

Active thrusting offshore Mount Lebanon: Source of the tsunamigenic A.D. 551 Beirut-Tripoli earthquake

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ABSTRACT

On 9 July A.D. 551, a large earthquake, followed by a tsunami, destroyed most of the coastal cities of Phoenicia (modern-day Lebanon). Tripoli is reported to have “drowned,” and Berytus (Beirut) did not recover for nearly 1300 yr afterwards. Geophysical data from the Shalimar survey unveil the source of this event, which may have had a moment magnitude (M_w) of 7.5 and was arguably one of the most devastating historical submarine earthquakes in the eastern Mediterranean: rupture of the offshore, hitherto unknown, ~100–150-km-long active, east-dipping Mount Lebanon thrust. Deep-towed sonar swaths along the base of prominent bathymetric escarpments reveal fresh, west-facing seismic scarps that cut the sediment-smoothed seafloor. The Mount Lebanon thrust trace comes closest (~8 km) to the coast between Beirut and Enfeh, where, as 13 ^{14}C -calibrated ages indicate, a shoreline-fringing vermetid bench suddenly emerged by ~80 cm in the sixth century A.D. At Tabarja, the regular vertical separation (~1 m) of higher fossil benches suggests uplift by three more earthquakes of comparable size since the Holocene sea level reached a maximum ca. 7–6 ka, implying a 1500–1750 yr recurrence time. Unabated thrusting on the Mount Lebanon thrust likely drove the growth of Mount Lebanon since the late Miocene.

Keywords: Lebanon, thrusts, submarine seismic breaks, tsunami, vermetid benches.

INTRODUCTION

Mount Lebanon, a ~160-km-long, ~3000-m-high compressive coastal range emerging from the eastern Mediterranean sea, lies adjacent to the 25°-rightward restraining bend of the active Levant fault system, the left-lateral transform that constitutes the Arabia-Sinai plate boundary (Fig. 1) (e.g., Freund et al., 1970; Daëron et al., 2004). Seaward from Mount Lebanon, the Levantine margin is particularly steep, reaching water depths of ~1500 m only 8 km from shore, adjacent to the deepest part of the Levantine basin (2000 m), which is floored by thickly sedimented (~12 km) oceanic crust of Mesozoic age (Makris et al., 1983). Onland, prominent thrusts that raise and fold Plio-Quaternary marine deposits and continental conglomerates are visible along the range front NE of Chekka (Fig. 1) (Tapponnier et al., 2001; Elias et al., 2001). One such thrust cuts through the city of Tripoli (Fig.

DR1 in the GSA Data Repository¹), forming a ~70-m-high cumulative escarpment (Bahsas scarp). Devastating earthquakes have repeatedly shaken Lebanon and adjacent areas during the past 2000 yr (e.g., Ambraseys and Melville, 1988; Guidoboni et al., 1994). Several historical events shook coastal areas more severely than inland regions, implying source locations along the Mediterranean shore or not far to the west. That active faulting takes place offshore is suggested by recent instrumental seismicity maps (Plassard and Kogoj, 1981; Fig. DR2), but little is known of the geometry and mechanism of

¹GSA Data Repository item 2007190, Figures DR1, 2, 4, 7, and 8 (photo, maps, plot, and numerical model output); items DR3 (historical and archeological data) and DR6 (biology of vermetid benches); and Table DR6 (vermetid samples specifications), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

such faulting. Here, we present new geophysical data obtained during the 2003 SHALIMAR cruise (Briais et al., 2004) that demonstrate the existence of submarine seismogenic thrusts offshore central Lebanon. Along with recently pub-

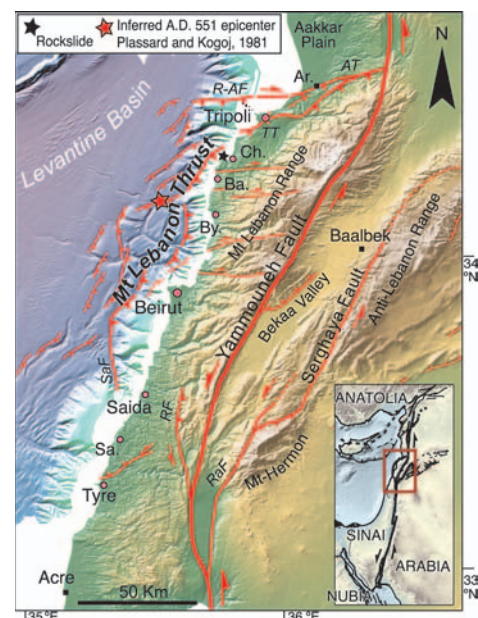


Figure 1. Active faults of Lebanese restraining bend. Map projected upon Shuttle Radar Topography Mission relief and new SHALIMAR EM300 bathymetry. Hitherto unknown thrust system (Mount Lebanon thrust) hugs continental slope base offshore Mount Lebanon. Red box in inset shows location of Lebanese bend along Levant fault system. Red circles are coastal cities that suffered Tsunami effects during the 551 A.D. event. City abbreviations: Ar—Arqa; Ba—Batroun; By—Byblos; Ch—Chekka; Sa—Sarafand. AT—Aakkar thrust; TT—Tripoli thrust; R-AF—Rankine-Aabdeh fault; RF—Roum fault; RaF—Rachaya fault; SaF—Saida fault.

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lished ages of young, uplifted wave-cut benches on the coastline (Morhange et al., 2006), the seafloor seismic breaks unambiguously define the source of the A.D. 551 earthquake, the largest event to have struck the Levant shore since Roman times. All the active faults responsible for past earthquakes in Lebanon thus now form a self-consistent tectonic framework.

COASTAL LEBANESE EARTHQUAKES AND THE EVENT OF 9 JULY A.D. 551

The historical earthquakes that were most strongly felt along the coast of Lebanon belong to two “sequences” separated by 500 yr of apparent quiescence. The so-called seismic crisis of the fourth to fifth century A.D. included five events (local magnitude, M_l , in parentheses): 303–306, Tyre-Saida (~7.1?); 348/349, Beirut (~7?); 450–457, Tripoli; 502, Acre (Akka) (~7?); and 551, Beirut-Tripoli (7.3–7.8?) (Plassard, 1968; Guidoboni et al., 1994). Of the events of the great eleventh to fourteenth century A.D. sequence that ruptured the entire Levant fault system from Aqaba to Antioch, culminating in the A.D. 1202, M_l -7.5 disaster on the Yammouneh fault (e.g., Ellenblum et al., 1998; Daëron et al., 2005), only three caused destruction on the coast, mostly in Tripoli and the Aakkar plain: 1063, Tripoli, Arqa, up to Antakya and Tyre (~7.1?); 1170, northwest Syria (7.5–7.9?), an event known to have primarily ruptured the Myssiaf fault (Meghraoui, et al. 2003); and 1339, Tripoli (Plassard and Kogoj, 1981; Ben-Menahem, 1991).

There is no question that the A.D. 551 event was the strongest coastal earthquake, and the only one unambiguously followed by a regional tsunami, as related in detail by many chroniclers (Data Repository item DR3). Historical accounts clearly restrict the maximum earthquake and tsunami devastation to the Phoenician coast from Tripoli to Tyre, even though 100 villages were also destroyed inland.

That this earthquake was tsunamigenic suggests that it ruptured the seafloor, with a fairly large dip-slip component. The location of maximum damage, exclusively along the Phoenician coast (Sieberg, 1932; Guidoboni et al. 1994), implies a local source, ruling out submarine faults far from Lebanon, even along the Cyprus subduction arc. Given the existence of small, instrumentally recorded shocks offshore central Lebanon (Fig. DR2), Plassard and Kogoj (1981) tentatively located the A.D. 551 earthquake epicenter at sea, somewhere between Beirut and Batroun (Fig. 1).

“FRESH” SEISMIC BREAKS ON THE SEAFLOOR BETWEEN ENFEH AND DAMOUR

During the SHALIMAR survey, we mapped a previously unknown, east-dipping, offshore thrust system with a complex geometry, involving stepping and parallel segments, as observed

along most foreland thrusts (Figs. 1 and 2). Major “range-front” ramps reach the seafloor at the base of the continental slope, where it is steepest, between Saida and Tripoli. They are offset by a ~10 km right-step west of Beirut. Farther out into the Levantine Basin, Plio-Quaternary turbidites detached above Messinian evaporites are folded to at least ~30 km from shore, where the seafloor is warped by growing anticlines above shallower, blind thrusts (Briais et al., 2004). Between these anticlines and the slope base, deep canyons incise the Jounieh plateau, which is uplifted by 150–200 m relative to the Levantine abyssal plain (Fig. 2A). The thrust system is limited to the south and north by two oblique lateral ramps: the Saida (SaF) and Rankine-Aabdeh faults (R-AF), respectively (Fig. 1). We interpret this ~160-km-long thrust system (Mount Lebanon thrust), together with the Roum fault and the Tripoli and Aakkar thrusts onland, to be responsible for the Plio-Quaternary growth of Mount Lebanon (Elias et al., 2003).

Using Ifremer’s deep-towed acoustic system (SAR), we surveyed the base of prominent, ~NE-

trending, NW-sloping tectonic escarpments transverse to submarine canyons, visible on the SHALIMAR EM300 bathymetry between Enfeh and Damour (Fig. 2). The SAR images, whose pixel resolution is 25 cm, show details of spectacular submarine ruptures and scarps that cut the smoothly sediment-mantled seafloor (Figs. 2 and 3; Fig. DR4). Though segmented, these fairly continuous breaks generally follow the base of the cumulative escarpments. Most of the scarps face west, consistent with east-wall uplift, and have sinuous, stepping traces, as befits dip-slip faulting. They are often paralleled by finer breaks, suggestive of small-scale, hanging-wall collapse or footwall shortening (Fig. 3). Offshore Jounieh, the slope-base break cuts across the Nahr el Kelb submarine channel and slide-blocks within it (Fig. DR4), which suggests a young age. In the south, we could follow two of these relatively fresh, roughly parallel ruptures for 25–30 km along strike, 8–18 km from shore (Fig. 3). In the north, we could only map 5–10-km-long segments of an echelon ruptures that appear to extend over greater distances. Given their geomorphic resemblance to subaerial, seis-

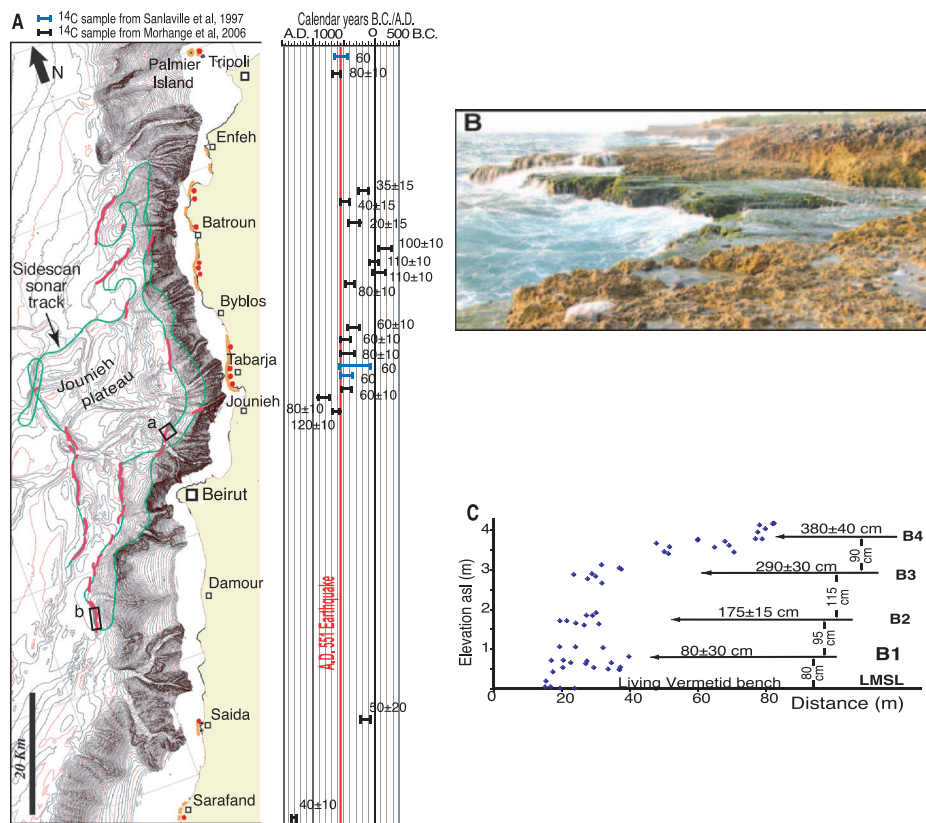


Figure 2. A: Left: Shalimar bathymetric map of proximal Lebanese offshore. Bold red lines are “fresh” seafloor seismic breaks. Boxes a and b indicate locations of SAR images in Figure DR4 and Figure 3, respectively. Right: 2σ calendar ages of ^{14}C dated “B1” vermetid samples (red dots), plotted along the coast with elevation above local mean sea level (LMSL) in cm, mostly predate the A.D. 551 event. **B:** Uplifted, karst-pitted vermetid benches near Tabarja. **C:** Projected total station measurements of bench elevations relative to LMSL (living vermetid surface in swash zone). Note significant scatter in elevation measurements on fossil levels, particularly B1 and B4, likely because of sub-levels with rounded edges and of irregularities due to deep pitting by microkarst.

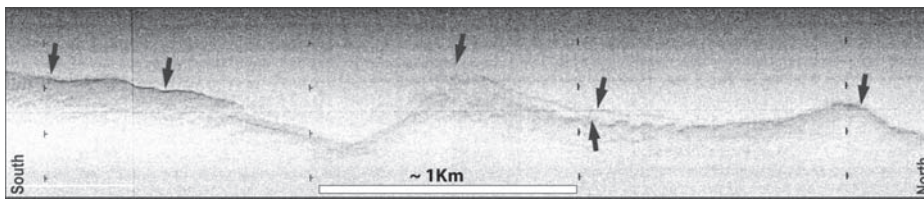


Figure 3. Seafloor seismic rupture. Sidescan sonar image of “fresh” seismic rupture along base of continental slope west of Damour (box “b” in Fig. 2A). Note sinuous, segmented trace, west-facing main scarp, and smaller parallel scarps on top of east (hanging) wall and away from main scarp base on footwall. Dark shades mark high backscatter. Insonification from top (west).

mic dip-slip ruptures, and their position near the foot of cumulative bathymetric escarpments, the seismic origin of such submarine breaks is not in doubt, although assessing whether they result from one or several earthquakes will require further investigation. Similar SAR-imaged breaks along the western stretch of the North Anatolian fault in the sea of Marmara were recently confirmed, by close-range imaging with Ifremer’s remotely operated vehicle Victor camera, to be due to one historical earthquake (1912 event) (Armijo et al., 2005).

The SHALIMAR data showed no evidence of submarine landslides except for small-scale slump scars and rockslides on or at the base of steep slopes south of Damour and near Batroun. It is thus possible to rule out the occurrence of a large local submarine landslide as potential sources of historical tsunamis along the Lebanese coast.

COSEISMIC UPLIFT OF VERMETID BENCHES ALONG THE CENTRAL LEBANESE SHORELINE

The discovery of active offshore thrusts sheds new light on the Quaternary geomorphology of coastal Lebanon. The stairs of abandoned, marine-cut terraces between Tripoli and Beirut (Sanlaville, 1977), whose heights in central Lebanon (up to 500 m near Tabarja) are unmatched either north or south, are most simply interpreted to reflect long-term Quaternary uplift resulting from the thrust-driven rise of Mount Lebanon (Elias et al., 2003). As documented in other regions of active tectonic uplift (e.g., Lajoie, 1986), such high terrace levels likely record ancient marine highstands coeval with warm interglacials/stadials (Sanlaville, 1977).

The presence of smaller-scale indicators of recent shoreline uplift, such as elevated marine notches, beach deposits, and wave-cut, shoreline-fringing bioconstructional platforms (“trottoirs marins”) (Data Repository item DR5), chiefly also between Tripoli and Beirut, can be accounted for as well. Specifically, two benches (“double trottoirs”), including the present (living) one, are visible only between Jounieh and Enfeh and on the islands offshore Tripoli (Sanlaville, 1977). Moreover, north of Jounieh and Batroun, a few stretches of multiple benches are observed. At

Petite Fontaine beach near Tabarja for instance, our total station measurements (Figs. 2B and 2C) document four distinct emerged bench levels (B1, B2, B3, B4), at average elevations of, respectively, 80 ± 30 , 175 ± 15 , 290 ± 30 , and 380 ± 40 cm above the local mean sea level (LMSL).

Given the dearth of preserved material, few of the higher fossil benches have been dated, but a sizable set of radiocarbon ages exists on the lowest one (Morhange et al., 2006), which corresponds to B1 at Tabarja (Table DR6). Between Enfeh and Beirut, 13 radiocarbon ages out of 15 argue for a relatively sudden “end” of the stable sea level recorded by the lowest “B1” bench during the sixth century A.D. at the latest (Fig. 2) (Morhange et al., 2006). Though slightly younger, one more Tabarja and two Palmier Island sample ages are not inconsistent, at the 2σ level, with a rapid, relative sea-level change at that time. Perhaps the death of emerged vermetids was delayed in the island because of the larger swash zone in the more open sea.

In map view, the active and recently ruptured traces of the submarine Mount Lebanon thrust ramps come closest to the coastline precisely where it is endowed with double trottoirs (Fig. 2). Hence, there is little doubt that the sudden sixth century A.D. emersion of “B1” in central Lebanon, by ~ 80 cm, was of tectonic origin, namely the coseismic shoreline uplift due to the A.D. 551 earthquake, whose macro-seismic epicenter was in all likelihood located offshore Tabarja (Fig. DR7). Higher fossil benches likely reflect similarly sudden uplifts caused by more ancient earthquakes, and it comes as no surprise that the clearest and highest raised, marine-cut Quaternary terraces are found near Tabarja.

DISCUSSION AND CONCLUSION

The source of the A.D. 551 earthquake and the processes responsible for shoreline uplift in Lebanon have long been debated. Sanlaville (1977), who first questioned whether the raised trottoirs might be related, in part, to the A.D. 551 earthquake, finally chose to interpret this relative sea-level change as a “brief, positive eustatic movement” (“Tabarjan”). Pirazzoli et al. (1991) later attributed prominent shoreline uplift around much of the eastern Mediterranean to a regional

“seismic crisis,” the “Early Byzantine Tectonic Paroxysm” (EBTP), including the great A.D. 365 subduction earthquake offshore Crete (Guidoboni et al., 1994). Darawchek et al. (2000) speculated that the A.D. 551 event ruptured a postulated extension of the Roum fault at sea, which the Shalimar survey has now demonstrated not to exist. More recently, on the basis of onland tectonic and geomorphic evidence, we proposed that the inferred Tripoli-Roum thrust—now mapped offshore as the Mount Lebanon thrust—was the most likely source of the A.D. 551 and 1063 earthquakes (Elias et al., 2001; 2003). Morhange et al. (2006) discuss the latter hypothesis in the light of their new vermetid ages, but fail to conclude on the relative roles of the EBTP, Tripoli-Roum thrust, and Yammouneh fault.

The SHALIMAR data essentially settle the issue, even though direct dating of the seafloor scarps will provide the ultimate proof. The submarine Mount Lebanon thrust range-front ramps are ideally positioned. To raise the Tabarja trottoirs 80 ± 30 cm above the LMSL, simple dislocation modeling in an elastic half-space (Okada, 1985) requires 1.5–3 m of seismic slip on these ramps, assuming they dip $\sim 45^\circ$ eastward in the upper 20 km of the crust (Data Repository item DR8). Such slip amounts are consistent with the estimated magnitude of the A.D. 551 earthquake, and sufficient to account for the tsunami observed. Historical evidence combined with the extent of vermetid death in the sixth century A.D. implies a rupture length of at least ~ 100 km, and possibly up to 150 km if the Rankine-Aabdeh lateral ramp was involved (Figs. 1 and 4), as suggested by two ages on Palmier Island (Table DR6). For such rupture lengths on thrust faults, empirical scaling laws predict an M_w of ~ 7.4 – 7.6 (Wells and Copper-smith, 1994), consistent with macroseismic estimates. Because strike-slip motion on the Yammouneh fault has been shown to produce only small local uplift (less than ~ 1 m in $\sim 10,000$ yr; Daëron et al., 2005), the inference that events on this fault might raise shorelines north of Beirut (Morhange et al., 2006) can be safely ruled out. The coastal ^{14}C vermetid ages confirm that the great A.D. 1202 earthquake, for instance, produced no uplift along the Lebanese shoreline. That benches offshore Tripoli are older than the seventh century A.D. in fact excludes the possibility that any of the earthquakes of the eleventh to fourteenth century A.D. sequence, including the A.D. 1063 event, ruptured the offshore Mount Lebanon thrust system. Hence, the destruction of Tripoli and Arqa by the latter earthquake may have been caused by slip on the Aakkar and/or Tripoli thrusts (Fig. 4).

The existence of multiple uplifted benches along the central Lebanese coast, and the similar vertical separation of the four benches we measured at Tabarja ($\sim 95 \pm 20$ cm on average), imply recurrent shoreline uplift by A.D. 551-

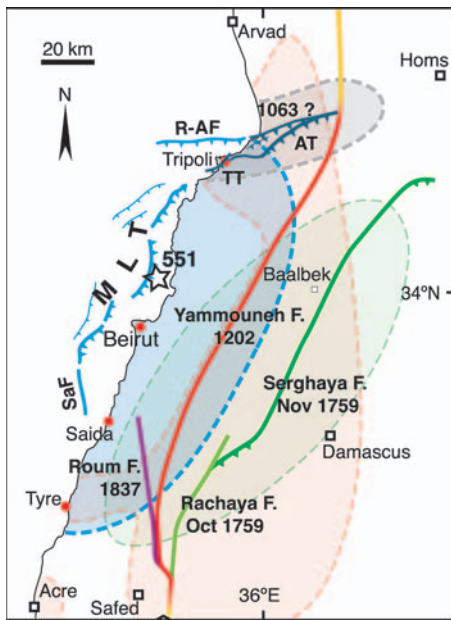


Figure 4. Most likely sources of A.D. 551 (open star—*inferred epicenter, this study*) and other large historical earthquakes in Lebanon (modified from Daëron et al., 2005). Colored patches enclose areas where macroseismic intensities >VIII were reported. Blue color corresponds to A.D. 551. (VIII isoseismal from Sieberg, 1932).

type events since the early Holocene, when the sea reached its latest, highest level, likely ca. 7–6 ka (Lambeck and Purcell, 2005). The return time of A.D. 551-size events must in any case be at least ~1500 yr. The seismic behavior of the Mount Lebanon thrust might thus be characterized by ~1500–1750-yr-long quiescence periods (four?) separating earthquakes clustered in a few centuries, as in the fourth to sixth century A.D. sequence. If so, the 1837 and 1956 events on the Roum fault and the 1918 event offshore Byblos (Daëron et al., 2005; Plassard and Kogoj, 1981) might be “forerunners” of worse to come. In keeping with this interpretation, one might expect the Mount Lebanon thrust to slip at an average rate of ~1 to ~2 mm/yr, the central Lebanese coast to rise above LMSL by 0.5 ± 0.1 mm/yr at most, and hence the highest raised marine terrace above Tabarja to be ~1 m.y. old, all plausible order-of-magnitude values. If the age of the latest sea-level highstand were only ca. 4 ka, as possibly consistent with archaeological evidence on the Israeli coast (Sivan et al., 2001), then the above rates might be 30% faster and the return time of A.D. 551-size events 30% less (~1 k.y.), which would make a repeat of this type of event long overdue. Clearly, dating of the higher vermetid benches and of cumulative seismic deformation on the seafloor are essential to test such inferences, as well as the apparent evidence for local, characteristic slip.

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