene age, mainly in the eastern sector, but this volcanism is not related to the configuration of a volcanic arc system associated with an oceanic subduction zone.

4) It is situated in the western side of an oceanic basin (Western Mediterranean Basin), whose formation has been related with the extensional collapse of a Paleogene Alpine orogen. The Alboran Domain was probably structured in this previous orogenic stage and then was extensionally thinned.

There are several proposed models to explain the origin of the Alboran Sea Basin (see discussion in Docherty and Banda, 1995 and in Lonergan and White, 1997) including basin formation in relation to 1) the western migration of a rigid microplate, 2) escape tectonic processes, 3) transtensional origin, 4) backarc basin related to E directed subduction, 5) backarc basin related to a retreating W directed subduction and/or slab pull associated with a detached slab, 6) orogenic extensional collapse related to asthenospheric diapir, crustal delamination and/or convective removilization.

We propose a mechanism of progressive backarc transtension to explain the generation of the Alboran Sea Basin. This process would be related to the Lower to Middle Miocene roll back retreating (towards the east, south and west) of a previous subduction zone NW directed, which corresponds to the splitting by means of gravitational collapse of a Paleogene Alpine orogen, in the context of a N-S convergence between Eurasian and African plates (Late Oligocene-Lower Miocene).

Two Mediterranean zones have been extruded by lateral escape tectonics to accommodate this shortening, the Betic-Rif and Calabrian arcs, controlled by embayements (free space) and promontories influence. In the Alboran region, the upper plate (Alboran Domain) of this subduction zone migrated westward (about 100-300 km) over an oceanic or very thinned continental lithosphere and collided to Southiberian and Northafrican margin in an oblique way. This westwards escape tectonic took place in the Lower Miocene and constituted a secondary convergent/transpressional component that generated a collisional arc in the upper plate thrust front, two transpressional zones one in each lateral borders and an extensional backarc basin. In this sense the Alboran Sea Basin is generated in the internal part of a westward moving plate coeval with the development of compressional structures in other parts of the region. When the upper plate collide against the normal continental crust of Iberia and Africa the extrusion mechanism is blocked.

The final configuration of the Alboran Sea Basin took place at Tortonian times, when the Eurasian-African plate NW-SE convergence is clearly transpressive respect to the possible plate boundary and caused transtensional and transpressional reactivations simultaneously. Also, certain slab pull process could exist in the Western Alboran Basin related to a subducted slab located around 45-150 km of depth as it show by a Pliocene collapse of the margin. Nowadays, the Eurasian-African transpressional convergence produces internal deformation in this area and compressional structures in the Gulf of Cadiz.

Acknowledgements

This work has been supported by a CICYT project, AMB 95-1151-E, of the Spanish Research Programme

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SUBDUCTION AND STRIKE-SLIP (TRANSPRESSION) IN THE BORDERS OF THE ALBORAN, CARIBBEAN AND SCOTIA PLATES: A COMPARATIVE STUDY

R. Vegas [1], J.T. Vázquez [2] and J. Acosta [3]

(1) Dpto. Geodinámica. Fac. Ciencias Geológicas. Univ. Complutense. 28040 - Madrid. Spain. ruidera@eucmax.sim.ucm.es

(2) Dpt. Geología, Fac. Ciencias del Mar, Univ. Cádiz, Campus Rio San Pedro, 11510-Puerto Real. Spain

(3) Instituto Español de Oceanografía, C/ Corazón de María, nº 8. 28002 - Madrid. Spain.

At present none of the large lithospheric plates is bounded by two subduction-related or collision zones with opposite polarity. This fact indicates the predominance of the ridge-push in the motion of plates. Nevertheless, the small Caribbean and Scotia plates, as well as the now inactive Alboran platelet, contain two compressive (transpressive) boundaries with opposite vergence joined by a frontal subduction arc. All the three small plates present clear evidence of large displacements along the parallel or almost parallel transpressive boundaries. Since these displacements are not related to a centre of expansion, the driven mechanism for these small plates remain unexplained. The other problem related to this particular plate configuration corresponds to the area of junction between the frontal subduction of the leading arc and the transpressive plate-boundary zone. Taking into account that the level of understanding for the three plates is unequal, it should be useful to compare their common features in order to advance some hypothesis concerning the problems mentioned previously and some of their consequences, such seismicity and internal deformation.

The Alboran, Caribbean and Scotia plates occupy the site of former seaways created during the first stages of the rupture of the Pangea. Their emplacement astride the main plate-boundaries, including large transport of crustal units and advance at the leading arc, has been related to the convergence of the large plates initiated during the Upper Cretaceous plate rearrangement. This sort of extrusion implies strong convergence that is only recorded in the Africa-Europe trajectory. But even in the case of the Alboran plate, the direction of the Africa-Europe slip vector coeval with the time of the westward displacement seems to be inadequate. Therefore, an ill-understood mantle flow as driving mechanism for this peculiar tectonic behaviour should be invoked.

The other main problem related to these small, intermediate, plates is the nature of their transcurrent lateral borders and the mode in which they merge with the frontal subducting arc. This is also a consequence of the origin of the escape of the intermediate plates, prevailing transcurrent or compressive tectonic regimes. In the Alboran plate the transcurrent borders corresponds to a crustal overthrust onto the African and Iberian margins and constitute the Betic and Rif ranges. Their present position is obscured by late extensional episodes, although a short segment of the Africa-Alboran limit has the shape of a strike-slip zone connecting the Rif and Tell chains of Northern Africa. Kinematic indicators show clear transcurrent motion along these margins inducing systematic block rotations along the disrupted cover of the African and Iberian margins. Deformation is at present accommodated by internal deformation of the intermediate Alboran plate, as shown by the distribution of the seismicity. A remnant of the frontal seismicity due to the advance of the Gibraltar arc can be found in a N-S zone of intermediate-depth seismicity that defines a near vertical plane delineating the chord of the arc. However, the main shocks are located outside of the arc, where the oceanic lithospheres of the big plates meet directly accommodating the convergence in a zone of important submarine uplifts and related basins.

Concerning the active, moving intermediate plates Caribbean and Scotia, the transcurrent borders show a remarkable resemblance in the segments where the oceanic lithosphere of this big plates is in contact with the overriding crustal slivers of the intermediate plates. Seismic images of the Puerto Rico Trench and the Scotia-Antarctica Plate Boundary Zone, far from the South Sandwich frontal arc, are remarkably similar, showing a limited subduction of the North American and Antarctic oceanic lithospheres respectively. This type of non conventional subduction implies the absence of volcanism and some sort of strain partitioning in order to maintain the shallow and limited underthrusting of the oceanic lithosphere. Moreover, in the juncture of this limited, lateral subduction and the frontal subduction, a sharp change in the dip angle for the lower plate should be considered. This may be supported by the attitude of the remnant seismicity in the inner part of the Arc of Gibraltar. The limited subduction can be connected with the collision found in the segments of the transcurrent borders where the lower plate, i.e. the large bordering plate, is formed by continental lithosphere. In this case the overthrusts resemble the crustal stacking in the Alboran transcurrent borders. This implies that if the coupling between the two plates is of sufficient extent, the occurrence of big shocks can be expected. As in the Alboran plate, some segments of the transcurrent borders correspond to zones of predominant strike-slip faults with minor, if any, sign of convergence. The occurrence of big shocks in long strike-slip faults can be expected, in particular in the intracontinental parts of these fault corridors. The internal deformation of the intermediate plates, mainly in direct relation with the converging transpressive borders, where crustal slivers can act as minor subplated, can obscure the kinematic indicators, and hence making impossible the determination of the direction of the relative plate motion between the intermediate plate and the surrounding ones. This constitutes another important problem for the definition of the main causes of the formation of these intermediate small plates. In any case, these intermediate plates have many features in common whose origin must be attributed to a characteristic plate setting. The comparison between the few examples, past and present, must help understand their formation and evolution.

Acknowledgements

This work has been supported by a CICYT project, AMB 95-1151-E, of the Spanish Research Programme.

USGS-MIDAS SEISMICITY MAP OF THE CARIBBEAN AND JOINT EFFORTS FOR SEISMOLOGIC COOPERATION

Christa von Hillebrandt-Andrade [1], Carlos Mendoza and Madeleine Zirbes[2] and Luis Odonel Gomez [3]

1. Red Sismica de Puerto Rico, Depto. de Geologia, Universidad de Puerto Rico, PO Box 9017, Mayaguez, PR 00681-9017 (christa@rmsismo.uprm.edu)
2. National Earthquake and Information Center, U. S. Geological Survey, Box 25046, M.S. 967, Denver Federal Center, Denver, Colorado 80225 (mendoza@ghtmail.cr.usgs.gov and zirbes@ghtmail.cr.usgs.gov)
3. Instituto Nacional de Recursos Hidraulicos, Santo Domingo, Rep. Dominicana (lgomez@codetel.net.do)

In 1998 the United States Geological Survey (USGS) and the Middle America Seismographic Consortium (MIDAS) published a seismicity map of the Caribbean region. The area covered by the map extends from 45°to 125° W and 5° S to 35° N. The seismicity data cover the years 1900-1994 and were obtained from the revised historical and instrumental earthquake catalogue with uniform moment magnitudes compiled for the Caribbean and Latin America by the Instituto Panamericano de Geografia e Historia (IPGH). To minimize incompleteness, only earthquakes of magnitude 4.2 or larger are plotted. Earthquakes are classified into three magnitude ranges and four depth ranges. The map shows a total of about 17,000 earthquakes for the time period considered. Active volcanoes of the region are also included as well as all cities with populations over 25,000. Bathymetric features are also shown and highlight important correlations between seismic activity and known tectonic features of the Caribbean. Apparent increases in seismicity can also be seen at plate-boundary transition zones where plate interaction changes from subduction to strike-slip motion (e.g., the Puerto Rico-Dominican Republic area and the Trinidad and Tobago-Venezuela region).

Publication of the Caribbean seismicity map is one of several initiatives pursued by MIDAS since its inception in 1990. Other activities include the installation of broadband stations in the Caribbean region, the establishment of an Electronic Seismic Data and Information Center in the facilities of the Puerto Rico Seismic Network in the Department of Geology of the University of Puerto Rico at Mayaguez (PRSN) and the planning of technical workshops for 1999 in Panama and Puerto Rico on broadband data processing and seismic data exchange. These activities have aided MIDAS to achieve its principal objective of promoting scientific interaction among participating institutions and facilitating the rapid, efficient, and widespread utilization of earthquake data by Middle America and Caribbean countries in routine observatory operations and in more advanced seismological research.

In 1993, a broadband station (UPIG) was installed in Panama City as a joint effort between the USGS, the Universidad Autonoma de Mexico (UNAM) and the Institute of Geosciences of the University of Panama. More recently in 1997, joint cooperative efforts between the USGS and UNAM led to the installation of a broadband station (LPIG) in La Paz, Baja California, Mexico. In 1998, this station was linked via Internet to the USGS National Earthquake Information Center. Since 1997, the Earthquake Unit of the University of the West Indies, Jamaica and the PRSN have been working towards the installation of a joint broadband station in Jamaica.

Through its Home Page (http://midas.uprm.edu), the MIDAS Electronic Seismic Data and Information Center provides interested parties information on the MIDAS Consortium, seismic stations and IPGH and MIDAS catalogues of events located in the MIDAS region (55° to 120° W and 5° S to 33° N). The MIDAS catalogue, which has a search engine, is automatically updated with the hypocentral information provided by the participating institutions. A special section in the webpage additionally provides information about significant earthquakes (magnitude or MM Intensity greater than six) that have occurred in the MIDAS region. For these events, each of the participating institutions contributes phase data and/or broadband waveforms; available moment tensor mechanisms computed for the earthquakes are also placed online as well as the epicentral map and comments and images of the earthquake and its effects. Links to useful earthquake information, data, services, utilities and programs are also included. Funds for the establishment of the MIDAS data center and webserver were secured through the cooperation of various participating institutes. Sources for additional funding are currently being sought to guarantee the maintenance and continual development of the data center.

Tectonic origin of "suprastructure-infrastructure" architecture, Northern Range, Trinidad

Weber, J.[1], with contributions by Ferrill, D.[2] and Teyssier, C.[3]

[1]Grand Valley State University, Allendale, MI 49401 USA
[2]Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, TX 78238-5166 USA
[3]University of Minnesota, Minneapolis, MN, 55455 USA

Weber et al. (in review) used temperature-sensitive quartz and calcite microstructures and fission track data to identify, describe, quantify, and map peak deformation temperatures in the low grade metasedimentary rocks across the Northern Range, Trinidad. Before this study, internal differences in thermal grade across the range had not been resolved (e.g., Frey et al. 1988). Deformation temperatures are relatively low in the eastern Northern Range and higher in the central and western Northern Range. Accompanying this east to west increase in thermal grade is a corresponding change in the geometry of D_1 structural fabrics. We propose that the Northern Range exposes two distinct tectonic packages that reflect vertical strain partitioning of the lithosphere in this Neogene transpressional orogen.

Rocks in the eastern (upper) package have relatively low deformation temperatures (200-330°C), upright and slaty D_1 fabrics, and NE-SW strikes (Weber et al. in review). Rocks with relatively low deformation temperatures and identical D_1 fabrics also occur in down-dropped fault blocks along the southern foot of the Northern Range (Weber et al. in review) and probably belong to the same upper tectonic package. Structurally underlying this upper crustal package are rocks that are pervasively transposed, highly strained, have been ductiley deformed at higher temperatures (up to 400°C), and contain recumbent D_1 structures (e.g., subhorizontal S_1 foliation) and strong E-W stretching lineations.

We interpret the eastern package as an upper crustal, non-eroded patch of the fold-and-thrust belt, which together with widely spaced strike-slip faults dominates the surface structure in central and southern Trinidad. We suggest that the highly and ductiley strained lower package represents an exhumed, mid-crustal, subhorizontal, detachment zone that separated continuous flow in the mantle (e.g., Russo et al. 1997) from highly partitioned, block-style, deformation (i.e., folds and thrusts with strike-slip faults) above.

This upright low-grade over flat high-grade structure, with lineations parallel to the belt, is identical to the suprastructure-infrastructure architecture in the Pyrenees, which was first described by De Sitter and Zwart (1960). Drawing on the Pyrenees analogue, we speculate that either a flat detachment or a complex transitional zone may separate the upper package from the lower package in the Northern Range. The origin of this architecture, which may be common in other transpressional belts, probably reflects vertical strain partitioning in the lithosphere. Flat detachments form in the weak, jelly-like, mid-crust to separate continuous flow in the mantle lithosphere from highly partitioned, block-style, deformation in the upper crust.

CARIBBEAN PROBABILISTIC SEISMIC HAZARD MODELING IN THE COMPLEX ZONES OF TRANSITION FROM SUBDUCTION TO STRIKE-SLIP: HISPANIOLA CASE STUDY

Chesley R Williams[1], Steven Masters[1], Guy Morrow[1] and Robert Muir-Wood [2]

[1]Risk Management Solutions, Inc, Menlo Park, CA 94025
[2]RMS Ltd, Peninsular House, 30-36 Monument Street, London EC3R 8LJ UK

The islands of the Caribbean experience a remarkably high concentration of natural hazards, including hurricanes and earthquakes. To aid insurers and reinsurers in managing their exposure to earthquake- related catastrophes in this region, a probabilistic seismic hazard model for the Caribbean has been developed. The model coverage extends from the Cayman Islands through the Northern Antilles to the west, through the Lesser Antilles and south to Trinidad and Tobago. The model is constructed from a series of seismic sources for which event probabilities and magnitudes have been defined. These seismic sources were delineated through the incorporation of island-specific models and paleoseismic studies, as well as detailed re-examination of historic observations and seismic catalogs.

According to this new model, the highest ground motions are observed in northern Hispaniola, where the 475-year-return-period MM intensity (10% exceedance in 50 years) is slightly greater than IX. The next highest hazard is observed in the Lesser Antilles on Antigua, Barbuda and Guadeloupe, where the 475 intensities are just slightly below IX. The lowest hazard (low VII) at 475 years is in the southern Lesser Antilles (St. Lucia south to Grenada) and along the southern coast of Puerto Rico.

Hispaniola represented one of the most complicated regions to model, since it involves a combination of thrusting under the northern coast (driven by convergence across the plate boundary) and numerous shallow crustal fault zones. To cover all of the possible seismic sources in Hispaniola, the final source model utilizes nine shallow surface faults and eight regional sources (Figure 1). Maximum magnitudes and return periods for the maximum events are shown in the table on the following page.

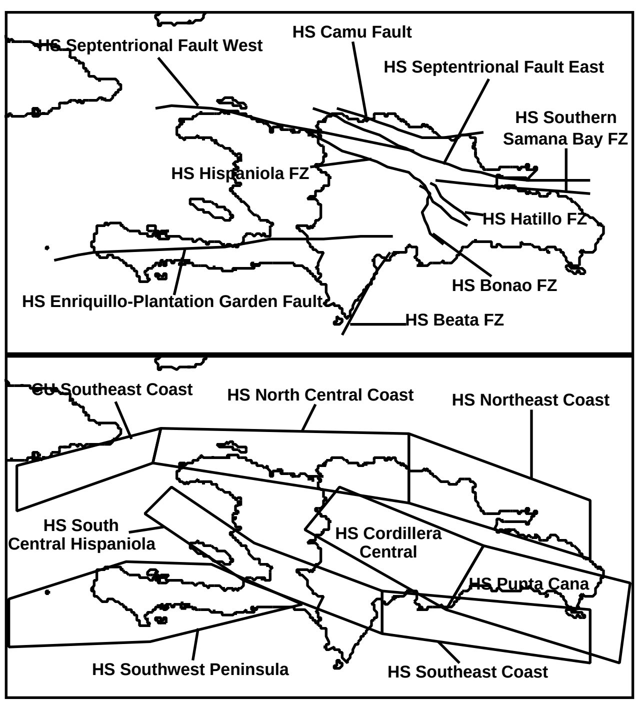

Figure 1. Seismic sources used in the Hispaniola component of the seismic hazard model.

Seismic Source Name	Max Magnitude	Max Return Period	Source Type
HS Beata FZ	7.40	3,000	fault
HS Bonao FZ	7.25	3,600	fault
HS Cordillera Central FZ	7.30	2,500	fault
HS Enriquillo-Plantation Garden FZ	7.80	800	fault
HS Hatillo FZ	7.10	3,600	fault
HS Hispaniola FZ	7.30	3,600	fault
HS Septentrional FZ East	8.00	800	fault
HS Septentrional FZ West	8.00	800	fault
HS South Samana Bay FZ	7.50	3,600	fault
HS Camu Fault	7.50	2,400	region
HS North Central Coast	8.30	1,300	region
HS Northeast Coast	8.00	1,000	region
HS Punta Cana Deep	7.80	233	region
HS South Central Hispaniola	7.60	333	region
HS Southeast Coast	7.80	675	region
HS Southwest Peninsula	7.60	333	region
CU Southeast Coast	7.50	150	region

Seismic source locations were delineated from tectonic regions, geologic maps, historical event rupture zones and microseismicity. During the development of the seismic source recurrence parameters, two critical issues arose:

1) How should the seismicity between the northern and southern coast sources be distributed?

2) How should the seismic moment release between the deeper plate boundary sources and the shallow crustal faults be partitioned?

For this model, roughly two thirds of the seismic moment was assumed to be released along the northern coast of the island. Of that, about 50% was attributed to the shallow crustal faults and the other 50% was associated with the deeper plate boundary sources dipping under the coast. Along the southern boundary of the island, the Enriquillo-Plantation Garden fault zone was assumed to play a very important role and was given a slip rate just slightly less than that of the Septentrional fault zone. The faults that step over from the southeastern coast to the plate boundary in the northwest have been given very low rates. The Cordillera Central source models the diffuse moderate magnitude events observed in the mountain region. Finally, the Punta Cana source accounts for the large intermediate depth events that occur under eastern Hispaniola.

The answers to the questions above have a critical effect on the resulting probabilistic seismic hazard model. More data to answer these questions are starting to become available through geodetic and paleoseismic studies, and we plan to update our model accordingly.

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