

## **PALEOTSUNAMI EVIDENCES FROM BOULDER DEPOSITS ON ARUBA, CURAÇAO AND BONAIRE**

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### **Abstract**

The paleotsunami debris deposits of Aruba, Curaçao and Bonaire are investigated with regard to their geomorphologic characteristics, spatial distribution and their depositional history during the Younger Holocene. Differences between three distinctive formations – ridges, ramparts and boulder assemblages are highlighted and related to their origin within the coastal environment. Relative and absolute age determinations proved evidence for the occurrence of three paleotsunami events at 400-500 BP, 1500 BP and 3500 BP. The tsunamis approached the islands from a northeasterly direction leaving the most impressive geomorphic traces on Bonaire and due to shadowing effects reduced sedimentary effects on Curaçao and Aruba.

## Introduction

Since the first recorded tsunami occurred off the coast of Syria in 2000 B.C. far more than 2000 tsunamis have been reported and over 6500 runup locations are documented in the most comprehensive database of worldwide tsunamis maintained by the National Geophysical Data Center of the United States (NGDC, 2001). Nevertheless, the current state-of-the-art knowledge concerning the sedimentary and geomorphic imprints of tsunamis along the coastlines of the world is strikingly poor. Worldwide only about 60 academic papers related to tsunami sedimentation exist - most of them focus on fine sediments - and among them only very few discuss geomorphologic or geologic consequences of tsunami events. In addition, most studies investigate local tsunami evidences and systematic documentation of tsunami depositional traces on regional scales are rare. In contrast, Aruba, Curaçao and Bonaire, located north of the Venezuelan coast in the Caribbean Sea, exhibit several attributes that have permitted a detailed regional characterization of the morphology of tsunami deposits (Fig. 1). Their study allow conclusions of paleotsunami occurrence for the Southern Caribbean over a geographical distance of more than 200 km. Hitherto, tsunami impacts were unknown for the ABC-islands and the debris formations have been exclusively attributed to hurricane-generated waves (DE BUISONJÉ, 1974).

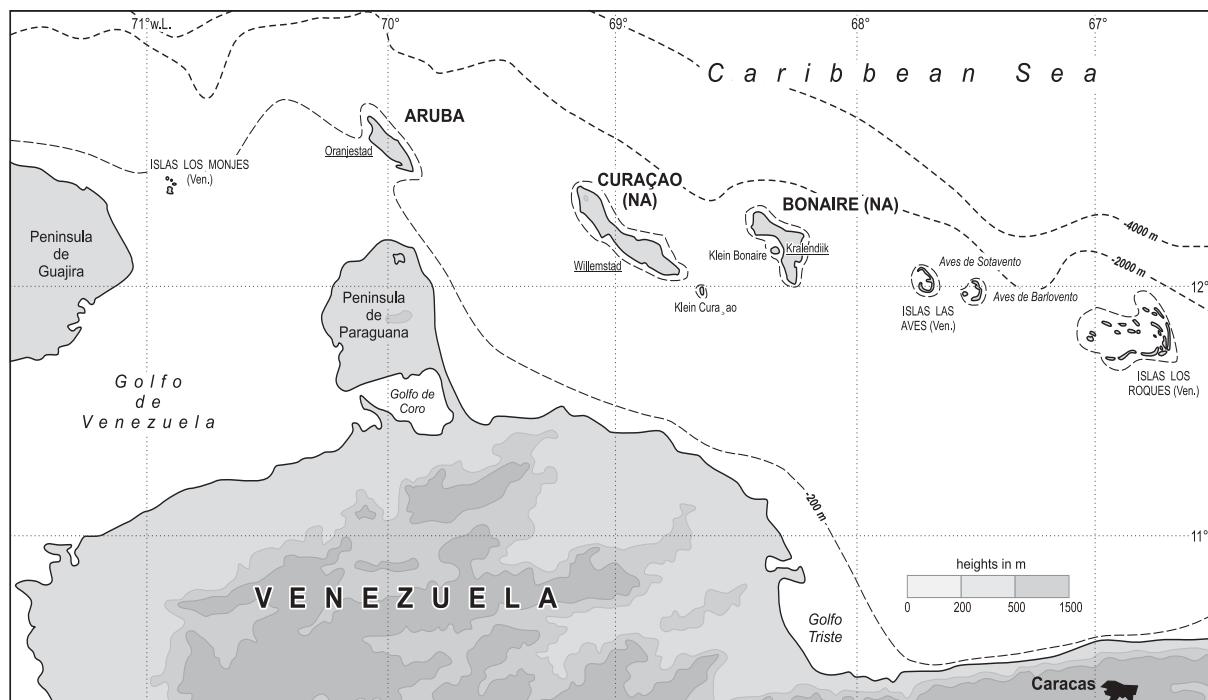


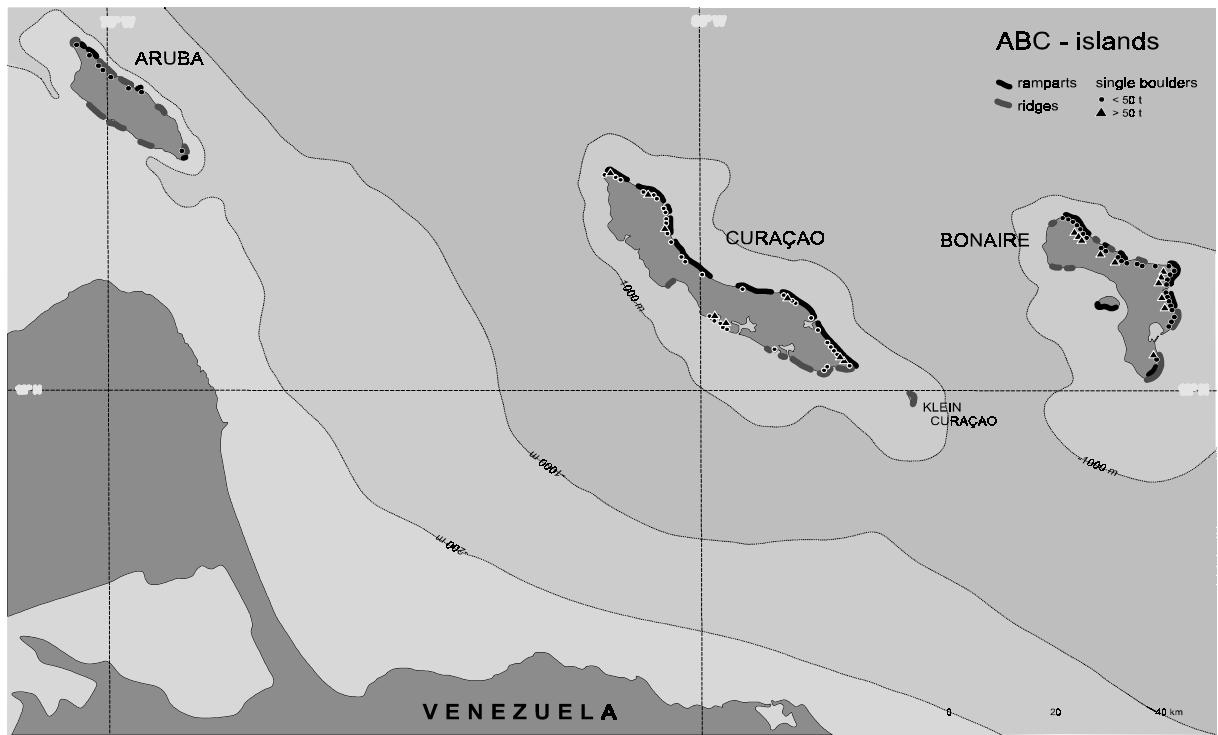
Fig 1 The islands of Aruba, Curaçao and Bonaire in the Southern Caribbean.

## **Methods**

We choose an inductive approach to differentiate between the main debris types and document their spatial distribution with a dense field survey and the aid of aerial pictures and GIS on maps. In order to exclude tropical cyclones as a depositional force the critical wave heights necessary to overturn boulders according to the hydrodynamic formulas adapted from NOTT (1997) were calculated. A number of stratigraphic, morphologic and historical data allowed us to determine the relative age of the deposits, for absolute age determinations over 40 samples were dated with appliance of the radiocarbon method. To determine the source area of the debris within the coastal environment we analyzed with a statistical approach the shape and the material of the fragments in leeward and windward debris deposits on Curaçao and Bonaire.

## **Discussion and Results**

Some physio-geographical factors favor the study of paleotsunami relicts on the ABC-islands: During the Quaternary, the islands have undergone a relatively slow vertical uplift and no neotectonic dislocations in the interpretation of the deposits have to be considered. The wide occurrence of carbonate rocks is responsible for a variety of specific geomorphologic features like notches, benches or algae rims, which can be used for relative and absolute dating. Due to their geographical position at the southern fringe of the hurricane belt, major tropical storms or hurricanes only occasionally touch the islands. This results in an excellent preservation of coastal deposits. The limited hurricane impact causes an increased stability of biogenous fine structures of the coastal area with respect to conclusions concerning the relative age of the forms and the intensity of the forming processes. The accumulations exhibit three main geomorphologic distinct types of paleotsunami debris formations, which have been distinguished as boulder assemblages, rampart formations and ridge formations (Fig. 2). Predominantly, the debris deposits have been accumulated on the northeastern sides of the islands, reaching from sealevel to a height of + 12 asl and extending up to 400 m inland. On a regional scale, the extent and amount of tsunami debris weakens from east to west with the highest energy impact on Bonaire in the east and a considerable lower impact on Aruba, the most westerly island.



*Fig. 2* Overview of impressive paleotsunami imprints on the ABC-islands.

Each formation exhibits a distinct morphology and geographic distribution related to a certain coastal configuration. Boulder assemblages contain blocks of  $> 100 \text{ m}^3$  in volume and with a weight of up to 281 tons (Fig. 3). They occur on all islands with the most impressive evidences on Bonaire and Curaçao, but in general, they are coinciding remarkably often with coastal sections, where the cliff front is nearly perpendicular and the supratidal zone is rather narrow.



*Fig. 3* An impressive boulder field south of Spelonk Lighthouse, Bonaire, situated in rather dense vegetation more than 150 m apart from the shoreline.



*Fig. 4* Rampart formation at Dos Boka, windward coast of Curaçao, located at + 6 m asl and about 40 m distant from the cliff front.

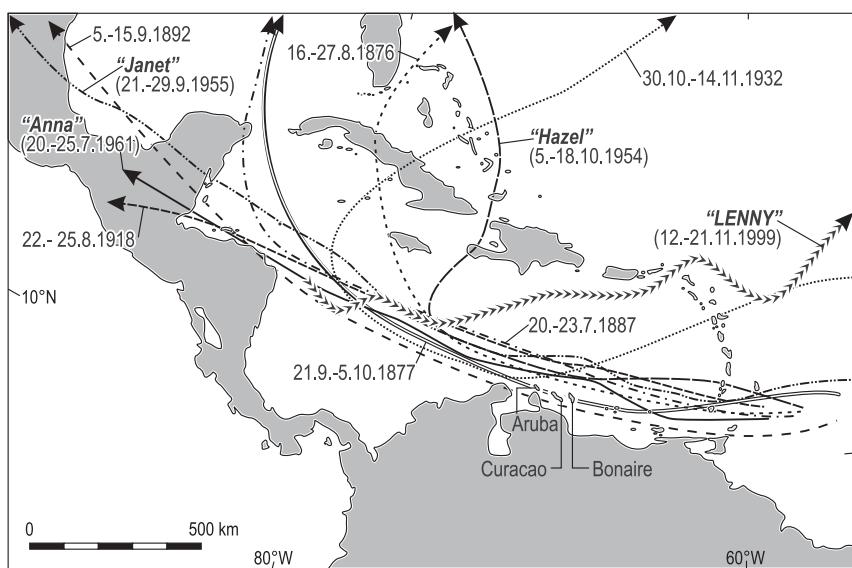
If the coastal physiography leads to the development of a rather broad supratidal with a more convex cliff profile, the amount of debris increases significant as more material from the rugged rock pool zone can be derived by the tsunami. That coastal environment favors the development of rampart formations (Fig. 4). They occur likewise on all islands with the most developed ones in northeastern Curaçao and along the east-exposed coastal stretch on Bonaire. The ramparts are located with their seaward margin in distance of at least 40 – 50 m from the active shoreline, in cases up to 100 m, at elevations usually ranging from + 6.0 to + 10.0 m asl, and they are becoming more scattered and thin out with increased inland extent. They consist of small to medium sized fragments and show a thickness of some decimeters up to one meter with a planar gently land inwards sloping profile. Unfortunately, most of the rampart formations are massively disturbed or even completely removed due to intensive mining exploitations in the past.

The ridge deposits often follow subsequently to the coastline and surf zone and consist of mostly well-rounded platy and rod-shaped coral fragments with some rare limestone boulders present (Fig. 5). Imbrication is a common feature. Predominantly, the rounded material is derived from coral debris out of the subtidal environment. These ridges occur along the southern, southeastern and western leeward coastlines, where they may extend over several hundred meters with width from 10 – 50 m and relative heights from 1 - 3 m.



Fig. 5 Subrecent debris ridge at Willemstoren, leeward coast of Bonaire.

In general, relating a geological deposit to a paleotsunami is in most cases a delicate exercise. One key problem concerns the differentiation between a storm-induced or tsunami-induced sedimentary record. For the ABC-islands, both - field observations and relative/absolute age dating - indicate clearly that a storm or hurricane-induced deposition can be definitely excluded and therefore the debris formations can be unambiguously related to tsunami events as the following arguments will highlight. During the time period 1605 – 2000 in total 14 hurricanes and 19 tropical storms, with maximum wind velocities between 100 – 120 mph (= 180 – 210 km/h) near the center, passed the islands within the 100 nm zone (Fig. 6).



*Fig. 6* Only few hurricanes passed within 100 nm from Curaçao, Bonaire and Aruba over the time period from 1605 to 1998 (Source: Meteorological Service of the Netherlands Antilles and Aruba, 1998).

The most significant event in the past was Hurricane *Lenny* in November 1999, an extremely rare hurricane with wind speeds > 160 km/h, formed south of Jamaica and moved eastward toward the Lesser Antilles. This direction of travel for a sustained period, is the first reported in the entire 113 year hurricane record (GUINEY, 2000). As a result of the rather unusual track, the islands of Aruba, Bonaire and Curaçao all experienced heavy surf conditions along their southwestern coastlines as *Lenny* passed 250 – 500 km north of the islands. The waves varied along the coasts, but were reported to be mostly in the range of 3 - 6 m. It can be clearly observed that the magnitude of the paleotsunami events exceeded the impact of hurricane *Lenny* significantly on all three islands. The storm-induced *Lenny* deposits are limited in spatial extent to the southwestern facing shorelines and their grain size distribution ranges only from centimeters to some decimeters, in no case larger

boulders has been transported onshore (Fig. 7 and 8). Smaller fragments of *Acropora cervicornis* are the most common components in the accumulated ridges and spits.



Fig. 7 Debris ridge (nearly 1 m high) consisting chiefly of rods of *Acropora cervicornis* branches with tongues of shingle. Pink Beach, leeward coast, Bonaire.

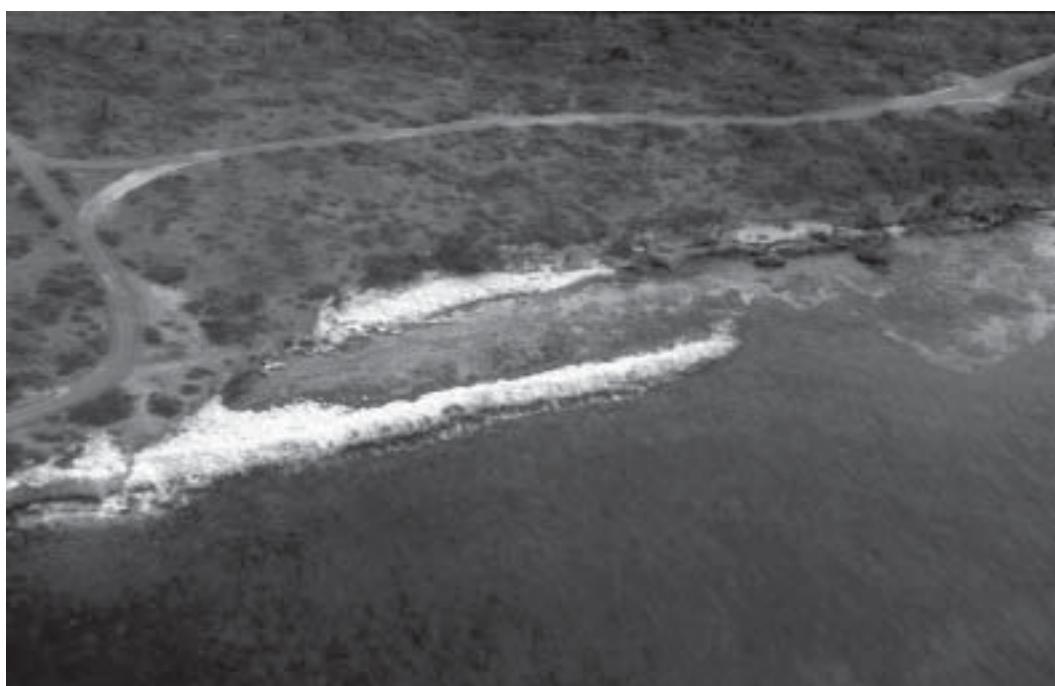


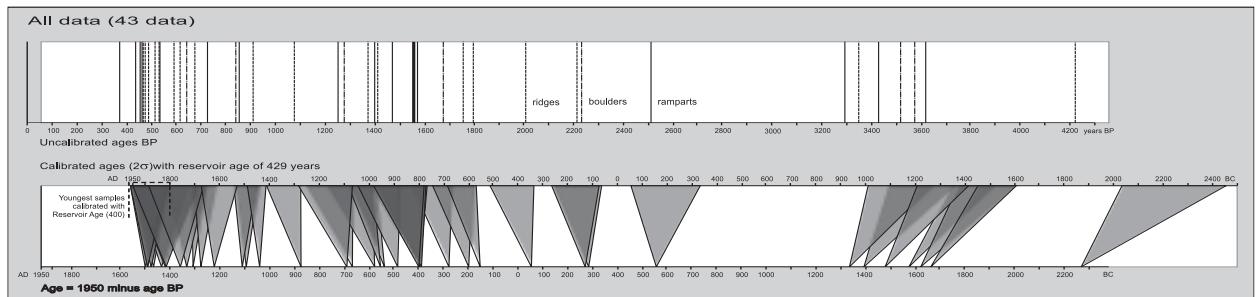
Fig. 8 Aerial view of the recently formed coral rubble spit by hurricane Lenny.

In addition, the application of hydrodynamic calculations verifies this suggestion. The results demonstrate that the possibility remains that extremely large hurricane waves may have the capability to overturn boulders of an insignificant quantity, but considering their present position in cases up to 12 asl, it seems to be unlikely that such waves will deposit them into their present position. From the measured 76 distinctive boulders on Curaçao (weight >1t) - except very few - all require storm wave heights, which never have been observed at any coastline of the world (up to 125 m!). For the 42 measured boulders on Bonaire none could be moved by storm surf regarding the required waves height of 14-89 m. Even on Aruba, where the boulders usually are much smaller, waves of 13 - 56 m would be needed. In contrast, the wave height calculated for tsunamis are well in the range of observed events.

Geomorphologic relationships between the debris formations and coastal features, e.g. rockpools and bench development, illustrate that at least a time period of some hundred years since the youngest tsunami event must have expired. Especially a closer look at the rockpool zone characterized by sharp, irregular limestone peaks with depressions of up to 60 – 80 cm depth and located between the debris deposits and the coastline confirms that suggestion. This rough sculptured zone reaches often up to 30 m inland and is strikingly completely free of sediments, although the rockpool depression would represent an excellent sediment trap for coarse material. In general, dating of coarse sediments is a difficult task since no stratigraphical sequence can be interpreted and no analysis methods of sedimentology can be applied in coarse sediments. Nevertheless, relative age indications allow a good estimation of the time range for the minimum and maximum age of the deposits. One important relative dating possibility of a tsunami impact is related to the preservation of bioerosive and bioconstructive coastal features (KELLETAT & SCHELLMANN, 2001 a, b). Estimations of the time period needed for the forming processes (bioerosion: ~1-2 mm/y; bioconstruction: ~2-5 mm/y) can limit the time range for the event relatively accurate. Transferred to the ABC-islands, it can be stated, that no signs of fresh outbreaks of limestone material either in the cliff front, the bench or the supratidal zone were found, so that the origin of boulders could be unambiguously identified. Subsequent bioerosive processes made the breakouts unrecognizable, indicating a minimum dislocation and depositional age of at least some hundred years. Limited bench development along coastal stretches with major tsunami impact point to several centuries without further impacts of tsunamis, again suggesting an age of some hundred to thousand years. Overall we can limit the maximum age range to the Younger Holocene as evident in particular by chemical and biological weathering processes and the spatial relation of the debris formations to the recent sealevel highstand, which reached the present level between 5000 and 6000 BP in this part of the

Caribbean, since when it remains very stable (RULL, 2000). Beside geomorphic imprints of tsunami occurrence the historical record has to be considered. On the ABC-islands no written or oral sources describing a tsunami impact exist, pinpointing also to a time span of minimum 350 – 400 years without the occurrence of any severe tsunami event, presumably since the Dutch occupation in 1634 AD or even the occupation by the Spaniards in 1527 AD.

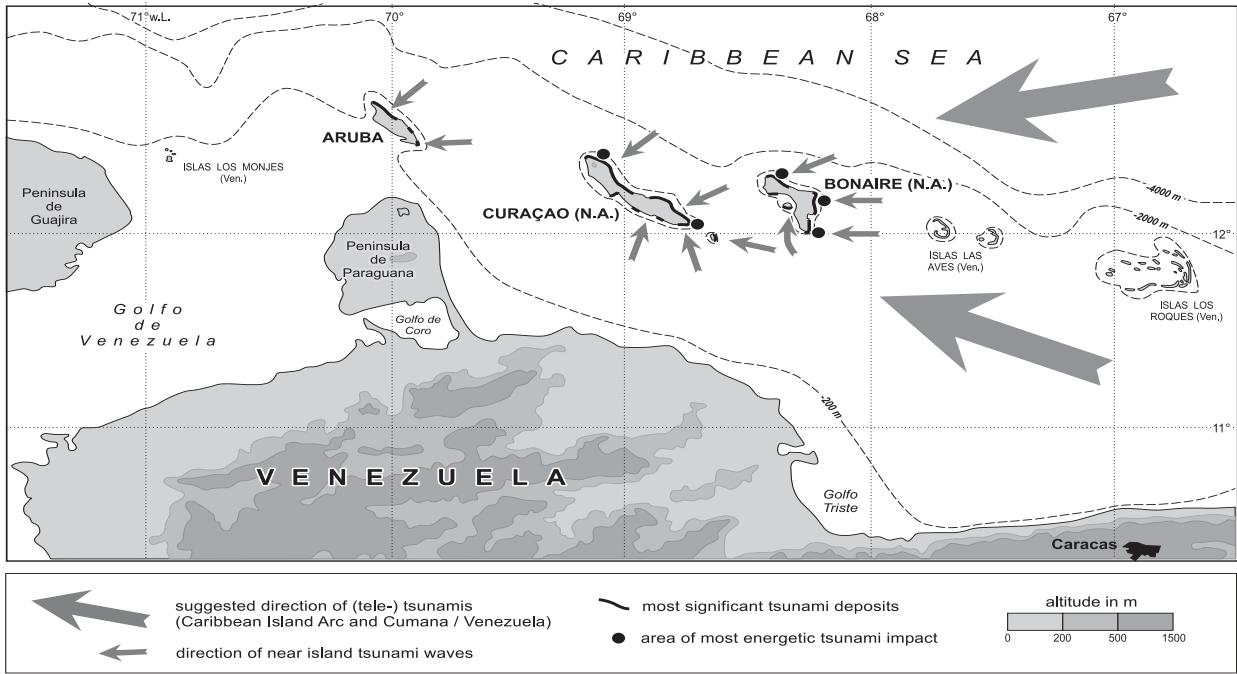
However, the resolution of relative age dating is insufficient to establish a more detailed chronology of the tsunami impacts, so that radiocarbon age determinations from 43 samples were performed from different geomorphologic units (boulders, ramparts, ridges) and on different material (vermetids, corals, gastropods). These conventional radiocarbon datings supplied a non-calibrated age range from  $370 \pm 32$  to  $4222 \pm 49$  years BP. The uncalibrated age data show a clustering in three main time units around 500 BP, 1500 BP and 3500 BP with intermediate periods of only infrequent or no age values (Fig. 9).



*Fig. 9* Age distribution of all 43 dated samples. The conventional radiocarbon ages are visualized as single line, the calibrated ( $2\sigma$ ) ages are presented in form of triangles. Reservoir age = 429 years.

The distribution of the age values supports the interpretation of the coarse debris deposits as tsunamigen, and is inconsistent with a hypothesis of a storm-induced origin. If storm events would have contributed at least partly to the depositions, we could expect an even distribution of the data samples over the time period, when the Holocene sealevel reached more or less the present height around 5000 BP (RULL, 2000).

The generating mechanisms of paleotsunamis of the described magnitude is unknown, but most likely they are related to seismic activity in the northeastern part (0 - 90° sector) of the Caribbean along the faults of the Caribbean Plate boundaries (Fig. 10). Another potential source region is the Southern Caribbean Plate Boundary Zone along the northern Venezuelan continental margin with clear evidence of neotectonic right-lateral strike-slip deformation including uplift and subsidence of large fault blocks along the fault zones.



*Fig. 10* Suggested direction of paleotsunamis impacting the ABC-islands.

## Conclusions

From this new, but still limited knowledge of the occurrence of paleotsunamis with severe magnitudes in the Southern Caribbean, we can derive that potentially catastrophic tsunamis may represent a much higher risk than at present recognized by the governmental organizations and the inhabitants of the Caribbean islands. The risk of severe tsunamis anywhere around the Caribbean is still largely unknown as geomorphologic observations of tsunami evidences are yet very rare and many presumed imprints of tsunamis have not yet been found, studied and mapped in appropriate detail. In the near future further efforts should concentrate on geomorphologic field studies on a Caribbean-wide scale to understand the nature of tsunami deposits and to precise and extend the existing Caribbean Tsunami catalogue comprehended so far by LANDER & WHITESIDE (1997). With regard to the results of this study it must be stressed with great emphasis that the establishment of a feasible and effective Intra-Americas Sea Tsunami Warning System as it is visualized by the Intergovernmental Oceanographic Commission of the UNESCO is an important step to mitigate future disasters. We hope to encourage with this study the governmental institutions on a local and a Caribbean-wide scale to intensify activities in tsunami related education, warning, management as well as research.

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