CHARACTERIZING ASTEROID INTERNAL STRUCTURE THROUGH TECTONIC ANALYSES. D. Y. Wyrick[1] , D. L. Buczkowski[2], and D. D. Durda[1], [1]Southwest Research Institute (6220 Culebra Rd, San Antonio, TX 78238; dwyrick@swri.org; durda@boulder.swri.edu), [2]Johns Hopkins University Applied Physics Lab (Laurel, MD 20723; debra.buczkowski@jhuapl.edu).

Introduction: Asteroids are thought to be the source bodies of the majority of meteorites on Earth [1,2] and are likely leftovers from the formation of the solar system [e.g., 3,4]. It is this direct relationship between meteorites and asteroids that reminds us all that understanding small bodies in our solar system is critical toward understanding the threat they may pose for Earth. In particular, characterizing the mechanical strength and internal structure of asteroids is needed in order to effectively mitigate, divert or destroy them as a potential impactors. Recent analyses of the tectonic deformation and geomorphology of small bodies provides important insights into the subsurface processes and geologic histories of these small bodies, which in turn provides constraints on their internal porosity, composition, and coherency. Critical data gaps remain in observations, however, namely high resolution imagery, topography (shape), gravity, and momentum transfer data that provide critical information on internal structure. Top priority should be considered for high quality data products from these smalls bodies in the coming decades through a combination of single and multi-spacecraft missions, as well as flyby opportunities on other missions.

There are three types of meteorites: irons, stony-irons, and stones, which are further subdivided into ordinary chondrites, carbonaceous chondrites and achondrites [e.g., 5,6]. Ordinary chondrites are the most common type of meteorite [e.g., 6,7]. However, reflectance spectroscopy of asteroids indicates that ~75% of all known asteroids are the carbon-rich C-type asteroids [8], which most closely resemble carbonaceous chondrites spectroscopically. S-type, or silica-rich, asteroids comprise less than 17% of known asteroids [8] but may be the source of the ordinary chondrites. Theoretically, the density of an asteroid can be used to determine its composition. An asteroid density close to 5 g/cm3 should be indicative of a stony-iron composition [9], while a density close to 3.3 g/cm3 should be more consistent with an ordinary chondrite [9,10]. However, the densities of S-type asteroids are less than 3.3 g/cm3 [e.g., 11,12], which may be due to the internal structure of the asteroids.

There are four states of asteroid internal structural modification [13]: 1) completely coherent; 2) coherent but fractured; 3) heavily fractured (e.g. [14,15]); and 4) rubble pile (e.g. [16,17,18]). If the bulk density of an S-type asteroid is lower than the measured density of comparable ordinary chondrite meteorites (~3.3 g/cm3), the asteroid likely has a high porosity inconsistent with a completely coherent asteroid [12]. The presence of long structural features on the surface of an asteroid is indicative of significant internal strength despite low density values, as the body must be coherent enough to preserve tectonic deformation [20]. Since small solar system bodies (<200 km radius) don't have sufficient internal heat energy to drive terrestrial-style tectonics [19], determining how these features formed yields important information about their nature and the geological history of such lineated asteroids.

Motivation: A recently published paper [20] provides the most current review of the nine asteroids that have been visited by spacecraft to date. These asteroids — 951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, 25143 Itokawa, 2867 Steins, 5535 Annefrank, 21 Lutetia and 4 Vesta — span the range of internal coherency, from rubble piles to solid and potentially mechanically strong bodies. Their analyses focus on the tectonics of the asteroids, models of linear structure formation, and implications for the internal structure of the asteroids. This provides a framework to consider the data needed to characterize the internal structure of potential impactors in the coming decades.

Asteroid lineaments observed by spacecraft on small bodies appear to have several different origins, and are indicative of variable interior structures. Lineaments on Itokawa (an S-type asteroid; [21]) have been associated with boulders and are consistent with the excavation of regolith by boulder movement on a "rubble pile" asteroid [22]. Many of the linear structures, such as those on Ida (S-type; [23]), Eros (S-type; [24]), Lutetia (possible E-type; [25]) and Vesta (V-type, [24]), appear to be due to impact [26,27,28,29, 30, 31], but some lineaments have no obvious relationship to impact craters. For example, pitted grooves on identified on Gaspra [32] as well as some of the linear structures on mapped on Eros [29] are indicative of a coherent asteroid with inherited structural fabric from a parent body [33]. Pervasive subsurface fracturing can also be distinguished by the polygonal shapes of some craters on Mathilde, Eros and Lutetia [29,34,35].

Vesta represents the other end member of asteroids as a fully differentiated body [31], with a mantle and core [36]. Vesta presents an intermediate style of tectonic deformation, with fractures and grooves similar to those observed on other asteroids, as well as largescale graben and trough structures more characteristic of tectonics on terrestrial planets. 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. The asteroid Lutetia is thought to be partially differentiated [37], but it lacks the tectonic signatures of Vesta, likely due to Lutetia's lower density contrasts and undifferentiated core [20]. 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. Note that the largest asteroid in the solar system, 1 Ceres, has not been considered here, as its status as a likely differentiated ice-rich dwarf planet places it beyond the size range we consider for impact threats. However, Ceres shares several tectonic features with the other smaller bodies considered here including pit chains and polygonal craters which provide insight into the near subsurface structure [38,39].

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. Our understanding of asteroid composition and structure has grown exponentially in the last few decades, leading to improved recognition and classification of asteroid characteristics based on strength and cohesion (i.e. solid bodies versus rubble piles). These initial observations and analyses all suggest structurally complex asteroid interiors. Understanding the heterogeneous nature of an asteroid's coherency and internal structure is needed in order to develop effective mitigation strategies for potential meteorite impact threats in the future.

Future Needs, Vision 2050: Priority should be placed in the next 10-20 years toward increasing the number of up close observations beyond the current nine asteroids to better characterize the range of potential impactors, including flyby opportunities on other missions. Within 20-30 years, asteroid divert/destroy demonstrations will be required to gain confidence in mitigation strategies. Future mission designs should retrieve high resolution image and shape data, in addition to spectral and gravity measurements, to characterize asteroid coherency. The recent decision by the European Space Agency to forego development on the Asteroid Impact Mission (AIM) severely curtails the data that can be collected from NASA's planned Double Asteroid Redirection Test (DART), and represents a loss of critical impactor information such as momentum transfer and internal strength. Future exploration should also consider joint multi-spacecraft collaboration built around understanding the physics of impacting an asteroid *in situ*.

References: [1]Greenberg, R. & Chapman, C. R. (1983) *Icarus*, 55, 455-481. [2]Burbine, T. H. et al. (2002) *Asteroids III*, Univ of Arizona Press, Tucson, 653-667. [3]Petit, J.M. et al. (2002) *Asteroids III*, Univ of Arizona Press, 711–723. [4]Bottke, W. F. et al. (2005) *Icarus*, 175, 111-140. [5]Weisberg, M. K. et al. (2006) *Meteorites and the Early Solar System II*, Univ of Arizona Press, Tucson, 19-52. [6]Krot, A. N. et al. (2007) *Treatise on Geochemistry*. Pergamon, Oxford, 1-52,. [7]Bischoff, A. & Geiger, T. (1995) *Meteoritics*, 30, 113–122, [8]Gradie, J. C. et al. (1989) *Asteroids II*, Univ of Arizona Press, Tucson, 316-335. [9]Britt, D. T. & Consolmagno, G. J. (2003) *Meteorit. Planet. Sci*, 38, 1161-1180. [10]Wilkison, S. L. & Robinson, M. S. (2000) *Meteorit. Planet. Sci*, 35, 1203-1213. [11]Belton, M. J. S. et al. (1995) *Nature*, 374, 785-788. [12]Yeomans, D. K. et al. (2000) *Science*, 289, 2085-2088. [13]Wilkison, S. L. et al. (2002) *Icarus*, 155, 94-103. [14]Chapman, C. R. (1978) Asteroids: An Exploration Assessment. NASA Conference Publication, 2053, 145-160. [15]Davis, D. R. et al. (1979) *Asteroids*, Univ of Arizona Press, Tucson, 528-557. [16]Hartmann W.K. (1979). *10th LPSC*, 1897-1916. [17]Asphaug, E. et al. (1998) *Nature*, 393, 437-440. [18]Wilson, L. et al. (1999) *Meteorit. Planet. Sci*, 34, 479-483. [19]Thomas, P. C. & Prockter, L. M. (2010) *Planetary Tectonics* Cambridge Univ Press, 233-263. [20]Buczkowski, D.L. and Wyrick, D.Y. (2014) *Volcanism and Tectonism Across the Inner Solar System*, Vol 401, doi:10.1144/SP401.18. [21]Binzel, R. P. et al. (2001) *Meteorit. Planet. Sci*, 36, 1167-1172. [22]Fujiwara, A. et al. (2006) *Science*, 312, 1330-1334. [23]Belton, M. J. S. et al. (1994) *Science*, 265, 1543– 1547. [24]Bus, S. J. & Binzel, R. P. (2002) *Icarus*, 158(1), 146-177. [25]Coradini, Aet al. (2011) *Science*. 334 (6055): 492–494. [26]Asphaug, E. et al. (1996) *Icarus*, 120, 158-184. [27]Sullivan, R. (1996) *Icarus*, 120, 119-139. [28]Prockter, L. et al. (2002) *Icarus*, 155, 75-93. [29]Buczkowski, D. L. et al. (2008) *Icarus*, 193(1), 39-52. [30]Thomas, N. et al. (2012) Planet. Space Sci., 66, 96-124. [31]Buczkowski, D. L. et al. (2012) *GRL*, 39(18), L18205. [32]Veverka, J. et al. (1994) *Icarus*, 107, 399-411. [33]Thomas, P. C. et al. (2002) *GRL* 29(10). [34]Thomas, P. C. et al. (1979) *JGR*, 84, 8457-8477. [35]Massironi, M. et al. (2012) *Planet. Space Sci.*, 66, 125-136. [36]Russell, C. T. et al. (2012) *Science*, 336, 684–686. [37]Sierks, H. et al. (2011) *Science*, 334, 487-490. [38]Buczkowski et al. (2016) *Science*, 353 (6303). [39]Otto et al. (2016) *47th LPSC*, #1493.