contributing to its collapse. Hough *et al.*[3] suggest that morphology and topography of a city, in addition to surface-rock type, must be taken into account if reconstruction guidelines are to be effective.

A fourth paper by Hornbach *et al.*[4] extends the terrestrial investigations to the offshore region, by mapping the detailed bathymetry of the Baie de Grand Goâve north of the earthquake epicentre. They find evidence for faulting in the seafloor sediments that aligns approximately with the onshore trace of the Enriquillo–Plantain Garden fault. But, more importantly, they discovered numerous submarine landslides, some of which were clearly triggered by shaking in January, with other deeply interred slides associated with former earthquakes. Deforestation of Haiti has aggravated soil and sediment loss and dumped huge volumes of unstable sediments on the steep slopes near the shore. When these sediments slump oceanwards they generate local tsunamis, several of which were observed shortly after the January earthquake. The landslides first suck down the coastal waters and then pile them up in a bulge offshore, which subsequently returns as an onshore surge. Although uplift resulting from the vertical ground motions during the earthquake almost certainly generated one of the tsunamis observed in January, slump-generated tsunamis were also triggered far from the earthquake epicentre. The ubiquitous presence of nearshore sediments caused by high rates of erosion in the Caribbean islands means that tsunamis can in principle be generated by fairly small earthquakes, a hitherto unrecognized tsunami risk associated with transform plate boundaries in oceanic settings.

Perhaps the biggest question that remains to be answered concerns the timing of the next significant earthquake on the Enriquillo–Plantain Garden fault system. Prentice *et al.*[5] carried out a diligent search along the surface expression of the fault for tell-tale signs of slip. Although they found no surface rupture relating to the January earthquake, their search revealed stream channels with abrupt left-stepping offsets of 1.5–3.3 m that probably formed during one of the two previous earthquakes in 1751 and 1770. These earthquakes twice destroyed the eighteenth-century capital[10]. The time elapsed, combined with the rate of long-term slip on the fault inferred from geodesy[1,2], suggests that this year would have been an appropriate time for the fault to slip again by about 2 m. Although this slip may indeed have occurred at depth[1,2], the uppermost 5 km of the Enriquillo–Plantain Garden fault has remained obstinately clamped shut, and could in principle rupture at any time, generating a M_w 6.6–6.8 earthquake[2,5]. In the absence of precisely dated material, it is difficult to be certain of the link between the observed fault offsets and the historical record. This would not diminish the case for a future earthquake on the Enriquillo–Plantain Garden fault, but might in fact argue for a pending earthquake exceeding M_w 7.2.

The *Nature Geoscience* Haiti special issue[1–5] documents some of the complexities associated with the tectonic plate boundary near Port-au-Prince, and reveals that the rupture mode associated with the 2010 earthquake defies any simple characterization. An orderly pattern of historical earthquakes may appear, once palaeoseismic trenching and the dating of offshore submarine slides extend the historical record back to pre-Columbian times. But we have yet to answer the questions of most concern to Haiti, relating to the timing and size of any earthquakes that assuredly lie in her future. ❐

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PLANETARY SCIENCE

Hidden martian carbonates

Evidence for the sedimentary carbonate rocks proposed to be prevalent on Mars has generally been lacking. Carbonate-bearing rocks found in the Leighton Crater may be associated with the formation of methane detected in the martian atmosphere.

Timothy D. Glotch

Today, the atmosphere of Mars is thin — with pressures between six and ten millibars — and consists predominantly of carbon dioxide. It may, however, have been much thicker in the past. The sequestration of much of the carbon dioxide of the ancient martian atmosphere by carbonate minerals could account for this apparent transformation, but evidence for abundant sedimentary carbonates is limited. Writing in *Nature Geoscience*, Michalski and Niles[1] report the discovery of carbonate- and phyllosilicate-bearing rocks in the central peak of Leighton Crater, southwest of the large Syrtis Major shield volcano, a finding that suggests carbonate rocks may be buried deep in the martian crust.

Valley network systems heavily dissect the martian southern highlands, and some craters contain unmistakable delta features, suggesting the presence of at least periodically abundant liquid water early in martian history[2–3]. A thick, greenhouse atmosphere must have been present to keep liquid water stable at the surface, but the fate of the ancient martian atmosphere, which presumably would have been dominated by carbon dioxide, is unknown. Although some portion of the atmosphere was undoubtedly lost because of interactions with the solar wind and impact-induced erosion, the sequestration of carbon dioxide in carbonate rocks is often invoked to explain the transition from the ancient thick atmosphere to the modern thin one[4].

Recent data from remote sensing investigations and *in situ* analyses by the Mars Exploration Rover Spirit and the Mars Phoenix Lander have provided evidence

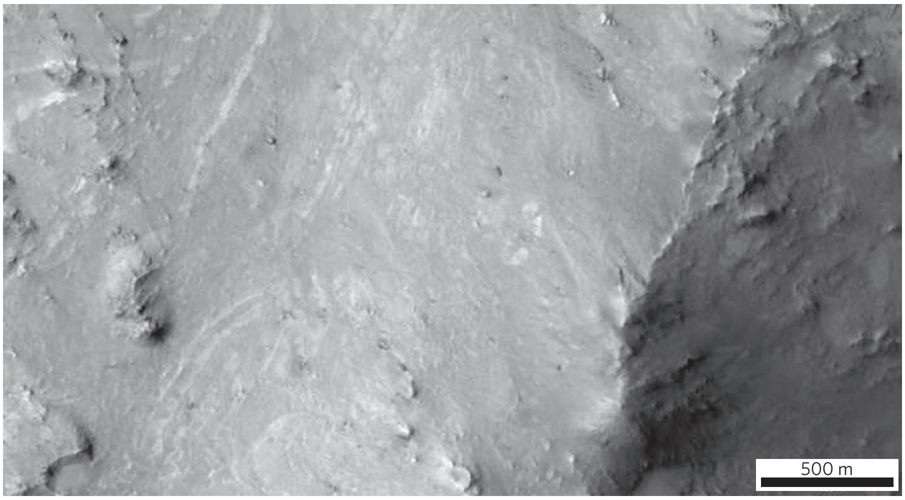

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Figure 1 | Layered carbonate- and phyllosilicate-bearing sediments in the central peak of Leighton Crater, Mars. Michalski and Niles[1] describe the presence of carbonates exhumed from deep in the crust during the crater-forming impact. The ongoing alteration of the mafic crust to carbonate and phyllosilicate sediments produces methane and could explain the plumes of atmospheric methane observed in this region.

for both sedimentary carbonate beds and fine-grained carbonates in soil and dust deposits[5–8]. Carbonate rocks identified at Gusev Crater[5] and Nili Fossae[6] were probably formed through the hydrothermal alteration of high-magnesium, low-silica rocks at near-neutral pH, and are roughly similar in composition to those seen in the ancient martian meteorite ALH84001[9]. On the other hand, carbonates found in the soils of the Phoenix landing site[7] and in the globally homogeneous dust[8] are probably the result of the interaction of atmospheric carbon dioxide with silicate grains, perhaps coated by monolayers of water. This process was suggested by simple laboratory experiments more than three decades ago[10].

Michalski and Niles[1], however, present definitive evidence of carbonate rocks originating from deep in the martian crust — a feature that is key to explaining the relative paucity of remote spectroscopic detections of sedimentary carbonate beds. Using remote sensing data, they describe the presence of carbonate and phyllosilicate bedrock in the centre of the Leighton Crater. They suggest that the rocks were exhumed from a depth of about six kilometres during the impact that formed the crater. The discovery of one deep carbonate deposit opens up the possibility that there could be more: until now, the suggestion that the missing carbonates were buried has been convenient but unsupported.

Michalski and Niles suggest that the carbonate-bearing rocks at Leighton Crater probably formed as a result of alteration by either hot fluids or contact with lava. In the former scenario, near-surface carbon-dioxide-rich fluids would have mixed with deep, hot, reducing fluids, altering the basaltic crust. In the latter, surficial sediments rich in carbonate minerals would have been buried by thick lavas from the Syrtis Major volcano. The heating of the rocks would recrystallize the carbonate and yield the observed phyllosilicate assemblage. Foliation of the bedrock related to the formation of phyllosilicates is evident in high resolution imagery of the region.

The site of the Leighton Crater and Nili Fossae carbonate deposits also corresponds to the location of a plume of methane in the martian atmosphere, which has been observed in the general vicinity of Syrtis Major[11]. Because the atmospheric lifetime of methane on Mars is no more than about 350 years, and possibly less than one year[12,13], the process that creates the methane must be ongoing. Hydrothermal alteration of magnesium- and iron-rich crust in the presence of carbon-dioxide-rich fluids produces phyllosilicates and carbonates such as those observed, as well as methane[1]. The correlation of these atmospheric and surface observations therefore suggests such hydrothermal alteration, which must occur at depth and must be active at present, to provide a continuous source of methane.

The exhumed carbonate-bearing rocks at the Leighton Crater could, according to Michalski and Niles, be representative of the deep-crustal source for the carbonate component of martian dust. If the carbonate source is deeply buried, that would imply that the carbonate within the fine fraction is ancient. However, recent isotopic measurements made by the Thermal and Evolved Gas Analyzer instrument on the Mars Phoenix Lander indicate an atmosphere that has relatively little ^{13}C, which was presumably removed by carbonate formation[14]. When compared with isotopic analyses of ancient martian meteorites, these results suggest that carbonate formation is an active process today, and that a deep-crustal source is not required to supply the carbonate fraction of the martian soil and dust.

It is important to remember, too, that sedimentary carbonates have been found in only three regions on Mars, and we still lack evidence for widespread deposits. High-resolution data from the Compact Reconnaissance Imaging Spectrometer for Mars instrument, the primary sensor used to identify and map carbonates in Leighton Crater and the Nili Fossae region, cover only 1.2% of the martian surface at present. This and future high-resolution spectroscopic-mapping missions will remain critical to piecing together the climatic history of Mars. Furthermore, though there have been some advances in quantitative modelling of remote spectroscopic data, this remains a critically underdeveloped field that is necessary not only to remotely identify minerals, but also to determine their abundances. The abundance is a key figure for refining models of the formation environments of these rocks. Determination of mineral abundance at high spatial resolution and with adequate global coverage will be a crucial step in resolving the fine details of geologic history and climate change scenarios for Mars.

Nevertheless, the findings of Michalski and Niles[1] represent an important step in verifying the carbon dioxide greenhouse model for the ancient martian atmosphere. ❐

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