GEOMORPHIC MAPPING OF EUROPA: CLUES TO AN UNDERLYING WATER OCEAN FROM THE TYRE MACULA REGION. S. Kadel[1], F. Chuang[1] and R. Greeley[1], J. Granahan[2] and F. Fanale[2], E. Asphaug[3] and J. Moore[3], G. Collins[4], J. Head[4], R. Pappalardo[4] and L. Prockter[4], R. Carlson[5], and the Galileo SSI and NIMS Teams. [1]Box 871404, Dept. of Geology, Arizona State University, Tempe, AZ 85287-1404; e-mail: kadel@asu.edu; [2]STI, Honolulu, HI; [3]Ames Research Center, Moffett Field, CA; [4]Brown University, Providence, RI; [5]JPL, Pasadena, CA.

Introduction: Newly acquired images of the Tyre Macula region of Europa, at both regional (170 m/pixel) and local (~40 m/pixel) scales, allow improved mapping and understanding of a variety of surface processes and resultant landforms on Europa. The origins and geologic contexts for non-ice component signatures on Europa have been addressed by combining co-registered Solid State Imaging (SSI) camera image sets with compositional data obtained by the Near-Infrared Mapping Spectrometer (NIMS). These signatures are typically associated with low albedo materials along ridge flanks and with 'micro-chaos' regions of broken up and resurfaced crust, and may represent saline hydrate minerals [1]. Surface features on Europa demonstrate a complex history of disruption of its icy crust. Features range from tightly spaced ridged plains to more widely spaced doublet and complex ridges, small shallow pit and dome-like features, disrupted 'chaos' areas, a relatively small number of simple bowl to multi-ring impact structures, dark wedges of young fractured ice that may be somewhat analogous to terrestrial spreading ridges, prominent ice polygons and uptilted ice blocks up to ~1 km high, and young fracture systems.

The outer 100 kilometers of Jupiter's moon Europa is thought to be composed of a shell of water ice and probably (in the past, if not at present) liquid water [2]. Of great interest is the question: What is the nature of the upper zone of the ice shell? Geomorphic mapping and compositional analysis of the Tyre region provide a good regional overview of the variety of Europan surface features and allow inferences to be made about the geologic processes, surface evolution, and ice shell thickness over recent geologic time.

Methods: Surface units on Europa were identified based on surface texture and morphology as observed in low sun angle, 170 m/pixel Solid State Imager (SSI) data from Galileo's fourteenth orbit around Jupiter in March, 1998. These units have been mapped throughout the study area and re-analyzed at high resolution (~40 m/pixel) in images from Galileo's fifteenth orbit around Jupiter in May, 1998. Morphologic characteristics at both scales were used to generate unit descriptions. Analysis of non-ice components on the surface of Europa was performed using data from Galileo's Near-Infrared Mapping Spectrometer (NIMS). Stereoscopic data for a part of the high resolution coverage was synthesized from two consecutive images with different viewing geometries, and a 3-D anaglyph was produced.

Surface composition of the Tyre region: Surface composition data for the Tyre region of Europa (centered at 34°N, 146.5°W) was collected by the NIMS instrument during Galileo's seventh orbit around Jupiter in March, 1997. These data (6.26 km/pixel resolution) were co-registered with a SSI image of Tyre (595 m/pixel) to create a composite showing the distribution of ice and non-ice minerals in geologic context [3]. Marked asymmetry in water ice absorption bands in some NIMS spectra have been interpreted to represent non-ice materials, such as hydrated salts [4]. Most plains areas in and around Tyre appear to be composed of relatively clean water ice [1]. However, high concentrations of the interpreted non-ice materials are associated with some (but not all) stratigraphically young doublet ridges, chaos regions and domes just to the south and west of Tyre. Enhanced hydrated salt concentrations may represent surface deposits from liquid water/ice slurries or frost deposits erupted from fractures between doublet ridges [5] or within areas of incipient (domes) or developing chaos. Concentration of non-ice materials by thermal alteration [6] may also have occurred.

The Tyre impact event did not form raised rims or a central peak, but did form a central smooth plains deposit and concentric rings. This morphology suggests an impact into rigid ice overlying a more fluid ice/slush and/or liquid water substrate [7]. Assuming the overlying ice shell froze progressively downward, it should be relatively depleted in salts with respect to any underlying liquid water reservoir [8] which may have been tapped by the above-mentioned fractures.

Geomorphic map of the Tyre region: We have produced a geomorphic map of the Tyre region using moderate and high resolution low-sun SSI images. Thirteen geomorphic units have been identified. These units include ridged and lineated plains; smooth plains; smooth, lineated and ridged bands; doublet ridges; blocky and hummocky chaos regions; hummocky plains; domes; and massifs. Numerous young fractures, scarps and small impact craters (most, if not all, of which are secondaries to Tyre) have also been mapped.

Mapping and creation of a generalized stratigraphic column, using superposition and cross-cutting relations, has allowed us to outline a general surficial geologic history for the Tyre region. The oldest units exposed in the region are the ridged and lineated plains. All other units have formed by modification, burial or destruction of this background unit. Resurfacing and tectonic activity produced smooth plains, and the smooth, lineated and ridged bands next. Deformation and ridge-building then began to localize into more widely separated doublet ridges, with four fairly distinct episodes of ridge building evident from our mapping. After the second of the four ridge-building episodes, the impact that formed the Tyre structure and its associated hummocky and smooth plains occurred, followed closely by the formation of domes and blocky and hummocky chaos regions throughout the region. The chaos regions (two types defined below) may represent a progression from lesser to greater disruption of the surface (blocky chaos to hummocky chaos). Finally, the last two episodes of ridge-building and associated fracturing occurred. Additional support for the hypothesis of ridge-building by effusion/extrusion of cryovolcanic materials from fractures [5] may be seen in the youngest ridge, which grades from low doublet ridge to fracture several times along its length.

Geomorphology from high-resolution images: High resolution (~40 m/pixel) images show surface details that offer new insights into crustal thickness and the development of 'chaos' regions. Densely ridged older plains units have broadly undulatory surfaces. A large (several hundred meters high) doublet ridge in the high resolution image is flanked by downwarped crust, suggesting an origin by loading of a relatively thin (several kilometers or less [9]) ice lithosphere, or by withdrawal of subsurface material. From both geomorphic mapping and stereographic analysis, we distinguish two types of chaos regions, blocky chaos and hummocky chaos, based on the number and size of observed blocks of pre-existing icy crust and the texture of the 'matrix' material at this resolution. Blocky chaos regions typically contain a coarse-textured matrix with identifiable rafts of pre-existing crust up to several kilometers across. As observed on other parts of Europa [10], the blocks typically have rotated and translated from their original positions. Blocky chaos regions typically have polygonal, apparently fracture-bounded, outlines with matrix material uniformly lower than the blocks and surrounding terrain. The blocks and matrix appear not unlike calved terrestrial icebergs frozen into their formerly fluid ocean substrate. Hummocky chaos does not contain large blocks and is composed of more finely textured matrix with a few small (tens to hundreds of meters across) blocks lacking recognizable pre-existing surface features. Hummocky chaos has smoother, more subdued margins with matrix and blocks typically upwarped above the level of the adjacent icy surface. The adjacent surface is sometimes, but not always, downwarped along hummocky chaos margins, as if loaded by these materials or undermined by withdrawal of subsurface material. The general appearance is one of greater disruption of pre-existing surface (compared to blocky chaos), perhaps by melt-through from below [11] with inflation and/or freezing expansion of slushy/liquid matrix material beneath a brittle ice shell.

Other features observed at high resolution include lineated and ridged plains and dark material on the floors of secondary craters (radial to the Tyre structure) and on the tops of some chaos blocks. This dark material is typically observed on the N-NE sides of crater floors, on or below sun-facing slopes, and on sun-facing slopes of blocks and ridges. These relations suggest a sublimation lag deposit origin for these darker deposits.

Summary and conclusions: Regional and local morphology of the Tyre region of Europa indicates that an impact penetrated through the surface ice to a mobile (perhaps liquid) layer. The surface was initially dominated by small-scale deformation into heavily ridged and lineated plains, followed by localization into larger, more widely spaced ridge bands and doublet ridges, with chaos and fracture formation dominating in the recent past. Two distinct types of chaos have been identified which, along with upwarped dome materials, appear to represent a continuum of features resulting from various degrees of surface disruptions associated with local lithospheric heating and thinning.

The highest concentrations of non-ice materials (salts) are located adjacent to doublet ridges and chaos/dome areas. These deposits may result from endogenic ridge-building, thermal alteration and/or water vapor venting processes. Such deposits are probably further concentrated as sublimation lag, as suggested by darker regions located preferentially on sun-facing slopes. Although the absolute age of the Tyre impact is uncertain, local and regional stratigraphic relations, combined with the very low impact crater density on the surface of Europa, suggest that low viscosity ice or liquid water was present beneath a thin (several kilometers or less) surface ice lithosphere on Europa in the recent past.

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