STRUCTURAL GEOLOGY

Invisible faults under shaky ground

The Haiti earthquake ruptured one or more buried faults, generated tsunamis and caused extensive structural damage in Port-au-Prince. Investigations in the epicentral region quantify seismic hazards but offer no clear views of Haiti's seismic future.

Roger Bilham

Haiti's January earthquake was no surprise. It was only a matter of time before a large earthquake struck. The earthquake occurred on a transform fault separating two tectonic plates that slide past each other horizontally. Named the Enriquillo–Plantain Garden fault system, it passes close to the capital, Port-au-Prince, and bounds the northern edge of the Caribbean plate, which moves west-northwestwards relative to the North American plate at a rate of 2 cm yr^{-1}. Based on this tectonic setting, in the minutes following news of the earthquake most seismologists familiar with the region jumped to three conclusions: that the earthquake would spawn no tsunami; that a roughly 30-km-long surface fracture would offset the two sides of the remarkable valley that marks the plate boundary just south of Port-au-Prince (Fig. 1); and finally that shaking of the capital would be greatest in the sediment-filled plains to the north of the city, sparing structures on the foothills of Port-au-Prince. Five linked papers[1–5] in *Nature Geoscience* prove that these assumptions were wrong.

Transform faults are only efficient in accommodating the relative sliding motion of plates when the fault parallels the direction of plate motion. With only a slight misorientation, any motion can fragment and distort the nearby plate interiors. The Enriquillo–Plantain Garden transform fault does not perfectly parallel the direction of plate motion, causing compression throughout much of southern Haiti[1]. This convergence is accommodated by the development of folds and thrust faults that ultimately cause the upward displacement of rock. These vertical movements of the crust are responsible for the formation of the islands of the northern Caribbean[5,6].

Comparisons of the ground surface near the epicentre before and after the earthquake, recorded using satellite radar and GPS data, clearly show relative horizontal movement of the ground. As expected, a metre or so of ground deformation occurred, typical of a M_w 7 earthquake on a transform fault.

ROGER BILHAM

Figure 1. The valley of the Enriquillo–Plantain Garden fault viewed from the west. Five papers in the *Nature Geoscience* special issue document the complexities of Haiti's 2010 earthquake[1–5]. The fault (dashed line) forms the northern boundary of the Caribbean tectonic plate. The January 2010 epicentre lies beneath the foreground, but although the fault may have slipped horizontally at depth, no surface rupture was found. The presence of substantial vertical motion implies that an invisible thrust fault steeply dipping to the north also slipped — the Léogâne fault. It is unknown whether this new fault also slipped horizontally[1] or whether multiple faults ruptured sequentially, including the Enriquillo–Plantain Garden fault[2].

The surprise finding was that 33–51% of the ground displacements observed in January's earthquake involved convergence and uplift north of the plate boundary near the town of Léogâne. The ground surface there was not broken by a fault rupture, but it clearly bulged. The surprise is further compounded by the observation that the earthquake

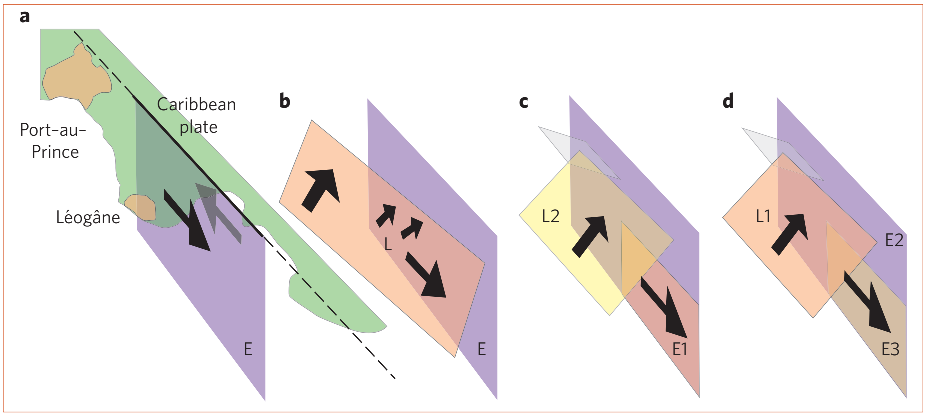

Figure 2 | Schematic models for subsurface slip in the Haiti earthquake. Simple slip of the Enriquillo–Plantain Garden transform fault (E) had been assumed initially (**a**). However Calais *et al.*[1] and Hayes *et al.*[2] propose three different scenarios, based on the lack of surface rupture. Calais *et al.*[1] propose that only the Léogâne fault (L) ruptured in a complex motion (**b**). In the preferred model by Hayes *et al.*[2], three faults were involved, with slip starting on the Enriquillo–Plantain Garden transform fault (E1) followed by slip on the Léogâne thrust (L2) (**c**). An alternative sequence of slip using the same geometry as (**c**) can explain the absence of surface slip (**d**). In this model, the earthquake started on the Léogâne thrust (L1) and stresses from this clamped the surface Enriquillo–Plantain Garden fault (E2) firmly shut, while simultaneously reducing fault-normal stress at depth. This would have permitted the deep Enriquillo–Plantain Garden fault (E3) to slip.

reversed the sense of long-term geological uplift of the mountains of the Haiti peninsula, causing them to subside relative to the sea floor. Coral communities were uplifted by ~60 cm and exposed offshore, south of Léogâne[2].

How the combination of subsurface plate convergence and sliding occurred is still not completely clear, largely because there is no inventory of subsurface faults on which to assign inferred slip[5]. Interpretative models thus must first pinpoint the positions and orientations of invisible faults that ruptured, then calculate the slip distribution on them — a precariously large number of variables to constrain.

Calais *et al.*[1] hypothesize that the earthquake occurred on a single fault (Fig. 2). They compute both its disposition and the distribution of subsurface slip necessary to emulate the observed ground deformation. Their hypothetical buried fault dips to the north and trends slightly anticlockwise from the Enriquillo–Plantain Garden fault. They suggest the fault slipped with a vortex-like motion, swinging from horizontal, transform motion to convergent, thrust motion as the fault rupture propagated. This single fault model satisfies both Occam's razor and the short pulse of seismic energy measured during the earthquake[2]. Moreover, a comparison of the measurements of the ground surface displacement to their model predictions is almost, but not quite, perfect.

Hayes and colleagues[2], however, obtain a better fit to the surface displacement data by invoking slip on a trilogy of faults that exhibit either transform motion or thrust motion, rather than a combination of both (Fig. 2). Furthermore, their fault model satisfies the constraints on the motion of the fault provided by many dozens of seismograms recorded throughout the world during the earthquake. The authors suggest that earthquake rupture initiated on or near the Enriquillo–Plantain Garden transform fault at depth. Second to slip was a thrust fault (the hypothesized Léogâne fault) that dips north with a location and geometry close to that proposed by Calais *et al.*[1]. Finally, a hypothesized third fault is invoked to account for a puzzling eastward displacement of the ground observed in the mountains due west of Port-au-Prince. In agreement with Calais *et al.*[1], the north-dipping Léogâne thrust fault would intersect the Enriquillo–Plantain Garden fault at a depth of 2–5 km. This poses a puzzle because the surface fault that follows the valley above this imaginary intersection line (Fig. 1) didn't budge an inch. The lack of surface rupture is a mystery.

It is certain that the three faults inferred by Hayes *et al.*[2] must have mutually triggered each other within several seconds of the main earthquake shock. But, had the Enriquillo–Plantain Garden transform fault slipped first, the stress changes[8] accompanying this initial rupture, though perfectly disposed for unzipping the fault all the way to the surface, are far from ideally aligned to encourage slip on the nearby Léogâne thrust fault. Hayes *et al.*[2] get around this difficulty by suggesting that powerful waves from the initial rupture were sufficiently violent to shake the Léogâne fault loose[7].

In contrast, had the thrust fault slipped first, it would have clamped the surface of the Enriquillo–Plantain Garden fault tight shut, and simultaneously reduced the stresses at depth, thereby allowing the transform fault to slip next. This sequence of faulting is consistent with the surface deformation data, albeit with larger misfit[2]. However, seismic data indicate that horizontal transform motion, rather than vertical thrusting, occurred first. For initial thrust faulting to have eluded detection by the world's seismometers, the initial slip on the Léogâne fault would have to have occurred too slowly to radiate seismic waves. Although we know that such so-called aseismic slip is quite common[9], there were no instruments sufficiently close to Haiti to detect the slow ground motions that would allow testing of this hypothesis.

The complexities of the earthquake thus remain unsettled. Without doubt, present attempts to describe what happened during the first 12 s of the rupture are too simple, but the best we can do given the available data. We know that damaging surface waves from the rupture raced outwards reaching Port-au-Prince, some 20 km to the east, even before subsurface fault rupture had ceased. Eyewitnesses in Léogâne and the capital reported that shaking and building collapse persisted for 35 s. Knowledge of the force of ground shaking experienced by buildings, and the variability of ground motions within a city is fundamental to building redesign efforts. Reconstruction has already started despite an absence of detailed knowledge of localized amplification of the ground motions that clearly occurred in January, and will do so again in the next earthquake.

Hough and colleagues[3] adopt a systematic approach to test whether the accelerations of ground motion were uniform throughout Port-au-Prince. They examine how different parts of the city — located on soft sediments, hard ground and mountainous ridges, respectively — responded to aftershocks that continue to shake the capital. The accelerations of ground motions experienced by structures built on the soft sediments north of the city were, as expected, roughly twice those experienced by buildings situated on firm bedrock. It was with some surprise, however, that they discovered that some of the strongest ground motions occurred not on the soft sediments, but on the foothills on which part of the city is built. For example, ground motions were amplified by a factor of 3.6 ± 0.7 on the ridge on which Hotel Montana had been constructed, clearly 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.

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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