FROM TRANSCURRENT FAULTING TO FRONTAL SUBDUCTION:
A SEISMOTECTONIC STUDY OF THE NORTHERN CARIBBEAN PLATE
BOUNDARY FROM CUBA TO PUERTO RICO

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Abstract. Recent marine and onland geophysical and geological investigations along the northern Caribbean plate boundary call for a review of its tectonic interpretation, in the light of a new compilation of the seismological data available from Cuba to Puerto Rico. We show that the shallow seismicity in the northeastern Caribbean is concentrated along an east-west trending lineament corresponding to the trace of the major strike-slip fault system. The most intense seismicity is located around restraining bends such as southern Cuba and northern Hispaniola. The stress and strain distribution deduced from focal mechanisms and microtectonic analysis lead us to infer a small N-S convergence component associated with the major eastward strike-slip motion of the Caribbean plate versus North America. Earthquake distribution and focal mechanisms suggest the existence of a lithospheric slab inherited from the frontal subduction under the Lesser Antilles dipping down under Puerto Rico and eastern Hispaniola. We propose a model in which this slab is disconnected from the Atlantic oceanic lithosphere by transcendent faulting along the plate boundary.

INTRODUCTION

As evidenced by Molnar and Sykes [1969], the Caribbean domain and Central America form a small lithospheric plate inserted between North and South America that is moving eastward relative to North America (Figure 1). Its northern boundary is a left-lateral transcendent fault system connected around its eastern end to the subduction of the Atlantic oceanic lithosphere under the Lesser Antilles. Recent geophysical and geological investigations have been conducted along the northern Caribbean plate boundary, both at sea [Scansen et al., 1989; Dillon et al., 1989; Calais et al., 1989a; Calais and Mercier de Lépinay, 1990b; Calais and Mercier de Lépinay, 1991] and on land [Calais and Mercier de Lépinay, 1989; DeZoeten and Mann, 1991; Calais and Mercier de Lépinay, 1990a; Mann et al., 1984; Heubeck, 1988]. They include Seabeam mapping, magnetic and gravimetric measurements, seismic reflection recordings, field mapping, and microtectonic analysis. In the light of a new compilation of the seismological data available from Cuba to Puerto Rico and these recent marine and onland geophysical and geological investigations, a review of the tectonic interpretation of the northern Caribbean plate boundary is called for.

Various authors have conducted seismological studies of the Caribbean plate since the first work of Sykes and Ewing [1965], especially along its northeastern corner (Puerto Rico/Virgin Islands area) [Kafka and Weidner, 1979; Murphy and McCann, 1979; Ascencio, 1980; Frankel et al., 1980; Frankel, 1982a, 1982b; Fischer and McCann, 1984; McCann and Sykes, 1984; Byrne et al., 1985; McCann, 1985]. McCann and Sykes [1984] point out that transition between strike-slip and subduction seems to occur abruptly around 74°W. However, they do not extend their investigations to the west of central Hispaniola and do not propose any model to explain the transition between strike slip tectonics and subduction in the northeastern Caribbean plate boundary.

On the basis of our tectonic knowledge of the northern Caribbean transcendent plate boundary, we focused our attention on the area between 78°W and 68°W longitude and 16°N and 21°N latitude (Figures 1 and 2a). The seismological data, some of which has already been displayed by these authors, are brought up-to-date using the recent International Seismological Center (ISC) bulletins. New focal solutions are computed in order to complement the already existing data set.

This paper seeks to bring out discussions on two problems:

1. How is the transcendent plate boundary (known up to eastern Hispaniola) connected to the frontal subduction (clearly illustrated under the Lesser Antilles)?
2. How can the seismological data explain the surface deformation evidenced along the plate boundary and help to constrain the kinematics of the Caribbean plate?

EARTHQUAKE LOCATIONS

Maps of Epicenters

The compilation of epicentral data given by the U.S. Geological Survey (USGS) for the interval 1962-1987 allows us to pick up 513 events occurring within our study area (Figure 2b). The increase and improvement of seismological networks in the last years allow for more accurate locations of earthquakes of low magnitude (Ml < 4). Therefore these newer plots increase epicenter density in many areas of smaller events. It must be noted that the recording of micro seismicity (Ml < 3) in the eastern part of Jamaica is the result of the existence of a local seismological network. The errors estimated for the recent events provide an average value of 10 km for the epicenters and a maximum discrepancy of 30 km in the depth estimation according to the determination of different institutions. Taking into account the scale of the study (a plate boundary), these errors do not represent a big constraint for our discussion. Moreover, the events we studied more thoroughly (see Table 1) are relocated by different authors or are recent enough to be correctly located.

1. Shallow earthquakes (depth ranging from 0 to 50 km) represent 91% of the events and are distributed over the whole studied area (Figure 3b). This distribution, however, defines four main domains of seismic activity: south of Cuba, east of Jamaica (mainly micro-earthquakes), north of Hispaniola and southeast of the Dominican Republic. As shown by the Figure 3b, the shallow earthquakes are in good correlation with active tectonic structures mapped in the northeastern Caribbean domain.
Fig. 1. The studied area in its geotectonic framework. Abbreviations are C, Cuba; J, Jamaica; P, Puerto Rico; H, Hispaniola; LA, Lesser Antilles; CA, Central America; CT, Cayman Trough; BR, Besta Ridge; 1, Polochic-Motagua fault zone; 2, Swan fault; 3, Oriente fault; 4, frontal subduction of the Lesser Antilles; 5, El Pilar fault zone; 6, Colombian Eastern Cordillera; 7, Dolores-Guayaquil fault zone; 8, Colombian subduction zone; and 9, Central America subduction zone.

Fig. 2. (a) Structural sketch map of the studied area. (b) General map of epicenter distribution. Abbreviations are CCB, Cabo Cruz basin; SDB, Santiago Deformed Belt; CS, Cordillera Septentrional of Dominican Republic; CV, Cibao Valley; CO, Cordillera Oriental of Dominican Republic; CSZ, Cretaceous suture zone; ET, Enriquillo trough; PSH, Presqu'île du Sud of Haiti; EPGFZ, Enriquillo-Plantain Garden fault zone; MAP, Muertos accretionary prism; WP, Windward Passage, and HB, Hispaniola Basin.
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Lat. and Long. are respectively latitude and longitude in degrees; A1 and P1 azimuth and dip of nodal plane 1; A2 and P2, azimuth and dip of nodal plane 2; S1 and S2, slip vector along nodal planes 1 and 2; AP, pressure axis azimuth; PRF, depth in kilometers; Mag, magnitude; Q, quality of the focal determination (decreasing from A to C). References are MS, Molnar and Sykes [1969]; K, Kafka and Weidner, [1979]; HRVD, Harvard Data Base; NEIS, National Earthquake Information Center; all others, this paper.

2. Deep earthquakes (depth greater than 50 km) represent only 9% of the recorded events. They are mainly located in the eastern part of Hispaniola (on land and at sea, Figure 3a). These events extend as a circular group striking around N120°. This group is remarkably isolated: it spreads westward as far as 70°30'W, eastward as far as 68°30'W, northward as far as 19°30'N, and southward as far as 18°N. It does not extend eastward as shown on the charts of McCann and Sykes [1984] and, consequently, does not show any continuity with the deep earthquakes associated with the subduction of the Atlantic lithosphere under the Lesser Antilles. These deep earthquakes cannot be directly correlated with active faults found on the surface.

### Location of Hypocenters on Profiles

**South of Cuba.** The GG' and CC' profiles (Figure 4) display earthquakes located between 0 and 50 km deep, that is, in the crust or in the upper mantle. This distribution is compatible with an horizontal strike-slip motion of the Caribbean plate versus North America along the Oriente fault. The CC' profile seems to show a progressive deepening of hypocenters on neighboring the main fault (Oriente fault). Profiles perpendicular to the Cuban margin, compiled by Sanchez Menendez and Vorobiova [1989] from data from the Cuban seismologic network, confirm this observation. They show a very high density of hypocenters straight below the Oriente fault, equally distributed between 0 and 50 km deep, and a group of hypocenters of a lesser density, whose lower limit clearly displays a low-angle northward dipping plane. The surface emergence of this plane exactly corresponds to the thrust deformation of the Santiago Deformed Belt [Calais and Mercer de Lépinay, 1991]. This hypocentral distribution therefore determines a "seismic corner", the pattern of which evokes that of a "flower structure", as suggested by Calais and Mercer de Lépinay [1991] on the basis of marine structural data.

*Hispaniola and the junction with Puerto Rico.* The profiles DD', EE', HH', II', JJ', KK' (Figure 4) come in addition to the profiles AA' and BB' made by McCann and Sykes [1984] on the eastern far end of Hispaniola and in the Strait of Mona.

On both WNW-ENE trending profiles (DD' and KK) we note a sudden eastward deepening of hypocenters, from longitude 69°40' on profile KK' and from longitude 70°30' on profile DD'. The JJ' profile, carried out west of these longitudes, does not show any deep earthquakes. This deepening of hypocenters is not gradual, as evidenced on profiles DD' and KK'. These profiles show a clear break in the hypocentral distribution from west to east between shallow and deep events.

From the north to the south, our profile EE' and the profile BB' provided by McCann and Sykes [1984] show an hypocentral distribution divided into two groups: on one side the shallow earthquakes to the north, on the other side the
deep earthquakes to the south. On all these profiles the group of shallow earthquakes exactly corresponds to the trace of the transcurrent plate boundary recognized through Hispaniola [Calais and Mercier de Lépinay, 1989] and to its eastward prolongation at sea. Moreover, Scanlon et al. [1987] have identified active strike-slip faults in the Puerto Rico trench and on its inner wall. Therefore we think that these earthquakes have to be related to subvertical strike-slip faults rather than to a Benioff plane as proposed by McCann and Sykes [1984]. Besides, the AA' profile given by these authors does not show any clear trace of such a plane, and neither does our profile II'.

The profiles EE' and II' show that no Benioff plane is associated with an hypothetical subduction of the Venezuelan basin oceanic lithosphere under Hispaniola and Puerto Rico, usually invoked to explain the setting of the Muertos accretionary prism [Ladd and Watkins, 1979; Biju-Duval et al., 1982].

In conclusion, hypocentral as well as epicentral distribution of earthquakes point out the disconnected character of the deep earthquake group of eastern Hispaniola versus other seismic areas. Moreover, whatever its azimuth, no Benioff plane may be clearly demonstrated under eastern Hispaniola.

FOCAL MECHANISMS

Twenty-three earthquakes, with magnitude ranging from 4.5 to 5.9, occurred in the studied area between 1960 and 1987. Seven focal solutions have been published by Molnar and Sykes [1969] and Kafka and Weidner [1979]. The USGS provided focal mechanisms for seven other events, computed with the moment tensor inversion method [Dziewonski and Woodhouse, 1983]. For the other events, we determined focal solutions from P wave first-motion polarities on the basis of the ISC bulletin data. Focal mechanisms parameters are displayed with their degree of confidence (A to C) in Table 1 and reported on map on Figure 5. The error for azimuth of P axis deduced from the resolution of the coefficients of the moment tensor has been computed from the knowledge of errors on each coefficient and eigenvalues, since P axis is one of the eigenvalues. This mathematical error on P axis is generally very low and never exceeds 12°. Error on P axis deduced from the different solutions that we propose from P waves first-motion polarities does not exceed a maximum of 40°.

From the Mid-Cayman Spreading Center to South of Cuba

In the western part of the studied area, Molnar and Sykes [1969] computed three focal mechanisms indicating strike-slip faulting on planes nearly parallel or perpendicular to the Cayman Trough direction. We reproduce one of them (event 1), located on a small transform segment shifting the Cayman Trough spreading axis. In this case the fault plane is obviously the E-W plane. All these mechanisms are well constrained and confirm the interpretation of the Oriente fault zone as a left-lateral transform fault.

Along the southern Cuban margin, the USGS computed a focal solution (event 2) describing a reverse fault with a NNW trending P axis. We determined a focal solution for event 3, located off Santiago de Cuba close to event 2. The focal solution is a transpressional mechanism with a subhorizontal NNE trending P axis. Both results are therefore in accordance with the compressive deformation evidenced by surface observation in this area (Santiago Deformed Belt). On the basis of these focal mechanisms, we show that the crust and the upper mantle are affected by compressive tectonics. The NW-SE trending wrench faults observed during the
Fig. 4. Earthquake hypocenters projected onto eight vertical sections. Location and width of the profiles are given for each section.
SEACARIB II survey [Mercier de Lépinay et al., 1989] might correspond to the fault planes of events 2 and 3. The NNE direction of subhorizontal P axis is in good agreement with the general southward thrust observed along the Santiago Deformed Belt.

North of Hispaniola

A recent earthquake of magnitude 5.0 occurred on September 3, 1987, in the northern Dominican Republic (event 4), in the western part of the Cibao Valley. The focal mechanism we computed, well-constrained, displays a transpressional focal solution with a N50° subhorizontal P axis. As evidenced from field observations in this area, the northern Dominican Republic is a domain of active tectonics, with N110° to N140° trending faults working at the same time as left-lateral strike-slip and reverse faults [Calais and Mercier de Lépinay, 1989; DeZoeten and Mann, 1991]. Microtectonic measurements in different spots located in the vicinity of these faults have been computed using Angelier's method of stress calculation [Angelier and Mechler, 1979]. The maximum principal stress sigma 1 always displays a subhorizontal dip and a N20° to N60° trending azimuth [Calais, 1990]. This direction of sigma 1, in agreement with the structural pattern of the active structures of northern Hispaniola, is in good correlation with the P axis deduced from the focal mechanism of the Cibao event. This focal determination therefore confirms the superficial geological observation: northern Hispaniola is under a transpressional tectonic regime, the principal compressive stress being subhorizontal and striking about N50°. Concerning the focal mechanism of the Cibao valley, we can infer on the basis of the structural data that a left-lateral motion occurred along the N110° trending fault plane.

Events 5 and 6 are located close to a compressive deformation area described by Dillon et al. [1989] at the bottom of the northern Hispaniola margin. Focal solutions 5 and 6 are compressive, with a N-S trending subhorizontal P axis. We interpret these earthquakes as the result of compressive tectonics along E-W trending reverse fault planes. As shown by the focal mechanisms, the motion along these faults is not pure convergence but includes a strike-slip component.

Other Events in Northern and Eastern Hispaniola

Event 8 displays strike-slip faults; a left-lateral motion on the N124° trending nodal plane is in good agreement with the major faults observed on the surface [Mercier de Lépinay, 1987].

Events 7, 9 and 10 show an EW trending P axis and suggest the existence of a zone of underthrusting under the northeastern coast of Hispaniola. A possible explanation is to interpret them as the westernmost witnesses of the subduction of an oceanic slab under Puerto Rico.

Southern Hispaniola

Events 18, 19, 20, 21, and 23, which are shallow, are located along southern Hispaniola and give transpressive focal mechanisms with a subhorizontal P axis trending approximately N-S.

Event 23 can be correlated to the active E-W trending strike-slip fault system of the southern peninsula of Haiti and the Enriquillo Trough. This fault system is composed of subvertical left-lateral strike-slip faults striking E-W and NW-SE, along which transpressive structures have locally been evidenced. On the basis of these observed structures, we infer the NW-SE trending nodal plane to be the fault plane.

Located south of the eastern Dominican Republic, events 18, 19, 20, and 21 correspond to the active compressive area of the Muertos accretionary prism. The compressive focal mechanisms are in accordance with the observed deformation. However, they reveal that a strike-slip component is associated with the reverse motion of the active faults under the Muertos accretionary prism.

Events 11-17 and 22 belong to the deep cluster described above and are located in the eastern part of Hispaniola. The
rather great magnitude (5.5 to 5.9) of these events allowed the computation of seven focal mechanisms, the majority of which are well constrained. All events, except the one published by Molnar and Sykes [1969, event 15], display compressive focal mechanisms. The two mechanisms we computed (events 11 and 12) are very close to the solutions published for the others events. For all those mechanisms, the P axis is subhorizontal and trends between N350 and N10.

DISCUSSION

Shallow Seismicity and Kinematics of the Caribbean Plate

As shown on Figure 5, focal solutions along the studied segment of the plate boundary display a very close general pattern for both shallow and deep events. Except events 7, 9, 10, and 15, all the focal mechanisms are transpressive. Plotted on a map, the P axes display the same homogeneity: most of them are distributed around a main direction striking N20° - 30° (Figure 5). All along the studied segment, the P axes are subperpendicular to the general direction of the left-lateral strike-slip fault system, except for three events (7, 9, and 10) among the 15 shallow earthquakes.

These results, when combined with structural and kinematics data, lead to the following comments.

Strain. Geological and geophysical studies allow us to image major active compressive deformation features trending subparallel to the strike-slip plate boundary (Santiago Deformed Belt [Calais et al., 1989]; Cordillera Septentrional of Dominican Republic [De Zeeuw and Mann, 1991; Calais and Mercier de Lépinay, 1989a]; Eastern Jamaica [Mann et al., 1984]). Structural analysis clearly demonstrates that these structures can be explained by a compressive tectonic regime.

Stress. Focal mechanisms of shallow earthquakes (Figure 6) and microtectonic studies [Calais, 1990] display an almost N-S trending principal compressive stress (sigma 1), subperpendicular to the trend of the strike-slip plate boundary itself.

Kinematics. The present-day east-west oceanic opening of the Cayman Trough imposes a strike-slip motion of 2 cm/yr along the northern Caribbean plate boundary. Otherwise, the last computations of the Caribbean plate motion versus North America [Calais, 1990] show that one rotation pole can account for all the observed structures along the plate boundary. This means that the strike-slip motion along the plate boundary is of much greater magnitude than intraplate deformation and microplate displacements as suggested by Heubeck and Mann [1991] and Scanlon et al. [1989]. We therefore think that the major displacement along the northern Caribbean border is actually strike slip. In this case, the high obliquity between the maximal principal stress azimuth and the relative motion direction must be explained: strain, stress, and kinematics have to work simultaneously.

By comparison with the San Andreas fault system, a transcurrent plate boundary displaying the same kind of stress pattern [Zoback et al., 1987], the observed stress and strain distribution along the northern Caribbean plate boundary may hardly be explained either in the hypothesis of a pure strike-slip motion of the Caribbean plate versus North America nor in the hypothesis of a pure north-south convergence. As demonstrated by Zoback et al. [1987] in the case of San Andreas, we think that this strain and stress distribution is the result of strike-slip motion combined with a minor convergence component. This convergence could result from the slow N-S relative motion of the North and South American plates relative to each other [Ladd, 1976; Pindell et al., 1988; Ross and Scotese, 1988; Calais et al., 1989b] or from microplate displacements within the Caribbean plate itself [Scanlon et al., 1989; Heubeck and Mann, 1991].

Deep Seismicity and the Transition From Frontal Subduction to Transcurrent Faulting

Along the southern Cuban margin, the northern Caribbean plate boundary is recognized as a main strike-slip feature, the Oriente fault. Through the Windward Passage this fault enters the Tortue Channel, follows the northern Haitian coast and continues eastward on land, into the Cibao valley in northern Dominican Republic [Calais and Mercier de Lépinay, 1991]. There is thus no continuity between the Oriente fault and the assumed subduction of the Atlantic oceanic lithosphere beneath Hispaniola. Besides, the shallow seismic event distribution is in good correlation with the active transcurrent faults and focal mechanisms are in agreement with the observed tectonic regime along this plate boundary. Thus we conclude that the northern Caribbean plate boundary, from Cuba to eastern Hispaniola at least, is a transcurrent fault system, not a subduction zone. A major problem is therefore to determine how this transcurrent plate boundary is connected to the frontal subduction of the Atlantic oceanic lithosphere under the Lesser Antilles.

A possible answer to this question can be given by the interpretation of the isolated deep seismic cluster of eastern Hispaniola. We already have pointed out the singularity of this geographically isolated seismic cluster where hypocenters can reach depths of 200 km. An explanation could be the hypothetical subduction of the Venezuelan basin lithosphere under Hispaniola and Puerto Rico, usually invoked to explain

Fig. 6. Azimuth and dip of the principal components of stress tensor deduced from shallow earthquake focal mechanisms.
the setting of the Muertos accretionary prism [Ladd and Watkins, 1979; Ladd et al., 1981; Biju-Duval et al., 1982]. Indeed, the presence of the Beata ridge (Figure 1) on the subducting plate could be responsible for an important deep seismic activity under eastern Hispaniola. However,

1. The deep earthquakes of eastern Hispaniola are not located in the direct prolongation of the Beata ridge, which trends approximately N35°E.

2. Consequently to an oblique collision, the Beata ridge outcrops on land, in southern Hispaniola [Mercier de Lépinay et al., 1988]. As it does not extend north of the Enriquillo trough, it seems difficult to imagine its existence further north, deep down, below the zone of deep seismicity.

3. The EÉ' and II' profiles do not show any Benioff plane associated with this assumed subduction of the Venezuelan basin oceanic lithosphere under Hispaniola. Therefore a mechanism of true subduction cannot be invoked here. Besides, the focal mechanisms, almost all displaying P axes trending about N-S, disagree with the mechanism of "pseudosubduction induced by the E-W shortening of the pericaribbean continental frame" [Stéphan et al., 1985, p. 47]. However, one cannot ignore the possibility that the collision of the Beata ridge might have an indirect influence on the seismicity in the east of Hispaniola by putting under compression the northern Caribbean border.

We therefore come back to the idea of Sykes et al. [1982] which seems to be the only possible explanation of this localized cluster of deep earthquakes: namely, the existence of a lithospheric slab under the northeastern corner of the Caribbean plate, inherited from the frontal subduction of the Atlantic oceanic lithosphere under the Lesser Antilles. The absence of volcanism in Puerto Rico and Hispaniola related to this subducted slab (in spite of a depth compatible with this phenomenon) can be explained by the fact that it has already been dehydrated owing to participation in the magmatism of the northern Lesser Antilles. In any case, the seismological data show that this slab does not exist west of 70°30'W, which is the western limit of the cluster of deep earthquakes of eastern Hispaniola.

We thus interpret the shallow seismicity of northeastern Hispaniola as the result of strike-slip motion along the northern boundary of the Caribbean plate (from Cuba to Hispaniola at least) and the deep seismicity of eastern Hispaniola as the westernmost evidence of a subducted lithospheric slab inherited from the Lesser Antilles frontal subduction. We propose that this lithospheric slab under eastern Hispaniola has been disconnected from the Atlantic oceanic lithosphere by transient faulting along the plate boundary, as exposed on Figure 7. This hypothesis accounts for the gap of seismicity observed between the deep earthquakes cluster of the Mona Canyon and eastern Hispaniola and the shallow earthquakes located further north. The presence of this deep seismic cluster could be the result of the breaking off of the slab. It is to be noted that the transition from strike slip to subduction occurs around the eastern end of the Bahama Bank, which probably controls the location of this transition.

CONCLUSION

Correlations between offshore and onland structural observations and seismological data lead us to outline the deep geometry of the northeastern Caribbean plate boundary and to determine the tectonic and kinematic regime along it. They lead us to the following conclusions:

1. The plotting of shallow events epicenters on a structural map of the northeastern Caribbean domain (Figure 3a) displays a very close correlation between seismic activity and tectonic features. The seismicity in the northeastern Caribbean is concentrated along an east-west trending lineament.

Fig. 7. Three-dimensional interpretation of the transition from frontal subduction to transcurrent faulting along the northern Caribbean (CAR) plate boundary.
corresponding to the trace of the major strike-slip fault system (Oriente fault, Tortue channel, Cordillera Septentrional of Dominican Republic, Puerto Rico trench inner wall). Moreover, the most intense seismicity is located around restraining bends of the major strike-slip fault system such as southern Cuba and northern Hispaniola. In southern Cuba, the northward deepening of earthquakes zone corresponds to a zone of south verging thrusts mapped on the seafloor. In northern Hispaniola, focal mechanisms, displaying P axes oblique to the east-west trending fault system, are in good agreement with microtectonic studies.

2. The stress and strain distribution along the northern Caribbean plate boundary deduced from focal mechanisms and microtectonic analysis cannot be explained by a pure strike-slip motion: a small N-S convergence component is associated with the major eastward strike-slip motion of the Caribbean plate relative to North America. This slight convergence component is in accordance with recent kinematics calculations [Calais, 1990].

3. Earthquakes distribution and focal mechanisms suggest the existence of a lithospheric slab imbricated from the frontal subduction under the Lesser Antilles. In our model, this slab dips down under Puerto Rico and eastern Hispaniola and is disconnected from the Atlantic oceanic lithosphere by a seaward faulting along the northern Caribbean plate boundary; the strike-slip motion thus "kills" the subduction.

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