the ejecta either during or subsequent to its emplacement. Both alternatives allow that unaltered material excavated from depth may be low-albedo and relatively silicate-rich.

Extensional tectonics driven by global thermal expansion. In order for global expansion to provide a plausible driving mechanism for Ganymede's endogenic extensional tectonics, tensional stress sufficient for brittle deformation of the lithosphere must have been applied on a time-scale comparable to or less than the Maxwell time for viscous relief of stress (viscosity divided by shear modulus). *Passey and Shoemaker* [1982] used observed degradational states of dark terrain craters to estimate a lithospheric viscosity of 10^{26} P, assuming that all degradation occurred by viscous relaxation. The corresponding Maxwell time is about 10^8 years [*McKinnon and Parmentier*, 1986]. However, evidence for removal of dark terrain craters primarily by volcanic burial implies that *Passey and Shoemaker* [1982] overestimated the amount of viscous relaxation that did occur and consequently underestimated lithospheric viscosity. Retention of significant relief in furrow-cut craters in the old dark terrain of southeastern Nicholson Regio is consistent with a lithospheric viscosity of several times 10^{26} P or greater, and therefore a Maxwell time of at least several times 10^8 to 10^9 years.

Zuber and Parmentier [1984*b*] calculated that radiogenic warming of an initially cold, undifferentiated Ganymede would have created 200-300 bars of tensional stress in the lithosphere, on a time scale of 3-5 x 10^8 years. This stress compares to tensile strength of crustal ice of tens of bars [*Hawkes and Mellor*, 1972; *Gold*, 1977], or a lithospheric strength of tens to 100 bars [*Golombek and Banerdt*, 1986]. Global thermal expansion therefore appears capable of having created several times the stress necessary for brittle extensional deformation of Ganymede's lithosphere, on a time scale much less than the Maxwell time.

One-celled mantle convection. A warming, undifferentiated Ganymedean interior would consist of concentric shells of ice-I, ice-II, ice-V and/or ice-VI, and ice-VII and/or ice-VIII, each with a complement of intermixed silicate. The Rayleigh number and viscosity of a Ganymedean mantle undergoing steady state convection about 4 x 10^9 years ago were calculated by *Sotin* [1986], who found a Rayleigh number of the order of 10^8 and a viscosity within ice-VI of the order of 10^{16} P. *Squyres and Croft* [1986] cited a lower Rayleigh number of about 10^6. Parameterized models of the thermal evolution of an initially cold, undifferentiated Ganymedean interior [*Zuber and Parmentier*, 1984*b*] suggest a period of internal warming of the order of 5 x 10^8 yrs, after which mantle viscosity would have decreased enough for convection to reach a steady state where internal heat production equalled lithospheric heat transfer by conduction and volcanism (assuming Sotin's mantle viscosity of about 10^{16} P).

In comparison to the high Rayleigh number expected to accompany steady state convection, the maximum Rayleigh number at which one-celled convection is stable in a uniform sphere is probably less. For a "fixed surface" condition in which the lithosphere does not participate in convection, *Hsui et al.* [1972] calculated that one-celled convection would transform into a two-celled pattern at Ra=3 x 10^4, although *Zebib et al.* [1983] calculated that a single cell would be stable at Rayleigh numbers in excess of 10^5. If a single convection cell were effectively to have a "free surface," then it would be stable at Rayleigh numbers at least as high as 5 x 10^6 [*Hsui et al.*, 1972].

One-celled convection of an undifferentiated Ganymede would require that all of the phase transitions of water ice in the mantle be unstable to convection. The convective stability of the ice-I/ice-II, ice-II/ice-V, ice-II/ice-VI, and ice-VI/ice-VIII phase transitions have been investigated by *Thurber et al.* [1980], *Bercovici et al.* [1986], and *Sotin and Murchie* [1988]. These workers have found that the most stable phase transition would occur at the base of the mantle's ice-II, where ice-V or ice-VI occurred; that its stability against convection is enhanced in a warmer, more vigorously convecting mantle with a lower viscosity; and that its stability against convection is decreased by greater thickness of the underlying convecting layer. *Bercovici et al.* [1986] suggested that convection in a differentiated mantle would not occur through the base of the ice-II layer at mantle viscosities $<10^{18}$ P, that is, at viscosities appropriate to a mantle undergoing steady state convection [*Sotin*, 1986]. *Sotin and Murchie* [1988] suggested that convection through the base of ice-II would not be expected in a differentiated mantle. However, no workers have as of yet investigated the convective stability of phase transitions in an undifferentiated Ganymedean interior.

Three aspects of the convection of a warming, undifferentiated Ganymedean mantle are suggested by these theoretical results. First, theoretical considerations seem at this time to allow the existence of a transient one-celled mantle convection pattern during the warming of an initially cold, undifferentiated Ganymedean interior, at a time in the satellite's history consistent with the inferred age of dark terrain (>3.8-4.0 Ga). Second, a single cell in a mantle undergoing whole-layer convection might have broken down into a higher-order pattern (two or more cells) before a convective steady state was achieved. Third, development of layered convection due to convective stability at the base of the ice-II layer might also have caused a change in the style of mantle convection before a steady state was achieved. The latter possibility is largely unconstrained at this time, and further investigation of it is needed.

CONCLUSIONS

Detailed geologic mapping of furrows and dark material units, observations of stratigraphic relations of structures and materials, and measurements of crater densities and calculations of relative crater ages of material units were used to constrain the origin of dark terrain and its furrows. Dark terrain itself consists of volcanic materials which have accumulated to a global average thickness of about 3-8 km. The geology of two hemispheric-scale systems of arcuate and radial furrows, centered at about 15°S,168°W and 60°N,50°W, respectively, is consistent with their having formed by reactivation of multiringed impact structures by endogenic global extension and dark material volcanism. A third system of radial furrows is arranged around an area of young volcanic deposits and intense extensional deformation of the lithosphere. This latter furrow system is proposed to have originated by fracturing of a circular, isostatic thermal uplift on which volcanic resurfacing and extensional deformation due to global tensional stress were concentrated. The greater width of endogenic furrows than of younger, endogenic grooves suggests long-term thinning of the elastic lithosphere, which would be consistent with prolonged warming of the satellite's interior. Major aspects of the volcanic and tectonic history of dark terrain could be accounted for by warming and one-celled convection of an initially cold, undifferentiated satellite interior.