THE RHEOLOGY OF ICE-ROCK MIXTURES – APPLICATION TO THE SATELLITES OF THE OUTER SOLAR SYSTEM.

C. A. Middleton[1], P. R. Sammonds[1], P. M. Grindrod[1], A. D. Fortes[1] and L. Vočadlo[1]
[1]Center for Planetary Sciences, Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT (ceri.middleton@ucl.ac.uk).

Introduction: Ice-rock mixtures are likely to occur throughout the solar sytem; understanding of their rheological properties have been based primarily upon studies of terrestrial glaciers and permafrost (e.g. [1,2]). It is likely that there is a large quantity of ice trapped in the Martian subsurface, especially at high latitudes, which may account for features such as patterned ground, polygonal fractures and lobate debris aprons, and be a source of water for exploration [3]. Ice-rock mixtures are also likely to have been, or still be, present in the outer solar system, both in the smaller bodies, such as Kuiper Belt Objects and in the larger satellites of the Gas Giants.

Many of these larger satellites are differentiated, as indicated by the gravitational moment of inertia factor [e.g. 4] but they probably formed from a more homogeneous mixture of rock and ice, which subsequently differentiated. In the case of Callisto, the most likely current structure as calculated from gravitational data is a partially differentiated interior, with an ice-rock core and an overlying ice shell [5]. This means that the thermal evolution of all the large icy satellites has been dominated by the rheology of an ice-rock mixture at some time in the past; the rheology of undifferentiated bodies continue to be controlled by the rheology of ice-rock mixtures to the present day.

Constraining the rheology of these materials is important in understanding the evolution of icy moons, since factors such as the viscosity control differentiation and convection, and hence the spatial distribution of heat-producing radionuclides and the efficiency of heat flow. These factors in turn control the possibility of melting and the formation and long-term stability of subsurface oceans. For example, Durham et al. [6] found that the relative viscosity of a pure ice mixture and an ice-rock mixture varied by up to two orders of magnitude. This increase in viscosity should inhibit convection, increasing the possibility of melting and sub-surface oceans [6].

Previous work: Most of the experimental data for ice-rock mixtures focus on terrestrial environments [1,2] but some experiments have been performed under conditions relevant to the putative permafrost layer on Mars [3]. That study found a brittle/ductile transition in the behaviour of the ice-rock mixtures at a rock volume-fraction of ~0.6. This coincides with the proportions of rock and ice that Nagel et al. [7] used as the packing limit for the concentration of rock in the core of Callisto. However, conditions in the interiors of icy satellites will differ from those described by Mangold et al. [3] since the increased confining pressure should inhibit brittle failure. Hence, rheological parameters obtained in those experiments cannot necessarily be extrapolated easily to different conditions.

The experiments of Durham et al. [6] were carried out at pressures and temperatures relevant to the interiors of large icy satellites. They found that the strength of an ice-rock mixture was greater than that of pure ice, and the viscosity was higher by up to two orders of magnitude. However their results were dependent on the material that constituted the rock fraction, possibly due to the size of the rock particles and associated fabrics in the samples.

The rheological parameters used in models of the thermal and structural evolution of the icy satellites are mostly those of pure ice. For example, McKinnon [8] treats the outer shell of Callisto as ice rather than an ice-rock mixture. Dependent on the mechanism of differentiation the outer shell may be pure ice (in which case using the properties of pure ice is valid), or may contain up to 10 wt% rock [8] (in which case using the properties of pure ice may not be valid). McKinnon [8] then assumes that the change is sufficiently small to not effect the viscosity within the error of the creep law.

There are however some models which consider the introduction of rock into the ices, for instance Nagel et al. [7] include the effect of rock on the viscosity of their ice-rock mixture during differentiation of Callisto, by assuming that the viscosity of the ice-rock mixture is a function of the viscosity of the ice and rock volume fractions. This is a scale invariant relationship, assuming that the dimensions of the particles are not relevant, which may not be a valid assumption, as the results of Durham et al. show [6].

Experiments: We aim to investigate the rheology of ice-rock mixtures at the conditions applicable to the icy satellites, specifically investigating the role of the volume fraction of rock, the grain size of the rock and ice and the grain size ratio, also considering at what volume fraction the rheology becomes dominated by rock rather than the ice.

We will also investigate the effect of the grain size ratio between the ice grains and the rock grains. The role of the grain size ratio was highlighted by [6] showing that finer grained particulates formed a network around larger ice grains, preventing the formation of a homogeneous mixture.

We will be able to compare our data to that of [6] and increase the amount of data available for the rheology of these materials under conditions likely in icy satellites. The importance of a large data set of rheological experiments on these materials is demonstrated by Durham et al. [6], who found different flow laws for pure ice from different data sets. An increase in data will reduce the ambiguity of the results.

This should also allow us to evaluate the assumption of Nagel et al. [7] that the viscosity is a scale invariant relationship, and also compare results with the results of Friedson and Stevenson [9] based on the viscosity of a suspension.

The first stage in the experiments will be to develop a sample preparation apparatus which will allow the ice grain size, volume fraction of rock and mixing of the sample to be controlled as accurately as possible.

Then experiments on samples of various rock fraction will be conducted at conditions comparable with the literature, with systematic variation in rock fraction, grain sizes and grain size ratio.

We will be using three types of loading cell to investigate the rheological properties of these materials.

Triaxial. The main experiments will be conducted under triaxial conditions; the rig uses nitrogen gas as the confining medium to generate pressures up to 300MPa in the UCL cold room at temperatures as low as 250K, with additional refrigerant on the pressure vessel allowing us to reach ~180K.

Uniaxial. To investigate lower temperature conditions, we will be able to use the uniaxial loading cell with an added cold stage which has a theoretical minimum temperature of ~80K.

True-triaxial. The newly commissioned true-triaxial rig will allow experiments to be carried out in biaxial stress states, relevant to near surface processes in the large satellites up to pressures of 50MPa and temperatures down to 240K.

Application of parameters: The rheological parameters obtained from these experiments will be used to model the structural and thermal evolution of icy satellites, allowing differentiation and convection to be modelled more accurately during the early evolution of these bodies. The results will also be of relevance to the mechanical stability of rock-ice regolith on the Earth and Mars, including possible applications to the mechanical properties, and stability, of clathrate-sediment mixtures in the deep ocean which may have been related to large, rapid global warming events in the past [10].

References: [1] Song et al. (2006) Scripta Materialia, 55, 91-94 [2] Parameswaran and Jones (1981) J. Glaciol., 27, 147-156 [3] Mangold et al. (2002) Plan. Space. Sci., 50, 385-401 [4] Anderson et al. (1996) Nature, 384, 541- 543. [5] Anderson et al. (2001) Icarus, 153, 157-161 [6] Durham et al (1992) JGR, 97, 20883-20897 [7] Nagel et al. (2004) Icarus, 169, 402-412 [8] McKinnon (2006) Icarus, 183, 435-450 [9] Friedson and Stevenson (1981) Icarus, 56, 1-12 [10] Reagan and Moridis (2007), GRL, 34.