Migration of Seismic Activity in the Northern Boundary of the Caribbean Plate?

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Abstract

Among the recent destructive earthquakes associated with the Caribbean Plate, the Ms 7.6 1976 Guatemala earthquake stands out: ground breakage was mapped along the Motagua fault for nearly 230 km, with mean left lateral displacements of approximately one metre and local displacements of as much as three times more. The evaluation of previous destructive events in the same area, based on the form and extension of isoseismal maps, leads to comparable Richter magnitudes associated with the Polochic-Chixoy fault. They represent major disturbances at the western end of the northern edge of the plate, which is assumed to drift eastwards at a rate of a few centimetres per year.

This paper explores possible evidence of such a slow propagating deformational process along the compound plate boundary. It summarizes the results of a time-space analysis of the known destructive and/or large instrumentally recorded events during the 1538-1976 period, with magnitudes at least equal to 7.0 associated with the above-mentioned plate border, which is nearly 3500 km long. The total number of events is 113, of which a third reached Mercalli intensities of at least Grade VIII; a third of these are concomitant with tsunamis. The sequence of occurrence of the 113 earthquakes shows west-east migration patterns. Therefore, large events with epicentres towards the eastern end of the northern boundary seem to belong to cycles of activity that begin at the northwestern end of the plate and which take about three and a half centuries to reach the other end. With the available data, several cycles of migration can be identified in historical times, recurring every 7 to 8 decades and with propagation velocities of 8.5^{o} /century.

The observation described above leads to the identification of relatively small areas some 350 to 400 km long, where the probability of large earthquakes occurring within the next 10 to 15 years is much higher than for neighbouring areas. This seems to be the case of five areas identified in the paper, whose total length is about half of the plate boundary length.

Introduction

Global tectonics indicate that the important tectonic processes occur primarily at boundaries between the plates, where the relative motions must be accommodated. It has been suggested that these motions may be associated with slowly propagating deformational processes that introduce stress changes large enough to trigger earthquakes at locations where the tectonic stresses are near rupture (Savage, 1971; King and Ma, 1988). Geological and seismic studies indicate that the Caribbean plate is moving eastward relative to the Americas plates. This movement, of a few centimetres per year, is accommodated by left-lateral faults along its northern boundary and right-lateral faults along its southern boundary. The Oceanic lithosphere of the North and South American plates is consumed along the eastern edge of the Caribbean plate and the oceanic lithosphere of the Cocos plate is consumed along the western edge at the Middle America subduction zone (Sykes and Ewing, 1965).

Deformation associated with the Caribbean plate motion occurs in broad plate boundary zones (PBZ) up to 250 km wide, which are wider than the much narrower plate boundaries found in oceanic crust (Mann et al., 1990). Crustal thickness is of the order of 12 to 15 km

The North American-Caribbean PBZ consists of a broad zone of Neogene left-lateral strike-slip deformation extending from the northern Lesser Antilles volcanic arc in the east, to the Middle America Volcanic arc in western Guatemala (Figure 1). The Neogene strike-slip system there consists of two distinct but parallel left-lateral strike-slip fault zones (see for example Mann et al., 1984). The borders of the plate have been the scene of destructive earthquakes since the founding of the first settlements early in the XVIth century.

In February 1976, the northwestern end of the northern PBZ suffered a major strain disturbance, when a Ms 7.6 destructive earthquake shook a large area of Guatemala, leaving a fresh 230 km fault trace along the Motagua fault, with mean permanent left lateral horizontal offsets exceeding one metre (Espinosa, 1976; Plafker, 1976). A similar, or larger, event has been traced through old documents by White (1985) back to July 1816, along the Chixoy-Polochic fault, with estimated Mw magnitude of 7.5 to 7.75 and permanent displacements in the range of 2 to 4.5 m. Both events have been considered unequivocal proof of the relative plate motion. Taking into account the shape of the isoseismals of higher intensity, the rupture was, in both cases, from east towards west. Comparable large earthquakes are known to have happened throughout the historical record in different sectors of the Caribbean plate borders (Sykes and Ewing, 1965; Grases, 1971, 1973; Kelleher et al., 1973; Shepherd and Lynch, 1992). Of these, this paper studies those linked to the northern PBZ of the plate.

The study essentially analyses the time-space sequence of large and/or damaging earthquakes throughout an observation period of 4.5 centuries, bearing in mind that observations and theoretical models suggest that the occurrence of large earthquakes tends to progress systematically in a given direction at a relatively uniform velocity, leading to periods of dissimilar activity.

Area Considered, Characteristics of the Data Base and Sources of Information

Area Considered

A detailed description of the tectonic features making up the northern PBZ of the Caribbean plate has been given by Mann et al. (1990) (Figure 1). The western edge is considered to be located at the Cocos-North American-Caribbean triple junction region. A clear cut has been made here at a geographical longitude of 93 ^{o}W which is the approximate coastline near the Guatemalan-Mexican border,between 14 ^{o}N and 15 ^{o}N.The eastern edge has been set north of the Tiburon Rise, at 61 ^{o}W and 16 ^{o}N. This PBZ, nearly 3500 km long, has some tectonic expressions on dry land, among which are the Motagua-Polochic-Chamelecon-Jocoatan fault systems. According to Mann et al. (1990), the most reliable rates of North American-Caribbean interplate displacement on major strike-slip faults in late Neogene times range from 1.3 to 20 mm/yr in Central America; 15 $\pm$ 5 mm/yr in the Cayman Trough; and between 6 and 7.5 mm/yr from on-shore areas of the northeastern Caribbean. Sykes et al. (1982) suggested a total rate of interplate motion somewhat higher (37 $\pm$ 5 mm/yr), which accounts for cumulative displacements of other features.

Data Characteristics

The earthquakes considered in this analysis have occurred throughout the historical period (1538-1976) and have epicentres within the broad band shadowed in Figure 1. Due to the fact that some areas do not have dry land (for instance: the areas between the Gulf of Honduras and the Cayman Islands) only instrumentally recorded events are to be expected in the data base.

TABLE 1. SAMPLE OF CASES OF ALLEGED MIGRATION (1)

SEISMIC ZONE	OBSERVATION PERIOD	MIGRATION VELOCITY (km/yr)	SOURCE
Anatolia	1939 - 1967	80	Richter (1958); Mogi (1968b)
Anatolia	1850 - 1979	50 - 10	Toksöz et al (1979)
Northeast China	1966 - 1976	110	Scholz (1977)
Philippines	1930 - 1960	50	Mogi (1973)
Kita-Izu (Japan)	1930 - 1962	12	Mogi (1969)
Sanriku (Japan)	1926 - 1965	150 - 270	Mogi (1968a)
Alaska - Aleutian	1900 - 1970	100	Kelleher (1970)
West Coast N. Amer.	1830 - 1970	60	Savage (1971)
San Andres Fault	1930 - 1972	3	Wood and Allen (1973)
Middle America	1717 - 1970	4	Grases (1975)
Caribbean North PBZ	1530 - 1976	9	This paper
Chile	1880 - 1960	10	Kelleher (1972)
Mariana Arc	1930 - 1965	50	Mogi (1973)
Tonga Arc	1900 - 1969	45	Mogi (1973)

(1) Modified from King and Ma (1988)

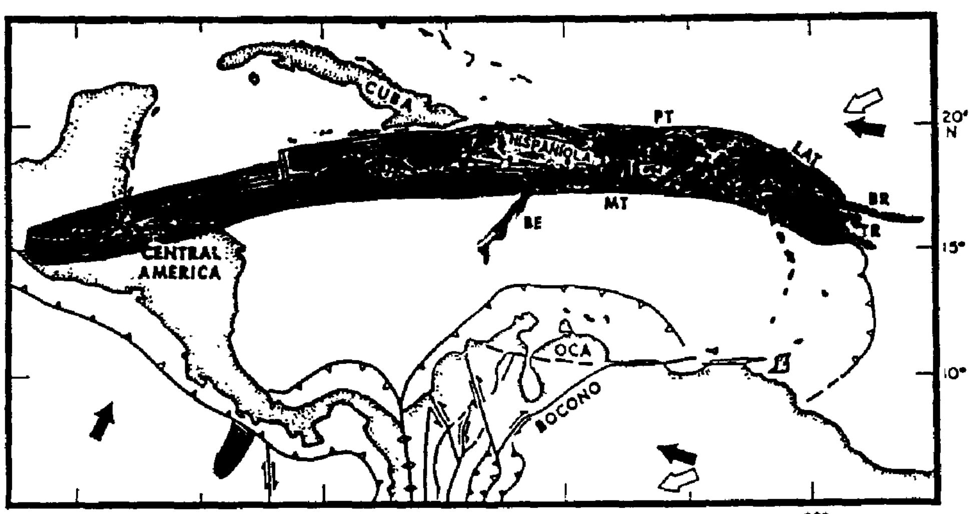

FIGURE 1. Generalized neotectonic features of the Caribbean region after McCANN and PENNINGTON (1990). Abbreviations are: Anegada trough (AT), Beata ridge (BE), Barracuda ridge (BR), Lesser Antilles trench (LAT), Main ridge (MR), Muertos trough (MT), Puerto Rico trench (PT), Tiburon rise (TR). Epicenters of the sample (1528-1976) within shadowed area.

In addition to the criteria mentioned above, the selected events meet one or more of the following conditions, which are presented in an order that reflects their relative level of trustworthiness:

i) Instrumentally recorded earthquakes (with or without associated damage) with Ms ≥ 7.0;
ii) Destructive events with an assigned epicentral Mercalli intensity of at least Grade VIII;
iii) Damaging tsunamis related with local events;
iv) Damaging events with an assigned Mercalli intensity of Grade VII or local intensity of Grade VI, although these last levels of intensity were not exhaustively searched.

Even in the cases where isoseismal maps exist, due to the small percentage of dry land in the area being studied, there is considerable uncertainty concerning the correct epicentre Also, since too many events lack an estimated focal depth, this parameter has been ignored in the analyses. Uncertainties as to the precise date of occurrence, which in no case exceed one year, can be ignored in this analysis. Finally, no attempt has been made to assign magnitude to past events; pre-XXth century Ms magnitudes have their origin in specific studies, duly referenced in the sources mentioned later and have been retained for further studies without a critical revision.

Data Base

The total number of events that fulfil the criteria described above is 113, of which:

a) About one third (40 events), instrumentally recorded or not, reached Mercalli intensities of at least Grade VIII;
b) One third of the last group (13 events) are linked to tsunamis and are reported as such;
c) One quarter of the total (28 events) reached intensity Grade VII;
d) A similar number (28 events) reached intensity Grade VI and;
e) The rest (17 events) are instrumentally recorded earthquakes with Ms ≥ 7.0 with unknown effects on man-made constructions.

Sources of Information

The following were the main sources of information used as a back-up for the data base:

i) Grases (1971; 1974 Vol. II): descriptions of pre-XXth century destructive events (totalling 198 references).
ii) BSSA, Seismological Notes (Vols. 1-72): descriptions and instrumental data for XXth century damaging and/or destructive events.
iii) Abe (1981), ISC (1900-1976), Feuillard (1985), Robson (1964): instrumental data for XXth century.
iv) Shepherd and Lynch (1992): revised catalogue of the area - excluding Guatemala - for the period (1502-1900) [totalling 69 references].
v) Grases (1993): synthesizes description of destructive events with available isoseismal maps; covers the 1502-1990 period [totalling 309 references, including modern evaluations of past events].

Time - Space Distribution

In order to represent the time-space sequence of occurrences in the data base, the geographical longitude has been used as a plotting variable, ignoring the changes of latitude along the PBZ. This linearization of the actual shape of the plate causes a certain distortion that has been ignored in the following analysis. The result of such representation is given in Figure 2, on which some comments follow:

i) The 1900 instrumentally recorded magnitude 7.9 earthquake (20 °N- 80 °W) should be displaced towards the west, according to McCann and Pennington (1990);
ii) 200 km rupture lengths have been arbitrarily assigned to tsunamigenic events (bold horizontal lines);
iii) Observed or inferred fault rupture lengths are differentiated from the previous by discontinuous lines;
iv) Question marks preceded by a T represent doubts as to whether tsunamis actually occurred; otherwise they reflect uncertainties concerning the assigned Mercalli intensity.

A migration pattern which has been repeated several times over the past 4.5 centuries is apparent in Figure 2 (shadowed bands). Therefore, given a certain geographical area, periods of low activity are interspersed among successive periods of high activity. To put it more clearly, given a certain area, the probability that it will be in the epicentral area of a very large earthquake is not uniform in time. Such periods, lasting approximately 40 years, are separated by comparable periods, lasting about 35 years, of a much lower probability of suffering a very large earthquake. Some statistical facts are:
i) 87 events out of the total sample of 113 events (77%) are within the suggested migration patterns, and 26 events (23%) fall outside:
ii) If only the highly destructive events are included, 13 have been tsunamigenic and 27 additional ones have assigned intensities equal to or larger than VIII; out of this group of 40 events, 88% are within the proposed migration patterns (shadowed areas);
iii) The less intense events, (28 with intensity VI) are the ones that fit the worst (57% within the shadowed bands and 43% outside them).

This observation is enhanced by means of a change of coordinates of the type:

$$t' = t - (93 - W)\ 100/8.5 \qquad (1)$$

where: t is the actual calendar year and W is the epicentral longitude in degrees. The result is given in Figure 3.

Discussion and Implications

In several areas of the world migration of the seismic activity has been claimed. One of the first observations came from the North Anatolia fault, a major PBZ between the Anatolian and Asian plates, recognized as a right lateral strike slip fault with slip rate estimates as large as 12 cm/yr (Toksoz et al., 1979). Migration of large earthquakes along this fault was first mentioned by Richter (1958). Later, on the basis of the occurrence of events of magnitude Ms at least equal to 7.0, a westward migration velocity of approximately 80 km/yr was suggested by Mogi (1968b). Further studies on the temporal and spatial distribution of seismicity performed by Toksoz et al. (1979), led to the observation that seismicity was not stationary over time: periods of high activity (1850-1900) and (1940-1979) bracketed a period of relatively low activity (1910-1939); this observation is comparable to the pattern presented here and the one found for Middle America in a previous work (Grases, 1975). Toksoz et al. (1979) also found a two-directional migration of earthquake epicentres away from a central region: the migration to the west with a velocity above 50 km/yr, and that to the east with a velocity of less than 10 km/yr. Mean slip rates were not uniform: 6 cm/yr for the 1910-1939 period and 12 cm/yr for the 1939-1977 period.

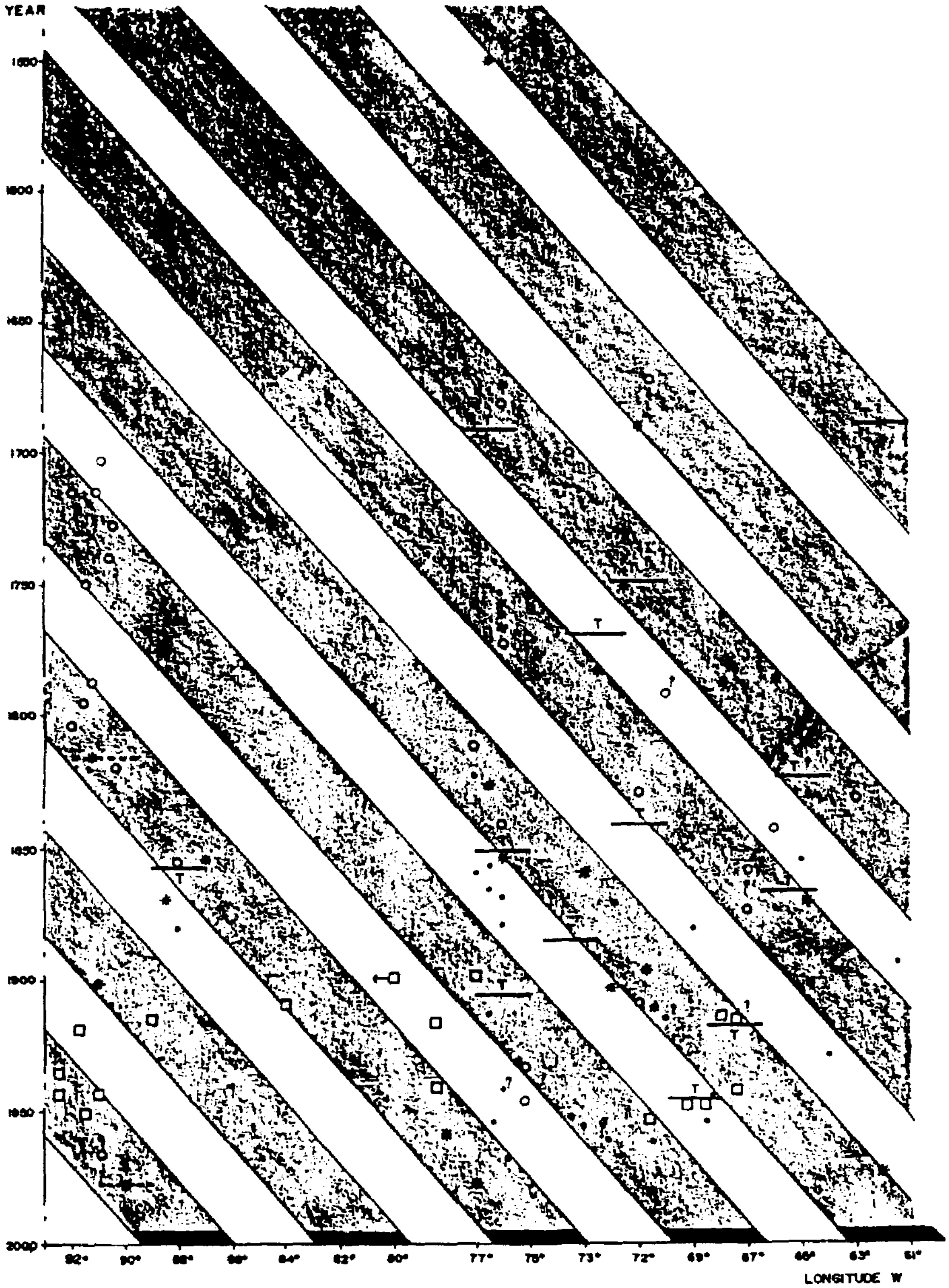

FIGURE 2: TIME-SPACE OCCURRENCE OF LARGE AND/OR DAMAGING EARTHQUAKES IN THE CARIBBEAN PLATE NORTHERN BORDER

—— TSUNAMIES
—-- FAULT BREAKAGE
✱ INTENSITY VIII
○ INTENSITY VII
• INTENSITY VI
□ INSTRUM. RECORD. $M_s \geq 7.0$
MIGRATION

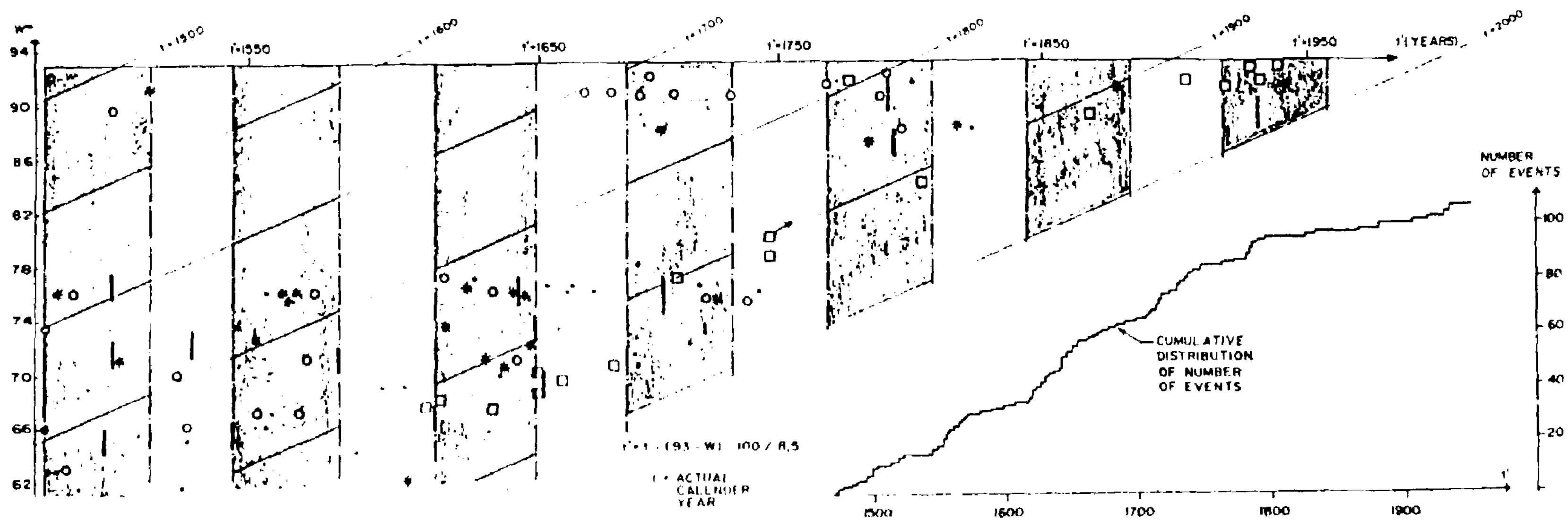

FIGURE 3 TIME-SPACE OCCURRENCE OF LARGE AND/OR DAMAGING EARTHQUAKES IN THE CARIBBEAN PLATE NORTHERN BORDER (SAME SIMBOLS AS IN FIGURE 2)

Other areas where migration has been alleged are given in Table 1. These values suggest that the idea of migration has been used in different contexts. Reports of very high velocities, near or exceeding 100 kilometres per year, appear to be more related to a sort of triggering effect from one event to the next, which does not seem representative of the slow progression of large periods of activity or non-activity reflecting strain liberation and strain accumulation along a plate boundary, such as the one described here. In fact, there are several instances where this high velocity trigger effect can be observed within the migration bands (shadowed areas) shown in Figure 2 (see for instance, the sequence of six events between 1910 and 1918 at 71 ^oW - 67 ^oW, with mean velocity of some 55 km/year).

There are several implications about the observed time-space seismic distribution. The first one is related to the recognition of the migration patterns, since they make it possible to identify areas prone to enter into periods of high seismic activity. Five of these areas, about 400 km long, identified in Figures 2 and 3, are expected to enter into such an active period during the next 10 years:

1) The Gulf of Honduras between 86^o W and 89.5^o W;
2) The Cayman Islands area (79.5^o W to 83^o W);
3) Areas of southern Cuba, eastern Jamaica and western Hispaniola (73^o W to 76.5^o W);
4) The Mona Passage and neighbouring areas (66.5 ^{o}W to 70 ^{o}W) and
5) The Lesser Antilles area between 63 ^{o}W and 61 ^{o}W at 16 ^{o}N approximately.

It is interesting to note that this last sector has been pointed out as a seismic gap by Dorel (1981) and Bernard and Lambert (1988).

Given the sharp differences between the active and inactive seismic periods, and also because they have occurred periodically for several centuries, it would seem as though the entire migration process is governed by rather simple mechanisms. This second implication has to do with the hazard evaluations of given sites, in the sense that the frequently used Poissonian 'memoryless' model, based on the mean return period, can be substantially improved by a probabilistic model which takes into account the known past history of occurrences as suggested in Figures 2 and 3.

Further analysis of the less well defined south PBZ is required in order to state anything useful for the understanding of the global plate mechanism. The incorporation of the full instrumental record, as well as other parameters now ignored, will allow the application of rigorous tests of statistical significance.

Conclusions

The time-space sequences of occurrence of destructive and/or recorded earthquakes with Ms larger than 7.0 over the past 4.5 centuries shows an apparent migration pattern along the northern boundary zone of the Caribbean plate in a west-east direction. Mean 'return periods' of such cycles are 75 years.

The inferred migration velocity is approximately 8.5^o /century (9 km /year), reflecting a slowly propagating deformational process along the compound boundary. This seems to reflect a type of migration different from others with claimed velocities one order of magnitude higher.

Available data suggest that certain sections of the considered boundary have a high probability of being in the epicentral area of strong earthquakes in the near future. Five of those sections have been identified and are given in the paper.

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Historical Seismicity of the Caribbean Region, 1933-1963

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Abstract

We have relocated 643 earthquakes that occurred in the Caribbean region (5 ^{o}N-25 ^{o}N, 50 ^{o}W - 90 ^{o}W) between January 1933 and December 1962. P and S arrival times published by the International Seismological Summary (ISS) for stations worldwide were used in conjunction with a generalized linear inverse routine to perform the relocations. With about ten exceptions, the relocated earthquakes fall within the defined plate boundary zones of the Caribbean, Nazca, Cocos, and North and South American Plates. These boundaries are much more clearly defined by the post-relocation events, however. Plate-boundary seismicity for this time period is most intense along the Middle Americas subduction zone (Guatemala to Costa Rica segment), the Panama Fracture zone, and in eastern Hispaniola and the Puerto Rico Trench region. A somewhat less well-defined tectonic boundary is marked by shallow earthquakes south of Panama. The Colombian and Venezuelan Andes are characterized by sporadic seismicity south of 10 ^{o}N. Although the Bocono Fault is clearly seismically active during this period, no events relocate to the vicinity of the Oca-Ancon fault system. Venezuela between 68 ^{o}W and 65 ^{o}W is devoid of all teleseismically detectable seismicity. The Lesser Antillean subduction zone is defined by isolated intermediate depth earthquakes. This area is marked by an almost complete absence of shallow seismicity from 16 ^{o}N to 13 ^{o}N, at the magnitude level of this catalogue (probably $m_b \geq 5.0$). The North America-Caribbean plate boundary is moderately well-defined by shallow events. Clearly intraplate earthquakes include five shallow events south of Jamaica near the Pedro Bank, two events at a location east of the Bahamas, two separate events near the Yucatan coast, and a single earthquake on the Nicaragua Rise near the Hess escarpment.

In both the Middle Americas subduction zone and the Puerto Rico Trench region, intermediate seismicity is sufficient to define subducted lithosphere at an accuracy comparable to that of modern teleseismically located catalogues. The deepest earthquakes in the region occur in the Middle Americas subduction zone and attain depths of 275 km. However, assuming perfect control on depth, only five relocated events were deeper than 200 km, all in Central America.

Accurate earthquake locations spanning the longest possible time period are essential for correct assessment of seismic hazard. Precise determination of patterns of historical (pre-1963) seismicity is especially important in the Caribbean region where plate boundaries are geologically complex and plate velocities are predominantly slow. By the time of the meeting, we hope to be able to report on event relocations in the Caribbean region back to 1899.