

SEISMICITY AND PLATE TECTONICS  
OF THE EASTERN CARIBBEAN

SEISMIC  
RESEARCH  
UNIT

By

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## ABSTRACT

The distribution of earthquakes in the Caribbean region closely follows the Greater and Lesser Antillean island chain and the coast of Venezuela. This zone is interpreted as one of differential movement between two separate plates of lithosphere, the first beneath the Caribbean Sea, i.e. enclosed by tectonic belt, and the second including the American continents and the western half of the Atlantic ocean.

Along the Lesser Antilles, the earthquakes are mainly concentrated within a westward-dipping layer corresponding to the subduction zone which is characteristic of island arc-fronts. Short strings of epicentres perpendicular to the arc indicate fracturing of the margins of the Caribbean and Atlantic plates, but are not considered to belong to any primary pattern of global tectonics.

In the Greater Antilles, the seismicity suggests active faulting offshore along the north and south sides of Puerto Rico and Hispaniola, and possibly also through the Anegada passage. Except for a short zone of probable underthrusting in eastern Hispaniola, the movement on these faults is believed to be mainly left-lateral transcurrent, although the evidence in support of this, from surface geology and earthquake mechanisms, is rather scanty. From Haiti through the Cayman Islands, remarkably little seismic energy has been released in the last 18 years, although widespread earthquake damage in the earlier historic period suggests that energy release over the last 300 years has been as high as in other parts of the circum-Caribbean belt.

The southern margin of the Caribbean has long been interpreted as a belt of large-scale, right-lateral, transcurrent faulting, thereby completing the geometrical pattern necessary for the convergence of the Caribbean and Americas plates along the Lesser Antilles. However, the absence of proven lateral



offsets of sufficient size, and the relatively low seismicity in this area during the last two decades, have been cited as evidence that the Caribbean is welded to South America and the southwest Atlantic, whilst major transcurrent faults extend from the Lesser Antilles to the mid-Atlantic ridge. The main objection to this is that the western Atlantic between the Lesser Antilles and the mid-ocean ridge appears to be almost totally aseismic and therefore represents a far less likely site for major east-west striking faults than does north Venezuela.

### Introduction

The most widely accepted hypothesis for the structural evolution of the Caribbean region (Hess, 1938; Hess and Maxwell, 1953; Rod, 1956; Alberding, 1957; Molnar and Sykes, 1969) states that the lithosphere underlying Caribbean Sea forms a rigid plate, which actively resists the westward movement of a second, larger plate consisting of the western half of the Atlantic together with continental North and South America. This hypothesis has recently been criticized (Ball and Harrison, 1970) on account of the absence of proven, large transcurrent faults along the southern margin of the Caribbean Sea, and because of the relatively low level of seismic activity in the same area during the last 18 years. An alternative hypothesis (Ball and Harrison, 1970) postulates a series of left-lateral, transcurrent faults extending from the Lesser Antilles to the mid-Atlantic, allowing differential movement between one plate consisting of the Caribbean, South America and the south-west Atlantic, and a second plate composed of the north-west Atlantic, North America and the Gulf of Mexico. A third hypothesis (North, 1965) suggests the eastward extrusion of the Caribbean region between the opposite-rotating continents of South America and the North Pacific.

The purpose of this paper is to present some recently obtained seismological data and to examine the extent to which they support the different tectonic models. The advantages of the earthquake data are that they provide a spatially unbiased guide to areas of present-day faulting. They are not restricted, as are direct geological observations, by problems of access such as the frequency and freshness of outcrops or drill sites. They also represent the only source of information for depths of greater than about 20km below the surface, which is the limit of penetration of marine reflection and refraction profiling. The limitations of earthquake seismology are that the period of instrumental recording is extremely brief in relation to geological time, whilst there is no way either of accurately reconstructing seismic activity before recording began, or of significantly accelerating the rate at which data can be collected.

#### Delineation of the tectonic belt

The main structural features of the eastern Caribbean are summarized in Fig. 1. The existence of a tectonic belt around the north, east and south margins of the Caribbean Sea is indicated by the recent elevation, folding and faulting of this strip of lithosphere; by the presence of thicker crust than in adjacent areas (Officer, Ewing et. al. 1959); by the occurrence of frequent earthquakes (Figs. 2, 3); by the juxtaposition of strongly positive and negative gravity anomaly belts (Hess, 1938; Masson-Smith, Andrew and Robson, 1970); and in the Lesser Antilles by active volcanism (Robson and Tomblin, 1966). This tectonic belt can be divided geographically and structurally into three parts, which are firstly the younger, primarily volcanic island arc of the Lesser Antilles; secondly the older island chain of the Greater Antilles; and thirdly the continental margin of South America. Each of these areas will be discussed in turn.



### Lesser Antilles

For the Lesser Antilles, the pattern of recent tectonic movements is relatively clear and consistent; the area is a typical island arc-front, along which crustal shortening is taking place through the sliding of the western Atlantic ocean floor beneath the eastern edge of a separate, Caribbean plate. Evidence in support of underthrusting along the Lesser Antilles includes the westward dipping zone of seismic foci (Figs. 4, 5), and the contrast between the strongly negative gravity anomalies to the east of the island arc, and the high positive anomalies along the upturned edge of the Caribbean plate. The axis of negative gravity anomaly coincides with the oceanic trench and with the surface outcrop of the seismically defined thrust zone. The southern part of this trench is filled with thick, low velocity sediments which have been uplifted to form the Barbados ridge, although the latter still possesses strongly negative gravity anomalies.

In addition to the main zone of underthrusting in the Lesser Antilles, at least three faults striking perpendicularly to the arc have been identified from the seismicity and bathymetry. Seismic activity along these faults perpendicular to the arc is not continuous, but has been observed intermittently for periods of a few months at a time. An example of high activity along three such faults is shown in Fig. 6. The first of these is indicated by a line of shallow earthquakes through Montserrat and Antigua which appears to represent a fracture in the margin of the Caribbean plate. From the bathymetry northeast of Antigua, where there is a clearly-marked, northward-facing, submarine escarpment, and from the presence of a similar though less pronounced southward-facing slope to the south of Montserrat, it is concluded that the offset is predominantly left-lateral transcurrent. The second fault zone is marked by the clustering of earthquakes along a northward-facing escarpment east-northeast of Guadeloupe,

similar to the one northeast of Antigua. However, the shallow events at the eastern end of this line lie farther east of the arc, close to the believed junction between the Caribbean and Atlantic lithosphere; this fault may therefore cut both the Caribbean and the Atlantic plates. Along the third line of suspected faulting, through the south of Dominica, the hypocentres all have focal depths of about 150 km and are therefore attributed to fracturing within the downgoing Atlantic plate. Thus it appears that, towards the line along which they converge, both the Caribbean and the Atlantic plates break into smaller, independently moving blocks. However, there is no evidence from the seismicity that these fractures run more than 200 km westward or 100 km eastward from the junction of the plates, so that they do not represent an independent, globally significant tectonic trend.

#### Greater Antilles

The structure of the two east-west trending segments of the circum-Caribbean tectonic belt, i.e. the Greater Antilles and northern Venezuela, is less conclusively established. Simple geometry dictates that if there is differential movement between the Caribbean and Western Atlantic lithosphere, with subduction beneath the Lesser Antilles, then there must exist complementary, transcurrent faults extending either westward or eastward from each end of the Lesser Antillean front.

The existence of transcurrent faults along the Greater Antilles was proposed by Hess (1938), who pointed out specifically the left-lateral offset between the metamorphic belts of Cuba and Hispaniola, which he attributed to faulting along the northern edge of the Cayman trough. Hess also indicated the strong probability of similar, left-lateral faulting in the Anegada passage between the Virgin Islands and Puerto Rico. Several earthquakes were located by Sykes and Ewing (1965) along a line extending southwestward through the Anegada passage, and cited



by them in support of faulting along this line, whilst high microseismicity in the Anegada Passage during a brief period of study has been reported by Murphy, Sykes and Donnelly (1970). Assuming, therefore, that major movements have occurred along the Cayman and Anegada fault zones, and that the Caribbean is a rigid plate moving eastward relative to the area north of it, some connection must exist between the Cayman and Anegada fault zones. One possible model, based on the seismicity observed by Sykes and Ewing (1965), has been suggested by Brace and Vogt (1970). This postulates a short, southwest-dipping zone of crustal subduction along the northwest coast of the Dominican Republic. The northern end of this westward-dipping underthrust joins the eastward extension of the Cayman fault zone, whilst the southern end swings into a transcurrent fault extending eastward across the south side of the Puerto Rico trench. The high frequency of earthquakes in the magnitude range 4.0 - 6.0 shown by Sykes and Ewing along this belt (Fig. 3), suggests that major faults may run along the entire southern side of the Puerto Rico trench, and that movements on the Anegada fault are subordinate. In contrast to Sykes and Ewing's epicentre map, however, the Trinidad-computed epicentres (Fig. 2), which span a slightly more recent time interval, show that during this period more seismic energy has been released along the line from Santo Domingo to St. Croix (i.e. along the south coast of Puerto Rico) than along the trench to the north of Puerto Rico. Fig. 2 also shows a notable absence of large magnitude events along the Anegada passage. Perhaps the only justifiable conclusion, under these circumstances, is that within a period as short as 18 years we cannot expect to see earthquakes distributed uniformly along all major fault zones, any more than within the same time interval we should expect eruptions from all dormant volcanoes in a given chain. Thus the qualitative relationship between earthquakes and faulting would appear to be valid, but the quantitative relationship between energy release within two decades and the mean rate of movement within geologically recent time cannot be

reliably established. From present evidence it appears that the Anegada trench, the Puerto Rico trench, the north and south coast of Hispaniola and the north and south margins of the Cayman trench are all possible sites for transcurrent faults, whilst a short zone of island arc-type underthrusting is likely beneath eastern Hispaniola.

An additional problem over the structure of the Greater Antilles arises from the focal mechanisms of four "lithosphere" earthquakes determined by Molnar and Sykes (1969) which show near-horizontal slip planes, which it is difficult to reconcile with the notion of transcurrent (normally near-vertical) faults. In a later note however, Molnar and Sykes (1971) suggested that of the four events, two which originated at intermediate depth at the western end of the Puerto Rico trench, may be related to internal deformation within a descending plate and not to differential movements between two independent plates of lithosphere. Thus it is clear that in the Greater Antilles, as in other parts of the Caribbean, many more well-determined focal mechanisms are needed before this type of information can be accepted as primary evidence for regional tectonics. The data required for such a study are now available and are being processed at the University of the West Indies in Trinidad. These include 80 eastern Caribbean earthquakes during the period 1965-1971, for each of which there are not less than 20 stations reporting first motions.

#### North Venezuela and Trinidad

The third and most controversial segment of the circum-Caribbean tectonic belt is the southern margin, along which the Caribbean plate adjoins the South American continent. An early hypothesis for the structure of this area, proposed by Hess and Maxwell (1953) and supported by Rod (1956) and Alberding (1957) postulated very large, transcurrent offsets along the El Pilar fault (Fig. 1), the estimate by Alberding (1957) being 475 km of right-lateral displacement.



More recently, however, Metz (1968) has adduced evidence from detailed field mapping that the maximum lateral movement along this fault since late Cretaceous is only 15 km. If the latter figure is accepted, then it must be concluded either that major transcurrent faults between the Caribbean and South American plates lie elsewhere, or alternatively that no large strike-slip movements have occurred and that the Caribbean and South American regions form part of a single plate. The latter alternative has been preferred in recent publications by Ball, Harrison and Supko (1969) and by Ball and Harrison (1970). These authors attach special importance to the observation that the recent seismicity of north-central Venezuela has been somewhat lower than that of the Lesser and eastern Greater Antilles, and cite this as evidence for the absence of major transcurrent faults in the area. Their model, following that of Funnell and Smith (1968), requires the existence of several very long, transcurrent fault zones extending from the Lesser Antilles to the mid-Atlantic ridge. This raises the basic question of the relationship between faulting and seismicity. If, as Ball and Harrison propose, low seismicity means relatively minor faulting across north-central Venezuela, then it would be expected conversely that, at least along some parts of the several transcurrent faults which they postulate between the Lesser Antilles and the mid-Atlantic, there should be significant earthquake activity. In fact there has been almost none; out of 1,633 regional hypocentres determined by the Seismic Research Unit for the years 1966 through 1969, only 14, i.e. less than one percent, lie within the broad area more than 200 km east of the volcanic Lesser Antilles and more than 100 km west of the mid-Atlantic ridge. Of these 14 events, moreover, only three were located east of longitude  $57^{\circ}\text{W}$ . Between longitudes  $53^{\circ}$ - $47^{\circ}\text{W}$ , i.e. up to the mid-Atlantic ridge, not a single hypocentre has been determined by the Caribbean network since it began to operate in 1953, even though the sensitivity of this network is adequate to detect events from magnitude 4.7 upward beneath the central part of the mid-

Atlantic ridge. The map of world seismicity 1961-1969, compiled by Barazangi and Dorman (1970), confirms the lack of activity between the mid-Atlantic ridge and the Lesser Antilles. Thus in the absence of recent earthquakes or other favourable evidence in the greater part of the west-central Atlantic, the placing of major faults through this area must be regarded as highly speculative.

The occurrence of fewer earthquakes during the last two decades in north-central Venezuela than in most other parts of the circum-Caribbean belt, was regarded by Ball and Harrison (1970) as important evidence for the welding of South America to the Caribbean. This argument merits careful analysis. There is no doubt, both from the epicentre map of Sykes and Ewing (1965) and for the more recent period up to 1969 (Fig. 2) that less seismic energy has been released along the central part of north Venezuela than in three other areas, namely west of Trinidad, in the northern Lesser Antilles, and in eastern Hispaniola. However, as was noted earlier, it can hardly be expected that the relatively brief instrumental record will show uniform energy release within individual segments of the region, even if such uniformity exists on the scale of centuries or millennia. It is therefore useful to consider the longer, historic record of earthquake damage, which for Venezuela has been summarized by Fiedler (1969). This illustrates that the historic intensity record for central Venezuela includes several very large earthquakes, and that the mean rate of energy release here over the last 200 years has probably been as large as, or larger than in Trinidad. It is of interest to note, in this context, that the same situation exists in the Jamaica region, where there has been a total absence of earthquakes of magnitude above 6.0 during the last ten years, although several very large earthquakes have occurred here in the earlier historic period, and the frequency of intensity VI or larger events in Jamaica since 1800 is 17 per century compared with 14 per century for Trinidad (Tomblin and Aspinall in press).



An alternative hypothesis to that of Ball and Harrison, which also postulates insignificant faulting along the southern margin of the Caribbean, with consumption of lithosphere along the Lesser Antilles, was proposed by North (1965). The latter author envisaged the Lesser Antillean frontal zone as having been extruded eastward, from a former site along the west coast of the Americas, by the clockwise rotation of South America and the complementary anticlockwise rotation of the north Pacific. For this, however, the necessary rotation at the circumference of South America must have been at least 2,000 km, which seems improbably high in view of the present symmetry between the South American and African continents. Moreover, coupling between South America and the Caribbean could not have been perfect, and would have increased the amount by which South America must have rotated, whilst generating minor left-lateral rather than the observed right-lateral offsets on the El Pilar and related faults. North (1965) did not specify whether he believed the South American continent to be rotating on its own, or complete with the south-western Atlantic. The former must be rejected in the absence of suitable structures along the eastern margin of South America, whilst the latter runs into the same difficulty as Ball and Harrison's model in that it requires major trans-current faults across the western Atlantic, plus the additional difficulty of implied transcurrent faults striking north-south along the southern half of the mid-Atlantic ridge. For these reasons North's model seems the least satisfactory of those which have been discussed.

A final point of interest arising from the recent seismicity of the southern Caribbean, to which attention has not previously been drawn, is the approximately north-south, linear trend of the numerous large-magnitude earthquakes west of Trinidad during the past decade (Fig. 2). If this is regarded as a southward extension of the Lesser Antillean subduction zone, then east-west striking,

transcurrent faults should join its southern end and thus lie to the south of the El Pilar fault. In fact the tectonic map of Bucher (1952) shows two right-lateral, transcurrent faults, the San Francisco and the Urica, in this area (Fig. 1), whilst a magnitude 6.5 earthquake (Fig. 2) near the western end of the Urica fault indicates active deformation. It may be that there are many more en-echelon, right-lateral transcurrent faults in this area and westward through the south of Caracas than have so far been identified, and that the sum of offsets on all of these faults amounts to hundreds of kilometres.

### Conclusions

The principal conclusions of this paper are as follows:

- 1) The borders of the Caribbean are clearly established from the seismicity as an active tectonic belt. Regional seismicity outside this belt is insignificant.
- 2) Certain areas of low energy release within the seismic belt during the last 18 years, are regarded as temporary anomalies. This conclusion is supported by the occurrence of widely destructive earthquakes in these areas within the earlier historic period. Consequently, these areas of low energy release in the last few decades may constitute areas of high present-day strain accumulation and seismic risk.
- 3) The distribution of hypocentres supports the notion of plate consumption in the Lesser Antilles, and is compatible with the transcurrent movement along the north and south sides of the Caribbean which is implied by the geometry of the tectonic belt.
- 4) The hypothesis of a smaller, intro-Caribbean and a larger, Americas-Western Atlantic plate is the one which agrees best with our present knowledge of the regional seismicity.



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