Dear Simon,

On behalf of my co-authors and myself I submit our revised manuscript.

Below are the collated responses to the comments from reviewers followed by a marked-up manuscript version. We strived to address all comments carefully and to the point.

Thank you for your help in seeing this work to the finish.

Sincerely,

Liviu Giosan

Collated Responses to Reviewers

Response to Interactive comment on "SHORT COMMUNICATION: Massive Erosion in Monsoonal Central India Linked to Late Holocene Landcover Degradation" by Liviu Giosan et al. by Anonymous Referee

We thank the referee for his/her suggestions:

This manuscript presented the sediment flux and age offset (TOC radiocarbon age off- set relative to depositional age) records since the Holocene from a sediment core in the Bengal Fan. Combined with previous precipitation and ecology reconstructions based on pollen and leaf wax carbon isotopes of the same core, they suggested strengthened human activity on the Deccan Plateau increased soil erosion and the age of exported organic carbon, which were recorded in the offshore sediment proxies of sediment flux and age offset. In general, the data is very interesting and impressive, the paper is well written and thus I recommend it to be published in Earth Surface Dynamics. However, there are some serious issues, such as provenance, effect of sealevel change, and estimate of age offset, which are not clearly illustrated in current MS. Thus I suggest a major revision. My comments are as follows:

1. The discussion about the provenance is very unclear. The authors only provided a figure with final result of percent of Deccan contribution by Nd isotope. However, there are no details how they estimated. At least they should provide information about the Nd isotopes of two end-members they used in the estimation. Moreover, it's more common to use Sr-Nd isotopes set to constrain sediment provenance rather than only Nd isotope, which is not convincing. To my knowledge, they should first compare all the potential river sources including Bramaputra and Ganges, not only Godavari River. Although the first two rivers are relatively a little far from the study core, however, they still possibly delivered suspended sediment to the core and they have at least 20-times higher sediment flux than Godavari River. This means that any small changes in the relative contribution between these two end-members will significant change the Nd isotopes seen at the core. I really don't think that the increasing Nd isotopes must indicate the higher sediment flux from Deccan Plateau. If this is the case, any changes of proxies at the core not necessary related to environment changes in source region, but also possible links to the relative contribution of two different end-members in different rivers. I strongly suggest the authors add Sr isotopes and constrain the provenance tougher by more clear end-members. This is the basis of this study must be carefully revised.

Our response to this point:

1. Isotopic end-members have already been noted in text and Fig. 1. A simple two end member mixing model wss used and we add new info in the supplementary on that:

   "The average εNd for the Deccan basalts is +1 ± 5 and for the Indian craton is -35 ± 8 (GEOROC Database, Geochemistry of Rocks of the Oceans and Continents, Max Plank Institute for Chemsitry, Mainz, Germany, http://georoc.mpch-mainz.gwdg.de/). The measured εNd value of a sample was expressed as a simple mixture of sediment derived from the two end-members:

   $$\varepsilon\mathrm{Nd}_{Sample} = f \cdot \varepsilon\mathrm{Nd}_{Deccan} + (1-f) \cdot \varepsilon\mathrm{Nd}_{Craton}$$

   Where (f) is the fraction of Deccan derived sediments, ($1-f$) the fraction of Craton derived sediments in the mixture, and f is a number between 0 and 1. "

2. We understand that some would think that presenting combined Nd and Sr is needed as a rule but that is not the case, neither is the way the radiogenic fingeprinting method has been employed here. There are many radiogenic isotope tracers that can be used in certain conditions for fingerprinting sources (Nd, Sr, Pb, Hf,...). However in our clear-cut case where sediment sources are so distinct Nd suffices. Sr would add an un-needed layer of complexity and uncertainty as it is affected by weathering and non-conservative. Weathering may be sometimes ignored but in the Godavari system it may not.

3. Input from distant sources such as the Ganges and Brahmaputra as the referee suggests can be safely ignored because (a) to our knowledge the core we study is by design the closest-positioned continental margin core to any river mouth ever to be studied, receiving input directly from the plume; (b) sedimentation rates are extreme and any external component would be highly diluted; (c) studies show that suspended sediments from northern peninsular rivers do not reach as far south (e.g., Bejugam and Nayak, 2017); (d) assuming that by some unknown and extreme mechanism Ganges-Brahmaputra material would reach the site, the discharge from Ganges-Brahmaputra decreased drastically 7000 years ago (Goodbred et al, 2000),

which would likely registered in εNd at our site or, if not, happened much earlier than the events we are addressing with our Nd measurements in late Holocene; (f) other works using independent proxies show a late Holocene increase in Deccan input – see response to another comment.

2. The possible effect of sea-level change on sediment proxies was not discussed. Although I agree with the authors that increased human activity and decreased landcover would potentially increased erosion. However, on the timescale since about 11 ky, the influence of sea-level must be considered. In my view, the general decreasing or increasing trend of all proxies occurred since about 8-11 ky, rather than only since about 2ky. This cannot be ascribed to authigenic influence, which only became evident since about 2ky. The influence of sea-level on sediment flux may be indirectly through upper current or coastal current, which possibly changed the relative contribution from different river sources. Please consider more thoroughly.

The events we describe and are of interest to this paper take place from mid to late Holocene after sea level stabilization at a location where the shelf edge is unusually narrow. We do not understand what the reviewer means by "authigenic" (definition: of minerals and other materials formed in place). If he/she refers instead to "autogenic" the comment still remains obscure to us. However, we added the following to clarify:

"Offshore from the Godavari mouth, a persistent sediment plume extends over 300 km during the monsoon season when over 90% of the fluvial sediment is discharged (Sridhar et al., 2008). Because the shelf in front of the delta is unusually narrow (i.e., under 10 km at our core location) copious sediment deposition takes place directly on the continental slope, resulting in sediment accumulation rates as high as 250 cm/kyr; Ponton et al., 2012). Owing to the narrow shelf, changes in sea level would also have minimal effects on sediment deposition at our site, especially after early Holocene when the global sea level reached within a few meters of modern values (Lambeck et al., 2014)."

3. The estimation of age offset is not clear. For example, they applied a equation as "error offset= ((err. TOC 14C measurement)2+(max. err. Foram 14C measurement)2)1/2" . Why? Where is the reference? Why not directly use offset between ages of TOC 14C and Foram 14C?

We used the equation mentioned to calculate the error and not the offset. The offset was calculated as the reviewer describes: "The age of the bulk TOC at the time of their deposition was estimated by taking the offsets between their radiocarbon content and the interpolated reservoir-corrected foraminifera-based radiocarbon age".

In addition, the supplementary table 1, 2, 3 wrongly wrote "yr" as "kyr". Table1, no errors provided for Nd isotopes. Table3, unclear for the captions of the age columns

We corrected kyr to yr.

The error of measuring Nd is already in the supplementary text.

In Table 3 but we made a modification that may help: instead of "14C age" we now use "TOC 14C age".

Refs:

Bejugam, P., Nayak G.N., 2017, Source and depositional processes of the surface sediments and their implications on productivity in recent past off Mahanadi to Pennar River mouths, western Bay of Bengal, Palaeogeography, Palaeoclimatology, Palaeoecology 483 (2017) 58–69

Goodbred Jr., S.L., Kuehl, S.A., 2000. Enormous Ganges–Brahmaputra sediment discharge during strengthened early Holocene monsoon. Geology 28, 1083–1086.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambradge, M., 2014, Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, Proc. Natl. Acad. Sci. USA, 111, 15296–15303.

Response to interactive comment on “SHORT COMMUNICATION: Massive Erosion in Monsoonal Central India Linked to Late Holocene Landcover Degradation” by Liviu Giosan et al. by P. Plink-Bjorklund (Referee)

We thank the referee for her comment and share her enthusiasm on the important role of precipitation variability/seasonality and vegetation cover in river erosion.

This paper discusses two key aspects of erosion. One being the role of sea-level fall and the second climate control. The former has long been considered a key control on river erosion, due to the early models of Fisk (1944), further applied and promoted by sequence stratigraphic models, where erosion is linked to sea level fall and the river valleys are later filled during succeeding transgression (e.g. Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; see discussion in Blum et al., 2013). More recent work exposes significant problems with this concept, as this concept ignores the role of drainage basin in erosion and sediment production and only considers the sediment produced by valley excavation. The concept also ignores other mechanisms of river erosion and causes for increased sediment production, as well as the backwater effects (see discussion in Blum et al., 2013; see also Lamb et al., 2012). Furthermore, where dated in great detail, the erosional river valley fills have been shown to contain falling stage, lowstand as well as transgressive deposits, as erosion and deposition are not mutually evasive processes and rather coincide spatially (see further review by Blum et al., 2013). What concerns climate control on erosion, then it is commonly referred to as a simple function of average annual rainfall, thus ignoring the effects of hydrological connectivity (such as the type of vegetation; e.g. Molnar, 2001; DiBiase and Whipple, 2011), as well as of the precipitation pattern (Leier et al., 2015; Plink-Bjorklund, 2015). High precipitation variability or seasonality, such as in monsoon conditions, causes surface water supply variability and focuses water and sediment discharge events to the wet seasons, such as in case of the Godavari. Thus, without increasing the annual average precipitation the water power and sediment transport capacity are increased in such river regimes. Increased aridity leads to reduced vegetation cover, but also may lead to increased rainfall intensity and thus flood intensity, thus increasing river’s ability to erode (see review by Plink-Bjorklund, 2015). This manuscript is a significant contribution as a well documented example to signify the role of precipitation variability/seasonality and hydrological connectivity (vegetation cover) in river erosion. It promotes further discussion and data collection for both of the common assumptions what concerns river erosion. The manuscript is clearly written and there are no grammatical issues. The only issue I have is with a sentence that references Blum and Hattier-Womack (2009), as is it makes it sound like the referenced paper simply supports the notion of sea-level control on river erosion, whereas it actually promotes the role of climate in river erosion.

We clarified our reference to Blum and Hattier-Womack (2009) as follows:

"Such complex variability did not inevitably follow the sea level cyclicity (e.g., Goodbred and Kuehl, 2000), which is usually assumed to control most of the sediment transfer from land to the deep ocean (see Blum and Hattier-Womack, 2009 and references therein for an analysis underlining the increased recognition for climate role)."

Response to interactive comment on "SHORT COMMUNICATION: Massive Erosion in Monsoonal Central India Linked to Late Holocene Landcover Degradation" by Liviu Giosan et al. by Y. Kulkarni

We thank Y. Kulkarni for his suggestions that are useful to improve our work. We respond here to his second comment, largely identical to his first, assuming that the last comment is the final one.

The short communication is based on the landcover, soil and its erosion from two different zones of lithologies present in Godavari Drainage Basin (GDB) which is also previously discussed by Kulkarni et al. (2015) based on the mineral magnetic studies of Godavari sediments and Bay of Bengal sediments. Their study show the general increasing trend in ferrimagnetic concentration in middle Bay of Bengal sediments suggesting to the dominance of Deccan source over quartzo-feldspahthic source for Late Holocene. They suggested the combine effect of distinct lithological units, geomorphic setup and spatial distribution of monsoonal rainfall plays an important role in sediment generation in GDB. Previously Sangode et al. (2001) also suggested the dominance of Peninsular Source over Himalayan source in Bay of Bengal sediments. Kulkarni et al (2014) based on mineral magnetic study inferred the dominant Deccan basaltic source over the floodplains of Godavari River for entire stretch as a result of intense weathering of Deccan plateau. Recently Cui et al. (2017) based on organic carbon and mineral magnetic analysis of well dated (AMS 14C) Godavari delta core 'CY' suggested the increasing Deccan basaltic source during Late Holocene particularly after nearly 6 cal ka BP. Their study also show the significant increase in ferrimagnetic minerals from nearly 3.2 to 3.1 cal. ka BP attested to severe decline in vegetation in Deccan plateau.

These are very useful works and we note them and cite as follows:

"The Nd isotopic signal points to an increase in the Deccan sedimentary output at the time, after a muted variability earlier in the Holocene when the Indian Craton consistently provided ~50-60% of the sediments (Fig. 2; see Supplementary Materials). Ferrimagnetic minerals interpreted as originating from the Deccan (Sangode et al., 2001; Kulkarni et al., 2014) also increase in late Holocene sediments in the Godavari delta (Cui et al., 2017) and Bay of Bengal (Kulkarni et al., 2015) supporting our interpretation. Augmented Deccan inputs were suggested for the Godavari delta (Cui et al., 2017) even earlier after ~6000 years ago, in step with the initial aridification."

We also now cite Cui et al. (2017), paper published after our manuscript was submitted, several times where appropriate.

Majority of CMZ is represented by Pranhita River basin rather than upper Godavari and the mixing may have a complex role in Godavari onwards is not considered.

We carefully use the term "upper basin", which includes much of the Pranhita basin, but agree that mixing would be a good topic for future detailed work.

Besides this, the Bikshamaiah and Subramaniyan (1980) although given detail account on chemical and sediment mass transfer in GDB and established some controlling factors for same, they did not classify the geology of GDB as two major geological units. The part of Godavari River in the Godavari graben is flowing above the Gondwana and Purana sedimentary units which although accounts for about 11% of basin (Biksham and Subramaniyan, 1988) but acts as major lithounit in main channel as well as in Pranhita River (A major tributary of Godavari).

Geochemically and especially isotopically our classification stands and has been used regularly when describing marine cores in the region (e.g., Mazumdar et al., 2015). The reason is that Gondwana and Purana sediments preserve the craton signature where they originated (e.g., Amarasinghe et al., 2014) especially for conservative properties as Nd, which is vastly different than the young Deccan signature.

Refs:

Amarasinghe, U., Chaudhuri, A., Collins, A.S., Deb, G., Patranabis-Deb, S., 2014. Evolving provenance in the Proterozoic Pranhita–Godavari Basin, India. Geoscience Frontiers.

Mazumdar, A., Kocherla, M., Carvalho, M.A., Peketi, A., Joshi, R.K., Mahalaxmi, P., Joao, H.M., Jisha, R., 2015. Geochemical characterization of the Krishna–Godavari and Mahanadi offshore basin (Bay of Bengal) sediments: a comparative study of provenance. Mar. Pet. Geol. 60, 18–33.

SHORT COMMUNICATION:
Massive Erosion in Monsoonal Central India Linked to Late Holocene Landcover Degradation

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Abstract

Soil erosion plays a crucial role in transferring sediment and carbon from land to sea, yet little is known about the rhythm and rates of soil erosion prior to the most recent few centuries. Here we reconstruct a Holocene erosional history from central India, as integrated by the Godavari River in a sediment core from the Bay of Bengal. We quantify terrigenous fluxes, fingerprint sources for the lithogenic fraction and assess the age of the exported terrigenous carbon. Taken together, our data show that the monsoon decline in the late Holocene, later exacerbated by the Neolithic adoption and Iron Age extensification of agriculture on the Deccan Plateau, significantly increased soil erosion and the age of exported organic carbon. Despite a constantly elevated sea level since the middle Holocene, this erosion acceleration led to rapid continental margin growth. We conclude that in monsoon conditions, aridity boosts rather than supresses sediment and carbon export acting as a veritable monsoon erosional pump modulated by landcover conditions.

1. Soil Erosion in the Holocene

On decadal to millennial timescales, climate is the principal natural control on soil erosion within a watershed via changes in temperature and precipitation as well as their impact on vegetation type and cover (Allen and Breshears, 1998; Reichstein et al., 2013). Global sediment budgets for the Holocene indicate that humans surpassed these natural controls and became the main driver of soil erosion by at least 2000 years ago (Montgomery, 2007; Wilkinson and McElroy, 2007; Dotterweich, 2013). Transfer of sediment, carbon and solutes from land to ocean is of crucial importance for understanding continental margin architectures as well as carbon and other elemental cycles. For example, soils contain about two times more carbon than the atmosphere and, as a result, small changes in the residence time of organic carbon in soils can significantly affect the atmospheric inventory of carbon dioxide (Lal, 2004). Besides heterotrophic microbial respiration, erosion is the principal process that releases carbon from soils. Eroded carbon can subsequently be degraded/reburied along the aquatic continuum to the ocean (Stallard, 1998; Aufdenkampe et al., 2011; van Oost et al., 2012).

In the absence of historical documentation of human impacts, the complexity of soil erosion hampers the reconstruction of carbon transfer processes prior to the last few centuries (e.g., Hoffmann et al. 2013; Dotterweich, 2013; Vanwalleghem et al., 2017). Consequently, global carbon budgets implicitly assume steady state conditions for lateral transport and carbon degradation along the aquatic continuum in pre-industrial times (Battin et al., 2009; Regnier et al., 2013; Chappell et al., 2015). In contrast, abundant archaeological and geological evidence (e.g., van Andel et al., 1990; Bork and Lang, 2003; Bayon et al., 2012; Dotterweich, 2013) as well as modeling (Kaplan et al., 2010; Wang et al., 2017) suggests widespread impacts of early human landuse on continental landscapes, soil erosion and associated carbon transfer processes.

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Here we present a soil erosion history from the Indian peninsula recorded in a sediment core retrieved near the mouth of Godavari River (Fig. 1) in the Bay of Bengal (NGHP-01-16A at 16°35.6’N, 82°41.0’E; 1,268 m water depth; ~35 km from the river mouth; Collett et al., 2015). The age model for the core based on 11 radiocarbon dates on mixed planktonic foraminifera was previously published by Ponton et al. (2012). The Godavari basin was not affected by tectonics at the Holocene time scale, or glacial/snow meltwater and strong orographic precipitation, which augment and complicate the water and sediment discharge of the larger Himalayan rivers like the Ganges or Brahmaputra. Instead, it integrates rainfall from the core monsoon zone (CMZ), the region of central India that is representative for both the mean monsoon regime and its fluctuations over the peninsula (see Ponton et al., 2012 and references therein). Consequently, over 90% of Godavari’s water discharge into the Bay of Bengal derives from summer monsoon precipitation (Rao et al., 2005), making its sedimentary deposits a prime target for continental climate reconstructions and a repository for sedimentary proxies of erosion prior and after the Neolithic adoption of agriculture in central India.

2. The Godavari Sediment System

Originating at an elevation of 920 m in the Sahyadri coastal range (*aka* Western Ghats) near the Arabian Sea coast, the Godavari crosses the entire Indian peninsula toward the Bay of Bengal (Fig. 1a). Because the coastal range limits penetration of the Arabian Sea moisture delivered by the monsoon (Gunnell et al. 2007), precipitation in the Godavari basin primarily originates from the Bay of Bengal. As a result, the climate is most humid at the coast (i.e., Eastern Ghats range) and becomes increasingly arid toward the interior on the Deccan Plateau (Fig. 1b). The natural vegetation reflects this gradual decrease in moisture: the headwaters on the Deccan are dominated by C_4-plant thornbush savannah adapted to dry conditions, whereas C_3-flora (deciduous forests) are dominant in the Eastern Ghats (Asouti and Fuller, 2008; Fig. 1c).

Sediments transported by the Godavari are sourced from two major geological units (Bikshamaiah and Subramanian, 1980). The upper river basin developed on the Deccan Traps, a large igneous province consisting of relatively young flood basalts (Cretaceous to early Neogene) that largely span the Deccan Plateau. The lower river basin developed over old Proterozoic to Archaean crystalline igneous/metamorphic rocks of the Indian Craton (Fig. 1d). The relatively young Deccan basalts retain a highly radiogenic mantle-derived Nd isotope composition (εNd of +1±5) while the old continental crust of the Indian Craton has a relatively unradiogenic isotopic composition (εNd of -35±8), yielding a sharp contrast between geological end-members. Thus, the sediment provenance for the Godavari sediments can be deduced from the Nd isotopic signatures of the detrital inorganic fraction in our core because the Nd signal remains unmodified through bedrock weathering processes (McLennan and Hemming, 1992; DePaolo, 1988).

Black soils cover the Deccan Plateau whereas red soils are generally typical for the Eastern Ghats (Bhattacharyya et al., 2003; Fig. 1d). Although both types of soils have been affected by landuse since prehistorical times, the black soils of the arid to semi-arid Deccan appear to be the most degraded at present (Singh et al., 1992). Intense soil erosion within the basin is reflected by the inordinately large sediment load of the Godavari relative to its water discharge (Bikshamaiah and Subramanian, 1980). In contrast to the dynamic Himalayan rivers of the Indo-Gangetic alluvial plain, Godavari and its tributaries are incised in rock or alluvium and have relatively stable sandy channels. As for other rivers affected by storms (Edwards and Owens, 1991; Hilton et al, 2008), extreme rainfall events are disproportionately important for erosion in the Godavari watershed and in subsequent transport of sediments to the ocean (Kale, 2003).

Given their incised morphology, shifts in channel position in response to floods are however rare above the Godavari delta (Kale, 2002). Floodplains are limited in extent (2% of the basin; Bikshamaiah and Subramanian, 1980), and loss of sediments to overbank deposition is minor (Kale, 2002). Therefore storage is minimal in these intermediate alluvial reservoirs that normally would increase the residence time of sediments, including particulate organic carbon.

Once reaching the Bay of Bengal, sediment delivered by the Godavari has constructed a large Holocene delta (Rao et al. 2005; Cui et al., 2017). Offshore from the Godavari mouth, a persistent sediment plume extends over 300 km during the monsoon season when over 90% of the fluvial sediment is discharged (Sridhar et al., 2008). Because the shelf in front of the delta is unusually narrow (i.e., under 10 km at our core location) copious sediment deposition takes place directly on the continental slope, resulting in sediment accumulation rates as high as 250 cm/kyr; Ponton et al., 2012). Owing to the narrow shelf, changes in sea level would also have minimal effects on sediment deposition at our site, especially after the early Holocene when the global sea level reached within a few meters of modern values (Lambeck et al., 2014). This relatively simple sedimentary regime of the Godavari system in combination with the monsoon-dominated climatology and the simple geology of the Godavari basin allows for relatively straightforward interpretation of sediment sources and transfer processes. The monsoon washload is rapidly and directly delivered to the continental margin without significant trapping in intermediate depocenters along the river. As the suspended load makes up over 95% of the total sediment transported by the Godavari (Syvitski and Saito, 2007), the washload-derived terrestrial proxies are representative for the production of fine-grained sediment in the basin. Potential contributions from resuspension of shelf sediments cannot be excluded but are likely minor due to the narrowness of the shelf; furthermore, given the large sedimentation rates on the shelf itself (Forsberg et al., 2007), the resuspended sediment is expected to be quasi-contemporaneous with sediments arriving on the slope directly from the river plume.

3. Hydroclimate in the Core Monsoon Zone

We have previously reconstructed the Holocene paleoclimate using the same sediment core discussed herein (Ponton et al., 2012; Zorzi et al., 2015). Terrestrial reconstructions were based on the carbon isotopic compositions of higher plant leaf-wax biomarkers (i.e., long-chain *n*-alkanoic acids C_{26-32}) and pollen, whereas contemporaneous sea surface paleoceanographic conditions in front of the Godavari delta came from the oxygen isotopic composition of planktonic foraminifer *Globigerinoides ruber*. Sedimentary leaf waxes provide an integrated $\delta^{13}C$ record of the flora in the CMZ that document an increase in aridity-adapted vegetation (C_4 plants) after the monsoon maximum in the early Holocene (Ponton et al., 2012; Fig. 2). The overall trend of the $\delta^{13}C$ leaf wax record agrees with the view that the seasonality of Northern Hemisphere insolation (Ponton et al., 2012) led to progressively weaker monsoons over the Holocene. However, two clear aridification steps are evident: between ~5000 and 4500 years ago, and ~1,700 years ago (Fig. 2). Pollen from the same core (Zorzi et al., 2015) reinforce these conclusions: coastal forest and mangrove pollen (Fig. 2) that are typical for the more humid coastal regions of the Eastern Ghats and Godavari delta declined over the Holocene.

Dryness-adapted thornbush pollen from the Deccan Plateau increased substantially after the second aridification step ~1700 years ago, overlapping well with the maximum contribution of C_4 plant-derived leaf waxes (see Zorzi et al., 2015). For the same time interval, the ice volume-corrected oxygen isotopic composition of planktonic foraminifer *Globigerinoides ruber* documented a series of low values interpreted as high salinity events at the Godavari mouths (see Ponton et al., 2012). Together these continental and oceanic records suggest that the CMZ aridification intensified in the latest Holocene via a series of short drier episodes (Ponton et al., 2012). This interpretation is reinforced by speleothem-derived records from central and northern India for the past thousand years (Sinha et al., 2011), and the overall evolution of the CMZ hydroclimate as seen from our core is supported by local reconstructions from the Lonar crater lake in central India (Prasad et al., 2014; Sarkar et al., 2015), Godavari delta (Cui et al., 2017) and other records from the larger Indian monsoon domain (Gupta et al., 2003; Fleitmann et al., 2003; Prasad and Enzel, 2006; Berkelhammer et al., 2012; Dixit et al., 2014b).

4. Erosion in the Godavari Basin

The Holocene sediment flux at our core location (Fig. 2) is representative for the Godavari continental slope (Mazumdar et al., 2009; Ramprasad et al. 2011; Joshi et al., 2014; Usapkar et al., 2016) and is driven by changes in the siliciclastic sedimentation rate as dilution by biogenic carbonates is less than 5% (Johnson et al., 2014). Despite a lower sea level at the time, the flux was relatively small in the early Holocene (~25 g/cm^2/kyr) but began to increase after 6000 years ago (~40 g/cm^2/kyr), as soon as the monsoon started to decline but well before the adoption of Neolithic agriculture and settlement of the savannah zone of the central peninsula (~4500 years ago; Fuller, 2011). Between 4000 and 3500 years ago permanent agricultural settlements spread throughout the Deccan Plateau. The associated small-scale metallurgy (copper-working) requiring firewood together with the agricultural intensification probably also affected erosion via widespread deployment of two cropping seasons (Kajale, 1988; Fuller and Madella, 2001). As the climate remained arid, sediment fluxes stayed high despite a phase of agricultural abandonment and depopulation between ~3,200 and 2,900 years ago (Dhavalikar, 1984; Roberts et al., 2016).

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A further step increase in the sediment flux (~90 g/cm^2/kyr on average) occurred after ~3000 years ago, this time with no apparent concomitant change in climate. The Nd isotopic signal points to an increase in the Deccan sedimentary output at the time, after a muted variability earlier in the Holocene when the Indian Craton consistently provided ~50-60% of the sediments (Fig. 2; see Supplementary Materials). Ferrimagnetic minerals interpreted as originating from the Deccan (Sangode et al., 2001; Kulkarni et al., 2014) also increase in late Holocene sediments in the Godavari delta (Cui et al., 2017) and Bay of Bengal (Kulkarni et al., 2015) supporting our interpretation. Augmented Deccan input was suggested for the Godavari delta even earlier after ~6000 years ago (Cui et al., 2017), in step with the initial aridification. New improvements in agricultural technology became widespread in the Deccan Plateau, including use of iron agricultural tools (Mohanty and Selvakumar, 2001) that required firewood-fuelled smelting Fuller, 2008). A new phase of agricultural settlement began in the middle Godavari basin (eastern Maharashtra) between ~3000 to ~2800 years ago (Brubaker 2000). However, the largest boost in sediment flux occurred after ~2000 years ago, when the monsoon reached its driest phase and when further increases in population occurred resulting in the founding of towns and the first cities of the region at the beginning of the Historic period (Allchin 1995; Parabrahma Sastry 2003). This doubling in sediment flux relative to the early Holocene values involved a basin-wide increase in erosion. The contribution from the Deccan Plateau, although at its maximum according to the Nd isotope mixing model, only accounts for a 15% shift in sediment source (Fig. 2).

Overall, watersheds with high precipitation have higher discharge and discharge magnitude is considered a primary regulator for sediment and carbon erosional fluxes to the ocean (e.g., Summerfield and Hulton, 1994; Ludwig et al., 1996; Galy et al., 2015). However, our Godavari record shows that erosional output is maximized by aridity because significant rain and seasonal floods still occur during the summer monsoon season (Mujumdar et al., 1970; Kale, 2003). Aridification and/or agricultural expansion lead to changes in vegetation type (i.e., forest decrease in favour of savannah) and cover (i.e., shrinking of naturally vegetated lands in favour of agricultural and/or degrading arid lands) that exacerbate soil erosion (i.e., Langbein and Schum, 1958; Dunne, 1979; Walling and Webb, 1983; Istanbulluoglu and Bras, 2005; Vanacker et al., 2007; Collins and Bras, 2008).

5. Carbon Export from the Godavari Basin

The terrigenous organic carbon exported by rivers consists of a mixture of dissolved and particulate components derived from contemporary vegetation and of carbon stored in bedrock, soils and fluvial sediments that may be significantly pre-aged (Smittenberg et al., 2006; Galy and Eglinton, 2011; Feng et al., 2013). On the Godavari slope, the terrigenous fraction dominates the total organic carbon (TOC) in marine sediments (Johnson et al., 2014). In agreement with this, TOC radiocarbon ages in our core have been previously found to be remarkably similar to co-located ages of the strictly terrigenous higher plant leaf wax fraction (Ponton, 2012). This age similarity also excludes interferences from within-river biological productivity (e.g., Eglinton and

Hamilton, 1967; Eglinton and Eglinton, 2008). To assess the variability of the terrigenous carbon age exported by Godavari River based on this understanding we used high resolution TOC radiocarbon measurements to calculate radiocarbon age offsets relative to the atmosphere (Soulet et al., 2016; see Supplementary Materials). Over the Holocene, these biospheric organic carbon radiocarbon age offsets in our core mirror the history of erosion in the basin (Fig. 2).

As a first order observation, TOC ages (Fig. 2 and Supplementary Materials) are significantly older (~200 to 2000 ^{14}C years) than their depositional age in our Godavari core. Before 5000 years ago the bulk organic carbon radiocarbon age offset were ~600 ^{14}C years old on average. In contrast, the highly erosional regime under both climatic and early human pressure in the late Holocene led to the export of significantly older carbon from the terrestrial biosphere, i.e., ~1300 ^{14}C on average. This increase in radiocarbon age offset occurred largely during the two aridification steps identified by Ponton et al. (2012): more abruptly between ~5000 and 4500 years ago and more gradually after ~1700 years ago (Fig. 2).

In the absence of significant storage in alluvial sediments in the Godavari catchment, several processes can explain the doubling in age offset over the Holocene: an overall slowing of soil carbon turnover in the drying climate of central India, a decrease in TOC contribution from contemporaneous vegetation relative to older (pre-aged) soil carbon input and/or deeper exhumation of soils contributing increasingly older carbon. Given the drastic changes in vegetation cover and increase in erosion in the Godavari basin, a decrease in soil turnover is unlikely during the Holocene aridification process (Carvalhais et al. 2014). In turn, the good agreement between the pollen and leaf-wax δ^{13}C records in our core (Ponton et al., 2012; Zorzi et al., 2015) with independent monsoon reconstructions suggests sustained delivery of recently fixed biospheric organic carbon to the delta. Thus, the doubling in age offset over the Holocene is best explained by increasing contributions from an older soil component, which could only come through deeper erosion. Because the age of soil organic carbon in soil profiles increases with depth (Trumbore, 2009), older mixtures imply a deeper soil erosion, whether uniform, or through gullies, which are common especially on the Deccan Plateau (Kothyari, 1996).

6. The Monsoon Erosional Pump

Overall, these multiple lines of evidence indicate that soil erosion in the CMZ, as integrated by the Godavari River, increased throughout the basin immediately as climate began to dry at the end of mid Holocene, and was further enhanced by Deccan agricultural activities in the late Holocene. The likely mechanism for this is the extreme seasonal distribution of the rainfall that characterizes the monsoon (Wang and Ding, 2008), which promoted erosion on the more sparsely vegetated landscapes (Molnar, 2001; DiBiase and Whipple, 2011; Plink-Bjorklund, 2015). Our findings thus point to a veritable "monsoon erosional pump" that accelerates during minimum landcover conditions when the protective role of vegetation is reduced, whether naturally or by humans. The volume of total eroded sediments since the mid Holocene must have been considerable as the continental margin growth accelerated with the shelf edge aggrading ~80 meters in the last ~2000 years alone (Forsberg et al., 2007).

This "landcover-mode" of the monsoon erosional pump must have been active before the Holocene as well, affecting the transfer of terrigenous sediment, solutes and carbon from land to the ocean. The beat of monsoon precipitation on orbital timescales is not well constrained but considered to be modulated by at a combination of precession and obliquity frequencies based on monsoon wind reconstructions (e.g., Clemens and Prell, 2003). Such complex variability did not inevitably follow the sea level cyclicity (e.g., Goodbred and Kuehl, 2000), which is usually assumed to control most of the sediment transfer from land to the deep ocean (see Blum and Hattier-Womack, 2009 and references therein for an analysis underlining the increased recognition for a climate role). Thus untangling the effects of the monsoon is difficult especially during the Quaternary (e.g., Phillips et al., 2014), but may be easier to discern earlier when the sea level change magnitude was reduced. Landcover effects are less likely to occur in the upper basins of Himalayan monsoonal rivers where elevation (i.e., temperature), orographic precipitation as well as other sources of water such as snow and glaciers promote ecological stability (Galy et al., 2008a;). The erosional pump in these high, steep regions is still active due to monsoonal seasonality but in a "topographic-mode" dominated primarily by landslides (Montgomery and Brandon, 2002; but see Olen et al., 2016 for an alternative viewpoint). However, the landcover-mode for the erosional pump should still be active in their lower basins where aridity controls vegetation type and cover (e.g., Galy et al. 2008b).

Recent coupled erosion-carbon cycling modeling suggests that long-term anthropogenic acceleration of erosion has had a significant impact on the global carbon cycle by intensifying the burial of terrigenous carbon (Wang et al., 2017). Whereas the monsoon domain only covers ~15% of the Earth's surface (Hsu et al., 2011), it used to export to the ocean ~70% of the sediment load from the Earth's largest rivers (see Syvitski and Saito, 2007 for a compilation for pre-damming conditions). Therefore, we suspect that the cumulative effect of the monsoon erosional pump on the carbon budget was substantial in augmenting the burial of terrigenous carbon during the Holocene and needs to be estimated for inclusion in assessments of the net soil–atmosphere carbon exchange.

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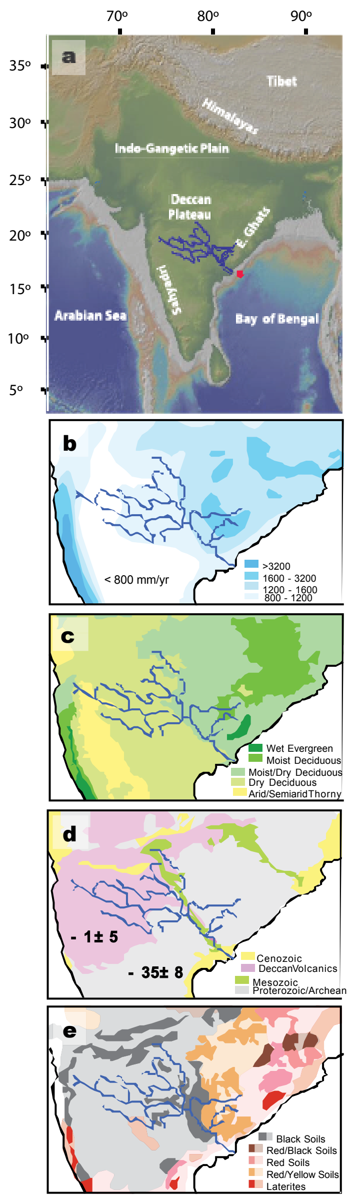
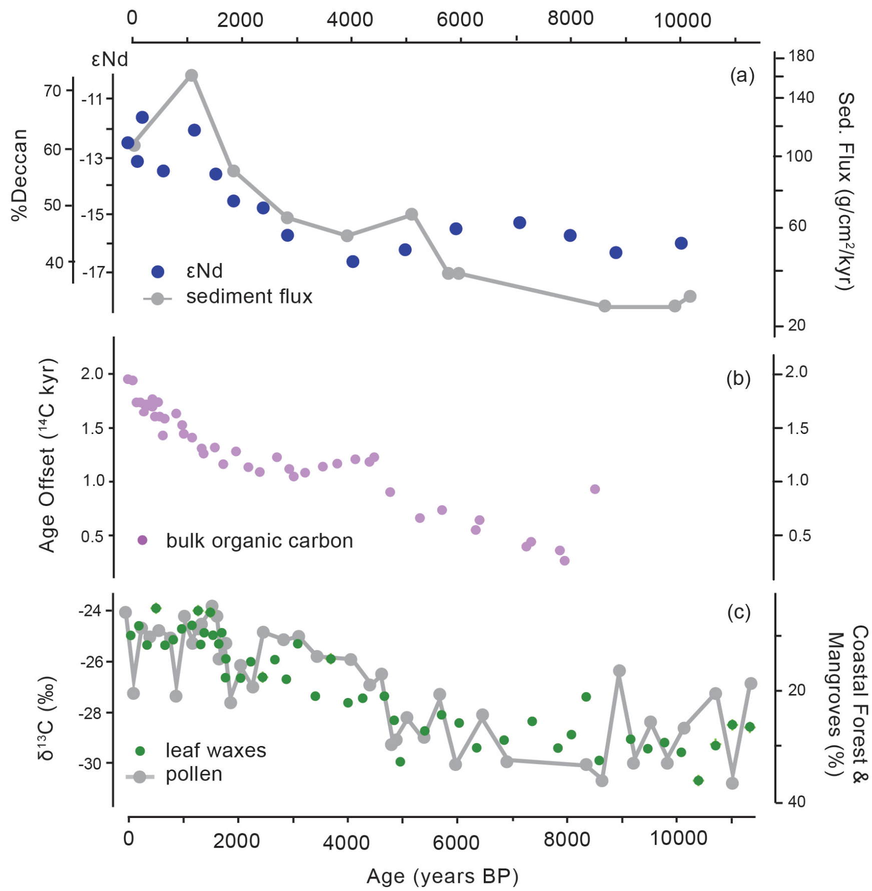


Figure 1. Godavari River drainage basin in its (a) physiographical, (b) hydroclimatic (Asouti and Fuller, 2008), (c) ecological (Asouti and Fuller, 2008), (d) geological (Bikshamaiah and Subramanian, 1980) and (e) soil cover context (NBSS&LUP, 1983). Core NGHP-01-16A location is indicated in (a) by the red dot. Average bedrock εNd values are shown in (d).

Figure 2. Paleoenvironmental reconstructions from core NGHP-01-16A for the CMZ as integrated by the Godavari River: (a) Sediment fluxes as mass accumulation rates and sediment sources from Nd isotope fingerprinting (Deccan Trap sediment contribution is estimated from a two-end member model; see text and Supplementary Materials); (b) TOC radiocarbon age offset relative to depositional age; (c) Hydroclimate and ecology from pollen (Zorzi et al., 2015) and leaf wax carbon isotopes (Ponton et al., 2012).



SHORT COMMUNICATION:
Massive Erosion in Monsoonal Central India Linked to Late Holocene Landcover Degradation

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Supplementary Materials

The detrital fraction provenance was assessed using Nd isotopic ratios (Supplementary Table 1). Nd chemistry was done with conventional ion chromatography following the method of Bayon et al. (2002). Nd analyses were performed on the NEPTUNE multi-collector ICP-MS at WHOI with the internal precision of 5-10 ppm (2 sigma). The external precision, after correction to value for LaJolla standard ($^{143}Nd/^{144}Nd$=511847) is approximately 15 ppm (2 sigma). $^{143}Nd/^{144}Nd$ isotopic composition is expressed here as εNd (DePaolo and Wasserburg, 1976) units relative to ($^{143}Nd/^{144}Nd$)CHUR= 0.512638 (Hamilton et al., 1983). Very low εNd values are generally found in continental crusts, whereas higher (more positive) εNd values are commonly found in mantle-derived melts (DePaolo, 1988), such as those of large igneous provinces.

The average εNd for the Deccan basalts is +1 ± 5 and for the Indian craton is -35 ± 8 (GEOROC Database, Geochemistry of Rocks of the Oceans and Continents, Max Plank Institute for Chemistry, Mainz, Germany, http://georoc.mpch-mainz.gwdg.de/). The measured εNd value of a sample was expressed as a simple mixture of sediment derived from the two end-members:

$$\varepsilon \mathrm{Nd}_{Sample} = f \cdot \varepsilon \mathrm{Nd}_{Deccan} + (1-f) \cdot \varepsilon \mathrm{Nd}_{Craton}$$

Where (f) is the fraction of Deccan derived sediments, ($1-f$) the fraction of Craton derived sediments in the mixture, and f is a number between 0 and 1.

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Sediment fluxes (Supplementary Table 2) were constructed as mass accumulation rates assuming negligible carbonate inputs (Johnson et al., 2014) using measured dry bulk densities on the samples used for foram radiocarbon dating and sedimentation rates from the age model of Ponton et al. (2012).

The high resolution series of bulk TOC ^{14}C content was measured at the Geological Institute and the Laboratory of Ion Beam Physics, ETH Zürich (Supplementary Table 3). The bulk TOC ^{14}C measurements made at ETHZ are detailed in McIntyre et al. (2016). Duplicates of 70-90 mg of freeze-dried sediment samples were weighed in pre-combusted silver boats (Elementar) and fumigated with HCl to remove carbonate (Komada et al., 2008). The samples were subsequently neutralized and dried over solid NaOH pellets to remove residual acid. The samples were then wrapped in a second tinfoil boats (Elementar9 and pressed prior to analysis.

Samples were graphitized by the automated graphitization equipment (AGE) and analysed for ^{14}C using the MICADAS system (Ionplus) and an ampoule cracker system following the procedure outlined in Wacker et al. (2013). The other batch was then run as gas on the coupled EA-IRMS-AMS system at ETHZ. The data for the TOC ^{14}C content showed that samples analysed using graphite and CO_2 are within 2σ of each other (McIntyre et al., 2016).

For microscale (≤ 20 μg C) AMS ^{14}C analysis, comprehensive procedural blank assessment is critical in order to constrain analytical uncertainty (Drenzek, 2007; Santos et al., 2010; Tao et al., 2015). An evaluation of the complete procedure used here (chemical extraction, derivatization, PCGC isolation, final clean-up and combustion steps) yielded a procedural blank of 1.2±0.4 μg C per 30 PCGC injections, with an $\Delta^{14}C$ of –382±126‰ (Tao et al., 2015). Separate assessment of modern and fossil C blanks yielded 0.8±0.2 μg of modern C contamination (i.e., $\Delta^{14}C$ = 0‰) and 0.5 ± 0.1 μg of dead C contamination (i.e., $\Delta^{14}C$ = –1000‰), with a combined procedural blank of 1.3±0.2 μg C per PCGC 30 injections with a $\Delta^{14}C$ value of –325±129‰. From this assessment as well as a previous assessment (Drenzek, 2007), we estimate that the analytical uncertainty for ^{14}C analysis of FAs ranges from 6 to 40‰ (ave., 12‰).

The raw and calibrated radiocarbon age models used to estimate depositional ages are from Ponton et al. (2012). The age of the bulk TOC at the time of their deposition was estimated by taking the offsets between their radiocarbon content and the interpolated reservoir-corrected foraminifera-based radiocarbon age (Supplementary Table 3). The reservoir correction used was 400 years. Taking a conservative approach we calculated the propagated error for the radiocarbon age offsets (Supplementary Table 3) as:

$$err.\ offset = ((err.\ TOC\ ^{14}C\ measurement)^2 + (max.\ err.\ foram\ ^{14}C\ measurement)^2)^{1/2}$$

where the maximum error for the foraminifera ^{14}C measurements used in the age model was 55 ^{14}C years (Ponton et al., 2012). The resulting errors for the offset range between 63 and 80 years.

Supplementary Table 1. Downcore measurements of $^{143}Nd/^{144}Nd$ composition with corresponding εNd for the Holocene section of NGHP-01-16A in front of Godavari delta.

Depth (mbsf)	Age (yr)	143Nd/144Nd	εNd
0.00	59	0.511999	-12.46
0.16	159	0.511973	-12.97
0.32	256	0.512035	-11.76
0.80	542	0.511946	-13.50
1.70	1085	0.512018	-12.09
2.50	1627	0.511945	-13.52
3.00	2019	0.511888	-14.63
3.60	2567	0.511888	-14.63
4.00	2990	0.511830	-15.76
4.80	4002	0.511780	-16.74
5.40	4936	0.511809	-16.17
6.00	6043	0.511847	-15.43
6.50	7116	0.511856	-15.25
6.90	8082	0.511832	-15.72
7.20	8873	0.511801	-16.33
7.60	10024	0.511822	-15.92

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Depth (mbsf)	Age (kyr)	143Nd/
0.00	59	0.511
0.16	159	0.511
0.32	256	0.512
0.80	542	0.511
1.70	1085	0.512
2.50	1627	0.511
3.00	2019	0.511
3.60	2567	0.511
4.00	2990	0.511
4.80	4002	0.511
5.40	4936	0.511
6.00	6043	0.511
6.50	7116	0.511
6.90	8082	0.511
7.20	8873	0.511
7.60	10024	0.511

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Supplementary Table 2. Downcore estimates of sediment fluxes for the Holocene section of NGHP-01-16A in front of Godavari delta based on calibrated foraminifera ^{14}C depositional ages.

Depth (mbsf)	Age (yr)	Sediment Flux (g/cm^2/kyr)
0.075	0	87.0
1.475	1104	151.2
2.975	1852	70.7
4.045	2895	47.8
4.775	4046	41.8
5.355	5331	49.2
6.015	5996	31.0
6.435	6198	31.0
7.215	9056	23.7
7.655	10314	23.7
7.885	10619	25.8

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Supplementary Table 3. Downcore measurements of bulk TOC measured at ETH and offsets to foram ^{14}C depositional ages for the Holocene section of NGHP-01-16A.

Depth (mbsf)	Age (kyr)	^{14}C Depositional Age (kyr)	TOC ^{14}C Age (kyr)	Error TOC ^{14}C Age (kyr)	^{14}C Age Offset (kyr)	Max. Error ^{14}C Age Offset (kyr)
0.265	223	31	1844	51	1813	75
0.350	274	117	1928	32	1811	63
0.440	328	205	1833	32	1627	63
0.485	355	249	1869	32	1620	63
0.545	391	305	1924	51	1619	75
0.660	459	410	1948	51	1538	75
0.755	516	494	2098	51	1604	75
0.840	566	567	2206	51	1639	75
0.890	595	609	2251	32	1642	63
0.940	625	650	2238	32	1588	64
1.035	681	726	2246	51	1519	75
1.085	711	766	2389	51	1623	75
1.145	746	812	2306	32	1494	64
1.235	800	881	2233	32	1352	64
1.305	842	933	2421	51	1488	75
1.635	1044	1166	2709	33	1542	64
1.825	1164	1293	2712	52	1419	75
1.865	1190	1320	2673	32	1354	64
2.060	1318	1446	2783	32	1337	64
2.315	1493	1607	2850	52	1243	76
2.365	1529	1638	2837	32	1198	64
2.640	1732	1811	3069	52	1258	76
2.835	1884	1935	3033	52	1098	76
3.090	2096	2100	3327	52	1227	76
3.315	2295	2253	3353	32	1101	64
3.365	2341	2287	3364	52	1077	76
3.560	2528	2427	3466	32	1039	64
3.855	2831	2652	3835	33	1183	64
3.915	2896	2700	3842	53	1142	76
4.085	3086	2842	3902	53	1060	76
4.130	3138	2881	3882	52	1001	76
4.310	3354	3042	4086	33	1044	64
4.575	3693	3299	4386	53	1088	76
4.745	3925	3476	4590	54	1114	77
4.965	4243	3723	4871	34	1148	65
5.140	4511	3934	5063	34	1129	65
5.180	4574	3984	5141	33	1157	64
5.355	4860	4213	5085	54	872	77
5.655	5384	4640	5301	34	661	65
5.865	5778	4969	5702	34	733	65
6.165	6382	5482	6063	34	581	65
6.200	6455	5546	6210	55	664	78
6.575	7290	6278	6704	56	427	78
6.605	7360	6340	6810	35	470	65
6.825	7893	6820	7218	56	399	79
6.860	7981	6899	7208	35	308	65
7.065	8510	7384	8276	58	892	80

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Depth (mbsf)	Age (kyr)	^{14}C Depositiona (kyr)
0.265	223	31
0.350	274	117
0.440	328	205
0.485	355	249
0.545	391	305
0.660	459	410
0.755	516	494
0.840	566	567
0.890	595	609
0.940	625	650
1.035	681	726
1.085	711	766
1.145	746	812
1.235	800	881
1.305	842	933
1.635	1044	1166
1.825	1164	1293
1.865	1190	1320
2.060	1318	1446
2.315	1493	1607
2.365	1529	1638
2.640	1732	1811
2.835	1884	1935
3.090	2096	2100
3.315	2295	2253
3.365	2341	2287
3.560	2528	2427
3.855	2831	2652
3.915	2896	2700
4.085	3086	2842
4.130	3138	2881
4.310	3354	3042
4.575	3693	3299
4.745	3925	3476
4.965	4243	3723
5.140	4511	3934
5.180	4574	3984
5.355	4860	4213
5.655	5384	4640
5.865	5778	4969
6.165	6382	5482
6.200	6455	5546
6.575	7290	6278
6.605	7360	6340
6.825	7893	6820
6.860	7981	6899
7.065	8510	7384

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