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POSSIBLE RAPID STRAIN ACCUMULATION RATES NEAR CALI, COLOMBIA, DETERMINED FROM GPS MEASUREMENTS (1996-2003)

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ABSTRACT

Global Positioning System (GPS) data from southern Central America and northwestern South America collected between 1991 and 1998 reveal wide plate margin deformation along a 1400 km length of the North Andes. Also associated with the oblique subduction of the Nazca plate at the Colombia-Ecuador trench is the 'escape' of the North Andes block (NAB). The NAB is delineated by the Bocono-East Andean fault systems and the Dolores Guayaquil Megasheare to the east, the South Caribbean deformed belt on the north and the Colombia-Ecuador trench and Panama on the west. Within the NAB many damaging crustal earthquakes have occurred which is most recently exemplified on January 25, 1999 (M_w = 6.1) Armenia earthquake. Preliminary analysis of recent occupations (2003 GEORED GPS) of several previously observed (1996-2001) GPS sites suggest shear strain accumulation rates in the Cauca valley near Cali of approximately 2.1×10^{-7} yr^{-1} and 1.6×10^{-7} yr^{-1}. These strain rates are measured within 2 Delaunay triangles with common vertices at Cali and Restrepo, which encompass areas, located north and west of Cali.

Seismicity has been monitored in the Cauca Valley for the last 17 years by the "Observatorio Sismológico del Suroccidente" (OSSO) since 1987 and by the Red Sismológica Nacional del INGEOMINAS since 1993. Their catalogs list numerous shallow earthquakes near Cali but nothing larger than magnitude 5. Historically, however, several large earthquakes are associated with the "Falla Cauca Almaguer" in locations both to the south and north of Cali in the Cauca valley. Preliminary calculations using the strain rates determined for these Delaunay triangles and a simplified Kostrov formula suggest possible decadal (30 – 90 years) recurrence intervals for M_w = 6.0 – 6.3 earthquakes, centenary (90 – 900 years) recurrence intervals for M_w = 6.4 – 6.9 earthquakes and millennial (900+ years) recurrence intervals for $M_w \geq 7$ earthquakes.

Key Words: GPS, Kostrov formula, recurrence intervals, seismotectonics, strain rates

RESUMEN

Los datos del sistema de posición global registrado desde la zona meridional de Centro América y el Noroccidente de Sur América, tomados en el periodo que comprende 1991 y 1998 revelan un amplio margen de deformación a lo largo de los 1400 kilómetros de longitud al norte de los Andes. Igualmente

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asociado a la subducción oblicua de la placa de Nazca en el corte de Colombia y Ecuador es el escape del bloque Norandino (NAB). El NAB está delineado por el sistema andino de fallas Bocono y el gran corte de Dolores, Guayaquil al este; el cinturón del Caribe sur; el corte de Colombia Ecuador, al norte, y Panamá, al oeste.

Dentro de esta zona han ocurrido muchos terremotos; como ejemplo está el más reciente, ocurrido el 25 de enero de 1999 en Armenia (M_w = 6.1). Los análisis preliminares de recientes ocupaciones (2003 GEORED GPS) de muchos GPS previamente observados (1996-2001) sugieren que la tensión en la acumulación de los cortes en el valle del Cauca, cerca de a Cali, son de aproximadamente $2.1 \times 10^{-7} yr^{-1}$ y $1.6 \times 10^{-7} yr^{-1}$.

Estas velocidades de tensión son medidas dentro de los dos triángulos Delaunay con vértices comunes en Cali y Restrepo, que comprometen áreas localizadas al norte y occidente de Cali.

Desde 1987 la sismología del valle del Cauca ha estado monitoreada por el Observatorio Sismológico del Sur Occidente (OSSO) y desde 1993 por la red sismológica Nacional de Ingeominas.

Se cataloga una lista de leves terremotos cerca a Cali, pero ninguno mayor a una magnitud de 5. Sin embargo históricamente muchos terremotos están asociados a la “falla Cauca Almaguer” en localidades cerca al sur y al norte de Cali en el valle del Cauca. Cálculos preliminares realizados con velocidades de tensión determinadas por estos triángulos Delaunay y la fórmula simplificada de Kostroy que sugiere posibles intervalos recurrentes de algunas décadas (30 a 90 años) para terremotos M_w = 6.0 – 6.3; intervalos centenarios (90 – 900 años) de terremotos M_w = 6.4 – 6.9 e intervalos milenarios (900 años o más) para terremotos de $M_w \geq 7$

Palabras clave: formula Kostrov, GPS, intervalos de recurrencia, parámetros de tensión, sismotectónica, tasas de esfuerzo.

INTRODUCTION

The Central and South America (CASA) GPS project was initiated in 1988 to study plate motions and crustal deformation in a tectonically active area of complex interaction among the Nazca, Cocos, Caribbean and South American Plates. Data from the CASA project collected between 1991 and 1998 reveal wide plate margin deformation along a 1400 km length of the North Andes (Trenkamp Et al. 2002). Associated with the oblique subduction of the Nazca Plate, the Colombia-Ecuador trench is the ‘escape’ of the North Andes Block (NAB). The NAB is delineated by the Bocono-East Andean Fault systems and the Dolores-Guayaquil Megasheare to the east, the South Caribbean deformed belt to the North and the Colombia-Ecuador trench and Panama on the West (Figure 1).

Within the NAB many damaging earthquakes have occurred. With this continuing threat of damaging earthquakes to major metropolitan centers, a large combined geological and geophysical study, *Microzonificacion sismica de la ciudad de Santiago de Cali*, was proposed and performed by INGEOMINAS (Alvarado Et al. 2003). In general, the project was a broad-based geological and geophysical approach toward understanding the stresses and deformation responsible for the neotectonics of the area. As a part of this study to assess the earthquake hazard potential near Cali and areas adjacent to the Cauca valley, a GPS project, *Geodesia: Red de Estudios de Deformacion 2003* (GEORED03) (Mora and Trenkamp, 2003) was coordinated and executed between July and September 2003 by the Volcanological and Seismological Observatory of INGEOMINAS in Manizales. The objective of the field project was a reoccupation of a subset of CASA stations and other previously occupied GPS stations in the Cauca region focusing on the city of Cali.

Plate tectonic models for southwest Colombia, based on regional mapping of the Tertiary and Quaternary deposits, show a series of graben shaped sub-basins located between the Cauca Patía and Romeral fault systems. Palinspastic reconstruction shows restraining bend, releasing bend and pull apart basins containing several tectonic blocks (Valle and Eduardo, 1999).

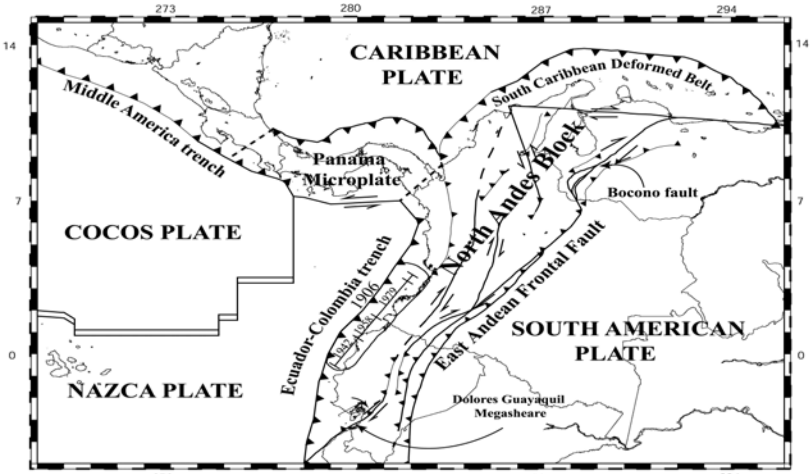

Figure 1. Generalized tectonic map of Northwestern South America and Southern Central America including the fault slip planes for the 1906, 1942, 1958 and 1979 earthquakes. Slip planes are from Kanamori and McNally (1982).

A gravity survey completed in 1964 shows two anomalies of interest on the west side of the Upper Cauca Basin, the Vijes and Cali anomalies. These two anomalies are bounded on the west by the Cauca fault and on the east by the Candelaria fault and separated by transverse faults. Seismic lines/sections confirm the gravity interpretations and show that the anomalies are not intrusions but are uplifted basement blocks (Noel, 1996). Also obvious from the seismic lines is an upper crust broken by numerous faults.

Seismic sources that affect Cali and the surrounding Cauca region are diverse. During the 20th century a four (4) large sequence and great subduction related earthquakes occurred. The first and largest event occurred in 1906 (M_w=8.8) and ruptured a 500 km length of the subduction interface on the Colombia-Ecuador trench between Manta, Ecuador and Buenaventura, Colombia (Kelleher, 1972, Kanamori and McNally, 1982).

Kanamori and McNally (1982) report that three smaller events in 1942 (M_w= 7.9), 1958 (M_w=7.8) and 1979 (M_w=8.2) re-ruptured most of the thrust fault plate boundary segment that ruptured during the 1906 event (Figure 1). These earthquakes are shallow (< 50 km) on the subduction interface. Other deeper earthquakes also occur that seem to be associated with deeper segments of the subduction interface. A third source of earthquakes is intraplate and occurs on faults in the shallow crust. These earthquakes have been most recently exemplified by the January 25, 1999 (M_w=6.1), Armenia earthquake and pose the greatest threat of damage to the populated areas of the Cauca Valley and environments. The seismicity in the Cauca Valley has been monitored for the past 17 years by the Observatorio Seismológico del Suroccidente (OSSO) since 1987 and also by Red Sismológica Nacional de INGEOMINAS since 1993. Their catalogs list numerous shallow earthquakes near Cali but nothing larger than magnitude 5. Page (1986) reports faulted alluvium in the vicinity of Palmira, a city near Cali, which suggests shallow seismicity during the Quaternary and historically several large earthquakes are associated with the "Almaguer fault" in locations to the north and south of Cali.

DATA AND DATA ANALYSIS

CASA data in Colombia consists of hundreds of sites, which have at least one epoch measurement. Of these sites and sites previously occupied by INGEOMINAS, a subset of 36 sites was chosen for the larger geological and geophysical project looking at zones of interest within and surrounding the Cauca valley and the city of Cali. Data was collected using 3 Trimble 4000 SSI receivers and Dorne Margolin Choke Ring antennas. Site occupations consisted of a minimum of three 8-hour observation days and were continuous over the 3 days when security conditions permitted (Table 1). All of the GPS data presented in this analysis and the larger GEORED03 study was processed using the JPL/NASA developed GIPSY/OASIS-II (GPS Inferred Positioning System/Orbit Analysis and Simulation Software) software (release 5) (Zumberge Et al. 1997). Loosely constrained solutions were obtained using JPL's fiducially free orbit (a "non-fiducially" orbit is one that is estimated without significant a-priori site position constraints), which were then transformed into the International Terrestrial Reference Frame 2000 (ITRF2000). In order to transform loosely constrained solutions into the ITRF2000 reference frame, daily 7 parameter transformations were determined using all reference sites (IGS tracking stations) used in our daily solutions and which are contained in the ITRF2000 position and velocity model. These are then applied to the daily solution, which transforms them to the desired reference frame (ITRF2000). Horizontal and vertical velocities were determined using a combination of all 352 daily solutions and 174 stations from the 1994, 1996, 1998, 1999, 2001 and 2003 surveys. A least squares inversion was used to estimate site velocities and position at an arbitrary epoch from the daily ITRF2000 coordinates weighted by the full covariance matrix of the coordinates. A scaling factor of 7.2 was applied to the input covariances so the reduced chi-square statistic equals 1.0. Reduced chi-square statistics that equal one indicate that the formal errors agree with the scatter of the measurements. The scaling by 7.2 is equivalent to scaling the sigmas by 2.68. Variance scaling assumes a Gaussian (normal) error distribution, removal of all human errors (blunders) from the dataset and systematic underestimation of the true errors by GPS software, which is generally accepted.

Table 1. THE EAST, NORTH AND VERTICAL VELOCITIES WITH ONE SIGMA ERRORS RELATIVE TO ITRF2000 OF THE 30 STATIONS WITH MULTIPLE YEAR OBSERVATIONS MADE DURING THE PROJECT GEORED03. SIX SITES WERE ESTABLISHED AND OBSERVED FOR THE FIRST TIME. THESE SITES WERE AQU2, CAFÉ, FRES, LETR, UVAL AND VERS AND WILL BE REOCCUPIED IN THE NEAR FUTURE IN ORDER TO ADD THEIR VECTORS TO THE GROWING SW COLOMBIA GPS DATABASE.

on.	Lat.	E	N	U	σ_E	σ_N	σ_U	Site
deg	deg	mm	mm	Mm	mm	mm	mm	
287.12	5.55	0.0	12.6	4.8	3.2	1.5	6.4	AQUI
282.61	6.20	7.3	12.3	1.1	0.7	0.4	1.3	BHSL
285.92	4.64	1.3	12.1	-35.3	0.5	0.4	0.6	BOGT
283.01	3.82	3.9	14.2	1.5	0.9	0.5	1.8	BUEN
284.04	4.75	9.0	14.0	-7.8	1.3	0.7	2.7	CAGO
283.64	3.50	4.0	13.9	-3.4	0.7	0.4	1.2	CALI
284.33	5.92	6.2	13.3	-3.1	2.0	0.7	3.1	FRDA
284.42	6.26	2.2	14.3	3.0	1.4	0.7	2.7	MEDE
283.40	0.98	2.1	9.2	4.7	8.7	2.3	8.2	MOCO
285.11	5.20	1.0	15.5	1.9	1.7	0.8	3.5	MQTA
284.53	5.03	5.0	14.2	-4.2	1.1	0.6	1.9	MZAL
284.57	6.18	7.4	14.1	-0.8	1.8	0.7	2.7	NEGR
284.70	2.94	2.1	13.2	-0.3	1.4	0.6	2.5	NEIV
284.87	4.47	1.4	14.3	0.2	1.5	0.6	2.7	OMBL
284.54	5.53	5.7	15.2	-2.1	1.3	0.6	2.6	PACO
282.74	1.22	1.5	12.2	-0.5	0.7	0.5	1.6	PAST
284.27	4.82	3.7	14.7	15.1	1.5	0.7	2.7	PERE
286.63	3.27	-2.9	10.0	-0.3	1.6	0.6	2.7	PLLE
283.42	2.48	1.7	13.5	13.2	0.8	0.5	1.8	PPYN
283.58	3.22	1.2	12.8	2.7	1.4	0.7	2.7	PTEJ
283.46	3.81	1.3	14.0	29.8	1.3	0.7	3.0	REST
284.57	6.18	6.4	14.1	-0.5	0.7	0.5	1.3	RION
283.85	4.40	2.4	12.8	-1.3	1.8	0.8	3.5	ROLN
284.39	4.87	3.8	16.6	-11.9	1.6	0.7	2.7	SRDC
283.78	4.09	5.6	13.1	1.2	1.5	0.7	3.1	TUL2
281.25	1.81	13.3	9.8	6.4	0.8	0.5	1.7	TUMA
286.62	4.07	-3.7	9.5	-1.0	0.8	0.5	1.7	VILL
284.40	4.98	1.4	15.2	-9.1	2.8	1.0	4.0	CHIN
284.70	2.94	2.1	13.2	-0.3	1.4	0.6	2.5	NEIV
284.34	4.56	2.5	13.9	-15.6	5.0	1.5	6.1	UNIQ

Velocities, in this study, are determined relative to the ITRF2000 reference frame (Figures 2 & 3). Due to an assumption that each daily solution is uncorrelated (white noise error model) uncertainties in the velocity estimates may be underestimated even though individual position uncertainties have been scaled to match the observed scatter. Recent analysis (Zhang Et al. 1997; Mao Et al. 1999; Dong Et al. 2002) have shown that a better description of noise in a continuous GPS time series can be obtained by incorporating both white noise and either "flicker" noise or "random walk" noise (both time related noise processes) into the error model. However, since every continuous GPS site will have its own "unique noise spectrum" it is not certain how best to apply these results to campaign style occupations which are too infrequent for noise characteristic determination. It is also not clear what noise model and weighting between available noise model should be applied to relative position time series over baselines a few hundred kilometers in length (Freymueller Et al. 2000) much less baselines which are less than 100 kilometers.

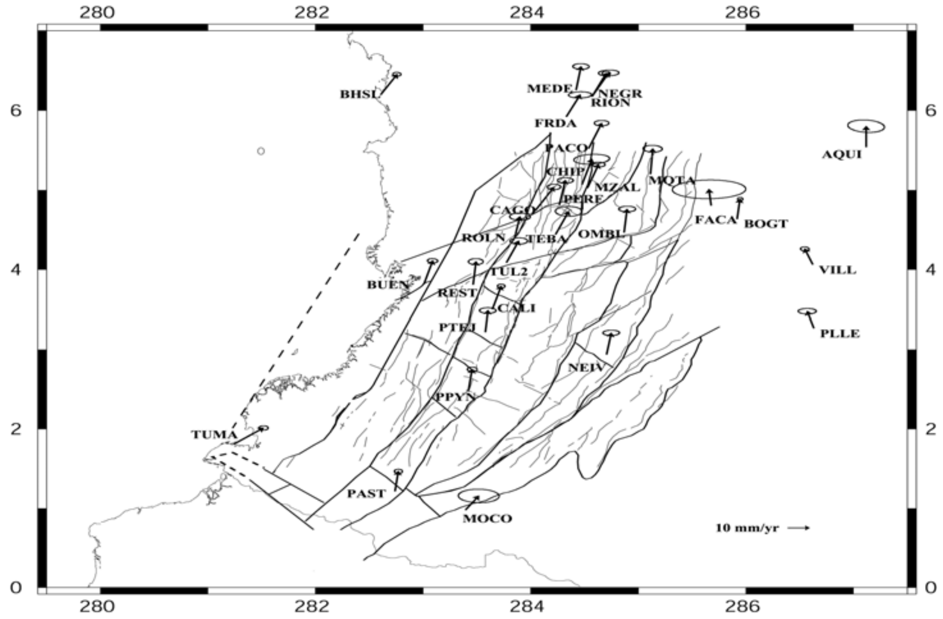

Figure 2. Vector field for sites observed during GEORED03. A few sites near PERE are not shown to maintain clarity of the figure. One site CHIP was added. It was re-observed at the end of the project because it was near the INGEOMINAS office and had been previously observed in 1999 after the Armenia earthquake. The CHIP/MZAL vectors and the RION/NEGR are interesting examples of the consistency of GPS measurements. (See Table 2 for the RION/NEGR vectors magnitudes). Overlain on the vector field is the 31 block grid used for the project Microzonificacion sismica de la ciudad de Santiago de Cali and a small sampling of the faults (light gray lines) in and around the Cauca valley.

RESULTS

For this study, only four stations are analyzed which are the four nearest to the city of Cali and which are also in a position favorable for the creation of Delaunay Triangles. These stations are TUL2, REST, CALI and PTEJ (Figure 3). For these sites CASA data collected prior to 1996 was removed from the strain analysis to minimize the effect of viscoelastic overprinting of the geodetic signal due to suggested ongoing viscoelastic effects from the 1979 (M_w=8.2) earthquake as reported in White et al. (2003). In order to solve for the velocity gradient tensor components $(\dot{\varepsilon}_1, \dot{\varepsilon}_2, \theta, \dot{\omega})$ and to estimate the shear strain ($\dot{\gamma}$) (Table 2), the loosely constrained ITRF 2000 daily solutions for all 174 stations were input as quasi observations into the Quasi Observations Combination Analysis (QOCA) software developed at JPL (Dong Et al. 1998).

The QOCA software permits forward and backward filtering of the daily solutions and tightening and loosening of geodetic constraints on selected stations. This is done to achieve consistency in results after all constraints are applied to the dataset.

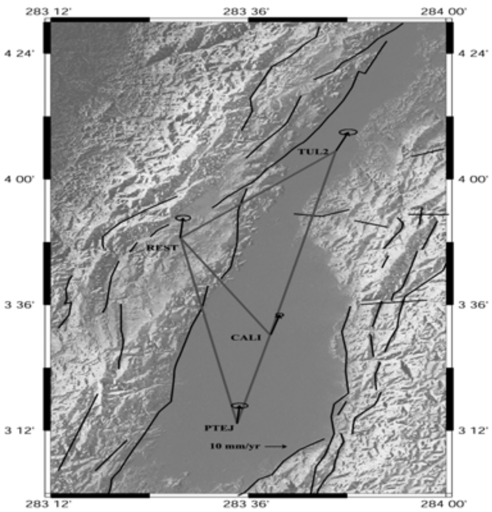

Figure 3. Map showing the topography of the region; the stations used in the strain analysis and the Delaunay triangles for which the strain was calculated.

For our purposes the data were processed forward and backward with tight and loose constraints on a subset of the global sites until the solutions were consistent. At all times the stations used in the strain analysis were completely unconstrained so that the results forthcoming were completely determined by the data and not artificially determined by tight constraints. At this step, the data prior to 1996 was removed from the input data to QOCA for the four stations used in the strain analysis and the strain rates were determined. Two separate data runs using both forward and backward filtering were processed and the average strain rates were calculated from a combination of these separate runs (Table 2)

The simplified Kostrov formula was used to determine the time for release of accumulated strain for different Moment energy release events These calculations were iterated using seismic moments for various synthetic Moment Magnitude events and the calculated shear strains until natural breaks (decadal, centenary and millennial) were discovered in the release time, see Figure 4.

TABLE 2. SEPARATE PROCESSING RESULTS OF THE RUNS USING THE QOCA SOFTWARE. LISTED IS THE EIGENVALUE PARAMETERIZATION $(\dot{\varepsilon}_1, \dot{\varepsilon}_2, \theta, \dot{\omega})$ ALONG WITH THE $\dot{\gamma}$ EVALUATION AND THE AVERAGE STRAIN RATES USED IN THE KOSTROV RECURRENCE RATE CALCULATIONS.

Delaunay Vértices	$\dot{\varepsilon}_1$	$\dot{\varepsilon}_2$	$\dot{\omega}$	θ	$\dot{\gamma}$
	10^{-8}strain yr^{-1}	10^{-8} strain yr^{-1}	10^{-8}strain yr^{-1}	degrees	10^{-8} rad yr^{-1}
CALI-REST-TUL2	15.7 ± 5.60	-0.98 ± 1.20	-0.43 ± 1.80	11.13 ± 6.88	16.74 ± 6.88
CALI-REST-TUL2	14.8 ± 5.62	-0.99 ± 1.19	-0.49 ± 1.80	10.46 ± 7.22	15.84 ± 6.88
Average used					16.29 ± 6.88
CALI-REST-PTEJ	24.5 ± 8.71	2.80 ± 1.41	-0.66 ± 2.69	-6.45 ± 6.59	21.65 ± 10.24
CALI-REST-PTEJ	23.2 ± 8.71	2.64 ± 1.41	-0.89 ± 2.69	-7.45 ± 6.94	20.59 ± 10.23
Average used					21.12 ± 10.24

These strain rates were then input into a simplified Kostrov formula $\mathrm{T} \cong \dfrac{M_O}{2\mu V\dot{\gamma}}$

Where M_o is the Moment energy release in dyne-cm, μ is the shear modulus taken to be $3x10^{11}$ dyne/cm^2, T is time, V is the volume being strained in cm^3 and $\dot{\gamma}$ is the shear strain rate.

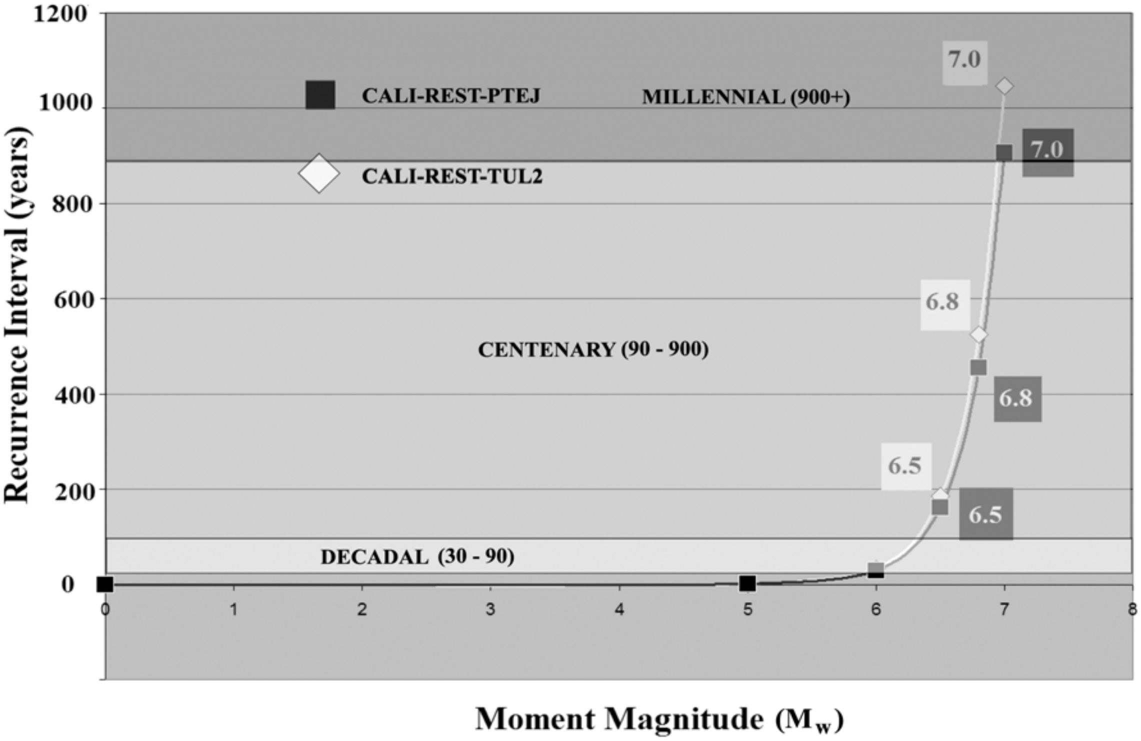

Figure 4. Results of the recurrence rate calculations using the simplified Kostrov formula. Decadal recurrence intervals (30-90 years) include earthquakes of magnitude (Mw = 6.0 – 6.3), Centenary (90 -900years (Mw = 6.4 -6.9) and Millennial (900+ years) (Mw ≥ 7.0+)

DISCUSSION

Instantaneous velocity gradients within the continental lithosphere in wide plate margin deformation zones such as the NAB are surely driven by plate tectonic forces. With the inception of space based geodesy, especially the Global Positioning System, the possibility of determining increasingly dense, instantaneous, three dimensional surface velocity fields has become a reality. The density and precision of these measurements has made possible the determination of strain rates which can be calculated to a certain degree of accuracy and the denser the measurements, the more accurately the straining areas can be mapped. Pollitz (2003) points out that there is a distinction between instantaneous velocity and steady state velocity in that instantaneous velocity is typically represented by geodetic measurements obtained over short time periods while steady state velocity is best described by fault slip rates over geologic time. And so, if the instantaneous surface velocity measurements represent the interseismic velocity field and not the steady state velocity field, this implies that the procedure of relating geodetically determined velocity fields directly to rates of seismic moment release and, subsequently, moment recurrence rates is not altogether correct. In fact, if, as determined in Pollitz (2003), the instantaneous velocities are potentially underdetermined steady state velocities the recurrence rates determined must be considered as maximal.

The strain rates determined in this study for these two Delaunay triangles near Cali (Table 2), while not high compared to subduction zone rates (10^{-5} – 10^{-6}) (Bilham Et al. 1989), are consistent with the seismicity that has been observed in this region of the NAB. The energy release rates were determined using conservative volumes, which increase the recurrence intervals but are believed to be valid for 1an area with a thin sedimentary cover similar to this section of the Cauca valley. These data are, however, very preliminary and all of the vectors except the vector at CALI are based on 2 epoch measurements. Although two measurements are enough for obtaining a vector, are certainly not very robust vectors and all of the sites have measurements, which are within the effective viscoelastic window reported in White et al. (2003) and will also have an affect on the results.

The historical record only goes back approximately 450 years and if the release is to be greater than M_w=6.6 then it may be an event to be expected in the near future. This would seem unusual or unlikely in the area since the largest recent events near this area have been nearer the M_w = 6.1 range. However recent paleoseismic work near the Pereira-Armenia region produced evidence of faulted offsets that may have generated an M_w=6.6 for a NE-SW trending fault and 'at least' M_w=6.9 for an E-W trending fault (Lalinde Et al. 2003). Maximum seismic magnitudes had been believed to be between 6.2 and 6.5, but this paleoseismic evidence brings a better understanding of the seismicity of the area over the last 30,000 years. In other words, this work and the work of many other scientific investigators indicate a need to study further the geodynamics of the area and apply the findings to the seismic risk in a more informed manner. This area is an area in need of site densification and multiple epoch observations in order to improve the strain analysis and focus the strain search to a localized set of faults. This information would then aid other researchers in the search for paleoseismic study locations, multiple front geologic and geophysical projects and possible permanent GPS site installation and observation.

CONCLUSIONS

The Cauca Valley of Colombia is a seismically active region of high potential risk to large population centers. A myriad of faults are being tectonically stressed which have repeatedly, in the past, slipped with devastating results. Unfortunately, the number of observable points throughout the valley and surrounding areas and resources for expanding the observational database are, at present, small but the need for a minimum 100 station GPS network throughout the valley surrounding the population centers of Cali, Armenia, Pereira and Medellín along with the two bounding cordilleras, Occidental and Central, is obvious. Our results while not conclusive and rife with difficulties are important in context with several other studies and historical documentation of seismic activity, which has affected Cali and other large population, centers in the region.

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