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Key Points:
- Models by Buffo et al. (2020) illustrate possible implications of salt transport in Europa's ice, by analogy with Earth's sea ice dynamics
- Salts may significantly affect thermal and transport properties of icy lithospheres of ocean worlds
- The new work is part of the emerging study of ice petrology

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The Salty Secrets of Icy Ocean Worlds

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Abstract As new insights have emerged in recent decades about the dynamics of sea ice, researchers have sought to extend these insights to ice covered oceans in the solar system, where nonicy materials preserved in icy lithospheres may hold clues to solid-state convection and the possible presence of life. The recent study by Buffo et al. (2020), https://doi.org/10.1029/2020je006394, considers the salt content of the ice covering Jupiter's moon Europa in the context of gravity drainage and mushy layer theory, and makes provocative predictions about the amounts of salts retained in the ice. A major question in such studies is how well the preservation and transport of salts in ice translates to the length and time scales of ices in ocean worlds. This work underlines the fundamental importance of including the role of chemistry in the modeling the structures and dynamics of the ice layers in ocean worlds.

Plain Language Summary Earth's sea ice is a laboratory for inferring the workings of the icy lithospheres of the solar system's ocean moons, for example, Jupiter's moon Europa and Saturn's moons Enceladus and Titan. Recent work by Buffo et al. (2020) is one of the first efforts to quantify the potential entrainment of salts into the bulk of Europa's ice, extending the analysis of Earth's sea ice to the larger scales occurring in ocean world ices. This work is an important step toward understanding processes that may govern the potential for life in ocean worlds, and the potential for their icy lithospheres to hold onto clues of that life.

1. Main Text

A raft of papers in the last decade has advanced our understanding of the physics of floating sea ice covering tens of millions of kilometers of Earth's ocean. Seeding this research has been the need to quantify sea ice's role in global ocean circulation, a need to understand the stability of the ice through time, and interest in the ice itself as an ecological niche. One recent 1D model, by Buffo et al. (2018), captures the gravity drainage of brines initially entrained within forming ice, which flow through interconnected pores and melt channels within the ice. In follow-on work that was just published, Buffo et al. (2020) have extended their model to estimate the entrainment and transport of salts in the ice covering Jupiter's moon Europa. This type of work is timely, as the community of planetary scientists studying Europa and related ocean worlds sets its sails for NASA's Europa Clipper mission (Howell & Pappalardo, 2020), and ESA's JUpiter ICy moons Explorer (JUICE) mission (Grasset et al., 2013), planned to arrive at the Jupiter system toward the end of this decade. However, the work poses many further questions that will need to be addressed in the coming years.

Europa's ice is global, and at least 3 km thick—possibly 30 km or more—covering an ocean as deep as 180 km (Anderson et al., 1998, Turtle & Pierazzo, 2001; Schenk et al., 2002). Sparse crater counts among the fractured ice suggest the average age of surface materials is less than 200 Myr (Zahnle et al., 2003). Materials retained in the ice could provide clues to the ocean's thermal and chemical evolution, its current composition, and the possible presence of life. Demonstrating mechanisms for extensive material entrainment into the ice would also support the existence of brine reservoirs near Europa's surface, hypothesized to explain the chaotic terrains covering much of Europa's surface (Collins et al., 2000; Kattenhorn & Prockter, 2014; Schmidt et al., 2011; Steinbrügge et al., 2020). Such near-surface brine reservoirs could themselves be abodes for life, and might be accessible by a future landed spacecraft (Blanc et al., 2020; Hand et al., 2017; Pappalardo et al., 2013).

Movement of brines through Europa's ice have long been of interest, in part because they present a way to transport oxygenated materials produced from radiation at Europa's surface into the ocean, where they

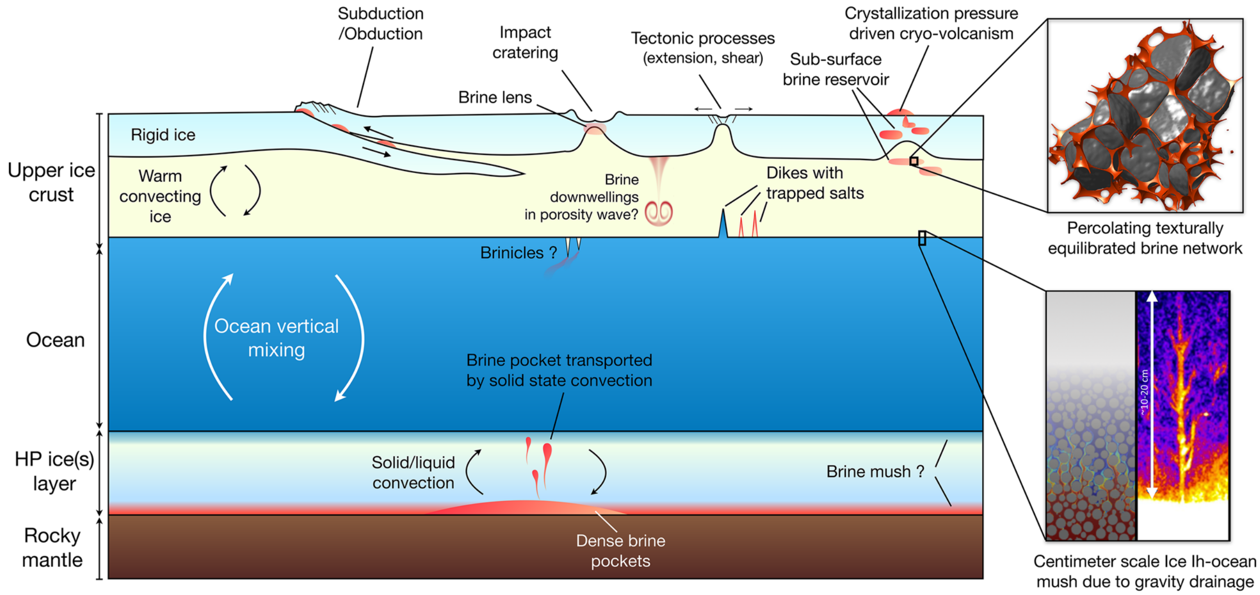

Figure 1. Phenomena in ocean world hydrospheres that are influenced by impurities such as salts and clathrates. The recent work by Buffo et al. (2020) considers the upper ice layer overlying the ocean, in particular the vertical drainage of melts depicted in the detail on the lower right (modified from that work). The insert with texturally equilibrated melt network (upper right) is from Ghanbarzadeh et al. (2017).

might provide energy for life (Hand et al., 2007; Russell et al., 2017; S. D. Vance et al., 2016). Tidal flexing of Europa's ice is expected to be a primary source of heat sustaining the ocean's existence (Tobie et al., 2003, 2005), and recent laboratory studies indicate that intragranular melts should form readily under such tidal flexing (McCarthy & Cooper, 2016). Intraice fluids should be gravitationally unstable amid relatively low-density ice. The ready percolation of brines along ice grain boundaries (Figure 1; De La Chapelle et al., 1999; McCarthy et al., 2013), should allow near-surface brines to drain into the ocean on 10,000-year timescales, if a permable pathway exists through the entire ice shell (Gaidos & Nimmo, 2000; Kalousova et al., 2014; Sotin et al., 2002). In the presence of thermal gradients, brines can also migrate laterally in pockets that then connect to larger reservoirs (Schmidt et al., 2011; Steinbrügge et al., 2020). Through such processes, the salinity of the ice shell may shape the dynamics of the ice and geologic features on the surface.

These prior studies have not included the influence of salts in a quantitative way that accounts for how their chemistry couples to putative melting and transport processes in Europa's ice. As in many geological processes on Earth, fractional crystallization and melting can create strong chemical gradients and density contrasts. Modeling the resulting kinetics, dynamics of fluid/solute transport, and the final mineral/fluid assemblages in ices taps into less explored regions of pressure, temperature, and composition in aqueous systems, as well as the rapidly advancing fields of reactive transport and terrestrial ice dynamics. Such effects may have primary roles in the vast hydrospheres of ocean worlds (Figure 1). New work seeking to quantify these effects in Europa's ice signals progress in this frontier in the study of icy ocean worlds.

The study by Buffo et al. (2020), one of the first studies seeking to quantify the effects of salinity, considers how specific ocean compositions and concentrations of salt may have been initially entrained into Europa's ice as it formed. By treating the different timescales of formation associated with different thicknesses of ice, the authors are able to explore how different thermal gradients affect the retention of salts in the ice. The new work matches measurements of salt retention in terrestrial sea ice cores at the meter scale, extending these to models of overall transport that span meters to tens of meters. Constitutive relations for the salt retention are obtained using available equilibrium chemistry. To examine the range of pressures and temperatures in Europa's ice, the team recomputes the constitutive relations for a series of depths within the ice, and thereby approximate the ice's local physical-chemical evolution.

While the work of Buffo et al. (2020) provides a needed advancement in terms of adding realistic aqueous chemistry to transport in the ice, it also underscores questions of scaling between Earth's thin ice sheets and the km-scale lithospheres of ocean worlds. The authors considered a top-down freezing scenario, in which initially very thin ice freezes to its present thickness. To make their reactive flow calculations tractable, they modified their model to actively track the permeable regions of the ice, determined as regions with porosity exceeding a specified critical value. This approach allowed them to extend their model from terrestrial scales of 10s–100s of cm and 10s–100s of days to the scales of meters and years appropriate to Europa. This innovation is a necessary step for considering Europa's ice. However, even longer distances of 10s of km, and timescales extending to centuries and longer, are almost certainly involved in the movement of salts within the ice, based on prior analyses of geodynamic processes cited above. Adding to this mismatch in scales, the authors do not account for eutectic salt precipitation or the precipitation of salt hydrates that would occur in their rapid freezing scenarios, possibly changing the retention of salt in the ice. The effect of pressure on thermodynamic properties is also ignored. Europa's outer ice shell pressure builds up to nearly 500 bars at 30 km depth. Effects of high-pressures include changes to the stability of high-pressure salt hydrates, shifts of the eutectic point, and changes in the fundamental thermodynamic properties of solids and aqueous fluids (Journaux et al., 2020a, 2020b).

Even with these simplifications in the models of Buffo et al. (2020), their predictions are worth considering. The new work is important for beginning to quantify the possible salt content of the ice. While others have noted that the concentration of salts within the lithospheres of icy worlds is certainly nonzero (S. D. Vance et al., 2019), the new work suggests an upper limit on the salt content. If Europa's ice froze rapidly in a manner similar to the formation of sea ice, regions near the top of the ice that formed first and quickest are likely to have held on to substantial amounts of salt, between 5% and 50% of the salinity of the original fluids. Buffo et al. (2020) estimate the bulk amounts of retained salts by considering freezing out of various concentrations of ocean that have been modeled over the years. Their upper-limit concentration for the ocean thus sets the salinity of the ice at 14 ppt by mass, nearly half the 34 ppt concentration of Earth's ocean, and about three times the nominal bulk salinity of multiyear sea ice (e.g., Weeks & Ackley, 1986). Obtaining this extreme concentration requires the constitutive relations for salinity in the ice to operate over scales of many km. The freeze-in also does not account for melting due to tidal heating or solid state convection. However, the high predicted concentrations may serve as a benchmark for regions of the ice where transport of fluids occurs rapidly and is limited in spatial extent (e.g., Schmidt et al. 2011; Steinbrügge et al. 2020).

This study also provides two interesting examples of freezing processes in geometries relevant for (i) basal fractures and (ii) shallow liquid pockets. The fracture case is especially interesting as it shows that even if the opening is short lived due to fast re-freezing (<1 kyr), significant amounts of salt can be trapped in pockets along the initial fracture walls, which might ease the later reactivation of fractures through mechanical weakening and melting point suppression. This example illustrates the unexpected effects arising from impurities in the ice. It should be noted that the authors acknowledge the limitations of their work in this example, as they neglect the formation of eutectic hydrate phases. Another effect not taken into account, especially important in the case of shallow liquid pockets, is the volume variations during freezing that can build up pressure in closed liquid pockets within the ice shell, enough to possibly trigger extrusion of cryo-magmas (Lesage et al., 2020).

The work of Buffo et al. (2020) provides testable hypotheses, as the presence of salts can affect the dielectric properties of the ice (Pettinelli et al., 2015), which could make the ice penetrating radar (Blankenship et al., 2009) on Europa Clipper susceptible to compositional variations. Due to such effects, regions of high salinity or perched water lenses could become observable from their influence on the reflection and attenuation properties of the ice under the right conditions. Overall, a higher bulk salinity in the ice may cause enhanced attenuation, which would impede efforts to sound to the depth of the ice-ocean interface, while the localized pocket described by Buffo et al. (2020) might instead be discerned as discrete features in the radargram. The detection of briny regions within Europa's ice using radar would be a boon to astrobiologists looking for potentially habitable regions in Jupiter's ocean moon.

Another strength of the recent work is to highlight where further research is needed. The model predictions are one-dimensional, ignoring lateral effects. They thus ignore heterogeneities in the entrainment of impurities in the ice, such as might arise from variations in heating below or within the ice. The adopted mushy layer theory (Feltham et al., 2006) and gravity drainage model (Griewank & Notz, 2013) will almost certainly be refined as research continues. As mentioned above, the model also ignores the influence of eutectic solutions that may upset the slow progress of gravity drainage and affect the final chemistry of the ice. Furthermore, the timescales involved in the evolution of Europa's ice shell are different from those of sea ice, where processes are governed by the seasonal freeze and thaw cycle. Consequently, effects that are slower and hence less relevant on Earth might become important, leading to competing processes within Europa's ice that might nullify the predictions of Buffo et al. (2020).

The new work underscores the importance of taking into account chemistry in describing the structure and chemical transport in ice layers of icy ocean worlds. The hydrospheres of larger icy worlds (e.g. Titan, Ganymede, Callisto) contain thicker ice shells of low and high-pressure ice polymorphs in contact with the ocean (Journaux et al., 2020a). The presence of salts or other solutes like ammonia, will most likely also create mushy layers (Kalousova & Sotin, 2020), where gravity drainage might play an important role in the dynamics, vertical transport, and potential habitability in different ice layers. In high-pressure ices, gravity-drainage effects may cause dense brines migrate toward the base of the HP ice layer rather than toward the upper ocean, trapping them at the seafloor. The stability of such layers has been demonstrated through laboratory studies (e.g., Journaux et al., 2013; S. Vance & Brown, 2013) and modeling (S. Vance et al., 2014, 2018), but the dynamical formation of such layers must be demonstrated with the kind of detailed modeling employed by Buffo et al. (2020). As with the ice I layer, the details of such effects will depend on the thermal and rheological structure of the ice, as well as the P-T-dependent thermodynamic properties of the fluids (Journaux et al., 2020a, 2020b). The work by Buffo et al. (2020) will hopefully inspire similar analyses applied to the broader range of pressure, temperature, and composition occurring in icy ocean worlds.

Data Availability Statement

Data were not used, nor created for this research.

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References

Anderson, J., Schubert, G., Jacobson, R., Lau, E., Moore, W., & Sjogren, W. (1998). Europa's differentiated internal structure: Inferences from four Galileo encounters. *Science*, *281*(5385), 2019–2022. https://doi.org/10.1126/science.281.5385.2019

Blanc, M., Prieto-Ballesteros, O., André, N., Gomez-Elvira, J., Jones, G., Sterken, V., et al. (2020). Joint Europa Mission (JEM): A multi-scale study of Europa to characterize its habitability and search for extant life. *Planetary and Space Science*, *193*, 104960. https://doi.org/10.1016/j.pss.2020.104960

Blankenship, D. D., Young, D. A., Moore, W. B., & Moore, J. C. (2009). Radar sounding of Europa's subsurface properties and processes: The view from Earth. In R. T. Pappalardo, W. B. McKinnon, & K. Khurana (Eds.), *Europa* (pp. 631–654). Tucson, AZ: University of Arizona Press.

Buffo, J. J., Schmidt, B. E., & Huber, C. (2018). Multiphase reactive transport and platelet ice accretion in the sea ice of McMurdo sound, Antarctica. *Journal of Geophysical Research: Oceans*, *123*, 324–345. https://doi.org/10.1002/2017JC013345

Buffo, J. J., Schmidt, B. E., Huber, C., & Walker, C. C. (2020). Entrainment and dynamics of ocean-derived impurities within Europa's ice shell. *Journal of Geophysical Research: Planets*, *125*, e2020JE006394. https://doi.org/10.1029/2020JE006394

Collins, G. C., Head, J. W., Pappalardo, R. T., N. A., & Spaun (2000). Evaluation of models for the formation of chaotic terrain on Europa. *Journal of Geophysical Research*, *105*, 1709–1716.

De La Chapelle, S., Milsch, H., Castelnau, O., & Duval, P. (1999). Compressive creep of ice containing a liquid intergranular phase: Rate-controlling processes in the dislocation creep regime. *Geophysical Research Letters*, *26*(2), 251–254. https://doi.org/10.1029/1998gl900289

Feltham, D. L., Untersteiner, N., Wettlaufer, J. S., & Worster, M. G. (2006). Sea ice is a mushy layer. *Geophysical Research Letters*, *33*, L14501. https://doi.org/10.1029/2006gl026290

Gaidos, E. J., & Nimmo, F. (2000). Planetary science: Tectonics and water on Europa. *Nature*, *405*, 637. https://doi.org/10.1038/35015170

Ghanbarzadeh, S., Hesse, M. A., & Prodanović, M. (2017). Percolative core formation in planetesimals enabled by hysteresis in metal connectivity. *Proceedings of the National Academy of Sciences*, *114*(51), 13406–13411. https://doi.org/10.1073/pnas.1707580114

Grasset, O., Dougherty, M., Coustenis, A., Bunce, E., Erd, C., Titov, D., et al. (2013). JUpiter ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the Jupiter system. *Planetary and Space Science*, *78*(0), 1–21. https://doi.org/10.1016/j.pss.2012.12.002

Griewank, P. J., & Notz, D. (2013). Insights into brine dynamics and sea ice desalination from a 1-D model study of gravity drainage. *Journal of Geophysical Research: Oceans*, *118*(7), 3370–3386. https://doi.org/10.1002/jgrc.20247

Hand, K., Carlson, R., & Chyba, C. (2007). Energy, chemical disequilibrium, and geological constraints on Europa. *Astrobiology*, *7*(6), 1006–1022.

Hand, K. P., Murray, A. E., Garvin, J., Brinckerhoff, W. B., Christner, B. C., Edgett, K. S., et al. (2017). Report of the Europa lander science definition team. Technical report, Jet Propulsion Laboratory, California Institute of Technology. JPL D-97667.

Howell, S. M., & Pappalardo, R. T. (2020). NASA's Europa Clipper—A mission to a potentially habitable ocean world. *Nature Communications*, *11*(1), 1–4. https://doi.org/10.1038/s41467-020-15160-9

Journaux, B., Brown, J. M., Pakhomova, A., Collings, I. E., Petitgirard, S., Espinoza, P., et al. (2020b). Holistic approach for studying planetary hydrospheres: Gibbs representation of ices thermodynamics, elasticity, and the water phase diagram to 2,300 MPa. *Journal of Geophysical Research: Planets*, *125*, e2019JE006176.

Journaux, B., Daniel, I., Caracas, R., Montagnac, G., & Cardon, H. (2013). Influence of NaCl on ice VI and ice VII melting curves up to 6 GPa, implications for large icy moons. *Icarus*, *226*, 355–363.

Journaux, B., Kalousová, K., Sotin, C., Tobie, G., Vance, S., Saur, J., et al. (2020a). Large Ocean Worlds with High-Pressure Ices. *Space Science Reviews*, *216*(1). https://doi.org/10.1007/s11214-019-0633-7

Kalousová, K., Schroeder, D. M., & Soderlund, K. M. (2017). Radar attenuation in Europa's ice shell: Obstacles and opportunities for constraining the shell thickness and its thermal structure. *Journal of Geophysical Research: Planets*, *122*, 524–545. https://doi.org/10.1002/2016JE005110

Kalousová, K., & Sotin, C. (2020). Dynamics of Titan's high-pressure ice layer. *Earth and Planetary Science Letters*, *545*, 116416. https://doi.org/10.1016/j.epsl.2020.116416

Kalousová, K., Souček, O., Tobie, G., Choblet, G., & Čadek, O. (2014). Ice melting and downward transport of meltwater by two-phase flow in Europa's ice shell. *Journal of Geophysical Research: Planets*, *119*(3), 532–549. https://doi.org/10.1002/2013JE004563

Kattenhorn, S. A., & Prockter, L. M. (2014). Evidence for subduction in the ice shell of Europa. *Nature Geoscience*, *7*(10), 762–767. https://doi.org/10.1038/ngeo2245

Lesage, E., Massol, H., & Schmidt, F. (2020). Cryomagma ascent on Europa. *Icarus*, *335*, 113369. https://doi.org/10.1016/j.icarus.2019.07.003

McCarthy, C., Blackford, J. R., & Jeffree, C. E. (2013). Low-temperature-SEM study of dihedral angles in the ice-I/sulfuric acid partially molten system. *Journal of Microscopy*, *249*(2), 150–157. https://doi.org/10.1111/jmi.12003

McCarthy, C., & Cooper, R. F. (2016). Tidal dissipation in creeping ice and the thermal evolution of Europa. *Earth and Planetary Science Letters*, *443*, 185–194. https://doi.org/10.1016/j.epsl.2016.03.006

Pappalardo, R., Vance, S., Bagenal, F., Bills, B., Blaney, D., Blankenship, D., et al. (2013). Science potential from a Europa lander. *Astrobiology*, *13*(8), 740–773.

Pettinelli, E., Cosciotti, B., Di Paolo, F., Lauro, S. E., Mattei, E., Orosei, R., & Vannaroni, G. (2015). Dielectric properties of Jovian satellite ice analogs for subsurface radar exploration: A review. *Reviews of Geophysics*, *53*, 593–641. https://doi.org/10.1002/2014RG000463

Russell, M. J., Murray, A. E., & Hand, K. P. (2017). The possible emergence of life and differentiation of a shallow biosphere on irradiated icy worlds: The example of Europa. *Astrobiology*, *17*(12), 1265–1273. https://doi.org/10.1089/ast.2016.1600

Schmidt, B. E., Blankenship, D. D., Patterson, G. W., & Schenk, P. M. (2011). Active formation of 'chaos terrain' over shallow subsurface water on Europa. *Nature*, *479*. https://doi.org/10.1038/nature10608

Schenk, P. M. (2002). Thickness constraints on the icy shells of the Galilean satellites from a comparison of crater shapes. *Nature*, *417*(6887), 419–421. https://doi.org/10.1038/417419a

Sotin, C., Head, J. W., & Tobie, G. (2002). Europa: Tidal heating of upwelling thermal plumes and the origin of lenticulae and chaos melting. *Geophysical Research Letters*, *29*(8), 74-1. https://doi.org/10.1029/2001gl013844

Steinbrügge, G., Voigt, J. R. C., Wolfenbarger, N. S., Hamilton, C. W., Soderlund, K. M., Young, D. A., et al. (2020). Brine migration and impact-induced cryovolcanism on Europa. *Geophysical Research Letters*, *47*, e2020GL090797. https://doi.org/10.1029/2020GL090797

Tobie, G., Choblet, G., & Sotin, C. (2003). Tidally heated convection: Constraints on Europa's ice shell thickness. *Journal of Geophysical Research*, *108*(E11), 5124. https://doi.org/10.1029/2003je002099

Tobie, G., Mocquet, A., Sotin, C. (2005). Tidal dissipation within large icy satellites: Applications to Europa and Titan. *Icarus*, *177*(2), 534–549. https://doi.org/10.1016/j.icarus.2005.04.006

Turtle, E. P., & Pierazzo, E. (2001). Thickness of a European ice shell from impact crater simulations. *Science*, *294*(5545), 1326–1328. https://doi.org/10.1126/science.1062492

Vance, S. D., Barge, L. M., Cardoso, S. S., & Cartwright, J. H. (2019). Self-assembling ice membranes on Europa: Brinicle properties, field examples, and possible energetic systems in icy ocean worlds. *Astrobiology*, *19*(5), 685–695. https://doi.org/10.1089/ast.2018.1826

Vance, S., Bouffard, M., Choukroun, M., & Sotin, C. (2014). Ganymede's internal structure including thermodynamics of magnesium sulfate oceans in contact with ice. *Planetary and Space Science*, *96*, 62–70. https://doi.org/10.1016/j.pss.2014.03.011

Vance, S., & Brown, J. (2013). Thermodynamic properties of aqueous MgSO4 to 800 MPa at temperatures from −20 to 100 °C and concentrations to 2.5 mol kg^{-1} from sound speeds, with applications to icy world oceans. *Geochimica et Cosmochimica Acta*, *110*, 176–189. https://doi.org/10.1016/j.gca.2013.01.040

Vance, S. D., Hand, K. P., & Pappalardo, R. T. (2016). Geophysical controls of chemical disequilibria in Europa. *Geophysical Research Letters*, *43*(10), 4871–4879. https://doi.org/10.1002/2016GL068547

Vance, S. D., Panning, M. P., Stähler, S., Cammarano, F., Bills, B. G., Tobie, G., et al. (2018). Geophysical investigations of habitability in ice-covered ocean worlds. *Journal of Geophysical Research: Planets*, *123*, 180–205. https://doi.org/10.1002/2017JE005341

Weeks, W. F., & Ackley, S. F. (1986). The growth, structure, and properties of sea ice. In *The geophysics of sea ice*, (pp. 9–164). Boston, MA: Springer.

Zahnle, K., Schenk, P., Levison, H., & Dones, L. (2003). Cratering rates in the outer Solar System. *Icarus*, *163*(2), 263–289. https://doi.org/10.1016/s0019-1035(03)00048-4