Introduction: Nearly 40 years after the crustal dichotomy was discovered [1], the origin of the crustal dichotomy remains one of the most important unresolved questions in studies of Martian geological history. Two types of models have been proposed to account for the crustal dichotomy: giant impact [2-6] and mantle dynamics [7-10], although hybrid models involving both impact and mantle dynamics are also proposed [11]. This study focuses mainly on giant impact and mantle dynamics models and is intended for providing a critical assessment of these two models in explaining the crustal dichotomy, particularly the crustal structure and crustal magnetization.

Giant impact and mantle dynamic models:

Giant impact models. Early impact models considered a single impact and multiple impacts [2,3]. However, as reviewed in [12], the single impact model had difficulties in identifying boundaries of the hypothetical impact basin to match the present-day dichotomy boundaries and also in the amount of the melting that such an impact may cause, while the multiple impact model had a probability problem to have the multiple impacts to occur in the same hemisphere. Recently, the single impact model was resurrected with new analyses of the gravity and topography [4] and new hydrodynamic modeling of giant impact processes [5] that appear to remove the difficulties with the original single impact model. The analyses of the gravity and topography removed the Tharsis volcanic construct and restored the original crustal dichotomy boundary in the western hemisphere [4]. The restored crustal dichotomy boundaries form an elliptical shape that may have resulted from an oblique impact [4]. Hydrodynamic modeling of impact processes showed that an oblique impact may reduce the melting, while producing an elliptical basin [5]. The single impact model was also proposed to explain the apparent lack of crustal magnetization in regions of the southern hemisphere that are antipodal to the impact [6].

Mantle dynamic models. The first model of mantle dynamics invoked degree-1 mantle flow induced by core formation process via Rayleigh-Taylor instability [7]. Such a degree-1 mantle flow was suggested to erode the primordial crust and cause the crustal dichotomy. Another model of mantle dynamics that was also based on Rayleigh-Taylor instability process invoked mantle overturn process after magma ocean differentiation and solidification [8]. Depending on mantle viscosity structure, such mantle overturn may lead to degree-1 mantle flow [13] and cause the crustal dichotomy. The third model of mantle dynamics is related to thermal or thermochemical convection process [9,10] that may lead to degree-1 mantle flow depending on mantle viscosity structure.

The first model was rather conceptual and did not consider detailed physical processes of the core formation and Rayleigh-Taylor instability. The mantle overturn model has been studied via numerical modeling [8]. Degree-1 mantle flow from the overturn may be generated if the dense layer is significantly less viscous than the underlain layer, as shown for a related mantle flow model for the Moon [13]. However, degree-1 mantle overturn flow has not been produced for continuously varying viscosity structure [14]. These two models due to their association with either the core formation or magma ocean differentiation imply formation of the crustal dichotomy at very early stages (i.e., the first 100 Ma of the Martian history).

The third model with mantle convection also requires certain mantle viscosity structure to generate degree-1 convection, and more specifically, the upper mantle needs to be ~20 times weaker than the lower mantle [9,10]. Different from the first two models, the convection model does not depend on Rayleigh-Taylor process and can occur on different time-scales ranging from 100 Ma to 500 Ma.

Among the mantle dynamic models, only the convection models started to consider melting and crustal generation processes [15,16], which is important for making specific predictions about the crustal structure that can be tested directly against the observations of the crustal dichotomy. However, this is a research area with rapid progresses.

Testing the models against observations:

Both the impact model and mantle flow model in their current forms have significant challenges in explaining some basic observations of the crustal dichotomy, particularly the crustal thickness variations and crustal magnetization. I argue that to test these two models, the models must incorporate crustal redistribution processes (i.e., crustal flow and modification processes) after the impact or melting process from mantle convection is considered.

The giant impact as proposed in recent studies [4-6] must excavate the original crust in the present-day northern lowlands and redeposit to the southern highland, a basic premise for the all the impact models. However, the ejecta distribution from such a giant impact is likely highly non-uniform [5,6], especially for the proposed oblique impact, as shown in recent stud-
ies oblique impact that display more than 100% crustal thickness variations outside the impact basin [5]. This is significantly different from the present-day crustal thickness distribution that largely shows bimodal distribution [17]. The hydrodynamic impact models, while successfully producing the northern lowland sized impact basin, did not discuss how the highly non-uniform crustal thickness distribution in the highlands due to the impact after the impact evolves to the observed crustal thickness bimodal distribution. This would require consideration of crustal redistribution processes via crustal flow and erosion that have been considered before under different context [18]. A more important question is how to maintain and preserve the dichotomy boundary to be like what was inferred in [4], with these crustal redistribution processes that seem to be required to explain the present-day uniform crustal thickness, considering that the dichotomy boundary may represent the largest crustal thickness variations.

One may argue for a uniform distribution of ejecta across the southern highlands, but this would have difficulties in explaining the observed crustal magnetization in the southern highlands. The ejecta would have added a layer of crustal material >20-30 km in thickness. With the temperature gradient constrained by modeling gravity and topography in the highlands [19], such a layer of ejecta would have raised the temperature of the underlying crust to demagnetize significantly the crust. A possible alternative to avoid such a difficulty is to assume that the observed crustal magnetization is associated with the cooling of the ejecta within an active dynamo at the impact time. However, it is unclear how the magnetic lineation can be acquired, given that the entire highlands with the ejecta would have cooled simultaneously.

The crustal magnetization is acquired most likely when the crust cools within an active dynamo field. The fact that the magnetization is much stronger in the highlands suggests that the magnetization records the crustal production processes that are responsible for the thickened crust and hence the crustal dichotomy [20]. The magnetic lineation has been suggested to be caused by either seafloor spreading or dike intrusion processes [20,21]. The magnetic lineation [22] appears to be concentric with a center at ~(70°S, 30°E). I found that this center location is very similar to that for the thickened crust. This provides another link between the crustal magnetization and the crustal dichotomy that has not been explored.

Mantle dynamic models predict melting production from upwelling plumes for Mars [15,16,23], and this necessarily leads to addition of crustal materials. However, the calculations seem to predict highly non-uniform distribution of the melts and crust [15,16], because of the non-uniform temperature distributions with the plumes. However, these mantle dynamic models have not considered the crustal redistribution processes that are deemed to happen after the new crust is produced. Given the complicated physics and rheology of the crust and mantle, it remains a challenge to model the crustal production and redistribution processes. However, to test the mantle flow models for the crustal dichotomy, it is not enough to only consider melting and crustal production as done in recent studies including from our group, and we must incorporate the crustal redistribution processes. The concentric magnetic lineation and the proximity of this center to that of the thickened crust may be explained in terms of mantle plume models. As the plume spreads out below the lithosphere, the newly created crust would form ring structures. When they cool in an active dynamo with occasional polarity reversals, the new crust would acquire concentric magnetic lineation.

Conclusions:
To test giant impact and mantle flow models for the crustal dichotomy, it is necessary to consider crustal redistribution processes including crustal flow. Magnetic lineation appears to be concentric with a center at ~(70°S, 30°E) which is close to the center of the thickened crust in the highlands, further suggesting that the crustal dichotomy and crustal magnetization are closely related. Therefore, crustal magnetization including the concentric magnetic lineation may provide a crucial test for crustal dichotomy models.