

STRUCTURAL HISTORY OF SOUTHEASTERN MARE SERENITATIS AND ADJACENT HIGHLANDS. W. R. Muehlberger, Dept. of Geological Sciences, The University of Texas at Austin, Austin, Tx. 78712 and Center of Astrogeology, U. S. Geological Survey, Flagstaff, Az. 86001.

SUMMARY: Successive deformations of southeastern Mare Serenitatis and adjacent highlands can be traced through time by identifying bent and fractured surfaces that are assumed to have been horizontal when formed. The decreasing magnitude of successive deformations and associated subsidence of the Mare Serenitatis basin shows that the lunar crust became progressively stronger through time. The earliest recognized folding deforms the ca. 3.8 b.y. [1] basalt of the Taurus-Littrow valley (Apollo 17 landing site): older highlands plains had not been tilted prior to this event. The second basalt sequence (ca. 3.5 b.y. [2]) is gently tilted toward the Serenitatis basin. The third and youngest (ca. 3.2 b.y. [2]) basalt sequence, the main filling of Mare Serenitatis, is barely tilted southeast showing that the lunar crust was strong enough by that time to maintain this load out of isostatic equilibrium to present (the mascon mass). Since ca. 3.2 b.y., contraction by cooling of the moon has put the outer shell into a compressional regime as demonstrated by the systematic patterns of wrinkle ridges formed by crumpling of the compressed plate of mare basalt. Wrinkle ridges are localized by either stratigraphic and structural discontinuities in the mare sequence or where large craters have penetrated the mare sequence. Asymmetric scarps of the Taurus-Littrow Mountains are also young compressional features. Wrinkle ridges began forming prior to the termination of ca. 2.5 b.y. old basalt eruptions in Mare Imbrium [3,4]. The localization of wrinkle ridges by large fresh craters and deformation of small craters, as well as similar evidence of youth on the scarps in the highlands indicates that deformation is still going on.

Stage 1 Deformation: Post-Taurus-Littrow Basalts: The Taurus-Littrow basalts have been folded into a broad north-trending anticline whose crest lies west of the Apollo 17 landing site. The present day structural relief, 700 m, is only partial because the present surface dips west to an unknown depth beneath the Mare Serenitatis basalt. The older highlands light plains east and north of the landing valley, including the floor of the crater Littrow, have dips equal to those of the basalt; thus no tilting occurred in the time interval between the deposition of these units. East of 32° longitude, the highlands plains are horizontal. The boundary of the east flank of the anticline is along one of the Serenitatis basin rings. The southern boundary of the anticline lies along the north base of Mons Argaeus, a structure radial to the Serenitatis basin.

Grabens (linear rilles) on the basalt-covered annulus of the Serenitatis basin indicate strong downwarping of the basin during this interval. Their prominent development around the southern and eastern quadrants suggests an asymmetrical warping that reaches a maximum in the southeastern sector. North of the landing site, the main graben (Rima Littrow I) trends obliquely across the anticline and continues into the highlands at a slight angle to the present margin of the mare basin. The lack of parallelism of Rima Littrow I to the presumed circular shape of Mare Serenitatis suggests that this is only an approximation to the shape of the older sagged surface. Other small grabens that trend parallel to the anticlinal crest are probably contemporaneous with both

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Rima Littrow I and formation of the anticline.

Other basalts along the southern and southwestern rim of Mare Serenitatis presumably contemporaneous with those of Taurus-Littrow [5], have also been broken by graben. Whether this region has been folded into a ring anticline similar to that of the Taurus-Littrow region is not known (topographic maps are not available). Stereoscopic study of photographs shows that the old basalts dip strongly toward the Serenitatis basin.

Stage 2 Deformation: Post-Basalt Near Dawes: Southwest of Mons Argaeus is a basalt unit that buries the older folded and faulted basalt [5]. A sinuous rille from a line of cones radial to Mare Serenitatis shows that the lava flowed toward Mare Serenitatis. Spectral data suggest that these basalts are titanium-rich [2]; they were probably extremely fluid [6]. The present-day slopes are such that the basalt should have run rapidly down the slope and not have spread laterally across the 30 km wide outcrop band, hence, the present day dip is interpreted to be greater than the initial dip.

Two other areas along the eastern and southwestern parts of the outer annulus of Mare Serenitatis also contain basalt of the second sequence of eruption [5]. These basalts are also gently deformed and cover the earlier graben. Spectral analysis suggests these are low titanium basalts (Serenitatis type of Soderblom, [2]), and thus they may be younger than Soderblom's [2] Tranquillity type (high-titanium) basalt near Dawes.

Deformation of these basalts has been limited to tilting. If sharp folding and/or faulting occurred after eruption of the second sequence, it must have been in the area now covered by the third basalt sequence that fills Mare Serenitatis.

Stage 3 Deformation: Post-Mare Serenitatis Basalt: The brownish gray basalt [7] that fills Mare Serenitatis has a cratering age roughly equal to the Apollo 12 and 15 basalts: about 3.2 b.y. [2]. The deformation of this unit is minor as compared to that of the older basalts. This decrease in amplitude of deformation through time can be ascribed to an increase in lithospheric strength sufficient by at least 3.2 b.y. ago for the Mare Serenitatis basalt to be supported out of isostatic equilibrium as a mascon.

The deformation of Mare Serenitatis since ca. 3.2 b.y. ago consists of a slight tilt to the southeast as shown by Apollo laser altimetry [8,9] and the formation of wrinkle ridges on the mare surface. The laser altimeter data also show that breaks in regional mare slope coincide with wrinkle ridges.

The mare wrinkle ridges of central and eastern Mare Serenitatis are north-trending elongate anticlinal zones, 5-15 km across, with sharp narrow asymmetrical upwarps about 1 km across, parallel to the main ridges. The amplitudes are generally less than 200 m. The shapes are consistent with a compressional origin with the axis of horizontal shortening being perpendicular to the fold axis. The main anticline represents the folding of the entire sequence of basalt flows and the tight narrow wrinkles represent the disharmonic folding of the upper layer (layers?). The location of the concentric wrinkle ridges is probably controlled by scarps along the buried basin margin. The change in strike of the wrinkle ridges at the crater Bessel in south-central Mare Serenitatis suggests that these wrinkle ridges resulted from deformation by stress concentration around a hole in compressed

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mare basalt. The location of some wrinkle ridges on other mare also appear to be directly related to prominent fresh craters. (eg: Lambert, C. Hershel; Mare Imbrium).

The wrinkle ridges of southwestern Mare Serenitatis differ in that the anticlinal ridges are offset by faults whose northwest strike lies at  $60^\circ$  to the strike of the fold axis. This consistent fault offset of the fold axis produces a strong asymmetry to the wrinkle ridge. The fault trend is nearly parallel to Imbrium sculpture in the adjacent highlands, a structure that probably underlies the mare at shallow depths in the marginal zone and which thus influenced the shape of the wrinkle ridge system.

The youth of the wrinkle ridges is shown by the fact that they deform young craters (eg: Littrow BB) and have unfilled cracks parallel to their crests [10].

Along the southeastern edge of Mare Serenitatis where wrinkle ridges extend into the annulus of older basalts, the amplitude of the ridge decreases sharply, a result of folding a different package of basalt flows. Those that extend into the Taurus-Littrow basalt west of the Apollo 17 landing site displace graben (Rima Littrow I-IV) and continue southeastward as asymmetrical ridges and scarps in both highland and mare surfaces to the crater Vitruvius. One of these, the east-facing scarp traversed by the Apollo 17 crew averages 80 m in height across most of the valley of Taurus-Littrow before it apparently dies out southward near the South Massif. It extends northward along the lower slopes of North Massif, continues for nearly 40 km along the western edge of the Taurus-Littrow highlands to crater Littrow B. The smooth appearance of the North Massif below the scarp as compared with the rest of the slope, and the smooth areas west of the scarp between Family Mountain and South Massif that also has open cracks that extend onto the avalanche deposit from South Massif, may be the result of recent movement along this fault. Seismic shaking is assumed to be the cause of the smooth appearance of the cratered surface of a moving thrust sheet. This continuing regional compression seems most likely to result from contraction of the moon during cooling since the termination of mare volcanism.

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