1-3 km. Superposed dark smooth material of central Marius Regio, with a thickness of 600 m to 2 km, would cap a sequence of materials perhaps 1.5-5 km thick if it overlies both a northwestern Marius-like deposit and an older Nicholson-like deposit. The dark material deposits of Galileo Regio, if also burying the same types of surfaces, would possess a similar cumulative thickness.

These estimates include only deposits which have been identified as surface exposures in areas covered by *Voyager* images. It is not unlikely that there are dark volcanic deposits which are completely superposed by younger dark materials and thus lack surface exposures. If these completely buried deposits are similar in abundance to those recognized as surface exposures, then a realistic estimate for the average total thickness of dark terrain may be 3-8 km. Alternatively the deposits identified as surface exposures may only be the uppermost layers of a substantially thicker sequence. However the 3-8 km thickness estimate is in good agreement with *McKinnon and Parmentier's* [1986] 5-km thickness estimate for dark terrain, which was based on the observation that many partly degraded ≥50-km craters in dark terrain exhibit light-colored ejecta. McKinnon and Parmentier interpreted this material to be mineralogically distinct subcrustal material exposed because the craters' transient cavities penetrated a discrete dark terrain crust.

Lithospheric thickness and thermal gradient. Golombek and Banerdt [1986] have calculated a relationship of the width of endogenic extensional features on Ganymede with the lithospheric thermal gradient. In short, a higher thermal gradient decreases both lithospheric thickness and the width of extensional features. A decrease in strain rate has a similar but much smaller effect over geologically reasonable strain rates. Both grooves and furrows are interpreted to have formed on geologic timescales, so it is valid to use widths of the two types of features as indicators of the general evolution of the lithospheric thermal gradient. Evolution of the lithospheric thermal gradient, in turn, is indicative of the thermal evolution of the underlying upper mantle.

The widths of furrows and grooves both exhibit significant lateral variability. For example, furrows averaging 10 km in width occur in Nicholson Regio and Galileo Regio [*Zuber and Parmentier*, 1984*a*; *Croft and Goudreau*, 1987], furrowed surfaces with relatively large and relatively small calculated crater ages respectively. Furrows in areas with intermediate calculated crater ages, such as Marius Regio and Barnard Regio, have narrower furrows averaging 6 km in width [*Zuber and Parmentier*, 1984*a*; *Croft and Goudreau*, 1987]. Grooves also vary considerably in width, at least from as narrow as 3-4 km to as wide as 11 km [*Squyres*, 1981, pp. 593 and 597]. However, as a class of features, furrows are distinctly wider than grooves. Average furrow widths of 6-10 km imply a lithospheric thermal gradient of 2°-6° km^{-1}, if the furrows originated as graben. In contrast, the typical 4-km width of younger grooves implies an increased local thermal gradient of 5°-20° km^{-1}, with the lower and higher values being the consequences of a graben or lithospheric necking model of groove origin, respectively [*Golombek and Banerdt*, 1986].

The general, long-term increase in the lithospheric thermal gradient suggested above implies warming of an initially cooler upper mantle, and is consistent with three major aspects of Ganymede's early geologic evolution. First, internal warming of Ganymede would have created global tensional stress [*Zuber and Parmentier*, 1984*b*], which is inferred in this study to have played a major role in furrow formation. Second, at least some internal warming is necessary for formation of a hemispheric-scale thermal uplift like that interpreted to have formed furrow system II. Third, the shift in tectonic styles on Ganymede from furrow formation to grooved and light terrain formation would have occurred at a time when Ganymede's interior was warming. This is consistent with the observation that the oldest light terrain ("complex grooved terrain") formed in an area characterized by prolonged concentration of volcanism, fracturing, and probably high heat flow.

A Paradigm for the Relationship of Dark Terrain Geology to Internal Structure and Evolution

In this study and those of Croft and others listed in the beginning of the "Discussion" section, the furrowed surface of dark terrain is interpreted to be a volcanic surface fractured by endogenic tectonic processes. This interpretation is in contrast to the "prevailing interpretation" of dark terrain as a primordial, impact-fractured upper layer of a differentiated ice mantle [*Passey and Shoemaker*, 1982; *Shoemaker et al.*, 1982; *McKinnon and Parmentier*, 1986]. The "prevailing interpretation" has in turn been used as a constraint on models of Ganymede's early thermal evolution [e.g., *Kirk and Stevenson*, 1987; *Mueller and McKinnon*, 1988]. Given the fundamental difference in the interpretations of the geology of dark terrain, it is appropriate to explore other possible models for Ganymede's early evolution. *Croft* [1985, 1986*b*] has proposed a model based on radiogenic warming of an initially cool interior, which makes predictions generally consistent with our interpretation of dark terrain geology (e.g., extensional tectonism, accumulation of volcanic deposits that bury an earlier crater population). In the following discussion we develop another model, beginning by considering dynamical processes which could have created the uplift interpreted to have formed furrow system II.

Consideration of Convection in a Sphere

Consider the internal layering of a Ganymede-sized, ice-silicate satellite that was partially differentiated by accretional heating, following adjustment of Rayleigh-Taylor instabilities on a time-scale of several times 10^8 years: a differentiated clean-ice upper mantle, an undifferentiated ice-silicate lower mantle, and a silicate-rich core [*Schubert et al.*, 1981; *Kirk and Stevenson*, 1987; *Mueller and McKinnon*, 1988]. Each layer may be viewed as a sphere or spherical shell through which internal heat is transported by conduction or convection.

The stable pattern of convection in a sphere or spherical shell is a function of the dimensions of the shell and its Rayleigh number [*Turcotte and Oxburgh*, 1967; *Turcotte et al.*, 1979]. Specifically, at low Rayleigh numbers the dominant wave number of convection (l) is a function of the ratio of the inner and outer radii of the shell (η) [*Busse*, 1975; *Busse and Riahi*, 1982; *Zebib et al.*, 1983]. For an internally heated sphere or shell with $0<\eta<0.27$, at low to moderate Rayleigh numbers $l=1$ and the stable pattern of convection is expected to be a single, axisymmetric convection cell with one rising current and one antipodal descending current [*Hsui et al.*, 1972; *Zebib et al.*, 1983]. At higher Rayleigh numbers, a two-celled or higher-order convection pattern could occur in a uniform sphere or thick shell [*Hsui et al.*, 1972]. For larger values of η (in thinner shells), at low to moderate Rayleigh numbers, $l \geq 2$ and a higher-order convection pattern is expected.