A review paper

• This does not (generally) carry out new analysis
• Instead it reviews a topic (often controversial)
• It describes and evaluates already-published arguments and comes to some conclusion
• Often it suggests how future work could resolve the issue

• If the title is a question, then the review should answer it! (to the extent it can be answered)
Does Europa have a subsurface ocean? 
Evaluation of the geological evidence


Abstract. It has been proposed that Jupiter's satellite Europa currently possesses a global subsurface ocean of liquid water. Galileo gravity data verify that the satellite is differentiated into an outer H₂O layer about 100 km thick but cannot determine the current physical state of this layer (liquid or solid). Here we summarize the geological evidence regarding an extant subsurface ocean, concentrating on Galileo imaging data. We describe and assess nine pertinent lines of geological evidence: impact morphologies, lenticularic, cryovolcanic features, pull-apart bands, chaos, ridges, surface frosts, topography, and global tectonics. An internal ocean would be a simple and comprehensive explanation for a broad range of observations; however, we cannot rule out the possibility that all of the surface morphologies could be due to processes in warm, soft ice with only localized or partial melting. Two different models of impact flux imply very different surface ages for Europa; the model favored here indicates an average age of ∼50 Myr. Searches for evidence of current geological activity on Europa, such as plumes or surface changes, have yielded negative results to date. The current existence of a global subsurface ocean, while attractive in explaining the observations, remains inconclusive. Future geophysical measurements are essential to determine conclusively whether or not there is a liquid water ocean within Europa today.
Structure

• Introduction
  – Why is this important? Putting it in context, previous work. Definitions, if required. Roadmap of rest of paper.

• Main Body
  – Different lines of evidence evaluated (surface observations, geophysics, impact craters etc.)

The purpose of this paper is to review and critically evaluate the geological and geophysical evidence relevant to the existence of an ocean within Europa currently or in the geologically recent past. In section 2 we summarize our knowledge about Europa's interior as revealed by Galileo gravity data and its expected physical state (ice or water) as predicted by thermal models. In section 3 we discuss the age of Europa based on its observed crater density, finding that our interpretations of Galileo images support a young, probably currently active Europa. Section 4 investigates nine lines of geological evidence, each of which has been noted in existing literature as suggesting a Europan ocean. The relevant Galileo SSI observations are reviewed, along with pertinent models derived from the imaging data; each line of evidence is evaluated critically, with discussion of whether the Galileo observations are indicative of liquid water, or whether warm ductile ice or a localized ice-liquid slurry could account for the observations. In section 5 our SSI search for current activity is reviewed. In section 6 we summarize the geological evidence and discuss implications for Europa's interior. In section 7 we review data from other Galileo instruments pertinent to the ocean issue. Section 8 considers how the ocean hypothesis can be tested with the upcoming Europa Orbiter spacecraft and potential future lander missions. Finally, in section 9 we present major outstanding questions relevant to a Europan ocean.
• Discussion
  – Summary: Evaluation of the Evidence
  – Further tests: Galileo or future missions

• Conclusion
  – How strong is the evidence for an ocean?
  – What is still uncertain or in need of further observations?

9. Major Outstanding Questions

Many questions about Europa have been answered with Galileo data, but many remain, as outlined throughout this work. Here are summarized five principal outstanding questions relevant to the current existence of a Euoran ocean.

1. What is the distribution of ice and liquid water within Europa today? Recently acquired Galileo data along with continued analysis and geophysical modeling will help to address this fundamental issue. Future geophysical measurements are necessary to answer this question more conclusively.

2. What is the age of the surface, and is Europa currently active? Improved determination of impactor fluxes, analysis of crater size-frequency distributions, understanding of processes that age surface materials, and searches for current activity will help to constrain Europa’s age and its degree of ongoing activity. Innovative techniques to more directly measure Europa’s surface age would be of great value.

3. Have there been changes in Europa’s heat flow and geological style through time? Geological mapping, morphological analyses, and geophysical modeling are vital to this issue, along with more extensive imaging coverage.

4. What impurities exist on and within Europa’s H2O-dominated outer layer? A combination of multispectral, theoretical, and laboratory investigations can address the nature and geological effects of Eurorian non-water-ice components, and their possible relevance to exobiology.

5. Have there been variations in Europa’s rotational and orbital characteristics through time? Geological mapping and theoretical modeling are necessary to better constrain the degree and rate of Europa’s nonsynchronous rotation and tidal evolution. Improved understanding of the geological histories of all four Galilean satellites is needed to address the issue of tidal evolution.
More on Introductions

• What is the main topic?
• Defines the terms of reference and vocabulary if needed e.g. “cryovolcanism”, “supervolcano”
• Explains why the topic is important
• Summarizes previous work / history of ideas
• Outlines the argument & logic followed in the rest of the paper (provides a roadmap)
• Sometimes provides a preview of the conclusions
1. Introduction

The outer solar system contains a stunningly diverse array of planetary bodies (Fig 1): Europa, with its bizarre array of surface features; tiny, geologically-active Enceladus; Titan, the only moon with a substantial atmosphere; Pluto, with its nitrogen glaciers; and many others. Over the last twenty-five years spacecraft measurements have revealed that many of these bodies are “ocean worlds”, possessing large volumes of liquid water beneath insulating ice shells. In this article we will review the exploration history of these ocean worlds, what we currently know about them, and what revelations the next twenty-five years may bring.

Ocean worlds are important for several reasons, but the most compelling is also the simplest: they could be abodes of life. Life as we know it requires liquid water, in addition to energy and nutrients, and all three requirements can potentially be satisfied within some of these bodies (Section 3.6). Future spacecraft investigations are likely to be increasingly focused on determining the extent to which particular bodies are potentially habitable.

There are at least two other reasons that ocean worlds are important to study. First, they represent systems that are both more complex and less well understood than the terrestrial planets. For example, on many ocean worlds the main source of heat is energy extracted from their orbits (Section 3.3.2). There is thus a strong coupling between thermal and orbital evolution which is almost entirely absent from the terrestrial planets. Similarly, the dynamics of global oceans beneath tidally-flexing ice shells represents a rich set of problems which have barely begun to be explored (Section 3.5). Second, the characteristics of these worlds provide clues to their history, and the evolution of the solar system as a whole. For instance, the fact that tiny Enceladus has managed to retain a global subsurface ocean may be telling us something profound about its orbital history (Section 3.3.2) and the evolution of the Saturnian system as a whole.

2. History of Exploration and Ideas

The main aim of this paper is to summarize how our understanding of ocean worlds has developed over the last twenty-five years. The subject is large enough that we cannot provide a comprehensive review. Instead, we have decided to focus on a series of questions, and to point the reader to other reviews where individual topics are treated in more detail. We discuss in turn the current understanding of where oceans are located; how they are detected; how they are maintained; characteristics and consequences of these oceans; and the extent to which they might be habitable. We begin with a general discussion of each of these topics, and then discuss applications to different ocean worlds. We focus in particular on the five bodies for which oceans are currently best established - Europa, Ganymede, Callisto, Enceladus and Titan - but where appropriate we mention other potential ocean worlds, including Triton and Pluto.
1. INTRODUCTION

Volcanism has long been implicated as a possible cause of weather and climate variations. Even 2000 years ago, Plutarch and others [Forsyth, 1988] pointed out that the eruption of Mount Etna in 44 B.C. dimmed the Sun and suggested that the resulting cooling caused crops to shrivel and produced famine in Rome and Egypt. No other publications on this subject appeared until Benjamin Franklin suggested that the Lakagigar eruption in Iceland in 1783 might have been responsible for the abnormally cold summer of 1783 in Europe and the cold winter of 1783–1784 [Franklin, 1784]. Humphreys [1913, 1940] associated cooling events after large volcanic eruptions with the radiative effects of the stratospheric aerosols but did not have a sufficiently long or horizontally extensive temperature database to quantify the effects. (Terms in italic are defined in the glossary, which follows the main text.) Mitchell [1961] was the first to conduct a superposed epoch analysis, averaging the effects of several eruptions to isolate the volcanic effect from other presumably random fluctuations. He only looked at 5-year average periods, however, and did not have a very long temperature record. Several previous reviews of the effects of volcanoes on climate include Lamb [1970], Toon and Pollack [1980], Toon [1982], Ellsaesser [1983], Asaturov et al. [1986], Kondratyev [1988], Robock [1989, 1991], and Kondratyev and Galindo [1997]. Past theoretical studies of the radiative effects include Pollack et al. [1976], Harshvardhan [1979], Hansen et al. [1992], and Stenchikov et al. [1998]. The work of H. H. Lamb, in fact, was extremely influential in the modern study of the impact of volcanic eruptions on climate [Kelly et al., 1998]. Since these reviews, a deeper and more complex understanding of the impacts of volcanic eruptions on weather and climate has resulted, driven by the many
studies of the impact of the 1991 Pinatubo eruption and continuing analyses of the 1982 El Chichón eruption in Mexico.

This paper reviews these new results, including the indirect effect on atmospheric circulation that produces winter warming of the Northern Hemisphere (NH) continents and the new impacts on ozone due to the stratospheric presence of anthropogenic chlorine. A better understanding of the impacts of volcanic eruptions has important applications in a number of areas. Attribution of the warming of the past century to anthropogenic greenhouse gases requires assessment of other causes of climate change during the past several hundred years, including volcanic eruptions and solar variations. After the next major eruption, new knowledge of the indirect effects on atmospheric circulation will allow better seasonal forecasts, especially for the NH in the winter. The impacts of volcanic eruptions serve as analogs, although imperfect ones, for the effects of other massive aerosol loadings of the atmosphere, including meteorite or comet impacts or nuclear winter.

The largest eruptions of the past 250 years (Table 1) have each drawn attention to the atmospheric and potential climatic effects because of their large effects in the English-speaking world. (Simkin et al. [1981] and Simkin and Siebert [1994] provide a comprehensive list of all known volcanoes and their eruptions.) The 1783 eruption in Iceland produced large effects all that summer in Europe [Franklin, 1784; Grattan et al., 1998]. The 1815 Tambora eruption produced the “year without a summer” in 1816 [Stommel and Stommel, 1983; Stothers, 1984; Robock, 1984a, 1994; Harington, 1992] and inspired the book Frankenstein [Shelley, 1818]. The most extensive study of the impacts of a single volcanic eruption was carried out by the Royal Society, examining the 1883 Krakatau eruption, in a beautifully produced volume including watercolors of the volcanic sunsets near London [Symons, 1888; Simkin and Fiske, 1983]. This was probably the loudest explosion of historic times, and the book includes color figures of the resulting pressure wave’s four circuits of the globe as measured by microbarographs. The 1963 Agung eruption produced the largest stratospheric dust veil in more than 50 years and inspired many modern scientific studies. While the Mount St. Helens eruption of 1980 was very explosive, it did not inject much sulfur into the stratosphere. Therefore it had very small global effects [Robock, 1981a]. Its tropospheric effects lasted only a few days [Robock and Mass, 1982; Mass and Robock, 1982], but it occurred in the United States and so received much attention. Quantification of the size of these eruptions is difficult, as different measures reveal different information. For example, one could examine the total mass ejected, the explosiveness, or the sulfur input to the stratosphere. The limitations of data for each of these potential measures, and a description of indices that have been produced, are discussed later.

Volcanic eruptions can inject into the stratosphere tens of teragrams of chemically and microphysically active gases and solid aerosol particles, which affect the Earth’s radiative balance and climate, and disturb the stratospheric chemical equilibrium. The volcanic cloud forms in several weeks by SO$_2$ conversion to sulfate aerosol and its subsequent microphysical transformations [Pinto et al., 1989; Zhao et al., 1995]. The resulting cloud of sulfate aerosol particles, with an e-folding decay time of approximately 1 year [e.g., Barnes and Hoffman, 1997], has important impacts on both shortwave and longwave radiation. The resulting disturbance to the Earth’s radiation balance affects surface temperatures through direct radiative effects as well as through indirect effects on the atmospheric circulation. In cold regions of the stratosphere these aerosol particles also serve as surfaces for heterogeneous chemical reactions
that liberate chlorine to destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole.

In this paper I first briefly summarize volcanic inputs to the atmosphere and review our new understanding of the radiative forcing of the climate system produced by volcanic aerosols. Next, I briefly review the results of new analyses of ice cores, since they give information about the record of past volcanism, and compare these new records to past analyses. The effects of eruptions on the local diurnal cycle are reviewed. Summer cooling and winter warming from large explosive eruptions are then explained. The impacts of volcanic eruptions on decadal- and century-scale climate changes, and their contributions to the Little Ice Age and their relative contribution to the warming of the past century, are next discussed. Then, I show that the simultaneous occurrence of the 1982 El Niño and the El Chichón eruption was just a coincidence and that it was not evidence of a cause and effect relationship. Finally, the impacts of volcanic eruptions on stratospheric ozone are briefly reviewed.
Homework – Week 4

• Write an Introduction for your topic (due next Tuesday)
• 600-1000 words
• Include some key references