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FINAL REPORT

GEOLOGIC INVESTIGATIONS OF OUTER PLANETS SATELLITES

NASA GRANT NAGW-135

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FINAL REPORT FOR NASA GRANT NAGW-135

(GEOLOGIC INVESTIGATIONS OF OUTER PLANET SATELLITES)

INTRODUCTION

This is the final report on research completed or in progress under NASA Grant NAGW-135. The research is divided into four tasks: (1) investigation of volcanism on Io, (2) a geologic study of the ancient heavily cratered regions on Ganymede, (3) a comparison of the cratering record on Ganymede and Callisto, and (4) a geological and chemical investigation of internal resurfacing processes on the Saturnian satellites. Tasks 2, 3, and 4 are being continued under a Voyager Imaging Science Data Analysis Grant from the Jet Propulsion Laboratory (JPL). The original NASA Grant (NAGW-135) was for research covering a two year period. Funds to cover this continuing research have now been transferred to JPL. Task 1 has been completed and is now being prepared for publication. The other tasks will be continued under JPL sponsorship.

Task 1 - Investigation of Volcanism on Io:

Interim results of thermal and structural modeling of volcanism on Io have been presented by Crumpler and Strom (1). This abstract summarizes the final results of the modeling. The basic analysis is an evaluation of the "magma trigger" mechanism for initiating and maintaining eruptions. Secondary aspects include models of the mechanical mode of magma emplacement, interactions with a sulphur-rich upper crust, and more speculative implications for Io's volcanism.

In simplest finite element form, the initial temperature (Tm) of the contact between sulphur in the upper crust of Io and a freshly intruded silicate magma is given by:

$$Tm^{t} = T^{t-1}_{m-1} + (2\Delta t\alpha_{m+1})^{0.5} \left[\left(T^{t-1}_{m+1} - T^{t-1}_{m-1} \right) / \left(\left(2\Delta t\alpha_{m+1} \right)^{0.5} + \left(2\Delta t\alpha_{m-1} \right)^{0.5} \right) \right] \quad (1)$$

Here m-1 is a finite plane within the sulphur layer, m + 1 is a plane within the silicate intrusion, α_{m+1} and α_{m-1} are the thermal diffusivities of the sulpher and silicate magma respectively, and t is time. The results for a reasonable temperature range of magma (1200-1500K) and sulphur (130-400K) are about 700K to 100K, or approximately the vapor temperature of elemental sulphur. A silicate sill or laccolith 10m thick will yield energetic vapor for a period of several weeks to several months depending on the precise vapor temperature and the amount of advective cooling of the sulphur-silicate interface. This model can account for the origin of plumes and sulphur flows, as well as for their observed temperatures (2) and lifetimes (3). If sulphur vapor temperatures at the contact are exceeded by no more than 40°K at the equator, then no sulphur vapor will be generated above about 50° latitude because the initial sulphur temperatures above these latitudes will not yield contact temperatures of the required temperature. This would explain the lack of large plumes in the polar areas.

The darkest deposits on the floor of the average dark caldera cover 10% of the floor area. If these are hot areas (475-600^{o}K), then the area of all dark calderas on Io covered by similar proportions of hot surfaces yields a heat flow from 0.8 - 2.9 W m^{-2}, in agreement with the observed flux.

Estimates of the probable depth to the silicate magma source (h_c) can be derived from laccolith hydraulics (4) in which:

$$h_c = \left(16\delta_{max}Eh^2/[3g\Delta\rho(1-\nu^2)r^4+\rho_s h/D\rho]\right)^{0.5} \qquad (2)$$

where δ_{max} is the laccolith thickness, E in Young's modulus, Δp is the magma-crust density contrast, h is the overburden thickness, ν is Poisson's ratio, r is the laccolith radius, and ρ_s is the sulphur crust density. Calculations indicate depths of 40 to 200km to magma sources, with a most probable depth near ~ 100km. Any magma capable of forming a laccolith has the necessary magma driving pressure to create surface silicate volcanism as well. A 40km thick crust is the minimum required to support the highest mountains of Io. For most viable mechanisms of building the observed mountains, however, a lithospheric thickness of 140km is required.

The amount of melt that must make its way to the surface to carry the nominal tidal heat input depends on the average temperature of the melt and its heat capacity. In order for silicate melts between 1200-1500^{o}K to move 1 W m^{-2}--the average of the tidal input and observed radiant output of Io--10 to 14 average laccoliths (r=20 km) need to be erupted at the sulphur crust-silicate crust interface per year. This is within the range of probable frequency of thermal outbursts estimated at 10 per year (5). This is also within the volume limits of silicate magma necessary to mobilize the volume of sulphur inferred to be cycled from resurfacing rates.

Temperatures much above the melting point of sulphur at the base of a sulphur crust would result in rapid overturn, or advection. Thus, the temperature at the base of the sulphur crust may be buffered at ~400^{o}K. For this reason the existence of a "sulphur ocean" is unlikely. Similarly, the base of the silicate lithosphere may be maintained at the silicate melting temperature. The depth to melting is constrained either by the depth to which stressing and fracturing penetrates the lithosphere and initiates advective heat transfer, or the depth to which melting first occurs from a given conducted thermal gradient. On Io, there is no lack of heat for melting at any depth, and therefore, the depth to silicate melting may be buffered by the depth of tidal fracturing.

Equation (1) sets a lower limit of 1200K for the silicate magma temperature if the base of the sulphur crust does not exceed 400K as implied above. Such a temperature is characteristic of silicic and alkalic magmas on the Earth (rhyolite or trachyte). The High K and Na in the Io torus may reflect high abundances of these elements in the silicate crust and magma, both elements being abundant in terrestrial silicic magmas. For all other elements of the thermal model of advection to work coherently, all magmas shallower than about 100km will have temperatures of about $1200^{O}K$. Active silicate volcanism on Io of silicic composition intruded in a sulphur-rich crust best explains the observed characteristics of its overall thermal budget and volcanic style.

References

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(3) Pearl, T.C., and N.M. Sinton, 1982, Hot Spots of Io. in D. Morrison, ed., The Satellites of Jupiter, Tucson, University of Arizona Press, 724-755.
(4) Pollard, D.D., 1969, Deformation of Host Rocks During Sill and Laccolith Formation. Stanford University, Ph. D., 134p.
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<u>Task 2 - Geologic Investigation of Ancient Terrains on Ganymede</u>: The geology and tectonics of the anicent heavily cratered regions on Ganymede provides information on geologic processes and thermal conditions early in the history of this satellite. They are related to the physical properties, stress and thicknesses of the outermost layer at the time the crust became rigid enough to record geologic events. We have recently completed a study of Galileo Regio, the largest area of ancient terrain on Ganymede. This investigation indicates that Galileo Regio is characterized by: (1) two principal morphologic terrain units (rough and smooth terrains), (2) craters in various states of preservation, and (3) a tectonic framework consisting of three furrow systems of different ages. The three furrow systems transect the rough terrain but pre-date all other terrains as well as the oldest craters larger than about 10 km diameter (Fig. 1). A broadly arcuate NW-SE furrow system dominates the tectonic pattern and is intermediate in age between widely spaced NE-SW and N-S furrow systems. The furrow systems were probably produced by extensional stresses that occurred during crustal solidification but before large craters could be retained. Smooth terrain is concentrated in the southern part of Galileo Regio and probably resulted from fluid extrusions along fractures associated with the dominant furrow system. The distribution of smooth terrain on Galileo Regio suggests that the ancient crust of Ganymede was relatively thin in the equatorial region and thickened polarward in this area. The origin of the furrow systems is very uncertain. The age relationships. morphology and

TECTONIC MAP OF GALILEO REGIO

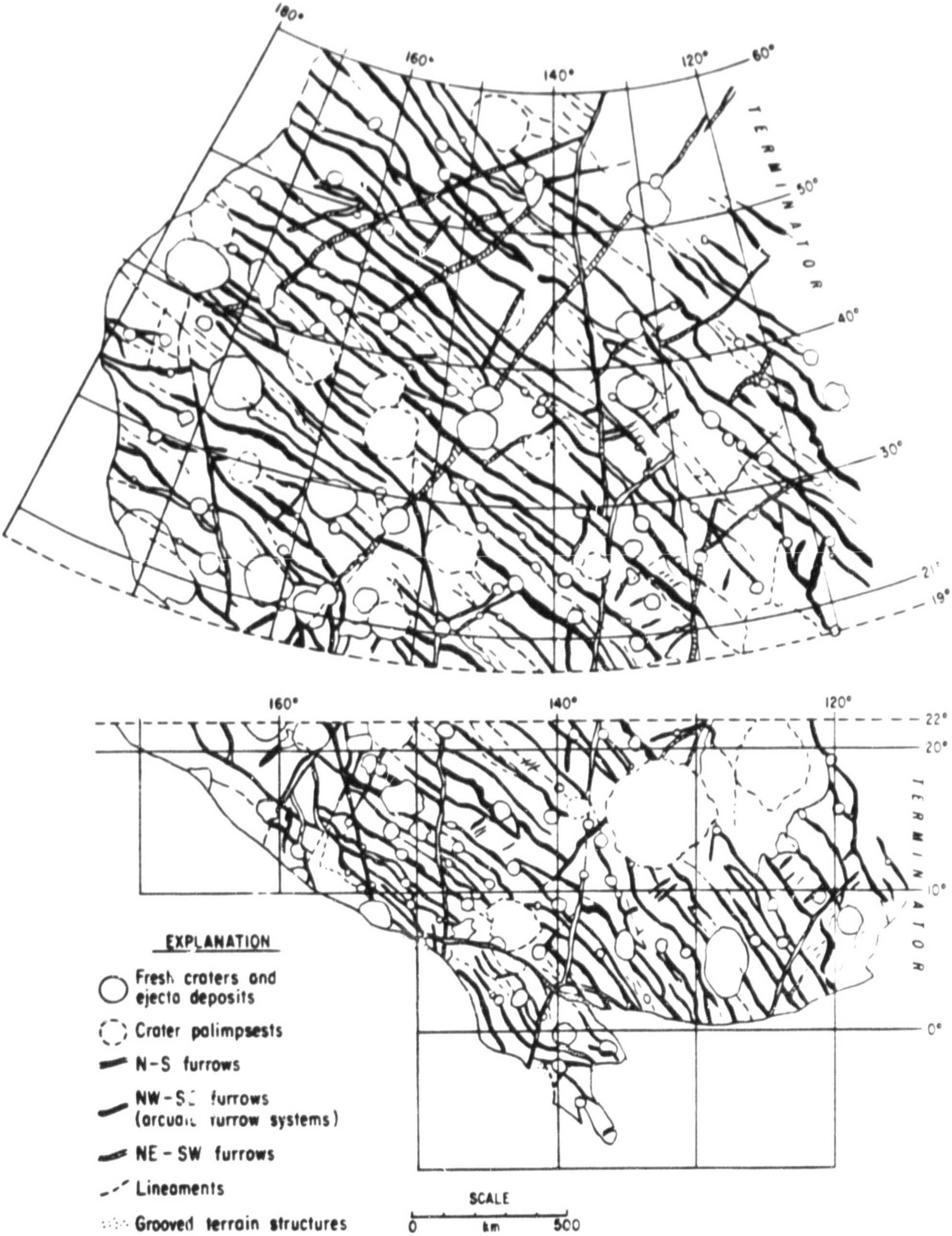

Fig. 1

geometry of the furrow systems does not favor an origin by impact or tidal stressing. A possible, but speculative, origin is crustal uplift caused by a plume-like convection cell in a fluid mantle underlying a thin crust. Stratigraphic and morphologic relationships among furrows and crater palimpsests suggest that palimpsest morphology is largely the result of impact into a rheologically weak crust rather than viscous relaxation.

We intend to extend our study of Galileo Regio to other areas of ancient terrain, particularly Marius and Nichelson Regiones. Marius Regio occurs directly west of Galileo Regio, and Nichelson Regio is antipodal to it. They also contain furrow systems which may be related to those on Galileo Regio. Detailed geologic and tectonic maps of these areas are required to understand the sequence of events that occurred early in Ganymede's history. The orientations and sequence of formation of the furrow systems should indicate the nature and direction of the stress field that produced them. This, in turn, will place constraints on their origin, and indicate whether or not convection plumes in a liquid mantle could explain their formation. This investigation will be carried out in collaboration with Dr. Steven Croft of the Lunar and Planetary Lab. and Dr. Ruggero Casacchia of the Dept. of Planetology, University of Rome.

Ref.--Casacchia, R. and Strom, R.G., Geologic Evolution of Galileo Regio, Ganymede, Icarus, in press.

Task 3 - Comparison of the Outer Planet Cratering Record:

The crater size/frequency distribution on Callisto is very different from that observed on the heavily cratered regions of the Moon and terrestrial planets. It is characterized by a marked paucity of craters greater than 40 km diameter and a different distribution function at diameters less than 40 km relative to the lunar, mercurian and martian highlands (Fig. 2). One proposed explanation of the paucity of large craters on Callisto is that great numbers of craters have been obliterated by viscous relaxation in the icy crust when it was more thermally active. Recent Monte Carlo computer simluations have shown that a lunar-like crater population modified by obliterating large craters to produce the observed Callisto crater population produces large variations in the crater density which are not seen on Callisto (Fig. 3). Other studies now in progress involve a comparison of the spatial distribution of craters on an area of Callisto with that of a lunar highlands area from which craters have been removed to produce the Callisto size/frequency distribution. Initial results indicate that the resulting spatial distribution of craters on the Moon is very different than that observed on Callisto (Fig. 4). These initial studies indicate that the Callisto crater population is a production population which records a different population of impacting objects than that responsible for the period of heavy bombardment in the inner Solar System. These types of comparisons will be continued under the proposed funding period.

Initial studies have shown that there are two crater populations on the Saturnian satellites characterized by two very

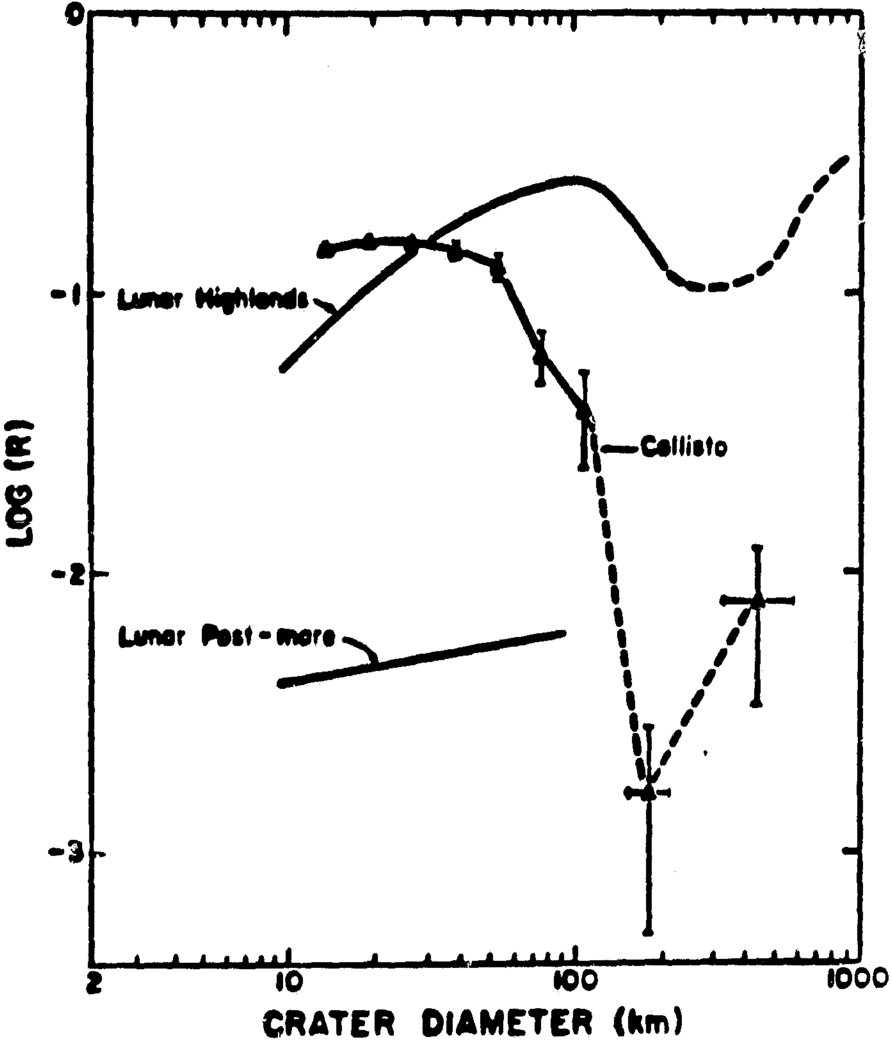
0
-1
-2
-3
LOG (R)
Lunar Highlands
Callisto
Lunar Post-mare
2
10
100
1000
CRATER DIAMETER (km)

Fig. 2

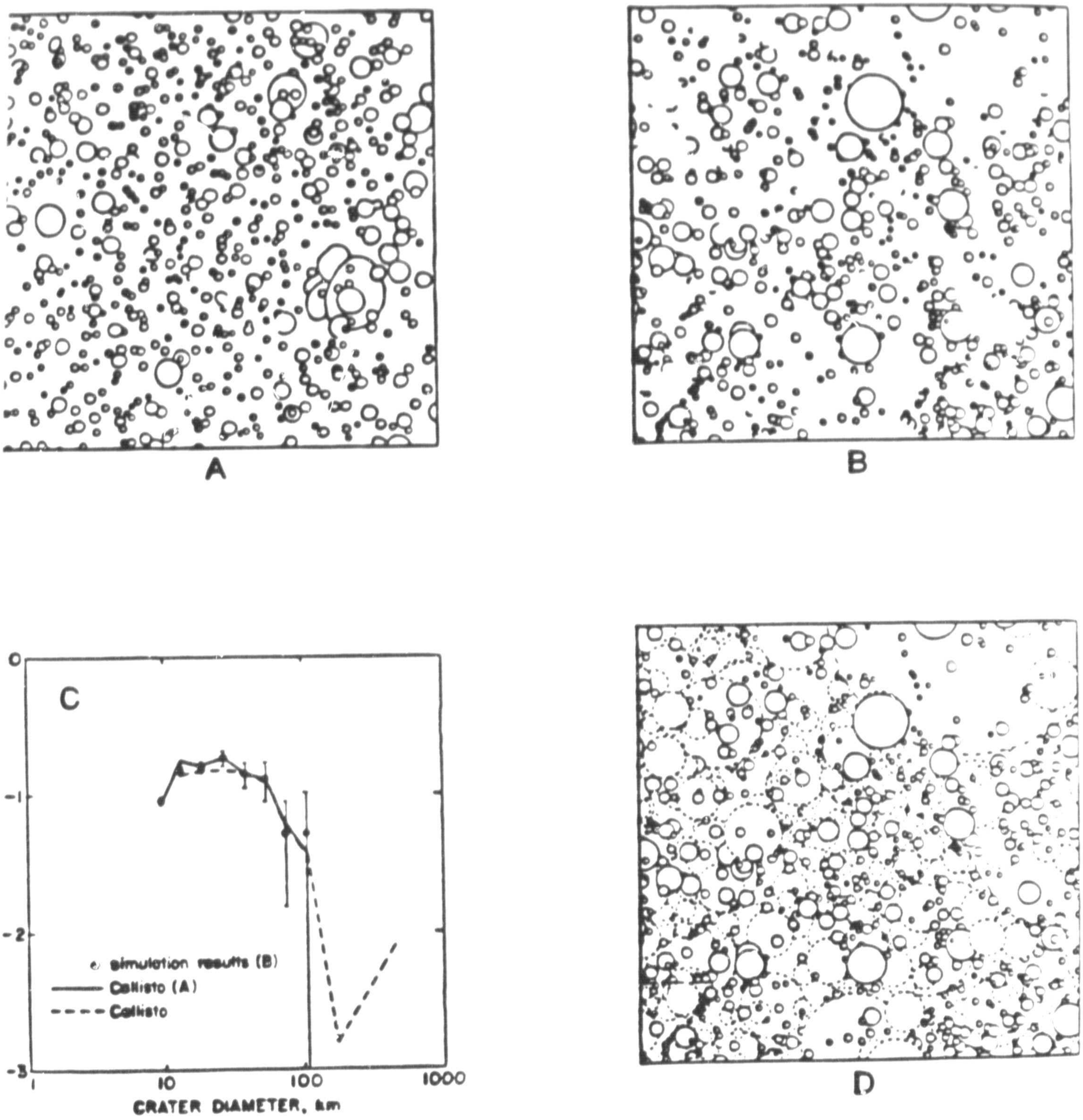

Fig. 3. Comparison of simulation results to the surface of Callisto. (2a) Craters on Callisto greater than 8 km diameter. (2b) Simulation of the surface of Callisto incorporating the effects of cryptopalimpsests. (2c) Size-frequency distributions of craters on the surface of Callisto: from Figure 2a (solid curve); from area measured by Strom et al. [1981a] (dashed curve); and from Figure 2b (dots and error bars). (2d) The simulation shown in 2b but with the locations of cryptopalimpsests revealed by the dashed circles.

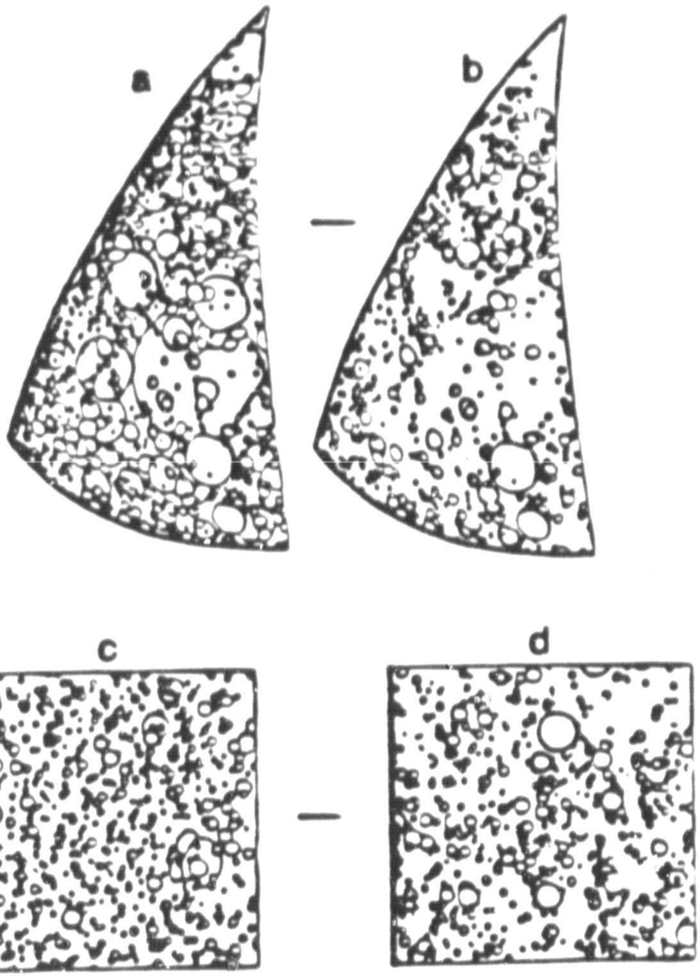

Fig. ~~3~~ 4. Spatial distributions of craters observed on the lunar area (a) the Callisto area (c), after crater removal from lunar area to produce Callisto size/frequency distribution (b) and from Monte Carlo computer simulation (d). Scale bars represent 100 km. Fig. 2c and d are from Woronow and Strom (4).

different size/frequency distributions. The older population is primarily represented on the heavily cratered surfaces, while the younger population is imprinted on resurfaced areas of Enceladus, Tethys, Dione and Rhea. Both of these populations appear to be different from those on Ganymede and Callisto as well as on the terrestrial planets (Fig. 5). This suggest that at least four, and probably five, different populations of impacting bodies have been responsible for the cratering record in the Solar System; two in the inner Solar System, one at Jupiter, and two at Saturn (Fig. 5). Currectly we are compiling more detailed crater counts over broader areas in order to more accurately characterize the size/frequency distributions of these two Saturnian crater populations and to determine crater density differences (relative ages) among the different satellites. We will undertake a detailed comparison between these crater populations and those at Jupiter and the inner Solar System in order to set tight constraints on the origin of these impacting populations.

The crater size/frequency distributions on Ganymede and Callisto are the same. The progression of crater morphologies with increasing crater rim diameter on both satellites is similar, but there are several important differences: palimpsests are less common on Callisto, larger crater structures on Callisto tend to be "giant" anomalous pit craters or "ripple ring" basins like Valhalla rather than multiring basins as on Ganymede, pits and domes tend to be smaller and more irregular on Callisto. Since the impactor populations on both satellites were apparently the same, some of these variations may be attributable

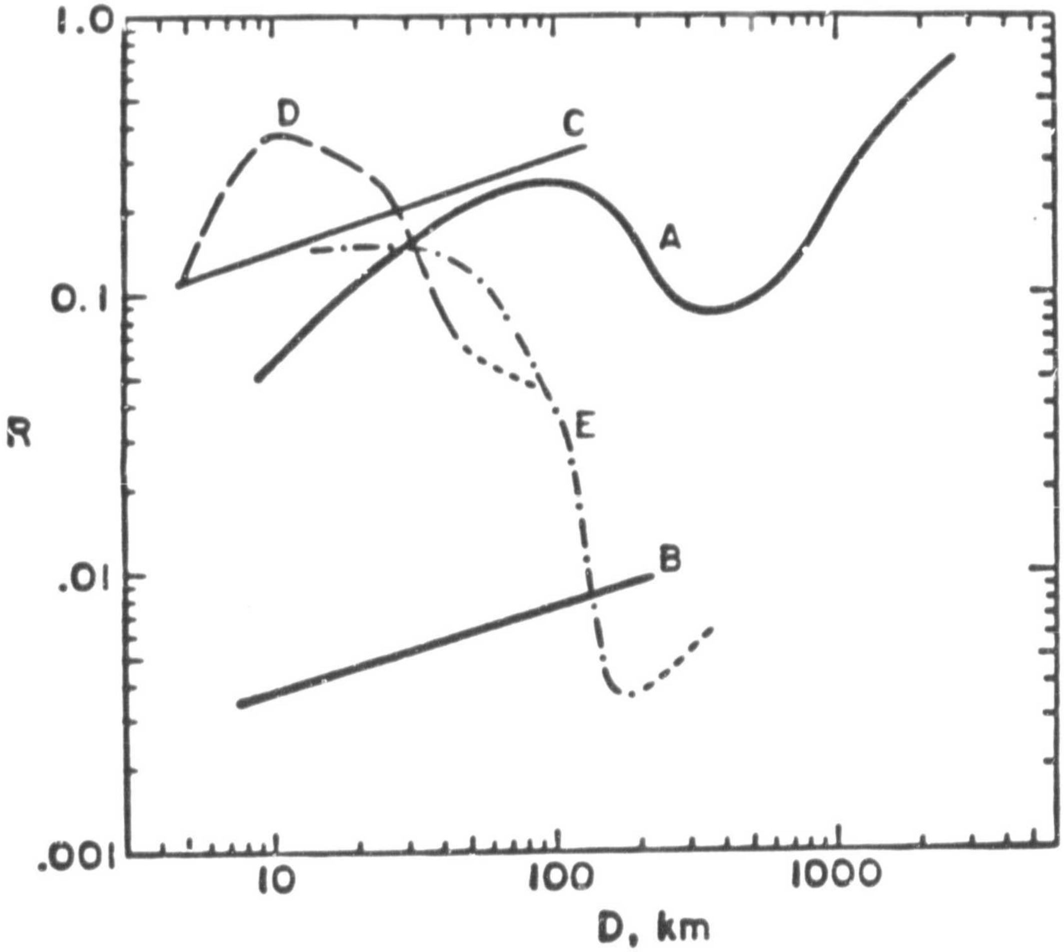

Fig 5, "R" plot of the size/frequency distribution of crater populations in the Solar System. Population A occurs on Mercury, Moon and Mars; B on Moon and Mars; C on Tethys, Dione, and Rhea; D on Mimas, Enceladus, Tethys, Dione, (Rhea ?); E on Ganymede and Callisto.

to differences in the thermal regimes of the outer layers of Callisto relative to Ganymede at the time of formation of the presently observed crater populations. However, modeling of pit crater and palimpsest formation indicates that thermal variations may not account for all the morphological differences and thus additional factors should be sought. One obvious possibility is the composition of the crust; e.g. pure ice on Ganymede and ice/silicate on Callisto. Another possibility is different rates of viscous relaxation. Reconaissance morphometrical analysis of the poorly defined structures in palimpsests, however, indicate inconsistencies between palimpsests and "normal" craters that are difficult to explain by viscous relaxation. Now that much statistical work on the crater populations has been done it remains to complete a detailed comparison of the morphologies and morphometries of craters on the two satellites, particularly of palimpsests, in conjunction with continued crater modeling, to constrain the relative roles of impact velocity, crustal composition, and viscous relaxation and other modification mechanisms in producing the characteristics of the observed crater populations.

An unsolved problem related to the icy satellites of Jupiter and Saturn is the recovery of the size/frequency distributions of the impactor populations that produced the observed crater populations. General scaling relations have recently been developed that relate the impactor size to the diameter of the transient crater as a function of impact velocity, surface gravity, impactor and planet density, etc., and empirical material constants. In order to apply these relations to the icy satellites, the appropriate material constants for ice and ice/silicate mixtures need to be determined. This has been done in part. A refinement of these parameters needs to be obtained by more careful analysis of the data available and possibly by some additional impact experiments. A second factor must also be quantitatively evaluated: the relation between the transient crater and final rim diameters for complex craters. The scaling relations apply to simple craters only, yet most of the craters used in statistical counts are complex. A theoretical model is being developed based partly on the theory and partly on field observations to establish the needed relation. Finally, an application of the same theory can be applied to the characteristic diameters of morphologic transitions: simple to complex, complex crater to basin, central peak to central pit, etc. Preliminary analysis indicates that the theoretical model can account for transition diameters as a function of planet. A more complete development of the theory and the application to observed crater populations on icy satellites is in progress.

Task 4 - Geological and Chemical Investigation of Internal Processes on the Saturnian Satellites: Encleadus, Tethys, Dione, and Rhea all show evidence of internal activity which has given rise to some type of ice "volcanism". Large areas on these satellites have been resurfaced. However, the mode of emplacement of this ice volcanism and its possible chemistry are not well understood. We plan to investigate the mode of emplacement of this ice volcanism by crater statistical studies and geologic mapping of the resurfaced areas. A very preliminary crater study of a resurfaced area on Tethys indicates there has been a diameter dependent loss of craters where small craters have been preferentially obliterated (Fig. 6). This suggests that the resurfacing material was emplaced by a flooding mechanism similar to the silicate volcanism on the Moon and other terrestrial planets. We intend to pursue this type of study for other resurfaced areas on the Saturnian satellites in conjunction with the geologic mapping.

Since the surfaces of these satellites are much colder than the melting point of H_2O ice, it is necessary to find some component that is easy to liquefy and has a relatively low vapor pressure. While many volatile materials do have a low melting point, their very volatility makes them less likely to exist on a satellite's surface for any time beyond a few hours. What is needed is a low melting compound with low volatility, preferably a compound or mixture with water. The infrared spectra of the Saturnian satellites have signatures proper to H_2O ice alone. But if a moderately volatile material is dissolved in the water, which lowers the melting point of water, and at the same time will eventually outgas or decompose leaving behind pure water, then we have a likely candidate for producing liquid flows on an icy satellite. Such a low melting point, low volatility compound is ammonia hydrate and its eutectic mixtures. A cosmic mix of NH_3 and H_2O would produce a liquid at the eutectic temperature of $173^{o}K$. Preliminary investigation indicates that

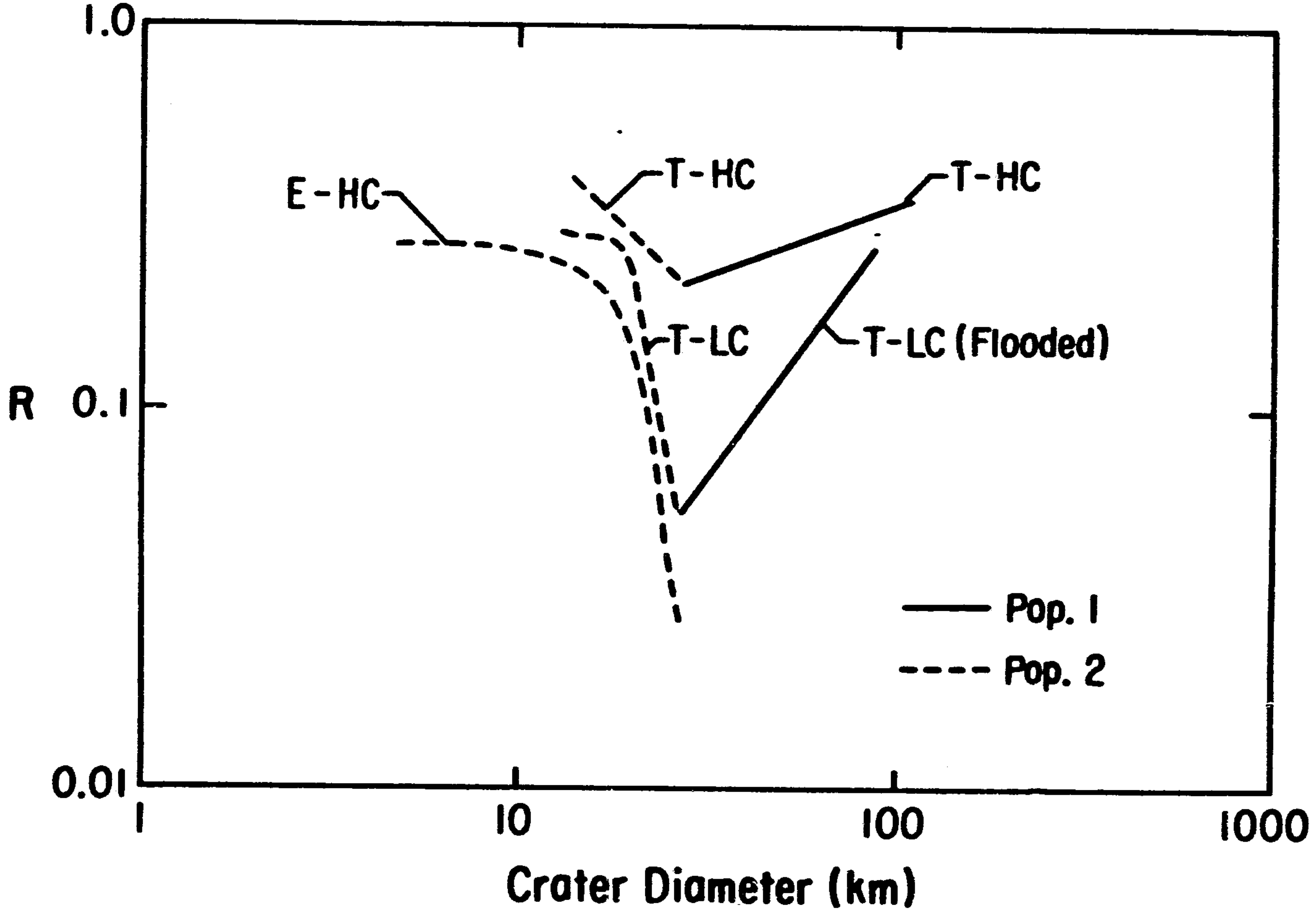

Fig. *6*. "R" plot of Tethys heavily cratered (T-HC) and lightly cratered (T-LC) terrains, and Enceladus heavily cratered terrain (E-HC).

as this liquid warms up from 173°K, it alternately is less dense, then more dense than pure H_2O ice. The original liquid at the eutectic point will float on pure ice, but in warming it becomes richer in H_2O, and when the temperature is approximately 200°K, the liquid becomes more dense than pure ice. Hence, the ability of the liquid to rise through an ice crust is a carefully limited, but distinct probability. The liquid outflow should gradually degas NH_3 and eventually become pure H_2O ice. A more carefully controlled series of investigations is required to determine the range of temperatures and compositions where NH_3-H_2O liquid is less dense and more dense than solid H_2O. The preliminary investigation had only limited control over the temperature. The viscosity of the NH_3-H_2O liquid also needs to be carefully examined. This part of the task will be done in collaboration with Dr. Godfrey Sill of the Lunar and Planetary Laboratory.