THE VOLCANIC AND TECTONIC HISTORY OF GANYMEDE Scott L. Murchie, *Department of Geological Sciences, Brown University, Providence, RI.*

Introduction. Recent studies testing for planetocentric or heliocentric crater-forming impactor bombardment of Ganymede [1,2] have provided the basis for a chronology of major volcanic and tectonic units based on crater density measurements [1,3]. Other recent studies have examined in detail the formation of surfaces of different age. Detailed mapping of structures and resurfacing materials in dark terrain and documentation of their age relations using stratigraphic relations and crater ages have led to testing of models of furrow formation [4,5,6,7,8]. Evidence has been presented that the earliest stage of grooved terrain formation was characterized by large-scale shear motions, including strike-slip faulting and distributed deformation [9]. In addition, the sequence and style of grooved terrain deformation and the thickness of light terrain have been investigated using detailed mapping and crater size-frequency measurements [1,10,11, 12,13,14,15]. In this abstract the interpretations from these studies are integrated with each other and with those from other workers, and are synthesized into an interpretation of the volcanic and tectonic history of Ganymede. In addition, the interpreted evolution of a representative portion of Ganymede's surface is described in detail; the Uruk Sulcus region (18°N-15°S,145°-164°W) is chosen for this purpose because it exhibits a wide variety of volcanic and tectonic features. The region is also depicted in six paleogeographic maps (Figs. 1*a-f*) whose ages are represented by normalized densities of $\geq$10-km craters per 10^6 km^2 (nN10) (i.e., normalized to 90° of arc from the leading edge, assuming heliocentric bombardment with $\delta = 15$ [1,2]).

Interpreted volcanic and tectonic history of Ganymede. The oldest surface observed on Ganymede, dark terrain, was emplaced by accumulation of dark volcanic materials to a thickness of several kilometers [1,3,5,6,7,8], completely burying an older, heavily cratered, probably Callisto-like surface. Smaller craters that formed during this period of widespread volcanism frequently were completely buried by younger dark-material deposits; larger craters were more commonly only partially buried [1,16], producing a flattened morphology that has been interpreted by some workers [e.g. 17] to have resulted from viscous relaxation. During or before the period of dark-material volcanism, two very large impacts created hemispheric-scale systems of radial and concentric fractures resembling the smaller Valhalla ring system on Callisto, centered at about 15°S,168°W and 60°N,50°W (furrow systems I and III of [4,5,6,8,9], respectively). Both systems were resurfaced by dark volcanic deposits of various ages and were repeatedly reactivated by global extensional tectonism to form graben, typically at or soon after the time of emplacement of dark-material deposits. Thus "furrows" formed over a prolonged period on surfaces having different crater densities, and they retained the radial and concentric arrangements of the impact-generated fracture zones, but they crosscut very few well-preserved older craters [1,5,6]. Both furrow formation and extrusions of dark material became increasingly concentrated with time toward a geologically "anomalous" region several thousand kilometers in size, centered at about 25°S,122°W [5,6]. As dark-material volcanism finally ended at least 3.8 Gyr ago, an enormous system of radially-arranged furrows formed (system II of [4,5,6,8,9]), centered on 25°S,122°W and extending at least 60% of the distance to the antipode [5,6].

A distinctly different style of tectonic deformation apparently then began. Large blocks of lithosphere underwent significant lateral motions, typically tens of kilometers in magnitude [9]. Some of the motion occurred across strike-slip faults; other motion occurred across 500- to 1500-km wide bands that were pervasively deformed by block rotations and formation of dark "reticulate" and lineated terrains. However, at least one much larger shear offset may have occurred: there are several lines of structural evidence that Galileo Regio, a circular dark terrain block approximately 4000 km across, underwent a clockwise rotation of about 14°, offsetting older structures across its boundary by about 500 km. Most of the shear motions occurred across a global structural "fabric" that was later reused by grooved terrain.

After most of the shear motions had occurred, light volcanic materials were emplaced in association with formation of linear "grooves." Light materials were emplaced both as flows and as "pyroclastic" deposits [11,15], and they accumulated to a thickness averaging 1-2 km [1,12]. Grooves are thought to be extensional tectonic features [18,19], whose formation was initiated by reactivation of older zones of weakness [8,13]. The grooves are organized on three scales: locally as sets of parallel grooves, and regionally as "superdomains" up to 2000 km in size within which there are one or two dominant groove orientations [14] parallel to older furrows [8,9,11,13]. Globally, the dominant orientation is at low angles to a small-circle system whose pole is near 70°-75°N,95°W. This global structural "fabric" may represent an old, buried furrow system, a combination of the effects of observed furrow systems, or possibly zones of weakness created during tidal despinning [8,10,14].

The oldest light materials were emplaced in the geologically "anomalous" area [1,6] as a distinct terrain type ("complex grooved terrain") [11]. As groove formation and light material emplacement became widespread, light grooved terrain commonly formed by a three-stage process [11]. First, dark terrain was dissected by throughgoing grooves and rift-like "groove lanes" into polygonal blocks; this first stage appears to have overlapped with the earlier period of shear offsets. Second, many of the polygonal blocks were resurfaced by light materials and were pervasively grooved, forming "grooved polygons." Groove width reached a minimum during this stage of deformation. Third, repeated formation of rifts or "groove lanes" occurred, commonly by reactivation of the older throughgoing grooves. Groove formation and light material emplacement had nearly ended by the time of formation of the youngest impact basins (e.g. Gilgamesh), although some light materials erupted through fractures opened by these impacts [13].

Interpreted volcanic and tectonic history of the Uruk Sulcus region. The surface that existed before emplacement of the oldest dark materials (Fig. 1*a*) is unknown but speculated to have been similar to the present surface of Callisto [16,20], possessing a high density of craters (heavy circles, Fig. 1) and scattered smoother, possibly volcanic patches. WNW- and NNE-oriented fractures (medium lines, Fig. 1*a*) were arranged concentric and radial to an enormous impact feature at 60°N,50°W, and other impact-generated fractures were arranged concentric and radial to an impact feature immediately to the southwest [4,5,6,9]. Both systems of fractures were first buried by dark volcanic material at an age no later than nN10=340, and the fractures were reactivated by extensional tectonism to form furrows. At an age of nN10=270 (Fig. 1*b*) intermediate-albedo dark material now exposed in central and eastern Marius Regio was extruded, and it partly buried contemporaneously formed system I furrows (medium lines, Figs. 1*b*-1*f*) in eastern Marius Regio. At an age of nN10=170 (Fig. 1*c*), lower-albedo dark material about 2 km thick was extruded to the north in Galileo Regio, and it buried all but the rims of the largest craters. Concentric system I furrows wider than those in Marius Regio then formed, possibly by upward propagation of buried furrows' bounding normal faults through the volcanic cover. Subradial system I furrows also formed, but with a regionally coherent NE orientation consistent with structural control by buried system III radial structures. All of these materials and structures were crosscut by system II furrows (heavy lines, Figs. 1*c*-1*f*) and by a throughgoing NNE-oriented trough following the trend of system I subradial furrows (dotted line, Figs. 1*c*-1*f*) [4,5,6,9]. At an age of nN10=150 (Fig. 1*d*) a zone of major left-lateral shear developed, and Galileo Regio was offset approximately 500 km relative to Marius Regio. Motion occurred by strike-slip faulting, and across a wide zone by distributed deformation including block rotations and formation of "reticulate terrain" (cross-hatching, Figs. 1*d*-1*f*) [9]. By age nN10=70 (Fig. 1*e*), part of the zone of distributed deformation had been resurfaced by light material about 1 km thick, and grooved polygons formed in lithospheric blocks bounded by throughgoing fault zones. (Throughgoing fault zones and orientations of other grooves are shown in Figs. 1*e*-1*f*.) A number of resurfaced groove lanes and a few grooved polygons continued to form at and near the throughgoing fault zones, at least until an age of nN10=50 (Fig. 1*f*) [11].

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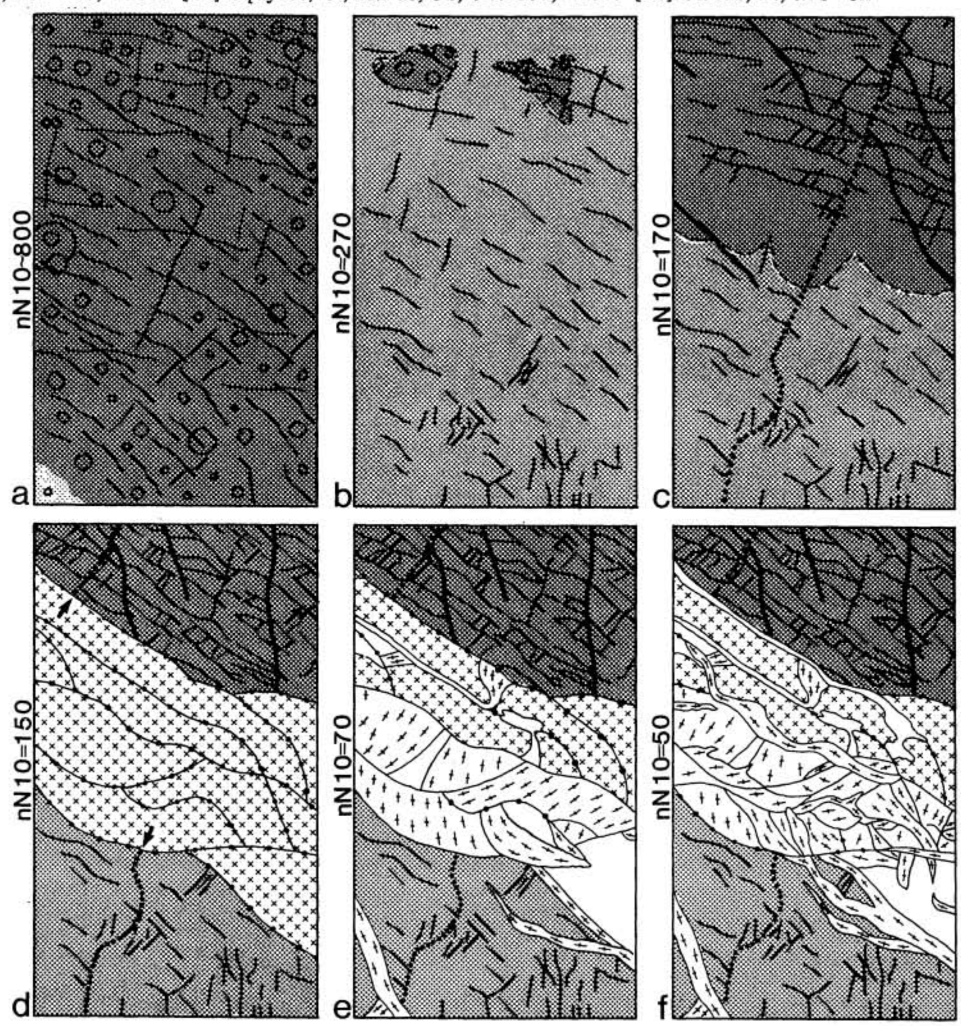

Fig. 1. Interpreted evolution of the Uruk Sulcus region. Width of the map area is 850 km; north is up.