Relative Sea Level and Abrupt Mass Unloading in Barbados during the Holocene

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Abrupt Mass Unloading and Relative Sea Level in Barbados during the Holocene

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Highlight

- An abrupt mass unloading of 30 ± 10 km^3 occurred in Barbados and caused isostatic adjustment of 0.45 ± 0.15 mm/yr.
- An uplift increases from 0.34 to 0.8 mm/yr at 11.2 ± 0.1 kyr BP in less than 0.2 kyr explain coral reef elevation in Barbados.
- 150 yr after the termination of Younger Drias and 300 yr before the abrupt mass unloading, a sea-level drop of 4.8 m occurred, corresponding to meltwater pulse MWP-1B.

Abstract

Coral reef records sea-level as well as vertical movement. In Barbados, uplift variation is necessary to interpret one of the most complete coral reef record. Here we show that an abrupt mass unloading of 30 ± 10 km^3 caused an uplift variation of ~0.45 ± 0.15 mm/yr using a modelling approach. Simulations have been conducted for different volumes and elastic thicknesses. Isostatic adjustment in relation with an abrupt mass unloading explain the observed uplift rate increase from 0.34 mm/yr to 0.8 mm/yr that occurred 11.2 kyr ago. The reconstructed sea-level curve highlight a sea-level drop of 4.8 m drop, with a delay of 150 yr from the termination of Younger Dryas cold event and 300 yr before the abrupt mass unloading. This sea-level drop corresponds to meltwater pulse MWP-1B and is not an artefact. A stagnation of 500 yr occurred from 12 to 11.5 kyr BP. Relative sea level records are useful to detect past landslides and erosion. Accurate analysis and reconstruction of sea-level permit to determine sea-level drop caused by warming during the last thousand years.

Keywords : uplift; sea level; coral reef; isostasy; meltwater pulse; landslide

1 Introduction

Rapid sea-level rise could be better understood studying ongoing changes in the climate system (Edwards et al., 2021; Hoojer and Vernimmen, 2021) and by studying the abrupt sea-level changes that occurred in the past (Gargani and Rigollet, 2007; Bard et al., 2010). Reconstruction of sea level could be based on well log and stratigraphic analysis (Haq and Schutter, 2008), seismic and geomorphological observations (Bache et al., 2015) or coral reef studies (Mesolella, 1967; Fairbank, 1989).

Reconstruction of sea level from coral reef must take into account tectonic movement (Radtke and Schellmann, 2006; Peltier and Fairbank, 2006), glacio-hydro isostasy (Austermann et al., 2013) and uncertainty associated with coral reefs species (Bard et al., 2016). Isostatic adjustment could be also caused by erosion (Gargani, 2004) and landslide (Smith and Wessel, 2000). Coastal erosion is underestimated (Regard et al., 2022) and coastal as well as marine landslides are numerous (Urgeles and Camerlinghi, 2013). Consequently, unloading processes on coastal vertical movement must be evaluate for accurate reconstruction of relative sea level curves.

Accurate reconstruction of relative sea level curves is of fundamental importance due to the numerous applications of these data. Relative sea level reconstruction could be used to determine local paleogeography (Zinke et al., 2003), to estimate regional vertical movements by comparing with a reference's sea level curve (Camoin et al., 2004; Pedoja et al., 2014) and to discuss paleoclimate variation (Fairbank, 1989; Blanchon and Shaw, 1995).

The most complete record of sea-level is based on coral reef drilled at Barbados. Coral reef record in Barbados is studied since several decades (Mesolella et al., 1969; Bender et al., 1979). This record was used to calibrate relative sea level during the last 500 kyr (Bard et al., 1990, Bard et al., 1990b; Gallup et al., 1994; Peltier and Fairbank, 2006; Abdul et al., 2016) as well as to determine local uplift (Radtke and Schellmann, 2006).

In this study, the role of an abrupt mass unloading in the Tertiary terrain of the Scotland District in the northeast of Barbados is investigated to estimates the potential uplift change of coral reef located in the southwest of the island, near Bridgetown (Figure 1), from 14 to 9 kyr Before Present (BP). More fundamentally, the new sea level reconstruction proposed in this study will be used to quantify the meltwater pulse MWP-1B (age, duration, amplitude).

2 Geological context

Barbados Island (430 km^2) lies on an accretionary prism above the subducting Atlantic lithosphere that passes beneath the crust of the Caribbean plate (Westbrook et al., 1988)(Figure 1). Deformed Tertiary sedimentary rocks are located below an uplifted Quaternary reef-related cover (Speed, 1981) with a maximum age of 500-600 kyrs (Radtke and Schellmann, 2006). The cause of passive uplift of sedimentary layers could be due to compressive tectonic at the plate junction, mud diapirism or shale movements in deeps overpressured zones (Deville et al., 2006).

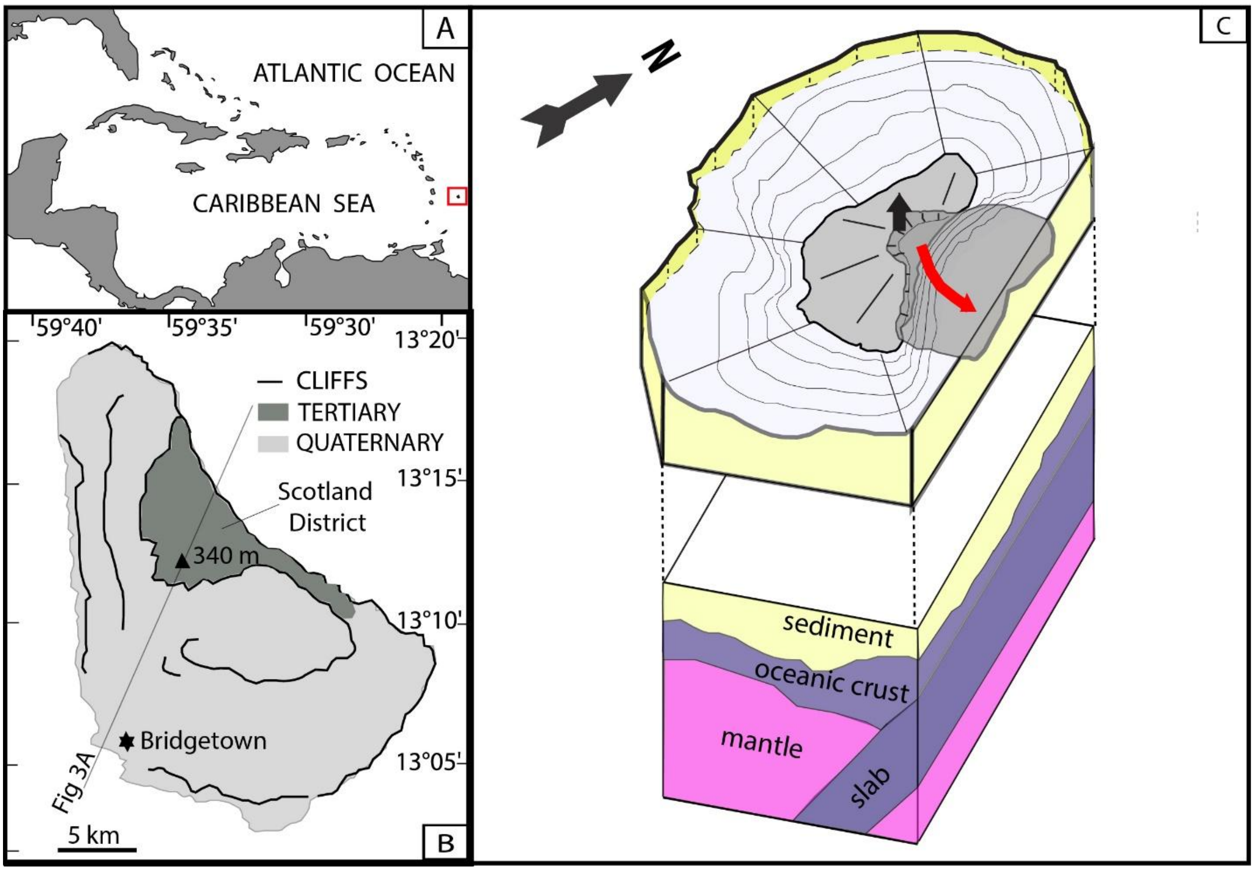


FIGURE 1: Geographic and geological context. (A) Location of Barbados Island in the red square, (B) Geological map of Barbados Island, (C) Schematic representation of mass unloading and lithosphere geometry.

Uplift rate in Barbados was not constant during the last 500 kyr (Radtke and Schellmann, 2006) (Figure 2). From 200 to 500 kyr, uplift rate was around 0.2 mm/yr whereas from 100 to 120 kyr ago, mean uplift rate was estimated to be of 0.47 ± 0.02 mm/yr (Radtke and Schellmann, 2006). From 35 to 11.2 kyr BP, an uplift rate of 0.34 mm/yr is often assumed (Peltier and Fairbank, 2006; Abdul et al., 2016). This uplift rate of 0.34 mm/yr was caused by tectonic compression or diapirism (Speed, 1981; Westbrook et al., 1988; Bard et al., 2016).

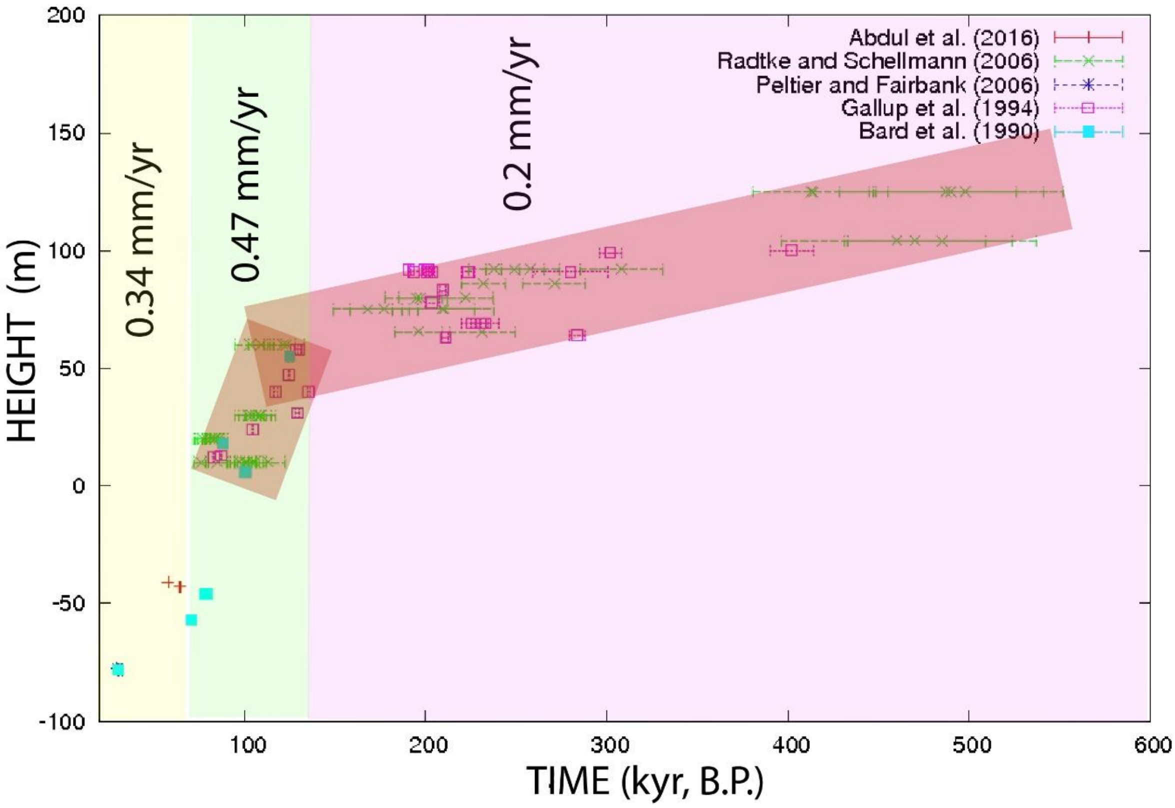


FIGURE 2: Coral reef elevation and uplift. (A) Height of coral reefs in Barbados with ages ranging from 20 to 600 kyrs (Bard *et al.*, 1990b; Gallup *et al.*, 1994; Peltier and Fairbank, 2006; Radtke and Schellmann, 2006; Abdul *et al.*, 2016) and uplift rates.

Without taking into account uplift correction, Barbados coral reefs have a significant offset from sea-level reconstruction suggesting the existence of an uplift (Peltier and Fairbank, 2006; Radtke and Schellmann, 2006; Abdul et al., 2016). The observed vertical shift from sea-level curve range from 10 ± 2 m at 10.5 kyr to 4 ± 1 m at 13 kyr (Figure 3). At 11.2 kyr BP, there is less data during around 200 yr.

Recently, it was highlighted that there were several meters of offset between coral reefs younger that 11.2 kyr and those older than 11.2 kyr (Abdul et al., 2016). This variation of altitude was first attributed to a meltwater pulse record (MWP-1B) (Abdul et al., 2016; Bard et al., 1996), but this offset was discarded by comparing with sea-level curves established in other places (Bard et al., 2016; Lambeck et al., 2014; Carlson and Clark, 2012). This shift was believed to occur 0.4 kyr after the end of Young Dryas (Abdul et al., 2016) that finished 11.610 ± 40 kyr BP (Cheng et al., 2020). Nevertheless, the possibility that an uplift variation with time occurred from 14 to 9 kyr has not been studied in Barbados, in spite of older uplift variations (Radtke and Schellmann, 2006).

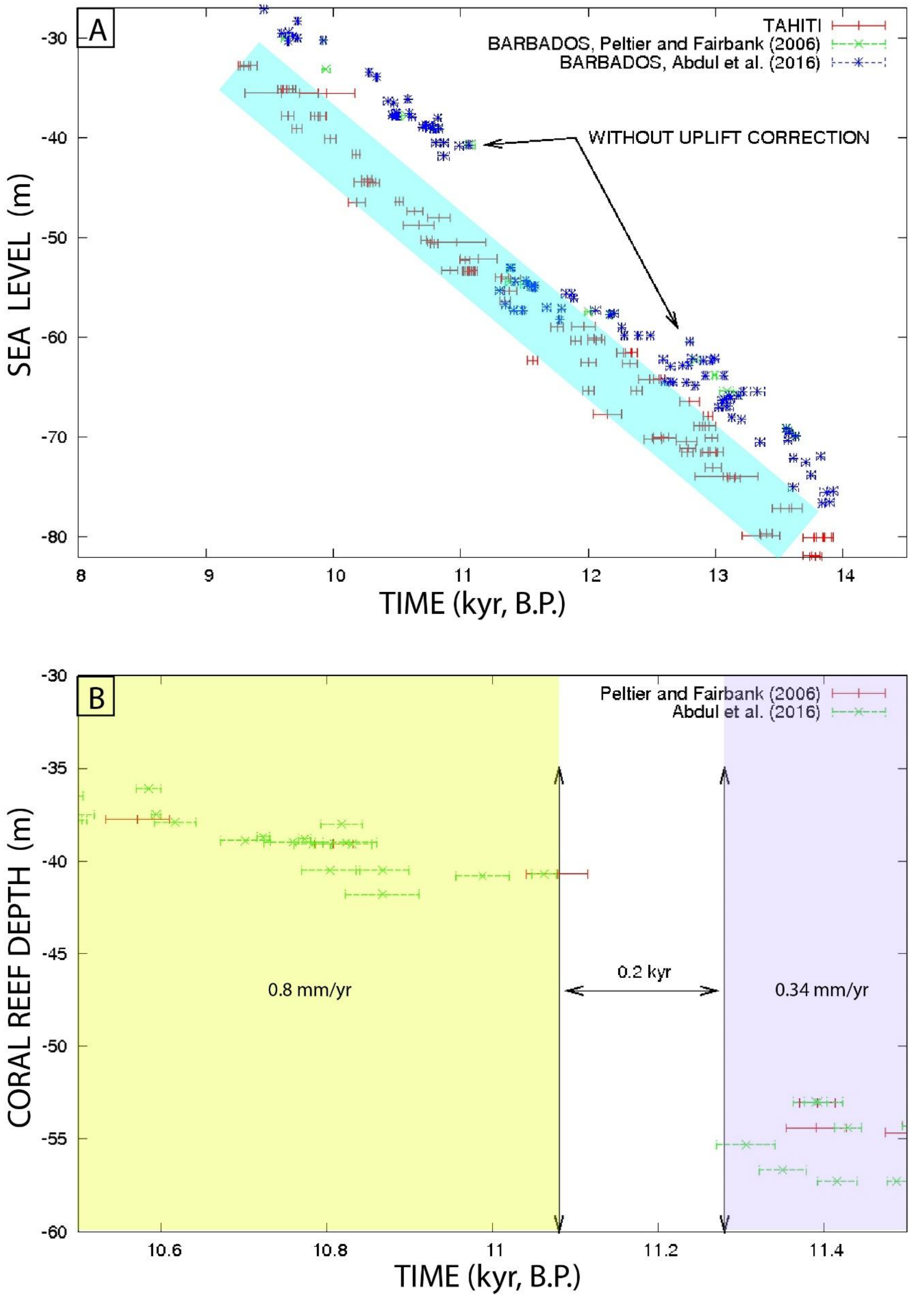


FIGURE 3: Coral reef elevation and uplift. (A) Sea level estimated from Tahiti coral reefs corrected from subsidence (0.25 mm/yr) in red compared with Barbados coral

reefs, without uplift correction, between 9 and 14 kyr B.P. in blue (Abdul et al., 2016) and green (Peltier and Fairbank, 2006). Data for Tahiti (Bard et al., 2010) and for Barbados (Peltier and Fairbank, 2006; Abdul et al., 2016) are only those of Acropora palmata for clarity. (B) Coral reef elevation vs age from 11.5 to 10.5 kyr before present. No uplift correction. The transition duration from the uplift rate of 0.34 mm/yr to 0.8 mm/yr is of 0.2 kyr and occurred from 11.28 to 11.08 kyr BP. Data are from Peltier and Fairbank (2006) and Abdul et al. (2016).

In the Northeast part of the island, the absence of Quaternary rocks on an area of ~60 km^2 suggests significant erosion or/and landsliding during the last 500-600 kyr. The volume of missing material caused by erosion and/or landslides in the Scotland District is significant (~10 km^3). Furthermore, bathymetric data suggests that missing material extend offshore the Scotland District. Landslides and erosion occurred in this area during the last centuries (Prior and Ho, 1972; Cruden et al., 2014), and are documented deep offshore on the accretionary prism (Pichot et al. 2016). Unloading associated with large landslides is able to generate isostatic adjustment (Smith and Wessel, 2000). High amount of erosion also generates isostatic adjustment (Gargani, 2004) which main observed features are uplift and geomorphological transformations of the slope (Gargani et al., 2010).

2 Methods

2.1 Isostatic adjustment modelling

In this study, the role of abrupt mass unloading on uplift rate variation is investigated for the period from 14 kyr to 9 kyr BP by modelling the isostatic adjustment. Isostatic adjustment is considered as an additional cause of uplift and is the only process modelled here. It must be added to the other mechanisms responsible of the preexisting 0.34 mm/yr of uplift rate.

Different unloaded mass were simulated corresponding to various volume displaced. Three different volumes were considered (3 km^3, 10 km^3, 50 km^3). A maximum of 10 km^3 could have been displaced from the Scotland District by erosion or landslides. Offshore, erosional features are observed and suggests supplementary mass unloading. Such volumes have been observed for a large variety of landslides or erosion. The estimation of the uplift depends also from the flexural rigidity.

In the Scotland District, the uplift w(x) can be obtained by solving the equation $\boldsymbol{\nabla}^2(D\cdot\boldsymbol{\nabla}^2 w(x,y))+(\rho_a-\rho_s)g\cdot w(x,y) = \rho_s g[z_{init}(x,y)-z(x,y)]$, where the rigidity is defined by $D = ET_e^3/[12(1-\nu^2)]$, with ρ_a and ρ_s the densities of asthenosphere and sedimentary rock, g the acceleration of gravity, $z_{init}-z$ the missing material thickness, E the Young's modulus, T_e the effective elastic thickness, and ν the Poisson's ratio (Turcotte and Schubert, 2001). ν=0.25, ρ_a =3179 kg/m^3 , ρ_s = 2800 kg/m^3, $E = 10^{10}$ Pa, 40 km < T_e < 60 km.

The elastic thickness in the Barbados area is of 50 ± 10 km (Lambeck et al., 2014; Jimenez-Diaz et al., 2014) corresponding to a flexural rigidity of around 10^{23} N.m^2. Resulting vertical motion rates are calculated considering a constant displacement, during 10 kyr after the abrupt mass displacement, in agreement with the time necessary to relax the viscous properties of the lithosphere of 10 ± 5 kyr after isostatic adjustment (Mitrovica et al., 2000; Van der Wal et al., 2010).

To avoid any overestimation of the uplift, the mass balance has been respected by loading a comparable mass on the model than material has been unloaded. The loading mass is located offshore, 35 km at the northeast of Barbados. In case of erosion and turbidite flow, this could overestimate the loading.

2.2 Comparison between modelled and observed uplift

In the present study, the modelling results concerning the uplift are compared with observed data. In Barbados, coral reefs permit to evaluate relative sea level variation and local vertical movement by comparing with a reference sea level curve. Barbados coral reef's data used in this study were published by Abdul et al. (2016) and Peltier and Fairbank (2006). The sea level curve considered as a reference is based on the data from Bard et al. (1990b, 1996, 2010). Only elevation obtained from Acropora palmata and U-Th are considered. Finally, a new reference sea level curve is built using the reference sea level of Tahiti and the relative sea-level curve of Barbados after correction of the uplift rate. Sea level trend from 14 to 9 kyr BP, based on Barbados and Tahiti coral reef records corrected from uplift is described and implication for meltwater pulse MWP-1B discussed.

3 Results

Abrupt mass unloading, such as large erosion and landslide, causes an uplift through an isostatic adjustment and impacted relative sea level variation. More precisely, the modelled uplift is less than 2 m for an unloading of 8.4 x 10^{12} kg, corresponding to a volume displacement of 3 km^3 of sedimentary rocks (Figure 4). The modelled uplift after an abrupt mass unloading of 10 km^3 is of 3.25 ± 0.75 m, depending on the elastic thickness of the lithosphere (Figure 5). When the mass unloading increases, the resulting uplift also increases. An abrupt mass unloading of 50 km^3 could cause an uplift of 6 ± 1 m (Figure 6A). The more the elastic thickness is, the less is the vertical displacement. The uplift caused by this process ranges from 3 to 6.5 m for a mass displacement of 20-40 km^3.

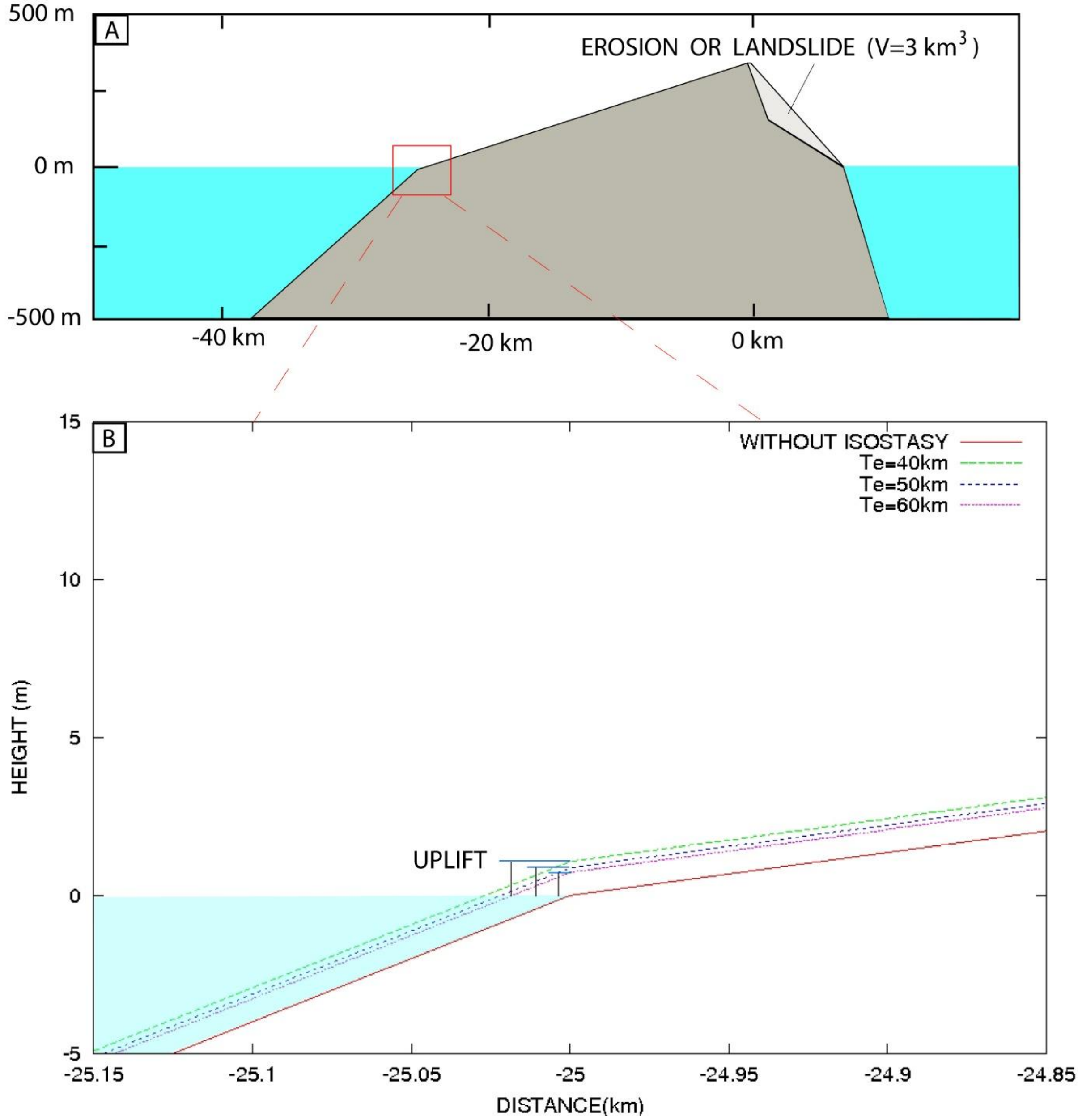


Figure 4: Isostatic adjustment after an abrupt mass unloading of 3 km^3. (A) Unloaded volume geometry, (B) Modelled uplift in the southwest part of the island after an abrupt mass unloading caused by an isostatic adjustment with elastic thicknesses of 40 km, 50 km and 60 km.

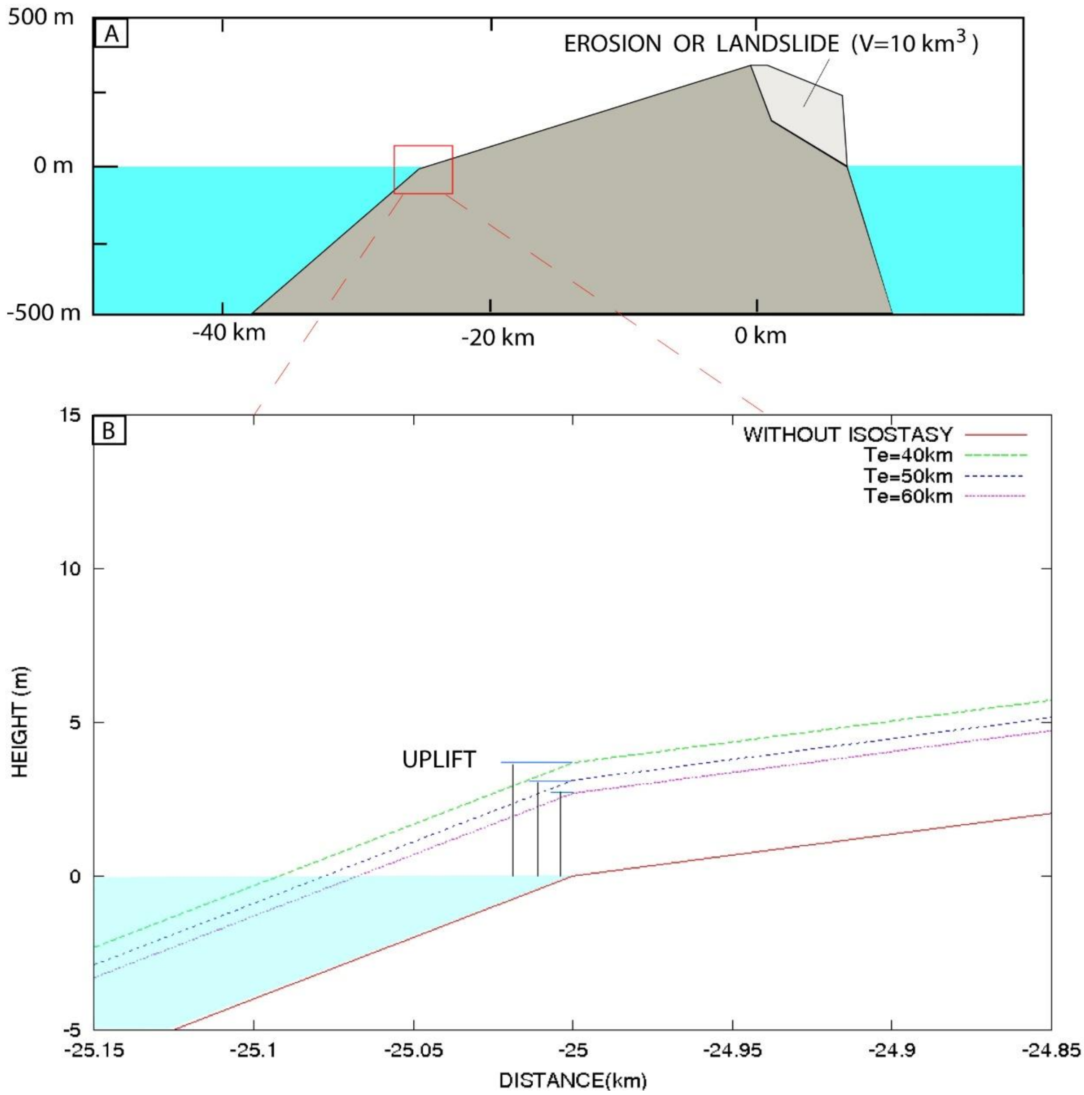
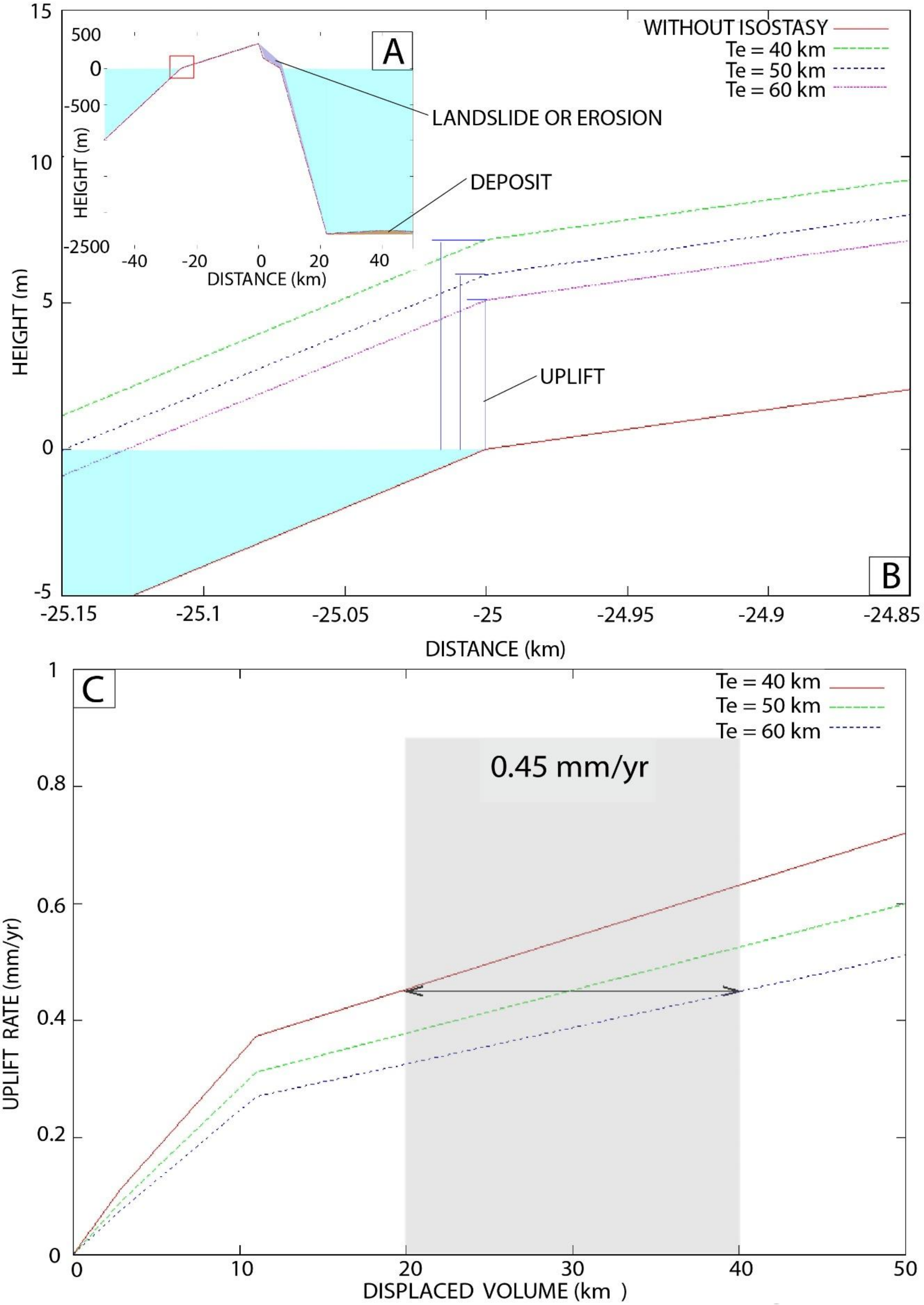


Figure 5: Isostatic adjustment after an abrupt mass unloading of 10 km^3. (A) Unloaded volume geometry, (B) Modelled uplift in the southwest part of the island after an abrupt mass unloading caused by an isostatic adjustment with elastic thicknesses of 40 km, 50 km and 60 km.

An uplift rate of 0.45 mm/yr in the southwest of Barbados, caused by an abrupt mass unloading of 30 ± 10 km^3 in the northeast of Barbados, is estimated by modelling the Barbados lithosphere with an effective elastic thickness of 50 ± 10 km (Fig. 6C). Part of the abrupt mass unloading (20 km^3) occurred offshore. The increases of 0.45 ± 0.15 mm/yr after an abrupt mass unloading of 30 ± 10 km^3 in the Scotland District explain the uplift rate increases observed in the Southwest coast of the Barbados from 0.34 to 0.8 mm/yr that occurred 11.2 kyr ago. The change in the uplift rate occurred in less than 0.2 kyr (Figure 3B). The accommodation of the uplift rate variation take place from 11.08 kyr to 11.28 kyr BP.



A
500
0
-500
-2500
HEIGHT (m)
-40
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DISTANCE (km)
LANDSLIDE OR EROSION
DEPOSIT
WITHOUT ISOSTASY
Te = 40 km
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Te = 60 km
UPLIFT
B
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HEIGHT (m)
-25.15
-25.1
-25.05
-25
-24.95
-24.9
-24.85
DISTANCE (km)
C
Te = 40 km
Te = 50 km
Te = 60 km
0.45 mm/yr
1
0.8
0.6
0.4
0.2
0
UPLIFT RATE (mm/yr)
0
10
20
30
40
50
DISPLACED VOLUME (km)

FIGURE 6: Isostatic adjustment modelling. (A) Topography and bathymetry modelling of Barbados Island before and after the abrupt mass unloading by erosion or landslides. The red square represents the area near Bridgetown, where have been collected coral reefs in previous studies at the Southwest of the Barbados and is detailed in Figure 1B. (B) Modelling of the isostatic adjustment after an abrupt mass unloading of 50 km^3 for different elastic thicknesses T_e with values of 40, 50 and 60 km. (C) Comparison of the uplift rate caused by the isostatic adjustment triggered by abrupt mass unloading with various volumes and for different elastic thickness. An abrupt unloading by a rock volume of 20-40 km^3 causes an uplift rate of 0.45 mm/yr.

This increase of uplift after 11.2 kyr permit to interpret the elevation of coral reefs from 14 kyr to 9 kyr in agreement with sea-level reconstruction from other areas. After reconstruction, a rapid sea-level jump of 4.8 m is observed contemporaneously with Meltwater pulse 1B, 11.5 kyr ago, 150 yr after the end of the Younger Dryas (Fig. 7), and 300 yr before the abrupt mass unloading. The sea-level jump was very short (i.e. 0.1 ± 0.05 kyr). This represents a sea-level rise of 65 ± 35 mm/yr, whereas the mean sea-level rise from 14 to 9 kyr BP is of 10.4 mm/yr.

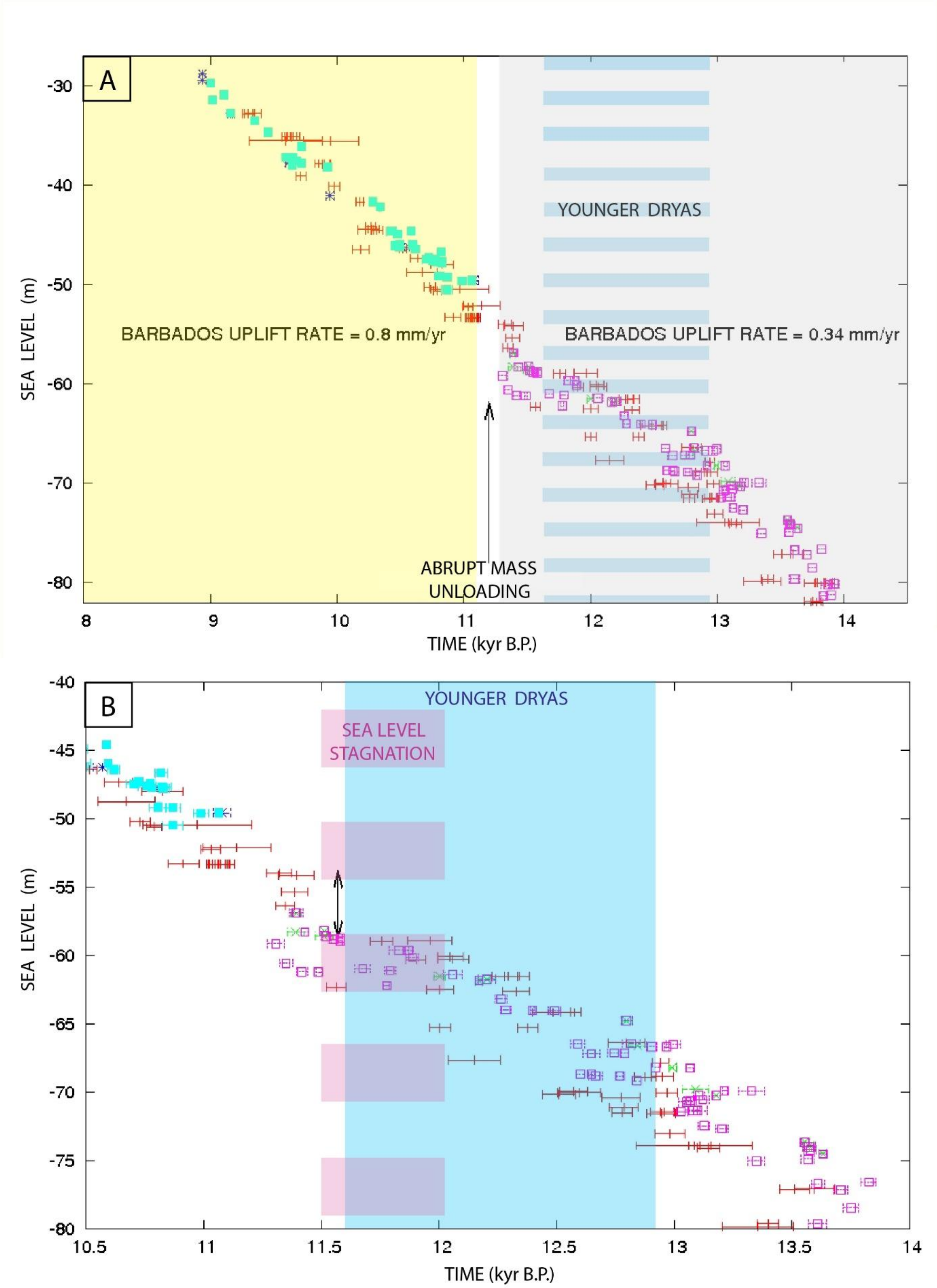

FIGURE 7: Sea level variation with time. (A) Sea Level at different ages from Tahiti coral reefs data in red (Bar et al., 2010) corrected from a subsidence of 0.25 mm/yr and Barbados coral reefs data (Peltier and Fairbank, 2006; Abdul et al., 2016) with a

correction of 0.8 mm/yr after 11.2 kyr in light blue (Abdul et al., 2016) and dark blue (Peltier and Fairbank, 2006) and 0.34 mm/yr before 11.2 kyr in green (Peltier and Fairbank, 2006) and pink (Abdul et al., 2016). (B) Sea-level reconstruction during the period 13.5 to 10.5 kyr from coral reef with correction of uplift for Barbados (0.8 mm/yr after 11.2 kyr and 0.34 mm/yr before 11.2 kyr) and subsidence for Tahiti (0.25 mm/yr). Data from Peltier and Fairbank (2006) in green and dark blue, Bard et al. (2010) in red, Abdul et al. (2016) in pink and light blue.

4 Discussion

4.1 Uplift rate variation with time

During the last thousand years, an uplift rate of 0.34 mm/yr was considered by previous studies (Peltier and Fairbank, 2006; Abdul et al., 2016). From 14 to 11.2 kyr BP, the 0.34 mm/yr of uplift rate were caused by tectonic compression or diapirism [Speed, 1981, Westerwood et al, 1988; Deville et al., 2006]. However, from 11.2 kyr to 9 kyr, an uplift rate of 0.8 mm/yr explain the observed data, coherently with sea level variations used as a reference. Sea level reference curve could be constructed using a tectonically stable area with (intraplate) where coral samples have been collected following an homogeneous protocol and accurately dated by U/Th method (Bard et al., 2010) or measuring the mean curve of numerous studies using heterogeneous methods but with an accurate statistical approach (Lambeck et al., 2014). If these curves converge for the last thousand years, they differ for older ages and the last glacial period (>14.5 kyr BP). In this study, the curve obtained in Tahiti Island (French Polunesia) using Bard et al. (2010) data is considered as a reference.

This uplift was partly (i.e. 0.45 mm/yr ; 56%) caused by the isostatic adjustment related to an abrupt mass unloading in the northeast of Barbados. Isostatic adjustment could explain the uplift increase during a short period of time (i.e. 10 kyr). Uplift changes during a longer period (>> 10 kyr) cannot be explained by this process. It is not excluded that such process may have played a role before the 11.2 kyr event, but this is beyond the scope of this study.

Previous studies, considered that these different uplift rates were representative of two distinct areas separated by a tectonic structure (Carlson and Clark, 2012; Bard et al., 2016). Consequently, elevation of coral reefs of core 7, 13 and 15 in the southwest of Barbados were criticized (Carlson and Clark, 2012) and Barbados sea-level reconstruction after 11.5 kyr BP considered as not representative (Bard et al., 2016). Nevertheless, due to the older age of coral reef located on core 7, 13 and 15 in comparison to the other data, it can be also considered that a temporal variation of vertical movement occurred. Barbados coral reef can be used, as those of Tahiti, to discuss sea-level variation during the last 14 kyr BP considering appropriate uplift rates. An uplift rate of 0.8 mm/yr after 11.2 mm/yr provide coherent results with previous sea-level reconstruction (Bard et al., 2010), uplift estimates (Carlson and Clark, 2012; Bard et al., 2016) and the cause of this uplift change is now explained.

4.2 Sea-level variation and climatic change

Sea-level rise from 14 to 9 kyr BP is almost constant at 10.4 mm/yr considering these corrections (Figure 7), in agreement with previous studies in Tahiti, Barbados and Huon (Bard et al., 2010). The main evolution during this period is between 12.0 and 11.5 kyr BP when a stagnation of sea-level occurred at –60.5 ± 1.5 m. This sea-level perturbation is due to the Younger Dryas cold event estimated to occur from the onset 12870 ± 30 yr BP to its termination 11610 ± 40 yr BP (Cheng et al., 2020). At 11.5 kyr BP, around 150 yr after the end of Younger Dryas, the present study shows that a rapid sea-level jump of 4.8 m occurred in less than 0.1 ± 0.05 kyr representing a sea-level rise of 65 ± 35 mm/yr, faster than previously estimated (i.e. 0.40 mm/yr; Abdul et al., 2016), contemporaneously with mi-Atlantic discharge increase (Tarasoc and Peltier, 2005). This sea-level drop is smaller than previously believed (i.e. 4.8 ± 1 m instead of value ranging from 7.5 ± 2.5 m to 14 ± 2 m; Blanchon and Shaw, 1995; Fairbank, 1989; Abdul et al., 2016) and occurred before than previous estimates (i.e. at 11.5 kyr BP instead of 11.45-11.1 kyr BP; Abdul et al., 2016), in agreement with Lambeck et al. (2014). This sea-level jump is not an artifact due to tectonic and isostatic adjustment, but was caused by ice sheet melting in response to North Atlantic warming. Spatial variation of the uplift rate in Barbados between 14 and 9 kyr BP are not necessary to interpret coral reef elevation, while applying temporal variation permit to obtain coherent results between Tahiti and Barbados sea-level reconstruction. Higher uplift rate (i.e. 0.8 mm/yr) applied for correction of coral reef elevation that are older than 11.2 kyr BP causes discrepancies with sea-level curve and are not justified.

There is a delay between sea level drop and Younger Dryas cold event termination in agreement with previous studies (Bard et al., 1996) that could be explained by thermal inertia of large ice sheet and ocean dilatation. It was lagged by 150 yr instead of 400 yr (Abdul et al., 2016) from Younger Dryas, but contemporaneously with meltwater megafloods from lake Agassiz (Blanchon and Shaw, 1995; Smith et al., 1993) or Lena River (Tesi et al., 2016). The main footprint of Younger Dryas on sea level is short (i.e. 0.5 kyr), but a slight reduction of sea-level rise begun around 12.80 kyr BP.

4.3 Cause of abrupt mass unloading

The abrupt mass unloading occurred 0.3 kyr after rapid sea-level jump and 0.45 kyr after the termination of Younger Dryas (Figure 8). At the termination of Younger Dryas, climate warmed (Cheng et al., 2020) and became more humid. Sea-level increases and wetter conditions are favorable to erosion and landslide (Brunetti et al., 2010; Urgeles and Camerlinghi, 2013; Gargani et al., 2006; Gargani et al., 2014; Gargani, 2020). This event occurred few time after the melting water pulse MWP-1B, contemporaneously with an increase of the number of landslides (Owen et al., 2007; Smith et al., 2011). If associated with erosion processes, the abrupt mass unloading of Barbados corresponds locally to a maximum vertical erosion rate of ~1 m/yr and a regressive erosion rate of 37.5 ± 12.5 m/yr during 0.2 kyr, representing fast headcuts retreat in comparison to analog erosion processes (Gargani, 2004; Gargani et al., 2010; Vanmaercke et al., 2016).

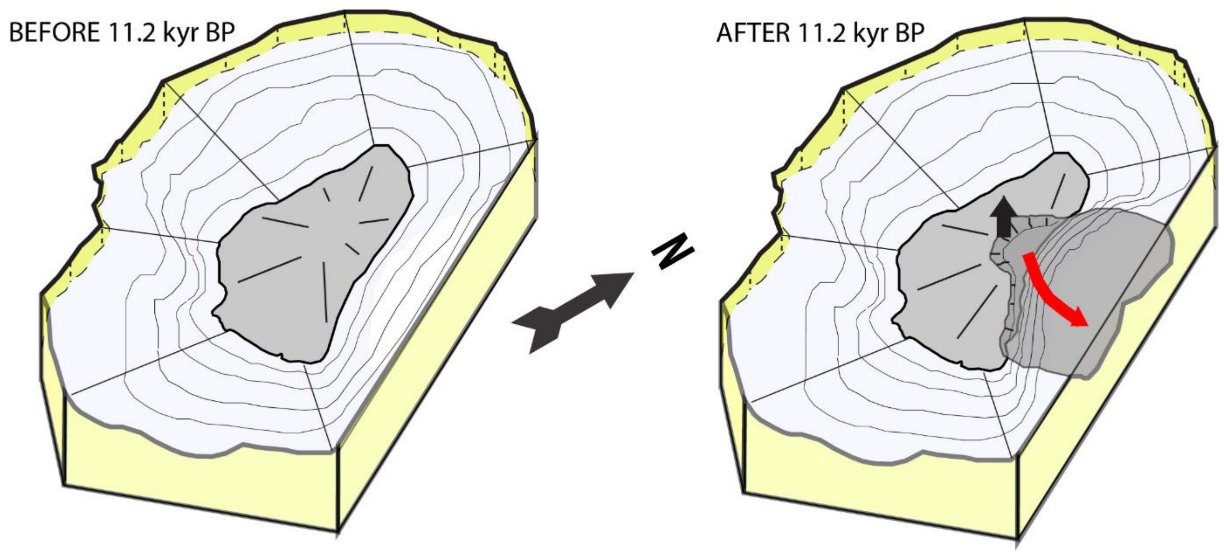

FIGURE 8: Schematic representation of the unloading process on geomorphology. Red arrow represents landslide or erosion process. Black arrow represents uplift.

5 Conclusions

Despite controversial results and continuous debate about the existence of meltwater pulse 1B in sea level, our results suggests that it is not an artefact, but that the rapid sea-level jump is smaller than previously estimated. Approximativly150 yr after the termination of Younger Drias, a sea-level drop of 4.8 m occurred, contemporaneously with megaflood events, after a short sea-level stagnation of 500 yr at –60.5 ± 1.5 m. An abrupt mass unloading occurred 300 yr after the sea-level drop. The abrupt mass unloading (landslide or/and erosion) occurred 11.2 kyr BP and caused isostatic adjustment. Isostatic adjustment, caused by an abrupt mass unloading of 30 ± 10 km^3 in less than 0.2 kyr, generates an uplift increase of 0.45 ± 0.15 mm/yr in Barbados. The uplift increase of 0.45 ± 0.15 mm/yr from 0.34 to 0.8 mm/yr at 11.2 ± 0.1 kyr BP explain coral reef elevation in Barbados that were not fully coherent with others sea level curves, previously to this study. Relative sea-level curves could be used to detect abrupt mass unloading.

Acknowledgments

The author declare no competing interests.

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