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The interpretation of gravity anomaly on lunar Apennines

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The lunar Apennines, located in the southeast of Mare Imbrium, is the largest range on the Moon. The gravity anomalies on profiles across the mountains reveal evidence of a great fault zone characteristic. The deep crustal structures of lunar Apennines are analyzed on the basis of topographic data from Chang'E-1 satellite and gravity data from Lunar Prospector. The inverted crust-mantle models indicate the presence of a lithosphere fault beneath the mountains. Inverted results of gravity and the hypothesis of lunar thermal evolution suggest that the lunar lithosphere might be broken ~3.85 Ga ago due to a certain dynamic lateral movement and compression of lunar lithosphere. This event is associated with the history of magma filling and lithosphere deformation in the mountain zone and adjacent area. Moreover, the formation and evolution of Imbrium basin impose this effect on the process.

the Moon, lunar crust, Apennine, gravity anomaly

Knowledge of the lunar internal structure and evolution is fundamental to understanding the origin and evolution of the earth and the solar system. With the increased world wide attention to the exploration of the moon over this past decade, new information and fundamental constraint on the internal properties of the Moon have become increasingly available by satellite missions such as Clementine, Lunar Prospector, SMART-1, SELENE, CE-1, and other satellite observations that mapped the lunar topographic and gravity fields.

The high spatial resolution Laser Altimeter data were obtained by the Chinese lunar explorer Chang'E-1 (CE-1) for over two months' measurement, which in turn has been used to produce a global lunar topographic model CLTM-s01[1]. In comparison with the previous topographic model, the CLTM-s01 with degree and order 360 has improved in data coverage, spatial resolution and elevation accuracy. It clearly reveals the major lunar geologic terrain features, especially the central peaks of impact craters. This improved topographic data provide us with important surface information to analyze the evolution and internal material distribution of the moon.

The advent of plate tectonic theory in the 1960s has revolutionized thinking in Earth Science, and provides a solid framework for understanding how the Earth' crust works. For instance, this theory explains with clarity how enormous mountain belts form on Earth. Associated with these mountain belts are specific characteristics of geophysical signatures. Thus, geophysical data such as gravity anomalies have been used to understand the underlying tectonic events in mountain belts and continental margins, such as Himalayas along the India-Eurasia plate boundary. The satellite gravity map of this area

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reveals two major positive and negative anomaly bands along the trend of the Himalayas, reflecting the distribution of lithospheric materials in the Himalayan region. There are numerous such examples on Earth and other planetary bodies. For this reason, satellite gravity anomalies are commonly accepted as a powerful constraint for investigating the internal structure and the evolution of planetary bodies. The latest lunar gravity map also shows that these kinds of anomaly trends exist on the lunar Apennines. Furthermore, the anomaly amplitude is almost the same as that above the Himalayas. Thus, two questions arise: What does this gravity trend reflect? Is it possible that the lithosphere of lunar Apennines also once suffered from plate collisions similar to those on the earth?

The Moon's internal evolution has basically ceased at present, so with no conclusive evidence to show whether the Moon possesses a layer structure similar to the earth. Previous studies[2−8] suggest the Moon is compositionally differentiated and hence stratified in density that essentially increases with depth. If this is the case, the mass contrasts from boundary undulations in the crustal layers can yield anomalies in the external gravity field. Thus, an analysis of satellite gravity field gives insight into the lunar subsurface structure. For example, Wieczorek and Phillips constructed a dual-layered crustal thickness model of the moon using the satellite gravity anomalies[7]. The crust-mantle structures under some lunar maria were further studied based on the Bouguer anomaly with Apollo 12-14 seismic constraint[4,5,9].

To investigate the origin of the gravity anomaly trend on the lunar Apennines (12°—30°N, 10°W—12°E), we have produced several crust-mantle models that explore the interior geologic structure along northwest-trending profiles across the mountains. From the inverted density results and lunar thermal evolution, we infer that there could be a deep rooted fault beneath the Apennines, caused by lunar lithospheric lateral movement in this region.

1 Topography and gravity anomaly of lunar Apennines

The Apennines, the largest range on the moon, extends almost one thousand kilometers, and forms the southeast portion of the 1200-km diameter basin defining the ring of Mare Imbrium[10]. But some units are dominantly unambiguous basin deposits. The Pre-Imbrium deposits consist of volcanic KREEP basalts[10,11] outcropping in the Apennine bench Fm. Figure 1 shows the topographic map of this area, which was obtained from the laser altimeter of CE-1 with a total radial error of about 31 meters[1]. It clearly delineates the arcuate northeast-trending Apennines that is bound by the three maria: Mare Imbrium, Mare Serenitatis and Mare Vaporum. The Apennines in particular forms an asymmetric mountain belt whose northwest flank descends with a steep slope, while southeast flank runs down to the Mare Vaporum with a comparatively gentle inclination. A large number of peaks and complex terrain in this area may indicate the existence of a strong compressive stress, which has led to the Apennines uplift.

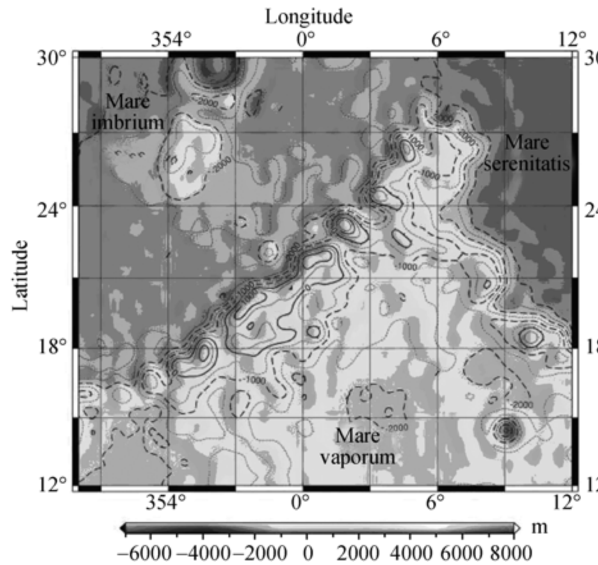

Figure 1 The topographical contour map of the lunar Apennines. The data are obtained by the lunar topographic model CLTM-s01 with 360 degree and order. The elevation refers to a sphere with the mean radius of 1738 km. The contour interval is 500 m.

According to the potential field theory, the gravitational potential of a point $p(\theta,\lambda,r)$ in a spherical coordinate system has traditionally been expressed as the sum of spherical harmonic functions:

$$W(p)=\frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}\left(C_n^m\cos m\lambda+S_n^m\sin m\lambda\right)\times P_n^m(\cos\theta), \tag{1}$$

where C_n^m and S_n^m are the normalization spherical harmonic coefficients, G, the gravitational constant, M, the mass of the planet, R, the average radius of the planet, θ, the co-latitude, λ, the longitude, r, the radius, and $P_n^m(\cos\theta)$ the associated Legendre function.

Due to the small flattening, the moon can be well approximated as a sphere. The terms of eq. (1) associated with $n=0$, 1 are the Moon's normal gravity potential and the higher order terms are the disturbing potential. So the anomalous gravity field of the moon is given by the partial derivative of the anomalous potential with respect to the radius, r in the radial direction. The formulas of the gravity anomaly Δg are given by

$$\Delta g = -\frac{\partial T}{\partial r} = \frac{GM}{R^2}\sum_{n=2}^{\infty}\sum_{m=0}^{n}(n+1)\left(\frac{R}{r}\right)^{n+2} \times\left(C_n^m \cos m\lambda + S_n^m \sin m\lambda\right)P_n^m(\cos\theta). \quad (2)$$

The best lunar gravity models at present are LP165P (2001)[12] and the latest SEG90d (2009)[13]. The former is produced by the tracking data and observed data from the Lunar Prospector combined with the tracking data from Clementine. The error in orbit determination of LP165P is in meter level, which is the best gravity model currently available for the moon[12,14,15]. Comparison with the latest lunar gravity model SEG90d produced by the Japanese lunar explorer SELENE indicates that the spatial resolutions of the two gravity models are identical for the nearside gravity field. However, the farside gravity field of the Moon is substantially improved in SEG90d. Because the Apennine area is located in the lunar nearside with surface topographic changes of about −3500—2000 m, the gravity anomalies (Figure 2) are evaluated from the spherical harmonic coefficients of the lunar gravity model LP165P using eq. (2) to degree and order 165 at 3 km altitude above the lunar mean radius of 1738 km.

In the area for our study, the gravity anomaly map (Figure 2) shows three areas of significant gravity high, one lying in the southeastern Apennines and running the full length of the mountains, another corresponding to Mare Serenitatis on the northeast corner, and the third coinciding with the lunar impact crater Eratosthenes on the southwest corner. In the northwest, a relative gravity low lies between the mountains and Mare Imbrium. The maximum negative anomaly is more than −200 mGal, whereas on the other flank of the Apennines the gravity high reaches values of +180 mGal. Hence a total gravity anomaly difference amounts to as much as 400 mGal between the two sides of the mountains. When analyzing gravity data derived from Apollo 15, Ferrari et al.[16] suggested that the regional gravity low on lunar Apennines resulted from crustal thickening, where it is uncompensated. By means of the FeO content derived from Clementine mission, the geology and composition of this area had been analyzed, and the results supported the idea that the Apennine Bench Fm. (24°—25°N, 356°—358°E) was made up of KREEP basalts of volcanic origin[10], and was older than Imbrium basin[10,17].

The close connection between the gravity anomaly's main trends and the surface geological features is evident when Figures 1 and 2 are compared. In particular, the positive and negative anomaly bands trends stretch parallel along the Apennine Mountains. In fact, the gravity effect generated by the surface topographic changes in this area cannot explain such a prominent magnitude of gravity anomaly, which also contains the gravity effect from subsurface structures.

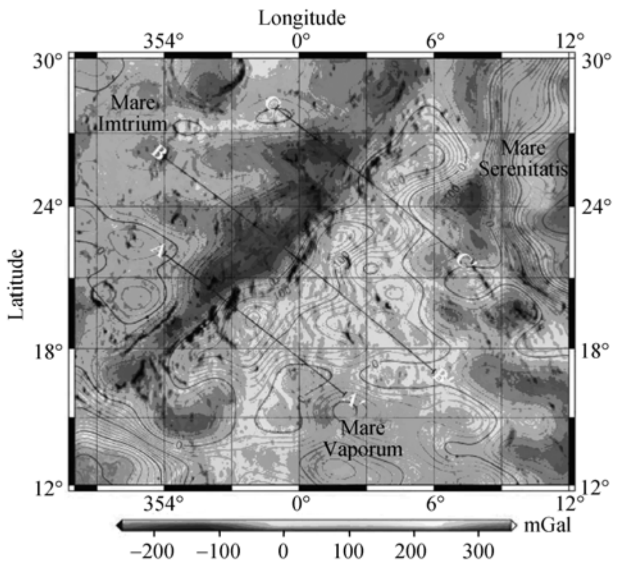

Figure 2 The gravity anomaly map of the lunar Apennines. The data evaluated at an altitude of 3 km above the lunar mean radius of 1738 km from the spherical harmonic coefficients of the 165 degree and order Lunar Prospector gravity (LP165P) model. Contour interval is 20 mGal. This shaded relief map is from the website: http://www.usgs.gov/. The three black lines indicate the transects over which gravity modeling will be carried out.

2 Inversion of gravity anomaly

2.1 Gravity anomaly and topography profiles

To model lunar crust-mantle structure, we have extracted gravity anomaly and topography data along three northwest-trending regional transects across the Apennines (shown in Figure 2). We observe that the characteristics of three anomaly profiles (Figure 3) are markedly consistent with typical gravity anomaly curve generated by a fault. In addition, the maximum anomalies are located above topographic high, and the gravity lows appear on the margin of Imbrium basin margin along the left flank of the Apennines.

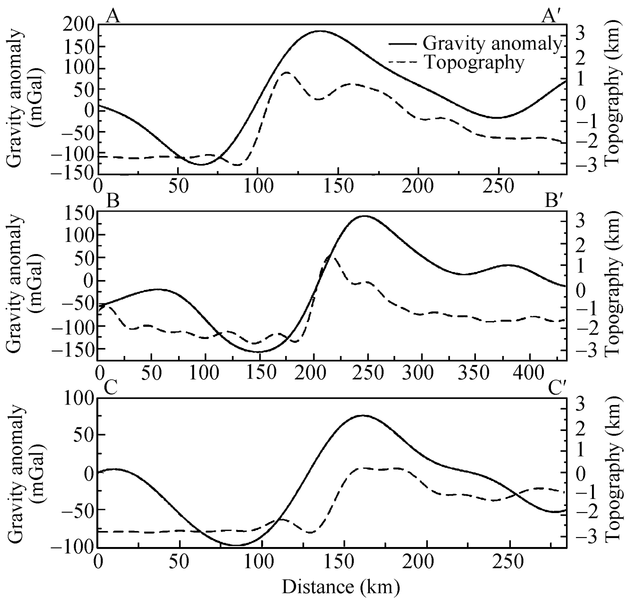

Figure 3 The topography and gravity anomaly profiles across lunar Apennines.

2.2 Crust-mantle model

In the current study, we have established simple subsurface geological structure models based on the dual-layered crustal thickness model[7,18] and placed Apollo 12-14 seismic data[5] as an constraint. In particular, the current lunar lithosphere may consist of the upper and, middle mantle and crust with a seismically inferred depth extent of 1000 km[8,19]. Hence, only the crust and mantle density layers are taken into account in this study. On the Apennines, the upper crust at a depth ranges approximately between zero and 80 km[8], while the thickness of the lower crust, with an average 31km, may vary from zero to 70 km[8]. The primary densities and depths of subsurface layers used in our study are listed in Table 1.

Table 1 Parameters of model bodies for profiles of Apennines

Lithosphere units	Mean depth (km)	Density (g/cm^3)	Density contrast (g/cm^3)
Upper crust	27	2.8	–0.3
Lower crust	60	3.1	–0.24
Mantle and the lower	>60	3.34	—

2.3 Modeling the Apennines profiles

Gravity modeling was carried out by way of a forward-modeling through two-dimensional polygons. The gravity effect of the lunar surface topography was also included in the model. Based upon the primary crust-mantle model, the depths of subsurface interfaces were adjusted by a trial-and-error procedure until an acceptable data fit was achieved. The best fitting between the observed and calculated gravity data was obtained with the most conservative solution. Finally, this study did not report in detail other local density variations and near surface geological factors. Inversion of gravity data has non-unique solutions as gravity anomalies result from the sum of all the gravity effects in the subsurface. In light of this, we have deduced two types of crust-mantle models that explain the gravity anomaly feature of the Apennines profile BB′ (Figures 4(a) and 4(b)). In Model 1 (Figure 4(a)), the presence of a normal fault below the Apennines significantly affects the gravity values of the entire model. Model 2 (Figure 4(b)) presents the subsurface structure with thrust fault beneath the Apennines, which we think is more consistent with the local long-term stress regime and lunar thermal history.

The Apennines is situated between the southeast of Mare Imbrium and southwest of Mare Serenitatis. The typical features of two maria with gravity high that roughly corresponds to the topographic low are generally thought to be created by post-impact mantle rebound[20−22], basalt filling and crust-mantle isostatic adjustment[4,23−25]. What's more, radial or concentric mare ridges and arcuate rilles (interpreted to be graben) are found almost all around the two maria. These features are assumed to have resulted from horizontal compression and tension.

According to the Anderson fault theory[26], reverse faults are easily generated by horizontal compression. In both cases (Figures 4(a) and 4(b)), we find the lateral crustal structure highly variable. The crustal "fold" state is potentially attributed to the long-term horizontal compression stresses. Accordingly, combined with the computed inversion modeling, the prominent gravity anomaly trend along the Apennines can be interpreted as due to a reverse fault beneath the Apennines (Figure 4(b)). In this case, the model fitting results of other profiles AA′ and CC′ are shown in Figure 5.

In summary, modeling results and local stress for the Apennines substantially support the hypothesis of a thrust fault with a displacement of almost 30 km under the Apennines (Figures 4 and 5). The gravity low be-

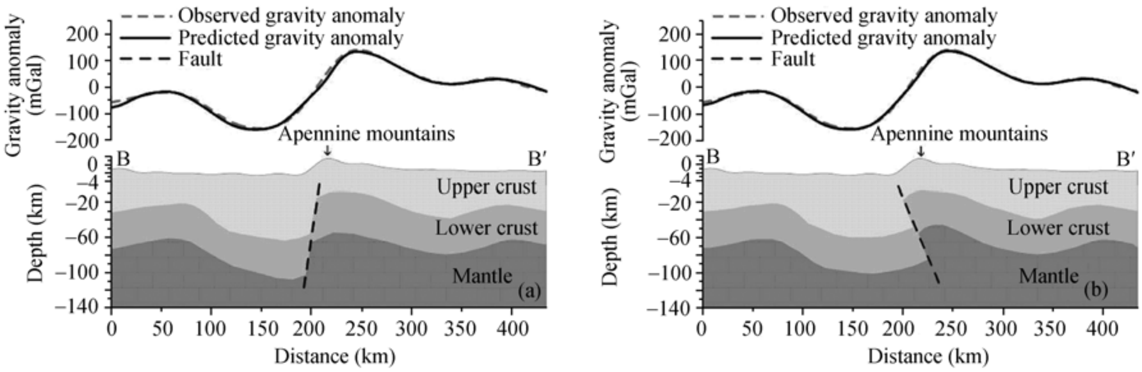

Figure 4 The inversion results along profile BB′ of lunar Apennines. (a) subsurface structure with normal fault; (b) subsurface structure with thrust fault.

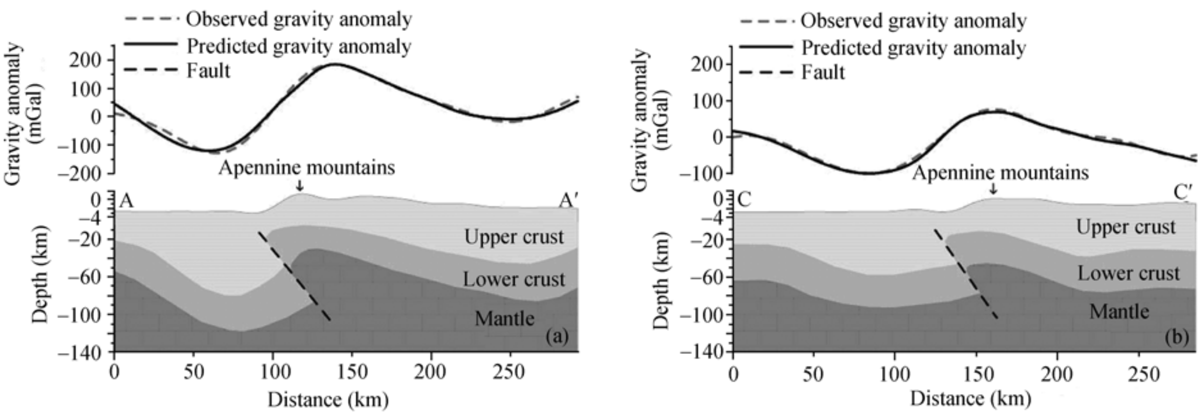

Figure 5 The inversion results along profiles AA′ and CC′. (a) Profile AA′; (b) profile CC′.

tween the Apennines and Mare Imbrium is generally attributed to the deepening of the crust. These two findings may somehow be related to the history of magma filling and lithosphere deformation in the mountain zone and adjacent area.

3 Lithospheric tectonic evolution

Compared with Earth's satellite gravity map, the gravity anomalies pattern of lunar Apennines is similar to that of the Himalayas[27]. Worthy of note are the marked differences. The anomaly difference is almost the same in the two regions, with the elevation difference of the former being only about half of the latter. Previous studies[28−34] took the Himalayan region as the youngest continental collision orogenic belt on earth. The Himalayan collision belt is the stable Cenozoic continental deformation zone caused by sustained strong subduction of the Indian plate beneath the Eurasian plate, which probably took place in the late Cretaceous or Paleocene after the closure of Tethyan oceanic basin[29]. On the other hand, combined with the constraint of geologic data and seismic survey, the INDEPTH profiles also support the hypothesis that the intact Indian lithosphere underthrusts South Tibetan Tethyan Himalaya crust, resulting in thickening of southernmost Tibetan crust[30]. For the moon, a question that begs for an answer is whether the geological structure of lunar Apennines was also formed through this kind of tectonic dynamics.

It is known the Moon is an end member among the planetary bodies in our solar system because its lithosphere has been relatively cool, rigid, and intact throughout most of the geological time. Recent surface topography has developed mainly from the impact cratering, but the internal processes, such as volcanism and tectonism, have also played an important role. On the one hand, the key to understanding the lunar tectonic movement is by gaining a rigorous understanding of its thermal evolution, which has been affected by magma and volcanic phenomena. Lunar magmatism can be grouped into three main stages of activity. The first stage is the early lunar differentiation and associated magmatism. Partial melting of the Moon soon after accretion is responsible for producing an anorthositic crust and a differentiated lunar interior. Stage II, lunar (pre-mare) magmatism (4.5—3.85 Ga), presumably followed ferroan-anorthosite formation and preceded the eruption of basin-filling basalts, which resulted in crust partial remelting and non-mare basalts. The last stage is characterized by the wide area eruption of mare basalts (3.85—1.0 Ga) and subsequent filling of many mare basins[19,35]. The 3.5—3.8 Ga period marks the peak in volcanic output[35].

On the other hand, plenty of meteorite impacts also acted on the lunar thermal evolution. Strong basin-forming impact not only shattered the subsurface, excavated immense ejecta and thinned the crust, but also caused heating of the crust and upper mantle, *in-situ* melting in the mantle[22,36], and lateral and vertical movements of the crust. This process could result in the impact-induced faults along the impacted basin margin[37].

Figure 6 illustrates the lithospheric evolution on lunar Apennines. During the Early Imbrian (3.85 — 3.72 Ga)[38], when Imbrium basin was excavated, such a giant impact induced the Imbrium crust thinning and subsidence, and resulted in displacing the solidus to deeper parts of the mantle. At the same time, the impact kinetic energy transferred to thermal energy near the surface caused part melting of near-surface materials. Finally, the thermal expansion and strong impact horizontal tensile stresses around the Imbrium basin margin would induce the rigid lithosphere rupture at basin edge, as shown in Figure 6(a).

Due to the impact heating and decompression melting[39], impact-induced thermal perturbations created

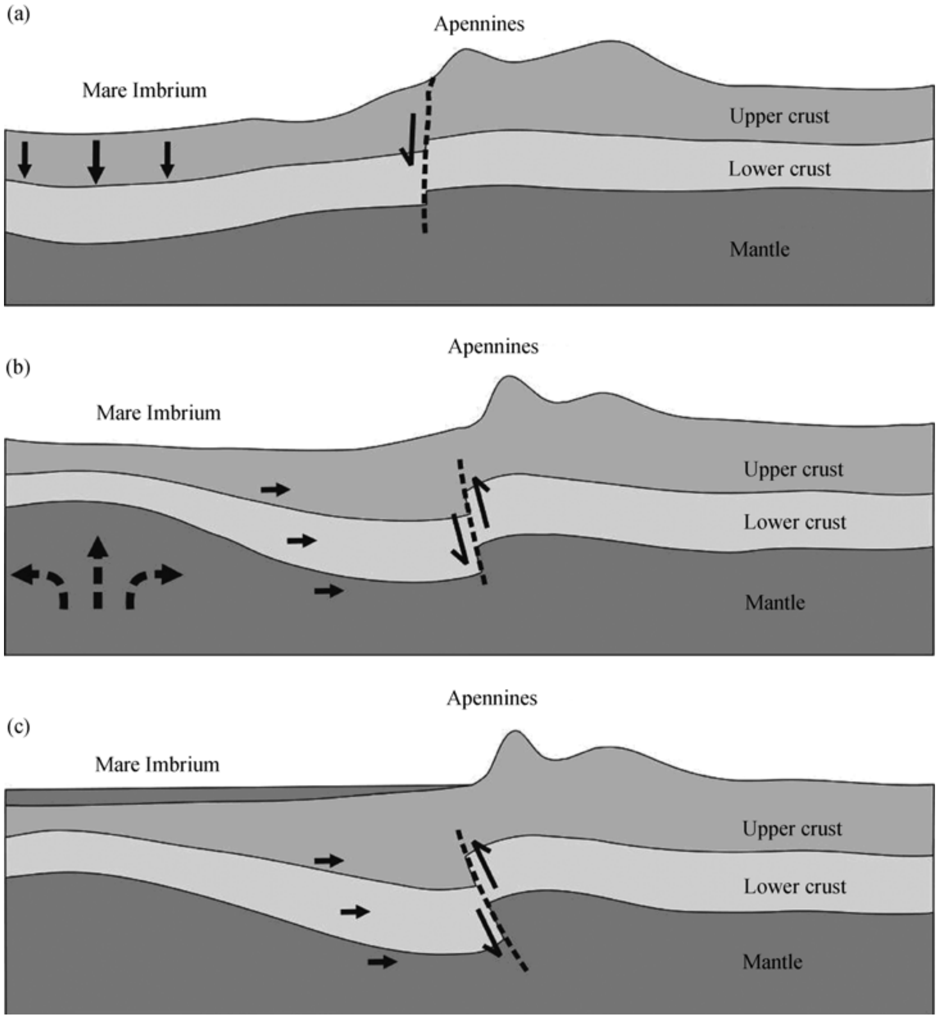

Figure 6 Diagram depicting the interpretation of topography and gravity of the Lunar Apennines. (a) Impacting stage; (b) post-impact; (c) at present. The dashed lines represent the fault line. Thick arrows indicate stress and direction. Dashed lines arrows represent thermal flow.

substantial lateral variations of temperature in the upper parts of the mantle. On the other hand, the isostatic uplift of the mantle[38,40,41] combined with the materials moving upward and melting from deeper parts of the upper mantle created localized convection[22]. Subsequently, this localized convection together with the impact-induced thermal perturbations in the upper mantle may develop whole mantle convection beneath the basin[22]. This circulation created a pattern with a central thermal upwelling and marginal downwelling[42], which was capable of driving the basin central materials laterally toward the surroundings. Moreover, the Serenitatis Basin is estimated to be older than the Imbrium Basin[43−46]. Accordingly, the materials on the margin of Imbrium Basin compressed the cold stable material of Serenitatis Basin, which might induce the stress release occurring along pre-existing tension fault. Thereby, under the influence of horizontal compression, the tension fault in this area could develop into reverse faults, causing the dense Imbrium lithosphere downward slip along the fault plane, as presented in Figure 6(b).

Mare basalt erupting during the Late Imbrian (3.2—3.72 Ga ago)[38] was also expected to be related to the thrust fault beneath the Apennines. As Imbrium basin and Serenitatis basin were filled with basalts, the strengthened loads associated with the mare basalt fill and isostatic adjustments of the crust-mantle facilitated lateral crustal mass transport[41] from beneath basins into the surroundings. Thus the Imbrium marginal lithosphere laterally moved and sank into the Apennines lithosphere caused by continued horizontal compression, which probably resulted in the reverse fault beneath the Apennines, as shown in Figure 6(c). In particular, the whole processes were also thought to have produced the intersection between Imbrium and Serenitatis basin rings, and the pre-Imbrian crust and Mountains uplift within the Apennines[10,24,47].

4 Discussion and conclusions

Based on the lunar surface topography and gravity data, we have investigated the evident gravity anomaly trend and tectonic characteristics on lunar Apennines by developing several subsurface mass models of the Moon. Our models define two major contributions to the regional gravity anomaly across the Apennines. The positive and negative anomaly band mainly originates from the deep thrust fault in the lithosphere, which extends along the Apennines. Another finding is that the crust thickening between the southwest margin of Mare Imbrium and the Apennines may support the broad gravity low in this area.

The integration of our results with lunar thermal evolution history suggests that: (i) The fault under the Apennines may have occurred at ~3.85 Ga ago after Imbrium Basin formation by impact. Because of the strong horizontal tensile stresses at Imbrium basin edge, the rigid lithosphere ruptured and tension faults developed. (ii) Subsequently, mantle isostatic uplift and thermal convection drove the basin central materials outwards laterally. Thus, the Imbrium materials compressed the older Serenitatis Basin on the Apennines, which make the tension faults turn into thrust faults. (iii) As the basalt flooded the Imbrium and Serenitatis basins, the strengthened loads contributed to the fault underthrusting the Apennines.

If this phenomenon is real, it may reflect that 3.85 Ga ago the Moon once consisted of several layers and had lithospheric plate movement similar to the present Earth. The factors that might have been important in influencing lunar lithospheric lateral movement may include the bombardment events, post-impact isostatic adjustments of large impact structures, crust-mantle isostatic adjustment because of the load from the mare basalts and the lunar thermal convection. This might throw light on the evolutionary history of the moon and other planets in the solar system. The lunar lithospheric structure still remains a challenge to geophysical research.

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