The only other impact melt samples from the Apollo 17 highlands (apart from glass formed by shallow-level recent impacts) are probably the troctolitic basalts found as clasts in some of the aphanitic rocks [e.g., 4]. A second high-K impact melt breccia proposed by [9] was not confirmed in the present analyses; instead, sample 72558 appears to be a typical "Serenitatis" melt.

A discussion of the origin of the aphanitic melt rocks and the "Serenitatis" poikilitic melt rocks was given by [3]. The poikilitic rocks have a lithic clast population limited almost entirely to plutonic igneous rocks such as norites and feldspathic granulites. The aphanitic rocks were faster-cooled, and contain a greater proportion and variety of lithic clasts; these clasts include surficial types such as impact melt and basalts, and felsite or granite clasts are common. The aphanitic rocks have accretionary and "bomb" characteristics; they are consistent with derivation from a much shallower target than the "Serenitatis" melts. Nonetheless, the targets were similar except that the shallower one was more aluminous and less titanian. The two groups could have been formed in the Serenitatis event, but in that case intermediate compositions might have been expected as well. Neither formed in a significant melt sheet, as they all contain conspicuous clasts and have fine-grained groundmasses. Even in the coarser melts, the clasts have not well equilibrated with the groundmass, even for argon [12]. Indeed, the aphanitic melt rocks do not show argon plateaus; their age is based on degassing of felsite/granitic clasts and is close to 3.86 or 3.87 Ga [13,14]. Clasts in the poikilitic rocks also compromise the melt age, although the best examples again suggest 3.87 Ga, presumably the age of the Serenitatis event [15,16]. Melt rocks with a composition very similar to either the "Serenitatis" melts or the aphanitic melts have not been found among Apollo 15 samples on the opposite side of the Serenitatis basin [17].

Sample 76055 has an older age, with a plateau that seems reliable at 3.91 Ga [18]. The sample is clast-poor (though not clast-free). The other two samples (72255 clast and high-K 72735) have not yet been dated, but are included in a laser Ar-Ar analysis in progress [17]. Samples of the "Serenitatis" and aphanitic melts are also included in the Ar study in an attempt to confirm and refine the age of Serenitatis and the possible relationships among the impact melt groups, as well as characterize the impact history of the Moon.

The characteristics of impact melt rocks are derived from the melt volume produced by the impact, from the clastic material entrained and picked up as the melt moved away from its source, and by the cooling environment. The characteristics can thus provide information on the lunar crust at and around the target site. Differences in composition of melt rocks can be interpreted as vertical or horizontal (or both) variations in crustal composition. Lithic and mineral clasts can be used to define the source rocks. The Apollo 17 impact melts suggest some variation in targets. The crust may be richer in titanium and poorer in alumina at greater depth. The deeper sampled parts seem to consist of pristine igneous rocks, particularly norites and troctolites, and some feldspathic granulites, whereas the shallower part has a greater complement of granitic/felsitic rocks and near-surface lithologies such as basalts, impact melts, and breccias. The lower part does not seem to consist of mixed megaregolith, but some components of the melt are as yet chemically unexplained.

The melt population sampled by the boulders and rake samples is not representative of the massifs, which contain more alumina and lower abundances of incompatible elements. The soil composition suggests a maximum of 50% of either "Serenitatis" melt or aphanitic melt as a component. There is probably a bias in that coherent material, particularly large boulders, is likely to be a late unit, such as melt produced in Serenitatis; pre-Serenitatis material presumably exists as smaller blocks within the ejecta pile forming the massifs.

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APOLLO 17: ONE GIANT STEP TOWARD UNDERSTANDING THE TECTONIC EVOLUTION OF THE MOON.
Virgil L. Sharpton, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA.

The Moon's landscape is dominated by craters and large multiring impact basins that have obliterated any morphological evidence of the surface and interior processes occurring in the first few hundred million years of lunar history. By ~4.0 Ga, the lunar lithosphere was thick enough to support loads imposed by basin formation and mare infilling without complete isostatic compensation [1,2]. Most of the lunar tectonic features developed since that time are local in scale, and are associated with vertical deformation in and around mare basins. These features include (1) tectonic rilles, or graben, located along the margins of major mare basins, such as Serenitatis; (2) wrinkle ridges of compressional origin located primarily within the mare units; and (3) mare topography [3,4] developed via flexure and in part controlled by basin substructure. The relative ages and spatial arrangements of these features are explained by flexure of the lunar lithosphere around mascon basins in response to volcanic loading and global cooling [1].

Our present understanding of the tectonic history of the Moon has been shaped in large measure by the Apollo program, and particularly the Apollo 17 mission. The landing site, in the Taurus-Littrow valley on the southeastern flank of Mare Serenitatis, allowed extensive examination of the tectonic expression within and around the southern portion of Mare Serenitatis from the CSM orbiting overhead. Serenitatis is particularly well suited for understanding the tectonics of basin loading because its volcanic stratigraphy is conspicuous and reasonably simple [e.g., 3], and numerous tectonic features are developed on and around the mare. The Scientific Instrument Module included the Apollo Lunar Sounder Experiment, which was designed to detect layering in the upper few kilometers of the Moon [5,6]; these data have placed important constraints on the size of the volcanic load and the lithospheric response [1,4–6].

Astronauts on the surface in Taurus-Littrow valley made detailed observations of the Lee-Lincoln scarp and other structures encountered along their extensive traverses. They also made gravity measurements and conducted seismic profiling to constrain the geometry of the subfloor basalts [7]. These data, in conjunction with the samples returned to Earth, permit a far clearer understanding of the origin and evolution of this key valley and its relationship to Mare Serenitatis. In this brief paper, I attempt to summarize some of the interpretations that have emerged since Apollo 17, focusing on some of the problems and uncertainties that remain to stimulate future exploration of the Moon.

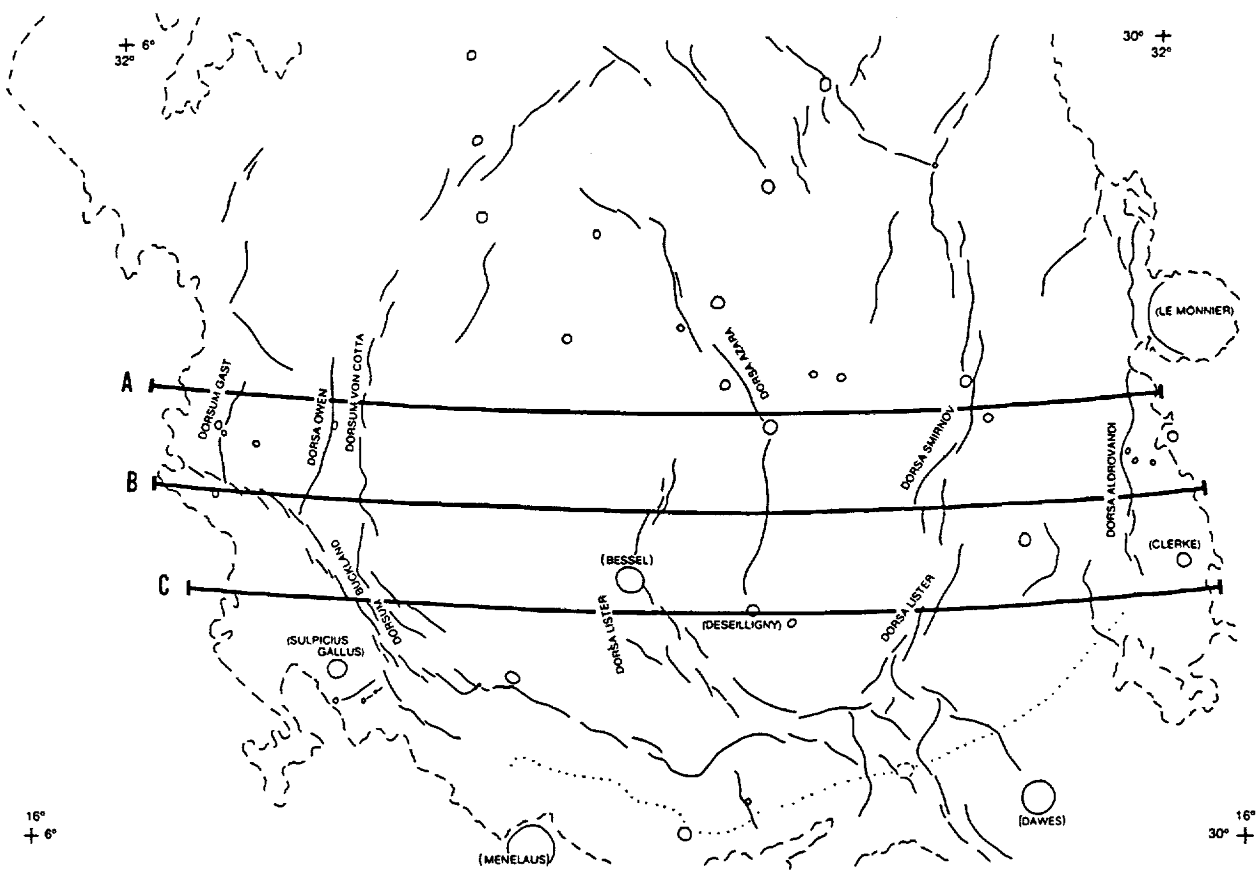

Fig. 1. Wrinkle ridge systems in Mare Serenitatis. Lines denote profiles shown in Fig. 2.

Taurus-Littrow Valley: Because of its steep, straight walls and flat floor, and its radial orientation to the Serenitatis Basin, the valley was interpreted as a graben formed during basin formation [8,9]. Although Apollo 17 subsequently demonstrated that the valley had been flooded by mare basalt [10,11], the graben model has never been reassessed. The North and South Massifs, which form the flanks of Taurus-Littrow valley, are similar to massifs of Montes Rook in Orientale [e.g., 12]. Radial topographic elements are also characteristic of the flanks of many large impact basins such as Imbrium, Crisium, and Nectaris. The nature of these landforms has been debated for decades, but much of the radial topography reflects scouring and related sedimentary effects during basin formation [13]. Consequently, the straight bounding walls and radial orientation of the Taurus-Littrow valley may reflect impact erosion rather than normal faulting. Furthermore, although the Apollo 17 traverse gravimeter and seismic profiling experiment demonstrated that a thick body of dense material occurs beneath the present valley floor [7], the assumption that this is all mare basalt may be premature. Montes Rook shows considerable evidence of embayment by and ponding of melt-rich Maunder Formation [12], suggesting that at least part of the 1.4 km of dense subfloor rocks comprising Taurus-Littrow valley fill could be Serenitatis impact melt.

Regardless of its origin, however, the Taurus-Littrow valley contains some intriguing surface features, some of which, like the Lee-Lincoln scarp, are clearly tectonic in origin, others, possibly so. Falling in the latter group is an interesting but unexplained topographic depression that runs along the boundary between the valley floor and South Massif. Referred to as a trough by the Apollo 17 astronauts on their traverse to Nansen Crater and station 2 [14,15], the depression is up to a kilometer wide and is deep enough to have left the astronauts with the impression that they were "clearly going downhill now" as they entered the trough [14]. In Apollo 17 photographs, the trough seems to be developed principally on and to the west of the Lee-Lincoln Scarp, i.e., the uplifted side, suggesting that it is somehow related to the structural deformation of the valley floor. The fact that this trough is evident at the base of a steep massif where talus accumulates indicates that it is a relatively recent feature.

Origin of Mare Ridges: During and shortly after the Apollo program, considerable debate raged over whether wrinkle ridges were products of volcanic [16–18] or tectonic activity [19–21]. Upon more detailed assessment of the Apollo data [e.g., 22], however, the consensus rejected the volcanic theory, and discussion shifted to whether these ridges were primarily folds or faults and, if the latter, whether strike-slip [23], vertical [24], or thrust faulting [25] was the principal mechanism involved. The Apollo 17 astronauts crossed the Lee-Lincoln scarp near South Massif, but no clear signs of faulting or folding were evident, possibly because of the thick mantle layer on the valley floor [15]. On the valley floor the scarp has the typical appearance of a wrinkle ridge consisting of discontinuous hills and sinuous ridge elements. As the scarp crosses into highlands at North Massif, however, it takes on the unmistakable expression of a fault scarp [19,20]. This link between a wrinkle ridge and a highland scarp indicates that at least some such ridges on the open maria are surface expressions of basement faulting [24].

Understanding the attitudes of faulting associated with wrinkle ridge formation is important for determining the amount of horizontal compression associated with basin loading. The west side of the Lee-Lincoln scarp is topographically higher than the east on the valley

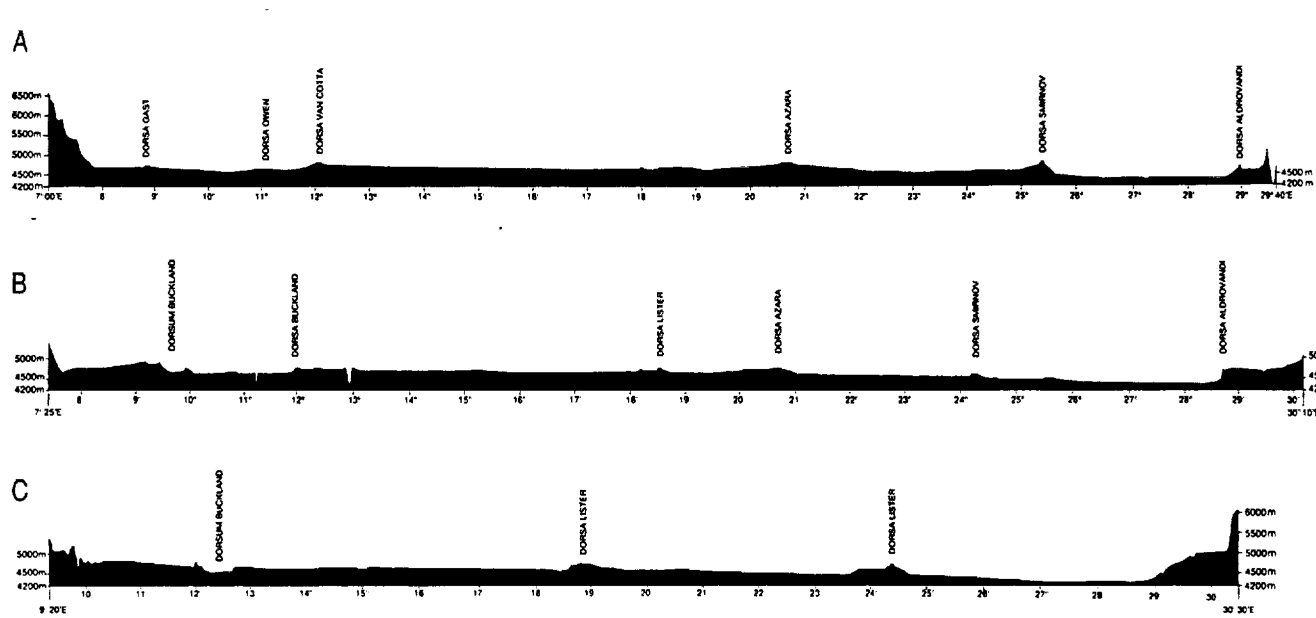

Fig. 2. Topographic profiles across Mare Serenitatis.

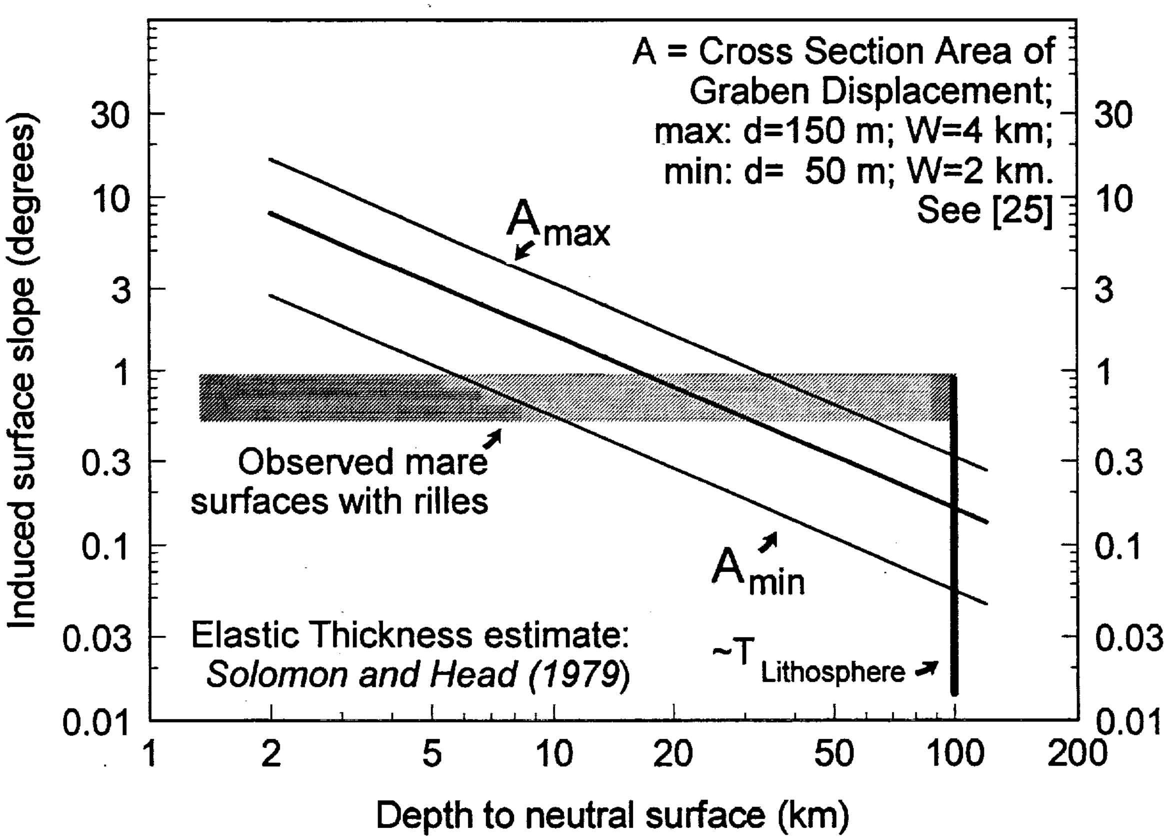

Fig. 3. Plot of the surface slope angle generated from rille formation as a function of depth to the neutral surface.

floor, and as the scarp cuts the valley wall of North Massif, its trend cuts sharply to the west. The slope of North Massif approaches 20°, therefore if the scarp is the expression of a westwardly dipping reverse fault, the dip must exceed 20°. The problem, however, is that the morphology of wrinkle ridge systems is highly variable and permits a spectrum of tectonic styles to be involved. Within Serenitatis alone, there are complex systems of ridges (Fig. 1), some of which have distinct vertical offsets, while others do not (Fig. 2). Two models have been proposed to account for the vertical offsets: thrust faulting [25] and nearly vertical faulting [24]. There does not appear to be any correspondence between the vertical offset across a ridge element and its topographic relief. Furthermore, apparent offsets across some ridges are produced because the ridge is developed on a sloping mare surface; when the regional trend is removed, so is the offset in several cases. This suggests that wrinkle ridges include a variety of compressional tectonic structures, perhaps ranging from simple thrust faults to nearly vertical reverse faults to complex zones of buckling [22]. There does not, however, appear to be any indication of substantial overthrusting.

Nature and Timing of Tectonic Rille Formation: Concentrically oriented tectonic rilles deform the flanks of many of the large mare basins including Serenitatis. These structures have been attributed to the extensional deformation associated with mascon loading [1]. Golombek [25] proposed that these graben were produced through simple extension, that the bounding faults intersected at a depth of a few kilometers, and that the faulted layer corresponded to the "megaregolith." In that analysis, graben formation due to bending was dismissed because under the assumed conditions, the mare surface would slope away from the graben by up to 10°. However, Golombek apparently did not consider the effects of increasing the thickness of the faulted layer. Figure 3 shows the surface slope that would result from layer bending to produce the size of lunar rilles observed (50–150 m deep, 2–4 km wide; [25]). If the depth to the neutral surface were half the thickness of the elastic lithosphere (~100 km; [1]), then the slopes induced by bending would be ≤1°, in excellent agreement with measurements of the slopes on mare surfaces containing linear rilles [4]. This analysis indicates that graben around lunar basins can be accounted for solely by bending of the elastic lithosphere.

The stratigraphic relationships between tectonic rilles and the major volcanic units exposed in mare basins provide clues to the timing of basin deformation. It has long been recognized that rille formation ended prior to 3.4 Ga [26]. In addition, assessment of southeastern Serenitatis shows that the oldest volcanic unit (unit I; Plenius basalts equivalent; [3]) was emplaced prior to the onset of rille deformation. There are no cases where unit I clearly floods or embays any rilles nor is there any indication that rilles are truncated at the boundary between this unit and the highlands. In constrast, rilles that intersect the younger unit II surface are consistently truncated and embayed by these lavas. Elongate collapse features, indicative of buried rilles, are observed on unit II in the southeastern portion of the basin, but no such features are evident on exposed unit I surfaces. Consequently, it seems that rille formation in southeastern Serenitatis began after unit I emplacement and culminated before unit II.

Samples returned from Apollo 17 indicate that the unit I basalts were deposited over a range of ~150 Ma from ~3.84 Ga to ~3.69 [27]. Thus the post-unit-I onset of rille formation appears to signal a relatively slow response of the lithosphere to the increasing volcanic load in the Serenitatis Basin. The most likely explanation for this involves the isostatic state of the Serenitatis Basin during early mare emplacement. It is conceivable that appreciable quantities of the early volcanics would be required to offset the mass deficiency created during the impact basin formation. If this is the case, volcanic infilling of the southern portion of Mare Serenitatis did not reach superisostatic levels until the majority of unit I was emplaced.

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MELTING OF COGENETIC DEPLETED AND ENRICHED RESERVOIRS AND THE PRODUCTION OF HIGH-Ti MARE BASALTS. Gregory A. Snyder[1], Lawrence A. Taylor[1], and Alex N. Halliday[2], [1]Department of Geological Sciences, University of Tennessee, Knoxville TN 37996, USA, [2]Department of Geological Sciences, University of Michigan, Ann Arbor MI 48109, USA.

Implicit in current understanding of the location of terrestrial enriched and depleted reservoirs is the notion that they are spatially separated. The depleted reservoir on Earth is situated in the upper mantle, and the complementary enriched reservoir is located in the crust. However, Earth reservoirs are continually being modified by recycling driven by mantle convection. The Moon is demonstrably different from Earth in that its evolution was arrested relatively early—effectively within 1.5 Ga of its formation [1]. It is possible that crystallized trapped liquids (from the late stages of a magma ocean) have been preserved as LILE-enriched portions of the lunar mantle. This would lead to depleted (cumulate) and enriched (magma ocean residual liquid) reservoirs in the lunar upper mantle. There is no evidence for significant recycling from the highland crust back into the mantle. Therefore, reservoirs created at the Moon's inception may have remained intact for over 4.0 Ga.