SHORELINES OF LIGEIA MARE, TITAN. E.R. Stofan[1], J.I. Lunine[2], R.D. Lorenz[3], R.L. Kirk[4], O. Aharonson[5], A.G. Hayes[6], A. Lucas[5], E.P. Turtle[3], S.D. Wall[7], C.A. Wood[8] and the Cassini Radar Team. [1]Proxemy Research, PO Box 338, Rectortown VA 20140 ellen@proxemy.com; [2]Cornell University, Ithaca NY 14853; [3]Space Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723; [6]US Geological Survey, Flagstaff, AZ 86001; [5]California Institute of Technology, Pasadena, CA 91125; [6]Miller Institute, U.C. Berkeley, Berkeley, CA 94720; [7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109; [8]Wheeling Jesuit University, Wheeling, WV 26003.

Introduction: Ligeia Mare is the second largest sea on Titan, with maximum dimensions of approximately 420 by 350 km, an area of approximately 126,000 km^2, and in excess of 2000 km of coastline (Fig. 1). It is centered at 78°N latitude, 249°W longitude. Unlike other maria on Titan, it has been completely mapped by the Cassini Radar, allowing a detailed analysis of its characteristics in radar data (see also Lucas et al. [1], this volume). Here, we focus on the general morphology of the shorelines of Ligeia, utilizing Earth analogues to better understand their possible modes of formation and modification.

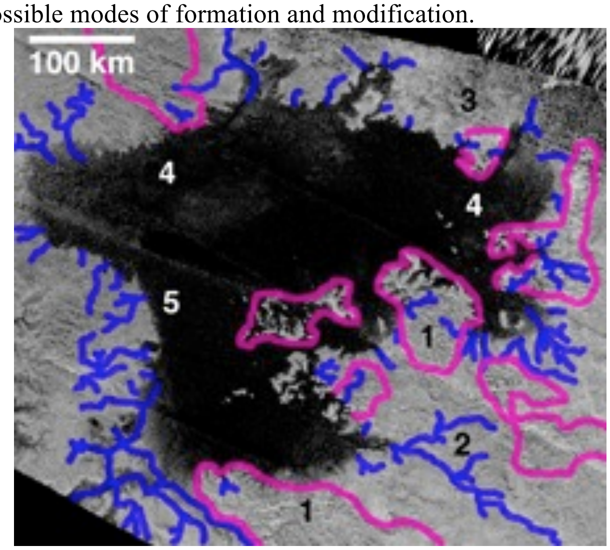

Figure 1. *Cassini Radar mosaic of Ligeia Mare (north at top, numbers refer to areas discussed in the text). Blue outlines some of the rivers draining into Ligeia; pink outlines hummocky terrain.*

Shoreline Classification: Shoreline morphology on Earth is the result of an interplay of number of different factors, including sea level history, tectonic history, rock type, and erosional and depositional processes (e.g., [2, 3]). Most terrestrial coastal classification schemes take these geologic processes into account, but also include some aspect of the biotic assemblages along coastlines (e.g., [4]). On Titan, we can disregard coastlines affected by living organisms (e.g., mangrove swamps, reefs), and we can also likely put aside coastlines that are formed by plate tectonics, volcanism and glaciers. This leaves a number of types of coastlines listed in Table 1. Coastlines can evolve from one type to another, as geologic processes, marine conditions and climate change.

Table 1. Types of terrestrial shorelines, after [2].

Process	Type	Example
Land Erosion plus sea level rise	ria (drowned river valleys)	Sydney, Georges River
	karst coast	Caribbean islands
	resistant rock (granite)	Maine
Subaerial deposition	delta coast	Mississippi Gulf coast
	alluvial fan or plain	Valencia coast, Spain
	dune-wind deposition	Narva
	landslide	Devon
Land process- tectonic	fault coast	Gulf of California
	fold coast	south Australia
Marine processes- wave erosion	irregular (caused by alternating rock types)	Dorset
	straightened (exposing structure)	north coast, Africa
Marine deposition	barrier coasts	North Carolina
	cuspate foreland	Lake Erie
	beach plain/mudflat	Spurn Bight

On Titan, seasonal evaporation of methane is likely to lead to either beach plain/mudflat shorelines as methane evaporates, as identified on the eastern shoreline at Ontario Lacus [5]; flooded coastlines such as ria shores may form as methane precipitates seasonally. Wall et al. [5] also identified a delta shoreline on the western shore of Ontario Lacus, and found that both the shorelines at Ontario have been modified by waves. At Ligeia, we would expect to find shorelines such as ria shorelines, indicative of sea level rise, possibly delta coastlines, dune-wind deposition, and wave eroded shorelines.

Types of Ligeia Shorelines: Two general types of coastlines are seen at Ligeia- crenulated (areas marked '1', Fig. 1) and subdued (areas marked '3', Fig. 1). The crenulated shoreline is associated with the hummocky terrain that constitutes much of the area to the south of Ligeia (outlined in pink, Fig. 1 and at '1's), which is heavily eroded. The subdued terrain at '2' in Fig. 1 is cut by numerous channels, likely the primary erosive mechanism on the hummocky terrain. The hummocky terrain only extends all the way to the shore on the southeastern coastline where the shoreline topography is the most pronounced; in other regions a more subdued unit forms a bench between the rougher terrain and the sea. A similar bench was identified in hypsometric data at Mayda Insula in Kraken Mare by Aharonson et al. [6]. Most of the shoreline of Ligeia is characterized by bays and coves, many of which are at the mouths of apparently flooded rivers that drain into Ligeia (in blue, Fig. 1). Bays and coves can form from differential wave erosion or from the flooding of river valleys. We know little about the bedrock geology of the Ligeia region, other than that it is likely dominated by water ice contaminated with minor constituents.

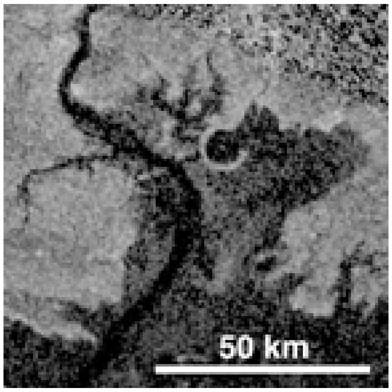

Figure 2. *Complex bay along Ligeia, with subdued shoreline topography. North is to top.*

The northern and western shores of Ligeia (at '3's, Fig. 1) are characterized by relatively smooth terrain also cut by rivers. In places offshore of this subdued terrain (at areas marked '4', Fig. 1; Fig. 2), the mottled appearance of Ligeia indicates that the radar is penetrating through the hydrocarbon liquids, indicating they are likely <5 m deep (e.g., [7]). This increased shallowness along nearly a quarter of the shoreline of Ligeia may be due to either a rise in sea level flooding low-lying terrain or large depositional fans extending in to the sea (or a combination of both).

At '5' in Figure 1, the shore of Ligeia forms a nearly straight line extending for over 50 km (Fig. 3). Straight segments of coast may form due to wave erosion or reflect structural control. Many of the rivers that cut through the hummocky terrain appear to be at least in part structurally controlled, and some are parallel to or run at angles to the shore, suggesting a possibly complex tectonic history for this region, and hinting that downwarping of the region may be responsible for the presence of Ligeia here.

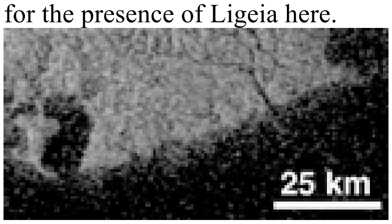

Figure. 3 *Possible fault-controlled shoreline on Ligeia, north is to the right.*

Conclusions: At Ontario Lacus, the presence of strandlines and a reduced lake level over the Cassini mission was found to be consistent with ~ 1 m of seasonal sea level change [5, 9]. However, the absence of subaerial deltaic deposits and the prevalence of ria coastline at Ligeia indicates sea level rise in excess of what is expected seasonally. This could be due to long term-forcings similar to the Croll-Milankovich cycle on Earth [8]. The eroded hummocky terrain and subdued terrain surrounding the sea are interpreted to have been modified by fluvial erosion, which has undoubtedly resulted in the extensive deposition of sediments in the sea and along the coast, resulting in low slopes around much of the shoreline. Some of the shallowing along Ligeia's margins (at areas marked '4', Fig. 1) may be flooded deltas, but the lack of subaerial deltas as seen at Ontario Lacus is also consistent with sea level rise. While Ligeia lacks the wave-modified beach and delta also seen at Ontario Lacus [5], much of the shoreline is subdued, possibly consistent with wave modification, although tides may also play a role. However, sea level rise is interpreted to be the dominant control on the morphology of Ligeia's shorelines. Observations by Cassini of Ligeia in the coming years will provide an opportunity to look for changes in sea level, as well as observe surface roughening associated with waves, although future missions that could measure sea depth and provide high resolution images of the shorelines are required to constrain the origin and evolution of the shorelines of Ligeia.

References: [1] Lucas, A. et al., this volume, *LPS 43.* [2] Shepard, F.P. (1973) *Submarine Geology*, J. Cutler, 517pp. [3] Cooper, J.A.G. and S. McLaughlin (1998) *J. Coastal. Res. 14,* A74. [4] Hayden, B.P. et al. (1984) *Eviron. Conserv. 11*, 199. [5] Wall, S.W. et al. (2010) *GRL 37*, L05202. [6] Aharonson, O. et al. [2011] *Eos Trans. AGU*, P32C-01. [7] Paillou, P. et al. (2008) *GRL 35*, L18202. [8] Aharonson, O. et al. (2009) *Nature 2*, 851. [9] Hayes, A. et al. (2011) *Icarus 211*, 655.