Isostatic uplift driven by karstification and sea-level oscillation: Modeling landscape evolution in north Florida

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ABSTRACT
Isostatic uplift of tectonically stable, passive margin lithosphere can preserve a record of paleo-shoreline position by elevating coastal geomorphic features above the influence of nearshore wave activity. Conversely, depositional ages and modern elevations of these features can provide valuable information about the uplift history of a region. We present a numerical model that combines sea-level oscillation, subaerial exposure, a precipitation-karstification function, and isostatic uplift to explore the dynamic geomorphic behavior of coastal carbonate landscapes over multiple sea-level cycles. The model is used to estimate ages of coastal highstand depositional features along the Atlantic coast of north Florida. Numerical simulations using current best estimates for Pleistocene sea-level and precipitation histories suggest ages for Trail Ridge (1.44 Ma), the Penholoway Terrace (408 ka), and the Talbot terrace (120 ka) that are in agreement with fossil evidence. In addition, model results indicate that the rate of karstification (void space creation or equivalent surface lowering rate) within the north Florida platform is ~3.5 times that of previous estimates (1 m/11.2 k.y. vs. 1 m/38 k.y.), and uplift rate is ~2 times as high as previously thought (0.047 mm/yr vs. 0.024 mm/yr). This process has implications for landscape evolution in other carbonate settings and may play an underappreciated role within the global carbon cycle.

INTRODUCTION
Isostatic compensation via uplift of the lithosphere is witnessed as a response to regional deglaciation (Whitehouse et al., 2007), valley incision through fluvial (Molnar and England, 1990) or glacial processes (Montgomery and Greenberg, 2000), and regional unloading of a mountain belt (Pazzaglia and Gardner, 1994). Karstification (creation of crustal void space through dissolution of rock) effectively accomplishes the same result by decreasing the crustal mass within a vertical column of lithosphere. The products of karstification are dissolved solids, which are transported to the ocean via groundwater and fluvial systems and swept away by ocean currents, thereby effectively removing mass as opposed to simply redistributing mass locally.

Elongate ridges and terraces along the Atlantic coast of north Florida (Fig. 1A), mapped and correlated by Winker and Howard (1977), reflect a rich history of nearshore sediment accumulation and sea-level oscillation. Marine fossils found in these ridges at elevations of ~50 m (above mean sea level) indicate an age of Pleistocene or younger (Pirkle and Czel, 1983), but paleoclimatic reconstructions of eustatic sea level indicate that sea level did not reach such elevations during that time (Lisiecki and Raymo, 2005; Miller et al., 2005). Despite the tectonically quiescent setting, epeirogenic uplift of the Florida platform has preserved these features at elevations of ~75 m above modern sea level. Carbonate dissolution has been recognized as an important denudation mechanism in humid temperate climates, and may help generate topographic relief, where landscape surfaces have patchy lithologic coverage of alternating siliciclastic and carbonate rocks (Simms, 2004). Opdyke et al. (1984), proposed karst development within the Florida carbonate platform and isostatic response as a mechanism for uplift of a series of Pliocene–Pleistocene beach ridges and elevated coastal terraces that trend subparallel to the modern Atlantic shoreline from South Carolina to central Florida. In their study, Opdyke et al. (1984) showed that measurements of dissolved solids in Florida’s springs yield a carbonate rock dissolution rate of 1 m of surficial limestone every 38 k.y. This rate of dissolution would be sufficient to uplift the Florida platform at a rate of 0.024 mm/yr (36 m/1.5 m.y.), through isostatic adjustment. In a study of dissolved carbonate concentration in northern and central Florida springs, Willett (2006) reported a minimum estimate of carbonate rock dissolution rate of 1 m of surficial limestone every 160 k.y., which corresponds to an uplift rate of 0.006 mm/yr (9 m/1.6 m.y.).

Anderson et al. (1999) presented a model of marine terrace generation within a landscape undergoing rapid uplift (~1 mm/yr), where terrace treads are being etched into coastal bedrock by wave energy-driven seafloor retreat during sea-level highstands. The Florida platform ridges and terraces differ in that they are depositional features abandoned when sea level falls, and are preserved only by isostatic uplift at elevations above subsequent sea-level highstands.

In this paper we describe the regional physiography and geology of north-central Florida, the landscape that motivated the geomorphic modeling presented herein. We present a numerical model that calculates lithospheric uplift as a result of a precipitation-driven karstification function (decrease of bulk crustal density) and
variations in subaerial exposure of a carbonate platform due to oscillating sea level. We then apply the model to the landscape of north-central Florida in order to estimate ages of beach ridges and depositional coastal terraces, based on the most recent estimates of sea-level history since the Pliocene. The modeled ages of sea-level highstands are compared to the elevations of uplifted beach ridges and coastal terraces to evaluate plausible ages for deposition of the observed coastal geomorphic features. Last, we discuss the implications of karst-driven isostatic uplift at other terrestrial carbonate settings, and comment on the role of these processes in the global carbon cycle.

**REGIONAL PHYSIOGRAPHY AND GEOLOGY**

North-central Florida is a low-relief region, with the exception of karstic landforms and several prominent north-south–trending ridges and terraces (Fig. 1A), which have been identified, from highest to lowest elevation, as Trail Ridge, the Penholoway Terrace, and the Talbot Terrace (Winker and Howard, 1977). Strike-parallel topographic profiles (Fig. 1B) show elevation variations along two of the surfaces. The strike-parallel profile for Trail Ridge reveals a smooth upward trend in surface elevation, from the Satilla River Valley to the highlands south of the Saint Marys River, which is abruptly truncated by irregular topography in the region of Lake Oklawaha, where surface features of karstification are prominent. The change from smooth to highly rugose topography, visible in this profile, corresponds to a transition from an area where the Miocene silicilastics (Hawthorn Group) are unkarstified at the surface to an area where karst has breached the surface exposure of the Pliocene Cypresshead Formation and undifferentiated Quaternary sediments, present in this part of the platform (Scott et al., 2001).

**MODEL DESCRIPTION**

To explore the interrelated processes of karstification and isostatic uplift, and to estimate ages of the paleoridges described here, we created a numerical model of karstification, isostatic uplift, and sea-level oscillation. By prescribing histories of precipitation and sea level, we use the model to calculate plausible ages and elevations of preserved paleoridges. We present the details of the various components of this numerical model in the following.

**Precipitation-Karstification**

As rain falls on the landscape and infiltrates to the subsurface, carbonate rock dissolution occurs, providing an efficient mechanism for material to be transported to the ocean as dissolved solutes. This process effectively removes mass from the carbonate platform and decreases the bulk crustal density, a term used in calculating the isostatic response. This bulk density decrease may be considered a decrease in the effective crustal thickness; void spaces (e.g., caverns, sinkholes) are created or enlarged as karstification proceeds, but the plan view area of the karstified region does not change. We define effective crustal thickness as the difference between the total bulk crustal thickness, measured from the surface of the Earth to the Moho, minus the vertical length equivalent of void space within a column of karstified crust. The relationship among material crustal density \( \rho \) (equal to density of limestone, as this is the material removed by dissolution), effective crustal thickness \( C_e \), bulk crustal density \( \rho_b \), and bulk crustal thickness \( C_b \), is

\[
\rho C_e = \rho_b C_b, \tag{1}
\]

illustrated graphically in Figure 2. In our model, we consider the terms \( \rho_b \) and \( C_b \) to remain as fixed quantities throughout a region's karstification history, implying that any change in bulk density necessarily requires a change in effective crustal thickness. Applying the temporal derivative to bulk crustal density, Equation 1 becomes

\[
\frac{\partial \rho}{\partial t} = \frac{\rho_b}{C_b} \frac{\partial C_b}{\partial t}, \tag{2}
\]

and provides an explicit term (temporal derivative of effective crustal thickness), whose absolute value is equal to the rate of equivalent surface lowering from karstification, where \( \rho_b \) is time. Smith and Atkinson (1976) determined that mean annual runoff correlates with rate of erosion due to karstification, and White (1984) developed an equation for solutional denudation rate as a linear function of runoff scaled by a combination of equilibrium constants determined by partial pressure of carbon dioxide and temperature.

In our treatment of karstification, we employ a simplified version of White’s (1984) equation, allowing us to define a relationship between precipitation and karstification rate:

\[
K = -\frac{\partial C_b}{\partial t} = \lambda \dot{P}, \tag{3}
\]

where \( K \) is area-averaged linear karstification rate (m/yr) and is equivalent to the absolute value of the time rate of decrease of effective crustal thickness. Karstification rate is proportional to \( P \), the multiyear, time-averaged, annual precipitation rate (m/yr), through a calibration constant, \( \lambda \) (dimensionless), which depends primarily on efficiency of carbonate dissolution, and is treated as a tuning parameter in our model. Equations 2 and 3 permit us to transform a time series of paleoprecipitation rate to a time series of evolving bulk crustal density, which is needed for the isostatic response calculation that follows.

**Isostatic Response**

As material is removed from the platform through karstification, the mass of crust decreases, but the bulk crustal thickness, \( C_b \), does not. This is because the majority of dissolution occurs below the surface, as void space creation, where groundwater has significant contact time with carbonate rock. We use a simple isostatic calculation, to compute lithospheric uplift resulting from mass loss (decrease in bulk crustal density) in a column of crustal material, for a given karstification rate:

\[
U = M = C_b \left( \frac{\rho_m - \rho_b}{\rho_m} \right), \tag{5}
\]

where \( \rho_m \) and \( \rho_b \) are initial and final crustal bulk densities respectively, \( \rho_m \) is the density of mantle material, \( g \) is gravitational acceleration, \( M \) is change in elevation of the base of the crust (the Moho), and \( U \) is surface uplift, which in the case of no appreciable surficial erosion (constant bulk crustal thickness through time), is equal to the change in elevation of the Moho. This calculation is shown schematically in Figure 2.

**Sea-Level Oscillation**

Geomorphic marking of landscape is done by sea-level oscillation. Shore-parallel ridges or terraces constructed by nearshore processes during sea-level highstands are abandoned and incorporated into the subaerial landscape during subsequent sea-level fall. When regional uplift is sufficient to raise an abandoned depositional ridge above the level occupied by future sea-level highstands, the ridge is preserved.
This process of generation and preservation of geomorphic features by steady uplift was illustrated in a model of marine terrace evolution by Anderson et al. (1999).

Sea-level oscillation also influences the amount of carbonate platform susceptible to karstification, as shoreline migration over a gently sloping continental shelf changes the width of exposure of vulnerable terrain. We account for this in the model by keeping track of the exposed surface area through time and multiplying that area by the karstification rate, $K$.

In our model, we track the history of potential preserved depositional ridges by marking a horizontal stripe on the crust at the time and elevation of each sea-level highstand. The marking is done at the time and elevation of each highstand, to ensure that these markers rise as the carbonate platform rises in isostatic response to karstification.

MODEL APPLICATION

Herein we describe a series of numerical simulations of karst-driven isostatic uplift of the Florida platform, and present results from one model run considered plausible for occurrence. An initial, somewhat idealized platform shape is used, bearing a slightly steeper slope rise on the Atlantic margin than Gulf Coast margin. In all model runs, the following variables were held constant: $C_N$ (35 kg/m$^3$), $p_C$ (2200 kg/m$^3$), and $p_{Ca}$ (3300 kg/m$^3$). In addition, we use consistent estimates for Pleistocene to present histories of sea-level oscillation and precipitation for all simulations, with the aim of simulating plausible scenarios of landscape evolution for the region. Modeled outputs are tested by comparison to modern cross-platform profiles.

The variable examined in the model runs is carbonate dissolution efficiency, $\lambda$, the magnitude of which affects the rate of void space creation, hence also the isostatic uplift, and ultimately, the vertical distribution and preservation of highstand markers. Over a series of 10 runs we vary $\lambda$ by an order of magnitude, from $10^{-5}$ to $10^{-4}$, including the value implied by Opdyke et al. (1984), $2 \times 10^{-5}$, which corresponds to an equivalent surface lowering rate of 1 m/38 k.y. Figure 3 shows the results of a run using $\lambda = 7 \times 10^{-5}$, which is comparable to modern conditions.

All runs simulate 1.6 m.y. of geomorphic history and use realistic estimates of sea-level and paleo-precipitation histories since the Pliocene, from published values and climate models, respectively. Sea-level history was obtained from the compilation by Miller et al. (2005) (Fig. 3A). Paleo-precipitation history was derived using paleoclimate model consensus output, which estimates this region to be 0.5 mm/day drier during the Last Glacial Maximum (LGM) (Laine et al., 2009). This allows us to derive paleo-precipitation history (Fig. 3B) by linearly scaling between modern and LGM values for sea level (0–120 m) and precipitation rate (1.27–1.09 m/yr). Modern precipitation rate for the region was obtained from Scott et al. (2004).

Carbonate platform exposure history, shown in Figure 3C, originates primarily from sea-level oscillating over the asymmetric carbonate platform. During lowstands, exposure of the platform is ~500 km, as compared to highstands when only 40% is exposed. Although a larger area of exposure is available during lowstands, the cool and dry nature of paleoclimate in Florida modulates this effect, as lower precipitation rates are associated with glaciations (lowstands). The result karstification and uplift histories (Figs. 3D and 3E) also display an “icicle” pattern, with upper limits of 12 km$^3$/yr of subterranean void space creation and 0.05 mm/yr of isostatic uplift. The pattern arises from the shape of the platform and shelf break; below ~50 m, there is very little platform widening per unit of sea-level lowering, as compared to times when sea level is above ~50 m on the gently sloping portion of the shelf. In addition, the assumption of instantaneous isostatic response preserves the modeled temporal pattern of uplift history, which would be extended horizontally, if a lag time to achieve isostatic equilibrium were to be included in the model.

The preservation potential of individual highstand markers is noteworthy. For a low carbonate dissolution efficiency run ($\lambda = 2 \times 10^{-3}$, not shown), only three highstand markers are preserved (1448, 408, and 120 k.y.) at elevations of 24, 17, and 14 m above modern sea level, respectively, whereas for a high-efficiency run ($\lambda = 7 \times 10^{-3}$, shown in Fig. 3F), six highstand markers are preserved (1448, 1354, 1240, 949, 408, and 120 k.y.) at elevations of 68, 49, 38, 37, 29, and 20 m above modern sea level, respectively. For comparison, a series of 10 topographic cross-platform profiles from north Florida, with 1 km spacing, are shown in Figure 3F. The simulations reveal that only a few highstand events are preserved by isostatic uplift because of the inconsistency of sea-level elevation reached by each highstand in the time series; many short-lived geomorphic markers of shoreline position are destroyed by a following transgression.

DISCUSSION

The model of precipitation, karstification, isostatic uplift, and sea-level rise presented herein produces the following ages for three geographically striking coastal ridge and/or terraces near the north Florida–southeastern Georgia Atlantic coast: (1) Trail Ridge ~1.44 m.y., (2) Penholoway Terrace ~408 k.y., and (3) Tallbot Terrace ~120 k.y. These ages arise from the rich, yet inconsistent, behavior of glacioeustasy, which provides various elevations for the history of sea-level highstands, a key component of the geomorphic preservation problem, on which we comment further below. Given the broad flexural wavelength of the Florida platform, the use of an Airy isostatic calculation is appropriate to determine the extent of uplift. The ultimate check on the plausibility of these modeled
aging is a comparison with the fossil record in the sedimentary deposits of each of these features. The currently accepted paleontological work indicates that all fossils identified in drill holes along the western side of Trail Ridge in southern Georgia are consistent with shallow-water marine deposition, and all species are extant, implying they are Pleistocene or younger (Pirkle and Czel, 1983). Our model ages are consistent with the fossil evidence.

To obtain the ages reported above, carbonate dissolution efficiency, $\lambda$, was set to a value (7 x \(10^{-5}\)) \(-3.5\) times that of the previous estimate (2.05 x \(10^{-5}\); Opdyke et al., 1984), and nearly 10 times that of a more recent estimate (Willet, 2006). These results imply the most rapid solutional denudation rate yet proposed for the area; \(-1\) m of surficial limestone lowering every 11.2 k.y. This translates to an isostatic uplift rate for the Florida platform two times faster than previously estimated (0.047 mm/yr vs. 0.024 mm/yr). Although higher than previous estimates for the area, this rate compares favorably with the range for tropical to temperate environments with similar runoff rates (White, 1988; Fig. DR1 in the GSA Data Repository1).

The geomorphic preservation problem was explored statistically by Gibbons et al. (1984) in their investigation of “obliterative overlap” of glacial advances and retreats. Their study illustrated that a likely number of glacial moraines survived a series of glacial-interglacial cycles. As noted by Anderson et al. (1999) in their investigation of marine terrace generation, when uplift is introduced to geomorphic survival problem, a long-term drift arises, increasing the preservation potential of geomorphic markers. A notable difference between the Anderson et al. (1999) marine terrace case and the karst-driven uplift case presented herein is the mechanism driving uplift. In the marine terrace model, uplift is prograded at a steady rate and tectonically driven, whereas in the model presented herein, uplift is driven by the timing and magnitude of climatic processes via the links among precipitation, karstification, and isostasy.

Does increased precipitation result in increased rates of karstic dissolution? Simple reasoning might suggest that more precipitation leads to more infiltration through the subsurface, allowing for greater dissolution by increasing the flux rate of groundwater. However, when considering the nature of karst aquifer void space configuration, an alternate hypothesis arises: steady dissolution might promote secondary porosity in carbonate aquifers, which in turn promotes more rapid flushing of the system, and this rapidly moving groundwater is not in contact with the aquifer rock long enough to become saturated with respect to carbonate (Martin and Dean, 2001).

What is the role of the karst-driven uplift process in the global carbon cycle? As isostatic uplift proceeds, the carbonate region maintains high elevation relative to sea level, and karstification of this terrestrial landmass continues to supply dissolved carbonate and calcite to the world’s oceans. It is possible that this uplift mechanism plays a significant role in the global liberation of the Earth’s carbon, which is sequestered in carbonate rocks. Periods of warming during glacial-interglacial cycles might be provided with a slight boost in the positive feedback if warmer and wetter climates go hand in hand and karstification is enhanced.

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