Potential role of event-driven sediment transport on sediment accumulation in the Cariaco Basin, Venezuela

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A S T R A C T

A sediment density flow was observed in the eastern Cariaco Basin during September 2008. Evidence suggests that this flow was likely triggered by a magnitude 5.2 earthquake that occurred on August 11, 2008, with an epicenter located at 10.51°N, 64.17°W (off the city of Cumaná, Venezuela). Elevated suspended sediments near the bottom were observed at the mouth of the Manzanares Canyon (>90 g m⁻², over a depth of 165 m) and decreased to ~11 g m⁻² (over a depth of 40 m) 42 km away from the canyon's mouth at the CARIACO Ocean Time-Series site. The sediment flux associated with this single event was ~10% of the total annual sediment flux that typically reaches the Cariaco Basin deep seafloor. Carbon to nitrogen ratios and isotope composition confirm that most of the organic matter transferred by the sediment flow was of continental origin (C/N ratios of ~17.67, δ¹³C of ~27.04‰, δ¹⁵N of 6.83‰). Our observations contribute to the growing body of evidence that suggests that submarine canyons are rapid, efficient sediment conduits of particles from shallow to deep waters, and that they should be included in efforts to constrain estimates of sediment and terrestrially derived carbon transport from the continental shelves to the deep ocean.

1. Introduction

Small mountainous rivers (SMRs), defined as those rivers that have headwaters at an elevation of more than 1000 m (Milliman and Syvitski, 1992), play a key role in the transport of terrestrially-derived sediment and organic carbon (OC) to the coastal ocean (Milliman and Syvitski, 1992; Syvitski and Milliman, 2007). Yet the ultimate fate of this OC remains controversial, despite its role in oxygen accumulation and as a potential sink for atmospheric CO₂ over geologic time (Burdige, 2007). For example, several studies suggest that much of the river-transported terrestrial OC that is deposited on the continental margin is efficiently remineralized due to a combination of remobilization and oxidation (e.g. Burdige, 2005; Aller and Blair, 2006). In contrast, in regions dominated by high erosion, high sedimentation and/or limited sediment oxidation, such as the Bengal Fan, continentally derived OC appears to be stored much more effectively (Milliman and Syvitski, 1992; Masiello, 2007; Hilton et al., 2008).

Smaller rivers also are more likely to experience episodic events such as floods, where the sediment and OC discharged to the sea within a narrow timeframe is considerable (Mulder and Syvitski, 1995; Warrick and Milliman, 2003; Milliman et al., 2007; Alin et al., 2008). The magnitude of this sediment discharge, as well as OC delivery and burial efficiency, is not well constrained due to both insufficient monitoring and the highly episodic nature of discharge events (e.g. Milliman, 1995; Warrick and Milliman, 2003; Hicks et al., 2004; Alin et al., 2008; Goldsmith et al., 2008; Hilton et al., 2008). This lack of knowledge is further exacerbated by the fact that many SMRs discharge onto narrow, active margins and/or directly into marine canyons, which help transport the sediment directly offshore (Paull et al., 2003; Puig et al., 2008; Palanques et al., 2008; Xu et al., 2010). Along seismically active margins, earthquakes can cause slope failure and turbidity currents, particularly in areas of unstable sediment accumulation such as alluvial deposits (Dadson et al., 2004; Syvitski and Milliman, 2007; Goldsmith et al., 2008), greatly increasing the supply of sediments to the ocean (Dadson et al., 2003; Eberhart-Phillips et al., 2003; Fine et al., 2005; Shirai et al., 2010).

Here we present observations of a turbidity flow in the Manzanares Submarine Canyon (Venezuela) during 2008. We explore the nature and implications of this event in terms of source material and mass transport to the interior of the basin, and its potential impact on the interpretation...
of paleoclimate records from the eastern Cariaco Basin, a tectonically
active area where terrigenous sediment delivery is dominated by SMRs.

2. Regional setting

Northeastern Venezuela is the most seismically active region of the
country (Audemard, 2007). The Cariaco Basin, located between
Cabo Codera and the Araya Peninsula (Fig. 1; Schubert, 1982) likely
owes its origins to tectonic activity. The Cariaco Basin contains two
sub-basins, each approximately 1400 m deep and divided by a saddle
of about 900 m. The basin is separated from the open Caribbean Sea
by two shallower sills (~145 m). West of the city of Cumaná lies the
Manzanares Submarine Canyon, which connects the Gulf of Cariaco
to the eastern Cariaco Basin.

Morelock et al. (1972) estimated that the Manzanares Canyon formed during the Pleistocene and linked its origin to the El Pilar
Fault. The El Pilar fault system is a right-lateral strike-slip fault located
in the northeast region of Venezuela that extends ~350 km in an
approximately E–W direction, roughly parallel to the coast (Audemard,
2007). More recent seismic surveys suggest that the canyon is not locat-
ed on the active trace of the El Pilar fault (FUNVISIS, 1994). Rather,
the canyon seems to have been carved by downslope sediment
flows, with sediment failure in the head and walls linked to earthquake
shocks (González et al., 2004; Audemard, 2006; 2007).

The Manzanares Canyon head opens at a depth of 50 m, about 2 to
3 km off the mouth of the Manzanares River, slightly to the west of
the city of Cumaná. The Manzanares River is a SMR that drains the
Serranía del Interior formation, part of the Cordillera de la Costa, com-
posed of Mesozoic metamorphic and igneous rocks. Nearshore cur-
rents transport river sediments to the west of the river mouth, and
most of this material is trapped by the Manzanares Canyon (Mora et
al., 1968). The predominant sediments in the upper canyon are silt,
clay, and coarse sand of continental origin (Morelock et al., 1972;
Morelock, 1982). While most of the sediment found in the canyon
comes from the Manzanares River, the Gulf of Cariaco (Fig. 1)
also contributes sediment (Mora et al., 1968; Caraballo, 1982). These
sediments are derived from the Cautaro and the Cariaco Rivers, as
well as from several smaller seasonal rivers (arroyos) (Gade, 1961;
Caraballo, 1982; Audemard et al., 2007).

The Cariaco Basin is influenced regularly by shifts in position of the
Intertropical Convergence Zone (ITCZ). During the first few months of
the boreal year the basin experiences the dry season, characterized by
strong Trade Winds and little to no precipitation. Starting in May, the
position of the ITCZ migrates northward and precipitation increases
in northern Venezuela. River runoff peaks between August and
September (Márquez et al., 2002; Peterson and Haug, 2006). Regret-
tably, none of the rivers that drain into the Cariaco Basin are currently
gaged; hence precipitation records have been used as a proxy of flu-
vial discharge (Lorenzoni et al., 2009). For the Manzanares River,
the precipitation measured at the city of Cumaná reflects the magni-

tude of river discharge (Márquez et al., 2002), with discharge rates
usually lagging the peak in precipitation by one month (e.g., precipi-
tation at Cumaná peaks during August, while river discharge peaks
during September).

3. Materials and methods

Hydrographic and light beam attenuation data were collected at the
CARIACO Ocean Time-Series site in the eastern Cariaco Basin
(10°30′ N; 64°43′ W; water depth of 1400 m) and at the mouth of the
Manzanares Canyon (10°30′ N; 64°22′ W; water depth of 1000 m,
Fig. 1) between September 1–5, 2008, roughly three weeks after a mag-
nitude (M) 5.2 earthquake occurred near Cumaná, Venezuela (10.51°N,
64.17°W) on August 11, 2008. The mouth of the Manzanares Canyon is
located ~42 km east of the CARIACO Ocean Time-Series site. The beam
attenuation coefficient of light at a wavelength of 660 nm (c_p(660),

Fig. 1. Bathymetric map of the study area. The Manzanares Canyon, Manzanares River, the Gulf of Cariaco, and the city of Cumaná are shown. Star shows the epicenter of the August 11, 2008, earthquake. Triangles show the CARIACO Ocean Time-Series site (Station 1) and canyon mouth (Station 2) locations.

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4. Results

Highest beam attenuation ($c_p = -0.15 \text{ m}^{-1}$) was observed at the Manzanares Canyon (hereafter referred to as the canyon mouth) between 850 and 870 m depth, within a suspended sediment layer that spanned from the seafloor at 1000 m to ~815 m depth (Fig. 2). Outside this turbid layer, $c_p$ was almost an order of magnitude lower ($-0.0025 \text{ m}^{-1}$), comparable to values measured repeatedly in the basin as part of the CARIOCO Ocean Time-Series program (http://www.imars.marine.usf.edu/CARI/). At the CARIOCO Ocean Time-Series site (hereafter referred to as the CARIOCO site), we observed a layer of high beam attenuation between 1215 and 1255 m, which is ~150 m above the seafloor (Fig. 2). The $c_p$ peak in this layer was 0.078 m$^{-1}$, about half of the peak value measured in the sediment layer within the canyon mouth. This value is almost three times higher than the $c_p$ normally observed at similar depths in the Cariaco Basin ($0.025 \pm 0.007 \text{ m}^{-1}$).

Other features of the beam attenuation profile at the CARIOCO station (Fig. 2) reflect the microbial community located at the oxic–anoxic interface (peak at 200–320 m; Thunell et al., 1999; Taylor et al., 2001) and intermediate nepheloid layers (INL’s) (between 120 and 170 m); the latter have been observed previously and determined to be of continental origin (Lorenzoni et al., 2009). Closer to the surface, high variability in particle concentrations was likely due to changes in phytoplankton concentrations and assemblage ($c_p$ was proportional to chlorophyll fluorescence, data not shown). Average POC and PN concentrations within the suspended sediment layer at the canyon mouth were 0.128 ± 0.01 g C m$^{-3}$ ($N = 3$) and 0.008 ± 0.002 g N m$^{-3}$ ($N = 3$), respectively. C/N ratios in the sediment plume at the canyon mouth averaged 16.4 ± 2.2 (Table 1). The $\delta^{13}N$ within the sediment layer averaged −27.04 ‰, whereas the $\delta^{15}N$ was −6.83 ‰.

A strong correlation between SPM and beam attenuation data was observed using the data collected during September 2008 ($R^2 = 0.82$, $N = 16$; $\alpha = 0.01$). This relationship was subsequently used to determine SPM integrated over the depth of the observed suspended sediment layers at both the canyon mouth and the CARIOCO site. Depth-integrated SPM at the canyon mouth (over 165 m) was ~90 g m$^{-2}$, while at the CARIOCO site it was ~11 g m$^{-2}$ (over 40 m). Unfortunately, the suspended sediment layer was below the deepest sediment trap (1200 m) maintained at the CARIOCO Ocean Time-Series site (Thunell et al., 2007). Thus, no additional particulate matter from this event was captured by the sediment trap located at ~1200 m.

5. Discussion

There are no significant currents in the deep portions of the Carrao Basin that resuspend sediments (Alvarez-Azcárate et al., 2009). Monthly transmissometer profiles collected as part of the CARIOCO time series indicate that normally there are no nepheloid layers immediately above the sea-floor (http://www.imars.marine.usf.edu/CAR/). As a result, the water below 400 m is typically very clear and homogenous (Virmani and Weisberg, 2009). Therefore, we suggest that the suspended sediment layers observed during September 2008 at the CARIOCO site and at the mouth of the Manzanares Submarine Canyon (Fig. 1) were the result of an event-driven sediment density flow. This is the second time since the beginning of the CARIOCO Ocean Time-Series Program in November 1995 that turbidity layers have been observed near the bottom of the basin. In July 1997, a 400 m thick turbidity layer located immediately above the bottom at the CARIOCO site, was observed after a M6.8 earthquake struck northeastern Venezuela on July 09, 1997 (Thunell et al., 1999; Audemard, 2006). High suspended particle loads of more than 1.0 mg L$^{-1}$ persisted at the bottom of the CARIOCO site for more than four months.

Submarine canyons are widely recognized as important conduits for the transport of terrestrial-derived material from continental shelves.

Table 1

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<th>Geochmical variables measured in the canyon mouth turbidity plume (870 m). Average values± standard deviations of variables collected at the CARIOCO Ocean Time-Series site at 1310 m between 1996 and 2007 are also shown. SPM data for the CARIOCO Time-Series site was estimated using the $c_p$ relationship described in the text.</th>
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<td><strong>CARIACO Time-Series site</strong></td>
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<td>SPM (g m$^{-3}$)</td>
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<td>POC (g C m$^{-3}$)</td>
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<td>$\delta^{13}$C (‰)</td>
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$^a$ From Woodworth et al. (2004).
$^b$ From Thunell et al. (2004).
to the deep ocean. (Mullenbach and Nittouer, 2000; Johnson et al., 2001; Paull et al., 2003; Liu and Lin, 2004; Xu et al., 2010). Events that enhance continentally-derived organic matter and sediment transport, such as storms (Dadson et al., 2003; Palanques et al., 2008), dense shelf water cascading (Canals et al., 2006), or turbidity flows to the deep ocean are critical, since the organic matter injected into the deep sea is not remineralized but buried. Thus, this organic material ceases to be part of the present day global carbon cycle.

Within submarine canyons, turbidity flows can be gravity-driven, resulting from energetic events such as earthquakes (Hilton et al., 2008), or flow-driven, induced by storms and floods, among other mechanisms (Canals et al., 2006; Palanques et al., 2008). The latter mechanism is particularly important if the river mouth is located near the canyon head, as the river plume can be advected directly into the canyon in the form of a hyperpycnal plume (Mulder and Syvitski, 1995; Johnson et al., 2001; Liu et al., 2008). Hyperpycnal flows, negatively buoyant subsurface freshwater plumes, contain high suspended sediment loads (usually in the order of tens of grams per L) that can be deposited inside the canyon and later remobilized (e.g., Kineke et al., 2000; Mullenbach and Nittouer, 2000) or can be funneled directly to the canyon mouth, if the density difference and velocity are sufficient (e.g., Johnson et al., 2001; Paull et al., 2003). Hyperpycnal flows have never been directly observed in the Cariaco Basin, largely because these events are generally short-lived and there is a lack of monitoring along the small rivers that surround the basin. Nonetheless, it is likely that such hyperpycnal flows have occurred, linked to anomalous precipitation events that have induced massive river flooding, such as in November–December, 1999. In this case, the mixture of “Nortes” (Lyon, 2003) and La Niña conditions in the Equatorial Pacific facilitated the setting for sustained, torrential rains along Cordillera de la Costa. In the Cariaco Basin, at the location of the CARIACO site, the delivery of sinking terrigenous flux increased six-fold during the 1999 flood, from an average of 10.45 g m$^{-2}$ month$^{-1}$ (measured in the 225 m depth sediment trap) to 69.34 g m$^{-2}$ month$^{-1}$ (http://www.imars.marine.usf.edu/CAR/). During November–December 2010, a similar event was observed, where precipitation along the Venezuelan coast increased threefold. Unfortunately, there is no corresponding measure of beam attenuation or sediment trap fluxes for that period.

In order to determine whether the sediment plume observed in September 2008 was caused by a hyperpycnal flow induced by anomalously large river discharge, the precipitation record measured at Cumaná for the month of August for the period 1967–2011. The average August precipitation for this period was 88 ±60 mm. During August 2008 precipitation recorded at Cumaná was 147 mm (NCDC), within the standard deviation of the precipitation in Cumaná during the month of August was threefold. In the Cariaco Basin, largely because these events are generally short-lived and there is a lack of precipitation along Cordillera de la Costa. In the Cariaco Basin, at the location of the CARIACO site, the delivery of sinking terrigenous flux increased six-fold during the 1999 flood, from an average of 10.45 g m$^{-2}$ month$^{-1}$ (measured in the 225 m depth sediment trap) to 69.34 g m$^{-2}$ month$^{-1}$ (http://www.imars.marine.usf.edu/CAR/). During November–December 2010, a similar event was observed, where precipitation along the Venezuelan coast increased threefold. Unfortunately, there is no corresponding measure of beam attenuation or sediment trap fluxes for that period.

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An alternative explanation for the observed suspended sediment event is that it was seismically triggered, either by the M5.2 earthquake that took place on August 11, 2008, at 10° 30.60′ N and 64° 10.20′ W (FUNVISIS, 2008) and/or by the aftershock of M3.0 that occurred in roughly the same location half an hour later. It is possible that post-seismic erosion rates near the Gulf of Cariaco and Cumaná increased after the earthquake, due to seismically-induced landslides, but it is unlikely that this material contributed to the sediment plume observed near the canyon mouth. Sediment that is seismically weakened is generally flushed to the rivers and ultimately to the ocean by storm runoff (Dadson et al., 2003, 2004), but as mentioned earlier, precipitation in Cumaná during the month of August was within historical values.

During July 1997, the turbidity flow was observed by Thunell et al. (1999) one week after the M6.8 earthquake. Data from the day before the earthquake (July 8th) showed no sediment near the sea-floor of the Cariaco Basin. This suggests that sediment remobilization occurred shortly after the earthquake. Whether part of the sediment in the turbidity flow observed in 1997 originated from co-seismic landslides is not known, but if this was the case, it is likely that it was mobilized by hyperpycnal plumes. Average precipitation for the entire month of July was 121 mm, above the historical (1967–1992; 1998–2010) average of 64 ±45. During the July 16 sampling at the CARIACO site there was no indication of a hyperpycnal layer. The suspended sediment layer near the sea-floor was still visible in November 1997 (http://www.imars.marine.usf.edu/CAR/). Similar to 1997, the suspended sediment layer after the 2008 earthquake persisted through December 2008.

SPM concentrations estimated near the bottom at the canyon mouth (1.0 g m$^{-3}$, Table 1) were similar to SPM measurements observed in the high turbidity layer after the 1997 earthquake at the CARIACO site (Thunell et al., 1999). Unfortunately, for September 2008, we only have the observations at the canyon mouth and at the CARIACO site. We used these observations along with the beam attenuation data to calculate the amount of sediment within the turbid layer. At the canyon mouth, ~90 g m$^{-2}$ was estimated to be within the sediment plume, while at the CARIACO site this decreased to ~11 g m$^{-2}$. This latter estimate represents ~10% of the total average annual vertical sinking flux measured at 1200 m at CARIACO. Since our observations were made several weeks after the earthquake, these earthquake-related suspended sediment concentrations should be regarded as minimum estimates.

It is difficult to calculate the total amount of sediment delivered to the deep Cariaco Basin by the August 2008 earthquake. Sedimentation rates in the eastern Cariaco Basin, estimated using sediment traps (Thunell et al., 2000), are on the order of 180,000 t of sediment per year. Thunell et al. (1999) found that approximately 145,000 t of sediment were transported into the basin after the large (M6.8) earthquake of July 9, 1997; this is 80% of the typical annual vertical sinking flux measured at 1200 m. However, they assumed sediment loads to be relatively low and uniformly distributed below the 1100 m isobath. Our 2008 observations showed significantly higher sediment concentrations near the canyon mouth. If we assume that the 1997 event had a similar spatial distribution as that of 2008, then the amount of material delivered during the 1997 event may have been twice as large as that estimated previously.

Average POC concentrations within the suspended sediment layer at the canyon mouth were almost three times higher than the average (1996–2007) monthly suspended POC concentrations measured at 1310 m at the CARIACO site. Moreover, the POC measured at the canyon mouth was about 10% of the SPM within the turbidity plume, an order of magnitude higher that the POC estimated to be transported by regional rivers to the ocean (Ludwig et al., 1996). PN concentrations within this sediment layer were similar to average PN values typically measured prior to the turbidity event. Therefore, the C/N ratios in the sediment plume at the canyon mouth were 16.4±2.2, or about twice the average C/N value for sinking particles at 1200 m at the CARIACO site. This is significantly higher than the predicted Redfield C/N ratio for marine organic matter (around 6–7, Hedges et al., 2002), which suggests this material was of continental origin.

The carbon and nitrogen isotopic composition of material within the suspended sediment layer at the canyon mouth is also indicative that the POC transported into the deep basin was primarily land derived. The δ13C at the canyon (average of −8.68‰) was higher than that normally seen at similar depths at the CARIACO station (~3.5‰; Thunell et al., 2004). A similar increase in δ15N, from an average of 3.5‰ to ~5.7‰, in the deepest CARIACO sediment trap (1210 m) was also observed by Thunell et al. (2004) after the strong 1997 earthquake. The δ13C (average of −27.04‰) was depleted relative to values observed normally at the CARIACO site (~20.7‰; Woodworth et al., 2004), with the latter being typical of marine organic carbon. Recent
studies by Hilton et al. (2010, 2011) suggest that a significant portion of terrestrial POC transported to the ocean by SMRs is fossil POC from exposed bedrock, and that this fraction has a δ¹³C range that overlaps that of modern POC. Hilton et al. (2011) further hypothesized that the high erosion rates of coastal mountain ranges result in efficient transport of this fossil OC into marine sediments with minimal oxidation. The direct funneling of continental POC by submarine canyons can further enhance this transport. Though the carbon content of the Serranía del Interior is relatively high (1–6%; Alberdi and LaFargue, 1993; Tocco et al., 1994), there is no data available on the isotopic composition of this geo-logic formation or the relative fraction of modern versus fossil OC contained in the sediment flow. Thus Hilton’s hypotheses cannot be confirmed or ruled out in this region.

There is significant evidence of earthquake-induced turbidity flows over geologic time in the Cariaco Basin. Sediment cores and seismic surveys of the canyon in the 1960s indicated that turbidity current deposition and slumping are common features (Morales and Ottmann, 1961; Morelock et al., 1972) as further documented by Thunell et al. (1999). Large turbidites, as well as microturbidites, have further been identified in the sediment record in the Cariaco Basin. Turbidites have previously been attributed to seismic activity, with the largest turbidites corresponding to earthquakes in 1900 and 1929 (Hughen et al., 1996). Since turbidite deposition in the Cariaco Basin does not seem to erode the underlying sediment, they could serve as paleoseismic records for the region (Thunell et al., 1999; Carrillo et al., 2008; Goldfinger, 2011).

Over 60 seismic events of M4–M5 have been recorded in northeastern Venezuela since 1996 in the area of Cumaná and the Cariaco Basin. Such events may provide the necessary weakening of substrate material and the trigger for the rapid mobilization of continentally-derived materials temporarily deposited at the head of the Manza- nares Canyon. Thus, the Manzanarees Canyon is likely to be an important source of sediments to the eastern Cariaco Basin and has the potential of funneling large quantities of terrestrially-derived organic matter down-canyon and effectively sequestering carbon on millen- nium time scales.

6. Conclusions

Event-driven downslope mobilization of sediment is an important means of continental OC sequestration and burial. A sediment density flow was observed within the Cariaco Basin during September 2008, the possible result of an earthquake that struck near the city of Cumaná, Venezuela, on August 11th, 2008. This single event trans- ported an estimated 10% of the average annual sediment flux to the seafloor of the Cariaco Basin. Furthermore, the OC within the sedi- ment plume appeared to be predominantly continentally-derived, reinforcing the hypothesis that turbidity flow events are significant sources of terrestrial carbon and sediment to the deep ocean.

The Manznaredes River mouth is located at the head of the canyon, and likely supplies most of the fine grained sediments and fresh car- bon that accumulate in the upper part of the canyon. This suggests that the canyon is an active depositional center, and its proximity to the Manznaredes River and Cariaco Basin is critical for sediment supply offshore.

The continental material estimated to have been delivered to the deep Cariaco Basin as a result of the sediment density flow is based only upon two measurements obtained almost a month after the seis- mic event. If we use these observations and assume a linear decrease in concentration and sediment plume thickness, and integrate the SPM over the entire area of the eastern sub-basin below 1000 m (approx- imately 1200 km²), we can loosely estimate that ~50,000 t of sediment and ~6600 t of POC delivered to the deep portion of the basin is a result of the sediment density flow. This would represent approximately a third of the average vertical sinking flux of sediment and POC that normally reaches the Cariaco Basin seafloor annually, all delivered during a single event. However, it is very difficult to accu- rately assess the amount of sediment and carbon that reached the deep basin based solely on these observations. In order to correctly assess the transport of continentally derived material through the Manznaredes Canyon, a more permanent observing system with sim- ultaneous points of observation is required. This would enable epi- sodic events to be captured when they occur and the ability to accurately measure the magnitude of material delivered to the deep basin.

Though there are other means of shelf to canyon sediment trans- port, earthquake-induced turbidites are uniquely preserved in the sediment record of the basin. Their study may provide insight into earthquake recurrence rates in Cariaco Basin, and help advance our understanding of continent carbon sequestration dynamics near margins that are affected by such episodic events. These observations emphasize the importance of submarine canyons as sediment conduits in our efforts to constrain off-shelf sediment and carbon.

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