Mare, or wrinkle ridges are common on the Moon, Mars and Mercury and their origin has been the subject of debate for many years. Theories of origin can be classified into volcanic, tectonic or a combination of these two. Virtually all evidence bearing on the origin of mare ridges comes from images of their surface morphology and topography and a variety of terrestrial analogs. Occasional examples of the intersection of mare ridges with other structures, such as craters, provide hints of their three dimensional nature. We have previously summarized and examined the evidence for lunar mare ridge origins proposed by previous workers and have concluded that mare ridges and their characteristic morphology are the surface expressions of tectonic deformation within the lunar lithosphere and that associated volcanic features are of minor importance and unrelated to the basic genesis of mare ridge surface structures. However, an important element of virtually all models for ridge origin is the subsurface nature of the structure and its relation to the geological units within which it occurs. Access to this type of information expands the data set and allows a definitive assessment of mare ridge origin. The Apollo 17 ALSE provided subsurface data for Mare Serenitatis and Mare Crisium. We have examined the data for Mare Serenitatis and reinterpreted the subsurface stratigraphy, structure and subsidence history for the basin. The purpose of this paper is to examine Serenitatis subsurface stratigraphy and structure in order to test hypotheses for the volcanic and tectonic origin of mare ridges and arches.

Description - The Apollo 17 groundtrack (rev. 16), ALSE radar returns, and the proposed stratigraphy across southern Serenitatis are shown in Fig. 1, reference 6. The portion of the groundtrack analyzed in this study includes, from east to west, the following geological units: Mons Argaeus (A', Fig. 1), Serenitatis highlands material; a small patch of unit I volcanics, the earliest volcanic unit; a small local deposit of basalt, unit II, emanating from a linear vent system radial to Serenitatis just south of the groundtrack; an areally extensive tract of unit III, the last basalt unit to flood the basin. Distinctive morphologic features in these units include: 1) linear rilles developed in unit I, but not exposed directly under the groundtrack; 2) Mare ridges and arches developed on unit III. A small mare ridge is seen at B (Fig. 1b, [6]), a broad arch extends from about B to F and contains several superposed ridges at C, D, and E, and two ridges are seen at G and H. The relationship of Serenitatis mare emplacement, lithospheric loading, basin tectonics, and lunar thermal history is treated elsewhere. Here we concentrate on the relation of surface features to subsurface stratigraphy and structure. Our interpretation of the subsurface stratigraphy is discussed in [6]. The first reflecting horizon is a thin (<5 m) regolith developed on top of unit I. The upper layer thus consists of 1 - 1.5 km of basalt, principally unit II but containing ~400 m of unit III at the top. The second reflecting horizon defines the boundary between the base of unit I (~1 km thick) and Serenitatis basin substructure (Fig. 1, [6]). Five major areas of subsurface disruption are noted (Fig. 1,[6]): 1) unit I is distinctly depressed along sharp boundaries at I and J. There is no ridge development associated with this feature although post-unit II (the present surface) subsidence is implied by the existence of a shallow (<250 m) depression between I and J. 2) At K a downstep of the basal unit I contact occurs from west to east but is less clear along the upper contact. There is no appar-
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ent surface manifestation. 3) A distinct offset in unit I (B) is reflected by a mare ridge at the surface. 4) Major complexities exist between B and F in the subsurface below the arch-ridge complex, Dorsum Lister. Basaltic units are thinned and appear to be draped over the large arch-like feature developed in the pre-mare basin material. 5) Tilting and disruption of unit I occurs between G and H and is manifested at the surface by two mare ridges (Fig. 1). We concentrate on the last three occurrences, where subsurface disruptions are correlated with surface arch/ridge development.

Assessment of Volcanic Hypotheses - 1) Ridges analogous to squeeze-ups and autointerruption in cooling terrestrial lava lakes [8] - The throughgoing nature of the disruption of units (top and bottom contacts) and the scale of disruption (tens of km in width involving multiple units) rules out a mechanism involving deformation of a cooling lava surface crust for these examples. The distinctive subsurface manifestation of all ridges and arches under the groundtrack also rules out hypotheses requiring these features to be simple surface flow features such as flow fronts or levees [9].

2) Ridges form from basaltic extrusions along dikes [10] - Several observations preclude a uniquely volcanic origin of this type: a) Tilting of unit I boundaries at B/H to a degree greater than the present surface topography requires deformation pre-dating ridge formation. These ridges and their subsurface manifestations cannot therefore be due to simple dike formation and extrusion. b) The widths of the disrupted zones below ridges and arches are orders of magnitude larger than common terrestrial dikes and lunar dike/fissure widths calculated from basalt vents and deposits [11]. The authors know of no mechanism by which the simple intrusion of a dike through horizontal basalts could produce deformation zones as wide and complex as those observed here. Therefore, the nature and the chronology of the deformation of subsurface layers and the width of the disrupted zones all rule out a uniquely dike-related origin for the ridges/arches and their subsurface structure. Extensive tectonic deformation seems to be required to explain these factors. As is commonly observed on Earth, subsidiary volcanism may be associated with zones of tectonic deformation. 3) Arches reflect shallow laccolithic intrusion with superposed ridges representing small extrusions [12] - Ridges at B, G and H have surface characteristics which appear to represent high angle vertical displacement (B) or disruption and downdropping of reflector horizons (between G and H), neither resembling laccolithic intrusions. The best candidate for such a process is Dorsum Lister (B-F) [5]. The cross section generally resembles the form of a classic laccolith, i.e., beds are updomed along an arch that is much broader than high. Several observations, however, preclude a simple origin by laccolithic intrusion and extrusion of lavas to form the associated ridges: a) there is no reflecting horizon defining the base of the intrusion. b) the volcanic unit I is thinned in the vicinity of the arch implying that the arch existed as a prominent topographic feature prior to the onset of mare volcanism. c) the minimum upbowing implied by the tilting of the base of unit I away from point F (1200 m) is a factor of 3 more than the surface relief on the arch. Thus b) and c) above imply a pre-unit III origin for the arch, whereas, if the arch were a laccolith deforming unit III by updoming and extrusion, it would have to have intruded post unit III. Thus subsurface evidence is inconsistent with Dorsum Lister or any mare ridges along the groundtrack being primary manifestations of either laccolithic or dike intrusion.

Assessment of Tectonic Hypotheses - 1) Mare ridges - At B, a mare ridge is underlain by a generally vertical disrupted zone with throughgoing deformation of unit I and a vertical offset on unit I exceeding present surface...
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topography. Vertical faulting in post-unit I time seems required, with offset decreasing with time. Mare ridges at G and H bound an area of disruption that appears to be downdropped during post-unit I time. The western edge appears tilted up and slightly overthrust. The structural relief on the tilted blocks exceeds the surface relief on the mare ridge at H; post-unit I deformation, perhaps compressional in nature, is implied with offset decreasing with time. These observations support tectonic origins for mare ridges, perhaps by vertical faulting [13] or of a compressional [14] nature. 2) Mare Arches - unit I thins beneath the flanks of Dorsum Lister and cannot be traced over the top. It appears to be draped over sub-unit I topography. The peak-ring structure of the Serenitatis basin has been hypothesized to lie under the mare in this position [15, 16]. The geometry of this structure is comparable to peak rings seen in the Orientale basin [17] and the highest point in the interior of Mare Serenitatis lies a few km to the northeast along the ridge crest. These observations are consistent with the presence of a major topographic feature in this location during the flooding and deformation of the mare units. Its presence served to influence thickness and accumulation of basaltic deposits in this area and concentrated stresses and deformation in this region during basin subsidence [18].

Conclusions - 1) Serenitatis substructure and stratigraphy confirmed a tectonic and deformational origin for the mare ridges and arches examined (Fig. 1), and rule out origins relying solely on volcanism. Subsidiary volcanic activity is plausible but not required by any observations in this region. 2) Mare ridges and arches exhibit distinctly different substructure in this region, suggesting two modes of deformation: a) ridges reflect throughgoing vertical or near-vertical zones of disruption and may represent both normal and compressional modes of faulting. Major deformation appears to have begun after the emplacement of unit I and to be of less significance after the emplacement of unit II. b) Arches appear to represent a combination of effects from the presence of buried or partially buried topography. In addition to the influence of the topography on the thickness and distribution of lava units, the topography acts as a stress concentrator during subsidence and deformation of the mare deposits, serving to localize deformation into a series of ridge features superposed on the buckled surface. We are presently documenting the detailed style of deformation associated with mare ridges and arches.