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Late Cenozoic cooling favored glacial over tectonic controls on sediment supply to the western Gulf of Mexico

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ABSTRACT

Terrigenous marine sediment records the landscape response to climate and tectonic perturbations. Here, we determined the source of Miocene–Pleistocene debris in the western Gulf of Mexico (WGOM) to understand changes in sediment supply during a greenhouse-glacial transition. Sediment composition at Deep Sea Drilling Project (DSDP) Sites 3, 87, and 89–91 shows a reversal in provenance following the onset of Pleistocene glaciation. During Miocene time, sediment was supplied to the deep WGOM from tectonically active, tropical highlands of southern Mexico, accumulating as sediment-gravity-flow deposits across broad deep-water fan systems. Then, following the mid-Pleistocene transition (ca. 0.7 Ma), the WGOM saw sustained (10^5 yr) influx of sediment from the north due to glacial erosion, high discharge, and expanded drainages across the Mississippi catchment. This major provenance shift points to the importance of glacial controls on marine sediment supply during late Cenozoic cooling.

INTRODUCTION

The late Cenozoic Era was marked by a cooling, rapidly fluctuating climate and widespread glaciation, resulting in what appears to have been a several-fold increase worldwide in marine sediment accumulation after ca. 4 Ma (Bell and Laine, 1985; Hay et al., 1988). There is considerable debate (see Molnar, 2004) around the driving forces behind this influx, with low sea level and uplift (Hay et al., 1988), landscape disequilibrium (Peizhen et al., 2001), or glaciation (Bell and Laine, 1985; Champagnac et al., 2012; Herman et al., 2013) cited as possible global mechanisms. Understanding these controls on sediment supply will help to constrain the dynamics between climate and the geosphere, a feedback system that regulates global change.

The western Gulf of Mexico (WGOM) basin is well positioned to study large-scale sediment supply under varying conditions, because it straddles the Tropic of Cancer and is bordered to the south and west by active tectonic regions of Mexico, and to the north by the wide coastal plain of the southern United States (Fig. 1A). Deep-water sediment of the WGOM was the first target of R/V *Glomar Challenger* on Leg 1 of the Deep Sea Drilling Project (DSDP) (Ewing et al., 1969), and again in 1970 on Leg 10 (Worzel et al., 1973).

The Sigsbee Abyssal Plain extends hundreds of kilometers across the WGOM (Fig. 1A) and is underlain by ~4 km of Jurassic to Neogene stratigraphy (Ladd et al., 1976). The continental shelf is wide along the Northern Gulf Salt Province and Campeche Bank, but it narrows along its western margin. The continental slope here is cut by two major canyon-like features: the Campeche Trough, comparable in scale to the Mississippi Canyon, and the Veracruz Tongue.

Proximal highlands to the west and south (Fig. 1A) are the result of mostly continuous late Cenozoic tectonic activity, including subduction of the Rivera-Cocos plates beneath North America and passage of the Caribbean plate to the south. The Trans-Mexican Volcanic Belt and Eastern Alkaline Province consist of arc-related intermediate-mafic rocks erupted at ca. 15–0 Ma (Ferrari et al., 2005). To the south, the Chiapas Massif contains middle–late Miocene plutonic and older basement rocks (Schaaf et al., 2002) rapidly exhumed in the late Miocene due to North American–Caribbean transpression (Witt et a., 2012; Molina-Garza et al., 2015).

The Mexican highlands contrast with the more muted landscapes north of the Rio Grande. Rivers reaching the northern WGOM margin are sizable and largely drain low-relief terrain, although some headwaters tap the Rocky Mountains. Also, a wide (~150 km) coastal plain has formed a depositional buffer between the Laramide–Rocky Mountains and other highlands and the continental margin since late Paleocene time (Galloway et al., 2011; Xu et al., 2017).

Here, we used an integrated provenance approach to characterize the terrigenous sediment at DSDP Sites 3, 87, and 89–91 (Fig. 1B), with comparisons to the Mississippi Fan and onshore sediment source areas, in order to identify the driving forces behind WGOM deposition during late Cenozoic cooling.

LATE CENOZOIC SEDIMENT DELIVERY TO THE WGOM

The stratigraphy and lithology of the studied cores (Figs. 1B and 1C) roughly correlate to the seismic designations of Ladd et al. (1976). Miocene strata are prominent across the southern WGOM and indicate average sedimentation rates (a.s.r.) of ~4–6 cm/10^3 yr, largely by sediment-gravity-flow deposition across a broad submarine fan (Ewing et al., 1969; Worzel et al., 1973), where the coarsest turbidites were recovered at Site 91 (Fig. 1C). The Pliocene section is thinner (a.s.r. ~2–4 cm/10^3 yr) and finer grained with more carbonate ooze, an indication that clastic sediment delivery to the deep WGOM had significantly slowed by this time. Pleistocene sediment indicates rapid deposition (a.s.r. ~10–20 cm/10^3 yr) of muddy fine-sand turbidites (Ewing et al., 1969; Worzel et al., 1973).

The provenance of deep-water WGOM sediment shifted with time. The tectonic affinity of sandstone framework grains changes from transitional–dissected volcanic arc during Miocene time to mixed terrane during Pleistocene time (Fig. 2A; Item DR1 in the GSA Data

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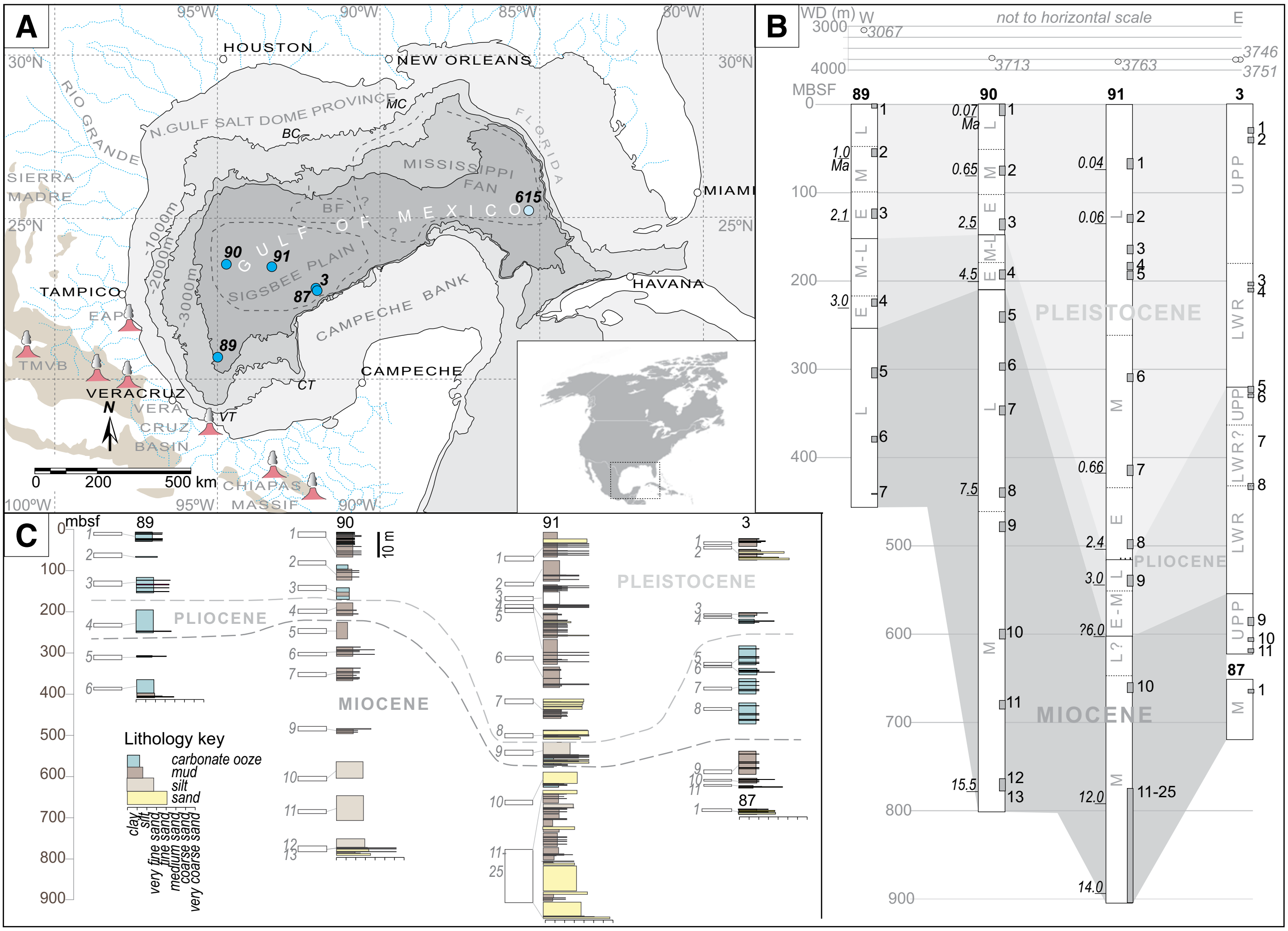

Figure 1. A: Gulf of Mexico region, including bathymetry, Mexican highlands (brown >1000 m), Trans-Mexican Volcanic Belt (TMVB) and Eastern Alkaline Province (EAP), Mississippi Fan (Bouma et al., 1986; Fildani et al., 2016), and Bryant Fan (BF; Tripsanas et al., 2007). MC—Mississippi Canyon; BC—Bryant Canyon; CT—Campeche Trough; VT—Veracruz Tongue. B: Depth (meters below sea floor [MBSF]) of Deep Sea Drilling Project (DSDP) cores (dark gray, numbered boxes). Age model (biostratigraphy) and ages in millions of years (Ma) are from Ewing et al. (1969) and Worzel et al. (1973), with their age divisions: early (E), middle (M), late (L), lower (LWR), upper (UPP). WD—water depth (m). C: Lithology of recovered core, expanded 10× vertically.

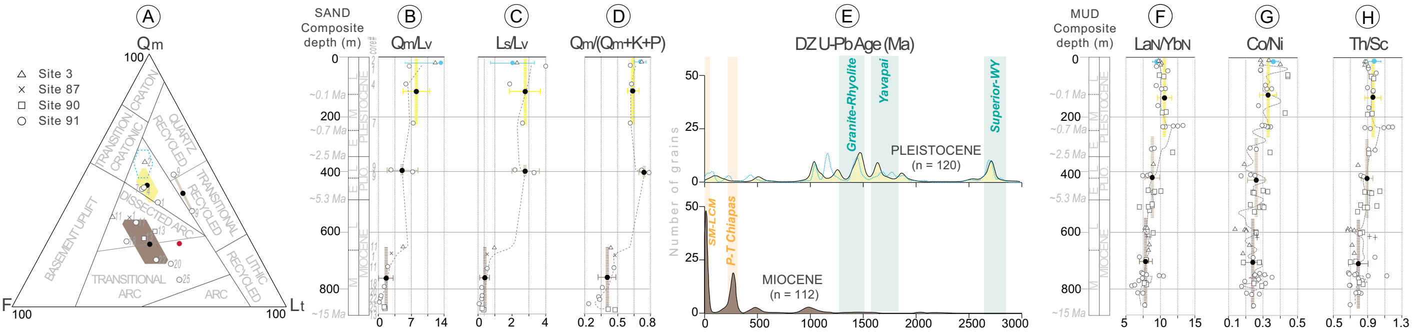

Figure 2. A: Monocrystalline quartz (Qm), feldspar (F), and total lithic grains (Lt) in sand of Deep Sea Drilling Project (DSDP) cores (*n* = 15; Item DR1 [see footnote 1]), shaded one standard deviation around mean (black dot): Miocene (brown), Pliocene (light brown), and Pleistocene (yellow). Blue dashed line is one standard deviation around mean from DSDP Site 615 on the Mississippi Fan (*n* = 8; Fildani et al., 2018). Red dot is mean middle Miocene sandstone from the Playuela field, Veracruz Basin (*n* = 22; Paredes et al., 2009). B–D: Grain-type ratios with composite depth below seafloor (m), where black dot is mean over age span (vertical bar) within one standard deviation (horizontal bar). Ls—lithic sedimentary; Lv—lithic volcanic; K—potassium feldspar; P—plagioclase feldspar. Dashed curves are running average (period = 2). E: Kernel density (KDE) curve for detrital zircon (DZ) U-Pb ages at DSDP Site 3 (Item DR2). Blue line is coeval Pleistocene sand at Site 615 (core 29; *n* = 82; Fildani et al., 2018). Age provinces unique to Mississippi catchment are Superior-Wyoming (WY; 2700–2800 Ma), Yavapai (1600–1800 Ma), and Granite-Rhyolite (1300–1500 Ma) (Fildani et al., 2016). Age provinces unique to southern Mexico are Permian-Triassic (P-T) Chiapas (240–290 Ma; Schaaf et al., 2002; Weber et al., 2007; Witt et al., 2012) and Southern Mexico–late Cenozoic magmatic fields (SM-LCM; <15 Ma; Ferrari et al., 2005; Molina-Garza et al., 2015). F–H: Geochemical ratios in mud (*n* = 40; Item DR3). N—chondrite normalized. Running average period = 5. PLIO—Pliocene.

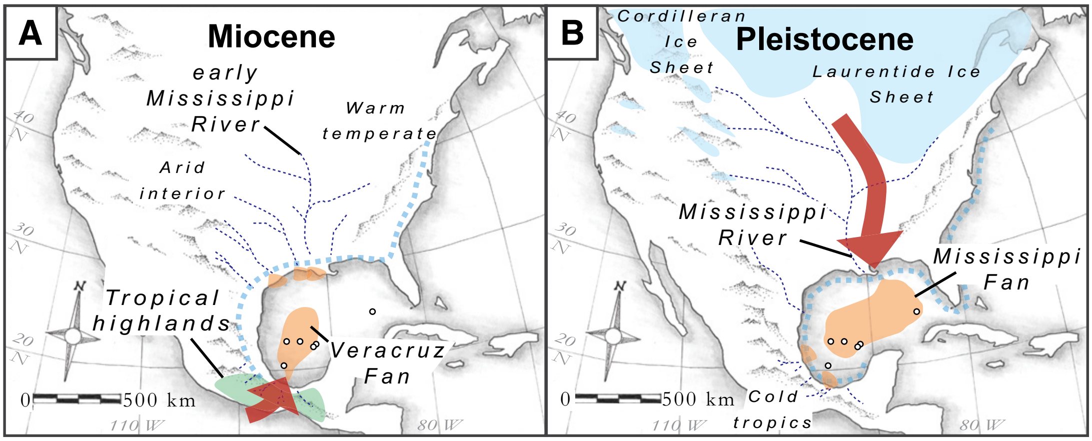

Figure 3. Paleogeographic scenarios for sediment supply to the western Gulf of Mexico (WGOM) in the (A) Miocene and (B) Pleistocene. Paleodrainages for Miocene and Pleistocene are from Xu et al. (2017) and Galloway et al. (2011), respectively. Paleoclimate is from Boucot et al. (2013). Sediment-source area for Miocene WGOM is shown in green; Laurentide and Cordilleran ice sheets and Rocky Mountain glaciers are in blue. Open circles are Deep Sea Drilling Project (DSDP) study sites. Scale bar is in km.

Repository[1]). Miocene sand is dominated by andesitic volcanic grains and plagioclase, with secondary quartz and potassium feldspar. The similarity to onshore Miocene sands from the Veracruz Basin (Paredes et al., 2009) suggests that the deep-water Miocene fan tapped into a southern Mexico source. In contrast, Pliocene sand is rich in carbonate lithic grains and quartz and plots separately across the quartzose–transitional recycled fields, suggesting limited sourcing from southern Mexico. Pleistocene sand is distinct from Miocene sand and closely mimics that of the Mississippi Fan, with fine-grained size and abundant quartz, potassium feldspar, and sedimentary lithic fragments. Through time (Figs. 2B–2D), there is an increase in quartz and sedimentary lithic grains compared to volcanic lithic grains and an increase in quartz compared to feldspars, as well as clear compositional separation between Miocene, Pliocene, and Pleistocene sands.

Detrital zircon (DZ) U-Pb age components at DSDP Site 3 (Fig. 2E) support (1) a southern Mexico (Chiapas region) source for Miocene sediment and (2) a northern (Mississippi catchment) source for Pleistocene sediment in the deep WGOM. In Miocene sand, age components at ca. 10 Ma, ca. 200 Ma, and ca. 500 Ma correspond to Miocene, Permian–Jurassic, and Cambrian intrusive rocks of the Chiapas massif (Schaaf et al., 2002; Weber et al., 2007; Witt et al., 2012; Molina-Garza et al., 2015) and late Cenozoic volcanic rocks of the Trans-Mexican Volcanic Belt and Eastern Alkaline Province (Ferrari et al., 2005). The components do not include Sierra Madre or Laramide age distributions common to similarly aged sand from the Rio Grande and other catchments to the west and north (Xu et al., 2017), long assumed to be the source for volcanic-rich debris in the WGOM (Ewing et al., 1969; Worzel et al., 1973). In contrast, late Pleistocene sand has a DZ signature like that observed for coeval (ca. 0.04–0.07 Ma) sand in the distal Mississippi Fan at Site 615, with prominent Granite-Rhyolite, Yavapai, and Superior Province components derived from northern North American terranes (Fildani et al., 2016) and lacking components unique to the Chiapas region. The change in DZ ages at Site 3 aligns with the petrographic trends (Figs. 2A–2D), which hold across all DSDP sites in the deepest WGOM and together support a south-to-north provenance reversal between the Miocene and Pleistocene Epochs.

We looked to the geochemistry of WGOM muds for a more continuous record of sources for late Cenozoic sediment (Figs. 2F–2H). Most useful are the ratios of immobile trace and rare earth elements sensitive to bedrock composition, i.e., those elements that are transferred in their original proportions from bedrock to secondary clays during source-area weathering (McLennan, 1989). The La_N/Yb_N, Co/Ni, and Th/Sc ratios signify the proportion of felsic to mafic bedrock (Taylor and McLennan, 1985; Tang et al., 2016), where increasing values indicate a more felsic sediment source. Elemental ratios in WGOM muds show a subtle break between samples of middle–late Miocene and latest Miocene age. Below this break, ratios are relatively steady through time and indicate a strong mafic component. Above the break, the ratios shift slightly toward the right, before steadily increasing during Pliocene and earliest Pleistocene deposition. Finally, the most significant provenance change was in full effect by the end of the mid-Pleistocene transition (ca. 0.7 Ma), where muds contain significant felsic components similar to muds of the Mississippi Fan.

GLACIAL OVERRIDE OF TECTONIC CONTROLS ON SEDIMENT SUPPLY

Taken together, our observations point to an ~180° shift in sediment provenance for the deep-water WGOM between the Miocene and Pleistocene Epochs, suggesting two very different sediment production systems, each sustained over long ($>10^5$ yr) periods of time (Fig. 3). The middle–late Miocene scenario—high sediment supply to a distal basin—is notable because the continental source area was probably less than 300 km wide and 500 km long, with relatively short river drainages (Fig. 3A). Warm, tropical conditions would have accelerated chemical weathering and the hydrologic cycle, with tectonics—via volcanism, topographic relief, exposure of fresh bedrock, a narrow shelf, and possibly earthquakes—being a primary factor, as observed for small mountainous catchments worldwide (Milliman and Syvitski, 1992).

Global cooling into the Pliocene appears to have suppressed the weathering and erosion of the tropical highlands in southern Mexico, leading to decreased sediment supply to the WGOM despite ongoing tectonism. What little Pliocene clastic sediment occurs is compositionally mixed (Fig. 2), with quartz/feldspar and volcanic/sedimentary ratios similar to that of the Mississippi Fan, while quartz/volcanic ratios and mud geochemistry indicate intermediate volcanic input. Whether this mixed signature represents early encroachment of the Mississippi Fan or increasing influence from western (Sierra Madre) sources is not clear.

By middle Pleistocene time (Fig. 3B), while volcanism and uplift continued in southern Mexico (Ferrari et al., 2005; Molina-Garza et al., 2015), tectonic drivers of sediment supply to the WGOM were overridden by glaciation and related processes not long after ice first advanced over North America (ca. 2.4 Ma; Thompson, 1991; Balco et al., 2005). Sedimentation rates in the WGOM increased significantly at ca. 2 Ma (Ewing et al., 1969; Worzel et al., 1973), and by the end of the mid-Pleistocene transition (ca. 0.7 Ma), debris came almost exclusively from the north via the Mississippi catchment and associated Mississippi and Bryant Fans (Bouma et al., 1986; Tripsanas et al., 2007). This provenance change was not due to eustatic sea-level fall, which would have equally affected the southern and northern margins of

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[1] GSA Data Repository item 2018382, Table DR1 (sand petrography data), Table DR2 (detrital zircon U-Pb geochronology data), and Table DR3 (mud geochemistry data), is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

the WGOM. Rather, sediment supply from the north was facilitated through the periodic advance and retreat of the Laurentide and Cordilleran ice sheets, specifically: (1) the mostly mechanical erosion of both Rocky Mountain uplifts and interior lowlands (Bell and Laine, 1985; Dethier, 2001) and high-discharge meltwater cycles (Shakun et al., 2016), and (2) drainage rearrangement along the ice front (e.g., Missouri River diversion; Fildani et al., 2018).

CONCLUSIONS

We detected a compositional shift in DSDP cores pointing to a reversal in sediment supply to the WGOM basin in the late Cenozoic: from southern tropical highlands during Miocene time, and then from northern landscapes by the mid-Pleistocene transition. The change was likely forced by glaciation rather than tectonism or sea-level fall, because these latter processes continued to affect southern Mexico even as its highlands had ceased to supply sediment to the Sigsbee Abyssal Plain. The changing provenance for late Cenozoic deposits in the WGOM suggests that a cooling climate can stymie weathering and erosion in tropical highlands, and that glaciation can override other controls on sediment supply over sustained ($>10^5$ yr) periods of time.

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