Introduction: Asteroids are the smallest and some of the oldest rocky bodies in the solar system [1,2]. As such, they provide important data points on the spectrum of tectonic styles and processes that operate on solid bodies. To first order, the density of an asteroid reflects its composition and can provide insight into its internal structure; however, the densities of S-type asteroids are less than 3.3 g/cm$^3$ [3,4], suggesting a high porosity inconsistent with a completely coherent asteroid [4]. The presence of long structural features on the surface of some asteroids is indicative of significant internal rock strength and coherency and is in many ways similar to planetary-scale tectonics. Since small solar system bodies (<200 km radius) don’t have sufficient internal heat energy to drive terrestrial-style tectonics [5], determining how these features formed yields important information about the nature and geological history of such lineated asteroids.

A number of different types of linear structural features—including grooves, troughs, pit crater chains and ridges—have been observed on a number of asteroids [6,7,8]. Grooves are characterized as a shallow, v-shaped gash in the asteroid and are most likely the result of simple fracturing of the surface, or perhaps the surface representation of larger fractures whose distinct edges have been muted by burial under regolith and crater ejecta. Troughs are wider than grooves and have distinct walls and floors; they may be the result of reactivation of pre-existing grooves or fractures, perhaps by later impacts causing further widening of existing cracks. Pit crater chains are linear assemblages of small depressions, theorized to be grooves or troughs that were covered by regolith that may now be draining into the underlying structure [9,10,11]. Ridges are linear topographic highs, as determined by image illumination and/or topographic data, and are probably the surface representation of thrust faulting under a compressive state of stress. We present a review of the solar system asteroids that have been visited by spacecraft—951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, 25143 Itokawa, 2867 Steins, 5535 Annefrank, 21 Lutetia and 4 Vesta—and discuss how analyses of linear structures observed on these small terrestrial bodies have implications for the tectonics of asteroids, models of linear structure formation, and the internal structure of the asteroids. We review Vesta in the context of a unique planetoid in our solar system, sharing characteristics of asteroid tectonics as well as planetary-scale tectonics.

Understanding the tectonic histories of these small rocky bodies provides insights into the dynamics of early solar system formation as well as understanding of the role of endogenic versus exogenic processes in tectonic styles of deformation. Models of Tectonic Formation on Asteroids: Decades ago, grooves were identified on the Martian moon Phobos in Viking orbiter imagery and interpreted to be the likely result of the large impact that formed Stickney crater, with which the majority of the grooves are associated (an exogenic process; [12]). However, the subsequent imaging of a variety of asteroids led to new models being proposed for the formation of asteroid lineaments that include both exogenic and endogenic processes, briefly described below.

Formation by impact. Numerical calculations indicate that impacts into asteroids could be responsible for the formation of fractures. Axi-symmetric calculations of an impact that would generate a Stickney-sized impact in a Phobos-like ellipsoid predict sizes of spall that compare favorably with the spacing of grooves and fractures seen on Phobos [13]. Other numerical calculations of impacts into Ida, a main belt asteroid, indicate that fractures can be generated far from the impact [14]. Indeed, a 3-D simulation of the formation of a large crater at one elongate end of Ida shows fracturing as far away as its antipode, where grooves have been observed on the asteroid [6]. Calculations suggest that impacts into the flat portion of an elongated ellipsoid generate circumferential fractures around the edge of the asteroid perpendicular to the impact normal; impacts on the curved ends of the asteroid result in fracturing mainly at the antipode [6]. These calculations assume simplified asteroid shapes and that the modeled asteroids are physically homogeneous.

Fabric inherited from a parent body. Another hypothesis suggests that the lineated small bodies are fragments of larger parent bodies, and it is on these pre-cursor planetary bodies that the lineaments actually formed. Two large-scale lineaments on Eros—the Rahe Dorsum ridge and the shallow troughs of Calisto Fossae—were found to be coplanar with a large flat region (the southern “facet”) on one end of the asteroid [15]. From this study, it was determined that the unit normal, or pole, of a plane described by a combination of Rahe Dorsum and Callisto Fossae, compared to the pole of the plane described by the southern “facet” of Eros, are roughly the same [15]. This suggests that the features
represent parallel planes indicative of a pre-existing structure throughout most of the asteroid, consistent with a fabric inherited from a parent body.

Down-slope scouring. An alternate hypothesis proposed for the formation of grooves on Phobos is scouring by rolling boulders [16,17]. While subsequent investigations determined that downslope scouring could not be the primary cause of the globally distributed lineaments on Eros [8], boulders have been identified in association with the lineaments on Itokawa, and are thought to be the cause of their formation [18].

Thermal stresses. It has also been suggested that some lineaments could be the result of thermal stresses [19]. The thermal stress model for lineament formation invokes long-term secular changes in the daily/weekly average surface temperature of a near-Earth asteroid as it first moves from the asteroid belt into the inner solar system, and then wanders around the near-Earth region [19]. Expected expansion and subsequent contraction of the asteroid could lead to observed lineaments, the orientations of which would significantly depend on the shape of the asteroid.

Tectonic Styles Found on Asteroids: Asteroid lineaments observed appear to have several different origins, and are indicative of variable interior structures. Many of the linear structures, such as those on Ida, Eros, Lutetia and Vesta, appear to be due to impact, but some lineaments have no obvious relationship to impact craters. For example, pitted grooves on Gaspra are indicative of a fabric in a coherent asteroid inherited from a parent body, as are some of the linear structures on Eros, and are consistent with previous suggestions that Gaspra and Eros are fragments of larger parent bodies [6,20]. Pervasive subsurface fracturing can also be distinguished by the polygonal shapes of some craters on Mathilde [21], Eros [22,8] and Lutetia [23]. The presence of long structural features on the surfaces of some asteroids is indicative of substantial internal strength, despite low-density values that indicate high porosity. Meanwhile, lineaments on Itokawa have been associated with boulders and are consistent with the excavation of regolith by boulder movement on a “rubble pile” asteroid [18]. It is therefore clear that determining how linear features formed on these asteroids yields important information about their internal structure and strength, as well as on the nature and history of the asteroid itself.

Vesta presents an intermediate style of tectonic deformation, with fractures and grooves similar to those observed on other asteroids, as well as large-scale graben and trough structures more characteristic of tectonics on terrestrial planets [24]. Vesta, being a differentiated proto-planet, is a unique body with which to study the roles played by internal rheologies and structures on the surface expressions of tectonism. Unlike many terrestrial planets, Vesta’s main stressors have been primarily exogenic (i.e. impacts) rather than internally driven; however, the inferred formation path of Brumalia Tholus suggests that Vesta’s geologic history may have included endogenic magmatism [25].

Conclusions: As a group, asteroids represent some of the earliest remnants of the early solar system. Deciphering the tectonic histories of these bodies provides insight into the complex dynamical and geological history of the inner solar system. Impact processes dominate the tectonic styles observed on many asteroids, but there is also evidence for structure inherited from parent bodies. Vesta represents a transitional form of tectonics that reflects its internal differentiation and impact history. As we approach the icy dwarf planets of Ceres and Pluto, a better understanding of the styles of tectonism and the endogenic versus exogenic processes involved in these smaller bodies will aid in the interpretation of tectonic deformation on all solid bodies in the solar system.